Realising Catastrophe:
the Financial Ontology of the Anthropocene

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Lay Summary

In the late 1980s, mathematical models, so-called 'catastrophe models', were brought into everyday use in the insurance industry, a sector that is fundamental for how our societies' manage and mitigate risks. These models simulate natural disasters, such as large earthquakes or storms. Because more and more such disasters occur, the models solve a growing problem: to know how much damage and financial loss a disaster would amass before it actually happens. This is important for insurance, who needs to know about possible future loss so it can calculate the price for insurance policies, determine how much funds it needs to save to pay for possible costs of insureds, and to stay financially afloat and overall profitable. By investigating these models and their use, this thesis shows three things. First, it provides a historical account of the emergence, developments and integration of catastrophe modelling into use in financial services from the 1980s until today, a practice which fundamentally redefined – and in part even created – a global financial market for trading natural disaster risk. Second, and more importantly, the thesis shows how by making them calculable, natural disasters have become a financial good that underpins the market-oriented way in which (primarily western) societies deal with such large environmental threats. Third, and most importantly, this thesis argues that natural catastrophes are, in fact, not 'natural' but are fundamentally created by society. Humans design their own environments, most importantly where and how buildings and settlements are built and maintained, with which natural phenomena such as storms or earthquakes interact. In other words, without us there would be nothing for these phenomena to interact with and, therefore, no catastrophe would occur. Because you almost always need insurance to buy and build a house, a factory, a road, etc. and it often has a say in how you do it, finance contributes to our human-made environments in important ways. Catastrophe modelling, by producing knowledge in form of *virtual* catastrophe in mathematical models, then, plays a major role in how finance helps design environments with respect to disasters and, therefore, helps 'produce' *actual* catastrophes in the first place. The important role that finance plays in social life in general, this thesis shows, also takes place in the ways how 'natural' disasters manifest and play out not only socially but also materially, not only virtually but also actually, in real environments. Therefore, the main finding of this thesis is the following: In environments that are *social*, *material* and *natural* at the same time (i.e., 'Anthropocene'), that what a catastrophe actually *is* (i.e., 'ontologically') is constituted also by *finance*. This 'financial ontology of the Anthropocene' is what this thesis suggests to add to our understanding of catastrophe and also of broader environmental issues such as climate change.

Abstract

This dissertation investigates how the financial risk management practice of *catastrophe modelling* is redefining the ontology of natural catastrophe. Drawing from and developing the concept of the 'Anthropocene', referring to co-production of the 'social' and the 'natural' on a planetary scale, the dissertation argues that simulation-based risk modelling of future 'natural' disasters in insurance and reinsurance markets is not just affecting how catastrophe is interpreted by economic agents, economised and financialised, but is also driving changes in the realisation of actual disasters. The thesis calls this recursive dynamic the 'financial ontology of Anthropocene catastrophe'. In developing the argument, the thesis extends actor-network theoretical perspectives on the Anthropocene to take fuller account of market devices, performativity and calculative practices in finance. Documentary research, 62 interviews and 14 participant observation episodes serve to reconstruct current practices of catastrophe modelling and its history since it emerged as a boutique risk management practice in the 1980s. Ultimately, it has become embedded in the calculative practices of some of the largest insurance and financial companies in the world and underpinning a specialist disaster securities market. Adding conceptual depth and fine-grained empirical detail to literature on the financialisation-Anthropocene nexus, the dissertation asks us to reconsider the boundaries between economic representations of the world and the meaning and occurrence of catastrophes in market societies. In an age of anthropogenic climate change, the thesis also serves as an analytical and historical underpinning of epistemic practices in climate finance in the emerging, even more encompassing, 'financial ontology of the Anthropocene'.

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List of Abbreviations

AAL	Average annual loss
AEP	Aggregate Exceedance Probability
AIR	Applied Insurance Research (vendor)
AMO	Atlantic Multidecadal Oscillation
ART	Alternative risk transfer
ATC	Applied Technology Council
CDMG	California Division of Mines and Geology
CEA	California Earthquake Authority
CEDE	Catastrophe Exposure Database Exchange (AIR)
CGS	California Geological Survey
CRESTA	Catastrophe Risk Evaluation and Standardizing Target Accumulations
CRO	Chief Risk Officer
CRS	Community Rating System
EBTRK	Tropical Cyclone Extended Best Track Dataset
EDM	Exposure data module (RMS)
ELT	Event loss table
ENIAC	Electronic Numerical Integrator and Computer
EP	Exceedance probability
EQE/EQECAT	Earthquake Engineering (vendor)
ERM	Enterprise risk management
FCHLPM	Florida Commission on Hurricane Loss Projection Methodology
FEMA	Federal Emergency Management Agency
FHCF	Florida Hurricane Catastrophe Fund
FINRA	Financial Industry Regulatory Authority
FONDEN	Fund for Natural Disasters of Mexico
FPHLM	Florida Public Hurricane Loss Model
FRPCJUA	Florida Residential Property and Casualty Joint Underwriting Association
FWUA	Florida Windstorm Underwriting Association
HERP	Headquarters for Earthquake Research Promotion
HURDAT	The Hurricane Database (by the US National Hurricane Center)
IBTrACS	International Best Track Archive for Climate Stewardship
IED	Industry exposure database
ILSs	Insurance-linked securities
IRAS	Insurance and Investment Risk Analysis System (RMS)
ISO	Insurance Services Office
JMA	Japan Meteorological Agency scale
LiDAR	Light Detection And Ranging
MMI	Modified Mercalli intensity scale
MMS	Moment Magnitude scale
NAIC	National Association of Insurance Commissioners
NDIC	Natural Disaster Insurance Corporation

NFIP	National Flood Insurance Program
NHC	US National Hurricane Center
NOAA	National Oceanic and Atmospheric Administration (US)
ODS	Open Data Standard
OED	Open Exposure Standard
OEP	Occurrence Exceedance Probability
ORD	Open Results Standard
OTC	Over the counter
PML	Probable maximum loss
PRA	Probabilistic risk assessment
PSHA	Probabilistic Seismic Hazard Analysis
RDM	Results Data Module (RMS)
RDOS	Risk Data Open Standards (RMS)
RMS	Risk Management Solutions (vendor)
SEC	Securities and Exchange Commission
SFHA	Special Flood Hazard Area
SLOSH	Sea, Lake, and Overland Surges from Hurricanes
SPV	Special purpose vehicle
SSHS	Saffir-Simpson Hurricane Scale
SSHWS	Saffir-Simpson Hurricane Wind Scale
USGS	US Geological Survey
VaR	Value-at-Risk
WMO	World Meteorological Organization

Content

Chapter 1. Introduction

> "the forms of catastrophe take the shape of their culture [...] isn't every system of prevention and deterrence a virtual locus of catastrophe?"
>
> (Baudrillard, 1992: 195f)

> "Why was Florida lucky not getting hit by a major hurricane lately? I mean, luck is the answer when you just don't have data. It's just all probability."
>
> (Interviewee U53, 2018).

Figure 1: left: Mosher, High Water Line, NYC, 2007, photo: Hose Cedeno, © Eva Mosher; right: Melhus, 99 Luftballons zur 98. Biennale di Venezia 2099, 2009, photomontage, © VH Bild-Kunst, Bonn 2018/Björn Melhus (Schneider, 2018: 108)

In 2007, the artist Eve Mosher undertook an art campaign in which she drew an over 100-kilometre-long white chalk line through the New York Bay Region including Manhattan and Brooklyn. She had taken projections from the journal Global and Planetary Changes and applied the modelled data to a representation of a then 1-in-100 year flood line – she "inscribed into the actuality of the city the abstract tables, curves, maps and diagrams of scientific articles" that projected future disaster (Schneider, 2021: 52; my translation). A couple of years later, the artist Björn Melhus proposed an art campaign for the 2009 Biennale di Venezia in which he planned to decorate the canals of Venice with balloons that would signify the sea level in the city at the end of the century, indicating the Biennale in 2099 to be underwater. While Melhus's proposal projected climate change's gradual sea level rise towards a fixed and not-yet actualised time horizon, Mosher's artistic projection would actualise five years after her campaign when Hurricane Sandy in 2012 devastated the city and its storm surge washed away her chalk line (ibid.).

Birgit Schneider sees such works of art, and especially Mosher's unintentionally realised "claim to reality", as following what Jean Baudrillard identified as the "seismic form" (Schneider, 2021: 53, 55). Illustratively using early warning systems and predictive modelling from seismology, Baudrillard mobilises such projection practices as producing instead of actualised seismic energy "symbolic energy" whose potential's impact on the real world supersedes that of an actual earthquake long before and after it happens (Baudrillard, 1992: 196). Unlike a catastrophic seismic wave, "the symbolic wave of an earthquake will most likely never subside: symbolic energy […] is incomparable to any material destruction." (ibid.). The production of modelled and projected disaster, in his argument, finds its way into the real world in a more lasting and 'real' way than actualised disaster ever could. Although seemingly a bold claim, Baudrillard refers to the real potential of anticipation of disaster where it has not happened yet and which requires a form of management, "in the absence of a real catastrophe it is quite possible to trigger one off by simulation […] Designed to thwart catastrophe, it materializes all of its consequences in the immediate present. Since we cannot count on chance to bring about a catastrophe, we must find an equivalent programmed into the defence system" (ibid.). For Baudrillard, it is the "mental effect of catastrophe: stopping things before they come to an end, and holding them suspended in their apparition", which is "the form of catastrophe inherent to the era of simulation" (ibid.: 196f). Art in its productive creation of intentional representations of worlds that intersect, one way or the other, with reality, achieves this reality claim of projection through materialised conceptual practices. Mobilising knowledge of any kind and projections onto the real world is inherent to any artistic act, and artists such as Mosher and Melhus make this explicit when they "use the thin and aesthetically meagre lines of scientists and insert them directly into reality" (Schneider, 2018: 107; my translation).

While Baudrillard's provocative and rather audacious understanding of catastrophe, simulacra and simulated-reality-becoming-real (or rather 'hyperreal') appears fitting for a conceptual application in art, elsewhere it can seem rather esoteric for understanding the role of disaster projection in epistemic practices, their ontological claims, and their societal and material consequences. Although not drawing on Baudrillard's concepts in its analysis, this thesis is asking from a pragmatist perspective (Muniesa, 2014), what constitutes catastrophe epistemically and ontologically if the 'real' was dominated or distorted by disaster projection activities; what the 'simulacrum' of catastrophe would be if one would take Baudrillard, against all better judgement, literally through a pragmatist lens. What does it mean to 'produce' catastrophe pre-emptively in projection practices to manage it by epistemic means – to try to 'know what's coming' in order to act on it – and what consequences does it have for societal 'reality' or, rather, for its 'realising' in a pragmatist ontology?

In putting forward an answer to the sociological meaning of this, this thesis is about the question of realising catastrophe. It is about the very practical connection of epistemology and ontology: how knowledge production realises very critical aspects of the contemporary world, a world that is comprised of social and material interactions where 'nature' and the 'social', especially when it comes to catastrophe, cannot be separated and is, thus, understood here as an expression of the 'Anthropocene'. As such, it focuses on a pivotal realm of Anthropocene market society, which has increasingly gained importance in the management of catastrophe: financial markets' disaster risk management. The understanding of the Anthropocene in this study includes not only general societal activities as sources of our planetary situation but also financial activities as active compounds of the shaping of the Anthropocene. The practical connection between epistemology and ontology that this study investigates in financial activities is centred around knowledge production, which forms a, if not the, most central practice enabling and underlying competition and economic performance in general. Disaster knowledge production, in this sense, realises markets and, for better or worse, crucial elements of the Anthropocene which markets find themselves embedded in.

With this focus, this thesis is generally situated in economic sociology. In particular, it draws on and extends the field of the social studies of finance (e.g. Birch and Muniesa, 2020; Caliskan, 2010; MacKenzie et al., 2012; Pardo-Guerra, 2019; Poon, 2009) with actor-network theory-based work on the Anthropocene (e.g. Latour, 2014a, 2017a). The socio-materiality of catastrophe, both as an economised and financialised object in financial markets and as an element of the Anthropocene ontologically shaped by financial practices, bridges those two fields in this thesis. Based on the notion of 'performativity' (e.g. Aspers, 2007; Callon, 2010; MacKenzie, 2006), the 'realisation' (Caliskan, 2007; Muniesa, 2014) of catastrophe via simulation modelling in finance is applied and extended to postulate socio-material impacts of epistemic and risk managerial financial practice on Anthropocene environments. Within the broader scholarship on 'financialisation' (e.g. Chiapello, 2015; Davis and Kim, 2015; van der Zwan, 2014), the 'financialisation of nature' (e.g. Keucheyan, 2018; Kill, 2014; Sullivan, 2013) is advanced by conceptualising and analysing the reciprocity between financial practices, models and markets and the ontological condition of the Anthropocene in which the notion of 'nature' as distinct from the 'social' is inherently problematised. As such, the thesis works within and extends concepts and empirical work around turning things into economic objects (Caliskan and Callon, 2009, 2010; Muniesa et al., 2016) by positioning Anthropocene catastrophe as co-produced by financial services, constructing market-shaped Anthropocene environments. Moved into Appendix A due to word-count limits, an extension of this thesis's argument towards climate crisis and climate finance constitutes the broader applicability of the concept towards a 'financial ontology of the Anthropocene'.

In line with and extending this body of scholarship, the very real construction and shaping of social and material worlds are processes that are, therefore, driven also by epistemic tools and practices from the financial realm. These practices' own epistemologies are, in turn, deeply entangled in the imperatives of competition and economic performance and extend these imperatives into the ontology of the Anthropocene of which they are an active part of. By performing disaster projections to manage catastrophe risks, actors do something similar as artists such as Mosher or Melhus. The drawing of chalk lines or the installation of balloons as insertions of disaster knowledge projections into reality, one could argue, is performed in the financial realm by market societies' primary risk management framework: insurance and reinsurance.

I. Catastrophe and Finance

On a global scale, catastrophe is abundant and so is the financial loss it amasses every year. According to Swiss Re, there were 189 'natural' disaster events (e.g. earthquakes, hurricanes, floods, etc.) in 2020, which accounted for $190 billion loss of which $ 81 billion was insured (Swiss Re, 2021). The annual average for the previous ten years is $79 billion insured loss with an annual ten-year average of 187 events, which means that 2020, economically speaking, was a slightly above average year. In comparison, 2005, the year of an unusually strong hurricane season including Hurricane Katrina, produced 'only' 164 events accounting for about $326 billion total and $142 billion insured losses (ibid). 2017 with its main driving factors, the hurricane cluster of Harvey, Irma and Maria, and particularly severe wildfires on the North American continent, however, turned out to be an even costlier year with a total of $ 369 billion loss of which $ 153 billion were insured (Swiss Re, 2018b). In the US and for wind-related disaster alone, an estimated $ 28.3 trillion worth of homes, businesses, and infrastructure is directly endangered by hurricanes (National Underwriter P&C, 2017).

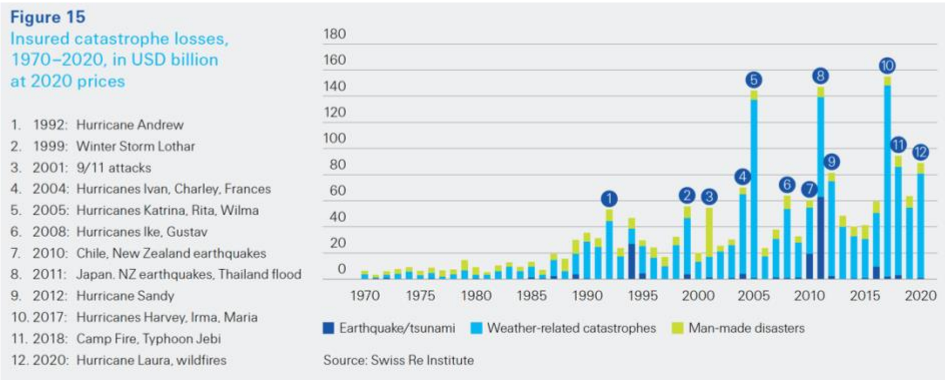

Figure 2: Insured catastrophe losses 1970-2020 (Swiss Re, 2021)

Insurance as a financial service is the primary arena in which finance's tendency to ingest ever more aspects of societal aspects is applied to catastrophe. Within insurance, disaster is part of the so-called 'non-life' property and casualty business (as opposed to life and health insurance), which insures anything from homes, factories, vehicles, to infrastructure or business interruption. Part of this risk management system are also the insurers of insurers, so-called reinsurance firms, who reinsure primary insurers' entire policy portfolios against major, solvency-threatening loss from disaster events. Primary insurance spreads the loss risk of individual insurance policies, for example for our houses or businesses, across its entire portfolio of insurance policies in order to distribute repair or replacement costs or make up for business interruption loss from the pool of overall collected insurance premiums. This insurance principle of 'risk-pooling' is folded withershins, so to speak, in the case of catastrophe reinsurance, where reinsurance deals involve many reinsurers agreeing to cover for only pre-defined portions of different 'tranches of risk' within individual primary insurance portfolios (see Jarzabkowski, et al., 2015).

Although both insurers and reinsurers deal with the risk of disasters, it is especially reinsurance that has to focus on large-scale catastrophe since through its reinsurance deals with primary insurers it has to make good the loss from disasters from a certain loss amount upwards, the so-called 'attachment point' – think of it like the deductible limit of your car insurance, where you have to pay repair costs yourself up to a certain amount from which on your car insurance takes care of the rest of the costs. In catastrophe reinsurance, this is the most common form of deal and is called 'excess-of-loss' reinsurance (in contrast to e.g., proportional deals, where the reinsurer is a partner of the primary insurer, directly sharing parts of both any loss and any premiums from insureds). To prepare for large loss, both insurers and reinsurers need to set aside capital for the event of having to pay loss claims, which is usually held in stable and liquid assets such as government bonds. Apart from these reserves, (re)insurers also have asset management arms where they manage their capital via investments in the capital markets, and which is an important part of their balance sheets in addition to premiums income and (re)insurance liabilities. As a complement to these 'traditional' forms of catastrophe (re)insurance, the so-called 'alternative risk transfer' space has developed since the 1990s, which mainly hinges on 'insurance-linked securities' (ILSs). These are structured financial instruments which securitise catastrophe risk in, for instance, catastrophe bonds. Even though the companies who construct, market and manage these instruments are not exclusively reinsurance companies in the traditional sense, they do increasingly provide reinsurance cover, too. The global reinsurance capital, much of which is dedicated to catastrophe cover, was estimated for 2021 to be at $658 billion (Seekings, 2021), of which ILSs as the 'non-traditional' part take up about 20% (Amwins, 2021).

Against this backdrop, one could assume that experience with, and knowledge on, 'natural' catastrophe is abundant given its frequent presence. For one of the core practices enabling the financial treatment of catastrophe, however, the production and usage of catastrophe knowledge presents a very complex task. To determine, hedge and manage the loss future disaster events pose to insureds, insurers, reinsurers and insurance-linked securities, financial practice requires knowledge on the likelihood and extent of future catastrophe expressed in risk values. Based on the thus produced 'riskiness' of insured objects, manifesting in their insurance policies, catastrophe risk can be priced in a risk-return format that, in principle, allows to cover for (re)insured loss and, at the same time, turn a profit for the (re)insuring party, keeping the (re)insurance principles of risk spreading and pooling afloat and with it market societies' main risk management system.

The locus of this knowledge production and the creation of risk values for catastrophe loss is the practice of *catastrophe modelling*, which is the central access point of this study to approach the question of the sociological meaning and implications of producing projected, future catastrophe in Anthropocene market society. The primary domain of catastrophe modelling is that of a small set of specialist firms that produce the tools in this field: *catastrophe models*. Fed by various types of public and proprietary data on, for instance, the environment, physical makeup, history and value of insured objects, these models simulate disaster events, such as hurricanes or earthquakes, which they unleash onto portfolios of insureds' objects and determine the probabilities of occurrence and severity of loss. The practices and tools of catastrophe modelling enable market-based catastrophe risk management by mediating social and material environments and simulating their interaction with catastrophic phenomena. In ascribing risks to specific objects and environments, catastrophe modelling provides financial services with the means to economise and financialise catastrophe to the extent that the (dis)incentive structures of insurance, for instance prescribing certain construction features to buildings or increasing premiums for disaster-prone locations, has effects for the actual social and material makeup of Anthropocene spaces. By means of such epistemic catastrophe projections, knowing about the 'riskiness' of catastrophe and putting a price on its actualised consequence and future mitigation positions catastrophe (re)insurance as an influential actor in the shaping of very real worlds. Like the practices of artists such as Mosher and Melhus, catastrophe modelling and its application in (re)insurance enables to inscribe into reality the projections of catastrophe that are yet to come, producing, in this way, also actualised catastrophe.

This interaction of epistemic practices and ontological realisation is the focus of this study. The thesis will theorise, historically investigate and empirically analyse how this interaction in finance has come into being, proliferated over time and has become an important arena of market societal reality, what I suggest to call a 'financial ontology of Anthropocene catastrophe'. It is the process of how particular modes of epistemic practices produce a financially shaped realisation of projected Anthropocene worlds, which have very real consequences – these consequences, however, can only be schematically studied here, due to the limited nature of a PhD thesis's scope. The central research question of this study, therefore, is: *How are the epistemic financial risk management practices of catastrophe modelling in disaster risk markets active in the ontological shaping of catastrophe in the market-societal Anthropocene?*

II. Studying Catastrophe Finance and Modelling Practices

When I had to present the outline of this project at a conference at the University of Edinburgh in 2017, I prepared my presentation slides with images to try make what was likely to become a rather dry talk about financial risk modelling at least visually more attractive. The first draft entailed a host of photographs from disaster sites. The problem that dawned on me with this representation of catastrophe had already been lurking during preliminary research on the project: catastrophe is somehow always mediated and represented and through it shaped, (re)constructed, (re)interpreted, appropriated. The issue here is less that journalistic photographs of disaster sites are, as any produced imagery, representations, but rather that the depicted appears as a reflection of reality without articulating the decisions made in the process of representational practices, aesthetic as well as content-related ones. What this study is about, though, is to show how representations of catastrophe are subject to specific decisions in their design with consequences not only in the relayed (re)interpretation of catastrophe but also in the very real environments they are inscribed in by financial risk management activities. Representations of disaster, in this way, are influential and active in the processes of managing and realising catastrophe. Therefore, I chose to select pieces of art as representations of catastrophe since their interpretative activities and decisions are explicit in their depictions.

This thesis, therefore, runs its analysis of catastrophe modelling, the creation of its tools, its embedding as an epistemic practice into financial usage, and the changes of those tools and practices by its users along illustrations via pieces of art and their representational practices. This reference to the art world goes beyond mere textual decoration and mobilises specific art practices and their influences on the representations they produce and reproduce, as it helps to explain how catastrophe modelling and its representations, its production and reproduction of catastrophe, changed over time. In opening the rather practical parallel between representational practices in art with those in catastrophe modelling, this thesis appreciates the active acts of (re)interpretations and decisions in the 'production' of catastrophe. One primary difference is, of course, that consequences in art reside first and foremost in the aesthetic and cultural realm, while those in catastrophe modelling appear in explicit financial, political, social and material arenas. Similar, however, is the fact that both realms do not seek universal truth of catastrophe but, instead, specific versions of it serving particular purposes: in art most often to aesthetically illustrate the drama, chaos and culture that disaster inflicts, in catastrophe modelling to provide epistemic means to manage specific financial risks. That does not mean, of course, that the social and political are meaningless to catastrophe modellers and financial actors, but the claim to the implicit factual and unfiltered reality of human suffering and devastation, that often comes across, for instance, in journalistic photographs of disasters, is not the primary concern of financial catastrophe risk management, and neither are the reality claims of artists, but always purposeful abstractions and (re)constructions of catastrophe. This study, therefore, ingests this framing of representing catastrophe by investigating the processes, practices, tools and environments of catastrophe 'production'.

a. Sources of Data

The primary empirical access points for this study were, therefore, actors who are active in the production of catastrophe representations and their usage in financial practice – as if following Mosher in her conceptualisation of the High Water Line project, the choices on the selection of sources of catastrophe knowledge, specific data and locational and temporal contexts, her intentions and goal setting, all the way to the practices involved in inscribing her representation of disaster into 'reality' by means of her chalk lines. Methodologically observing and understanding practices of catastrophe 'production' in finance in this sense required an ethnographic framework engaging with practitioners in this field on the backdrop of documents on and from the field. The primary object of concern were the developments in producing disaster knowledge in science and finance in the becoming of financial catastrophe risk management. The mode of empirical investigation and analysis of this study is, therefore, a historical one, which traces the emergence, introduction, organisational and institutional integration, usage and changes of catastrophe modelling and their related financial risk management practices and tools. To uncover, understand and trace these developments systematically, three sources of data were used: interviews, observations and documents. These data were designed to deliver information on two interrelated areas of interest, (a) the history of the field of catastrophe modelling until today and (b) an as deep as possible understanding of the technical and financial practices and tools, their different usages and struggles.

b. Ordering of the Field and Sampling

With this focus, the main unit of analysis was that of 'communities of practice'. The central notion of knowledge, and how it is connected to practices and markets, is positioned towards how it is produced, reproduced, changed, applied, and how it informs decision-making and (inter)action in everyday market environments. Through document analyses 'explicit' knowledges have been analysed, but to understand how knowledge and its production creates, maintains, changes, and shapes markets, practiced or 'tacit' knowledges are needed (Archer, 2006). This focus on "knowing in action" (Amin and Roberts, 2008: 354) acknowledges practices and knowledge as interactionally intertwined in a "system of relationships between people, activities and the world" (Lave and Wenger, 1991: 98). As an explorative project, the ordering of the field drew on a loose understanding across definitions of communities of practice (Amin and Roberts, 2008; Brown and Duguid, 1991; Gherardi, 2005; Knorr-Cetina, 1999; Lindkvist, 2005) with a focus on their different sites.

This helped the scoping of the field into three broad groups of actors involved in 'producing' catastrophe in finance: (1) those who build proprietary catastrophe models, which are professionals at specialist analytics companies, so-called catastrophe model vendors; (2) those who have a deep understanding of catastrophe models and their use and support catastrophe modelling in financial practice but are not primarily engaged in their creation, for instance professionals at (re)insurance brokerages, consultancies or industry initiatives, but also academics active in relevant disciplines; and (3) those who are directly using catastrophe models for pricing and managing catastrophe risk of financial institutions, for instance professionals in risk analytics and modelling, actuarial functions, underwriting, capital modelling or investment functions at insurance, reinsurance, insurance-linked securities firms and institutional investors. Against the backdrop of my masters thesis (Kob, 2014), which formed a pilot to this study, a preliminary overview of the rather intimate field of catastrophe modelling existed and provided the basis for a list of firms and actors central in the field.

Although insurance is often a national and regional business, catastrophe markets especially through their structural dependence on reinsurance and capital markets are inherently international. However, the history and the dominant centres of these markets are fundamentally 'western' borne, with Europe, the United States, but also Japan as arguably the most involved ones (Borscheid et al., 2014; Borscheid and Haueter, 2012). The field of catastrophe modelling, with some exceptions, has primarily developed in the US. Here, the first and until today most influential catastrophe modelling firms emerged not only due to the US's dominance in financial services but also because the US with its various disaster-exposed geographies of wealth is the largest catastrophe insurance market. And although this analytics market is international, too, most historical developments took place in the US or in Europe with very clear reference to the US. This resulted in fieldwork focused on people and firms active primarily in these regions.

Sampling for the first group of actors (professionals at catastrophe model vendors) was straightforward because there are three dominant firms and a number of smaller specialist modellers. All three major firms have been founded and are headquartered in the US, although they also have offices in most major financial hubs worldwide, most notably in London. Sampling for the second and third groups concentrated also on actors and firms active in these regions. Because (re)insurance is a relational business (Jarzabkowski et al., 2015a), financial centres such as London, New York and Bermuda yielded enough density of firms and professionals from most involved global regions to locate the majority of informants and places for observations.

Before starting fieldwork, a number of individuals were identified through existing contacts and monitoring of industry press and reports for all three groups of actors. In addition, major catastrophe risk modelling and (re)insurance industry conferences were identified for participant observations. Also, one influential insurance industry initiative on catastrophe modelling agreed to visits and industry workshops in London. Already identified informants in the US and Bermuda were also contacted before fieldwork commenced. Since the financial industry is known to be hesitant towards access to external researchers, it was critical to activate existing and establish new contacts with key individuals in the field in order to use their referrals to further expand contacts throughout the field. Here, especially one major industry conference in London proved helpful, as the observations made there helped identify and confirm additional key individuals. With this strategy and an explorative research design, most of the sampling after starting fieldwork was, therefore, based on 'snowballing' until information from informants, observations and documents, alongside a growing understanding of the networks in the field, yielded saturation, i.e., that further referrals to individuals, firms and events pointed to those who had already been contacted, interviewed and observed and the content of information started becoming repetitive.

c. Fieldwork

Fieldwork commenced in early March 2018 with interviews and observations in London. From April until June, it continued in the US in New York, Boston, Omaha, Chicago and the San Francisco Bay Area, and in Hamilton, Bermuda. Additional interviews and observations were conducted in London in Summer and Autumn 2018. In the framework of an institutional visit to the New School in New York in Spring 2019, another set of interviews and one observation were conducted in New York, Boston, Connecticut, and New Jersey. In addition, a small number of interviews were conducted online between, as was an online conference in 2020. Also, a small number of interviews and two observations were taken from the pilot study, i.e., fieldwork conducted for my master thesis in 2014. One interview, conducted by myself in 2021, was agreed to be taken from a research project led by Dr Katharina Dittrich at Warwick Business School (Dittrich, 2021), where I have been a research fellow since November 2020. Except for four individuals, whose historic roles are publicly known and cannot be masked, all informants have been anonymised. A total of 62 interviews were conducted, 57 of them in person and five online. In total, 14 observations were completed, five in person and one online at industry events and conferences, and eight in person at firms' offices and small workshops. Triangulation was ensured in form of cross-checking information across informants and subsequent mapping of information and possible contradictions. Primarily, however, triangulation was performed via document sources, which included a broad range of industry press, practitioner literature, academic literature (from applied fields such as meteorology, earth science, finance, etc.), internal documents accessed through informants (such as original catastrophe bond contracts, analytics reports and other technical annexes), as well as historical archives (such as the archives of the US's National Association of Insurance Commissioners and the Oral History Series of the Earthquake Engineering Research Institute) and public financial filings.

As a general rule, information was granted enough authority when at least two informants mentioned or verified it and if at least one document source independent of these informants confirmed it.

III. Outline of the Thesis

The thesis is structured along historical developments of the practice of catastrophe modelling and the field of market-based catastrophe finance, complemented by two conceptual chapters. The first, chapter 2, delineates the conceptual framing of the problem and analysis. First, the notion of the Anthropocene is discussed and framed within actor-network theoretical perspectives, which offer a socio-material lens for the connection between epistemology and ontology. The problem of catastrophe is elaborated and conceptualised as a socio-material assemblage of human and non-human agencies. A literature review is presented on social science accounts at the nexus of catastrophe, (re)insurance and modelling before introducing the concrete conceptual and analytical framework of this thesis. It situates itself against the backdrop of knowledge production and performativity in market practices and devices and conceptualises catastrophe modelling as comprising three primary elements. First, *socio-material mediation*, which determines that aspects of hazard-prone environments (such as geophysical and meteorological specificities, buildings and their material features, etc.) need to be 'sensed' by various processes and practices of socio-material mediation (such as environmental sensor networks, public and commercial data collection on built environments, etc.) to produce different representational repositories, resulting in a 'multinaturalism' in representing the world. Second, *simulation*, through which future catastrophe is produced by various modelling practices and devices with multiple understandings of how phenomena, such as earthquakes, interact with the represented worlds of mediated repositories, resulting in a 'multirealism' of possible contextual disaster. Third, these epistemic and the subsequential risk managerial practices are operating under the condition of *experimentality*, an in-flux state of permanent, reciprocal changes of socio-material environments and markets which necessitates continuous adjustments of knowledge and practices. These elements constitute the financial ontology of Anthropocene catastrophe.

Chapter 3 sets the scene for the emergence of catastrophe risk in market societies, which started at the latest with globalising trade, insurance and fire disaster in the $17^{th}/18^{th}$ century. It presents a historical overview of catastrophe knowledge in science and the emergence of an eventually probabilistic understanding of catastrophe from the 1960s onwards, which gave rise to early catastrophe modelling practices. Stochastic and probabilistic insurance practices in form of zoning systems and the so-called 'probable maximum loss' metric marked the intimate entanglement of catastrophe knowledge production in science and financial services before the first commercial catastrophe modelling firms were founded in the late 1980s.

Chapter 4 focuses on the emergence of two pivotal commercial catastrophe models which were developed right before two major disaster events, Hurricane Andrew in 1992 and the Northridge Earthquake in 1994, provoked sustained and fundamental changes to catastrophe (re)insurance markets and practices, ushering in an 'era of catastrophe'. Two types of modelling approaches represented by each model are analysed in detail and their then perceived superior abilities to project catastrophe loss as opposed to traditional actuarial practices are historically discussed. The epistemic-ontological reach that these new practices promised is analytically located at the 'fracture line' between modelled and actualised catastrophe where models ingest actual and then produce modelled catastrophe with consequences for how environments are insured and risk-managed.

Chapter 5 is the second conceptual chapter which introduces a concept of technology use in the context of catastrophe modelling. This chapter sharpens the conceptual lens of chapter 2 to analyse the applied usage of catastrophe models in (re)insurance practice in the remaining chapters as the way how the financial ontology of Anthropocene catastrophe is enacted. It draws on a combination of concepts from appropriation art practices and approaches of technology use to develop the notion of *socio-material appropriation* to analyse epistemic, socio-material and power shifts in uses of catastrophe models across model creators and users. In this mode of technology use, catastrophe models but also their users and creators both appropriate each other and are themselves appropriated in multiple, situated moments of financial risk management. Actual, insured environments are financially managed on this basis of proprietary catastrophe production in multiplicity, who eventually experience actualised disaster events. Here the multiplicity of produced catastrophe is consolidated by practices of mediation and afterwards multiplied again in refined but new versions of simulated future catastrophe for continued financial risk management. This cyclical and reciprocal relay of multiplication and consolidation characterises a 'loop of Anthropocene catastrophe' in which finance conditions actual environments to certain degrees via modelled and actualised catastrophe in continuous feedback loops.

Chapters 6 through 9 apply this concept of socio-material appropriation in the analysis of catastrophe model production and use after its introduction into practice after Hurricane Andrew and the Northridge Earthquake. Chapter 6 analyses the take-up and integration of catastrophe modelling firms' services by (re)insurance practitioners from the early 1990s on, highlighting that these epistemic practices were dominated and catastrophe risk management 'appropriated' by commercial catastrophe modelling companies. Three case studies, the Californian Earthquake Authority, the Natural Disaster Insurance Corporation and the National Flood Insurance Program, are presented as examples for attempting to centralise catastrophe 'production' for the practice of insurance rate setting. Chapter 7 then shows how catastrophe modelling as a market practice was established rather in a decentralised mode, with the case study of the Florida Commission on Hurricane Loss Projection Methodology, representing regulation at the level of catastrophe model creators rather than its application. This critical positioning of catastrophe modelling firms elevated their position as the ones 'appropriating' (re)insurance practices and systems, most of whom were implementing models into everyday practice without a deeper understanding of the intricacies of these devices. Catastrophe model vendors as creators and distributers of models and modelling practices emerged in a pivotal position appropriating public and proprietary knowledge, devices and data, producing subsequently proprietary catastrophe projections in contextual multiplicity.

Chapter 8 marks the point where this dominance of vendors started shifting towards (re)insurance practitioners with another series of major disaster events in the 2000s, a growing sophistication of users' appropriation of models since the early 2010s, and the expansion of the insurance-linked securities markets, which initially developed in the 1990s on the back of catastrophe models. This growing sophistication of model users both expanded the depth of model integration into financial institutions' operations and structures and accelerated the multiplicity of modelled catastrophe production via in-house alterations of models and situated customisations. Chapter 9, then, analyses the notion of 'owning a view of risk', a sentiment grown out of the appropriational shift towards users. A case study of a problematic model update by a major vendor underpins this shift. The institutionalisation of 'owning a view of risk' and user-specific proprietary catastrophe production, expanding model use beyond underwriting, for instance, towards capital modelling and investments, frame catastrophe modelling as integral to economic performance and competition.

These appropriational dynamics of proprietary catastrophe production have an influence on actual socio-material environments via the crucial role of insurance in market societies' risk management by attributing risk to its objects, for instance, by prescribing or discouraging how and where buildings can be built or maintained. While finance's influence on the shape of environments in this way is a complicated one and characterised by struggles of adhering to such prescriptions, actual disaster and its environments are themselves appropriated by these forms of proprietary epistemic and financial risk management practices. The result is a financial ontology of Anthropocene catastrophe in which financial institutions are key in proprietarily 'sensing' disaster environments in multiplicity, and in which both users and creators of models produce proprietary catastrophe projections, whose purpose is not the uncovering of any singular truth but multiple, contextual versions of projected yet performative catastrophe for profitable financial risk management of, thus, market-shaped socio-material environments.

After concluding in chapter 10, with a summary of the argument, a discussion of the thesis's limitations and contributions, and reflection on its implications, the thesis provides in Appendix A a discussion and analysis on finance and climate change. It suggests that the field of climate finance currently emerges as another form of appropriation of such performative epistemic practices, carrying over important concepts from catastrophe modelling and adding new ones, as a way to actively manage the climate crisis, steering towards an even more encompassing 'financial ontology of the Anthropocene'

Chapter 2. Literature Review & Theoretical Framework

Figure 3: Selection of Olphaert den Otter's 'World Stress Series', tempera on paper. From top left to bottom right: Lucht-Water 28/11/2011, 2011; Lucht-Water 16/01/2013, 2013; Water-aarde 25/08/2015, 2015; World Stress Painting Earth, 2014.
Courtesy of Olphaert den Otter

In 2009, Dutch painter Olphaert den Otter started producing what he calls "World Stress Painting", an ever-expanding series of paintings (exceeding 200 pieces), in which he depicts landscapes of catastrophe.[1] Scenes of catastrophe's impact, seemingly right after the disastrous upheaval of the space has come to a rest, usually revolving around at least one of the four elements, water, fire, air and earth, as media of destruction. Always visible are remnants of human artefacts: broken, sunken and scattered about the depicted landscapes. One thing, however, you will never find in works of this series are humans themselves, but only what remains of *activities* of humans and of those of the 'destructive elements'. This points to two fundamental aspects of what will follow throughout this thesis. For one thing, these are precisely the contents that are captured in the devices and practices through which natural catastrophe is *realised* for the financial realm. For the other, it denotes, in a rather metaphorical way, what in 2012 has initiated stratigraphy to officially investigate the notion of the *Anthropocene* as a 'new' geological epoch. Here, den Otter's scenes provide a contemporary hint to what historically already has happened and has been recognised by earth systems science: the residue of human activity

[1] See: https://www.olphaertdenotter.com/copy-of-world-stress-painting

has left an unremovable imprint on the planet, 'World Stress' has literally sunken into the earth's strata and evaporated into the atmosphere.

I. Anthropocene

What does this mean for the relationship between humans and their environment or 'nature'? Scientifically, the notion of the Anthropocene fundamentally problematises this line of differentiation, and, indeed, for social science it makes it impossible. In earth systems science[2] it obscures and complicates the causal relations between human and non-human activity in changes to the earth's geology, biosphere and atmosphere: the Anthropocene, whenever it started exactly,[3] is "the onset of processes through which human activities began to move crucial aspects of Earth System function well outside the preceding envelope of variability" (Oldfield et al., 2014: 3). In earth systems sciences, the impact is seen as so dramatic that the initiators of the scientific debate on the Anthropocene, Paul Crutzen and Eugene Stoermer, noted in 2000 that without major disasters such as large asteroid impacts or large-scale pandemics, "mankind will remain a major geological force for many millennia" (2000: 18). Human activity is one of the major contributors to environmental change,[4] and the dualism of human and nature, therefore, "no longer provides an adequate basis for assessing the functional dimension of human-environmental interactions" (Oldfield et al., 2014: 4).

In social sciences, the notion of the Anthropocene necessitates nothing less than the recognition of "a profound mutation in our relation to the world" (Latour, 2017a: 8). Since the suggestion of the term emerged roughly 20 years ago, it received growing attention throughout the social sciences, sometimes referred to as the 'Anthropo-scene' (Lorimer, 2017), almost necessitating a topography of the term itself (Bińczyk, 2019). As Toivanen et al. (2017) remark, for instance, in 2012 there had already been enough diversity on the subject to identify at least seven distinct usages of the concept of the Anthropocene (Dibley, 2012), ranging from a radical temporal shift, attachment between

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[2] This mixture of different natural science disciplines focusing on environmental and climate change comprises a combination of geology, climatology, meteorology, oceanography, astronomy, and some other related fields (Barry et al., 2008).

[3] The Anthropocene Working Group of the International Commission on Stratigraphy (a body of the International Union of Geological Sciences) deliberates since 2012 on whether to officially ratify the Anthropocene as a geological epoch, and on its starting point in geological history (Zalasiewicz et al., 2017). The debates range from counting-in the Holocene (e.g. Lyons et al., 2016), or counting from the advent of agriculture from Neolithic times (e.g. Ruddiman, 2013), or the start of industrialisation from around 1850 onwards (e.g. Crutzen and Stoermer, 2000), to the start of the Great Acceleration from 1950 onwards (e.g. Steffen et al., 2007), whereas the latter two seem the most likely candidates (Steffen et al., 2016; Zalasiewicz et al., 2015).

[4] For an overview see Waters et al., (2016).

earth and earthlings, new ecological-economic systems, to dissolved modernist progress. Bonneuil (2015) identifies Anthropocene narratives, such as the naturalist, the post-nature, the eco-catastrophist, and the eco-Marxist narratives. Additionally, Toivannen et al. (2017) differentiate more epistemologically between approaches to the Anthropocene, such as the geological, biological, social, and cultural Anthropocene.

Meanwhile, a range of terms and concepts evolved on the back of the Anthropocene notion partly as concretisations or as counter-concepts, such as the 'Technosphere' and its derivative 'Technocene' (Nancy, 2015; Hui and Lemmens, 2017), the 'Eurocene' (Sloterdijk, 2014), the 'Plantationocene', the 'Chthulucene' (Haraway, 2015, 2016), the 'Capitalocene' (Malm, 2016; Moore, 2017), or the 'Anglocene' (Bonneuil and Fressoz, 2017). They evoke different emphases on politicised causes and accountabilities of anthropogenic environmental change and crisis, drawing attention to the origins of our "current planetary situation" (Davis and Turpin, 2015: 9). Across notions of humans and nature, terms in and off themselves are getting increasingly problematised. For instance, the human as a clear-cut denominator and a collective 'we', its universalism especially with regard to accountability for environmental impacts, is becoming questionable and politically untenable (Chakrabarty, 2012), while notions such as 'environment' with objects such as 'CO2' fall neither distinctly in the domain of humans nor in that of non-humans (Morton, 2013). What these concepts and the initial term of the Anthropocene certainly have in common is that as salient words they should not be thought of as "smoothing over contention, but of linking epochal discussions in the social sciences with those in the natural sciences and environmental movement" (Hetherington, 2019: 3).

In turn, these attempts of grasping our 'planetary situation' are a manifestation of a deep rupture in the demarcation line between human and nature, and for the social sciences particularly that between culture and nature. This latter line has evolved in Europe as a concrete analytical device only towards the end of the 19th century, "allowing a simultaneous discrimination between distinct orders of phenomena and distinct means of knowing about them" (Descola, 2012: 31). Ontological and epistemological concerns are at its heart, as well as practical questions of knowledge production. Descola highlights the friction and juxtaposition of ecological determinism or naturalist reductionism, an often evolutionist perspective granting ultimate power to the constraints of given environments, and cultural relativism or semiological idealism, which grants authority to culture into which nature is, by e.g. semiotic means, embedded (2013). For determinism/reductionism, it is rather to "biology that the task of justifying the existence of a cultural phenomenon is given" (Descola, 2012: 18), i.e., that culture is a product of nature. For relativism/idealism, nature is in a sense unknowable at first and "comes into existence as a relevant reality only when translated into the signs and symbols that culture attaches to it" (ibid.: 28), i.e., nature is enacted by culture. This opposition between universalism and relativism is a transposition of that of nature and culture and extends into a seemingly unresolvable situation: “to matter and life, universal laws; to institutions, relative norms” (ibid.: 76). The extension of this limitation to humans/society versus nature, then, means that they remain ontologically and epistemologically distinguished (Castree, 2005). The question arises, whether in the wake of the Anthropocene, in many accounts marking the collapse of this opposition, the divide between ‘geocentric’ and ‘anthropocentric’ can be actually overcome? Is it a moment in the history of thought that allows us, by virtue of material and political urgency, to fundamentally rethink this relationship?

a. ANT and the Anthropocene

Particularly actor-network theory (ANT) frameworks provide a line of thought that enables to focus on what the Anthropocene *reveals*, rather than what it holds in and of itself amidst its terminological ambiguity. ANT, of course, emerged from science studies, in which a major focus is to investigate the roles of scientists, their practices, instruments and objects in fact production. The Anthropocene, now, demands to leap further: to understand the active role of humans “in the very existence of the phenomena those facts are trying to document” (Latour, 2014a: 2). For collapsing demarcation lines, an approach that seeks to “reinject […] in its fabric the facts manufactured by natural and social sciences and the artefacts designed by engineers” (Latour, 1996: 370) provides a particularly fitting lens because it can take epistemological practice and socio-material manifestation – “how ontologies are shaped in action” (Jensen, 2004: 232) – into account. But what about ‘natural’ nonhuman actors, or better ‘actants’, as more than, for instance, semiotically represented by science and somewhat mutated through engineering’s artificial mobilisation of the natural (e.g., propulsion systems and thermodynamics, material science, etc.)?

What gives ANT approaches an advantage here, is that they attempt to take seriously both the material – the represented – and the semiotic – the representation – and in so doing, try to tackle the problem exemplified before by Descola (“to matter and life, universal laws; to institutions, relative norms”), or in other words, the analytical and ontological problem that occurs when “[n]ature unifies […] cultures divide […] More nature means more unity. More cultures, more divisions” (Latour, 2011: 8). Tackling this problem from an ANT perspective, therefore, does not mean to *re*-solve it, to solve the division by unification, but to make explicit the divisions now revealed also within nature: no more “sovereignty of nature” but a “multinaturalism” (ibid.: 10), no nature anymore as an object per se but as a subject, or rather multiple subjects, sharing “agency with other subjects that have also lost their autonomy” (Latour, 2014a: 5).

As such, “nature does not exist (as a domain), it exists only as *one half of a pair pertaining to one single concept*”, to which Latour refers as “Nature/Culture” (Latour, 2017a: 19, 16). Here, their *relationship* is important, since in ANT frameworks they are marked by the *interactions* that form them, which brings the focus on *agency*. The 'single concept', then, is one that is filled by multiple subjects' interaction and their ontological interdependence.[5] Here, the original individual terms, 'nature' and 'culture', are conceptually already dissolved. What remains is myriad interaction between 'subjective' entities that ceased universally distinctive allocation to either of those original terms. Taking account of this and effectively extending the scope of ANT to grasp what an Anthropocene era reveals, Latour in his most recent work mobilises the chemist James Lovelock's 'Gaia' hypothesis.

The crucial point of Lovelock's hypothesis[6] is that organisms have been an active part, in addition to geochemistry and geophysics, in how the Earth has evolved (Lovelock, 1991). A good illustration is a reversed perspective he developed while working for NASA: not to ask why Mars is not like Earth, but to ask instead why Earth is not like Mars. Lovelock assumes that Mars once had an atmosphere that vanished upon a chemical equalisation, and asks what prevents this to happen on Earth, i.e. what keeps the atmosphere in chemical disequilibrium (Latour, 2017a). And the proposed answer is *organic life*, which not only adapted itself to its environment, but which also had a sustained impact *on* its environment. Amongst the points that make this view particularly attractive for ANT are two aspects: first, it allows for a further extension of the agency of nonhumans and simultaneously it allows for the recognition of human agency in and on the earth system, and therefore allows to grapple with the Anthropocene on the level of agency. Second, it allows to identify within Lovelock's hypothesis a non-hierarchical treatment of all those actants, agencies and agents, a principle of ANT in general (c.f. Latour, 2005; Latour et al., 2012). The actual space in which these agencies are assembled is the so called "critical zone […] a few kilometers thick between the atmosphere and the bedrock" (Latour, 2018: 78). It is here, and nowhere else, where this terrestrial arena of multiple agencies resides.

Now, to make explicit the focus of active interaction of agencies, neither Lovelock nor Latour subscribe to anti-evolutionism,[7] but they add active organisms to the notion of a rather asymmetrical evolution who not only 'work on themselves' but also where "each one *bends* the environment around itself […] intentionally manipulates what surrounds it 'in its own interest' […] to make its own survival

[5] In this sense, calling it 'Nature/Culture' seems more like a terminological critique to signify what it problematises rather than coining and mobilising it as an actual analytical term.

[6] It seems not entirely relevant whether the original and contested Lovelockian Gaia hypothesis holds in all parts from a purely natural science standpoint, because for Latour it simply allows to conceptualise a socio-material theory of agency that includes the earth system, since, in an ANT perspective, agency is distributed. And this distribution is now not limited to the field of fact production and the 'socio-technical', but to the field of the 'critical zone', which is "the point of departure and also the point of return for all the sciences that matter to us" in an Anthropocene lens (Latour, 2018: 78).

[7] See Latour, 2017a: 134, and also 2017b.

slightly less improbable" (Latour, 2017a: 98). Humans' capability of altering their environment is extended into a "general property of living things" (ibid.: 99), including not only animals or insects but also plants, bacteria, microbes, etc. In this sense, the approach is not anthropocentric but 'critical zone-centric' (which includes, of course, 'Anthropos'), and intentionality, one big issue ANT has to wrestle with (e.g. Collins and Yearley, 1992a, 1992b), becomes so abundant that each individual intentionality is enmeshed with so many others that their interconnectedness makes it impossible to assign more or less supreme versions of intention. And with this in mind, Latour's particular conceptual mobilisation of Gaia refuses an order in which there exists a superstructure, something sui generis superior to what it is made of (Latour, 2017b; Latour et al., 2012). The Anthropocene points to precisely this lack of a 'superorganism', a situation in which no higher order ('Nature', 'the Human', God, or any other singular unifying principle) reigns over this critical zone, the actual habitat in which all the agencies have to make do with one another in multiplicity.

b. Epistemology and Ontology

For epistemology, of course, this complicates the state of affairs, since science is folded into this whole situation and can, therefore, not act as, or produce, a unifying principle either. If the Nature/Culture denominator has collapsed, and "society is *never* external to science" (Jensen, 2004: 246) then *having been and being* in the Anthropocene is as internal to science as science is integral to the Anthropocene. Science and knowledge production enveloped in this way are understood as 'situated knowledge', where it *ontologically matters* where, when, by whom and with whose (human and nonhuman) help knowledge is produced (Haraway, 1988, 1991), and where there is no "view from nowhere" for epistemic work (Latour, 2017a: 127). Amidst, and itself part of, a multiplicity of agencies, science captures some of this agency and by *doing* so is not passive – observing and representing – but itself active – intervening and constructing – in the multiplicity: "epistemology *collapses into* ontology" (Jensen, 2004: 248). Reality is reconfigured by a science 'in action' working with and on the objects of scrutiny, *adding* something to them: by "*doing* practical ontology […] knowledge is constructed precisely at the intersection of the many different agencies concretely interacting in the world" (ibid.: 248f).

To be more precise, agency is given to actants through (and by the creation of) "metamorphic zones" (Latour, 2014b: 15). By carving out what an entity is doing, that is, for instance, working on the entity in an experiment to provoke a not yet known action, a performance is registered. Only after this registering, this performance can be assigned a competence, i.e., what properties the entity is endowed with, and by this second, semiotic, act, agency is as*sign*ed to the entity. Realised in the 'metamorphic zone', this is the move from *action* to *agency*, where entities are shaped, or take shape (i.e. morphed), where human and nonhuman exchange properties before they (and subject/object) are distinguished (i.e. meta) – this is where "all agency emerges" (ibid.), a conceptual arena sometimes referred to as a ‘flat ontology’ (Edward, 2016). And here the problematised division of nature and human, epistemologically streamlined by the division of academic disciplines, has collapsed into an Anthropocene era,[8] and so has epistemology into ontology: the question "‘How is the human mind able to *know the world objectively*?’ has become a totally *practical* question: ‘How can we *describe life on Earth* in which human traces — not to say leftovers — are so ubiquitous that *natural and artificial* have become *impossible to set apart?*’" (Latour, 2014b: 22f; my emphases).

All these agencies’ assemblages, including the human ones, make up the critical zone, have sunk into its strata, evaporated into its atmosphere, distributed across its surface and bodies of water over time: Earth in the form of the critical zone is itself "an agent of history", or "geostrory" (Latour, 2014a: 3) in which, for example, "[t]he climate is the historical result of reciprocal connections, which interfere with one another, among all creatures as they grow" (Latour, 2017a: 106). Olphaert den Otter, the World Stress painter introducing this chapter, made a telling (presumably unrelated) material choice for his catastrophic landscapes: he uses egg tempera as the paint medium.[9] It produces not only a very bright colouring (Botticelli made use of this, for instance, for The Birth of Venus and Primavera), it also dries incredibly fast and is one of the longest-lasting materials, by far exceeding oil paint’s durability. Just like Anthropocene’s ‘geostory’, if a stroke has been brought onto the canvas, it concretises immediately and cannot be corrected, it stays and you can only work *with* it: no way back, no revisions, all imprint is forever. With the advent of modernity, egg tempera started vanishing from painters’ palettes and only returned in the second half of the 20th century. Its cultural materialisation lasted but it skipped modernity’s minds and practices, just as the Anthropocene was already unfolding but only now is pressing itself and all its agencies into today’s ontologies of science, politics, societies and economies.

Distributing agency, therefore, is not only an ‘ontological’ task in general, but it is also, especially in times of the Anthropocene, political (Latour, 2014a), and, as we will see, also a financial one. And there are few phenomena in which this is better illustrated than in the case of this thesis’ main focus, that of ‘*natural’ catastrophe*.

II. Anthropocene Catastrophe

In July 1972 at Dumont d’Urville Station in Antarctica, peak sustained wind speed of the so-called ‘katabatics’ (coastwards moving cold air) was measured at 327 km/h, 199 mph (SPNO, 2019), the

[8] On the growing confluence of social and natural science disciplines on Anthropocene research see Ellis et al. (2016), Toivanen et al. (2017), Latour (2017a: e.g. 120), or Oldfield et al. (2014)

[9] Egg tempera uses egg yolk as the binding agent for the colour pigment, which is then mixed with water. The resulting paint is particularly clear as all elements of the mixture completely dissolve into one another.

strongest winds ever measured. Even though these winds are entirely different from the storm systems known as tropical cyclones, such as hurricanes, these wind speeds superseded the qualifying hurricane strength threshold on the Beaufort scale (≥ 118 km/h, ≥73 mph) by 277% — Hurricane Katrina in 2005 during its second and third landfalls exceeded this threshold by 170%, both at 201 km/h, 125 mph (Knabb et al., 2005). One of these two events only very few people might be aware of, while the other has entered the world's collective memory as one of the most devastating natural disasters in recent history. One quite obvious reason what differentiates these two is that the latter occurred in a space rather densely populated by humans, artefacts and capital, while the former happened on a continent that is nearly completely deprived off any inhabitation.

The United Nations Office for Disaster Risk Reduction has long defined a natural catastrophe as a "[n]atural process or phenomenon that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage." (UNISDR, 2017).[10] The focus here, but also elsewhere (e.g. IFRC, 2017; WHO, 2017), tends to identify the natural catastrophe as the meteorological or geophysical phenomenon itself. However, the determining factor that makes 'natural' disaster catastrophic is not the meteorological or geophysical phenomenon itself, such as a hurricane, earthquake, tsunami or wildfire, disrupting an otherwise stable environment, but indeed this very environment that it is made up of. Catastrophe in the Anthropocene is a complex entanglement of factors, such as human settlement behaviour, accumulation of capital, building materials, enforcement of building codes, emergency policies and much more.

A storm is not a catastrophe unless it blows off roofs or causes storm surges to flood residential or commercial areas – uninhabited spaces are rarely subject to catastrophe unless they are endowed with some form of meaning, such as 'pristine' or endangered 'natural heritage'. Crucial is that if roofs had not been blown off or the storm surge had been diverted by a river into a nearby lake, the storm would only have been a storm, not a catastrophe. Catastrophe is the unfolding of different interacting agencies of natural phenomena, material objects and artefacts, and social make-ups and behaviours. The socio-material world renders a geophysical or meteorological phenomenon catastrophic by its very existence: natural catastrophe is entrenched in an ontology of agency and interaction of humans and nonhumans. In the Anthropocene, "there's no being outside the system: we are here" (Jeremijenko and Hannah, 2017: 199), and we are not a bystander but 'in alliance' with the natural phenomena — we are (at least) equal co-producers of catastrophe, for it is always equally subjected to us as we are subjected to it. While many of the natural catastrophes referred to in this thesis will be in some way connectible to climate and environmental change, such as cyclone storm systems, wildfires or floods, some others,

[10] This framing has since changed and recently has shifted the political focus towards human sources of 'natural' disasters, as is discussed in the conclusion chapter.

such as earthquakes or volcano eruptions, are not. This, however, does not remove them from the Anthropocene, since they actualise in meaningful catastrophe only as long as they interact with human and artificial entities. As such, the term *natural* catastrophe is rather unsuitable against the backdrop of the Anthropocene notion and is, thus, termed in this thesis's conceptual framework as 'Anthropocene catastrophe'.

Here, an analytical socio-material differentiation is needed to allow for a more precise perspective on what constitutes Anthropocene catastrophe: its two crucially interlinked dimensions, *occurrence* and *severity*. While there is absolute certainty, for instance, that there will be a major earthquake event fundamentally reshaping the coastline of California at some point in the future (c.f. Schulz, 2015), it is highly uncertain *when* and *where exactly* it will occur and *how severe* it will be.

a. Occurrence

Although there is a long history of large natural disasters (c.f. Mauch and Pfister, 2009), the problem at the heart of catastrophe's occurrence lies in the individuality and infrequency of an outcome that emerges as catastrophic. Geographically, it is generally rather easy to know today very roughly *where* a lot of natural disasters usually occur. Earthquakes, for instance, primarily occur along tectonic plate boundaries (Morgan, 1991). Tropical cyclones, such as hurricanes and typhoons, follow a geographical pattern in their occurrence as there are specific atmospheric conditions necessary for them to form, such as a sea surface temperature of at least 27C° (Gray, 1998). Tropical cyclones' catastrophic potential unfolds when they make landfall. It is, therefore, coastlines and to some extent also areas further inland from landfall, where disaster usually occurs, and, as stated before, fundamentally only in areas inhabited by humans and/or artefacts. It gets, however, more difficult to determine *when* they occur. Due to their forming conditions, tropical cyclones have a temporal window. For hurricanes, for instance, it is the North Atlantic hurricane season, which runs from June to November and normally peaks between early and mid-September when the difference between sea surface temperature und air temperature is the greatest (AOML, 2006). Earthquakes and tsunamis on the other hand, are generally unpredictable in terms of when they occur (Kerr, 2011).

b. Severity

The other dimension is the severity of Anthropocene catastrophe, that is *how* it unfolds. Climate change can only reveal a marginally proven influence on the outcomes of individual large-scale natural disasters but clearly increases, for instance via rising sea temperatures, the general likelihood of severe weather events (c.f. Trenberth et al., 2015). By far the major determinant for catastrophe's severity is its socio-material environment. It is what makes the occurring of geophysical or meteorological phenomena catastrophic and the level of severity depends on how socio-material spaces react to them: "It's not the earthquake that kills you, […] It's the buildings." (Muir-Wood, 2016: 74). The rather recent increase of loss, starting in the second half of the 20th century, is not only an indicator for the rising number of meteorological phenomena but even more so for the increase of socio-material concentration of both inhabited areas and accumulated capital, the materialisation of the Great Acceleration: the number of large-scale 'natural' catastrophes quadrupled between the 1950s and the 1990s, while economic loss increased 14-fold – and this is even before the 1990s saw both a steep increase especially in heavy storms and floods and an ever intensifying inequality in terms of wealth and geographical settling accumulation (EIOPA, 2015).

Over the centuries, responses to catastrophe have primarily been structured in diffuse, varying, and nonlinear intervals of changes to building designs. Depending on the most recent local catastrophic threat, building materials and structural designs would shift. For example, a method in use from eighth century Turkey and Greece was widely enforced in 16th century Istanbul (then Constantinople) due to the lack of their mainly stone-built houses' ability to withstand earthquakes. It applied 'timber lacing', a basic structural design principle from boat-builders. Over the centuries, this design spread to Europe, known as 'half-timbered' (England), 'colombage' (France), or 'Fachwerk' (Germany), where it was primarily used to withstand strong winds or heavy snowfall (Muir-Wood, 2016). Since the first industrial revolution, urbanisation increased heavily and the prevalent danger was fire (Borscheid and Haueter, 2012), which started to fuel the demand for brick buildings at the end of the 18th century (Wermiel, 2000). By the late 19th century, most new western urban spaces became 'fire-proof' borrows of brick buildings, which eventually had to face other natural phenomena again, in which brick designs became perilous. In the US, for instance in Charleston, South Carolina, in 1886 (Robinson and Talwani, 1983) or in San Francisco in 1906 (Nason, 1981) earthquakes caused especially brick buildings to collapse, which killed considerably more people and caused much greater loss than older, wooden-framed buildings. At the end of the 19th century, steel-reinforced concrete was developed and increasingly standardised (Giedion, 1995). It was fire-resistant, but also combined the flexibility and stability to resist physical forces of both vertical (storms) and horizontal (earthquakes) acceleration, as well as the weight and material durability to withstand flooding (Muir-Wood, 2016). With the start of the 20th century, steel-reinforced concrete gained prominence as a cost-efficient and universal building material and entered the urban stage, most prominently with modernist architect and urban planner Le Corbusier (1924). A great number of especially multi-story types of these buildings have until today a large open space supported only by pillars instead of inside walls on the ground floor level. A major earthquake in Mexico City in 1985 made the flaws in this design choice visible as over 250 of such multi-story buildings completely or partly collapsed (Chandler, 1986). The open ground floor space turned out to be a serious weak spot, known to engineers now as “soft story failure”, lacking rigidity and compromising buildings’ structural integrity (Muir-Wood, 2016: 103).[11]

Another, connected, aspect are building codes, i.e. regulatory rules for owners, builders and retrofitters on how to construct buildings and their enforcement, which generally varies a lot (Kertesz, 1993; Wang, 2014). Building codes came into modern application as result of disasters such as London’s 1666 Great Fire and that of Chicago 1871. Codes’ existence and the state’s capacity for enforcement plays a determining role in Anthropocene catastrophe, most explicitly exemplified by the 2010 earthquake in Haiti where building codes partly existed but had not been enforced at all, adding to the general socio-economic reasons for lack of earthquake protection (Bilham, 2010). Furthermore, defence structures and other environmental alteration also play an important role in the unfolding and severity of catastrophe. Sea walls and levees are built for shielding off floods caused by storms or tsunamis. They can, however, increase the severity of a catastrophe if they are actually breached, prominently demonstrated by 2011’s Tohoku tsunami. What turned out to be especially perilous here was the confidence in these structures: planners had the Fukushima nuclear power plant constructed near to the sea, amongst other reasons for easy cooling water access, convinced that the sea wall’s protection would be sufficient (Raby et al., 2015). An example for environmental alteration and how it influences catastrophe’s intensity is the Mississippi River-Gulf Outlet, an artificial water channel built by the US Army Corps of Engineers, which connected New Orleans’s port with the Gulf of Mexico (USACE, 2017). Due to the design of the channel, the water during Hurricane Katrina in 2005 pushed in, surged, and the dams and levees along the channel were breached. It caused the flooding of the east of the city; it is suspected to have caused critical breaches of floodwalls at another canal further east, and is said to have generally increased the storm surge following Hurricane Katrina by 20% (Warrick and Grunwald, 2005). Considering these various determinants, catastrophe’s ontology, therefore, appears as a hugely complex entanglement of numerous socio-material factors throughout these intertwined dimensions of occurrence and severity.

The dimension of occurrence refers to the Anthropocene more in terms of looming anthropogenic influences on the climate, expressed primarily in rising and more volatile temperatures (relevant for e.g., tropical cyclones, hailstorms, blizzards, extremely heavy rainfall, floods, wildfires). The dimension of severity, on the other hand, points more immediately to the active and purposeful human influence, or rather originality of catastrophe, which includes, therefore, also geophysical phenomena. For instance, the examples mentioned on building designs and environmental alterations are an

[11] This description does by no means try to sketch out a linear history of building design development but serves only as a series of examples.

intricate part of what one could call the 'geostory' of Anthropocene catastrophe. And one way of socially and economically dealing with this is the arena of insurance. As introduced in the introduction, this financial sector forms the modern centrepiece of market societies' coping strategy with catastrophe. A very loose analogy to the conceptualisation of catastrophe offered above can be found in the differentiation in insurance industry lingo between 'peril', the "damage-causing event", and 'hazard', "that what makes the damage worse […] [for instance] when a house is not bolted to the foundation" (Roth, 1997: 3). It is only a loose analogy, of course, because the hazard, i.e., the socio-material determinant, *is* the house in this thesis's conceptualisation, and not just the lack of bolting, which itself is yet another, additional part in the socio-material assemblage of catastrophe.

Producing knowledge on Anthropocene catastrophe and its associated risks via the practice of catastrophe modelling, sits at the heart of this sector's epistemic and ontological work. In the remainder of this chapter, I will offer a way to bring together conceptually the notion of Anthropocene catastrophe and a sociological perspective, with an emphasis on social studies of finance and science and technology studies, on how the financial sector characterises an intricate part of catastrophe and generates and shapes, by means of its epistemic practices and devices, what I call a 'financial ontology of Anthropocene catastrophe'. To start, I will sketch out the existing literature on natural catastrophe risk and its financial mobilisation, before introducing in more detail my socio-material conceptual framework.

III. Social Science Accounts on Catastrophe, (Re)insurance and Modelling

I distinguish accounts on catastrophe, risk and finance in the social sciences into two sets with respect to their applicability for this thesis. The first set focusses on risk as a concept and means of government (mainly in the sense of Governmentality Studies) and insurance as problematised managers of global risks in the sense of Beck's 'World Risk Society' as well as a question of capitalism and state. For example, Bougen (2003) criticises Beck's un-insurability thesis[12] and argues that coherence and sustainability of liberal governmental risk-networks "maintain the insurability of catastrophic events" (ibid.: 253). The main trajectory of his analysis captures how 'capitalist ingenuity', i.e., securitisation, and (neo)liberal government use specific rationalisations of risk to shift uncertainties towards market-based risk management and away from the state as a bearer of catastrophe risk. O'Malley (2003) draws on Bougen, re-actualising the conceptual tension between risk and uncertainty and positions it within Governmentality Studies – specifically highlighting the "neo-liberal political and technical operation of

[12] Ulrich Beck famously draws on newly emerged global risks in late modernity such as climate change, terrorism, or nuclear waste. He argues that these new forms of global risks evade the possibility of traditional insurability, and might even challenge insurance's general role today, due to their incalculability, delocalised nature and their potential non-compensability (Beck, 1992, 2006).

rendering catastrophes governable privately" (ibid.: 277). Uncertainty[13] appears as a central governmental technique and the constitution of liberal subjects advances via quantification and risk. Catastrophe risk, then, is moved to the private, individual sphere of 'neoliberal' self-governance of the modern subject in the sense of Ewald's classical account on insurance as modern governance of liberal subjectivity (1991). Ericson and Doyle (2004) also lean towards the concept of Governmentality while criticising Beck's programme, and mainly argue that risk, as a form of governmental vehicle, has been used to entrench terrorism risk after the US 9/11 attacks. According to them, this is accomplished by using insurance rationales and techniques of catastrophe risk assessments, claiming insurance uses rather economic and "non-scientific forms of knowledge" and is "eager to turn threat into opportunity" (ibid.: 168).

While these perspectives are politically telling and perhaps even normatively compelling, they offer only limited insight into how catastrophe and financial risk management are concretely produced or into how they relate to the Anthropocene. Those perspectives can all too easily slip into portraying the sphere of economy, finance and markets in a one-dimensional way as a space in which the liberal era thrives and where liberal government shapes and is shaped by 'neoliberalism' – there is more to it than just this. Instead, this thesis seeks to document, and as far as possible explain, how this market of seemingly unforeseeable uncertainties was indeed created, and how its epistemological status and authority are maintained – in short and possibly slightly exaggerated, how natural catastrophes became and have been stabilised as financial objects. Simply ushering catastrophe markets into the corner of the extremes of 'neoliberalism' does not yield many new insights or much explanatory power. For instance, differentiating rather simplistically between scientific and 'market-based' (i.e., non-scientific) knowledge fundamentally overlooks how knowledge about catastrophe risk is produced and only then made financial specifically through a reciprocity of science and markets throughout society. Particularly here, the acknowledgement of the ways in which science, society (and therefore markets as well), 'nature' and catastrophe are folded within the Anthropocene becomes ontologically central.

[13] A widely used distinction between risk and uncertainty, also drawn upon by Governmentality Studies (although in a critical way), is that of Frank Knight (1933). Risk, here, appears as the state of future unknowns which are (tried to) made sense of by statistical and probabilistic means. Put simply in this way: risk is uncertainty made calculable and thus approached through ordering this uncertainty by formalisation and 'rational' mathematical predictions. Uncertainty, on the other hand, is the acknowledged incalculability of future unknowns approached through 'judgements' (ibid.: 229). Governmentality Studies draw on risk by a distinction such as Knight's, stating that there is in fact "no risk in reality" (Ewald, 1991: 199) but only (liberal) rationalisations of uncertainty, purposefully morphed into risk as a governmental tool of (self)conduct.

Still falling into this first set of accounts, a more recent approach with a deeper notion of 'nature' is that of Ramzig Keucheyan (2016). He frames nature as a fundamentally political entity, whose ecological crisis in capitalist frameworks yields solution attempts: financialisation on the one hand, and military responses on the other. He identifies catastrophe and climate insurance as the main driver for a 'financialisation of nature' out of which more 'exotic' financial vehicles emerged, such as climate derivatives and catastrophe bonds. Keucheyan conceptualises the intricate relationship of insurance and finance as the fundamental (pre)condition of globalising capitalism (Keucheyan, 2016: 57), while he notes that via (re)insurance globalised climatic risk costs are intimately connected to local demographic, urban and economic development (ibid.: 69). This, however, does neither incite Keucheyan to include these aspects as integral to catastrophe itself nor does he include knowledge production as an intimate part of it. He, instead, remains in framing an "ontology of catastrophe" (ibid.: 70) that rests on the portfolio perspective of (re)insurers as a 'hyper-correlated' tail event, i.e., an event that invalidates the principle of risk spreading of smaller and more frequent risks such as road accidents (Keucheyan, 2018: 488).

Keucheyan focuses not on a detailed, ethnographic analysis of actual empirical practices in this arena of financialisation, despite his numerous and interesting examples on the matter in general, but his main argument seems to be a rather macro-level (eco-)Marxist perspective on the relationship between capitalism and state, in which "[i]n the modern era, capitalism, nature and the state [...] constitute an indissociable triptych" (Keucheyan, 2016: 153). Even though he frames nature as purposefully constructed on the intersection of the state and capitalist intent (ibid.: 102), he seems to use nature, at the same time, as an antipode, something external to society that is, by virtue of capitalist ingenuity and urgent yet profit-seeking risk management, integrated via financialisation strategies. With a socio-material Anthropocene perspective, however, treating 'nature' even implicitly as something external to society, markets, politics, etc. underplays the ontological significance of the assemblage of agencies that play into one another beyond the means of management and profit of risks and devising climate geostrategies in the face of 'green wars'. However, with the term "derivative nature" Keucheyan refers to ways that bring about "the financialization process of (re)constructing nature by modelling it" (ibid.: 85). This will be something that this thesis will focus on, too, not as a term but as a mechanism of de- and re-construction – one that, however, is also ontologically and not only epistemologically significant.

A second set of accounts on natural catastrophe and its markets yields more tangible understandings in this direction and is more oriented towards the practical, technical, and concrete elements of this area. The so far most extensive account on reinsurance and catastrophe risk has been the ethnographic study of reinsurance underwriters and market mechanisms by Jarzabkowski, Bednarek and Spee (2015a). They show that the reinsurance market and especially the pricing of catastrophe reinsurance deals is embedded in relational interconnected individual and collective practices. Catastrophe is transformed into tradable financial entities of risk by diverse calculative practices of technical but foremost 'contextual' knowledgeable expertise and experience. Jarzabkowski et al. place these chains of interconnected and reiterating practices at the heart of making this market for catastrophic risks (Kob, 2017).

Most of the practices in constructing reinsurance deals are centred around "consensus pricing" within an annual cyclical process, which involves numerous interconnected calculative practices across a considerable range of actors and firms who collectively agree on prices in a particular blind auction format (ibid.: 26). This feature of 'relational consensus pricing' is set within a market, whose price dynamics, although only implicit in their account, ultimately hinge on the occurrence and severity of actual catastrophe. In this traditional reinsurance system, according to Jarzabkowski et al., catastrophe models are but one of many devices and techniques used in the process of risk assessment and especially pricing of reinsurance. The change in market practices and thus the change of the market as a whole with the increasing relevance of insurance-linked securities, sometimes referred to as the 'convergence of (re)insurance and capital markets' (c.f. Cummins and Weiss, 2009; Lechner et al., 2016), potentially shift risk practices more towards an overreliance on catastrophe models, and erode the traditional system's practices. Jarzabkowski et al. warn that introducing more abstract and model-based capital market risk practices might lead to an over-abstraction of risk-assessment and an underappreciation of intercorrelation within portfolios in a similar way as happened with mortgage backed securities credit default obligations in the financial crisis.

While this thesis owes a much deeper understanding of the traditional reinsurance market and how it deals with catastrophe risk to the work of Jarzabkowski et al., they focused on models only in how specifically they inform relational reinsurance underwriting practices rather than models' socio-material roles in an Anthropocene setting. "We show how these models generate ever-increasing legitimacy for calculative practice, yet at the same time underwriters arrive at prices that incorporate a complex understanding of the deal and the market that goes *beyond* the parameters provided in models." (Jarzabkowski et al., 2015a: 89). This thesis focuses more on the relationship between models and their socio-material environment (which includes firms, markets and Anthropocene environment) with catastrophe modelling as the axis of investigation, rather than Jarzabkowski et al.'s focus on the more specific client relationship between reinsurers and insurers. This thesis is in this sense complementary to their study.

Another very insightful account is that of Collier (2008). His approach is the most sociological contribution so far to the theme of catastrophe (re)insurance with an emphasis on simulation via catastrophe models. He stresses the difference between different forms of “calculative rationality” of risk as he contrasts “archival-statistical knowledge”, the form of risk knowledge in Beck’s work, to “enactment-based knowledge” (ibid.: 225). The latter refers to what he calls “enactment” through simulations which is used for “acting out uncertain future threats” (ibid.). The major difference, Collier states, is twofold. First, in terms of data, enactment does not hinge on historical event figures but brings together different abstracted parameters of potential future events by means of modelling. Second, the assessment is an enactment of future events, running the models so to speak, and not “statistical analysis of distributions of risk over a population” (ibid.: 226). He traces a genealogy of enactment-based forms of knowledge and assessments of uncertainties through three different episodes of usages of these “event models”, including natural catastrophe models (ibid.).

While his central concept, *enactment*, is a useful tool for analysing the role of simulation in risk assessment, the rather sharp contrast to statistical methods drawing on historical data might, however, be oversimplified. It is true that (most) contemporary catastrophe models are not just deterministic anymore, but the underlying assumptions of how catastrophe unfolds, occurrence and severity, are based on past experiences, whether disentangled from concrete events or not. The ‘archive’ is, therefore, of great importance for catastrophe modelling and this form of enactment. This might not be of great interest for Collier’s programme, which attempts to describe a distinct, additional rationality of risk as a critique and extension of Beck’s Risk Society programme. But the oversimplification does underplay the problem of knowledge about the different parameters within the model components and omits the interconnectedness of these practices and those of (re)insurance and financial markets. Collier also ignores the profound socio-material aspects of catastrophe risk, knowledge production and their intricate relationship with what, since the time of his article, social scientists have learned to call the Anthropocene. As has been highlighted above, catastrophe is a complex of interactions of different sets of agencies, and knowledge and its production are as fluid as catastrophe itself. The market for natural catastrophe risk incorporates catastrophe’s socio-materiality in producing its financial ‘ontology’. But it also adds the socio-materiality of markets and its devices, such as financial risk metrics, organisational configurations, market-political and epistemic struggles.

Another more recent contribution, specifically on insurance, has been offered by Weinkle (Weinkle, 2017; Weinkle and Pielke, 2017). She problematises catastrophe models’ knowledge production with a specific emphasis on its political dimension. A scientification of insurance premiums pricing as the move towards catastrophe modelling shifts the debate from insurance regimes, and how they are understood and managed, to ‘real’ or ‘true’ measures of risk (Weinkle and Pielke, 2017: 547). One political sphere Weinkle touches on is the one of homeownership and the connection between catastrophe insurance and access to mortgages in the US. Here, insurance regimes enable real estate development amidst discourses of acceptable versus unacceptable risks, deemed 'true', i.e. reliable, by legitimisation of catastrophe modelling. A particularly interesting aspect is the dispersed and rather unstandardised (US) state-level governance via model certification and how sharp disagreements amongst model vendors about individual model outputs are made visible in this process – which Weinkle identifies as a strong signifier for (model) uncertainty[14]. Scientific uncertainty adds to it; evolving and changing knowledge in science such as meteorology as well as conflicting theoretical and methodological fields throughout science diffuse rather than clarify knowledge used by models (ibid.: 560).

As will be discussed further down, the central aspect of catastrophe modelling is not just uncertainty, i.e. "that more than one outcome is consistent with expectations" (Weinkle and Pielke, 2017: 550). It is the open-endedness of the relationship of knowledge production and non-knowledge across all fields and sites concerned, which is embodied by the simulation aspect of modelling. Also, the socio-materiality of catastrophe and models is only implicitly part of Weinkle's approach, which, nonetheless, lends important insights into the political gravity of catastrophe modelling. These political factors add to the understanding of Anthropocene socio-materiality of catastrophe since the value of houses, its shifts up- and downwards, have an impact on catastrophe model assessments of the inventory of portfolios, which highlights a certain circularity within this type of modelling. If the value of a home is influenced by the cost, or even the sheer availability, of disaster insurance, then, of course, this impacts on the potential loss value within the portfolio, on which basis the cost of disaster insurance is then, again, based, and influences in the physical development of specific hazard-prone areas. This demonstrates the entanglement of the social, political, economic, and the material within catastrophe modelling amidst an Anthropocene context.

Yet another recent contribution is that of Rebecca Elliott (Elliott, 2021) and her programmatic vision of a 'sociology of loss', in which she suggests to appropriate climate change as a contributor to sociology. She highlights the necessity to recognise the "materiality of loss" (Elliott, 2018: 309) in the face of the Anthropocene. Similarly to the perspective offered in this thesis (but with a less socio-material lens), Elliott recognises what I will refer to in the next section as 'ongoingness' ('open-endedness' and an 'in-flux' state) of socio-material interaction in the Anthropocene that blurs stringent categorical distinctions of the political, social, material, natural, economic, etc.: in the context of "'natural' disasters and hazards associated with rising sea levels, shifting precipitation patterns, and extreme heat and cold […] loss is something that is both reacted to and actively produced, both materially real and socially constructed and mediated" (Elliott, 2018: 323). As 'ongoingness' in Elliott's

[14] Weinkle is implicitly drawing on what the industry and model engineers call 'model uncertainty', that is uncertainty inherent in the models themselves beyond the phenomenon that is being modelled by them.

case, I understand the need to capture the constantly changing parameters of catastrophe, which result not only in epistemic uncertainty but also (and partly because of this) in an ontological entanglement with social and political measures and struggles.

In her empirical work, Elliott primarily focusses on flood insurance policies and particularly on the institutional framework of the US's National Flood Insurance Program (Elliott, 2017, 2019). Here, she also focuses on its flood hazard maps and their epistemic power to deem certain regions riskier than others and, therefore, to price insurance premiums higher or lower. She situates her argumentation partly in welfare state analysis and opens it up to the domain of natural catastrophe (Elliott, 2017). The question of responsibility, moral claims of choice and deservingness in the context of (US) disaster policy confront those risk instruments in political struggles. On the one hand, flood insurance transformed flood disasters into "scientifically foreseeable, patterned events that can ostensibly be planned for by individuals on the basis of probabilistic risk assessment", while political groups contest risk maps' legitimacy "on the basis of competing assumptions, data, and models" (Elliott, 2017: 417, 425). While Elliot's target in this argumentation is that of the role of the welfare state and discourses around deservingness, which this thesis will not focus on, it lends important evidence for the interconnectedness of socio-materiality of catastrophe. For instance, through political struggles it becomes clear that unaffordability of catastrophe insurance, for example for flood risk since 2014, enables to live in flood-prone areas, which effectively keeps or even increases the level of catastrophe's severity dimension, since repair and re-building is covered while (social and economic) costs for re-settling to lower-risk areas might come in higher for potential flood victims.

The assemblage that is catastrophe appears here as one at the intersection of political struggle, epistemic contestations, and socio-material affordances. Elliott highlights the move from – in her case floods – 'Acts of God' to predictable events that yield personal and state responsibilities. In line with Elliott's remarks but in a more broader sense, precisely because of the intricate entanglement in and with the Anthropocene and the corresponding socio-material understanding of catastrophe, I will avoid completely the notion of 'Act of God' (e.g. Hirschman, 2016; Jarzabkowski et al., 2015a; Powers, 2012), even though the expression refers to the financial services' and legal language, rather than being used directly as a metaphysical or analytical term. But to underline the argumentation of this thesis, it is precisely not something that ever lacked earthly involvement – catastrophe is unforeseen on the level of detail, yes, but ontologically it is very much and literally 'down to earth'.

The overall question that this thesis will offer an answer to is the following: in the context of the Anthropocene (an epoch in which knowledge production is not passive but an active element of ontological becoming), how are the very practices and instruments of market societies that produce this knowledge actually active in these ontological processes? Most of the literature acknowledges (commercial) natural hazard risk science and practice as enablers of turning natural catastrophe into a calculatable and, therefore, commodifiable thing, but it is more than just financialisation: it is not just an epistemic vehicle in the realm of profit seeking but it is, more fundamentally, deeply entangled in catastrophe's very ontology. If, as noted above, the Anthropocene necessitates the recognition of "a profound mutation in our relation to the world" (Latour, 2017a: 8), then one important question is *how* we relate to it. One way, of course amongst many, is a financial one, which bleeds into nearly every other relation in today's, indeed capitalistic, 'planetary situation'. The next section will clarify the conceptual toolbox that I will deploy throughout this thesis to make sense of, understand and analyse catastrophe and catastrophe modelling and their entanglement in and with finance and the Anthropocene.

IV. Conceptual Framework

This toolbox of different conceptual notions is the result of an investigation that has been of an explicit explorative nature, i.e., one that purposefully lacked a concretely envisioned outcome, hypothesis or scope. Therefore, what follows now is to a large degree the consequence of what Karin Knorr Cetina calls 'intuitionist theorizing', a way of theoretically grounded pick-and-choose from different concepts driven by the empirical field (Knorr Cetina, 2014). In line with this form of theorising and in conjunction with what Woolgar and Pawluch call 'ontological gerrymandering' (1985), the following conceptual framework 'bends' the theoretical selection toward the observed empirics, placing the concepts in the observed. For the remainder of this chapter, I will engage in a brief discussion of markets, knowledge production and performativity, followed by the introduction of this thesis's three main conceptual notions – *socio-material mediation*, *simulation* and *experimentality* – which are central to, then, conceptualising a financial ontology of Anthropocene catastrophe.

a. Knowledge Production, Performativity and Markets

To a large extent against the backdrop of science studies and their reflections on how fact production is involved in reality formation, the social studies of finance are often concerned with the impact knowledge production in financial arenas has on what constitutes the financial in and beyond markets. Contemporary economic sociology and social studies of finance highlight that knowledge production of economic entities is one of the major constituting aspects of economic reality. Knowledge production in economic spaces is, however, not a straightforward process and, more importantly, it is not passive. That is, created knowledge in economic market contexts is not only a mere positivistic understanding of a distant, observed world, but it is instead through these observations a very active producer of the economic world itself (Caliskan and Callon, 2009, 2010; MacKenzie and Millo, 2003). But it is not economics alone which calculative spaces are made of. It is rather that economics facilitates a space of possibilities to bring into economic fields heterogeneous elements and incorporate them into calculative practices and by that render them economically meaningful (Callon, 1998).

In order to mediate and create relationships between economic agents, calculative practices have to be established to provide for a comprehensive and homogeneous understanding of the entities to be exchanged, making them by means of valuation what they subsequently will be: a comparable and exchangeable good (Callon and Muniesa, 2005). For the case of natural catastrophe, catastrophe models sort, order, and abstract the messy material world of natural catastrophe in a way that they can enter into a "formal, calculative space", they are epistemic, calculative and what Callon et al. call a "market device", which configures "economic calculative capacities and [qualifies] market objects" (Callon et al., 2007: 4–5). Calculation, in turn, is not a universal property of human agents but the very "concrete result of social and technical arrangements" (ibid.). Catastrophe modelling provides the central calculative epistemic devices and practices of these arrangements, merging scientific and financial knowledge production and practices by opening up a calculative space that is the catastrophe risk market.

This generative influence of epistemic practice, such as research, planning, design, on the unfolding of the empirical, the 'real' world, is generally referred to as 'performativity' (e.g. MacKenzie, 2006; MacKenzie et al., 2007). Knowledge of entities changes – sometimes even creates – these entities the moment it is produced and applied; knowledge is as consequential and real as the 'real' itself, so to speak. In that sense, a very real part of catastrophe is not only the actualised entanglement of natural phenomena and socio-material assemblage, but the knowledge about this entanglement as well. Certain market devices, such as catastrophe models, are, then, not only epistemic but also involved in ontological work – note that, as discussed above, anything concerned with an Anthropocene environment, something catastrophe models very much are, already constitutes this general state of 'epistemology collapsing into ontology'. Via, for instance, language and articulation (e.g. Lepinay, 2007a, 2007b, 2011), infrastructural properties (e.g. Pardo-Guerra, 2019; Poon, 2009), processes of deliberation (e.g. Caliskan, 2010) or calculative mathematical formulas (e.g. MacKenzie, 2003; Millo and MacKenzie, 2009), economic reality in different markets and settings is formed and evolves.

Even more fitting, because of its procedural character, I would like to refer to this evolving or formation as *'realisation'* (Muniesa, 2014; Caliskan, 2007). Particularly in the context of Anthropocene catastrophe, knowledge production is in permanent negotiation, and so one can say that, based on its calculative practices and devices, the financial catastrophe risk market emerged in a form of "experimentation phase" (Callon, 2009: 539). Any market is filled with heterogeneous actors, instruments, technologies, politics, and institutions, which can prevent a market containing only "cold sources" (ibid.: 541), that is a plain model of economic exchange. The "hot sources" that are controversies, alliances to change rules, debates, in other words "irreducible uncertainties" are in constant negotiation and movement and magnify experimental characteristics of markets (ibid.). With a focus on catastrophe modelling as the key epistemic practice in catastrophe finance, all aspects that make up this practice and its devices become part of these 'hot sources'. All this comes into play when practices in, related to, and dependent on catastrophe modelling *realise* catastrophe for and through financial services and markets and by that *realise* a financial ontology of Anthropocene catastrophe – this understanding, therefore, reflects the pragmatist perspective this thesis is loosely situated in, "reality as effectuation and signification as act" (Muniesa, 2014: 16). I will now draw out a conceptualisation of three interrelated and interdependent elements of this realisation: socio-material mediation, simulation and experimentality.

b. Socio-Material Mediation

The recognition of the Anthropocene forms an intricate underlying of a socio-material understanding of catastrophe, which fundamentally blurs the lines between notions of the social, the technical, the material, and the natural. This advances further by recognising knowledge production's active role in the realisation of the 'environment' and subsequently of catastrophe. This assertion can not only be based on the socio-material reading of different interacting agencies in the unfolding of Anthropocene catastrophe but also by way of looking at how Anthropocene environment is experienced and acted upon. In knowledge production, the socio-material is kept in the Anthropocene by means of *sensing*, what Jennifer Gabrys terms "becoming environmental of computation […] environment is not the ground or fundamental conditions against which sensor technologies form, but rather develops with and through sensor technologies" (Gabrys, 2016: 9). The relationship to environment today, in- and outside of science, is mediated through a ubiquity of sensing devices, such as satellite systems, anemometers, weather monitoring systems, or seismographs. This drives knowledge production of catastrophe risks since the scientific analysis of catastrophe is enabled in the first place and performed through the data which precisely these very instruments produce: these devices determine the dimension of occurrence of catastrophe and have had a historically constituting role in knowledge production of catastrophe, as will be shown in chapters 3 and 4. But also regarding the dimension of severity, services and devices such as Google Earth(Mitchell-Wallace et al., 2017), but most importantly insurance companies in form of their exposure and claims data, play a big role in this assemblage, since they serve as crucial data input for catastrophe modelling.

Part of Gabrys's argument can be read in that one mainly has access to the environment by means of processes of active socio-material representation. Through sensing devices and practices "environments […] are involved in processes of becoming along with these technologies […] environments become computational" (ibid.: 9). Perception of the environment such as wind, precipitation, ground motion, or air pressure are “no longer understood as a cognitive operation performed by a single human but is conceived as an event distributed through numerous sensing processes, bodies and sites” (Tironi, 2017: 3–4). With regard to Andrew Pickering’s understanding of knowledge production as hinging on the interaction between researchers, instruments, and objects of scrutiny, and in-built (almost Kuhnian) politics and goals to this scrutiny, which change along the processes of interaction (Pickering, 1994), sensing technologies are not neutral and passive instruments but meant to sense and represent by data production something preconceived and purposeful. Knowledge production is ordering the multiple device-mediated experiences of socio-material environments by means of modelling: sensing is “all the ways in which computers input data into internal calculative processes in order to output data in another form” (Gabrys, 2016: 10). Sensing technology is a fundamental part of what Paul Edward calls a “vast machine”, a network of climate science and data as a global knowledge infrastructure that is dispersed and multiple and in-flux: climate knowledge relies on “shimmering data [that] never resolves into a single definitive record” (Edwards, 2010: xviii). Moreover, for instance in meteorological prediction, only 10% of the data originate in actual instrument readings – synthetic data makes up the largest part in climate, weather and earth science (ibid.: 22, 445), which, therefore, is subject to assumptions, interpretations and is not simply straightforward readings. Particularly this last aspect directly connects data creation with the next section’s notion, that of simulation.

c. Simulation

Co-produced in this way through sensing, environment usually feeds in the form of data into models, while it is often produced already by modelling of some sort. In this way, simulation should not be viewed as something that necessarily comes, chronologically, after sensing but they should be understood as interdependent parts of one process. Modelling is, amongst other things, the embodiment of goals underlying epistemic practices, it is a central part in “goal formation” of knowledge production, which in itself always remains experimental, i.e. not finite and always changing (Pickering, 1993: 578). Models synthesise knowledge about the world into what Philip Agre calls a ‘grammar of action’ (Agre, 1994). Even though he applies this notion to forms of socio-technical surveillance, in the case of catastrophe modelling it is the abstraction of objects into a space which ascribes to these abstracted signifiers of objects a ‘grammar’, that is a systematised and abstracted understanding of these objects’ *interactional* agencies – how agencies within the assemblage of the socio-materiality of occurrence and severity produce catastrophe.

An understanding of a ‘grammar of *inter*action’, then, holds an inherent idea of goals as to what is to be modelled and for what purpose. There are theoretical and procedural decisions and choices to be made in modelling since there is never only one way to represent the world. Goals as images of future states of affairs are, then, maps for extrapolating present knowledge towards imaginaries about possible futures and this is achieved via *simulation*. Simulation continuously bridges the relentlessly moving gaps of experience and the knowledge of it between past, present and future. Simulation, for instance in economic contexts, "constitutes the very vehicle for the realization of business, with realization understood in both the sense of becoming actual and becoming meaningful" (Muniesa, 2014: 128). But it is not only business that is realised. Catastrophe is disassembled and broken down into components which are reassembled, by means of mediated information, in a model on the basis of a generative understanding of it. The dimension of simulation becomes the producer of new 'realities', understood here in a loose analogy to Baudrillard, as mentioned in the introduction chapter.[15]

Catastrophe modelling disentangles the socio-material complexity of catastrophe into building blocks of it and by that into a compartmentalised understanding of its abstracted unfolding: by way of modelling, catastrophe is synthesised by de- and recontextualisation. Because it is fundamentally an

[15] One can see an, admittedly only superficial, analogy to abstracted objects both in the sense of 'calculation' (Callon, 1998) and as denominated by an abstracted 'grammar' (Agre, 1994) in Baudrillard's work. He describes the consequences of detaching a thing from its originally and individually designated signifier or 'sign', a detaching from reality and by so doing fundamentally problematising reality itself. This thesis, however, does not want to engage in a discussion about post-modern reality or the lack of it, but wants to extract, possibly in a rather blunt way, the idea of how spaces of new realities are constructed by means of simulation and what this can tell us about an Anthropocene ontology in market societies. Models, for Baudrillard, are ways of production which superseded modern serial-production (Baudrillard, 1993). While the latter, a "second-order simulacra" (ibid.: 53), is seen as a form of copying from an original, models replace the original in a generative turn. They act, so to say, as an original without any other origin than "reproducibility" itself (Baudrillard, 1993: 56). The model, instead of the original or a copy thereof, becomes the ultimate "signifier of reference" (ibid.). Production on the basis of a model, then, is an operation of simulation, and by way of simulation on the grounds of models the detachment from the 'real' is complete. Anything that might have been an original signifier or sign has not only been detached from its original but also disassembled and reassembled in a model on the basis of a 'code' that is a generative understanding of the 'real'. The dimension of simulation as "third-order simulacra" (ibid.), then, becomes the producer of new realities, as the "real is produced from miniaturised units, from matrices, memory banks and command models – and with these it can be reproduced an indefinite number of times" (Baudrillard, 1983: 3). Where my conceptual bricolage becomes very explicit is here: while Baudrillard refers instead of the 'real' to the 'hyperreal', which supersedes the real, I diverge (philosophically rather unsystematically) from this notion. Instead of a hyperreal which is both literally rather hard to grasp and leads the discussion into a different direction, I would like to argue that (by means of the ontological work in the Anthropocene, knowledge production and markets, as discussed above) the effect that simulation has is precisely that it *realises* socio-material reality that is actual and tangible and, more importantly, conditions Anthropocene catastrophe again.

operation of carving out possible futures, catastrophe modelling resolves the separation of the 'real' and the 'imaginary' so that catastrophe, how it is dealt with in risk markets, remains both modelled and actual, since it is the reference point for 'real' practices, decisions and socio-material interventions. Simulation can, therefore, be understood as concept or theory 'in action', as enacted theory and assumptions of interactional agencies both in-situ and in-vivo. An indication towards this can be read between the lines of Weinkle and Pielke's observations of the influence of modelled catastrophe risk on housing prices and real estate development (2017). Here, models' risk outputs determine the price for insurance, which in turn determines the affordability of mortgages or legal ability to build a house. The concurring value of then built houses, its shifts up- and downwards, have then, again, an impact on catastrophe model assessments of the houses in the insurance portfolio, which highlights a certain circularity. If the value of a home is influenced by the cost, or even the sheer availability, of disaster insurance, then, of course, this impacts on the potential loss value within the portfolio, on which basis the cost of disaster insurance is iteratively then, again, based. This holds an implicit reference to the performative aspects of catastrophe modelling – "the simulator produces 'true' symptoms" (Baudrillard, 1983: 5).

d. Experimentality

Experimentality is meant to refer to the two previous notions as a *general condition* under which a realisation of Anthropocene catastrophe takes place. It is meant to 'socio-materialise' the quite inflationary notion of 'uncertainty', which is analytically often rather coarse. For this, a deeper reflection on knowledge and knowledge production is needed to, then, identify the necessity for a notion that is different from 'uncertainty' for analysing the realisation of catastrophe in an Anthropocene era.

Knowledge production as an active component in ontological evolving, with regard to the concept of performativity, is the result of interactions of different types of active agencies of both human and material kind (Pickering, 1993, 1994, 1995). This is important for the analysis of catastrophe and its modelling because, as argued above, a socio-material understanding of catastrophe as multiple interacting agencies enables to refer to catastrophes as active and interwoven participants in the process of knowledge production itself. Knowledge constitutes through what Pickering calls a "mangle of practice" (Pickering, 1995). Research always is an interaction of agencies between researcher (as the individual, a social group, and their specific aims), instruments, and the object of scrutiny (Pickering, 1995). The ontological realisation constitutes objects that are "manipulated by means of various tools in the course of a diversity of practices. Here it is being cut into with a scalpel; there it is being bombarded with ultrasound; and somewhere else […] it is being put on a scale in order to be weighed. But as a part of such *different activities*, the object in question *varies from one stage to the next*." (Mol, 1999: 77; my emphasis).

These processes take place in a trial-and-error form of adjustments and readjustments of all entailed elements, which makes knowledge production in this sense inevitably *open-ended* and thus always experimental as all parts of the process are *in constant flux* and outcomes are unclear. New knowledge, then, informs further readjustments and thus not only describes a reality but *changes it* in its application to processes of new knowledge production. Also, the production of knowledge, in its inextricable relationship with ignorance or non-knowledge, continuously illuminates what is not known (McGoey, 2012). And especially the relationship between ignorance and uncertainty, which might sometimes be understood as a rather deterministic one in which the decrease of ignorance, i.e., increase of knowledge, decreases uncertainty, appears different then. For instance, as Pielke argues: knowledge production can "add significant uncertainty" (Pielke, 2001: 151) and this is ever more relevant when, as in this case, Callon's "hot sources" (2009: 541), i.e. the interactional struggles of markets and socio-material configurations, are integral to these very entanglements.

Knowledge production about Anthropocene catastrophe conforms in this sense with the argument that "[new] knowledge can only be produced after a successfully failed experiment", which fails successfully only 'in vivo' (Gross, 2016: 621). The operation of modelling, then, happens as 'downscaling' "by means of simulations" (ibid.). Knowledge production of socio-material catastrophe in the Anthropocene – within the confinements of mediation and simulation – is in itself an ongoing real-world experiment. Centrally, for instance concerning catastrophe's severity dimension, there are constant re-adjustments of socio-material adaptation via, for instance, building designs, materials, and building codes, defence structures, polices, etc. However, 'provoking' catastrophe's multiple socio-material agencies via, for instance, new sea walls or different building designs, takes too much time (especially for finance) to yield a not yet exactly known reaction – "man cannot afford to wait", as one early catastrophe modelling pioneers put it (Friedman, 1972: 5) – it has to be provoked via simulation. Back-testing, then, is an ultimately necessary operation for planning and further risk assessment. Catastrophe modelling, therefore, plays an active part in these real-world experiments.

Now, this 'real world' itself is, of course, an Anthropocene one. To be more precise, it is the 'critical zone' – Earth's permeable near-surface layer between its crust and Troposphere – that reaches in the Anthropocene's congruence with Latour's 'metamorphic zone' – this conceptual arena in which action becomes agency and where epistemology collapses into ontology. The critical zone is at the same time location, object and subject of operations of the metamorphic zone, where Anthropocene catastrophe is realised at the intersections of permanently in-flux socio-material and mediated environment, simulation and inherent experimentation. This assemblage is characterised by 'feedback loops' as the recognition of agencies and history, the historical agent that Earth has become: "[h]istory surprises us and obliges us to start all over again every time […] If the feedback loops are similar in form, their contents, rhythms, and extensions are different in each case" (Latour, 2017a: 138). As we will see throughout the empirical cases provided throughout this thesis, this is particularly true and illustrative for catastrophe: each 'proper' catastrophe, its occurrence and severity, is so very different than the last.

The condition that characterises this situation is what I would like to call *experimentality*. A socio-material, Anthropocene and performativity-oriented framework necessitates a more agency-oriented notion of a condition that might be otherwise called 'uncertainty'.[16] Since the Anthropocene yields a world in which agency, knowledge production and ontology are intimately intertwined, it is the *relationship* between knowledge and uncertainty that becomes analytically at least questionable if not even unhelpful, as Pielke reminded us a few paragraphs above. It is agencies in the critical zone and practices in knowledge production that are the drivers of the realisation of the 'real' in the Anthropocene. In the case of catastrophe and its manifestation in the financial world, practices are informed, produced and affected by negotiating, surpassing, and disputing about catastrophe by means of mediated data and simulation, which *produce specific* uncertainty in this space: theoretical uncertainty, sensing uncertainty, user uncertainty, model uncertainty, etc.; aspects that contribute to Callon's 'hot sources' and which will be investigated in detail in the following empirical chapters.

I propose to view these 'empirical uncertainties' – they are mainly practitioners' terms – not as the precondition for creating risks, in the Knightian sense noted above, but as the *products of risks*, risks that are generated in and for the financial field of knowledge production of catastrophe. In finance, catastrophe modelling is, in this sense, an *experimental* practice that is not about searching for a specific or even temporal 'truth' (Kouw, 2012), but it is performed to be used, to enable the practice of risk management of insurance, reinsurance and securitisation via producing catastrophe risk as a financial good. Here, risk is, then, not simply the abstract and systematised quantification of uncertainty, but risk is understood as *practiced*. Even though only very implicitly, an understanding of risk as practice in this sense can be read between the lines of Jarzabkowski et al. (2015b; Kob, 2017). A rather fluid conceptualisation of risk as something contextually dependent on the very practices and relationalities it was generated by and for: risk as an entity is constructed and played out by the participating actors through their interconnected practical framework in everyday practice. At the same time, risk in this thesis is also understood as materially produced through 'enactment' (c.f. Collier, 2008) in form of models and metrics via simulation. And this reverberates throughout the socio-material Anthropocene,

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[16] On a rather analytically practical level (and apart from the lack of a notion of agency), using the term uncertainty would also necessitate differentiating multiple levels and qualities of it, while at the same time needing differentiations from the empirical field's ubiquitous usage of the notion of uncertainty. The result would be a rather confusing and potentially not very precise montage that would not yield analytical potential and rigor – and, again, would ignore agency as a central factor.

which is continuously changing, both independent of but also as a reaction to those risks and subsequent uncertainties, which are, for instance, implicitly noticeable in Weinkle's and Elliott's works discussed above.

Experimentality is the *condition* under which ontological realisation in the Anthropocene takes place. It (a) fundamentally hinges on agency, (b) acknowledges knowledge production as an active part in (c) a socio-material world that is permanently changing, and which (d) entails risk and uncertainty as ad-hoc and pots-hoc practices and products of assemblages of experimentality (assemblages which have already been at play before risk and uncertainty have been produced). Here, also uncertainty does not serve as a 'unifying principle' (with respect to the discussion on the Anthropocene above) but receives meaningfulness as a consequence of risk as actively practiced. Practiced risk here is based on socio-material mediation of information and simulation and, therefore, is fundamentally dependent on and consequential in the multiplicity of agencies in the critical zone. Experimentality, thus, is the condition under which catastrophe is realised in the Anthropocene, where the Human/Nature distinction is dissolved and where, in an appropriation of Latour's words for the case of catastrophe, "[a]fter each passage through a [catastrophic] loop, we become *more sensitive* and *more reactive* to the fragile envelopes that we inhabit." (Latour, 2017a: 140). This, however, does not necessarily mean becoming qualitatively better at it, but that there is a non-teleological increase in experiencing and responding, sensing and modelling, or in other words, *socio-material mediation* and *simulation* in every further realisation of Anthropocene catastrophe.

e. Financial Ontology of Catastrophe

What does all the above mean concretely for the rather specific arena of financial services in market societies? Even though the concepts above are in principle applicable for any site of ontological becoming of aspects pertaining Anthropocene environment and knowledge production, they are particularly helpful for understanding finance's role in this wider 'planetary situation' of ours. And one way to launch a perspective on this is by focusing on the pivotal practice that is catastrophe modelling as market device and practice, the mode in which this thesis approaches this field.

Experimentality as a condition under which catastrophe markets exist is not only the mode in which the socio-materiality of Anthropocene catastrophes is captured and co-produced by catastrophe modelling. It is also the mode of the application of catastrophe models in markets (including, for instance, uncertainties, usages, interpretations, socio-technical interactions, routines, organisational set-ups, politics, interests, etc.) that is situated in the realm of experimentality. Here, catastrophe modelling is performed to be used for practicing risk. To produce catastrophe risk as a financial good, finance becomes an active agent in the *realisation* of catastrophe itself, and it is precisely here where I identify the financial ontology of catastrophe. In this final section, I will illustrate this identification by mobilising the conceptual framework laid out above.

Since socio-material environment cannot be captured on a different level than on that of actual agencies, the operations of ontological action are at work in concrete localities: "Earth itself can no longer be grasped globally by anyone. This is precisely the lesson of the Anthropocene", which puts at work the notion of 'multinaturalism', discussed above (Latour, 2017a: 136). Socio-material mediation only takes place in concrete local sites, taking part in realising catastrophe here. An illustration of this is, for instance, the 'Science on a Sphere' project of the US's National Oceanic and Atmospheric Administration (NOAA).[17] It is an animation of the globe showing recorded earthquakes in chronology of occurrence from 1901 to 2000. This animation is based on a database that entails every known earthquake since their recording was enabled by the invention of the seismograph. While the animation runs and if you keep focusing on California, you will see a little explosion of flashes representing earthquakes here from the 1930s onwards, while the rest of the animated globe keeps 'blinking' at its previous pace. This is because those areas in California became more densely populated, accumulating economic significance while being situated in an earthquake-prone locality, which prompted the installation of a dense network of seismometers in this region. In the US, the first building codes, the National Building Code, was created by the insurance group National Board of Fire Underwriters in 1905 leading to California's own Uniform Building Code in the late 1920s (Scott, 2006b: 46). Only with this registration, this mediated experience, could then building codes be set up, building designs altered, loss systematically identified, mapped and classified, insurance contracts written, etc. – realising what becomes a catastrophe is impossible without socio-material mediation. And it happened here precisely because of a socio-material environment that was beginning to be captured by financial risk management (more on this historical aspect in chapter 3).[18] Today, insurers such as Sompo Japan Nipponkoa Insurance, for instance, actively set up flood sensors measuring precipitation for parametric insurance products (Artemis, 2019b) – financial services actively engage in multinaturalism.

This engagement is fundamental for simulation. However, what is to be simulated is at the discretion of those who give meaning to it, that is who perform and use it. The demand for catastrophe models reflects what is considered meaningful for financial risk management. For instance, where there

[17] See: https://sos.noaa.gov/What_is_SOS/. For direct access to the animation see: https://www.youtube.com/watch?v=jhmF-IwP6uM&feature=youtu.be.

[18] From the 1970s onwards, the animated globe suddenly lights up constantly, which represents the worldwide capture of a seismographic network: from then on, earthquake was fully in the realm of an Anthropocene realisation of catastrophe and by becoming 'sensitive' in this way, this form of mediation captured also Earth's tectonic plate boundaries.

is little *financial* risk to be produced, there is usually no catastrophe modelling (connected to the so-called 'protection gap'). Even though simulation is an intricate part of realising catastrophe, non-existent commercial simulation does not mean that there is not any simulation present. Simulation does not necessarily require computer modelling, it is rather, in a loose Baudrillardian sense, what is composed of 'code' and 'model', an abstracted compartmentalised quality of an entity (e.g. DNA) and a way to re-compose the 'real' on its bases (e.g. the human body). Knowledge, for instance, of how flooding plays out in the originally quite populated Bangladeshi mangrove forest does exist and therefore plays a role in how catastrophe realises here – simulation is not absent. But commercial modelling is absent because there is not enough financial risk producible here, loss is financially too low. Catastrophe here, therefore, is realised differently: the waterfront's banks crumble and catastrophe encroaches continuously. This is very different in the US, where the resources for producing catastrophic risk are the highest in the world. Here, for instance, hurricanes Katrina (2005), Ike (2008), Sandy (2012), or Harvey (2017) unveiled previously neglected aspects – and therefore in the re-adjustment of models *added* to catastrophe's 'grammars of interaction' – such as coastal flooding, storm surge, inland damage, precipitation flooding; so-called 'unmodelled loss components'. Also, the socio-material assemblage interacting with those aspects is something that needs active denomination in simulation activities. For instance, what is included in the so-called inventory module of a catastrophe model (i.e., which objects take part in catastrophe's interaction) determines what is deemed at stake and what is not. What we are *sensitive* to and to what and how we *react* to a 'catastrophic loop' in the Anthropocene determines not only the next loop's experience and reaction but, fundamentally, the loop itself.

The outcome of this assemblage in the financial arena is what I call the *financial ontology of Anthropocene catastrophe*. Here, the way finance produces risks and uncertainties formats particular intellectual qualities on how experimentality plays out, since the forming of financial risks follows logics and uses instruments that are specific to the *financial* management of social, political and economic issues. An example for a logic would be portfolio theory as a way in which to think about what is at stake. 'Value-at-risk' metrics are an example for an instrument, which calculatively mobilises acceptability or unacceptability of dangers to what is at stake and how to react to it. (Both of these examples and others will be discussed in the following chapters.) Catastrophe is, therefore, composed by means of the effective configuration of socio-material mediation and simulation under experimentality which form and deploy the financial ontology of Anthropocene catastrophe.

By realising catastrophe in this way, simulation is heavily dependent on the experimental factors of specific localities, and due to the inherent condition of experimentality, the 'real' is multiplied within the same and between different localities and contexts. While socio-material mediation engages in 'multinaturalism', simulation engages in 'multirealism' (whereas both remain part of the same process, as argued above). Considering active ontology and performativity, “reality is *done*, [and] if it is historically, culturally and materially *located*, then it is also *multiple*. Realities have become multiple.” (Mol, 1999: 75). The twofold multiplication – multinaturalism and multirealism – is fundamentally grounded in agency, which unfolds in experimentality rather than ambiguous uncertainty. Anthropocene catastrophe is, therefore, *always real* – both modelled and actualised – precisely because of its active socio-material ontology: conditioned by experimentality, it is shaped by, and reshapes through, agencies and financial practices at the intersection of socio-material mediation and simulation, and by doing so mobilising the financial ontology of Anthropocene catastrophe.

Chapter 3. Catastrophe, (Re)insurance and the Roots of Catastrophe Modelling

Sometimes, when you are on your way down to the old Altona Fischmarkt in the port city of Hamburg, you can find yourself in soaking shoes or even wet trousers. Often when there are higher than usual tides or during rather frequent spring floods, the entire marketplace is under water and the old fish auction hall appears as if it emerges directly from the river Elbe itself. From there, following the docks to the east, you will reach the street Deichstraße at Nikolaifleet in the city's old town, which, in the first half of the 19th century, was home to the cigar factory of Eduard Cohen. At this address, a fire broke out during a night in early May 1842 which would lead to the establishment of the world's first reinsurance company, introducing a new dimension to the business and practice of risk management and marking the start into financially dealing with the socio-materiality of catastrophe.

I. Globalisation and the Emergence of Catastrophe Risk

Two major reasons for the intensifying danger of fires in the 18th century can be found amidst increasing industrialisation: transnational trade and urbanisation. Among colonial exploits of tradable goods such as tobacco, tea or herbs, was sugarcane as a raw material. While initial British demand for rum and refined sugar rose, sugarcane grew to become a major global business. However, plantations in the West Indies colonies and refineries in Europe and North America were regular sites of large fires due to the evaporation of sugarcane juice, accounting for the majority of bankruptcies in mid-18th century England (Borscheid et al., 2014). As a reaction around 1780, London's sugar manufacturers founded insurance companies which specialised in fire and industrial risk and also started "export[ing] this modern form of insurance." (ibid.: 26). Borscheid et al. identify this as the start of an increasingly global-spanning insurance network, since this kind of business was by nature cross-regional and cross-national. Keucheyan (2016) notes that while the globalisation of capitalism relied on the emergence of finance, finance itself would have not been able to develop without insurance. Amidst growing global trade and urbanisation, fire and shipping risks (not only of tobacco or herbs but also, roughly until the beginning of the 19th century, of slaves) and industrial accidents, propelled the business of (non-life) insurance[19] and later reinsurance into a sizeable industry of its own, with firms originating mainly in England and central Europe (Borscheid and Haueter, 2012).

At that time, London had already suffered from its Great Fire of 1666 after which the first fire insurance companies in Britain were set up starting in 1680. Roughly a century earlier in Hamburg, fire

[19] The terminology of non-life insurance business in shipping casts a particularly troubling shadow on colonialism and the enslavement and trade of predominantly African people, who would be insured as transported goods and cynically, therefore, fell technically into the 'non-life' risk insurance category.

insurance contracts had already been started to be written since the end of the 1580s[20] (Borscheid, 1985). Starting with the fire at Cohen's cigar factory, nearly two centuries after London, Hamburg suffered a similar fate in 1842 with a great fire devastating the city's (largely half-timbered) old town and parts of its commercial centre (Borscheid and Haueter, 2012). Due to then already established fire insurance underwriting, insurers were hit hard by fire loss which forced many of them into, or to the brink of, bankruptcy. As a direct reaction to this, the Kölnische Rück (Cologne Re) was organised the same year and the charter signed in 1846 – it was set exclusively to insure insurers and became "the world's first specialist reinsurance company" (Borscheid et al., 2014: 44). Big fires in growing commercial and urban spaces would follow elsewhere, for instance in the US in Chicago 1871 (Penuel, 2011) or in Boston 1872 (Hornbeck and Keniston, 2017).

The central problem for insurers in general, but especially for the concrete spatial factors of urban fire risk, is the 'concentration of exposure' to the same kinds of risks in policy portfolios (Grace et al., 2003). A high geographical concentration of houses in the books of an insurer means a high risk for serious accumulated loss in case of spreading fire. While the development of probability theory, emerging in the 17th century (Esposito, 2014), merged with life-insurance practices in the mid-18th century, e.g. with the first modern life-insurer Equitable formed in 1762 England (Borscheid et al., 2014), sophisticated techniques for risk assessment had not brought into practice for the growing fire-related non-life insurance (Turnbull, 2017). Instead, for fire insurance underwriting a rather simple portfolio risk-exposure assessment technique was applied since the late 18th century, so-called "pin-mapping" (Kozlowski and Mathewson, 1997: 323), for which insurance maps of the areas where insurers held policies were pierced with pins signifying individual insured property (Grossi et al., 2005). This representation of portfolios' fire-risk concentration informed underwriting and later also reinsurance purchase decisions, and was also used for underwriting wind-related risks, such as hurricanes, since the 1930s in the US (Kozlowski and Mathewson, 1997). This measure did neither include any estimates for the occurrence nor the severity of catastrophe, but focussed solely on risk diversification by visual means: in case of catastrophe, insurers would have made sure to have evaded high local risk concentration while having written enough policies in many other regions whose premiums income could then compensate for potential loss at one specific site.

Therefore, unlike life-insurances' actuarial probability calculations and numerical representation of risk (Borscheid and Haueter, 2012), fire and catastrophe insurance used visual representations of risk. The main reason for this difference in underwriting practices and decision making was one of data availability. With the developments in probability theory and statistical

[20] They already included not only coverage for fire damage but also, for instance, insuring the creditor side of mortgages.

calculation in mid-17th century Europe and prominent proponents such as Blaise Pascal, Jan de Witt or Gottfried Leibniz, statistical practice was eventually applied for life insurance pricing (Borscheid et al., 2014). For life insurer Equitable, the basis for its pricing technique were mortality tables produced by Richard Price in 1776 (Braun, 1963), and in Germany until the mid-19th century, the cleric Johann Peter Süssmilch's mortality tables served similar actuarial purposes (Borscheid et al., 2014). Although tedious, the registration of deaths (later linked with other demographic factors) is a more or less straightforward collection of data and the result is a broad dataset of numerous individual data points distributed over time: mortality data simply was made available and has been ever since. In contrast to death, which for insurers is mainly the averaged life-span of groups of people with a straightforward unit of exposure (Turnbull, 2017), catastrophe is a multi-dimensional complex and, relative to the eventual death of people, a rather rare experience. But equally important as the rareness of catastrophe was, of course, the lack of measuring techniques, methodologies, and knowledge production of natural phenomena such as ground motion, seismic shocks, wind speed, or storm behaviour, which prohibited the production of data.

II. Knowing and Acting on Catastrophic Natural Phenomena

When you walk up Pitt Bay Road towards the harbour, one of the main yet tranquil streets in Hamilton, Bermuda, you will have passed by offices of most of the biggest players in the global reinsurance and alternative risk transfer markets (most of the rest are located a ten minutes' walk from here on Victoria Street and its vicinity close to the Bermuda Monetary Authority). Over the past 30 years, Bermuda has become one of the three major hubs for these markets – the other, older two are Zürich and London. Finance professionals and lawyers in suits with creased Bermuda shorts will have passed you by in the warm subtropical breeze. Walking through the beautiful Queen Elizabeth Park Par La Ville and catching some much-needed shade under the trees, you will reach Reid Street, named after one of Bermuda's colonial governors during the 1840s. Down this street, in the garden of the administrative Cabinet Building, Major General Sir William Reid has also been dedicated an obelisk memorial. While Bermuda will play a big role in the more recent history of disaster risk transfer markets, it did not in the 19th century. Yet, its former governor, Reid, did. Or rather, that of what he marked the start of: the systematic study of potentially catastrophic natural phenomena.

a. Understanding and Sensing Catastrophic Natural Phenomena

The first catastrophic natural phenomenon that was turned to by emerging modern science were hurricanes in the late 18th century (Muir-Wood, 2016). At that time, British Navy log books were utilised as standardised meteorological registers (Naylor, 2015). The technique involved rather cumbersome inspections of logbooks in which storm sightings were reported alongside longitudinal positions of the respective ships measured by chronometers. This method of data production enabled to trace back storm paths and became the first encounter of a systematic study of hurricanes, put forward by William Reid's findings on marine storm behaviour, published towards the mid-19th century (Reid, 1838). A few more studies followed these initial findings (e.g. Piddington, 1889) until towards the end of the 19th century steam ships became more commonly used, which weren't dependent on wind and which could take other, less storm-ridden routes (Muir-Wood, 2016; Schwartz, 2015). However, in the mid-20th century, the study of storms and cyclones was continued (e.g. Palmen, 1948) and soon, from the 1950s onwards, revolutionised by numerical computer modelling and forecasting (Smagorjnsky, 1983) and later satellite technology (Edwards, 2010).

A means to systematise storms in a generalisable and comparable way are classification systems, which are expressed, first and foremost, in *scales*. With anemometers being around in various forms since the mid-15th century (NASA, 2010), wind speed has been a long established measure. However, storms, in a very pragmatic and indeed a socio-material way, are more than just the speed of wind since the context of strong winds matter. Storms are wind-in-context, such as tornadoes (on land) or cyclones (on the ocean). Scales systematise wind by measuring and contextualising it, making wind by means of scaling a 'storm' in the first place. One of the earliest systematic storm scales was the Beaufort scale devised in 1805 by Frances Beaufort (Courtney, 2002). At first, the originally 13-category scale did not have reference points to wind speed but was based on observations of the wind conditions, for instance, to sea conditions or to a vessel's sails and masts. From the mid-19th century, the scale was accompanied by anemometer readings, with a coefficient to link the scale to wind speeds. Tropical cyclone scales today depend on maximum sustained wind velocity over a predefined period of time usually 10 metres above ground or water and the respective tropical cyclone basin specifications. Atlantic, Eastern and Central Pacific cyclones are classified on the five-category Saffir-Simpson scale, which was the first 'simple' scale for public use referring to effects of tropical cyclones. Other basins in principle use the same but always slightly context-adjusted versions of this scale, such as the Western Pacific basin with its four-category Typhoon Committee Tropical Cyclone scale. Other scales are, for instance for on-land storms, the TORRO (UK) or Enhanced Fujita (North America) tornado intensity scales.

More complicated to study scientifically proved to be earthquakes. The great earthquake of Lisbon in 1755 inspired the first ideas of scientific encounters to make sense of these phenomena beyond the realm of religion or fate (Udias, 2013). Seismology, the science of earthquakes, emerged (however not yet institutionalised) against this backdrop around the start of the 19th century, with John Mitchel recognising earthquakes as accelerated underground waves (Sorkhabi, 2005) and the first seismographs designed by Luigi Palmieri and John Milne in the mid-19th century (Musson, 2013; Nave et al., 1999). Similar to the storm path reconstruction method of William Reid, Robert Mallet mapped historical earthquake data geographically and discovered distinct patterns of earthquake 'belts' around the globe (Mallet, 1858). After the rupture and permanent displacement of the San Andreas Fault in 1906, which devastated San Francisco's brick buildings and caused numerous fires, Harry Reid developed the 'elastic rebound theory',[21] which is still the central theory for earthquake-generating mechanisms today (Reid, 1909; Udias, 2013).

During the 1950s it became evident that seismic instruments were able to pick up detonations of hydrogen bombs (Muir-Wood, 1985), which led the US government to invest substantially into the construction of a global monitoring network for detecting earthquakes in the 1960s (Hutt et al., 2011). Global weather monitoring systems in general came into being; most fruitfully in the Cold War period (Edwards, 2010). Added advanced satellite technology in the 21st century enabled the 'Interferometric Synthetic Aperture Radar', which revealed "the complete pattern of elastic rebound around each new earthquake fault rupture" (Muir-Wood, 2016: 71).

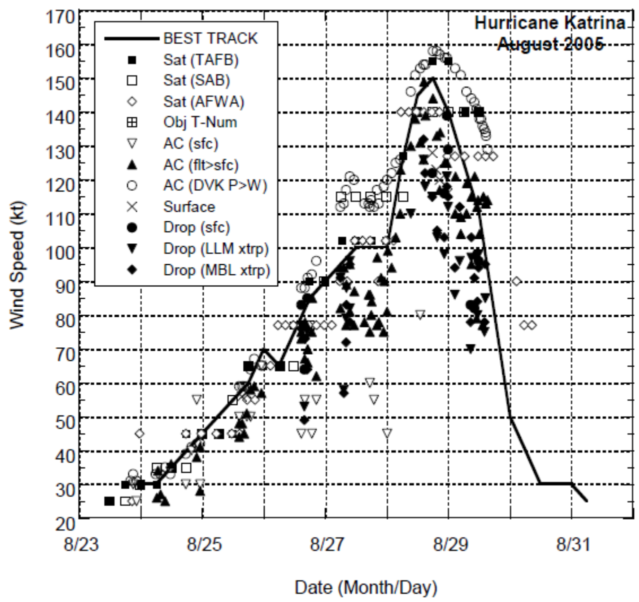
One of the first seismic scales was the six-category Rossi-Forel scale towards the end of the 19th century (CDP, 1895; Rossi and Forel, 1881) which was the basis for an adaption by Mercalli and Cancani at the beginning of the 20th century, the Mercalli-Cancani scale. Its translation into English and technical revision by Wood and Neumann (1931) was again revised in 1956 by Charles Richter, who before also had developed a nine-category magnitude logarithmic scale for earthquake energy release (Richter, 1935). Richter's magnitude scale quickly became the quantification standard for earthquakes, generally the new 'currency' for communicating earthquake strength, and remains well-known today (Muir-Wood, 2016). It was modified in the 1970s under the name 'moment magnitude scale' or MMS and is applied by most scientific and state institutions today. Another intensity scale of eight degrees was developed in Japan from the 1950s onwards, the Japan Meteorological Agency scale or JMA (Kawasumi, 1951). The 'Modified Mercalli intensity scale' or MMI is, after a series of substantial alterations (c.f. Dowrick, 1996), also still widely used today.

Generally for meteorological, hydrological and geophysical observation today, for instance the World Meteorological Organization (WMO) and its Integrated Global Observing System, which include its Global Observing System, Global Climate Observing System and Global Ocean Observing System, are informed by 10,000 manned and automatic surface weather stations, 1,000 upper-air-stations, 7,000 ships, 100 moored and 1,000 drifting buoys, a three-digit number of weather radars, 3,000 commercial aircraft mounted with special measuring equipment, 16 meteorological and 50 research satellites

[21] The elastic rebound theory explains how energy in rocks on opposite sides of a fault builds up and deforms the rocks. The earthquake occurs once the internal strength of the rocks is exceeded, which leads to their breaking and release of energy and subsequent displacement of ground surface (Betbeder-Matibet, 2008).

(WMO, 2020). Measuring instruments or sensing devices often include thermometers (air, soil, water temperature), barometers (atmospheric pressure), hygrometers (humidity), anemometers (wind speed), seismographs (ground motion), pyranometer (solar radiation), rain gauge (precipitation), wind socks (wind speed and direction), disdrometers (drop size distribution), ceilometer (cloud ceiling), tensiometers (soil moisture), radiometers (radiation such as UV), and remote sensing such as radar altimeters (e.g. satellite-based wavelengths of ocean waves), LIDAR (e.g. chemicals in atmosphere or vegetation sensing), or stereographic aerial photography (e.g. topographic imaging).

Amidst all these devices and systems, the socio-material mediation of meteorological, hydrological and geophysical phenomena always takes the form of an assemblage, a stitching-together of multiple mediated (i.e. observed and estimated) data points, such as the illustrative wind speed curve of Hurricane Katrina in Figure 4. In practice, the academic cyclone and climate scientist P63 tells me, “when you want to use the observations, whether it be in-situ observations or the re-analyses that are partly model products or anything else, you know, yeah, you have to understand these issues. [They] are different for every dataset and every *use* of the data on how the limitations come into play. But one that doesn't change is that one should understand what one is dealing with and it's very easy to underestimate the subtleties or the things one doesn't know that one should know about the data, whether they are pure observation or model influenced.”



Selected wind observations and best track maximum sustained surface wind speed curve for Hurricane Katrina, 23-30 August 2005. Aircraft observations have been adjusted for elevation using 90%, 80%, and 80% reduction factors for observations from 700 mb, 850 mb, and 1500 ft, respectively. Dropwindsonde observations include actual 10 m winds (sfc), as well as surface estimates derived from the mean wind over the lowest 150 m of the wind sounding (LLM), and from the sounding boundary layer mean (MBL).

Figure 4: Selected wind observations and best track maximum sustained surface wind speed curve for Hurricane Katrina, 23-30. (Knabb et al., 2005: 38)

b. Categorising and Scaling Disaster: Catastrophe-in-Context

The ways in which extreme meteorological, hydrological and geophysical natural phenomena are classified, in one way or another always relate back to the socio-material realisation of catastrophe, enabled by the embeddedness of both socio-material mediation and simulation in an Anthropocene world. Indeed, devices such as scales provide a central illustration of this entanglement and also of the ontological becoming that is involved in the interplay of socio-material mediation, simulation and experimentality, the central concepts of this thesis introduced in chapter 2. Earthquake scales, for instance, are never completely straightforward, independent and objective with respect to the actual space in which the ground motion takes place. As stated above, and similar to anemometers and wind speed, seismographs had been around before most earthquake-related scales were developed. However, the first scales that were created, such as the Mercalli-Cancani scale (later Modified Mercalli scale MMI) or the Japan Meteorological Agency scale (JMA), were and are *intensity* scales, which are grounded in contextual observation of the *effects* of ground motion in a specific locality – an earthquake is ground motion-in-context.

Intensity scales based on observation, so-called 'felt' intensity, classify according to *observations* of how ground motion affects the built environment and sometimes even reactions or emotional states of affected populations. A 'strong' shaking on the MMI, for instance, is intensity class VI and observes: "Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight" (USGS, 2020). The contextual nature of this measure can be helpful for earthquake risk assessment because the same energy released by different ground shakings can have very different effects on the same built environment (Betbeder-Matibet, 2008) – the socio-material assemblage of catastrophe's agencies plays out differently every time.

While intensity scales can be understood as ordinal scales, where comparisons and levels between scale degrees or classes do not allow for meaningful interpretation, *magnitude* scales do. Magnitude scales, in contrast, are ratio scales based on *physical measurement*, the 'size' or strength of an earthquake, such as seismic energy release manifesting as amplitudes of waves recorded by seismographs. They not only allow to simply differentiate between degrees, but they also have meaningful distances between the degrees, the numerical values are relational to one another while intensity scale degrees are only relational in terms of their order.

But the question is, of course, where to set the degree thresholds for magnitude scales if they are to be meaningful in practice. Technically, for instance since Richter introduced a logarithmic scale, the thresholds are the logarithmic numerals of the amplitude of waves on a seismograph, which means that every increase in one whole number (i.e., threshold) corresponds to a tenfold increase of the seismographic amplitude and a 31.6-fold increase in released seismic energy. So, the logarithmic function, for the sake of simplification and handleability, keeps the number of thresholds low, while the relationship between the thresholds is exponential and not linear. Richter developed his original magnitude scale in California and, as a result, anywhere where the earth crust is different, his calibration turned out to be inaccurate. But even if transposed to another or even general geological context, a pure magnitude measure alone will not be sufficient to reflect the earthquake as a whole – earthquakes of different qualities (e.g. from different faults such as 'interplate' or 'interslab') can have, for instance, very similar moment magnitudes but one might not be felt at all while the other produces significant damage to structures (Choy et al., 2002). Socio-material mediation, as noted in chapter 2, is always local, in context and an interactional mutual interdependency of environment and sensing.

So, in addition to measuring and reporting different magnitude metrics, intensity scales and measures are a vital component, because they give meaning to the abstracted and decontextualized measure of magnitude on a socio-material level. In a comparative study of intensity and magnitude scales, Devenport and Dowrick find that "[f]elt intensity scales have some drawbacks but are based on *real* damage" while "[i]nstrumental parameters are more objective but have sparse coverage and are *not* directly associated with *real* damage." (2002: 4; my emphasis). Also, no magnitude scale is driven by the entirety of a seismic wave-train, which results especially for very strong earthquakes in a "systematic underestimation of a magnitude", the so-called "spectral component of magnitude 'saturation'" (Bormann et al., 2012: 18) – in other words: these scales are discrete and somewhat finite and not continuous, so they 'saturate' towards their higher end even though stronger events might have scored higher (c.f. Kantha, 2006). A streamlined and decontextualised measure of seismic energy release, therefore, will not tell you what happens to a particular set of buildings in individual socio-material contexts.

However, also shifts in intensity scales are inevitable over time as the building codes and construction practices vary and develop and the effect-side of ground motion differs, for instance with soil conditions (Betbeder-Matibet, 2008) – intensity, rooted in socio-materiality, is in-flux and changes constantly. Taken all these points on both kinds of scales into account, it is not overly surprising that correlations between the two are relatively loose and low; for instance "where very high peak [ground acceleration magnitude] values have been recorded they have not been accompanied by any remarkably high felt intensity values" (Davenport and Dowrick, 2002: 3). Scales are not simply passive devices but are part of the assemblage of agencies in an Anthropocene world. Scales such as those described *do* many things: for example, they play an active and substantive role in decision-making for evacuation management, they are also central for establishing, verifying, challenging and updating building codes, structural and infrastructural design regulations, or for engineering specifications for defence structures, but most importantly: scales and their values make catastrophe cognisable, analysable and communicable in the first place.

Epistemic devices such as scales, by classifying catastrophe and influencing socio-material environments, become part of the ontology of catastrophe themselves. And they do so primarily by means of simulation. As discussed in chapter 2, simulation and socio-material mediation are not independent but parts of the same process in which ontology can be 'shaped in action'. Simulation, here, is expressed in the ways magnitude and intensity are brought together. One part of this is to develop an understanding of interactional agencies at play between those two, to determine the 'grammars of interaction' that constitutes catastrophe-in-context. Simulation does not, in the conceptualisation of this thesis, necessitate, for instance, computer modelling per se, but represents more generally a particular epistemic practice with ontological features. Goal formation is the other part, where different measures produce different data against the backdrop of what they ought to represent and for what purpose this representation is to be used. One reason for using and sticking with a logarithmic scale for magnitude measures, for instance, was that in terms of (Arabic) numerals, it was easier to relate them on a meta level to similar numerals of intensity scales (often noted in Roman numerals). But empirically they shift constantly, and they do not correspond straightforwardly in any way, as noted above with regards to Davenport and Dowrick's study.[22] This brings us to the underlying condition of experimentality.

c. Scaling Experimentality

As characterised in chapter 2, experimentality is the condition under which socio-material mediation and simulation operate. It constitutes a situation in which knowledge production and ontological realisation of catastrophe are open-ended due to the interaction of a multitude of agencies in an in-flux Anthropocene socio-materiality. The Saffir-Simpson hurricane wind scale (SSHWS) embodies the interplay of mediation, simulation and experimentality rather well. Developed in the early 1970s by Herbert Saffir and Robert Simpson, the scale was initiated by the need for a comprehensive and straightforward classification of tropical cyclones, in this case hurricanes (NOAA, 1972; Saffir, 1973; Simpson, 1974). Interestingly, even though it was originally meant to reflect the interplay of the weather phenomena's parameters, such as wind speed and central pressure, and the damage this inflicts on built structures – Saffir was a structural engineer and Simpson a meteorologist – it was inspired by the original

[22] Sometimes, for instance if you look up the Richter magnitude scale on Wikipedia, you will see a table in which a 'strong' earthquake category VI on the MMI (intensity) corresponds with a 'light' earthquake at 4.0-4.9 M_L and a 'moderate' earthquake at 5.0-5.9 M_L on the MMS (magnitude). This is incorrect in principle as these relationships are not given in any systematic way (c.f. PNSN, 2020).

Richter magnitude scale (Kantha, 2006), which, as stated above, purposefully did not incorporate intensity effects. However, until today Saffir-Simpson is used for signifying both intensity and magnitude.[23]

As most scales, the Saffir-Simpson scale underwent numerous modifications. Modifications can already be understood as consequences and part of experimentality, since they are reactions to 'feedback loops', the practical recognition of agency and historicity, which occur on the in-flux intersections of socio-materiality and knowledge production where ontological realisation takes place. Originally, the scale was termed Saffir-Simpson hurricane scale (SSHS) – without the explication of 'wind' – because it incorporated not only wind speed (maximum sustained velocity over one minute) but also central pressure and, in particular, storm surge height. Since storm surges are one of the most destructive characteristics of tropical cyclones at landfall, this measure – or rather simulation feature – was originally an integral part of the scale, brought forward by Simpson, then director of the US National Hurricane Center. The SSHS scale combined the dimensions of magnitude and intensity on one scale with five distinct categories. Each category was assigned threshold values for physical measures of wind speed and central pressure (socio-material mediation), and corresponding potential numerical surge height and qualitative effects for the affected socio-material environment from both wind and flooding damage and other consequences (simulation), such as infrastructural disruption and difficulties for evacuation measures (NOAA, 1972, Appendix A). Despite practical issues such as the unrealistically distinct threshold borders[24] or the saturation towards the scale's highest end (similar to the MMI), the SSHS was, with a number of smaller modifications, continuously in use for any tropical cyclone system in the Atlantic and northern Pacific that was stronger than tropical storms until a major and fundamental revision in 2009.

Against the backdrop of the very destructive and surge-intense Hurricane Camille in 1969, classified as the highest Category 5, the Mississippi Gulf Coast region north-east of New Orleans used, amidst other indicators, Camille's SSHS category as a benchmark for assessing hurricane risk and estimates for potential evacuation needs. In 2005, Hurricane Katrina had originally been a Category 5 but upon arrival at Mississippi's coastal strip it had reduced to a Category 3. The socio-material aspects here had been led by the Camille benchmark: the reinforcement and structural protection measures in this location had since then been adjusted according to Camille (Kelman, 2020). Residents,

[23] For storms, intensity and magnitude are often (and sometimes confusingly) called hazard and intensity (c.f. Kantha, 2006).

[24] The thresholds would flip a hurricane over into a higher or lower category if wind and central pressure measure (magnitude) moved only by one digit around the threshold (Kantha, 2006), while, in theory, damage (intensity) rises by a factor of four per distinct category increase (Schott et al., 2019).

consequently, did not evacuate the area since it was assumed the local structures could withstand a Category 3 hurricane. Though being a Category 3 at this point, Katrina turned out to be a significantly larger storm system than Camille (in terms of spatial size, which is not captured by the scale), carrying with it substantially greater amounts of surge water. The surge was roughly 25% higher and swept away multiple buildings and killed 200 of the residents. Muir-Wood speaks of an "invisible wall" in the minds of the residents (Muir-Wood, 2016: 22), and this is precisely one of the aspects of what is meant by simulation's interaction with ontological becoming of socio-material reality of catastrophe. Both, the grammar of interaction (the assumed correspondence between wind speed and central pressure to surge height) and the mechanics (if wind speed and central pressure are measured at Category 3 and empirically the surge is more like Category 5, the overall hurricane still remains at Category 3) of simulation embedded in SSHS played out and were integral part of catastrophe here. Not only was the behaviour of residents provoked by it, but also the built environment and settlements in this region over a long period of time. Conditioned by experimentality and driven by agency within the same socio-material assemblage, an 'invisible wall' in simulation can move an actual wall in the real, one way or the other.

After this particular catastrophic feedback loop – "we become *more sensitive* and *more reactive* to the fragile envelopes that we inhabit" (Latour, 2017a: 140) – all components except sustained wind speed were removed from the scale, "to provide a more scientifically defensible scale […] in this revised version – the Saffir-Simpson Hurricane *Wind* Scale (SSHWS)" (Schott et al., 2019: 2). This scale, revised in 2009, is in use until today in various forms, with derivatives of it for other tropical cyclone basins.

For the context of scales, used here as an illustration of what will become a more complex (dis)entanglement of elements once we focus on catastrophe modelling itself, the two dimensions of magnitude and intensity are the field- and device-specific scientific expressions. It might have become obvious at this point, that this thesis understands them as being specific equivalents of catastrophe's more general analytical dimensions of *occurrence* and *severity*, introduced in chapter 2. One is the dimension of the natural phenomenon, in this case the way they are expressible, measurable and describable in terms of these phenomena's disentangled and compartmentalised physical components, its building blocks. The other is the dimension of the socio-material components which interact with the phenomenon, and on which basis catastrophe is realised. Important to note, however, is that the device of a scale can only provide a deterministic relationship between occurrence (magnitude) and severity (intensity), and even that, as seen in the example of the SSHWS, is not an easy relationship. The dynamics of performative simulations of those dimensions' relationship, however, intensify when it becomes a probabilistic one.

The move to a probabilistic treatment of catastrophe in the (re)insurance world would take a while. Until the late 1970s, all these scientific insights into potentially catastrophic natural phenomena were applied by only few in the (re)insurance business. Even the technique of pin-mapping discontinued in the 1960s, because it was time-consuming and seemed unnecessary: during the 20th century, construction practices and materials, such as the standardisation of steel-reinforced concrete, and fire-fighting advanced while, mainly in the US, major earthquakes became rather rare and from the 1960s on the number of severe hurricanes, despite Camille's high intensity, overall dropped significantly to a long-term low (Kozlowski and Mathewson, 1997). In their absence, the socio-material determinants of catastrophe changed with ever growing settling behaviour (especially on the coasts) and ever-increasing urbanisation. Due to shrinking income in non-life property (re)insurance from lower fire risks, natural catastrophe policies were written from the 1950s onwards but without the more sophisticated actuarial practices applied, for instance, for accidents or theft (Muir-Wood, 2016). Another reason was, for instance in Australia until the 1970s, that loss due to storms were considered "similar in nature to fire losses" and managed like fire risks (Walker, 1997: 12). Consequently, insurers issued coverage partly without protecting against catastrophic loss by reinsurance cover and more generally "the insurance industry lost the discipline of measuring and managing exposures susceptible to catastrophic loss" (Kozlowski and Mathewson, 1997: 323).

III. Thinking Catastrophe Probabilistically

"We're looking at scenarios where a significant amount of campus gets flooded" – we are both looking out of his office window onto Charles River that separates Cambridge from Boston. "From a hydrodynamic point of view, you know, this is not actually a river so much as a lake that's separated from the ocean by dam, just down there". He is pointing towards the Museum of Science further down the river, which covers this side of the three-locked Charles River Dam system. The Massachusetts Institute of Technology or MIT, the campus where I am visiting interviewee O89 is known for producing a number of researchers, who are central to both disaster-related sciences and disaster risk markets. While I had met him first at a catastrophe finance conference in London – he is often invited to industry events as a speaker – he is indeed an academic, whose paths, however, intersect very frequently with this part of global financial services. From MIT's campus across Harvard Bridge over into Boston, it is about a 30 min walk to reach AIR Worldwide's headquarters, the first commercial catastrophe modelling company and until today one of the two market leading firms. As we will see, proximity and intersections between academia and financial services are very common patterns in this field.

"It's quite *probable*", he continues, "that a sufficiently strong storm causes a surge that overtops the dam, causing the river to go up at the same time that heavy rains cause a pulse of freshwater to come down and flood Back Bay Boston and the campus. And as sea levels go up and as storms become more violent, that becomes *more probable*". To think and practically manifest catastrophe in calculations and models as *probabilistic* has, however, historically not been straightforward. At the same time during the post-war period when MIT would produce two particular people – Carl Allin Cornell and Don Friedman, who's work would enable this way of thinking and practice especially for the financial services – a more general move towards probabilistic thinking and practices emerged, into which non-life (re)insurance slipped only gradually.

a. Groundwork in Probability Thinking and Practice

Probability calculations and statistics during this time further developed especially in physics. In the wake of deeper foci on equilibrium behaviour of thermodynamic systems and particles in the early 20th century, the interplay of physics and statistics intensified. One outcome of this was a practical turn: from – initially – computing many single simulations of physical dynamics and deriving from them spatial and time averages towards – then – calculating these physical observables via random sampling from canonical distributions (Betancourt, 2017). Generally, in the late 1940s and 1950s computer technology advanced significantly, prominently featuring the development of the Electronic Numerical Integrator and Computer (ENIAC) in the US.[25] Here, the generation of exact random samples for estimating physical observables became possible and against this background Klari Ulam, Stan Ulam and Nicolas Metropolis developed and formalised the 'Monte Carlo method' (Metropolis, 1987). It made possible the generalisation of random sampling and increased statistical representativeness for any mathematical computerised simulation. For cases where there were no or only little actual data, random sampling proved pivotal in the development of computer simulations of rare or even unprecedented events (Galison, 1997). For catastrophe, these general developments would eventually bring forward an important part of how to format the relationship between occurrence and severity that constitutes catastrophe. As discussed above, if this relationship is a deterministic one, it creates many practical and conceptual problems for practices and devices that try to characterise and determine catastrophe. These developments in artificial sampling and computerised simulation would change this relationship significantly in the post-war period.

From the late 1940s onwards, nuclear power was developed for civil use in the US and a new form of risk calculation emerged: 'probabilistic risk assessment' or PRA[26] (Perkins, 2014). This method was designed to estimate the likelihood of accidents, specifically in the context of constructing nuclear

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[25] The ENIAC programme was founded by the Meteorology Group at the Institute for Advanced Study (IAS) in Princeton in 1946 (Smagorjnsky, 1983). The construction of one of the most powerful computers of that time, the first one to run rather complex computer simulations due to novel working storage capacity in computer memory modules, was to a significant extent designed for modern weather forecasting.

[26] This name, however, only became official in the mid-1970s.

reactors for the Manhattan Project, and later more generally in running commercial nuclear power plants and the danger of potential radioactive release. It was a technique that mathematically calculated the probabilities of failing systems and subsystems of reactors (Carlisle, 1997). Part of the groundwork for this method was also laid in the ENIAC programme, to which Nicholas Metrolpolis initially was invited to construct a computational model for a thermonuclear reaction to be run on the machine (Metropolis, 1987). In a long process, politically initiated by US President Eisenhower's 'Atoms for Peace' UN speech in 1954, the US Nuclear Regulatory Commission eventually released a central report in 1975: the 'Reactor Safety Study', also known as the Rasmussen Report (NRC, 1975). It was aimed at communicating and assuring the scientifically legitimised safety of commercial nuclear power plants by drawing out risk probabilities and concluding that the "risk of death from a reactor accident was about that of being struck by a meteorite" – this report publicised and legitimised PRA and probabilistic thinking in risk analysis on a broader scale (Carlisle, 1997: 932).

b. A New Relationship between Occurrence and Severity

The development of PRA from the 1950s onwards promoted probabilistic thinking not only in nuclear and, in the aftermath of the Apollo 1 disaster in 1967, in aerospace safety (c.f. Cooke, 2009) but also in structural engineering and seismology. In the mid-1960s, Carl Allin Cornell, a structural engineer, developed stochastic methods to test how random physical loads, such as ground motion, wind, or vibration from traffic, affect buildings (Cornell, 1964; Muir-Wood, 2016). Long holding a professorship at MIT, Cornell's Alma mater had been Stanford University, an institution at the forefront of earthquake engineering and a place out of which roughly 20 years later one of the two major catastrophe modelling firms would be founded. At the same time Luis Esteva, a graduate student at the Universidad Nacional Autonoma de Mexico, was exploring the relationship between the frequency of earthquake occurrence and ground motion (McGuire, 2008). Their collaboration in the mid-1960s proved to be fruitful, as Esteva developed some of the first probabilistic seismic-zone-maps giving information on probabilities of ground motion (ibid.).

Cornell subsequently developed a more generalisable concept for describing the probability of extreme values of ground motion which he created specifically to be applied to his findings on building behaviour, thus, for structural design decisions. While extreme value distributions could be (very crudely) calculated for floods or wind-phenomena by using historical figures, for earthquakes and ground motion this was not possible due to the substantial lack of accurate historical data and, where it existed, lack of quality of these data (ibid.). Cornell determined the probability of ground motion exceeding the statistical annual maximum motion without the need of a sufficient historical record of earthquake-data (Cornell, 1968).[27] The core output was the "probability of exceedance" of ground motion above an annual average expressed in the "ground motion hazard curve", building on multiple individual strengths of ground motion and their likelihood of occurrence (McGuire, 2008: 334, 330). Another outcome of Cornell's stochastic studies was the understanding that distributions of extreme values of ground motion caused by earthquakes proved to be similar to extreme value distributions of other natural phenomena (ibid.: 332), which made this method a generalisable concept for the stochastic description of extreme natural phenomena. Analog to the more general PRA approach, Cornell's method was coined 'probabilistic seismic hazard analysis' or PSHA. The difficult relationship between occurrence and severity, discussed above, by treating it stochastically was starting to overcome its deterministic character and proved to be a central aspect towards a *probabilistic understanding and practice of catastrophe*. As argued above, defining and formatting this relationship is done by developing and explicating a grammar of interaction, the way these two dimensions interact. The goal formation here was a purposeful orientation towards the socio-material world, in particular for structural design concepts. The components of simulation of catastrophe were shaped strongly by Cornell's work, as it influenced both the subsequent intellectual and practical developments on catastrophe modelling and the ontology of catastrophe itself: from then on, his work would be used for analytically determining building codes around the world (ibid.), and by doing so directly impacting on, and changing, catastrophe's socio-material dimension of severity.

c. The Cradle of Catastrophe Modelling

The spill-over into the financial realm has been this particular approach's application. While the majority of the (re)insurance industry had not picked up on evolving sophisticated methods in the probabilistic treatment of natural catastrophe, Travelers, a US insurer, founded the Travelers Weather Research Center and the Travelers Weather Service in 1955 for analysing the relationship between weather phenomena and insurance liabilities (Muir-Wood, 2016). The Research Center's initial staff were nearly exclusively meteorologists from MIT with some early expertise in probability computation and coding (CIA, 1960). Part of this first core staff was Don Friedman, who started developing models that would explore the consequences of natural phenomena for insurance portfolios (Guy Carpenter, 2011). Friedman constructed distributions on the basis of historical weather data and Traveler's historical loss data, initially a rather mundane data production for the insurer's actuarial staff (Friedman and Roy,

[27] As a solution, Cornell treated earthquake occurrences as a Poisson process which changes the calculation from a time-dependent into a time-independent one (Field, 2005). Herein he factored the ground motion via the Gutenberg-Richter law (ibid.) which describes a deterministic relationship between earthquakes and magnitude (Gutenberg and Richter, 1949). This treatment, in a methodological way, might have been somewhat influenced by the probabilistic 'turn' to random sampling and canonical distributions described above.

1966). While the mathematical and stochastic description of catastrophe had been advanced by Cornell, the fundamental problem of a lack of large and diverse enough data sets and, even more so, data that indeed anticipated current states of catastrophic situatedness, was first approached in the 1970s by Friedman. Restricted to insurers' necessary awareness of changing conditions of insured objects, he added to Cornell's approach the problematisation of a permanently changing socio-material world. Historical data is insufficient for inferring future states of catastrophic spaces as the space itself, and therefore its very changes, are a major determinant of potential catastrophe:

> "What is needed is not actual damage that occurred as a result of past geophysical events, but damage resulting to the present distribution of properties [...] what it would cost if a comparable earthquake occurred today and affected the present type, distribution, and value of property. [...] [a model] artificially produces geophysical events that mathematically interact with a given geographical array of properties. [...] measures [...] which, because of his short life span, man cannot afford to wait for nature to produce." (Friedman, 1972: 5)

The crucial idea here is twofold: first, catastrophe is treated as a potential future state of affairs; it becomes *probabilistic*. Second, the historical (non-existent) data is produced artificially by inventing a catastrophic past that is then extrapolated into the future; it becomes *simulated*, or rather, its simulation intensifies. Probabilistic catastrophe models until today still bear the same basic structure that Friedman designed conceptually in the early 1970s. They consist of four basic 'modules': a) the hazard module, b) the inventory module, c) the vulnerability module, and d) the loss module (Grossi et al., 2005). The principle is to simulate synthetic catastrophic natural phenomena in the hazard module. The attributes of the natural phenomenon, ground motion for instance, are applied to the insured property in the inventory module with all parameters available, such as geographical location, construction type, height, or building materials. The consequential calculations are performed in the vulnerability module, the heart of every catastrophe model entailing the very crucial 'damage functions', which usually are the core of proprietary knowledge of commercial modelling firms today. Finally, the loss module derives from the projected damages the costs for repairs, compensation, or replacement, i.e., the liabilities for the insurer which are booked as loss. Relative to the computational power at hand, these models, then, ought to simulate numerous variations of a catastrophic event (today usually by far exceeding 10.000 variations) and represent all the different possible outcomes into a probability distribution. This is the framework in which the relationship between occurrence and severity will emerge in a new, probabilistic way, on the heels of new grammars of interaction and a range of specific and at times often conflicting goal formations. The important step of turning catastrophe into something probabilistic enabled these devices and practices to become something very different and much more than, for instance, catastrophe scales.

Friedman sought to set out a more ‘rationally’ informed decision-making and pricing of insurance and reinsurance coverage. However, Friedman himself at that point anticipated this to become a rather background aspect of actuary-like practice to produce “’actual’ long-term values of risk” (Friedman, 1984: 58). But it was not due to his own rather humble view that this at that time mostly intellectual endeavour came into actual practice only later. It was due to limited computational power and, more importantly and as stated above, because until the 1990s the insurance and reinsurance industry, with very few exceptions, generally neglected systematic precautionary measures to analyse and hedge against natural catastrophe (Kozlowski and Mathewson, 1997).

d. Catastrophe Risk Quantification and Probable Maximum Loss

“In all these businesses” – he means Californian earthquake engineering consultancies in the 1980s and later catastrophe modelling firms since the 1990s – “there is a nexus of networks between people and universities. […] The three major institutions in California were Stanford, Berkeley and Caltech [California Institute of Technology]. So if you are in this field you cannot avoid having interactions with all the academics of all three institutions. And a lot of their alumni went on to work for the US GS [US Geological Survey] or in these consultancies.” Interviewee I64 was educated in structural engineering at MIT in the late 1960s, took classes here by Allin Cornell, and after a spell at Stanford’s Graduate School of Business spent his time in the 1980s working in corporate finance contexts and towards the end of that decade mainly modelling interest rate risks.

> “Then we had Loma Prieta Earthquake in 1989, and EQE at that time had been founded six or seven years earlier, and they were doing earthquake engineering, retrofits for buildings, etc. [EQE’s co-founder] called me up and said ‘wow, you know, we had this big earthquake and we’re just busy, busy, busy here, business is rolling in and you, you know, maybe think about coming to work for us?’ He was the visionary, he was not a technical guy [...] he knew that I was working [in finance]. They were starting doing a lot of work with insurance companies [...] And he said, ‘at EQE we‘re developing preliminarily earthquake risk models’ [but] they were not portfolio models yet.”

He pauses and remembers an earlier question of mine on Cornell: “we actually hired Allin Cornell to consult. And he came to the offices – I hadn't seen him in a long time. And we were trying to develop concepts of how to incorporate probability theory into these [insurance] portfolio models that we thought we would gonna try to do, because we had some insurance clients.” Apart from Cornell, who at that time had moved back to Stanford after 20 years at MIT and who had only briefly consulted at EQE, I64 remarks, “we had probably more people from UC Berkeley than Stanford but we had both in our company. You know, [EQE’s other co-founder] went to UC Berkeley. Just because geography, I mean our offices were in San Francisco/Oakland and so we were close to Berkeley.”

From there, just a few stops on Bay Area Rapid Transit's Orange line I reach Berkeley. When you walk south from the main campus of University of California at Berkeley's, you will get to an old and steeper part of the town. You have to climb stairs that lead you through many terraces of old and often wooden or half-timbered private homes of which many were commissioned by senior academic staff since the early 20th century, and you will finally reach the upper side of Panoramic Hill. Keeping its name's promise, here you have a stunning view of the upper San Francisco Bay, framed by bridges: to the south San Francisco-Oakland Bay Bridge, to the north Richmond-San Rafael Bridge and straight ahead to the west the iconic Golden Gate Bridge. Today, it is not only the universities here and state agencies, such as the California Earthquake Authority, that are concerned with catastrophe, but also a community of companies that emerged from the 1980s on. Behind the southern fringes of the view that you have from Panoramic Way, EQE (now CoreLogic), I64's employee since the early 1990's and a firm which went on to become the third-largest catastrophe modelling firm, have their offices in downtown Oakland and San Francisco. Outside of your view down the southern San Francisco Bay in Newark are the headquarters of Risk Management Solutions or RMS, until today the largest catastrophe modelling firm. Down there it is only a short drive across Dumbarton Bridge to Palo Alto and Stanford University, where Charles Richter graduated in 1920 and where Allin Cornell completed his PhD in 1964 and to where he returned in 1983. From your view on Panoramic Hill to the north you see a little bay with the mouth of the Corte Madera Channel, a bit before Richmond-San Rafael Bridge arrives at San Quentin. Here in Larkspur, an almost sleepy place with affluent but small office buildings, the west coast offices of Nephila, the world's largest insurance-linked securities firm, reside.

Just down the Hill at UC Berkeley, geologist Andrew Lawson in 1895 identified the San Andreas Fault, a continental transform boundary between the Pacific and North American tectonic plates which extends far into the south of California (Lawson, 1908; Simpson et al., 1981). During the faults' major rupture in 1906, most of San Francisco was destroyed, in part by the ground motion itself but most by following fires (estimated magnitude M_w=7.9; intensity MMI=XI, extreme). In 1989, the fault ruptured again heavily in this area with the Loma Prieta earthquake, this time it was less fires but more ground displacement and infrastructure failures that occurred (magnitude M_w=6.9; intensity MMI=IX, violent). Here in this context in the wider San Francisco Bay Area, the concentration of historical significance for catastrophe modelling is probably one of the highest in the world. And here, in fact also at UC Berkeley, already a while before the likes of EQE and RMS were hiring finance-savvy people such as I64, the link between financial services and catastrophe-focussed science was laid out by Karl Steinbrugge and the generalisation of the probable maximum loss or PML measure.

In 1977, the probabilistic understanding of catastrophe was evolving specifically in catastrophe reinsurance with the introduction of a framework called 'Catastrophe Risk Evaluation and Standardizing

Target Accumulations' or CRESTA (CRESTA, 2017; Grossi et al., 2005). Although in the US the rate of earthquake and hurricane occurrences had dropped from the late 1960s on, they did occur elsewhere, for instance in Nicaragua (1972), northern Australia (1974), and Guatemala (1976), which produced loss especially for reinsurers (Munkhammar and Themptander, 1984). Because of rather opaque loss information supplied by insurers, the major internationally active European reinsurers set up new requirements for reporting portfolio information: "to obtain reinsurance, insurers would need to provide the total insured values of all the properties they covered for specified geographic areas, known as 'Cresta Zones'." (RMS, 2013: 12). The CRESTA zone maps were based on the concept of Luis Esteva's probabilistic seismic-hazard maps (Esteva, 1963).[28] These maps drew up the probabilities of occurrence of events for specific quadrants in hazard prone areas and their physical impact to those quadrants. CRESTA set new reporting practices as a form of self-regulation for and by the (re)insurance sector to obligatorily declare to-be-reinsured portfolios by means of CRESTA zone risk (RMS, 2013), demanding insurers to report potential "damage factors per CRESTA zone" (Grossi et al., 2005: 109). Following Cornell's method for determining extreme values of the physical outcomes of natural phenomena, these extreme values were applied to the specific distributions of the overall values of insurers' portfolios.

The output of these calculations was 'probable maximum loss' or PMLs. The method was conceptually based on Engle and Shield's work on earthquake loss estimates (Engle and Shield, 1934) and further developed by Karl Steinbrugge (1982) into an earthquake exposure measurement which remains widely applied until today. Engle and Shield produced their initial concept starting in the 1930s for the Board of Fire Underwriters of the Pacific. Steinbrugge, an engineer at UC Berkeley, explicitly integrated this insurance-related method into earthquake engineering methodology. For example, found in the Oral History Series archives of the Earthquake Engineering Research Institute, Henry Degenkolb, a well-known early earthquake engineer who served on the US President's Task Force on Earthquake Hazards Reduction notes: "Karl [Steinbrugge] took over from Harold Engle and Jack Shields […] the old insurance people and he was picked by Harold to follow up on that." (Scott, 1994: 171). Steinbrugge headed the Pacific Fire Rating Bureau for a long time himself, which in the 1970s became the nation-wide Insurance Services Office (ISO) (Scott, 2006a) and was involved in insurance rate setting for the property and casualty insurance industry, performing statistical and actuarial services and supplying data, for instance, on building codes. Since 2009, the ISO is a full subsidiary of the analytics firm Verisk, who also owns AIR Worldwide, the first catastrophe modelling firm (focused more on in the following chapters).

[28] Before CRESTA in 1977 these maps were nearly exclusively used by governmental agencies and research services such as the US Department of Housing and Urban Development or the US Army Corps of Engineers (Kozlowski and Mathewson, 1997).

The basic principle of PMLs is that a territory is divided into zones to which maximum outcomes of events are ascribed; insured buildings in these zones are divided into classes of different construction types (Wong and Dong, 1996). On this basis, the maximum loss to these properties are deduced, while the output, the PML itself, is the total loss relative to a return-period of the potential event: “A 500-year return period loss of $100 million, for example, implies that losses above this amount have a probability of 0.2% of occurring in any given year” (Grossi et al., 2005: 139). Subsequently, from the introduction of CRESTA and the PML measure “conversations between insurers and reinsurers were now focused on ‘what is the PML?’” (RMS, 2013: 12). The data requirements of CRESTA were analogised to the industry’s ACORD data-management and formatting standards (ACORD, 2017; CRESTA, 2017), which served as an additional means to standardise catastrophe risk data formats and management throughout the industry. The measures and metrics of CRESTA and PMLs signify particularly the conceptual proximity to intensity and magnitude scales introduced earlier in this chapter. Both, but of course primarily PMLs as the underlying rationale, bring together catastrophe’s dimensions of occurrence and severity in a deterministic way but taking probabilistic aspects such as return periods of events into account. However, they were not yet generating artificial data and simulated catastrophe events in the way Don Friedman had envisioned. But the PML measure and its integration into the (re)insurance sector via CRESTA zoning was the first more fundamental and broadly applied entanglement of catastrophe-related science and the financial services.

Before the turn of that decade, however, “the insurance industry did not take a great deal of interest in catastrophe modelling […] The ready availability of reinsurance at relatively low rates and a twenty year history of low losses were major contributors to this attitude.” (Walker, 1997: 15). This would fundamentally change in August 1992 with the then and until 2005 costliest tropical cyclone catastrophe in US history, Hurricane Andrew, and two years later with the Northridge Earthquake in California.

Chapter 4. Socio-Material Breaking Points and the 'Fracture of Reality'

Figure 5: Fabio Giampietro, 'Thanatos', 2019, oil on canvas. Courtesy of Fabio Giampietro

An example for a place that very impressively embodies the long-lasting and intimate entanglement of socio-material environment and catastrophic phenomena is the city of Catania in eastern Sicily. Situated roughly 25 km south of Mount Etna, the Metropolitan City of Catania is one of the determining factors that make Etna one of the planet's 16 'Decade Volcanoes', a designation by the International Association of Volcanology and Chemistry of the Earth's Interior as the most violent active volcanoes *in proximity of populated areas* (IAVCEI, 1994). Life with Etna has not only mythologically – Gaia's youngest son Typhon was trapped underneath Etna by Zeus – or behaviourally run long and deep – locals will explain to you that as long Etna puffs smoke everything is ok, it is when it stops puffing that things are going to get dangerous – but first and foremost socio-materially. Not only does Etna supply the volcanic soil that provides fertile ground for vineyards and orchards, but you will also pass by countless buildings in Catania that are built from volcanic rock itself, such as the impressive Cattedrale di Sant'Agata (its dome can be seen in the lower left corner of the painting above). It is ironic that volcanic rock as a building element makes a more flexible and durable material than most others and seems to prove particularly resilient during earthquake-induced acceleration (Jackson et al., 2014), which always accompanies volcano eruptions.

A few minutes from the cathedral in a small art gallery, Arionte Arte Contemporanea, hangs a painting by the Milanese artist Fabio Giampietro. Similar to Olphaert den Otter, the World Stress Series painter mentioned in chapter 2, most of Giampietro's paintings lack depictions of actual humans, but entail, as the primary representation of humans and their activity, Anthropocene (metropolitan) landscapes.[29] While den Otter soberly confronts us with the aftermath, the residue of catastrophe, Giampietro processes a surreal actualisation of the Anthropocene which is about to clash with itself. Supposedly antagonistic elements (fire and water) are entangled here in a potentially "destructive coexistence", an inevitable Etna and "the wave made of buildings that represents how men are forging the world".[30] This particular painting, Thanatos, named after the mythological personification of death, was produced for an exhibition on Eros, the god of love. The scene, however, does not represent a straightforward antagonism in the sense of modernity's Nature/Culture divide but depicts its inherent mutuality and the tensions ("Thanatos is since ever counterposed to Eros") *within* the Anthropocene itself.

As already mentioned in chapters 2 and 3, the inherent and inevitable Anthropocene tensions culminating in catastrophe, or rather catastrophic loops, refer ontologically not only to pure materiality, politics, or social dynamics but also to finance. 'Buildings forming a breaking wave' is also the result of financial tides and different currents of financial knowledge and practices, so to speak. The initial determining breaking points through which catastrophe finance and the practice of catastrophe modelling would fully emerge, change and evolve, and thereby enact a financial ontology of Anthropocene catastrophe, would take place in the first half of the 1990s amidst Hurricane Andrew and the Northridge Earthquake. They would not only fundamentally reshape the catastrophe market landscape but also deliver the final push to a fully developed probabilistic relationship between occurrence and severity, and an unfolding of a financially induced socio-materiality of catastrophe.

This will create what by the end of this chapter will emerge as catastrophe's 'fracture of reality', the in-flux tension and constantly moving breaking point between a modelled catastrophe and an actualised one. Because both feed epistemically and ontologically into one another, this fracture of Anthropocene catastrophe's inherent tension is the location where socio-material experimentality becomes most active. Catastrophe, as argued in chapter 3, is always catastrophe-in-context and the importance of this context's degree is captured by two parallel modelling techniques which developed amidst Andrew and Northridge: *aggregate* and *bottom-up* modelling. They constitute two core elements of catastrophe modelling and at the same time both represent and engage the relationship between occurrence and severity of Anthropocene catastrophe by realising and fracturing it as

[29] See: http://fabiogiampietro.com/works/

[30] Fabio Giampietro quoted from my correspondence with him in March 2020.

probabilistically simulated and financially mediated. At least for the case of catastrophe and finance, this is the point of a substantive “mutation in our relation to the world” (Latour, 2017a: 8) out of which a financial ontology of catastrophe will emerge.

I. Socio-Material Breaking Points: Aggregate Hurricanes

Figure 6: Early catastrophe modelling machines. Left: Sun Microsystems' SPARC 390. Middle: Karen Clark showing 9-track data tape reel. Right: Hewlett-Packard HP-97 print calculator. Photos taken by J. Kob, 2018

“If you want history: that’s my computer museum out there!” She nods towards behind the glass wall of her Boston office’s conference room. “That big box weighs about 500 pounds. It was the first time you could run a cat model not on an IBM mainframe computer. That’s a SPARC 390, it came off the assembly line in 1987. […] And those reels of tape, […] that’s how we got the data.” Among the exhibits of her little museum (which also include a RAID Hard Drive and an SGI ‘Supercomputer’) is a Hewlett-Packard HP-97 print calculator, which was the everyday technical device reinsurance underwriters used in pricing catastrophe treaties before catastrophe models entered the market. The calculator was donated to her by a reinsurance vice president who was amongst the early users of her first catastrophe model product for reinsurers, CATMAP. Karen Clark is the founder and former CEO of the first commercial catastrophe modelling company Applied Insurance Research or AIR.

“I am an economist […] I really liked building statistical models on a computer […] So I went to one job interview because it sounded perfect, it was a research department in an insurance company that did modelling of the economy […] it was very innovative for a company to do that at that time.” In the early 1980s, Clark started to work for the Boston-based insurer Commercial Union Assurance in a division applying econometric forecasting models to calibrate liabilities and anticipate claims in connection with potential economic downturns. In 1982, the company’s underwriters wanted to increase non-life property business for hurricanes but were constrained by the firm’s risk limits. To overcome these limits, they needed a ‘rational’ alternative on which they could base their underwriting decision (Hemenway, 2012). “My first project was, they said ‘we think we have a hurricane exposure problem along the coast but we don’t know how to address it, so can you give us an idea?’”. Initially tasked with computing actuarial probable maximum loss (PML) figures for the potential hurricane policies, Clark came across Don Friedman's 1972 modelling papers (Friedman, 1972, 1984). Friedman had constructed only deterministic models but had laid the intellectual groundwork and architecture for stochastic modelling of disasters. "So I thought, we need to have a probability distribution. What if I know a Cat 4 [SSHWS Category 4 hurricane] hits the Northeast and it's gonna blow my company up – well but what's the probability of that?"

In 1975 the US Weather Service initiated a large study on US hurricanes and storm surges of the past 70 years, conducted in cooperation with the US Nuclear Regulatory Committee and the US Army Corps of Engineers (Schwerdt et al., 1979). This study would also form an addition to the US National Hurricane Research Project's continuously evolving databases of historical hurricanes, HURDAT (NOAA, 2020a), which today are the main sources for historical hurricane data that catastrophe modellers tap into. Clark used Friedman's model approach, took the US Weather Service's report on hurricanes, and created Monte Carlo simulation-based probability distributions to produce average annual expected loss and, from the higher percentiles of the distribution, PML values.

The crucial aspect in her modelling approach is the alignment with that of Friedman's rather intellectual idea: that synthetic catastrophe is needed instead of purely historical catastrophe records since loss data for actual extreme events is rare and imprecise – it needs to become *probabilistic* – and, more importantly, the probability "distribution is not stable since many *factors* that influence it *change* with time […] Inputs may be changed to see how the loss distribution is altered" (Clark, 1986: 67f; my emphasis) – it needs to become *simulated*.

a. Probabilistic Hurricanes and Reinsurance: The First Commercial Catastrophe Model

In her model, annual hurricane landfall frequency was created from historical observations. For instance, within the sample period 1900-1978 there were 25 individual years in which no hurricane made landfall in the US, 25 years where one landfall occurred in each year, 14 years with two per year, etc. The landfall data, for Clark, fulfilled the criteria of a Poisson distribution (ibid.: 71), a time-independent probability distribution still used for event frequency distributions in some models today.

On a spatial level, landfall locations entered the model by segmenting the US coastline from Texas to Maine into roughly 60 zones with counts of landfalls for each zone. As mentioned in chapter 2, there are regional differences where exactly tropical cyclones make landfall, so uniform probability distributions on landfall location were not useful. Since she had not enough data to derive either actual relative frequencies or evidence for randomness in locational landfall distribution, she created smoothed frequency values for the zone averages (ibid.; Ho et al., 1975: 14). Eleven data points per zone were calculated with different, exponentially smoothed weights for each data point derived from time-series low-pass filtering methods (Craddock, 1969: 214; Duchon, 1979).

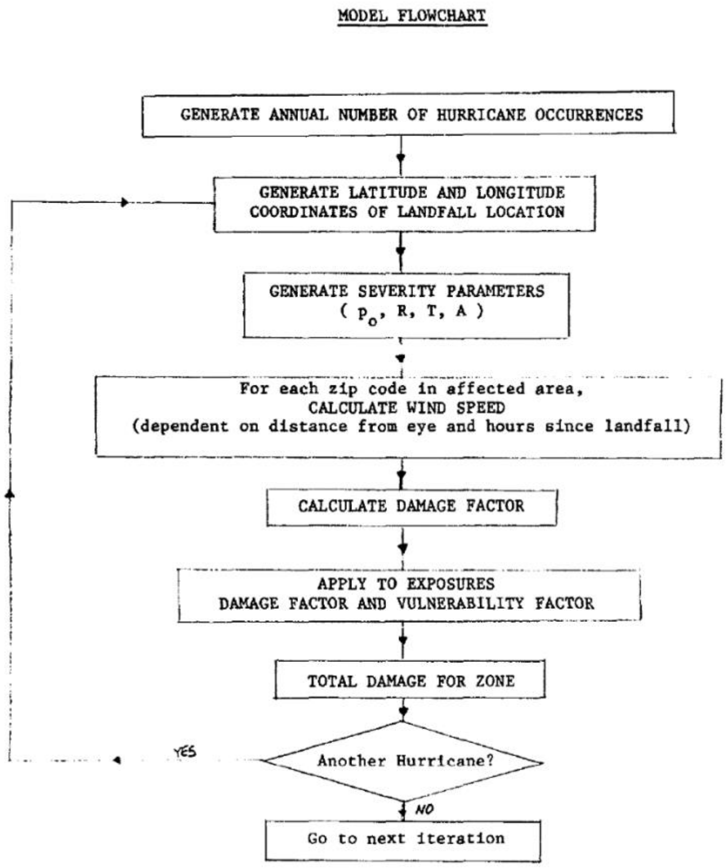

Figure 7: Model Flowchart of Clark's windstorm model example. (Clark, 1986: 70)

The weights were estimates that are meant to take into account a potential (but not known and therefore assumed) seasonality and to reflect the relative time distances between the observed landfalls: more weight in the averages was given to the more recent landfalls while less weight was given to the older ones. This is how practice gives meaning – greater or lesser importance – within simulation (here an aspect of catastrophe's grammar of interaction) at the discretion of the modeller. Scaled-up to a macro-level and to today's practices, this particular meaning attribution, of course amongst many other aspects, has an effect on rate-setting of insurance policies and therefore on what and how should be built in which location: the socio-material severity dimension of catastrophe. More generally, Clark noted that "[c]omplete and accurate data were available for most of the hurricanes that struck the US in this time period [from 1900 to 1978]" (Clark, 1986: 69). In fact, the data was neither complete nor accurate as the HURDAT project, the umbrella data project into which these data were integrated, underwent several massive re-analysis phases due to inaccurate data and extrapolations (NOAA, 2020a). This exemplifies the experimental nature by which both socio-material mediation (here US hurricane data) and simulation (here smoothing landfall location distributions) are conditioned.

The hurricane strength in this model was based on four fundamental meteorological parameters that allow wind speed and cyclone movement to be calculated: minimum central pressure, maximum winds radius, forward speed and wind inflow angle (Clark, 1986: 76). Since these variables are not independent and vary depending on location, “their correlations must be explicitly formulated within the model since the correlations will impact the variance of the model output, i.e. the estimated hurricane loss distribution.” (ibid.: 77). In other words, the grammar of interaction of catastrophe needed to be explicated: disentangled into building blocks and then reassembled in simulation. A strongly determining factor when controlling for location in hurricane strength is its position’s latitude, primarily because a tropical cyclone’s main energy source is the upwards-moving moist air from warm sea surface temperatures and as latitude increases, i.e., the more north the location over water, the lower the sea surface temperature and the less kinetic energy there is for circulation in the storm system.

Relatively strong linear relationships to latitude existed for maximum wind radius and for forward speed, so Clark generated simulated values out of these correlated relationships directly for the different locational zones. Central pressure and inflow angle, however, were less straightforward in their relationships with latitude, so she used the empirical distributions. In both variations to produce values – simulating from correlational relationships or from empirical distributions – it is obvious that these functions were based on purely statistical relationships that hinge on historically derived behaviour, which is basically, but in more complex dimensions, still the case for most catastrophe modelling today: “they mimic those statistics by generating their own [storm] tracks. And then they look at the history of measured storm wind speeds which go along with those tracks and use that to ‘model’ [he air-quotes with hits fingers], statistically model the wind speeds” (O89). This is an important aspect which highlights that Collier’s differentiation, discussed in chapter 2, between “archival-statistical knowledge” and “enactment-based knowledge” (2008: 225) as different calculative rationalities is not as straightforward *in practice*. In other words, socio-material mediation involves both synthetically enacted *and* archive-based environment and therefore are both an integral part of simulation.

Against the simulated storm path, the model derived damage inflicted by wind (i.e., not yet including, for instance, storm surge). Clark differentiated between direct damage and factors that moderate this damage, such as construction type and construction age (Clark, 1986: 85). The model calculated locational wind speed and damage expressed in dollar values by geographical unit to which the insurance inventory input was formatted to insured value by ZIP code. These so-called ‘damage functions’ are until today the most proprietarily protected part of catastrophe models and are generally not accessible. In her publicised paper, Clark did not give any concrete details on those functions, the core grammar of interaction between natural phenomenon (here wind speed) and socio-material environment (insured structures). Another reason was the fact that Clark ended up initially targeting reinsurers who had at the time less detailed exposure information but worked more with aggregated portfolio-level values.

Since probabilistically representing something that has not yet happened and possible futures' variations are the stochastic means to try to cover the breadth of potential outcomes, all the above needed to produce as many variations of the future as possible, but these futures are fragile. Monte Carlo simulation produced random values for the variables employed in the model and the synthetic nature of those values was deemed necessary since modelling on empirical distributions "precludes the possibility of generating a value of the variable outside the observed range, and the observed range may not include all possible values of the variable", which means that a model such as Clark's (and basically any other catastrophe model until today) "will have an a priori theory of the shape of the probability distribution underlying each random variable" (Clark, 1986: 88f). The main burden of a model's 'accuracy', therefore, rests on the qualitative and quantitative assumptions concerning each variable underlying the simulation and the debates around different assumptions and the decisions to choose a particular one will, as will be shown in the following chapters, have huge impacts on entire markets and their underlying socio-material worlds.

On this basis, the variations of potential outcomes, this synthetic multirealism that eventually becomes actual in one way or another, is produced by multiple iterations of the model until the overall loss estimates 'converge' in the probability distribution towards what is then assumed to be the "true" loss distribution (ibid.: 90). Of course, whether it is actually true or not can only be controlled once *a* variation of catastrophe actualises and the accumulated loss from claims are empirically counted. But until then, from the 1990s onwards one could work with a modelled 'truth' on which to base decisions. The requirement for a minimum threshold of numbers of iterations, a minimum synthetic sample size, highly depends on the nature of the correlation of variables. It also pertains to the more obvious material dependency of sheer computing power (ibid.: 91). This experimental condition underlies every simulation, but especially the ones that will be confronted with actualised results in form of catastrophic loops, which will have been moderated by the simulation in the first place by enabling, for instance, certain real estate or commercial area development.

The output of the model was formatted in a way that (re)insurance practitioners could use. The simulated loss estimates were outputted as the annual expected loss, as a fraction of the overall liabilities. The PMLs were based on the tail-end of the underlying distribution on four different confidence levels (80% = $\alpha_{20\%}$, 90% = $\alpha_{10\%}$, 95% = $\alpha_{5\%}$, 99% = $\alpha_{1\%}$) that represented the probabilities of the annual expected loss being exceeded. Depending on the loss distribution, these confidence levels or alpha errors could be linked to the more (re)insurance-generic expression of PMLs, that of return periods such as 1-in-100-year loss.

b. Aggregate Modelling

Clark's hurricane model was the first commercial probabilistic catastrophe model forming the basis of a vendor modelling firm, AIR, which she founded in 1987. Her old employer, Commercial Union Assurance, in the mid-1980s had cut back its spending on research, "I wouldn't have been able to work on the hurricane model. They basically just shelved that. They never did anything with it". In that time, she had published her approach in the Proceedings of the Casualty Actuarial Society (Clark, 1986) and attracted the attention of the broker E.W. Blanch (Hemenway, 2012).

E.W. Blanch, a mid-sized US (re)insurance brokerage firm that throughout the 2000s would merge as Aon Benfield into the Aon Corporation (one of the three major (re)insurance brokers worldwide), at the time attempted to enter the market for brokering catastrophe reinsurance deals. As mentioned in chapter 3, the (re)insurance market was embedded in the US's socio-material environment of the 1970s and 1980s which advanced in construction measures and firefighting efficiency and had not seen major catastrophic events. "Cat [catastrophe] reinsurance, why brokers love it, is you get 10% of the premium but there's not a lot of work to it. You know, if there is no cat, you don't do anything – you basically just market it. [...] So, it was very nice business to have because it was pretty much all margin" (interviewee I35). For E.W. Blanch, who until then had not done business on catastrophe risk, Clark's model was the means to fast-forward expertise on this risk class – "I knew this was exactly the way to go forward", noted their chief actuary Wacek (Hemenway, 2012). Clark declined a job offer and instead E.W. Blanch became AIR's first client. While E.W. Blanch started utilising the hurricane model for a new service they introduced, marketed as 'Catalyst', for insurance risk analyses (Wacek, 1987), AIR entered into a five-year 'non-compete' agreement with them which denied Clark access to primary insurers, "we could only work with reinsurers, so we kind of specialised in that".

Even though AIR in the early 1990s expanded into modelling for primary insurers as well, this limitation until then provoked a particular modelling technique which a few years after Hurricane Andrew contributed to significant debate and changes in the industry's data practices – an important struggle especially for catastrophe's socio-material mediation. The very first design of Clark's model was aimed at primary insurers, who have access to detailed exposure data – data on the insured properties including location, value, construction types, deductibles, age, etc. Location data to primary insurers was, for instance, usually available on ZIP code-level at the time. While E.W. Blanch ran this model type for their primary insurance clients via their Catalyst service, this model design was not applicable for reinsurance clients. Despite the efforts and usage of CRESTA zoning, discussed in chapter 3, detailed exposure data was not submitted by insurers to reinsurers – "for wind, nobody was using CRESTA to send their data […] we didn't get that data", tells me the reinsurance underwriter I35. CRESTA also turned out to be perceived as rather arbitrary for specific spatial risk distribution of insurance portfolios; PML calculations "are affected less by gross exposure by an artificially determined geographic region than by the specific location and loss characteristics of [an insurer's] book of business" (NAIC, 1994b: 775). What reinsurers, especially Lloyd's of London syndicates, did at that time to assess potential loss, was deducing from information they had, insurers' premiums data by (US) state, and applied the so-called 'market-share' approach. Combining all insurers' premium per state and then taking the relative share of an individual insurer, reinsurers applied this market share to general industry loss estimates from PMLs, for instance from CRESTA or industry reports (e.g. Kozlowski and Mathewson, 1995). Highly simplified, for example, the market share of an insurer A in Florida is 20% and a report estimates a PML for the entire insurance industry from a hurricane in Florida at $1 billion, then the hurricane maximum loss exposure to reinsurer B is its relative reinsurance deal share from insurer A's $200 million PML.

AIR adjusted and had named their reinsurance model CATMAP in the late 1980s and with it contributed to the level of 'multinaturalism' of socio-material mediation as it increased the sourcing of data to explicate the socio-material environment of catastrophe. After learning especially from Lloyd's syndicates about the current reinsurance practices, CATMAP integrated the market-share approach into its methodology. To map out potential exposures for reinsurers on a more fine-grained level, Clark merged data in a patchwork from multiple sources. For example, they fed-in data from Claritas Inc., an early marketing data company which used, processed and enriched US census data. "[T]hey would say by ZIP code how many single-family homes are there, how many apartments are there, how many commercial businesses are there". To deduce the values of those properties, AIR also used local housing price data and calculated average house prices per ZIP code. This form of data sourcing and integration produced the first version of what modellers came to call an 'industry exposure database' or IED. A.M Best, a specialised (re)insurance rating agency and especially in the US, where (re)insurance is regulated on state-level, de-facto co-regulating entities on the federal level, formatted their insurance premiums data for CATMAP use in accordance with the AIR IED format.

Capturing the socio-material world by means of sensing – producing and enriching census data and gathering policy premiums data, for example, can be seen as forms of sensing – is a specific market-societal way of socio-material mediation and with its fundamental importance for modelling it is both practically and epistemically integral to simulation. This more fine-grained exposure data of the industry, and via the market-share approach per insurance company, was run on CATMAP against its hurricane module, substituting what was in the original design meant to run against one individual insurer's detailed exposure data. Instead of rather 'stationary' industry loss projection reports and then figuring out on state-level the individual market-shares, CATMAP produced a dynamically updatable and more detailed library of modelled exposure and loss data for US hurricane risk. "[A]ll the 300 US insurers were just in a list and they [reinsurers] would just pick one, say StateFarm, and they would just hit the button […] it would go through all the industry event losses and just apply StateFarm's market share and then we'd come up with the loss distribution" (KC). The loss distribution is what Risk Management Solution (RMS) would later term 'exceedance probability' or EP curve: "RMS invented that language" but the fundamental tools existed before this language. Reinsurers could input the specific excess-of-loss coverage layers of their reinsurance deals with individual insurers and the simulation would output "the expected loss, it gave the standard deviation, it gave all the percentiles, it would do the marginal impact".

Before Hurricane Andrew in 1992 fundamentally changed the (re)insurance landscape and practices and brought catastrophe modelling to the forefront, reinsurers could primarily only use state-level premiums data from insurers, "StateFram would say 'I'm not sending any of my exposure data out there. Let them just use whatever they use.'" (I35). One reason why insurance companies are generally uneasy about sharing exposure and loss data is that this data represents experience on which grounds risk, aggregation and pricing calculations are performed, something valuable in the market as it adds to a firm's competitiveness. Another reason at the time (and today in a similar way too) was that, sticking with the example of the big US insurer State Farm, "State Farm expends considerable sums of money to collect and compile the loss information. When combined with premium and expense information, it would be possible for competitors to determine where State Farm is operating profitably and reduce the price to a level less than that charged by State Farm. […] State Farm does not want others to see that information" (StateFarm representative in NAIC, 1994a: 528).

But since especially reinsurance was and still is a relational space with a lot of interpersonal ties and interaction (Jarzabkowski et al., 2015a), information sometimes would informally be passed on. From this, one would know or make an educated guess on the portion of an insurer's exposure in one specific county of a state, "you could say 'I think 50% of the exposure is in this county, I block that [in the AIR model]'" (I35). And then "CATMAP would automatically distribute the rest to the other counties, so under the hood, CATMAP was actually making the calculations by the county level" and not on state-level (KC).

Amidst this particular reinsurance practice community, Clark's initial modelling had to focus on the portfolio-level. Even though this would change in the 1990s with AIR's broadening of its client base, the general gradual integration of catastrophe modelling throughout the (re)insurance sector, and the emergence and growth of other vendor modelling firms, it did differ from another way of approaching catastrophe's grammars of interaction. Clark's practical and intellectual background as well as the model approach's initial practical goal setting, reinsurance, influenced this particular style of simulation: a particular way of realising from 'multirealism', that of *aggregation* on portfolio-level. Statistically averaging-out was an important means because the very detailed interactions of natural phenomena and the socio-material world were produced for entire portfolios rather than individual properties. While the take up of Clark's CATMAP had started around the turn of the decade, Anthropocene catastrophe had not yet provoked its application on actualised events. The first catastrophic 'loop' through which a commercial catastrophe model would have to prove itself, however, would come in the summer of 1992 with Hurricane Andrew.

c. Hurricane Andrew 1992

If we think of Fabio Giampietro's Thanatos painting introducing this chapter as capturing Anthropocene catastrophe folding into itself and about to play out its actualising grammar of interaction, it might have been a similar impression for Karen Clark in August 1992. Although AIR and E.W. Blanch had already begun to offer hurricane catastrophe models, catastrophe modelling's influence on decision making and pricing remained marginal. One reason was that hurricane models were estimating much higher PMLs than any of the more 'rule-of-thumb' and experience-based underwriter estimates, actuarial calculations and the CRESTA-informed PMLs would have assumed (Lewis, 2007). Parallel to these developments, a range of pivotal US events for (re)insurance began to occur. Hurricane Hugo, in September 1989, ploughed through the Caribbean and South Carolina, causing over $10 billion total loss in the US of which about $4.2 billion were insured, marking the costliest hurricane in US history until then (Golden et al., 1994; Insurance Journal, 2009). Socio-material environment during Hugo was particularly exposed since building codes in the affected areas did not equip for a storm and surge of this strength (Schwartz, 2015). The same year, the Loma Prieta Earthquake in Northern California, the event that landed I64 a job at soon-to-be catastrophe modeller EQE, caused $10 billion total loss of which nearly $ 1billion were insured (Munich Re, 2015). Earthquakes, as mentioned in chapter 2, are independent of any particularly patterned seasonality. For hurricanes, however, the late 1980s and early 1990s were marked by a general increase of accumulated cyclone energy introducing at the latest from the mid-1990s on a lasting "high-loss regime" (Wyss, 2014: 557). It was one important factor adding to a combination of socio-material aspects that would fundamentally reshape the global catastrophe (re)insurance landscape.

On August 24, 1992, Hurricane Andrew made landfall in south Florida at SSHWS Category 5. After devastating parts of the Bahamas first, Andrew hit the US coast at Homestead Air Force Base and Miami-Dade County with 230 km/h, 140 mph, wind speeds and the lowest central pressure at 922mb, the third lowest of any storm in that century (Rappaport, 1993). Even though it was relatively small in terms of its spatial size, Andrew brought with it an over 5 meter, 17 feet, surge inflicting huge damage at landfall (Schwartz, 2015). Here, the interplay of previously weaker storms, relatively low PMLs and, as mentioned above, an insurance regime eager to underwrite hurricane policies on the coast at 'low risk', had been previously driven by a socio-material environment of relatively low loss. Actuarial models had taken the previous decade as the base for risk calculations (Wyss, 2014), while at the same time, and partly because of this, private and commercial real estate development in low-lying and waterfront areas had continued to shape the socio-material environment (Twigg, 2012) with which Andrew now started interacting.

The industry, based on static reports and actuarial estimates, had previously calculated maximum insured loss from a worst-case scenario hurricane in Florida (including hitting Miami, which Andrew did not) to about $7 billion (NAIC, 1996b: 1143). U42, an industry veteran and insurance-linked securities specialist, explains to me that the common risk concentration projection for US coastlines by (re)insurers had until then assumed a decadal population growth of 50% and extrapolated this onto the loss from the Great Miami Hurricane of 1926. For an Andrew-like event, they initially "modified the Great Miami hurricane [loss] because Andrew was a little bit south of Miami, maybe like a third of that. So we've got a third Great Miami loss and then we grow that by 50 percent every decade until today. [...] And that number is probably something like a few billion dollars. And that's why the insurance market thought that Andrew was low-billion dollars loss".

When Andrew approached, the industry's adjusted estimates were between $3 and $4 billion insured loss (Lewis, 2007; Muir-Wood, 2016). Clark fed the data on Andrew, such as central pressure or maximum winds radius, into her model, which estimated the expected insured loss to about $13 billion. The major difference was that it applied a longer-term storm frequency than the actuarial models (Wyss, 2014) and, as explained above, a finer granularity of the socio-material environment that would interact with the model's damage functions. After completing the simulation, she faxed the results to major (re)insurers. After months of claims that totalled at around 720.000 (NAIC, 1995a), the actual loss that Andrew and its socio-material environment had produced piled up to about $16 billion in insured loss and about $27 billion total loss (McChristian, 2012). Apart from general variability in models, one reason why Clark's model was still off by a few billion is assumed to be due to partly ignored building codes in some of the affected areas (Lewis, 2007); "25% of the insured losses from Hurricane Andrew could have been prevented through better building code compliance and enforcement" (Kunreuther, 1996: 172). This was a socio-material aspect of catastrophe that was not yet reflected in the model.

Andrew caused a structurally deep and epistemically almost epiphanic fracture throughout the (re)insurance world and Clark's marketing intervention logged catastrophe modelling as its potential new bridging device. While 126,765 homes were either destroyed or damaged and over 250,000 people were left homeless, eleven insurance companies went into bankruptcy, many more to the brink of it, and reinsurance capacity was getting scarce (Borscheid et al., 2014). Insurers could not cope with the number of claims and in the aftermath many left the Florida property/casualty market or aggressively raised prices and deductibles (Davidson, 1996). Major insurers with more than 5 % market share in Florida reported significant insurance rate level increases of more than 40% in the years between 1992 and 1995 (NAIC, 1995b: 677). As a reaction, the State of Florida set up a number of residential state (re)insurance facilities to provide cover for by now more than one million households unable to find firms willing to insure their property against hurricane risk (McChristian, 2012), later retaining the second-largest insurance market share in Florida (A.M. Best, 2019). Between 1992 and 1996 in the US alone there had been 20 catastrophe-related insurance insolvencies (Davidson, 1996). Due to solvency provisions in the face of increased excess loss after Andrew, especially reinsurance for large-scale catastrophe was in high demand, which increased reinsurance costs (NAIC, 1994a) and, therefore, the attractiveness to expand this business from a supply-side perspective.

As mentioned earlier, Hurricane Andrew did not only elevate catastrophe modelling as a means for catastrophe risk management, it also changed socio-material mediation of catastrophe as exposure reporting was increasingly enforced, as Clark tells me, "People always say Andrew was the turning point for the models, but it was also the turning point for primary insurers starting to collect better data and also start giving that to the reinsurers". A.M. Best, the (re)insurance rating agency, increased from 1992 on their emphasis on analysing insurance business's catastrophe exposure. They introduced in 1993 the requirement for insurers "with material property […] exposures to provide it with some type of probable maximum loss analysis. Companies that cannot, or will not, provide this information may be subject to adverse rating action. […] A.M. Best requests nationwide gross loss data from all perils" (NAIC, 1994a: 524f).

While the main development had been the fully probabilistic treatment of catastrophe by the AIR model, exposure and loss data were increasingly requested in more detail from then on, too. Clark's initial aggregate modelling approach had somewhat found a way around the exposure data problem by inferring from multiple sources in a patchwork of socio-material mediation. However, a second modelling approach of *bottom-up* modelling, developed in parallel on the US West Coast, transformed how socio-materially mediated environment would be realised in the financial realm itself.

II. The Fracture of 'Reality': Bottom-Up Earthquakes

"A number of us used to be in EQE […] and left. There were four people at EQECAT who actually started [in 1995] the first office of RMS [Risk Management Solutions] in London". Today's address of this branch, where I am sitting with I03 in a nice and quiet corner office overlooking the Thames, is not far from the historical Lloyd's of London market in the heart of the City. RMS is very deliberately located here right across The Monument to the Great Fire of London, the Doric column at Fish Street Hill and Monument Street, close to Pudding Lane, where the devastating 1666 fire had started. People such as I03 in the

1980s would have worked primarily on earthquake risk for the nuclear industry at the engineering firm EQE. “And then, finally, we started getting projects out of the insurance industry around 1990. And because we were using the same probabilistic methodology but for the nuclear industry, we then suggested to the insurance industry ‘you should be using these same approaches’. And they weren’t overly interested at the time but then they started losing so much money between 1987 and 1994 – that actually encouraged them to move over”.

As a long-term modeller at RMS, I03 is today deeply engrained in the conceptual side of capturing catastrophe’s in-flux grammar of interaction, something he calls “to keep moving the frontier of modelability” – he had just returned from a meeting with the US Treasury on terrorism risk modelling. In a long-running UN effort on disaster risk reduction, RMS was also recently involved in how to measure risk reduction performances of countries: “You can’t measure it based on what happens. Because in Haiti 1900 to 2010, less than ten people died in an earthquake and then in one afternoon, 200,000 people died. So, the shape of this mathematical distribution is so fat-tailed, you can’t measure it from a short period of data. The only way you can measure it is modelling. […] We’re moving into a world where catastrophe modelling is dramatically expanding out beyond the insurance industry on how you measure risk”. The core of simulation, socio-material mediation and experimentation in this to-be-modelled world – model performance feeds back into policy here, not just insurance risk pricing and management – is the problem of history and experience, “the fundamental issue is that history is not enough to tell you about risk. You have to make a synthetic history. I mean, that’s the issue” – the issue that especially Friedman had intellectually wrestled with in the 1970s and that formed the fundamental aspect in Karen Clark’s modelling on hurricanes in the 1980s.

Between the early days of catastrophe modelling and today, this fundamental issue remains: it represents the very condition of the Anthropocene in experimentality in which humans and nonhumans, including such things as models, interact and produce an in-flux socio-material environment. And despite an exponential increase in development and usage of catastrophe models since the late 1980s, the inevitable gap between an actualised catastrophe and a model persists: “So yeah, there is *no reality* here” but only “the reality of how good a model is”. During the time of the switch to a ‘high-loss regime’, starting to materialise with Hurricane Andrew in 1992, this rupture of ‘reality’ disturbed the socio-materiality of catastrophe and its financial practices. For a long time, “the insurance industry had fantastic experience […], they did everything based on experience. And there were people in the market, the Lloyd's market, who were really wise about these things. But we [catastrophe modellers] were bringing these analytical tools and we would confront each other”.

For much of the 1990s, despite the eventual uptake of catastrophe models, such as insurance policy rate setting or reinsurance risk aggregation, there were partly substantive doubts as to how reliable models would be and whether they should be used as external drivers for central risk and underwriting decisions. While Hurricane Andrew and Karen Clark's AIR model in 1992 had produced an initial idea of a new 'reality' in which models seemed superior to history and experience, the Northridge Earthquake in California in 1994 magnified a more complicated relationship between socio-material mediation, simulation, experimentality and Anthropocene catastrophe. "For 10 years [experienced (re)insurance professionals] would ask the question 'What was your Northridge loss estimate?' They knew that that was your Achilles heel", remembers I03. The remainder of this chapter will focus on the reason for this acclamation, this aspect of the beginnings of commercial catastrophe modelling that grew out of earthquake engineering, insurance and *bottom-up* modelling. Together with AIR's initial approach of a more reinsurance and aggregation focus, this fracture of 'reality', the growing normality of multirealism through modelling, laid the foundation for an increasingly financial ontology of Anthropocene catastrophe.

a. Earthquake Engineering, Socio-Material Mediation and Modelling

Figure 8: John A. Blume Earthquake Engineering Center at Stanford University (left) & physical dynamic acceleration model of Alexander Building (155 Montgomery Street, San Francisco) by John A. Blume 1934 (right). Photos taken by J. Kob, 2018

While AIR had emerged directly from the insurance industry with an initial focus on hurricane modelling a few years before Hurricane Andrew, EQE and RMS emerged before the 1994 Northridge Earthquake from an engineering background. EQE, introduced in the previous chapter, had until then primarily been an earthquake engineering company amidst many others, such as the renown John A. Blume and Associates. The majority of them had grown out of the specialised academic earthquake engineering community in California, and partly re-perpetuated back into this community; for instance, Stanford University's earthquake engineering facility had been heavily funded by John Blume, giving it its name, the John A. Blume Earthquake Engineering Center, where many from this community had been educated. "There were a number of companies around, which were very, very analytical around earthquake engineering in the 1980s. And EQE decided to go the opposite way and say, 'we should be empirical […] get out and study earthquakes, look to see exactly what happens and use that learning for really understanding what goes on […] almost anti-analytical, you could say, favouring the empirical", tells me I03. EQE had been heavily involved in risk assessment and retrofitting of mainly large commercial buildings, most prominently nuclear power plants. A practice that applies, among other things, structural and scenario measures of very individual structures and geophysical locations, and it was influenced by the more general move towards the probabilistic risk assessment (PRA) rationale and Cornell's probabilistic seismic hazard analysis (PSHA), discussed in the previous chapter.

EQE's modelling at this time, driven by its more empirical rationale, as I64 tells me, meant a "very engineering-based and principally single-site" focus, and, for example for nuclear power plants, they "would model dynamics of not only the structures of the containment vessel but all the equipment and piping […] and soil-structure interaction". In other words, it was modelling literally from the ground up, as I01 tells me, "thinking about the problem as an engineering services problem […] EQE was very engineering-centric". It involved studying the individual structure on-site and producing, for instance, detailed structural models of the individual building, dynamic analyses investigating and testing in models the structures' elasticity during horizontal acceleration. "It would be extremely foolish to take those detailed models and apply them to a traditional single-family dwelling or even a high-rise building […] you wouldn't have enough money in the world to do that for [normal] commercial buildings." (I64). Apart from providing and selling earthquake engineering safety studies and subsequent retrofits (c.f. Tao and Coty, 1992), this modelling approach had been EQE's main focus during the 1980s until after the Loma Prieta Earthquake in 1989, when the idea slowly concretised to offer simplified model analyses to the insurance industry. This idea, of course, had already been applied by Clark for hurricane risk on the East Coast. For earthquake risk analysis, however, it had also been approached much closer to EQE and with a more concrete focus on risk assessment catering to the insurance industry and realising catastrophe as a financial object.

Risk Management Solutions, or RMS, had been founded in 1989 out of Stanford University by Hemant Shah and Weimin Dong. As opposed to EQE, it did not convert an already ongoing earthquake engineering business towards insurance analytics services but targeted from the start insurance as its clientele more in the form of a software company; initially RMS abbreviated Risk Management Software (c.f. NAIC, 1994a: 631). The angle from which RMS approached this field was also a product of the embeddedness of science and insurance in California. Prior to both EQE and RMS, the California Department of Insurance had set up mandatory PML measures for insurers after discovering in hearings in 1975 that a mere 5% of buildings had acquired earthquake insurance, which also instilled worries about firm's solvencies (NAIC, 1995d). They applied Steinbrugge's PML approach by collecting data via questionnaires handed out to insurers, on the back of a series of official studies on different vulnerabilities of building types. One such study was the so-called ATC-13 study, produced by the US's Applied Technology Council (ATC) in 1985 (ATC, 1986). In a volume in the archive of the Earthquake Engineering Research Institute, one former ATC member reported that "ATC has quite an interest in insurance. [...] A liaison member from the insurance industry comes to all board meetings [...] Of course, the insurance industry's concern tends not to be with individual buildings as such, but with the bigger regional issue of how an earthquake can impact many buildings in a large area. They are less interested in the kinds of things that concern structural engineers." (Scott, 2006a: 58).

With these insurance concerns at this point rather loosely in mind, a group of academics, including RMS co-founder Dong and co-founder Shah's father Haresh Shah, at Stanford's Blume Earthquake Engineering Center developed what would become the corner stone of RMS's analytic approach and practice, the Insurance and Investment Risk Analysis System or IRAS. Similar to Clark, who published her modelling approach to her professional field, the Casualty Actuarial Society in 1986, IRAS was first presented to the World Conference on Earthquake Engineering in 1988 (Dong et al., 1988). Different to Clark's case was that it emerged out of an academic and not an insurance-internal context. Although IRAS was leaning head-on into a financial services use case – "IRAS [...] provides consultation on earthquake risk for insurance and investment banking industries" (ibid.: 1083) – I03 recalls, "they didn't quite know who this was for at the time. And actually, this is why they had the investment and insurance aspect of it".

b. Socio-Material Earthquake and Insurance: The First Commercial Earthquake Model

While the link between commerce and meteorology had been intensified from the 1970s on and concretised in the 1980s (Randalls, 2010), seismology and earthquake engineering, as already discussed, had already been embedded in commercial fields long before the 1980s. This embeddedness allowed the IRAS project group to utilise a large, already existing body of resources on California spanning from academic analytic and empirical work, institutionalised capturing of earthquake faults, sensing networks, building structures and code regulation, to insurance studies and insurance regulation amidst an academically driven entrepreneurial environment which in the 1980s started to become known as Silicon Valley. While Clark's initial approach targeted primarily technical actuarial rationales, IRAS focused more on highlighting the software aspect of their application, a practical and marketing emphasis which RMS used as a differentiator in this emerging sector, "they were trying to be the Microsoft of the 1990s" (I64). Already the initial conceptual publication of their IRAS system to an earthquake engineering community reads in part like a white paper for a software application. The fundamental elements of their approach, though, capture the basic ideas of earthquake modelling on the heels of a bottom-up methodology from an insurance lens as opposed to AIR's aggregate approach for a reinsurance context.

The central aspect of synthesising history for a projection of possible futures was also in IRAS the determining element, as earthquake catastrophe is projected as a future event becoming *probabilistic* and thereby producing it by means of *simulation* from the de- and re-compartmentalised grammars of interaction of catastrophe. The model follows the basic principles of Friedman's conceptual modulation of catastrophe models, which Clark had followed too. The flowcharts in Figure 9 appear more complicated than Clark's – "her model, compared to [RMS's and EQE's] models, were relatively simplified" (I64) – but mainly display in more detail the elements of the model structure, which generally are (and still remain) the same for all models: the hazard module (here SHES), the inventory module (here input Data I, II, II in SRES-1 and also V in SRES-2), the vulnerability module (here Risk Evaluation model in SRES-1 and also Modification model in SRES-2) and the financial loss module (here, also in the Risk Evaluation model in SRES-1 and SRES-2).

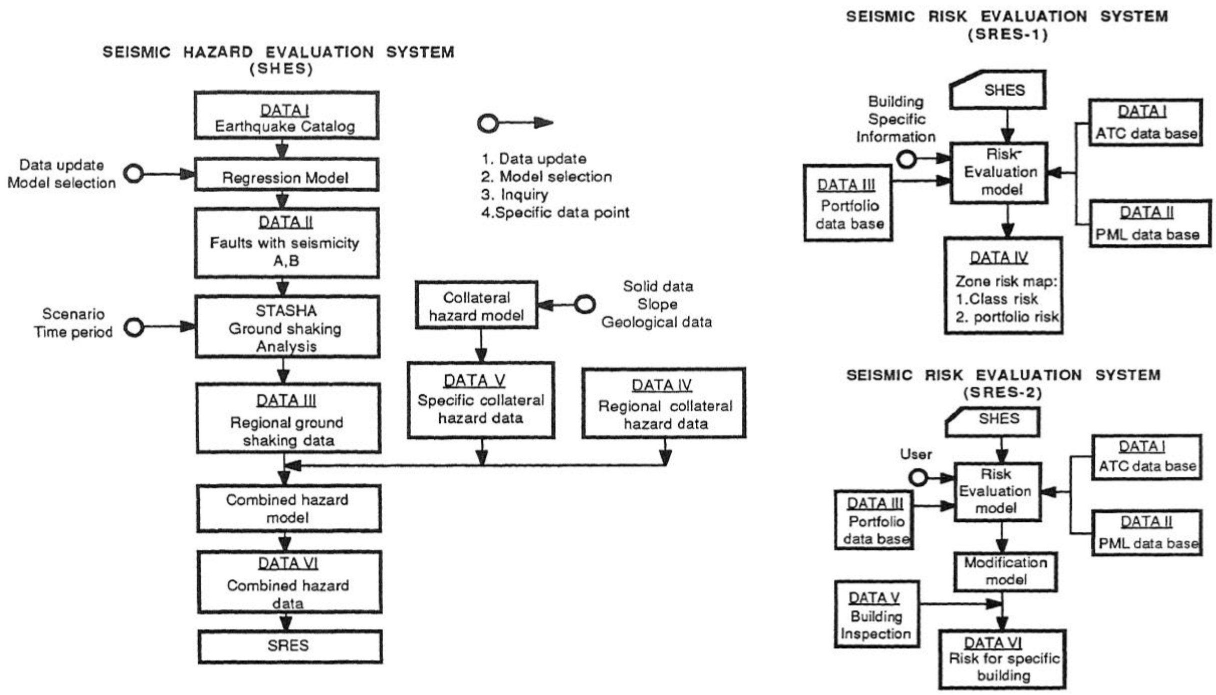

Figure 9: Model Flowchart of IRAS earthquake model modules, SHES, SRES-1, SRES-2. (Dong et al., 1988: 1086)

The Seismic Hazard Evaluation System (SHES) generates the earthquake simulation by piecing together the compartmentalised elements of the geophysical and seismic phenomena. Other than AIR's initial model, which modelled wind damage only, IRAS classified hazard on common earthquake engineering principles into three categories – something that became later a standard for all hazards in catastrophe models. The "primary hazards" are fault break and ground vibration (Dong et al., 1988: 1084), something that is commonly associated with the epicentre of an earthquake. The engineering lens, however, considers also the more detailed features and consequences of this unfolding. "Secondary hazards" are, therefore, ground shaking that result, for instance, in "foundation failure" (settling of the ground foundation of a building below the level of original construction), soil "liquefaction" (reduction of affected soil's stiffness), or landslides (ibid.). These features of geophysical phenomena affect other local physical systems as "tertiary hazards", such as structural failures of dams or fire outbreaks, for instance due to gas pipe damage (ibid.).

The materiality of earthquakes, their origins as sudden fault ruptures, is physically local and geographically fixed – other than hurricanes, which themselves move as hazards and where specific local origin is not the locality of catastrophe itself. So, modelling earthquake from the bottom up, i.e., starting from a very detailed and local level of socio-materiality, appears intuitively natural. However, Clark's very first model attempt was to model on a granular level, too, but her initial client focus on reinsurance complicated this due to the lack of detailed exposure data, which reinsurers did not have. Two important and connected reasons for RMS (and also EQE) to apply a bottom-up modelling approach, in addition to the very local nature of earthquakes and their community's practical and academic background, were, therefore, the goal setting of their modelling, an insurance focus, and the nature of its specific mediated socio-material environment, detailed data on built structures and their immediate geophysical situatedness. "Our focus, because we were initially earthquake, was much more individual risk underwriting […] You're underwriting *this* office building, *this* factory […] our first model, IRAS, was much more focused on individual risk", as Hemant Shah tells me.

Really fine-grained and individual building modelling was made an option in IRAS with the SRES-2 module (see Figure 9 SRES-2 input Data V and VI and Modification model), something that was the core of EQE's modelling practice at the time. However, the general ambition of IRAS was not to replicate earthquake engineering-focused practice but using this bottom-up approach in a simplified and generalisable framework specifically for insurance risk assessment (see SRES-1 input Data I, II and III). This made applying a "probabilistic approach for hazard analysis" (Dong et al., 1988: 1084) more necessary, since a probabilistic framework allows to compensate for variability and less detail (as shown in Clark's model discussion above). The experimentality that conditions the interaction of geophysical phenomena and an Anthropocene socio-material environment is expressed in modelling for insurance portfolios in a variability of effects, for example, "in the buildings, because when you have thousands and thousands of properties you don't have detailed information about each building." (I64).

While Clark did not have one central comprehensive report which already combined the relationship between catastrophe's two dimensions, occurrence and severity, for earthquake and California it existed, among other sources, in form of the ATC-13 report. It did not only include data and analyses, for instance, on seismological earthquake shaking characterisations, damage effects from secondary and tertiary hazards, a range of damage effects of various building types such as low-rise wood-frame, unreinforced and reinforced masonry, or high-rise steel or concrete structures, but also to some extent insurance data such as insurance maps and data from the Insurance Services Office (ATC, 1986). In combination with Steinbrugge's PML method and its database, which existed at this time in quite some detail here, RMS's IRAS model based part of its central damage functions on the ATC-13 study. Because at this time PMLs were only reflecting a static history, not-yet-happened future earthquakes would only be reflected if the socio-material environment was broken down and ran against simulated re-compartmentalised future events. The ATC-13 study used so-called "damage threshold" to account for randomness, i.e., possibly unprecedented unfolding, of future catastrophe characteristics such as location, size and time of a potential earthquake.

This deep level of entanglement of the geophysical phenomenon and damage characterises bottom-up modelling and exemplifies how interdependent socio-material mediation and simulation are in this process. The ATC-13 study supplied features for both these elements which enabled IRAS to only require building type classification according to ATC standards from insurers as part of the exposure data, (Dong et al., 1988). "Instead of having a vulnerability curve that was based on engineering principles [as in powerplant analyses], the vulnerability functions were based on simple building characteristics such as type of construction – was it wood-frame or was it brick, for instance – and then whether the building was of a certain vintage in terms of when it was built, and then whether particular vulnerability characteristics related to things like, is the house above a garage?" (I64). Socio-material mediation through insurers was, therefore, directly linked to a fine-grained yet straightforward process of sensing socio-material environment – a detailed but abstracted environment. But in a way, this posed the opposite side of the problem that Clark was confronted with in her aggregation approach, which lacked detail that she tried to compensate by using multiple sources and means of inferring socio-material environment.

c. Bottom-Up Modelling

What the approach of bottom-up modelling, in contrast, made more difficult was a fully probabilistic treatment of catastrophe, something that Clark had already implemented. Because of its very localised embeddedness, earthquakes had been treated by earthquake engineering so individually, for instance in terms of specific faults and its surrounding socio-material environment, that it was in practice bound to scenario instead of fully probabilistic modelling – earthquake as catastrophe-in-context was too much in context here for a financial services treatment. Probabilistically tending to an insurance portfolio perspective would emerge over the 1990s from both coasts, when AIR, RMS and EQE would fully target the same user market and their methodologies would increasingly converge, most importantly with what developed as 'exceedance probability' or EP, which will be discussed in chapter 8. At this point in the late 1980s and early 1990s, however, RMS tried to engage this problem by developing a precursor method of EP, something they called 'bounded max'. Most probably an outcome of combining a PML measure with the ATC-13's 'damage threshold' in IRAS, 'bounded max' integrated the fully deterministic and history-based PML measure with a probabilistic treatment of simulated earthquake scenarios. "The models weren't fully stochastic; they didn't generate full distributions" across the entire insurance portfolio of a client, clarifies RMS's Shah. Instead, the model produced "bounded scenarios", which means that they modelled loss for specific regional sites.

The bottom-up approach here was, again, led by the entanglement of earthquake engineering and insurance. Because Steinbrugge's PML approach distinguished California into different earthquake zones, according to known faults and previous fault ruptures (1982), "what at the time was called 'zone A', which was a San Andreas earthquake in Northern California, or 'zone E', which was a Southern California earthquake […] the early models that we built were based on these [zone] scenarios", explains Shah. At the same time and partly based on this zoning, building codes were an important focus coming from the "engineering design community […] where you had these concepts of 'what do you design to?' […] the 475-year return period [one-in-475 years chance] is the design standard for commercial property; in the nuclear industry it was like one-in-2000 years". To clarify, a one-in-100-year earthquake is a way of expressing the return period, the chance of occurrence, of an earthquake event that is brought into an integral relationship to a level of maximum damage relative to a certain magnitude and intensity expressed in economic loss by the PML value, which, in turn, defines the socio-material quality of this earthquake event.

Since these PML thresholds and building designs were assigned to different zones, for an insurance underwriter the risk values varied, because, for instance, likelihoods of specific strengths of earthquakes (magnitude, i.e., occurrence) vary depending on the zone and therefore on the affected socio-material environment (intensity, i.e., severity). "We would say 'don't look at a magnitude 7.5 earthquake in northern California and a 7.5 in southern California because the probabilities are different. So, if you're gonna use a 7 in northern California, that's like a 6.5 in Southern California'", says Shah. This way of bottom-up modelling, therefore, was 'bound' to zone characteristics and thus to different scenarios, but 'bounded max' allowed at the same time "a way of normalising" across California zones; in other words, putting different potential unfoldings of catastrophe in relationships to one another for insurance portfolio perspectives.

While RMS was founded on the premises of catastrophe modelling at this time, EQE further developed its more earthquake-engineering centric EQEHAZARD model for financial purposes "after RMS. […] [EQE] were already leaders in earthquake engineering beforehand. After RMS, they got into [modelling], they came a bit late." (I03). Although the method of 'normalising' catastrophe across zones for portfolios via ‘bounded max’ was an approach only RMS had started developing, the general rationale of earthquake modelling was similar for both RMS and EQE. “We knew that RMS was beginning to do some modelling […] Hemant Shah targeting the insurance market […]” (I64). “In the beginning it was very much […] RMS had an earthquake model, EQE had an earthquake model, and we all started building similar models.” (HS). In contrast to the aggregate approach by AIR on hurricanes for reinsurance, at this point in the early 1990s, RMS and EQE had developed the bottom-up approach for insurers.

The tension within catastrophe-in-context between too little context – aggregate modelling – and too much context – bottom-up modelling – is the constantly moving line on which catastrophe’s rupture of ‘reality’ occurs – ‘there is no reality here’. And this tension, this reality ruptured for the first time for catastrophe modelling on the morning of January 17th, 1994, in northwest Los Angeles.

d. Northridge Earthquake 1994

If you take the scenery of Giampietro’s Thanatos painting (figure 5) as a vignette of Anthropocene catastrophe, then it captures quite well what happened during the Northridge Earthquake not only to the earthquake’s victims but also to catastrophe modelling. While Etna on the painting puffs concerningly but without erupting – the residents’ assurance that its omnipresent and familiar danger does not pose an immediate threat – the town is in destructive upheaval, materialising its inherent Anthropocene catastrophe in a self-referential actualisation interacting with other agencies than those of old and familiar Etna. The name itself, Northridge Earthquake, already provides a hint to this situation. While the name was assigned to this event because the epicentre was believed to have originated in the heavily affected Los Angeles neighbourhood of Northridge, the 6.7 magnitude earthquake had its actual epicentre underneath the more southern neighbourhood of Reseda – the name, however, stuck. As with Catania and looming Etna, the affected Counties of Los Angeles, Ventura and Orange are among those US regions that are most familiar to (earthquake) catastrophe (Petak and Elahi, 2001). Subjected to the extensive San Andreas fault system, which cuts through most of California, also more regional faults such as the Oak Ridge fault in San Fernando Valley had been well known sources of earthquakes (Morton and Yerkes, 1987) – continuously looming danger like that of Etna to Catania.

The actual earthquake on January 17, however, originated from a previously unknown thrust-ramp fault, which does not divide the ground surface and which is therefore called a ‘blind thrust fault’ – although called Northridge blind thrust, it lies about 18 km beneath Reseda. Blind thrust faults at that time began to “constitute a new, previously unrecognized class of seismological faults underlying broad areas of the western Transverse Ranges including Los Angeles basin”, concluded a 1995 report on the Northridge Earthquake produced by EQE and the Governor’s Office of Emergency Services (EQE and OES, 1995: 2–1). Unknown faults, of course, cannot be reflected in models since models are inherently self-referential and bound to their own grammar of interaction's 'reality'. One important element of earthquake simulation is integral to its local emphasis, which is that the distance of exposed structures to the points of rupture requires attention, because the level of damage is relative to this distance.

But what ruptured catastrophe modelling's 'reality' with Northridge much more intensely than this unknown fault was the socio-material environment that interacted with it. Giampietro's Anthropocene 'wave made of buildings that represents how men are forging the world' in his Thanatos painting actualised in southern California with a surge of unexpected structural failures in buildings on the heels of the earthquake's seismic waves. Of course, damage can be problematic even to buildings that have been designed and built according to building code regulations (Northridge 20 Symposium, 2014), but Northridge revealed that the entire engineering community had overestimated certain critical construction features. For instance, reinforced concrete structures revealed vulnerabilities in newer buildings. The most affected ones, however, were especially wood-frame, soft-story, and steel buildings (ibid.). Nearly all fatalities and a now estimated half of the earthquake's property damage was due to damage of wood-frame buildings, "far higher than experts had anticipated" (ibid.: 23). Reflected in catastrophe models, "[t]he mean damage ratios for wood frame buildings was underestimated by the models of the time, which meant that due to the geographical concentration of buildings, the correlation of probabilistic ground motion and loss in the models were below the actual losses" (Grossi et al., 2005: 131). EQE's I64 reports that "we talked to some architects and builders and found […] the [building] codes hadn't changed much but the whole new design of the homes had changed. For example, the inclusion of a lot more windows and the concept of building house-over-garage [soft-story structures]. And some of the homes went from a simple little box to elaborate geographical footprints and then building them on hillsides. So, it was really the practice of architectural changes making these homes much more vulnerable to earthquake damage".

Also, structurally important and costly failures in welded steel joints of steel buildings became prominently known with Northridge, coming as "a complete surprise to many structural engineers who had been using these details all over the world. […] [reinforcement of replacement] costs can be as much as $4000 to $6000 per beam-column joint, and most building owners would rather not be made aware of these problems in their buildings. […] the nature of the weld failures has raised serious concerns about the safety of all modern high-rise buildings with this type of [joint]" (Scott, 2006b: 26f). All this affected modelling outcomes because "anything we produce ourselves is conditioned by the assumptions we've made about component pieces [in the models]", tells me I03.

Even though at the time of Northridge, catastrophe models were used by only very few in the insurance sector – the National Association of Insurance Commissioners estimated that "10% of property and casualty insurers used some form of catastrophe modelling" (NAIC, 1994a: 653) – EQE through its longer-standing reputation in the earthquake engineering and earthquake safety community applied its new modelling for the Californian state. “The California Office of Emergency Services retained EQE to assist the State with its application and administration of disaster aid by producing an immediate estimate of the total damage. The day of the earthquake, EQE used its EQEHAZARD software to produce […] initial damage estimates. […] The $15 billion total damage estimate became the basis for the Governor's appeal to the President and Congress for aid to California. […] To our knowledge, this was the first use of this technology to improve overall disaster response.” (EQE, 1994).

III. Experimental Reality: A Financial Socio-Material Environment and Probabilistic Catastrophe

EQE’s official initial loss estimate of $15.1 billion (Rabinovitz, 1994) was the projected total loss from the earthquake, but of this, the projected *insured* loss estimate would have been much smaller. I03, who at the time still worked at EQE, reports that “the initial [insured] loss estimates […] were 1.5 to 2 billion dollars, and the ultimate [insured] loss was about 14 billion. So, it was almost ten times higher than the initial estimates. The initial estimates were what was in the models, so EQE had grossly underestimated the size of an earthquake of this size”. Since I was unable to retrieve EQE’s original initial *insured* loss estimate from archival sources, there cannot be absolute certainty around the actual projected number. However, if one, admittedly very crudely, infers from the fraction of the affected buildings the percentage of insured property and applies this to EQE’s total loss estimate of $15.1 billion, then the result of $3.71 billion[31] is about double of what I03 reports but remains fairly low in general after all.

The overall loss of the Northridge Earthquake were repeatedly re-estimated over the following two years, rose substantially with every new analysis and later was calculated at between $41 and $44 billion and the overall insured property and casualty loss settled between $12.5 and $13.9 billion (c.f. Northridge 20 Symposium, 2014; Petak and Elahi, 2001). Producing ad-hoc estimates of catastrophe is tough for catastrophe modellers until today, which is why immediate estimates provided by vendor modellers tend to be in form of a range that is usually considerably wide. I18, a modelling manager told me in the context of their initial loss estimates in 2017 on Hurricane Harvey, “it’s sticking your neck out

[31] Commercial property made up 36.4% of the overall affected structures (Petak and Elahi, 2001: 6) of which about 20% had a form of earthquake insurance (ibid.: 9), so the insured fraction of affected commercial structures is (36.4/100)*20 = 7.28%. Residential property made up 49.3% of the overall affected structures (ibid.) of which between 30-40% had a form of earthquake insurance (Northridge 20 Symposium, 2014: 27; RMS, 2004: 11), for simplicity I take 35%; so the insured fraction of affected residential structures is (49.3/100)*35 = 17.26%. Therefore, the combined fraction of the two main underwriting classes of insured structures calculated on EQE’s initial overall loss estimate is (15.1/100)*24.54 = $3.71 billion.

from between the trenches". Northridge was the first time this was felt by modellers. The insurance community at that time, then mostly watching from the side-lines of catastrophe modelling, "weren't happy with it at all", reports interviewee P02, who started working for EQE in 1994. For at least the rest of the decade, Northridge became the vignette for this fracture of 'reality' of catastrophe modelling, its "Achilles heel", as I03 called it.

The 'reality of how good a model is' had been disturbed by the bottom-up practice of detailed assumptions on socio-material environment, which reverberated through this modelling practice into insurance portfolio perspectives. In the models of that time, the linkage between earthquake engineering and insurance had been present, but Northridge revealed that for modelling it had been skewed towards the engineering side of the practice. The ATC-13 study as one of the primary devices mediating socio-material environment – "Everybody picked that up […] It is still used in some models" (U15) – did not capture enough what was important to insurance loss, which is different "to how an engineer would assess damage […] insured means, if you have a crack in your wall somewhere, you get your whole house repainted" (I03), also homes' "contents, chimneys, and garden walls" (Roth, 1997: 9) or the "sprinkler system pipework collapsed in thousands of offices and stores […] many commercial insurers paid out more for water spoilage than for shaking damage" (Muir-Wood, 2016: 151). It became clear that insurance claims and loss data were the better socio-material sensing device even in detailed bottom-up modelling. In the aftermath of Northridge, "[t]estimony from representatives of the ATC itself supported the use of claims-based curves [damage functions] as the best available source of information for the link between shaking intensity and damage." (Grossi et al., 2005: 112).

The relationship between occurrence and severity in the practice of catastrophe modelling from this point onwards had, therefore, not only reached a fully probabilistic level, but it was also marked by an enclosed linking to insurers as socio-material mediators of Anthropocene environment. While aggregate modelling had pushed the fully probabilistic treatment of catastrophe for financial services, bottom-up modelling integrated financial services as epistemic mediators of catastrophe: "Through working for the primaries [insurers], it meant that we got access to the companies themselves who were collecting claims data after an event. And so, we would use this claims data to feed back into the process of calibrating the model", explains I03. Since insurance is an active part in how socio-material environment can be realised by providing sometimes required approval by granting insurance cover, for instance, to real estate development, and holding detailed knowledge of those structures, insurers are integral to Anthropocene environment and its condition of experimentality. "They are constantly, and insurers don't realise that, inadvertently *performing scientific experiments on loss*".

The Northridge Earthquake massively depleted the insurance sector in California and, similar to Florida after Hurricane Andrew, led to firms bordering on insolvency and an even larger withdrawal from the insurance market. Property and casualty insurers in California in 1994 had an overall premiums income of $32.8 billion of which earthquake insurance premiums were estimated at around $1 billion (Roth, 1997: 3), which was dwarfed by the incoming $12-14 billion of claims. Counting-in insured damage that was caused by the earthquake but covered by other policies such as car insurance or workers compensation, the costs for insurers were about 23 times higher than their premiums earnings in 1993 (Muir-Wood, 2016: 151). Between the earthquake and mid-1995, 93% of California's property insurers had stopped renewing or underwriting new earthquake insurance policies (Roth, 1997). As in Florida in 1992, the disaster insurance market in California had vanished in the face of the emerging high-loss regime of Anthropocene catastrophe. As a result, the state had to fill the gap by creating in 1996 the California Earthquake Authority, or CEA, to provide a basic earthquake cover for Californians, which became by August 1997 the largest residential earthquake insurer in the world (NAIC, 2010).

EQE, in a successful competitive bid with RMS, became the CEA's model agent and the central basis of insurance rate-setting for the State of California (which will be discussed in chapter 6), and remains in this position until today (Marshall, 2018). So, despite the underestimated loss, the Northridge Earthquake had elevated catastrophe modelling into broader practices. Meanwhile, E.W. Blanch, Karen Clark's first client, had by then embedded itself into the catastrophe risk business, initially on the basis of AIR's hurricane model in the late 1980s, and now became the firm "responsible for obtaining reinsurance contracts for the CEA" (ACI, 1996: 43). Arrived in a 'high-loss regime' by the mid-1990s, Hurricane Andrew and the Northridge Earthquake had not only disturbed and turned the previous regime. In forever fracturing catastrophe's 'reality', actualised Anthropocene catastrophe and AIR, EQE and RMS had realised financially fully probabilistic catastrophe in simulation and financially mediated socio-material environment.

In line with this, if you compare the two rather technical sections on AIR's and RMS's models in this chapter, you might have noticed that for AIR's hurricane model, more emphasis was devoted to the hazard module, i.e., how Clark de- and re-compartmentalised hurricane features to explicate catastrophe's grammar of interaction. RMS's IRAS model discussion, on the other hand, emphasised more the inventory and the vulnerability module, i.e., the socio-material environment and the damage functions explicating the effect-side of catastrophe's grammar of interaction. The purpose of those differently analysed modes and elements is to reflect catastrophe modelling's differing original trajectories and targeted communities. In this, the socio-material spaces out of which the practices of catastrophe modelling grew and ultimately converged (which will be covered in the following chapters), both represent and actively engage the fracture of 'realty', the tension that is inherent in Anthropocene catastrophe. And despite the merging of these modelling approaches, this moving fracture line remains until today as the very location where Anthropocene catastrophe's experimentality is most vigorously at play. This influx fracture line is the place where epistemology collapses into ontology and vice versa. It becomes, however, only meaningful and socio-materially consequential, once catastrophe modelling enters everyday usage, which will be turned to now.

Chapter 5. Socio-Material Appropriation

"Our whole society is aboard the Raft of the Medusa." Jules Michelet, 1819 (Chimot, 1995: 33; my translation)

"We are not all in the same boat. We are all in the same storm." Damian Barr (2020)

From 1760 onwards, the Register Society was founded at Edward Lloyd's coffee house out of which the Lloyd's of London insurance market had already begun to grow. The Society assembled and classified information about vessels and their conditions, such as hull quality and material, its rigging or its masts, and regularly published it as the 'Register of Shipping'. The Register was a very early risk management device for marine insurance (LR Foundation, 2021) and could be understood as the first-of-its-kind, public exposure database for insurance underwriters and insured merchants and shipowners. As the young Lloyd's market's early information system, it accompanied the already established 'Lloyd's List', a weekly newsletter on shipping news and arrivals and departures of vessels, which is still published today and is, therefore, one of the longest-running journals in the world (McCusker, 1991). In the Register and the List, during the 1810s, you would have found popping up a French Navy frigate, Méduse, primarily because it successfully engaged British merchant vessels and Royal Navy warships during the Napoleonic Wars in the Mauritius campaign – the Register and the List included not only merchant and private vessels but also military ships (Lloyd's, 1969; Winfield and Roberts, 2015). Then, in 1816, the Méduse became more widely known by being at the centre of one of the most infamous disasters of maritime history. It was beached on the Bank of Arguin, off the west coast of Africa, and, in the process, consumed the lives of 136 men who tried to rescue themselves on a makeshift raft, where starvation, mutiny, murder, suicide and cannibalism occurred (Balkan, 2008; McKee, 2000; Miles, 2007). The Méduse's inexperienced and overambitious captain was to blame for the disaster, an aristocrat put in charge as a result of the Bourbon Restoration following Napoleon's defeat, when royalists were staffed in the senior ranks of the French military to ensure royalist control.

Although this, in the sense of a classic differentiation, was a human-made disaster, its representation particularly in art can serve as a good illustration of the *appropriation* of risk modelling for Anthropocene catastrophe, which will be this chapter's focus. Not too far from the Lloyd's coffee house, in whose Register and List the Méduse appeared until it shipwrecked in 1816, the disaster was immortalised by Théodore Géricault's classic painting Le Radeau de la Méduse, or The Raft of the Medusa, in its 1820 and widely successful second exhibiting at William Bullock's Egyptian Hall in

Piccadilly. Completed in 1819, Géricault's painting, which depicts a dramatic scene of the remaining survivors aboard the raft signalling a ship on the horizon, became an icon of French Romanticism and initiated a new artistic movement which arguably substituted Neoclassicism. It also inspired a new style that had at its centre the very scene Géricault had created on the canvas, including being one of the first art works of that era that featured social and political critique (Alhadeff, 2002).[32] Several aspects of Géricault's work on the piece and how it was received and taken on by other artists help illustrate not only artistic representation of disaster, but, more importantly, key features of the commercial modelling of catastrophe from the 1990s until today.

Figure 10: Théodore Géricault, Le Radeau de la Méduse, 1819, oil on canvas.

In order to produce on canvas the catastrophe of the Medusa, Géricault used multiple means and sources of information and conducted an excessive amount of research into the incident and the very materiality of things by, for instance, building a scaled model of the raft and observing its behaviour on water, or investigating the texture and colours of victims' bodies in morgues (Ravalico, 2017). As we have seen especially in the previous chapter, deep analyses of many different conditions, interactions and socio-material aspects are central in building a catastrophe model, too. Géricault also visited survivors of the tragedy in hospitals and interviewed them, much like post-disaster surveying of catastrophe's severity and updating modelled grammars of interaction. Géricault produced a large

[32] For instance, at the top right of the scene is a black man, the figurehead of the composition, as the person most likely to be successful in signalling a far-away rescue vessel, which serves as a clear reference to Géricault's opposition to French colonialism and royalism of the time.

number of preparatory paintings and sketches, going through numerous sequences of different aspects and variants of the events, giving in some versions more weight to the mutiny and in others more attention to the rescue ship sighting or cannibalism (ibid.). As we have seen, playing out different versions of disaster events and choosing different foci and weights of aspects is key to produce catastrophe in models.

Figure 11: selection of studies for the Raft of the Medusa. From top left to bottom right: Théodore Géricault, Body Parts: Study of Arms and Legs for "The Raft of the Medusa," 1818 or 1819; Théodore Géricault, Cannibalism on the Raft, 1818; Théodore Géricault, The Sighting of the Argus, 1818 (Ravalico, 2017)*; Théodore Géricault, The Best of Friends, 1818 or 1819; Théodore Géricault, Ringleaders, 1818 or 1819*(Dewar, 2020).

Unlike many of his artistic contemporaries, who would work on the overall composition directly from the start, Géricault arrived at an overall concept based on empirical work and underlying assumptions, and drew only a rough outline on the canvas before completing each figure and component in the painting individually using models (human and non-human ones) one by one (Dewar, 2020). Trying to fit all the aspects that are important into one overall catastrophe model is somewhat like trying to capture an event such as the disaster aboard the Medusa Raft: explicating individual, isolated aspects of, then, re-composed interactions of those elements. Reflecting detail and, in a way, realism, this was a technique Géricault became famous for: bridging the represented and the real – "Géricault's work expressed a paradox: […] how could the painter reconcile art and reality?" (Laborie, 2010) – by assembling individual aspects in detail and then 'curating' them in an overall context (Kob, 2020). In so doing, Géricault had to alternate between painting from 'original' empirical objects, such as two survivors, Corréard and Savigny, and 'artificial' objects such as friends and colleagues acting as models for characters on the raft (Ravalico, 2017). As discussed in the previous chapter, catastrophe modelling, too, uses physical and digital, mediated empirical and estimates-generated data and models. As we will see throughout this and the next four chapters, composing an overall catastrophe model from many different aspects, data, and submodules embodies decisions, for instance, on assumptions, different scientific preferences, or access to data, and also holds organisational aspects that have paramount consequences in how Anthropocene catastrophe is realised.

The overall aim of this thesis is to investigate and explain how catastrophe modelling practices and devices are active in the epistemic and ontological processes of Anthropocene catastrophe. Like the description above of the composition of the Raft of the Medusa, much of this thesis up to this point has been about multiple aspects of the emergence of catastrophe in modelling, its conceptual backdrop, its intellectual and practical origins and early developments in financial services, and, with the previous chapter, the initial construction and design types of the first commercial catastrophe models. However, a concept or design, whether purely intellectual or even in principle with practical intent, is ineffective, maybe even meaningless, if not contextually applied. The remainder of this thesis, therefore, not only further investigates aspects of the construction or design of catastrophe in models, but adds the chiefly important element of use or, more precisely, the *appropriation* of catastrophe via catastrophe modelling, the element through which it receives not only actualised meaning but through which it finally becomes socio-materially consequential.

I. Technology Use

On a general level, the vantage point of the remainder of this thesis will be applied catastrophe modelling and how use evolved both its application and models. Usage of technology is, of course, an established field of inquiry in the social sciences as well as in industrial and product research (e.g. Hyysalo et al., 2016; Suchman, 1993). Intertwined with relationships between science and technology are technological development and processes of knowledge production within, and driven by, social environments, often referred to as the 'social shaping of technology' (Williams and Edge, 1996; Mackenzie and Wajcman, 1999; Sørensen and Williams, 2002). And although devices themselves are a central element to any analysis of technology, "there is no one essential use that can be deducted from the artifact itself" (Oudshoorn and Pinch, 2003a: 2). It is, therefore, important to consider the "context of use", the use in practice itself and, consequently, to analyse technology and users as "co-constructed" (ibid.: 3). In this line, there have been a range of different and overlapping approaches to technology use and users especially in science and technology studies.

The 'social construction of technology', for instance, has an emphasis on the relationship between flexible interpretation and an eventual stabilisation of technology within 'sociotechnical ensembles' and users' involvement in technological change (Bijker, 1995a, 1995b; Kline and Pinch, 1996). Actor-network theory-leaning approaches (e.g. Akrich, 1992; Akrich and Latour, 1992) highlight this specific aspect by analysing technological objects as parts of wider and heterogeneous networks of multiple interacting humans and nonhumans, in which technologies bear 'scripts' which "attribute and delegate specific competencies, actions and responsibilities to users and technological artifacts"

(Oudshoorn and Pinch, 2003a: 9). Agency is central here as the reciprocity of actors' relationships (such as designers, users, objects, etc.) plays a central role in technological development. Whether users 'subscribe' or 'de-inscribe' (i.e., reject) uses prescribed by designers becomes an important focus here. Of course, this has been extended into the social studies of markets, giving central importance to devices such as models, formulas or ledgers and interaction in markets and with market actors (see chapter 2).

Technology use in more cultural-focussed approaches have concentrated on technological objects as taking part in the shaping of social relations, identities and culture in general (e.g. Lury, 2011), particularly on consumers, for instance, as 'cultural experts' (Du Gay et al., 1997; c.f. Oudshoorn and Pinch, 2003b). Especially the process of technological transfer into everyday culture and contexts of users, conceptualised as 'domestication', has been a fruitful approach which highlights reciprocity in that "both technical objects and people may change" in the process of emergence and development of technology (Oudshoorn and Pinch, 2003b: 14; Silverstone and Hirsch, 1992; Mansell and Silverstone, 1996; Lie and Sørensen, 1996; Verhaegh et al., 2016). While most approaches focus primarily on the design and its evolving, domestication approaches begin with the user in their analyses of technology. Feminist and gender studies also invoke an active and central role of user influence and participation, with a particular focus on women's technology use, on technological change (e.g. Lerman et al., 1997; Saetnan et al., 2000) and the roles of different groups or categories of users (Casper and Clarke, 1998). Most importantly, feminist approaches highlight power relationships across involved actors and the distribution of power as an empirical enquiry rather than assumed linear relations between, for instance, active expert designers and relatively passive users and lay persons (e.g. Haraway, 1991; Lie and Sørensen, 1996). In turn, semiotic approaches focus on how designs of technology constrain use and 'configure' the user (Law, 1991), while the ones designing are also embedded in processes of configuration themselves (Mackay et al., 2000).

However, by whom and on what exactly the "configuration work" (Oudshoorn and Pinch, 2003b: 9) is actually performed, and what consequences 'working around' (intended or unintended) constraints of emerging technologies has (e.g. Gasser, 1986), is of central importance. It is significant for the analysis of catastrophe modelling here, as it has fundamental socio-material impacts on the devices, the ways they are used and, ultimately, on how Anthropocene catastrophe is realised. While 'configuration' might refer to the technological object or infrastructure itself, it seems necessary to carve out an analytical perspective that aligns with the integrative and ontologically 'flat' overall conceptual approach of this thesis. In other words, a perspective that analyses technology use not only as integral to its construction or design, but also to socio-material environment and, therefore, as internal to and active in Anthropocene catastrophe. It is more than 'configuration work', it is the ingestion of practices and devices that changes both ends of the relationship between design and usage and pertains more to what Mackay and Gillespie describe as the "social appropriation of technologies" (1992: 698).

The term appropriation in Silverstone and Hirsch's process of domestication of technology serves to describe the first of four phases where it mainly refers to the transfer of ownership of the object or service to the users (Silverstone and Hirsch, 1992) and, for instance, Verhaegh et al. speak of "appropriation work" as a junction of user-supplier reciprocity on embedding technology in user environments (Verhaegh et al., 2016: 205). However, Mackey and Gillespie give the term a more central place by emphasising it as one of three "conceptually distinct spheres" in the analysis of technologies: design (i.e., invention, conception, development, etc.), marketing and appropriation by users (1992: 691). They criticise that (at the time of their paper) technology studies approaches have put too much explanatory weight on the first, the design sphere, where social origins of technology are traced. In addition, they stress marketing's role in the social shaping of technologies as the field that also informs design but, more distinctively, mobilises consumption, thereby evoking that "demand is socially constructed" and placing it within the realm of the analysis of technology (ibid.: 698). This serves as a bridge to the third sphere, that of the social appropriation of technology. Invoking Wajcman's note on the 'double life' of technology, users (often as consumers) are active, socially situated subjects who "may redefine a technology in a way that defies its original, designed and intended purpose. Thus, the appropriation of technology is an integral part of its social shaping." (ibid.: 699). In this, appropriation emerges as a sort of counterpart to design in the sense of concrete and subjective use, which, although not limitless due to sometimes unbridgeable material and/or legal constraints, shapes technology in ways that "cannot be 'read off' from either the physical technology, or from the social forces behind its development" (ibid.: 701). Users produce meaning under social, political and ideological conditions and, therefore, meaning of technology and their uses are "not inherent in the object, but related to its context" in which the "producer-consumption relationship is thus a complex and changing one" (ibid.: 704f).

However, even though Mackey and Gillespie note that the 'spheres' they identify are "not discrete, causally related, or sequentially ordered" and acknowledge appropriation as the "sphere where these two forces [design and deployment of technology] come together" (1992: 691, 709), they nonetheless seem to overlook the overarching potential of the concept of appropriation, since in *all* those spheres of which technology is a product, there is appropriation at work. They limit appropriation to the "*subjective social* appropriation of technologies" (1992: 698; my emphasis) in a seemingly juxtaposed position to design (similarly but more subtle and more recently, so did Suchman, 2016: 131). However, I would like to suggest that appropriation, at least in the analysis of catastrophe modelling, can serve as a concept that allows to go beyond this juxtaposition when we focus not only on 'subjective social' appropriation but on appropriation as a form of reciprocal interaction of multiple socio-material agencies across Anthropocene catastrophe. To do so, I suggest a more extended concept of appropriation in this analysis, drawing from the art world, where the term itself bears much more central significance.

II. Appropriation as Hermeneutic Practice

Figure 12: Appropriating the Raft of the Medusa. From top left to bottom right: Eugène Delacroix, Liberty Leading the People, 1830, oil on canvas; William Turner, The Slave Ship, 1840, oil on canvas; Martin Kippenberger, The Raft of the Medusa, 1996, oil on canvas; Banksy, graffiti; José Manuel Ballester, La Balsa de la Medusa, 2010, photography on canvas.

Géricault's Raft of the Medusa not only sparked a shift in 19th century French art but remained influential well beyond its initial Romanticist framework. The techniques and way of organising the work on the painting became a template as much as the arrangement of the scene's elements, the pictorial architecture and the inherent political and social critique. The Raft distinctively influenced many other artists, such as Eugène Delacroix,[33] William Turner,[34] Édouard Manet,[35] Frances Danby, Gustave Courbet, or Aguste Rodin. Many artists of Géricault's time and until today dissected in detail the painting's composition and "have created their own versions and interpretations of The Raft of the Medusa […] choosing to reinterpret or adapt" (Velimirović, 2017), such as Martin Kippenberger,[36] Banksy[37] or José Manuel Ballester.[38]

While the earlier cases from the time of the Raft's first exhibiting and the following decades in the 19th century drew on and *used* many, sometimes all, central aspects of Géricault's work especially in the Romanticist framework, the latter cases even more explicitly *make use* of the Raft itself for their specific purposes. The latter fall into the broad modern art practice that during the 20th century came to be known as 'appropriation art' (Evans, 2009). On the heels of Walter Benjamin and Roland Barthes, of course, Jean Baudrillard's ideas around 'simulacra' and 'simulation' were picked up by artists,

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[33] The most immediate example for this is its influence on Eugène Delacroix, who even acted as a model for one of Géricault's castaways on the Raft (Delacroix is the figure in the middle of the bottom of the painting, laying face-down with an arm stretched out, righthand of the corpse who is held by its despairing and red-hooded father). Delacroix's masterpiece Liberty Leading the People, commemorating France's July Revolution that put an end to the Bourbon Restoration in 1830, holds many compositional, technical and political references to Géricault's painting.

[34] Very prominently, it strongly inspired William Turner and apart from the most obvious one, A Disaster at Sea (1835), it stimulated The Slave Ship (1840) both in terms of its composition and the expression of social critique. Turner's socially critical Slave Ship painting, originally titled 'Slavers Throwing overboard the Dead and Dying—Typhoon coming on', depicts a historic and disturbing scene aboard the slave ship Zong in 1781, where ill slaves are thrown overboard amidst an incoming storm "because insurance would be paid for any cargo jettisoned in order to save the ship." (Roberts, 1998). Insurance has indeed gone a long and complicated way in any type of catastrophe throughout the evolution of the global economy (Baucom, 2005).

[35] Manet is often considered the first 'modernist' painter, whose response to Géricault's work must, therefore, include the latter as an important factor in the "genesis of modernism" itself (Fried, 2003: 791f).

[36] Martin Kippenberger in 1996 created a 49-piece series of different media (paintings, photographs, lithographs, a rug) themed around the Raft, with the most prominent one recreating the original composition in a red comic-graffiti style, injecting self-portraits and text elements, thematising Krippenberger's own mortality (he indeed died a year later).

[37] In 2015, Banksy created a stencil graffiti Raft version on a harbour wall in Calais, calling for solidarity with Syrian and other refugees during their exodus into Europe that year. The piece was later altered with graffiti by unknowns into yet another interpretation voicing an oppositional critique.

[38] More technically, José Manuel Ballester in 2010 took the Raft of the Medusa and a number of other well-known classic paintings and digitally removed all humans from those classic pieces, imposing a new perspective on space and redirecting attention away from the originally intended centres of known but altered works of art.

especially in the 1970s and 1980s in New York, with appropriation as a subversive strategy, even suggesting it as “the very language in which the postmodernist debate was conducted” (ibid.: 14). But, rather than the intellectual drivers of this particular movement, I would like to focus instead on the practice, the technique of appropriation as it has emerged in art, and integrate it into the concept of use in technology to make explicit the in-flux reciprocity of the appropriated, the appropriating and appropriation-objects, and how it pertains to the ‘flat ontology’ that underpins this thesis’s analysis: the explanation of how the production of catastrophe in finance via catastrophe modelling, models and related practices become active in realising Anthropocene catastrophe in the financial realm and beyond.

While appropriation in approaches of technology studies, as argued above, has been drawn on as one element of many in the use and development of technology, appropriation in art arguably may well be seen as the very central momentum of (at least modern) art practice. Copying existing pieces of art, for instance in painting, has always been and remains a central part of apprenticeship in the very practice of the craft, while more distinctively in modern art, ‘copying’ became the end in itself with techniques such as collages, readymade or montage (Evans, 2009: 15). But the notion of appropriation is conceptually and historically distinct from mere copying as, for instance, already Roman appropriation of Greek art bears a “symbolically transformative character” (Schneider, 2003: 217), it implies *change*. In a formal way, therefore, appropriation as an art practice refers to *taking something out of a specific context* and *inserting it into a different one*. Artists of very different media, styles and genres, such as Pablo Picasso, Marcel Duchamp, Roy Lichtenstein, Andy Warhol, Richard Prince, Karel Appel, or Jeff Koons have produced pieces using “pre-existing objects or images” where “the point was very much the way that the identity of the image or object had been transformed” (Chilvers and Glaves-Smith, 2009). It is a practice in which it varies distinctively what and how much changes are made and for what purpose – “the art of appropriation involves a considerable degree of craftsmanship” (ibid.).

The important point is that art recognises that where practice is conducted, there is *always* appropriation involved – there is “nothing before hybridity” (Schneider, 2003: 217) – which, on a practical level, precedes Benjamin’s analysis of a cultural move into an era of (mechanical) *re*production. Appropriation art’s very crucial *practical* questioning (or in its most radical form outright rejection) of notions of originality is important here, since it helps underpinning in this thesis’s conceptualisation the inherent problematisation of differentiating between origin/original design of technology and its use once it is indeed in-use. In art, “most often there is no absolute original […], but just a context in which something has been known to be produced for the first time (which might yet be a variation of a previous theme […]).” (Schneider, 2003: 221). Any technology, of course, also draws on pre-existing objects, techniques, infrastructures, knowledge, practices, or to put it more generally: the appropriation of elements of other socio-material environments and contexts. In catastrophe modelling, I have already emphasised the importance of concepts, objects and practices of specific environments and contexts, for instance regarding the two distinct modelling approaches of aggregate and bottom-up modelling in chapter 4, or for involved disaster-related science and practices in the case of storm and earthquake scales in chapter 3.

Appropriation, therefore, can serve the analysis of technology here as a practice and process that operates along the socio-material interaction of what and who is appropriated, who and what appropriates and the concepts, practices and artefacts that manifest at their intersection – three elements that I would like to call *appropriated*, *appropriators* and *appropriation-objects* – and where *all* elements emerge in *reciprocal transformation* in this process. This is an understanding of appropriation in art in the sense of Schneider's conceptualisation of "*appropriation as hermeneutic procedure*" with the '*appropriating act*' at its centre (Schneider, 2003: 221; my emphasis). This act involves, with reference to the term's etymology and to Ricoeur's understanding of Gadamer, "the process by which one makes one's own […] what was initially other or alien" (Ricoeur quoted in ibid.), while it involves not simply a possessive move but also a dispossessive one that replaces something previous. The hermeneutic core here lies precisely in the change in practice and understanding as a result of "interpreting the Other's artefact" – a process that is, of course, not without power differentials because positions in the interaction of appropriation are empirically "not equal" (ibid.: 222). But in the context of technology use and catastrophe modelling, it is a slightly different dynamic (as we will see further down) than in the context of, for instance, what is often referred to as 'cultural appropriation'. Central in the hermeneutic sense in Schneider's concept of appropriation is that it aims at reconciling agency *and* understanding in that it emphasises transformation of both appropriated and appropriator. With reference to Thomas (2001), Schneider understands "appropriation as a two-way process, […] the inherent 'unstable duality' between rejection and acceptance of *both giving* to and *taking* from the Other" (Schneider, 2003: 225; my emphasis).

If we understand appropriation in art, in this line, as a hermeneutic practice that instigates reciprocal transformation of all three elements – appropriated, appropriator and appropriation-object – how does this translate into technology studies? I suggest for the analysis of technology and its usage to view appropriation, in the way elaborated here, as the driver of technology itself, its development and its societal significance, materialisation and actualisation. Only in practice, technology becomes meaningful and socio-materially consequential. The result of applying this concept to the field of technology, however, means (a) that the interactional dynamic of appropriation accelerates as the environments and contexts multiply with every application of a user and any intervention by a designer as acts of appropriation. The reciprocal transformative nature of appropriation also (b) necessitates to acknowledge within the continuum of, for instance, producer and user of a technological device, that the positions of appropriator and appropriated switch constantly. The transformation inflicted by this switching, of course, (c) hinges primarily on agency and its distribution.[39] Where most technology studies approaches aim at differentiating modes of design, deployment and use, and assign appropriation to one particular step in adopting technology, I would like to emphasise how appropriation of technology as a practical hermeneutic can be seen as encompassing and overarching all relationships and interactions in the spaces where technologies appear, therefore bridging the more common 'micro' perspective of appropriation in technology studies and a more 'macro' level.

A few contributions evoke appropriation of technology in a more macro-oriented way. For instance in Hornborg's work, 'technologies of appropriation' capture technologies deployed by a (mainly western) "global minority" to maintain and accelerate desirable modern lifestyles where "technology itself [serves] as a strategy for appropriating and redistributing time and space in global society" as "time-space appropriation", which enables less "saving time and space, but [rather] redistributing it" (Hornborg, 2016: 18, 58, 65). This pertains primarily to labour (time) and resources (space and energy), where the notion of 'technological progress' masks the effective translocation of exploitation and extraction to the peripheries of political and economic global power. "Modern technology can be reconceptualized as a strategy to locally save (human) time and (natural) space, at the expense of time and space lost elsewhere in the world-system", which leads Hornborg to understand "technology *as* appropriation" (ibid.: 73, 160; my emphasis). This notion of appropriation as a form of (rather zero-sum) 'asymmetric transfer', found primarily with regard to cultural and (post)colonial foci of investigation, is extended to the use of technologies here. But, echoing mechanisms of cultural appropriation in the political sense, appropriation serves here almost exclusively as capturing the deliberate, although at times masked, *strategy* of stable and established groups of appropriators as the execution of uneven economic and political global power.

Other contributions turn appropriation into what is in cultural analyses referred to as strategies of 're-appropriation', i.e., the strategy of claiming back from established appropriators to actively instigate political change. For example, "habilitative technological appropriation" serves as a concept to capture "individual economic agents […] social structures, technical artefacts or technologies and combinations of them" involved in counter-hegemonial strategies to repurpose existing technologies, for example, for "cooperative and low-carbon usage" to enable a de-growing economy (Likavčan and Scholz-Wäckerle, 2018: 1674). Especially the latter could also be read, although more formally, along the lines of appropriation in arts as a possible "concept to conceive of the brokering practices" between

[39] For instance, the technological device can be transformed by a competent user so that also the producer re-contextualises the device, such as the case of the telephone (Oudshoorn and Pinch, 2003b).

different contexts (Schneider, 2003: 218). These concepts of appropriation are framed mainly within unequally distributed power dynamics in a global political context with, understandably, not as much emphasis on more 'mundane' technology use and practices on a micro level. Appropriation as a hermeneutic practice in the way suggested in this thesis, however, operates via the notion of agency and emphasises continuous transformation of, and switching of positions between, appropriated and appropriators. By being ontologically 'flat' in this way, appropriation can bring macro and micro closer together and allows with the notion of agency and its distribution a more nuanced analysis of power relations with regards to technology and its usage. Another, even more important aspect is, however, materiality.

Now, for all technologies but especially those that are primarily active in knowledge production, such as those involved in risk modelling practices, appropriation in the way conceptualised here is, of course, fundamentally *socio-material*. As elaborated in chapter 2, the socio-material framework of this thesis renders knowledge production in the Anthropocene as an active element of ontological becoming. Anthropocene catastrophe, as already exemplified in the previous chapters, is an in-flux interaction of many different non-human and human agencies, including epistemic devices and practices, that are involved in "*doing* practical ontology" (Jensen, 2004: 248). Here, working on and with the objects of scrutiny involves *adding* something when "knowledge is constructed precisely at the intersection of the many different agencies concretely interacting in the world" (ibid.: 249). The concrete performative move, the practical ontological becoming, is one in the mode of reciprocal transformation of the appropriation act, in which a device or object, too, switches sometimes into the position of the appropriator appropriating other involved humans and non-humans.

In this Anthropocene framework (and to differentiate it terminologically explicitly from 'cultural appropriation'), an adapted version of Schneider's appropriation as hermeneutic procedure emerges as what I would like to simply call: *socio-material appropriation*. It penetrates into technologies' farthest peripheries of socio-material environments, i.e., Latour's entire 'critical zone'; that is to say, this analysis is 'appropriating appropriation' as the concept of technology use for Anthropocene catastrophe, maybe even for the Anthropocene in general (as is argued in Appendix A). If the conceptualisation of this analysis, outlined in chapter 2, is followed through in a stringent way and the Nature/Culture divide is dissolved in the Anthropocene, then the assertion that "most cultural practice is 'appropriation' in that it is part of a continuum (both historical and spatial) of all human endeavour" (Schneider, 2003: 217), it needs to be extended to what otherwise would be denoted as 'Nature' into a socio-material Anthropocene setting. An example where this transformative reciprocity of appropriation of human and nonhuman, 'artificial' and 'natural' agencies is taken serious in practice is, for instance, the 'tropical modernist' architecture of Geoffrey Bawa, whose structures are deliberately designed and built to be incorporated and 'taken over', i.e., appropriated, by the jungle plants into whose midst they are placed. This concept itself has been appropriated by other building designs, re-contextualised in urban spaces such as Singapore or Milan, where plants are planted onto and incorporated into building structures as, for instance, carbon sinks and build-up of green space in congested urban areas, where positions of appropriator and appropriated switched again in particular ways. With the concept of socio-material appropriation constructed here, the "back and forth […] between the designer and the user" (Akrich, 1992: 209; Oudshoorn and Pinch, 2003b: 11) is both extended towards all agencies active in the 'critical zone' and inscribed within the in-flux back-and-forth of experimentality. Precisely because of the continuously changing reciprocal transformation, the appropriation act is fundamentally experimental, becoming an active part in the ontological becoming of the Anthropocene.

III. Socio-material Appropriation in Catastrophe Modelling and the Multiplicity of Catastrophe in Markets

"If there is no 'original' after all, any notion of a composite original can only be arrived at through the study of the distribution, or epidemiology, of its many variants" (Schneider, 2003: 225). After having done so in the previous chapters with the advantage of analysing a not-yet-fully-applied practice and technology, what follows with the advent of catastrophe modelling in financial practice from the mid-1990s onwards is the much more complex situation of applied, active, transformative usage. Its practical application instils thinking and realising catastrophe in particular and practical ways: the many variants of the socio-material appropriation via catastrophe modelling in finance and the consequential intensification of a financial ontology of Anthropocene catastrophe by multiplying catastrophe for financial risk practice.

The way in which Anthropocene catastrophe is *realised* here, is in the mode of multiple, interactional and transformative acts of *socio-material appropriation*. What I suggest here for the analysis of catastrophe risk markets and catastrophe modelling, is, therefore, not only a notion of technology use but also an extended perspective of Muniesa's and Caliskan's notion of 'realising' (see chapter 2). Once catastrophe modelling entered the practical, everyday realm of financial services, it did so in the mode of socio-material appropriation, reciprocally transforming the elements of simulation and socio-material mediation. This mode of appropriation becomes an element driving the in-flux experimental state of Anthropocene catastrophe and thereby emerges as an active set of agencies involved in realising it. Of course, with regard to notions of originality mentioned above, the initial construction of catastrophe models has already been marked by multiple and different socio-material appropriations, since many pre-existing elements were combined in, then, new ways to carve out what emerged as catastrophe modelling. Against the backdrop of the previous chapters and this initial, conceptual emergence of catastrophe modelling, the actual use of catastrophe modelling is then, however, not some kind of second-degree appropriation as a practice on a different level, but construction/design and usage converge and become at some point almost indistinguishable in the mode of socio-material appropriation. Once adopted by market participants, catastrophe modelling has left the 'laboratory' configuration and becomes an in-vivo experimental practice. As an epistemic device and practice, the 'laboratory' of catastrophe modelling multiplies to each user, firm and product, and all those usages leave only the multiplicity of transformative socio-material appropriations to analyse, whose outcomes are equally multiple versions of modelled and sometimes actualised catastrophe.

The access points of practical socio-material appropriation in catastrophe modelling are, of course, the elements of socio-material mediation and simulation. Socio-material mediation appropriates socio-material environment and myriads of different sensing processes, devices, infrastructures and data (which often have been intended for very different purposes). Simulation appropriates different assumptions, theories, evidence, etc. that are mobilised to explicate catastrophe's grammars of interaction for specific purposes at the discretion of the modeller (both users and modellers). As argued before, financial services provide an important aspect of mediating socio-materiality, for instance, by creating and compiling exposure and claims data. Specific goal settings and practices provoke different styles of simulation in which at least the level of catastrophe's grammar of interaction is treated and plays out differently.

In a situation where catastrophe modelling enters everyday usage and emerges through continuous transformation by socio-material appropriation of simulation and socio-material mediation, a multiplication of environments and contexts takes place. As will be empirically shown in the following chapters, this reciprocal process of appropriation across all involved actors and agencies is driven by continuous re-contextualisation[40] in and of political positions, regulatory frameworks, local, regional and global spatiality, different markets and products, different socio-material environments, different scientific disciplines, positions and discourses. Through this multiplication of re-contextualisation, the 'multirealism' of simulation and the 'multinaturalism' of socio-material mediation are accelerated, which transforms catastrophe modelling and its devices throughout these networks of acts of socio-material appropriation. The outcome of this mode of multiplication and transformation is the production of a multiplicity of contextualised catastrophe in financial application, individually and locally produced in and for each risk transfer and risk product. Consequently, through the reciprocities between finance and the 'real' economy and Anthropocene world, this multiplicity of contextually

[40] Other than the concept of cultural appropriation, as it is explicitly not re-appropriation that is invoked here, since modelling is continuously transformed and socio-materiality is in constant flux. There is, therefore, no 'originality' or singular, original context that could be claimed back from appropriators. It is ever new, sometimes more or less nuanced, contexts that drive socio-material appropriation as a practice and process.

produced catastrophes, each to lesser or greater degrees, change aspects of socio-material environments and help realise actualised Anthropocene catastrophe in specific ways.

This multiplicity of contextual catastrophe in financial services is principally driven by the imperative of competition. As a market-societal way of dealing with catastrophe, the socio-material appropriation of catastrophe modelling takes place in the framework of competitive markets. Despite the constant local and specific re-contextualisations, the overall framework of the market in which most, and the most dominant, actors and environments are situated, remains common to all transformation. It is through the situatedness in competitive markets that the interactional dynamics of socio-material appropriation accelerate. Every re-contextualisation of simulation and socio-material mediation in modelling – resulting in individual, contextually and locally situated versions of catastrophe – is not only a firm-specific and internal risk governance and management provision but, more fundamentally, an important means of competitive performance in the market: “the better science you provide, the better business you will have” (interviewee U60). There is, so to speak, no singular model or modelled catastrophe which is produced centrally and then used by all, but the production of modelled catastrophe is market-shaped, i.e., decentralised in economic activity. Framed by competitive market conditions, the socio-material appropriation of catastrophe modelling asserts itself at the experimental point where reciprocal transformation of appropriator, appropriated and appropriation-object promises to gain a competitive edge: at the margin between modelled and actualised catastrophe, the ‘fracture of reality’. It is where the experimental state of Anthropocene catastrophe is most at play and where catastrophe for the financial realm is produced in the era of catastrophe modelling.

IV. Realising the Financial Ontology of Anthropocene Catastrophe

The disaster of the frigate Méduse was initially dissected and its aspects specifically appropriated in practice, de- and re-compartmentalised, de- and re-contextualised, and assembled in its first ‘modelled’ version by Géricault in his Raft of the Medusa. Both the object of art, or ‘model’, itself and the appropriating practices that produced it were, then, subjected to multiple acts of appropriation and resulted in multiple situated versions of Méduse’s disaster, all with different contexts, foci, techniques, inputs, references and final outcomes. Socio-material appropriation in catastrophe modelling plays out in this mode as well. The first models were products of acts of appropriation of many different aspects, practices, objects, etc. until they themselves began to be subjected to multiple acts of appropriation once they entered usage. This produced and continues to produce a multiplicity of versions of catastrophe with each such act, with reciprocal transformations of all elements involved including the initial and subsequent models themselves, catastrophe risk production, management and products, and (in intended and unintended ways) the concrete socio-material environments of Anthropocene catastrophe.

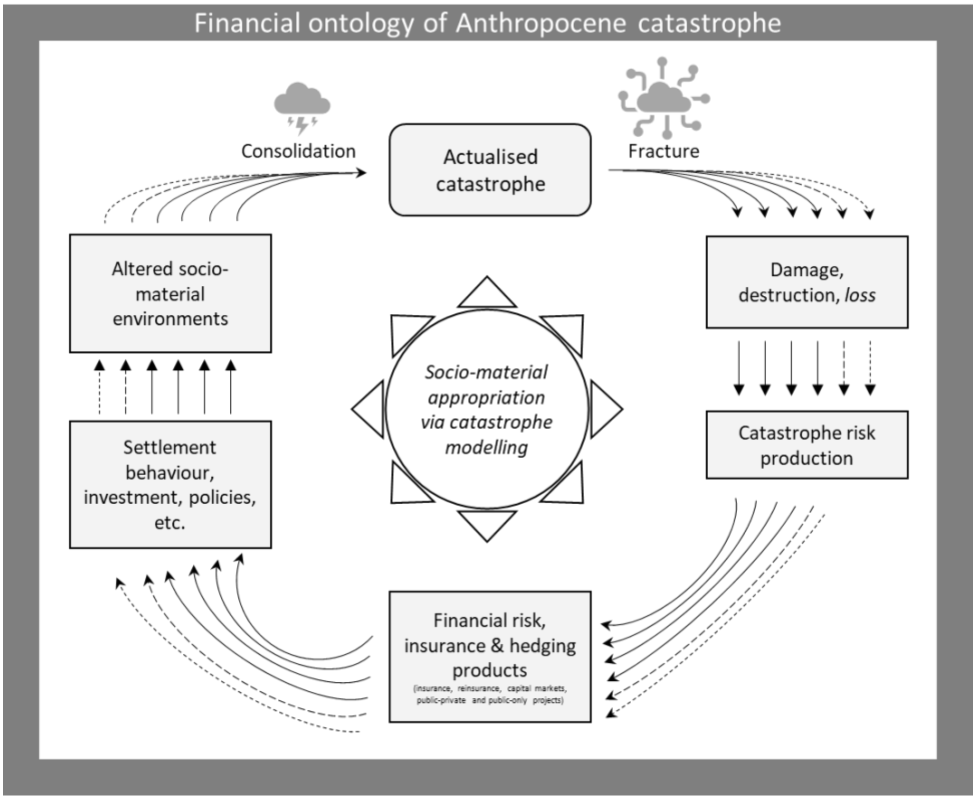

Figure 13: The loop of Anthropocene catastrophe.

The fracturing of 'reality' – "there is no reality here" but only "the reality of how good a model is" (I03) – is the consequence of the multiplicity of catastrophe (represented by the multiple parallel arrows in Figure 13), driven by myriads of individual and ultimately competition-driven acts of appropriation in catastrophe modelling and related practices. This fracture is eventually consolidated by actualised catastrophe, the actualised materialisation of interactional agencies within the Anthropocene. This moment of 'truth' consolidates the multiplicity of modelled catastrophes which have themselves not been aiming for a singular 'truth' but for enabling the situated management of Anthropocene experimentality throughout the fracture – a specific portfolio, a specific financial product or product line of a specific firm situated in a specific market and exposed to specific Anthropocene environments. Catastrophe in finance, in this light, is the product of the practice of socio-material appropriation at the 'fracture of reality'. There are as many versions of catastrophe as there are firms or even different firm-internal acts of appropriation in catastrophe modelling. To clarify, what is meant here by 'versions of catastrophe' is not simply the production of thousands of simulated event iterations in the hazard module of a catastrophe model, but all the different acts of appropriation of catastrophe models, and related practices (see Jarzabkowski et al.), in risk production for specific and contextually situated financial decisions, products and risk transfers within firms and throughout markets. Catastrophe risk production and practice here emerge not simply as a Knightian quantification of uncertainty but as socio-material appropriation to navigate and try manage the experimental state of the concrete agencies of Anthropocene catastrophe in which each firm, its products and portfolios are situated – "You're underwriting *this* office building, *this* factory" (Hemant Shah). These become themselves, in turn, yet another set of active agencies within Anthropocene catastrophe's experimentally: appropriating catastrophe modelling also means socio-material appropriation of and by Anthropocene catastrophe itself, for instance by prescribing risk mitigation measures such as building and behavioural provisions in insurance policy conditions or provision or denial of access to insurance-conditioned real estate development and mortgages. These aspects realise concrete socio-material environments of, again, eventually actualised Anthropocene catastrophe, which in turn explicates the epistemological-ontological dynamics of realising catastrophe in market societies. To clarify, though: market-shaped socio-material environments in this way do not necessarily adhere to the prescriptions of disaster mitigation and adaption but are products of the struggles around these conditions, for better or worse.

Once consolidated, all 'bets' of modelled catastrophe are at the same time off and start anew. Catastrophe risk here is conceived in practice through producing modelled catastrophe until catastrophe is actualised, the sequential catastrophic loop after which risk is conceived anew in the next loop. With the anticipation of actualising catastrophe, financial 'reality' of catastrophe is, therefore, fractured prior to it, multiplied by myriad acts of socio-material appropriation in modelling and risk management until all agencies of actualised Anthropocene catastrophe consolidate 'reality' for all again, the end of one loop and the beginning of a new one. However, as will be exemplified especially in chapter 9, consolidation is itself also not free of acts of socio-material appropriation of simulation and socio-material mediation, and is, therefore, also not freed from the in-flux state of market-shaped experimental Anthropocene catastrophe. "If the feedback loops are similar in form, their contents, rhythms, and extensions are different in each case" (Latour, 2017a: 138). As explained in the previous chapters, this is the mode in which multiplicities of interacting agencies are in-flux, including atmospheric conditions, tectonic plates, settlement behaviour, building behaviour, real estate development, policies, market competition, sensing networks, financial epistemic practices and devices themselves and much more.

In this performative setting, *assigning risk to specific socio-material environments and objects is a way of distributing agency throughout the Anthropocene*. And since assigning risk is based on situated acts of socio-material appropriation of simulation and socio-material mediation within financial services, catastrophe modelling and its related practices play an active role in this distribution of agency. As already argued at several points throughout this thesis, agency in the Anthropocene is not simply an a priori assignment, but it is distributed in multiple arenas in which 'epistemology collapses into ontology' which pertain to different fields such as the material, social, political, economic, etc. An important aspect of the loop of Anthropocene catastrophe is its socio-material environment, for instance, whether, how and where buildings are constructed within a concrete space. The broadening of catastrophe modelling's appropriation by a growing user community adds to these interacting agencies even more concretely those agencies active in financial markets. Since market participants must navigate their competitive position in catastrophe risk and capital markets, situated production of catastrophe in the mode of socio-material appropriation in catastrophe modelling is a key driver of economic performance. Who and what assumes the position of appropriator and appropriated, and how reciprocal transformation plays out is, therefore, conditioned by agencies active in the market space, including what Callon calls 'hot sources' (Callon, 2009). Catastrophe models are, first and foremost, market devices and appropriation here is configured by market actors, dynamics and affordances of both producers and users of those practices and devices. Anthropocene catastrophe is, therefore, actively ontologically shaped by market imperatives and dynamics via the distribution of agencies throughout socio-material Anthropocene environments.

What will follow in the next four chapters is the empirical analysis of socio-material appropriation via catastrophe modelling and the proliferation and transformations of the production of a multiplicity of situated catastrophe in financial services. I will present a set of case studies that will explicate specific series of acts of socio-material appropriation and catastrophe production (micro). This selection of cases is driven and structured by more general and overall (macro) transformations of the appropriation of catastrophe modelling and are analytically and historically divided into two major phases on which the next four chapters will focus. The starting point here is in the mid-1990s, until when, as already discussed, (re)insurance had been relying on concrete, yet insufficient, history before appropriating catastrophe modelling. Appropriation art, conversely, in its postmodernist extreme had until then relied on the "supposed death" of history (Evans, 2009: 22). Coincidently not only conceptually but in a way also empirically, this changed for both realms around the same time, with Hurricane Andrew and the Northridge Earthquake for (re)insurance and for appropriation art, most prominently, with the "implosion of the Soviet Union", after which each of them faced a surprisingly similar result, that of an emergence "of a multiplicity of histories in the moment of the 1990s. The challenge for the appropriationist artists now is to discover new ways of dealing with these 'unresolved histories'" (Evans, 2009: 22). (Re)insurance and finance, on the other hand, were about to settle on their way of dealing with it by embracing the market-shaped multiplicity of simulated and socio-materially mediated 'history' by turning it into a multiplicity of 'futures' via modelled catastrophe in the socio-material appropriation of catastrophe modelling.

Chapter 6. The Era of Catastrophe Modelling Phase 1: Modellers as Appropriators

> "We are in an era of natural catastrophe, be it here, California or Japan." (Bill Nelson, Insurance Commissioner of Florida, in NAIC, 1995a: 2)

In the late 1980s and early 1990s, catastrophe modelling had not emerged as a self-standing field of scientific enquiry unveiling a particular truth or academic discipline but was developed to serve a particular purpose, that of financial risk management, and driven by a particular principle, that of competitive markets. Since the two initial socio-material breaking points, Hurricane Andrew and the Northridge Earthquake, catastrophe modelling became an applied, gradually institutionalised practice, a new and legitimised genre of risk assessment in financial risk management. Catastrophe modelling usage since the mid-1990s would be marked by multiple acts of socio-material appropriation, all with many different and individual goal-settings and in different immediate settings of market, political, social and material situatedness with different underlying struggles. What will follow now is the magnification of some of the most relevant shifts in appropriation in the developments of applied catastrophe modelling. The selection of empirical cases is oriented along developments of more fundamental macro shifts in socio-material appropriation of catastrophe modelling. Historically and analytically, I identify two different successive phases: 1. Multiplying catastrophe (1990s – 2005, chapters 6 and 7) and 2. Owning catastrophe (2005-present, chapters 8 and 9). These phases are by no means discrete in the sense that a phase would replace or exclude the other, but, on the contrary, they evolve in a continuous and non-teleological process. It is rather in a Foucauldian sense that a phase entails and is embedded in its predecessor. Understanding this almost genealogical development allows to recognise how Anthropocene catastrophe is realised and managed today.

This and the following chapter on the first phase will analyse and explain how catastrophe came to be produced in situatedness of (re)insurers by catastrophe modelling firms and how catastrophe production emerged in multiplicity. In this phase, the positions of appropriator and appropriated on a macro level are rather fixed with catastrophe modellers and their models as the dominating appropriators of catastrophe production appropriating (re)insurers, their practices, systems and devices, a situation that will dramatically change in the second phase analysed in chapters 8 and 9.

The analysis of the first phase will start by drawing on the prevalent mode of appropriation in catastrophe modelling from the mid-1990s onwards, in which vendors and models started to appropriate risk assessment and pricing practices. It will, then, analyse forms of 'centralised' catastrophe production in modelling in the US with the cases of the California Earthquake Authority, the Natural Disaster Insurance Corporation and the National Flood Insurance Program. This is followed in chapter 7 by an analysis of the increasing market and political dynamics around catastrophe modelling, represented by the institutionalisation of socio-material appropriation in catastrophe modelling in form of the Florida Commission on Hurricane Loss Projection Methodology, and the evolving vendor character of catastrophe modelling firms and their increased appropriator position throughout the 1990s until the mid-2000s. Finally, the analysis of this first phase will end on a discussion of the state of proprietary catastrophe production and carve out four central characteristics on the dynamics between public and proprietary knowledge and between vendor firms as 'loss simulators' and (re)insurance as 'loss sensors'.

I. The Advent of Catastrophe Model Usage

> "[A] technological revolution has occurred, triggered by the development of sophisticated computer models capable of simulating insured losses in catastrophic events. These models allowed a far more sophisticated analysis of the insurance process. The models indicated that the historically accepted methodologies used to develop insurance rates and solvency tests may have been severely flawed. The new data suggests that current rate levels in high risk areas may be grossly inadequate and past estimates of probable maximum loss may have been dangerously over optimistic. If correct, the new estimates of catastrophe loss potential will have profound effects on the public, including: how much their insurance costs, how their coverage is structured, how their homes are constructed, and where they are able to live. Some consumers may be forced to engage in expensive retrofitting activities or face a decline in value of their properties. Banks may experience an increase in risk on their mortgage portfolios. Home builders may see tougher building codes and restrictions on development in some areas." (Musulin, 1997: 342f).

In other words: producing modelled catastrophe and assigning risk can be a highly consequential way of distributing agency throughout the market-societal Anthropocene. This assessment of an insurance actuary in the Journal for Insurance Regulation published in 1997 came on the heels of the socio-material breaking points of Hurricane Andrew and the Northridge Earthquake. The statement projects the socio-material transformational potential of catastrophe modelling not only for the (re)insurance industry but for Anthropocene environments in general. In the aftermath of those major disasters, it was driven, first and foremost, by the subsequent scarcity of capital and high demand for catastrophe risk cover. As discussed in chapter 4, a host of only closely avoided and some actual insolvencies were followed by a general retreat of many insurers from areas that now became considered epicentres of the new high loss regime. Florida and California both had to install different forms of public insurance and emergency funds to grapple with these new market realities in this 'era of natural catastrophe'.

The advent of this era is also the main reason why today most people in neatly creased shorts who pass by the obelisk memorial of the early hurricane-researching governor Sir William Reid in Bermuda's capital are (re)insurance professionals (mentioned in chapter 3). Hurricane Andrew's massive loss provoked a huge demand for new risk capital and led a number of newly founded and mainly catastrophe-specialised (re)insurance firms to enter the global stage amidst steeply rising premiums, or what in the industry is called a 'hard market'. Because there were some existing insurance traditions here but primarily for tax and regulatory reasons, those new firms chose Bermuda as their official domicile, even though the market they primarily aimed at was the US's[41] (Cummins, 2008). The combination of "losses from Andrew and the reassessment by the insurance industry of its exposure to property catastrophes" (ibid.: 6) drove the formation of both direct insurers and reinsurers here, particularly the so-called 'class of 1993' of eight new catastrophe reinsurers backed by a total of $4 billion of new capital. Especially these reinsurers were driven by a new analytical emphasis which would be followed by the entire industry over the coming decades: they integrated catastrophe modelling into their entire risk assessment, pricing and capital allocation. While these 1993 firms were explicitly "founded on catastrophe models" (Wyss, 2014: 558), the appropriation of catastrophe modelling led to a more general transformation. It instilled (re)insurers to start "basing their business more and more on probability and computer-aided modelling techniques for virtual events and simulated losses of unprecedented size" which transformed especially reinsurance "into a knowledge-processing and knowledge-producing industry" (Borscheid et al., 2014: 220).

On a practical level, this knowledge production focused on the appropriation of catastrophe modelling for insurance rate, premium, solvency and capital calculation through the production of firm- or portfolio-specific, situated modelled catastrophe, i.e., the multiplication of catastrophe at the fracture of catastrophe's 'reality'. While this transformation was one materialising over the second half of the 1990s and more intensely in the 2000s, in the early and mid-1990s models were not yet broadly applied. Apart from very few firms, such as Swiss Re with its SNAP-EQ, "a global earthquake model and they actually used it" (U15), appropriation of catastrophe modelling emerged at the centre of practical, economic, regulatory and political turmoil. These very struggles over producing catastrophe for insurance became themselves a "major driver of the availability crisis facing property insurance consumers in high risk areas" with the consequence of an "increased demand for public funding of catastrophe losses to ease the shock of free market reactions" (Musulin, 1997: 343). During this first

[41] As mentioned in chapter 1, the US was and remains until today by far the largest insurance market including that for non-life catastrophe insurance (III, 2020).

phase of the appropriation of catastrophe modelling, the emerging multiplicity of catastrophe for situated financial risk management of Anthropocene catastrophe was driven by the position of vendor catastrophe modellers as appropriators of (re)insurance processes and practices.

II. Catastrophe Modellers as Appropriators

Even though catastrophe modelling was not yet in full use, market participants were already very aware of its existence. P02, who had transferred into EQE in 1994, reports that he started to "spend the first few years trying to persuade people that cat models were useful tools [...] that, you know, cat modelling had value", but at that time people like him had only limited success in convincing firms, "they were very cynical". Especially the high level of discretion and only very limited disclosure of aspects in vendor models' submodules – modellers' emerging proprietary grammars of catastrophe's interaction – were met with suspicion: "In the early days, the vendors were very tight about protecting their proprietary information" remembers U60, who at the time worked for a large reinsurance firm. The State of California's Chief Actuary, for instance, emphasised vendor models' "proprietary nature claimed by modelers [...] An issue that casualty actuaries face is how to opine on or submit a [insurance] rate based on outside input. The actuarial profession is currently wrestling with this issue." (NAIC, 1995d: 924). The yet missing conception especially by actuaries of catastrophe models in an insurance context was hard to establish even from the vendor modellers' side, for instance for EQECAT's P02 at the time: "Almost nobody was trained to use them. And what's worse is, the people in the insurance industry who have the greatest statistical training, which are the actuaries, were not asking the right questions either". In addition to the fundamental differences between catastrophe and actuarial modelling, actuarial practice had previously also practically been limited by the material lack of catastrophic history. U15, a seasoned (re)insurance catastrophe modeller, notes that "actuaries were never around catastrophes, because their actuarial background is to manipulate claims data" and there had simply been too few data up until the 1990s. From the regulatory perspective, states across the US "expressed concern about the proprietary information used to construct the models" (NAIC, 1995b: 679).

The emergence of the broader socio-material appropriation in catastrophe modelling is marked here particularly visibly by the reciprocity of the "'unstable duality' between rejection and acceptance of both giving to and taking from the Other" (Schneider, 2003: 225), that is the determining characteristic of transformation. The few that already utilised catastrophe models at this time "were using them semi-blind", as P02 reports. Using something 'semi-blind' means, of course, that usage is not self-directed and, therefore, the direction of appropriation in this case is explicitly tipped away from the user: usage is appropriated socio-materially by the vendor modellers via the design of the models, in particular the shielding around damage functions: "the calculations, the way they're done is very complicated, so everything was kind of kept secret", reports the modeller I13. P02 explains, "people couldn't really understand them, so, you know, there was only one point of view, […] you couldn't sort of use them inelegantly. You either used them or didn't use them". This initial dynamic of the socio-material appropriation of risk assessment practices and understanding began to emerge with the incremental take-up of catastrophe modelling for calculating catastrophe loads and rates. "So, we had this methodology, that was kind of done behind the scenes and we gave you some sort of results. If you tried to reproduce some of the results, you couldn't because the calculations were done behind the scenes in one way [e.g., those in the vulnerability module] and the ones you could reproduce [e.g., those in the hazard module or the financial module] were done another way […] it is like a black box" (I13).

Anthropocene catastrophe's grammar of interaction would increasingly become proprietary and emerged as a "business asset" that needed to be protected from "disclosure to competitors" (Harrison and Nordman, 1997: 319). Apart from the reason of protecting vendor modellers' intellectual property in the context of an emerging competitive market around risk analytics, this configuration of appropriation was reinforced by the general perception of models' "mind numbing complexity" (Musulin, 1997: 343). This led vendors' assumptions that a greater openness of models could also lead to an inappropriate form of use whose potentially inadvertent consequences might be blamed on them. "[T]hey were concerned that the users didn't understand enough about building models to be able to use that information properly. So, they thought it would be easier if they didn't tell them." (P02).

Although asymmetrical in terms of power distribution, these newly forming interactions between vendors, models and the financial industry are fundamentally reciprocal. The 'hermeneutic' core of the act of socio-material appropriation, as argued in chapter 5, is the change in practice and understanding as a result of 'interpreting the Other's artefact'. Who or what assumes the position of appropriated and appropriator in this hermeneutic procedure hinges on the degree and dynamics of distributed agency with regard to this interpretation. The distribution of agency works through how catastrophe modelling can be practiced and understood, which was at this point nearly exclusively at the discretion of the modelling firms. In turn, modellers actively appropriated the industry's established risk practices. Although fundamentally different in terms of their setup and organisational evolution, all three vendor modelling firms, AIR, EQE and RMS, at the time needed to interpret and build up an understanding of the (re)insurance contexts and their 'artefacts', their devices and practices, which modellers' models were supposed to appropriate. For example, although already coming from within the insurance world, Karen Clark and AIR had to interpret and understand the market-share approach, the way reinsurance deduced information on socio-material environments of to-be-reinsured insurance portfolios. This 'interpretation of the Other's object' and the subsequent appropriation of this practice by AIR and its model led to a more general initial goal setting and modelling approach (discussed in chapter 4).

An example of a more 'active' interpretation of (re)insurance 'artefacts' provides RMS. Building a self-narrative and culture around the notion of 1980s and 1990s Californian technological entrepreneurism, RMS had formed itself on science, engineering and software personnel on the one hand, and consultants and business analysts on the other: "the first 50 RMS people, almost half of them were smart, hungry business analysts who otherwise could have worked at Goldman or McKinsey" recalls RMS's co-founder Hemant Shah over a coffee in San Francisco. "We didn't know a lot about insurance", he adds. They followed an almost ethnographic approach, a hermeneutic reading of the industries' everyday practices. Catastrophe models and modelling were conceived and developed as something that is as much about for what and by whom it is applied as much as it is about catastrophe itself, which is why eventually a multiplicity of *situated* and *contextualised* catastrophe versions emerged throughout catastrophe risk markets and not a few generalised ones (which will be elaborated in this and the next chapter). And this was driven by the early acts of appropriation by vendors since disaster-related science, as explained in chapters 3 and 4, had of course existed before, "these were not new concepts", but instead for RMS, it was insurance that was new, an 'Other's artefact' that needed to be interpreted and understood: "let's understand the insurance side".

"And so, we used to spend weeks on the road […] working super closely with clients and be like 'teach us, explain how this industry works. […] we were, in a way, outsiders without a whole lot of preconceived notions about insurance". In the beginning, Shah and his colleagues would sometimes, for instance, ask for manuals of industry practices, "and they would laugh at us and say 'you don't get it. There's not like a finance textbook. It's all we've learned over ten, 15, 20 years.'" These were the "wise" insurance professionals that interviewee I03, of one of the modelling firms, mentioned in chapter 4, who had "fantastic experience" and who, once their world was understood by modellers, "we would confront". However, as Shah explains, to get to this point, in the early 1990s they had to "spend endless amounts of time not on the earthquake model but understanding 'what is an underwriting use case? What is a reinsurance contract?' […] I sat in a box at Lloyd's for two weeks […] looking through files to understand what data do you actually collect. […] What data is available and why can't you get better data? […] And we would go into the field with the loss control engineers, we said, 'we'll follow you as you visit [damaged] buildings [and] when you do your reviews to advise the underwriters on the risk.' […] We dug into every use case: insurance underwriting, reinsurance underwriting, reinsurance buying, commercial insurance underwriting, actuarial pricing, loss control […] we just soaked it all up". Those interpretations, which shaped RMS's and other modellers' models, provoked a feedback into (re)insurance practices, once catastrophe modelling was applied for and, eventually, by the industry.

(Re)insurance firms as users at this point were, therefore, not in the position of the appropriator but instead its risk assessment was starting to become appropriated by modellers, socio-materially embedded in their appropriation objects that are catastrophe models. Since Andrew and Northridge and the dawn of the new high loss regime, the in-flux state of Anthropocene catastrophe's socio-material environment was magnified. Modellers' position as the new appropriators of catastrophe risk assessment was driven by the perceived need for simulated instead of previously actualised, historical disasters. The transformation that emerged already shimmered through the commentaries of regulatory market observers who identified a shift in risk practices:

> "Historical loss information is a good predictor of future losses as long as there are no significant changes in the environment in which the coverage is provided. It is this belief that drives the work product of the casualty actuary. Climatic changes combined with a changing exposure base tend to cause insurers to be less trustful of historical information. Insurers are quick to point out that more people are building very expensive dwellings and businesses in areas that are subject to significant catastrophe losses. Thus, insurers argue that using old ratemaking methods will lead to inaccurate results. They challenge regulators to discard traditional ways of thinking and join the modern age where complex models are used to assist in identifying the most accurate possible rate indication." (Nordman and Piazza, 1997: 361).

Of course, during Hurricane Andrew, as noted in chapter 4, Karen Clark and AIR put catastrophe modelling on a more visible stage by famously faxing her model's loss estimates on the unfolding disaster directly to (re)insurers. Although this is the common narrative of the first actual and effective use case demonstration of catastrophe modelling (e.g., Lewis, 2007; Muir-Wood, 2016; Weinkle, 2017), the stage on which it was put in this context was, at that time, a relatively closed one and it was not the only driver of the uptake of modelling. Without curtailing the historical importance of this particular act of appropriation, there was a series of different stages in different contexts which tabled catastrophe modelling and contributed to its increased appropriation in and of (re)insurance practices.

For Théodore Géricault, the French Romanticist painter, the first exhibiting of the Raft of the Medusa did put it on an exposed stage, but it was only with its second exhibition that the Raft received wider and more consequential reception, and one reason was a seemingly mundane socio-material difference in how it was appropriated by the exhibitions themselves. In the Paris Salon, where the painting premiered in 1819, it was hung very high up in the Salon Carré (Laveissière, 1991) and despite its enormous size it could only be observed from afar.[42] In its second staging in 1820, it was exhibited in

[42] The exhibition had been commissioned by the Bourbon government, which was the object of critique in the Raft painting and which might have contributed to the painting's positioning in the Salon. For a visualisation of the Salon's spatial distribution of the exhibition's pieces of art see: https://sites.google.com/a/plu.edu/paris-salon-exhibitions-1667-1880/salon-de-1819.

the Egyptian Hall in London where it was hung close to the ground, allowing its details to be inspected more carefully by onlookers and deploying its monumental size's intended effects.[43] This second, more public and socio-materially more magnifying context was the actual hallmark of Géricault's success and the primary factor establishing the Raft and its art practice in a concrete and lasting way. While Hurricane Andrew and Karen Clark had staged catastrophe modelling in 1992 for the first time more publicly, another staging of it after the Northridge Earthquake was 'curated' for the initial establishment of the California Earthquake Authority (CEA). It was a very magnifying staging, in this case, of insurance's 'artefact' of ratemaking and catastrophe modelling as its appropriation object in which the 'exhibition's' socio-material assemblage was distinctly complex and which publicised a large range of acts of socio-material appropriation.

One of the central and most fundamental insurance practices is, of course, determining the price for an insurance policy, the insurance rate. The central aim in insurance 'ratemaking' is that insured "neither pay more nor less than his or her fair share of expected loss costs and insurer expenses. Insurers [and regulators] generally have that same goal. Disagreements sometimes occur over whether or not the rate level proposed will lead to that result." (Nordman and Piazza, 1997: 361). This is one of the most crucial points where financial services markets' agencies add to Anthropocene catastrophe's fracture of 'reality' and distribution of agency. During the CEA ratemaking process, however, the concrete catastrophe model used was itself exposed to multiple points of appropriation acts and although embedded in struggle, the result was a solidifying transformation of catastrophe risk assessment and ratemaking. Historically, it magnifies the emerging role of modellers as appropriators of risk knowledge and catastrophe production in insurance, the struggles this role provoked and the context it was embedded in. As such, it informed and drove important aspects of the industry and regulatory debate around catastrophe modelling in the 1990s. The more 'centralised' production of catastrophe in the CEA case also marks an outlier to what in parallel and soon after would emerge as the until today dominant market-shaped and 'decentralised' mode of producing catastrophe for managing Anthropocene environment, which will be turned in chapter 7.

III. Appropriating Ratemaking: USQuake and the CEA

"We went through a three-month hearing. I testified extensively and then other people in the company testified – it was very stressful!" remembers EQE's I64. In 1994 right after Northridge, EQE's modelling subsidiary had entered into a joint venture, EQECAT, with one of the large and established (re)insurance

[43] There was a high "significance of the hanging height in terms of compositional legibility and artistic intention – given the manner in which the raft itself is contrived to 'project' into the viewer's plain, thus blurring the line between spectator and participant" (Riding, 2004: 8).

brokers, Guy Carpenter, and had operationally separated from its parent, EQE International. Not even Karen Clark's first hurricane model had been so immediately and officially involved in post-catastrophe analysis as EQE's EQEHAZARD model by the California Office of Emergency Services. In the process of setting up the CEA, I64 was part of a team of EQECAT representatives to testify on their new USQuake earthquake model in 1997 during what would become "the most complex and lengthy insurance rate filing case in California" (Grossi et al., 2005: 109).

An early driver of catastrophe modelling's uptake and the first phase of reciprocal transformations of models, model companies and financial services firms, would become the socio-material appropriation of catastrophe modelling in processes of insurance ratemaking. For insurance firms, insurance ratemaking is fundamental for the subsequent premiums pricing, which operationally also informs firm's capital allocation and enterprise risk management (Grossi et al., 2005: 97). Insurance rates are the prices that are applied to a particular insurance product, such as earthquake insurance, for an individual 'unit of exposure', such as a home, while the insurance premium is what the insured is charged overall. The insurance rate as the basic unit measure "considers the risk characteristics of what is being insured […] For earthquake insurance, the rate is based on the susceptibility to shake damage of the structure and contents, the proximity to known faults, the characteristics of the faults, and the soil conditions under the structure" (Roth, 1997: 4). Ratemaking for any insurance product is, therefore, fundamental for all parties involved and in almost all countries and frameworks regulated to ensure at least two things: first, "to protect insurance consumers from excessive premiums or unfairly discriminatory premiums", and second, "to protect insurance companies (and therefore insurance consumers) from inadequate premiums that may threaten company solvency." (Powers, 2012: 142).

This tension between protecting both consumers and insurance firms (and therefore the market as a whole) through ratemaking is exacerbated by its socio-material implications. The provision of such 'adequate rates', especially in environments of more frequent Anthropocene catastrophe (whether this is earthquake with more catastrophic consequences, wildfire, tropical cyclones or other phenomena), is often essential and sometimes legally required in the real estate market, its development and what is often referred to as 'mitigation'. The very socio-material environment as the active enabler and part of Anthropocene catastrophe is in-flux to quite a degree due to market society's provision of risk management through the active linking of insurance and real estate (c.f. Taylor, 2020). In California at that time, for instance, increased surcharges for more at-risk constructions that were built in years with weaker building codes and incentivised retrofitting towards a different rate, or an insurer's outright refusal to underwrite, were and are ways through which "the insurance industry can promote mitigation" (Roth, 1997: 12). However, the regulatory and market context of a principally voluntary and private insurance market directly affects the socio-material environment here, too. For instance, since earthquake insurance was written in California for the duration of one year, insured frequently would "shop around" for best deals in a market space in which "inspection retrofit requirements vary from company to company, and many policyholders may prefer a company that does not require proof of retrofit or does not otherwise take vulnerability into account in setting rates", while houses themselves are "usually constructed by a builder who just meets the minimum [building] code requirements and makes money selling the houses as quickly as possible" (ibid.: 13). Generally, there is a big difference in the 'mitigation' effects of insurance between residential and commercial lines of business. Commercial lines in individual policies, for a factory for example, amount to a much higher insurance value and premium and therefore inspections, checks and enforcement – ways in which insurance actively manages socio-materiality of catastrophe – is priced into the gross premium, while individual home insurance premiums would not be able to cover this within the range of affordable rates for insureds. Socio-materiality of Anthropocene catastrophe is deeply embedded in market structures and dynamics here.

The socio-material magnitude of the Northridge Earthquake reverberated through the linkage of insurance all the way into the huge and largely residential real estate market of California. The founding of the CEA, therefore, needs to be seen not only as an attempt to reanimate the property insurance market, but, more broadly, as an intervention to save the hugely important and tax-revenue strong residential real estate and mortgage markets. In California since 1985, property insurers were legally required to provide a "statutory 'mandatory offer' of residential earthquake insurance" to clients who could then decide to include it in their general homeowners insurance contract (Marshall, 2018: 75). Property insurers' refusal of writing earthquake insurance contracts after the immense Northridge loss, therefore, meant that homeowner insurance itself would not be written, a form of coverage that "is typically *required* as a condition of obtaining and maintaining a home mortgage" (ibid.). Managing socio-material Anthropocene environment can be tricky, especially if it is in part based on a market-societal risk management regime that deploys insurance as an important vehicle of socio-material mitigation – a system that, now, threatened to dismantle much bigger markets than just the one of insurance itself.

Catapulted into the new 'high-loss regime', property and homeowner insurers "were, frankly, too afraid! They didn't know their risks as it turned out" (I64), and as California's new insurance commissioner at the time put it: "The threat of earthquakes has resulted in a virtual shutdown of the market for new homeowner insurance policies […] the entire insurance industry […] is engaged in a panic run for the border." (Moss, 1999: 339). As a consequence, the CEA was emphasised as an alternative risk pooling mechanism in 1995 and its establishment approved by the State in September 1996 (ibid.).

The rather unique concept of the CEA meant that, unlike many other government catastrophe insurance frameworks, it did not force private insurers to participate but remained voluntary. The participating insurers would commit capital to the CEA and, upholding the earthquake insurance mandatory offer within homeowner insurance, would offer a policy, "the 'mini policy', [which] has a 15 percent deductible, $5,000 in contents coverage, and $1,500 in additional living expenses" (ACI, 1996: 17). The unusually high 15% deductible[44] (i.e., the insured's own contribution in loss claims) and the very narrow damage coverage of those policies convinced the majority of insurers to support this construct since "it would cap their liability" (Moss, 1999: 340). As a so-called "public instrumentality of the State of California" (Marshall, 2018: 91), the CEA would be a "'privately financed, publicly managed corporation' […] with the effect that *earthquake risk becomes the responsibility of the CEA* […] Firms joining the CEA effectively ceded control of *earthquake policy design and pricing to the CEA*" (Zanjani, 2008: 18, 20; my emphasis) and once approved, 75% of insurers active in the state had already committed to the CEA programme. It is here, where the ratemaking becomes chiefly important because it is set for the entire CEA programme including its reinsurance. The CEA was becoming "the near monopoly provider for residential earthquake insurance in California" (CR, 1997). This specific insurance ratemaking for California was significant also in terms of market magnitude since it applied to a state that had a GDP of around $800 billion and ranking right behind the UK and before Canada at the time (LAO, 1995). And it would be done, for the first time, by means of socio-material appropriation of catastrophe modelling, with EQECAT's USQuake catastrophe model at its centre.

a. Staging USQuake

In March 1995, EQECAT, RMS and a few other modelling experts expressed in informational hearings at the California Assembly that catastrophe risk had to be reassessed and that insurers were "unable to accept more risk" (ACI, 1996: 42). In those days, the modellers would have many visits at state insurance and regulators' offices. "I still remember going to LA and having an interview with the Department of Insurance people. And Hemant Shah and Haresh Shah [of RMS] were just walking out of the room and we [EQECAT] were walking into the room." (I64). RMS and EQECAT entered into a competitive bid on an assignment that was advocated by the state's Chief Casualty Actuary. At a federal-level insurance regulator meeting in 1995, "Richard Roth (Calif.) explained that underwriters were inconsistent within a given company before catastrophe modelers came on the scene. Initial solvency concerns led the California Department of Insurance to become interested in catastrophe modeling. […] the Department has also focused on the appropriateness of inclusion of catastrophe modeling results in the ratemaking process." (NAIC, 1995d: 924). One reason for this might have been its deep-rooted earth science and engineering community, which was, as discussed in chapter 4, already quite connected to the insurance

[44] Deductibles here had previously ranged between 5-10% (Grossi et al., 2005: 108).

community and was encouraged even further now: “California also suggested that closer work with the engineering and scientific communities would be desirable.” (NAIC, 1995b: 680). These precursor contacts proved vital for modelling firms: “we [EQECAT] ended up getting selected to being the modeller for the CEA.” (I64). What exactly drove the decision is hard to establish, but EQE’s early engagement producing loss estimates for the State might have helped. Another, and possibly more important, point was that EQECAT allowed limited insight into its USQuake model. It emerged as a rather unique arrangement amidst the increasing issue of vendor modellers protecting their proprietary information.

“You know, in the creation of the CEA, there were concerns that the CEA would not ever use any taxpayer money, so it would have to be self-financed. And so, the models became the basis for figuring out what the risks were, to quantify how much financing it required and how much business they could write and, most importantly, what premium they could charge.” As I64 explains, in this market environment even the public CEA’s insurance rates needed to be constructed like other rates within competitive frameworks as “economic products, the result of supply and demand forces” (Grossi et al., 2005: 97). And catastrophe models were positioned as the facilitators “to calculate the fair price for catastrophe insurance” (Muir-Wood, 2016: 142). Here, the formation of insurance premiums based on rates is determined by a range of factors, such as the degree to which a rate satisfies a shareholders’ projected return expectations, the ability of a company to compensate potential loss by appropriate rates and thereby lowering its “ruin probability”, retaining a high credit rating to avoid credit risk, or the insured’s expectation of potential loss relative to premiums (ibid.). Hinging directly and indirectly on actual insurance rates, the design of the CEA concentrated these factors into one central ratemaking for all insurers involved and for the pool of reinsurers, brokered through E.W. Blanch (Karen Clark’s client and early catastrophe model user).

While insurance rates are almost always regulated (see e.g. Powers, 2012), California mandates the ‘file and use’ principle in which regulators must approve rates before they can be properly implemented into policies. Its rate filing was reviewed in public hearings before an Administrative Law Judge, a framework that enables interested parties, especially consumer groups, to formally intervene. Along with organisations such as the Consumers Union, The Economic Empowerment Foundation, with its director Selwyn Whitehead, had been a regular intervenor in ratemaking hearings and represented consumers at quarterly meetings of the National Association of Insurance Commissioners, or NAIC, the federal-level organisation of state insurance regulators.

Already in late 1994, Whitehead emphasised that “[t]wo actuaries can review identical information and arrive at different conclusions. […] She did not want a situation where an outside entity could dictate rate levels without adequate public review and comment.” (NAIC, 1994b: 856). After RMS, EQECAT and some other experts had been included in informal hearings in early 1995 and, eventually, EQECAT was selected the modelling agent of the yet-to-be formally established CEA, Whitehead had immediately joined the newly set-up NAIC Subgroup on Catastrophe Modelling. Highly critical of the new approach, she advocated a legal framework "that requires the disclosure of catastrophe model assumptions" since she "believes that the use of secretive, undisclosed catastrophe models to support rate filings is not in the public's best interest." (NAIC, 1995c: 836). The assumption was that due to higher risk values outputted by models, future insurance rates and premiums would rise significantly, or in other words: the rate setting process would be appropriated by the new vendor modellers "using unverifiable technology to 'make up' exorbitant rates for catastrophe insurance – rates that are so high that consumers are effectively priced out of the market" (Whitehead, 1997: 379).

"Then the CEA was in existence, and I have spent a considerable amount of my time going to Sacramento [...] to explain to legislators how this earthquake risk modelling really works because these people had no clue", remembers I64. The CEA became operational with provisional 'interim rates' in December 1996 "determined through the use of a catastrophe model" (Grossi et al., 2005: 109), namely EQECAT's USQuake. "[T]here was a big hue and cry in the state about having a model to use to set rates, and this had been the first time that this had been attempted. So, there was a very lengthy rate filing case, in 1997, where we had to go to a public insurance rate making forum where essentially our model was on trial! There were four or five intervenor groups challenging the scientific methods of the model." (I64).

These "evidentiary public hearings on the CEA rates" had been demanded by consumer groups and subsequently granted by the Department of Insurance in January 1997 (CR, 1997). Insurers and the Seismic Safety Commission requested participation in February and hearings on the initial, interim, model-based rates commenced in May and lasted until Fall 1997 (ibid.). An arrangement made between EQECAT and the Department of Insurance to try solve the issue of protecting USQuake's proprietary information while still being part of this public examination had been set up prior to this in anticipation of the need for scrutiny of modelling methodologies. It involved the State Geologist who headed the California Division of Mines and Geology (later renamed California Geological Survey), who had been "working out an agreement with EQE […] to provide him (and only him) with access to receive proprietary information. He then will evaluate the EQE model and report to the department of insurance" (Nordman and Piazza, 1997: 367). This arrangement had been fixed in the 1996 legislation as due diligence procedure since "analytical methods and assumptions of the risk assessment [must] have been approved by the Insurance Commissioner" (ACI, 1996: 19).

Despite this arrangement, "the EQECAT model was public in the sense that it was used by the CEA to model rates, but it was still proprietary in the sense that some of the vulnerability functions and our way of creating all of the probabilistic distributions were proprietary", explains I64. Therefore, in interpreting the 'artefact' USQuake, the parties involved in the hearings (including EQECAT) needed to understand, de- and re-contextualise the ways in which USQuake itself appropriated certain elements within its submodules, primarily scientific and financial practices, knowledge and data; in other words: what it used to assemble modelled catastrophe. On a formal level, it was about how the model was in concurrence with available geophysical data and 'best available science', a legal requirement which was made mandatory for using models in ratemaking in the California Insurance Code 10089.40 a year later, which remains until today.

Because the CEA policy conditions were blanketed with fixed deductibles and a limited cover range, a direct comparison to pre-Northridge rates is not overly telling. However, given the narrowed cover of the new CEA policies, a former Texas insurance commissioner and consumer advocate prominently testified that "homeowners were being charged 30% too much for their quake insurance" (Reich, 1997), agreeing with the general verdict of consumer groups that the CEA's policies and their rates "offer too little for too much" (Howard, 1998b). The CEA's preliminary but already applied USQuake-based rating structure, i.e., the cluster of rates set for risks associated with differentiated types and ages of homes and geographical locations, magnified publicly for the first time the experimentality at the 'fracture of reality' and the struggle over how to fill and stabilise it. Never had a rate filing hearing been so extensive and contested and the unprecedented political dimension of modelling provoked views that "the use of proprietary models shifts the rate adequacy decision making process from the regulator to a third party simulation model vendor. The regulatory process is thus circumvented." (Whitehead, 1997: 379).

At the same time, openly staged for the first time in the CEA hearings, catastrophe modelling was itself subjected to multiple acts of appropriation – like a public exhibition of a piece of art and the ways it finds itself adapted both in different understandings and practices of artistic discourses, such as the Raft's second and socio-materially more magnifying exhibition at the Egyptian Hall. Socio-material appropriation of catastrophe modelling involves, as argued in the previous chapter, the switching of positions of appropriated and appropriator with the consequence of reciprocal transformation. The 'interpretation of the Other's artefact' invokes a practical hermeneutic process of change, regardless of whether the tone of judgement is a rejecting or accepting one. The very fact that all sides involved in the CEA hearings, both critical and favourable voices, appropriated the USQuake model for variations of rates changed both the model, practices and understandings of those involved and the rates, if only because they had to take the model serious as an entity embodying and distributing agency in the socio-materiality of catastrophe risk assessment and, consequently, in Anthropocene environments. Since the points of access of catastrophe modelling's own appropriation of Anthropocene catastrophe are simulation and socio-material mediation, it is, of course, the dimensions of occurrence and severity through which catastrophe is dis- and reassembled and which, on a micro level, is the locus of acts of appropriation during the ratemaking hearings.

The basic principle to calculate insurance rates involves three components: the so-called 'average annual loss' (AAL), 'risk load' and 'expense load'. Expense load represents usually stable and easily identifiable administrative factors such as processing costs, taxes, or commissions, whereas "[c]atastrophe models are essential to calculate AAL and risk load" (AAA, 2018: 12). (1) AAL is the expected annual loss from a potential stochastic disaster event averaged over a usually long range of years of simulated history. It is calculated as the sum of event iterations for the probability p of the event's occurrence in one year and the associated loss L for this event (ibid.). (2) The risk load represents the level to which an insurer needs to set aside additional capital to account for loss beyond the average annual loss, i.e., to provide for catastrophic loss and avoid bankruptcy. Since this fundamentally depends on the components of the AAL and the volatility around it – "the higher the volatility, the higher the likelihood of insolvency, therefore the higher the risk load" (ibid.: 13) – the risk load is often calculated as the standard deviation, σ, of the modelled loss around the AAL, i.e., the averaged variation around the probabilistic loss values. These are catastrophe's dimensions of occurrence and severity brought together in the form of probabilistic likelihood of their simulated catastrophic interaction in a given year, AAL, and its experimentality of in-flux simulation conditions represented by the risk load.

b. Occurrence

A common assumption regarding earthquakes is that the probability of their occurrence is random and independent of their faults' last rupture, what in modelling is referred to as 'time-independent' probability and which is often computationally described by a Poisson distribution (Wyss, 2014: 259; McGuire, 2008; Cornell, 1968). Both the US Geological Survey (USGS) and the California Division of Mines and Geology (CDMG) calculated in their surveys and frequency models at the time on a time-independent basis, even though they had already contemplated (but not officially applied) an emerging, new approach (WGCEP, 1988). This alternative approach, only conceptually mentioned but not broadly applied by Cornell himself (Cornell, 1968), is to assume, in accordance with the elastic rebound theory, that the stress caused by friction between rocks builds up over a certain period of time until it ruptures and energy is released, which materialises in ground motion (Wyss, 2014). The probability of earthquake occurrence here is conditional on faults' individually fixed time intervals – simply put: the longer no rupture, the higher the likelihood of occurrence – and is, therefore, referred to as 'time-dependent' probability, computed often by gamma, Brownian, or lognormal distributions (e.g. Matthews et al., 2002). Even though those two approaches do not necessarily exclude one another in practice, it remains until today an ongoing scientific debate around preferences in using one over the other, while in practice they tend to be blended by now (e.g. Griffin et al., 2017). Only in the late 2000s, the USGS started considering and analysing (c.f. Petersen et al., 2007) and then actually modelling on time-dependency in addition to time-independence (Petersen et al., 2008).

Because modellers cater to the (re)insurance industry, temporality in modelling is important and provides the context and environment for the goal setting of simulation, a particular way of realising from 'multirealism': since insurance contracts, including the CEA's, are often written for the duration of one year, time-dependency becomes an important perspective and corresponds to what modellers in a more general way often also call the 'short-term view'. "USQuake has used time-dependent recurrence frequencies *since 1997* ", describes a more recent model fact sheet by EQECAT, "[i]n regions such as California where earthquakes are common, time dependence, and thus the model, represents not only the definitive scientific consensus, but also portrays risk within the *foreseeable future*, *not just the theoretical 'long-term'*." (CoreLogic, 2015; my emphasis).

USQuake produced earthquake occurrence frequencies for the CEA rate structure more than twice the historical record (Grossi et al., 2005), which would have led to higher insurance rates. Unpacking an argument already made over a year before the hearings (NAIC, 1995d: 921), on the basis of the actual 150-year (i.e. non-simulated) history of Californian occurrence data, the Economic Empowerment Foundation claimed that there had not been any changes in seismicity in California and, therefore, rate increases of large proportions would not be justified. "[C]ontrary to what earthquake modelers say, earthquakes are not going to hit all places at the same time." (NAIC, 1997: 1832).

Because occurrence has not only a temporal but also a spatial dimension, geographical location becomes very meaningful in modelling loss especially if probabilities are conditioned by different fault's rupture time intervals. Time-dependent modelling, in this case, appropriated geographical differences that already differentiated, and thereby co-produced, the concrete socio-material environment of Anthropocene catastrophe. Time-dependent simulation performs a split between actual history and artificial history, since it de-contextualises the individual 'real' history of a fault, by identifying its empirical rupture interval along with geological features of its physical dynamics and re-contextualises the empirical interval and a modelled version of its physical dynamics in the simulated artificial history of occurrence probabilities. One part of what cascades through the AAL to the risk load calculation is the standard deviation, σ, of the time intervals between occurrences of individual historical fault ruptures, where a smaller σ (less variation) leads the model to weigh time-dependent probabilities higher, while a higher σ (more variation) puts more weight on time-independent probabilities – "differences in σ would affect both recurrence rates and loss costs" (Grossi et al., 2005: 111). USQuake derived from the occurrence dimension "a breakdown by ZIP code of more than 2.000 different rating zones" (Slanker et al., 1999: 150) across California. Throughout these zones, rates varied significantly and some consumer groups criticised that the derived premiums would be "about twice as much for only about half the coverage available prior the CEA" (Hunter, 2001: 64).

In light of this politicly driven affordability issue, and contrary to the risk-based-rates principle of 'equivalent rates for equivalent risks', the rating zones in the model were consolidated into 19 adjacent territories to even out granular price spikes and for two remaining very high-risk territories "the CEA capped rates in those areas and raised them elsewhere" (Slanker et al., 1999: 150). This political appropriation of the model's mapped probabilities was met by criticism whose line of argument showed already consequences of the transformation of the initial appropriation of USQuake: the administrative law judge ruled in early 1998 after the hearings had ended that "premiums [vary] unfairly for different areas that have similar seismic risk" (Howard, 1998b), emphasising that "the methods for determining rates for different territories [were] unfairly discriminatory" and that the "CEA should [instead] consider soil types in determining rates" because of the "impossibility of precisely predicting earthquake frequency, severity or loss" (Johnson, 1998). At the same time though, the judge did rule favourably on the temporal dimension, the higher frequencies, arguing that that the benchmark frequencies produced by the USGS and the CDMG, were 'state of the art' because they had previously published reports (e.g. WGCEP, 1988) in which they at least discussed and experimented with time-dependent frequencies (Grossi et al., 2005).

c. Severity

"People criticised us left and right! The testimony involved not just the ground motion information […] we also had testimony on the vulnerability functions", remembers I64. To model loss for an averaged annual event probability, the event severity needs to be simulated on the basis of modellers' grammars of interaction, the damage functions in the vulnerability modules of a model. What interacts here are, primarily, building features and the movement of surface on which buildings are built. Just as much as RMS's IRAS model, EQECAT's EQEHAZARD had appropriated the 1985 ATC-13 report for building classifications on aspects such as age, material, and construction types and their behaviour during horizontal acceleration – "ATC-13 […] is the basic analysis used by the insurance industry" (Roth, 1997: 12). USQuake appropriated it for the building classifications but had run it against about 50,000 Northridge Earthquake insurance claims (Grossi et al., 2005), finance's socio-material mediating of Anthropocene catastrophe's environment. Even though claims and loss data from insurance firms came to be considered the better source of information on the socio-material objects, intervenors criticised that USQuake founded its damage functions only on the extreme event of Northridge (ibid.). Re-contextualising the ATC-13 analysis within the actualised catastrophe of Northridge, 'sensed' by financial services' measure of claims, emerged here as a socio-material appropriation of ratemaking with potentially higher rates.

Against the backdrop of these and several other aspects that determined the proposed rate structure, such as underinsurance factors, demand surge estimations, certain CEA-specific policy sublimits and retrofit discount rates (ibid.), the hearing's board eventually voted for a decrease of rates, to a large part "recognizing that a quake risk model prepared for the agency was faulty" (Reich, 1997). It argued for rate decreases in light of "EQECAT […] indicating it has revised the method used to predict earthquakes" (CR, 1997) – USQuake had been politically appropriated on a technical level which provoked calibration changes. In November 1997, the Insurance Commissioner, who has the authority to derive concrete legal decisions from such hearings, approved amending the CEA's "rate application to reduce the contested rates by approximately 11,5%" (KPMG, 1998: 10).

At the same time, ground motion modelling and data, provided by the USGS, had been widely accepted and EQECAT's long relationship with the institution within the Californian earthquake science and services community had proved to be vital. USQuake was "pretty much in concurrence with the USGS. We had to do some additional mapping to get their hazard model to build into our model because we had a simulation model, so there was a lot of work. But [an EQECAT employee] knew Marc […] at the CDMG at the time. They were very good friends professionally, so we really had great access into exactly how the USGS did it." I64 describes precisely the act of socio-material appropriation at play here. The interpretation of the Other's artefact, in this case the USGS's ground motion model, leads to a hermeneutic treatment that changes one's own practice and artefact, here USQuake, while the Other's changes too in this re-contextualisation. Appropriation is not simply a technical tweaking of the device, i.e., an exclusively 'material' dimension, but, of course, a social one too: "that was very important because the legislation required us to use the latest available scientific information and on the ground motion-side, the hazard side, that was the USGS" (I64). Just as much as the material, the social dimension of appropriation, too, is subject to the switching between positions of appropriator and appropriated, which further drives transformation. The administrative law judge in her ruling in early 1998 questioned "the accuracy of computer models used to estimate average annual losses" (Sanchez, 1998) and "ordered the Authority to recalculate the rates" (Hunter, 2001: 64). The main reason behind this ruling was that the judge found that the calculations were "based on a 24-year-old U.S. Geological Survey assessment of the impact of ground-shaking on buildings" (Howard, 1998a), which was a reference to assessments underlying the very central ATC-13 study and which she considered outdated. Disassembling and reassembling catastrophe and distributing socio-material agency is not only a technical and scientific task but just as much a political and legal one.

Against this backdrop, the judge recommended a rejection of the CEA's already amended rate application, while the Insurance Commissioner's office noted that "experts are much better suited than one [administrative law judge] to make the scientific judgements required in the case" (Howard, 1998b).

The Commissioner opened yet another round of testimony (KPMG, 1998: 10). The CEA's CEO at the time reiterated that the USGS study remained to be state-of-the-art science and that EQECAT and the CEA had "used formulas that were accepted by scientists" (Johnson, 1998). He added: "I'm an insurance company. I'm not a seismic agency. My job is that when I take policyholders' money, I am supposed to put it in a reserve to pay claims. It's not to become the leading scientific voice in California" (Howard, 1998a). Producing catastrophe for insurance is, in other words, not about producing a singular truth but about situated risk management. After a much shorter round of testimonies, the Insurance Commissioner rejected the judges' decision and approved the formerly amended rates in December 1998 (KPMG, 2000: 12). "At the end of the day, the model was accepted for use in filing rates. And so, from a commercial standpoint for EQECAT, that was a big feather in our cap" (I64). EQECAT, which later became CoreLogic, is until today the primary modelling agent of the CEA (Marshall, 2018).

IV. Attempts and Forms of Centralised Catastrophe Production

Although the CEA remains a rather unique construct until today, its first few years were nevertheless a pivotal moment for the socio-material appropriation in catastrophe modelling: the reciprocal transformation along the appropriated insurance practice of ratemaking by modellers as appropriators via a catastrophe model as the appropriation-object. However, as one of the first more formal attempts of model-based insurance processes, this initially very centralised production of modelled catastrophe in the CEA ratemaking was still driven by the *consolidating* effect of the Northridge Earthquake amidst the initial realisation of the new high loss regime which would form, in this case, the new catastrophic loop of Californian earthquake disaster (and which lasts until today as there has not been a major actualised earthquake catastrophe since). In contrast to the consolidating effect of actualised catastrophe, the *multiplicity* of catastrophe and the fracturing of catastrophe's reality emerged as a result of political and economic market dynamics. The advent of the high loss regime would provoke the management of catastrophe in financial services not in the mode of consolidation but in the mode of multiplicity of catastrophe.

"The one-two punch of Andrew and Northridge forced insurers to reassess their exposure to catastrophes *nationwide* [...]", not only in the perceived epicentres of the new loss regime (Moss, 1999: 338). A scientific consultant at the large insurer Chubb in the mid-1990s remarked: "If in fact the past is not a good guide to what will happen in the future, the entire underwriting basis of what insurers are doing is flawed. That's a scary thought when you think of the billions of dollars that are at stake." (ibid.). This general sentiment provoked in the US an ultimately unsuccessful plan to form an entity like the CEA but for storm, earthquake, volcanic and tsunami risk on a nationwide level, the Natural Disaster Insurance Corporation, or NDIC.

a. Unsuccessful Scaling of Centralised Catastrophe Production: the Case of the NDIC

The legislation act proposal H.R. 1856 (The Natural Disaster Protection Partnership Act) recommended in 1995 to Congress the NDIC as a nation-wide "private not-for-profit corporation" (US Congress, 1995: 12). As in the CEA construct, participating insurance firms were supposed to offer the "NDIC's hurricane and earthquake coverage as an addition to a homeowners insurance policy", they would process and operate the NDIC's policies including premiums collection and claims management (US Congress, 1995: 13). Insurance firms not participating in the NDIC would have been obliged to offer their own earthquake and hurricane policies. Similar to the CEA, the NDIC was supposed to assume a considerable portion of catastrophic loss risk: participating insurers would have had to cover at least 50% of hurricane and at least 10% of earthquake claims in case of an event, while the rest would be taken on by the NDIC (ibid.). The NDIC concept was initiated by the Natural Disaster Coalition, an insurance industry group, interested in penetrating catastrophe risk markets but ideally with limited direct exposure of their own books. The idea was that the NDIC "would bear all the associated risk. Much like the CEA, the NDIC would effectively cap the disaster liability of private insurers." (Moss, 1999: 341). The excess loss mechanism, in case a large catastrophic event incurred a deficit in the NDIC's own finances, was meant to allow debt instruments, such as bonds or bank loans. More importantly, however, it was granted to borrow directly from the US Treasury (US Congress, 1995: 13) to back up catastrophe loss between private reinsurance capacity limits and $25 billion, after which a separate federal reinsurance vehicle would have kicked in for loss between $25 and $50 billion (NAIC, 1996a: 754).

In a similar constellation as the CEA, the insurance rate structure and premiums calculation would have been based on catastrophe modelling, prompting that the proposal's initial "analysis used the most sophisticated computer models available to assess the risks posed by earthquakes and hurricanes. […] Any future NDIC Board of Directors will need to hire consulting experts in the field of disaster risk assessment." (US Congress, 1995: 11, 14). Although the new modellers initially started out from their respective particular peril type, they soon branched out towards building models for others, too. RMS, for instance, in the 1990s was in the process of converting their initial IRAS model into what is until today named their RiskLink model suite, "IRAS evolved into RiskLink and then RiskLink evolved into different flavours of RiskLink" (Hemant Shah). Like EQECAT for the CEA, RMS was about to become the NDIC's modeller: "NDIC's actuaries sought assistance of several disaster risk consulting firms. After considering the merits of each firm contacted, a consulting agreement was made with Risk Management Solutions" (US Congress, 1995: 14). The proposal put to Congress here explicates the central role the RMS RiskLink model would assume in setting expected loss, average annual loss (AAL), and premiums for both insurance and reinsurance programmes. Federally centralised catastrophe production for US-wide catastrophe insurance would have been appropriated by RMS as the model consultant of choice. In the process of the rate structure, RMS was also supplied with data from the Insurance Services Office

(ISO) and the three largest insurance firms in the market at the time (Allstate, State Farm and Farmers Group of Insurance Companies), from which they created a database which "accounted for 80 percent of all insured residential structures in the Unites States [and] 30 percent of all insured commercial structures."(ibid.). As already mentioned, these data as proprietary forms of socio-materially mediated Anthropocene environment are rarely shared. Catastrophe models are calibrated against these data and the more data, the more contextual the calibration and the 'better' the proprietary grammars of interaction of catastrophe, which is an advantage for the model in the analytics market itself. Even this one-off data access meant a big advantage for RMS amidst a situation in which "we'd all compete vigorously" (Hemant Shah).

The NDIC, however, never came into existence due to several reasons. Although having had in principle also many non-industry proponents (Brown, 2017), one issue was the "NDIC's federal charter and obvious public purpose" despite its private legal format (Moss, 1999: 343). In case of a large catastrophic event, it was expected that the government would likely feel obligated to cover for the Corporation's liabilities: "[t]ens of billions of dollars of insurance company liabilities could be shifted onto the federal government", assessed a Congressional Budget Office analysis (ibid.). Connected to this was the problem of ratemaking itself. Amidst the tension between mandated affordability and actuarial soundness of rates, which for the case of a federal-level entity such as the NDIC was considered "incompatible", the capacity of model-based ratemaking was called into question, "given the enormous uncertainties regarding disaster forecasting" (ibid.), much like the Federal Law Judge's verdict in the CEA case. In case of becoming financially impaired, it "could require the federal government to assume responsibility for the NDIC's actions without the ability to regulate its rates and underwriting standards" since due to its private legal status "[u]nlike Fannie Mae and other government-sponsored enterprises [...] the NDIC would be completely unregulated." (ibid.). Against the backdrop of these and other concerns, the proposal was withdrawn in 1996.

b. Excursus: Flood Risk, Insurance and the Case of the NFIP

Focused on in the following chapter, the development of catastrophe production in the financial realm would emerge in multiplicity, produced not in a centralised form like the NDIC. However, even though the NDIC was an unsuccessful attempt of broadscale, federal-level, quasi-public catastrophe insurance, there are a number of different variations of such constructs in operation in different countries (c.f. CCS, 2008; Crichton, 2008; OECD, 2016). For the case of the US, the largest catastrophe risk market and cradle of commercial catastrophe modelling, it is the National Flood Insurance Program, or NFIP, which needs to be mentioned here. This 'excursus' serves the analysis and line of argument in that it explains, in part, why the socio-materiality of floods, in the US case via the NFIP, has emerged in a 'centralised' catastrophe production rather than in a 'decentralised' way, and, therefore, has only very recently featured as an explicit focus of catastrophe modellers. It exemplifies the political dimension of socio-material catastrophe while it remains a kind of exception amidst the rest of Anthropocene catastrophe types. The political and societal struggles and contestations in connection with the NFIP in the US especially over the course of the last decade (c.f. Elliott, 2017) are enshrined by some calls for decentralised and more market-shaped management of flood risks, which developed along the emergence of catastrophe modelling from the 1990s on.

Flooding is an outlier among catastrophe phenomena. It sits squarely to most other peril types as it is often one of many consequences caused by them, although almost always the most devastating one. The ontology of floods, therefore, has a peculiar echo in the catastrophe risk space, since flooding as a complex of socio-material interaction is epistemically divided into several types along its *sources.* As the 'overflowing of the normal confines of a body of water', floods can materialise, for instance, as flash floods, riverine floods, coastal floods or storm surges, groundwater floods, dam burst, debris flows, or floods as a consequence of ground shaking such as tsunamis (OECD, 2016: 18). In this epistemic framework, flooding is often represented and modelled in catastrophe models as a so-called 'secondary' peril.

The socio-material ontology of floods intensifies and is intensified by both other catastrophe phenomena causing them and the frequent entanglement and simultaneity of different flood types in individual events. The academic hurricane and climate scientist, O89, in chapter 3 referred to this when he sketched the image of a potential storm hitting Boston, which would likely combine a storm surge, a possible riverine flooding and a flash flood submerging parts of Back Bay Boston and the MIT campus. Superstorm Sandy in 2012 infamously caused various types of flooding from debris flows in Haiti all the way to the storm surges and coastal floods along the US East Coast, further amplified by an intense full moon-induced tide (Gibbens, 2019). Another recent and actualised example is Hurricane Harvey (2017), which in the US caused not only coastal flooding but, much more dramatically, forms of groundwater and flash flooding in the Houston metro area due to the incredible amounts of precipitation that this storm system brought with it. At an industry conference in 2018, a former vendor modeller employee and then Head of Cat Risk Management at one of the largest global insurers told us in the audience in shocked awe that "the volume of water dropped was circa 1.3 times of that of Lake Geneva – it was extraordinary and the *earth crust* was pushed down by it by around 2 centimetres in this area!"

The panellist continued and explained that although the NFIP and Federal Emergency Management Agency (FEMA) flood maps had been updated in 2017, there were areas where flooding had not been expected, for instance, because overwhelmed drainage systems had not been considered. A lesson to be learned, he remarked, would be to figure out "how these man-made artefacts like drainage systems, you know, how do they respond to such an extraordinary amount of rainfall load? […]

As a consequence, I think, we just can't model hurricane risk and loss in the future without incorporating flood losses much more directly." As briefly mentioned, some of these socio-material interactions that are part of the complex ontology of floods had been integrated as 'secondary' perils in the proprietary grammars of catastrophe's interaction within hazard submodules of catastrophe models.

Although flooding has always produced considerable portions of the overall loss amounts of 'primary' perils (especially tropical cyclones but also earthquakes), it has only rather recently surfaced as a bigger and more fine-grained focus in commercial modelling. On the one hand, this is because of the loss-driving ontology of floods amidst the intensifying effects of continuously increasing urbanisation and stronger materialisations of climate change effects – Swiss Re recently framed it as 'not so secondary' anymore (Swiss Re, 2019). On the other hand, however, one important reason why it has largely remained a secondary focus in catastrophe modelling, is due to the US's societal, economic and political contexts in which flood risk has been situated over the course of the second half of the 20th century. Since the US has long been and still remains the largest catastrophe risk market and primary reference point in the development of catastrophe modelling, the conference panellist's note on the NFIP and FEMA flood maps is a paradigmatic reference to the peculiarity of flood risk in modelling and insurance amidst catastrophe risk in general.

The US's NFIP is itself a creature of socio-material breaking points and actualised catastrophe. Reflecting flood catastrophe's ontological position amidst other catastrophe phenomena, the NFIP was a reaction to two very different large flood events in the mid-1960s (NAIC & CIPR, 2017). One was caused by the Great Alaska Earthquake or Good Friday Earthquake of 1964, which remains the second-largest earthquake ever recorded, a 'megathrust earthquake' of 9.2 M_W (Muir-Wood, 2016). The second flood catastrophe was caused by Hurricane Betsy's storm surge in 1965, an SSHWS Category 4-equivalent cyclone (Knowles and Kunreuther, 2014). Since the Mississippi floods of 1927, the private flood insurance market had failed amidst a number of market dynamics (for instance, adverse selection, i.e., insurers underwrite only low risk polices while insureds only purchase policies if they are susceptible to high flood risk; or too high risk-based premiums due to the relatively high frequency of flooding in general) (NAIC & CIPR, 2017). The NFIP was founded in 1968 prior to a wave of different disaster-related governmental policies and institutions, which during the 1970s created among others the Environmental Protection Agency (1970) and FEMA (1979) (Knowles and Kunreuther, 2014: 342), after which the NFIP would eventually become part of FEMA's managerial responsibilities.

Based on federal guides and reports on flood damage reduction, the '100-year flood', i.e., a flood size with an occurrence rate of 1% in a given year, became the reference point for assessing flood risk by federal agencies (ibid.: 334). For the NFIP from these early analyses, flood zones across the US were created and represented on flood insurance rate maps, whereas the '100-year floodplain' designates Special Flood Hazard Areas (SFHAs) in which the take-up of a flood policy became quasi-mandatory with the conditionalities of mortgage regulations. Since the 1973 Flood Protection Act, properties which are financed through loans or mortgages by federally regulated lenders must be covered by flood insurance if they are located in a SFHA (NAIC & CIPR, 2017: 24). While premiums are calculated based on these flood maps, policies for properties inside SFHAs additionally incorporate also some structural features of building types, especially a damage function of the so-called "base floor elevation", which measures a building type's first floor height in relation to an averaged 100-year flood water height estimate (Kousky and Shabman, 2014: 4).

However, even though relying on financial incentives and insurance policies, the approach behind the NFIP to socio-materially manage environments of Anthropocene catastrophe is conceptually and practically distinct from private, market-based insurance approaches. Although the policies are priced via flood zones, "property is located using a model of potential flood depths coupled with damage curves at a *national rather than local level*. […] flood losses are *averaged nationally* instead of tailored to each specific location" (NAIC & CIPR, 2017: 32f; my emphasis). The level of de-contextualisation and abstraction of socio-material environments and catastrophe's grammar of interactions is, therefore, very high, even though the NFIP is explicitly underwriting insurance and not reinsurance where concrete socio-material context matters. The NFIP used for their ratemaking at least until the late 2010s the averaged 100-year floodplain and base-floor elevation damage function instead of a "structure-specific flood frequency determination" and a coupled average annual loss (AAL) calculation, let alone a risk load (AAL-exceeding loss) component (ibid.: 35). The NFIP does not include catastrophic, i.e., extraordinary large, annual loss in its pricing and is, instead, authorised to borrow from the US Treasury in case of capacity-exceeding loss claims (a form of government-based reinsurance) (NAIC & CIPR, 2017: 25). It is also legally rather limited in its overall policy portfolio composition and management (Kousky and Shabman, 2014: 4). In this way, the NFIP produces catastrophe in a different way than commercial catastrophe modelling, since, among many other reasons, the goal setting and appropriated risk management practices are very different ones here.

Although technically a voluntary scheme, the NFIP binds communities, via mechanisms such as mortgage-mandated flood insurance, to adopt flood prevention and mitigation efforts, while SFHA-located communities remain only eligible for federal disaster assistance if they participate in the NFIP (NAIC & CIPR, 2017: 24). Designating SFHAs is a way to distribute agency across environments of Anthropocene catastrophe, and in this case policy-driven rather than market-driven. The '100-year floodplain' is a device that ingests a rather complex socio-material situation which actively includes adherence to 'floodplain management' by communities, requiring regulation to recognise "that the NFIP must support other goals beyond providing insurance." (Kousky and Shabman, 2014: 2f). This was intensified in 1990, when the Community Rating System (CRS) was implemented as a ranking-based programme in which a higher rank due to implemented flood risk management measures of a community leads to NFIP insurance rate discounts in high-risk SFHAs of up to 45% (NAIC & CIPR, 2017: 31). This means that the pricing structure and practice of the NFIP was mainly driven by affordability and mitigation goals rather than by solvency- and risk-based pricing: "In essence, NFIP rate setting does not mimic the rate-setting process that would be used by a private insurance company because the NFIP does not face the same costs, management requirements, or objectives as a private insurer." (Kousky and Shabman, 2014: 2).

Among the two US-based cases of 'centralised' production of catastrophe discussed here, the NFIP is a very different construct than the CEA because of both social and material reasons. Societally born out of different political eras, the CEA was mandated and constructed explicitly to be a tax-independent entity without access to public funds for reinsurance. Even though both NFIP and CEA are not allowed to produce overall profit, their mandates inherently differ in that the NFIP does not imitate a typical insurer because it is primarily aimed at *affordability* of coverage while the CEA is meant to generate a market mechanism that primarily enables the *availability* of coverage (NAIC & CIPR, 2017: 66). This has fundamental structural consequences. With its mandate and direct access to the US Treasury, the "NFIP was not required to charge actuarial sound rates for the risks exposed" (ibid.: 64). And although this was set to change after insolvency-provoking Hurricane Katrina and the subsequent Biggerts-Waters Flood Insurance Reform Act of 2012 (followed by the devastating Superstorm Sandy loss and another amendment to the Reform Act), its transformation towards risk-based pricing and 'actuarially acceptable rates' is still ongoing and remains socially and politically highly contested (Elliott, 2017).

In contrast, as shown in its ratemaking above, the CEA acts as a more 'traditional' insurer whose "rates are estimated by actuaries using traditional techniques along with modern scientific modelling", while regulators remark not only for earthquake but also for flood risk that "there are no alternatives to the CAT models" although their outputs generally hinge on "the circumstances of the portfolio of risks being modeled" (NAIC & CIPR, 2017: 64, 56). Having control, to some degree, over an overall portfolio, which the NFIP lacks and the CEA has, in turn enables and necessitates to "estimate severe loss" via modelling in order to forward excess loss risk to reinsurance markets instead of invoking federal debt (ibid.: 66).

Since the ontology of floods sits squarely to, and itself emerges out of, a number of other catastrophe types, it often manifests different flood types in simultaneity. Flood, therefore, is spread out spatially across all its potential origins' geographies and temporally occurs with higher frequency, particularly in contrast to geophysical phenomena such as earthquakes, which are (at least on land) fundamentally local and very infrequent. Regarding meteorological phenomena, especially with climate change-induced storm and precipitation patterns at the very latest since the 1990s, and in line with the emergence of the financial high-loss regime of Anthropocene catastrophe, the largest loss events for the NFIP since its inception in the late 1960s have been caused by tropical storms and cyclones occurring since the mid-1990s (NAIC & CIPR, 2017). This is especially consequential for the severity dimension of catastrophe, since storm surge induced flood damage, socio-materially mediated by insurance claims, has produced up to 20% higher loss compared to other flood types (Kousky and Michel-Kerjan, 2017). These differing socio-material ontologies of Anthropocene catastrophe, of course, feed back into catastrophe risk and the socio-politically induced structural dimension of its management. Apart from the differences in goal setting and structure, even an NAIC report, which seems to be in favour of risk-based ratemaking, admits that in contrast to the NFIP, "the financial strength of the CEA was a product of geological fortune and not the outcome of a strong insurance business model." (NAIC & CIPR, 2017: 65).

Overall, this socio-material embeddedness of flood risk is a major reason why the production of catastrophe for its risk management has developed in a centralised and primarily non-commercial way. In the US and the rest of the world, occurrence and severity of floods have heavily increased since the early 1990s (OECD, 2016: 19). Yet, there remains until today only "limited involvement of private insurers in the primary market" of flood coverage in the US (NAIC & CIPR, 2017: 47). And where it is involved, it arbitrages on the margin of NFIP-produced catastrophe as it is often "characterized by selective picking of specific properties in the NFIP Special Flood Hazard Areas (SFHA) carrying coverage which may be considered overpriced [by the NFIP]." (ibid.). Commercial catastrophe models, by treating it mainly as a secondary peril, have incorporated flood to some degree in their submodules, since "even though flood was excluded from nearly all property policies, insurers were still occasionally required to pay flood losses when the primary cause of loss was indistinguishable between wind or flood" (ibid.: 56). This is partly also in line with public scientific practice, where flood's ontological appearance would result "from a tropical cyclone [where it] will often be classified as part of the meteorological event rather as a separate hydrological event and therefore not recorded as a flood in […] data sets." (OECD, 2016: 20). However, catastrophe models become sometimes the qualifiers of flood damages' ontology, which is also politically tricky, as O89 notes: "Another ugly thing about this is that they [modellers] get into a wrangle between the government and the private insurance company. Was it wind [privately insured], is it our baby? Or is it the water [NFIP insured], your baby?"

The combination of its ontological diversity and embeddedness in other peril types and, in the case of the US, the existence of the NFIP resulted effectively in a nearly exclusively public flood mitigation system for flood risk and, therefore, a lack of uptake in insurance, commercial modelling and catastrophe production beyond the NFIP's and FEMA's flood maps. However, precisely because of flood's ubiquitous catastrophic socio-materiality, it is an empirical case of particular social and political importance. Flood risk and the NFIP are, therefore, highly relevant cases for the analysis and explication of the socio-materiality of catastrophe especially amidst climate crisis, which has been formidably done recently by Rebecca Elliott (2017, 2018, 2019, 2021). From the perspective of this thesis's analysis, it integrates neatly in the overall perspective of Anthropocene catastrophe and, in Elliott's case, especially the explicit political and social discourse, practices and struggles around Anthropocene flood catastrophe and a 'sociology of loss'.

Chapter 7. The Era of Catastrophe Modelling Phase 1: Multiplying Catastrophe

The National Disaster Insurance Corporation (NDIC) might have effectively become a combination of CEA and NFIP for federal hurricane and earthquake insurance (e.g. Davidson, 1996). A multi-catastrophe-type NFIP that would, however, mandate availability rather than affordability of cover and base its rates and premiums on risk-based pricing primarily by means of RMS's proprietary catastrophe models (like the CEA via EQECAT), backed-up by federal debt from the US Treasury (as the NFIP), in addition to bonds, loans and private market reinsurance (like the CEA). Similar to the wave of disaster-related legislation and vehicles such as FEMA and the NFIP in the 1960s and 1970s after the Alaska Earthquake and Hurricane Betsy, the 1990s saw a host of disaster-related policy and regularity activity after Andrew and Northridge. However, while the majority took place on the state-level and produced a number of institutions, the federal-level activities did not lead to a kind of nationwide multi-peril NFIP-CEA hybrid in form of the NDIC. Instead of a centralised production of catastrophe for risk management, a diverse landscape of state-level regulation was created on whose grounds a market-shaped multiplicity of catastrophe production emerged.

I. Market-Shaped Catastrophe Production: From Consulting to Vending

Early users of catastrophe models were reinsurers and specialist rating agencies such as A.M. Best. A structural reason was that reinsurance is often out of scope of national or state insurance regulation due to its international level of activity and disconnect to end-consumers. Catastrophe modelling was, therefore, not subject to regulatory approval in "pricing unregulated reinsurance products" where it was considered reinsurers' "fiduciary responsibility to use the best information available, regardless of its acceptability to regulators in the rate filings of primary insurers" (Musulin, 1997: 351f). For primary insurers, however, regulation is a major factor. Since models had been partly used for solvency estimation and rating by rating agencies in the mid-1990s, it was argued that, consequently, "their use in this setting may make it difficult to deny their use in [primary insurance] ratemaking" (ibid.: 355). In California, the consolidating pressure of the Northridge Earthquake and the reanimation of the homeowner insurance, real estate and mortgage markets was baked into the CEA via its centralised, model-based ratemaking. In most other cases, the reactions to the high loss regime were more compartmentalised. In an even stronger market-based orientation than in the CEA's case, it was not the ratemaking processes of insurers that would undergo a process of public scrutiny, but the focus would instead become that "[r]egulators must determine if the *models* presented are statistically valid and produce credible results." (NAIC, 1995c: 835; my emphasis).

While a number of states developed forms of dealing with the new high loss regime and catastrophe modellers as the new appropriators of insurance risk assessment, Florida's reaction in the aftermath of Hurricane Andrew from the second half of the 1990s onwards might have been the most influential one with its creation of the Florida Commission on Hurricane Loss Projection Methodology, or FCHLPM. Similar to California and earthquake risk but indeed with a number of actualised hurricane-related events since the early 1990s, Florida serves the catastrophe landscape as a main reference point until today: "Other coastal states face similar challenges, but because no other state has the exposure to hurricanes that Florida possesses, the state has become a laboratory, of sorts, for what works – and what does not." (McChristian, 2012: 2). Although exclusively focused on hurricane models, the FCHLPM would become paradigmatic for the overall transformation of modelling firms as 'passive' consultants, equipped with risk assessment expertise, to 'active' vendors of distributed software devices, the appropriation-objects that became catastrophe models.

Amidst a situation of catastrophe modellers' emerging appropriation of (re)insurance practices and the persistent issue of 'black-boxed' models shielding proprietary grammars of catastrophe interaction, calls for regulatory treatment of model-based insurance activities became louder. For instance, states started to amend their reporting procedures for private insurance firms, mainly in form of so-called General Interrogatories, which are disclosure questionnaires in which the use of models was described (NAIC, 1994b: 775). Yet, Florida had started developing ideas around actively screening catastrophe models directly (NAIC, 1994b: 699). One idea pushed by both consumer groups and a number of state insurance regulators was the development of a "regulatory catastrophe model as a basis to compare with proprietary models" (NAIC, 1995a: 634). Its potential effectiveness, however, was called into question due to regulators' own lack of expertise on the matter and trade secret issues around the proprietary nature of the models. Nonetheless, a decade later, Florida indeed became the first state with its own public catastrophe model for its residual insurer. Structurally much more important and prior to this, however, Florida instead developed a certification process directly for proprietary models: "Florida had established a task force [on a regulatory model]. [...] This effort was modified to simply assess existing proprietary models" (NAIC, 1995a: 641).

a. Institutionalised Appropriation of Catastrophe Models: the Florida Commission

The consolidating pull of Hurricane Andrew's aftermath resulted in Florida in the founding of two different state-sponsored catastrophe (re)insurance entities and the transformation of an already existing one. The Florida Windstorm Underwriting Association (FWUA) had already been established in 1970 to cover wind insurance for beach-front property in the Florida Keys, mandating private insurers to underwrite in this otherwise underserved area (OPPAGA, 2006). However, it expanded its underwriting of policies substantially within just five years after Andrew by almost 700% (McChristian, 2012; Musulin and Rollins, 2001). As a direct reaction to Andrew, the Florida Residential Property and Casualty Joint Underwriting Association (FRPCJUA) was formed in 1992 as an "insurer of last resort" (OPPAGA, 2006). Unlike FWUA (and also the CEA and the NFIP), it would underwrite residential property polices directly as a public insurer, holding by 1996 almost one million residential policies, more than 17% in the state (ibid.). At the same time, amidst a collapsing private storm and homeowner insurance market, insurers were allowed to reduce their number of Florida policies by only up to 5% annually until 1997 (McChristian, 2012: 5), and under milder conditions even until 2001 (Grace et al., 2003: 62). Additionally, the Florida Hurricane Catastrophe Fund (FHCF) was established in 1993 as a mandatory public catastrophe reinsurer, backing both FWUA and FRPCJUA and required all Floridian property insurers active to purchase reinsurance from it (ibid.). In contrast to a private reinsurer, it could issue "post-event bonds" for financing capacity and was exempt from federal premiums taxation (Musulin and Rollins, 2001: 126); its books are, indirectly but ultimately, linked to the state's financial management. Therefore, Florida's reaction to Andrew both in terms of insurance and reinsurance were quite different from the CEA-concentrated Californian approach.

In 1995, Florida established the FCHLPM – in the industry often simply referred to as the 'Florida Commission' (e.g. Reinsurance News, 2020). As an outcome of Florida's situatedness in the emerging high-loss regime, the Florida Commission was embedded in a "total rethinking of the methods for funding severe hurricane losses among all parties – an effort facilitated by major advances in measurement techniques for meteorological phenomena, structural damageability, and insurance losses", which assembled "several competing catastrophe simulation tools" amidst the three state-run (re)insurance facilities in addition to private property insurers and reinsurers (Musulin and Rollins, 2001: 121f). The Florida Commission was placed as an independent authority within the Florida State Board of Administration and it initially included the directors of both the new residual insurer FRPCJUA and the public reinsurer FHCF, the director of the Florida Division of Emergency Management, a number of actuarial, statistics, computer, and natural scientists from academic institutions, and a consumer representative (NAIC, 1996a: 755). Purposefully entangled with the states' catastrophe risk facilities, it was created to meet Florida's perceived "need to accurately and reliably project hurricane losses for insurance purposes" (ibid.). The Florida Commission was explicitly positioned towards the entire hurricane insurance community, private and public, to "encourage the use of sophisticated actuarial methods and models" (ibid.), and thereby embodying the state's evolved sentiment towards catastrophe models: "The Legislature clearly supports and encourages the use of computer modelling as part of the ratemaking process." (NAIC, 2010: 181).

The initial setup of the Florida Commission involved itself a series of appropriation acts towards catastrophe modelling and models. First, until the end of 1995 it performed a hermeneutic reading of this 'Other's object' to build up an understanding of catastrophe modelling and establish initial standards and guidelines (NAIC, 1996a: 755, 2010: 183). Second, this was followed by active appropriation with the Commission's first revision of existing principles and practices of hurricane catastrophe models by mid-1996. This second initial appropriation act, directly focused on "adopting models" and "output ranges" (NAIC, 1996a: 755), was a combination of internal meetings to evaluate models, the creation of test data sets to be run and outcomes resubmitted by modellers, and in-house inspections of models and practices at modellers' offices (Musulin, 1997). Especially the latter was an attempt to deal with the mounting black-box problem. The attempted scrutiny of model components was, of course, at odds with modeller's proprietary sensitivity, especially given the public nature of the Commission's operations under 'sunshine law', i.e., guaranteeing public access to public processes and documents. The on-site visits were, therefore, brought up as a solution, since they would be administered by groups of independent and non-disclosure-bound experts whose findings would then be shared with the Commission, sometimes in the form of closed meetings where such trade secrets would be discussed, and then generalised and published in the final reviews (Mitchell-Wallace et al., 2017; Musulin, 1997; NAIC, 2010). Such initial teams consisted of meteorologists, computer scientists, actuaries and engineers whose on-site access to models resulted in the development of standards "to assure that models have certain common characteristics. There are standards on storm sets (frequency and severity), wind fill, a damagibility component (damage curves), and an actuarial component (measuring deductibles and copayments)." (NAIC, 1996a: 755).

Finally, the Commission set up a standardised evaluation process as a permanent appropriation of catastrophe modelling for ratemaking and later also more explicitly for probable-maximum loss (PML) calculations. Until today, this process involves three steps: identification, analysis, and findings (NAIC, 2010: 183). Models are identified by being submitted by modellers or solicited by the Commission. The standardised core analysis was derived from the initial standards-setting process. It contains five 'modules' of which the first two are questionnaire-based submissions by modelling firms describing the models in detail and providing a background of the modelling firm. The next two modules practically and materially test the models with test data sets followed by an on-site audit by an independent expert team. The last module is a presentation by the modelling firm on their model. The Commission, then, deliberates and votes on either accepting, accepting subject to modifications, or rejecting a model. This standardised process as the regulatory appropriation of catastrophe models was activated with general but explicit "standards for the specifications of a computer model on June 3, 1996." (ibid.).

Since the main expertise in catastrophe modelling continued to develop within catastrophe modelling firms, an evolving relationship of reciprocal transformative appropriation emerged between them and the Florida Commission. Since 1996, "[t]hose original standards have subsequently been revised and then adopted" annually (and since 2009 biannually) with each new model certification and verification cycle (NAIC, 2010: 183). In 1996, AIR's hurricane model was the first one to be officially certified, followed by EQECAT's and RMS's new hurricane models in 1997 (Grossi et al., 2005: 80). Until 2009, all larger modelling firms' hurricane models had since been deemed acceptable (NAIC, 2010: 402–6). From the second half of the 1990s on, commercial catastrophe models and their firms became the officiated producers of catastrophe for financial services: "The models approved by the Commission will be deemed admissible and relevant in rate filings with the Department of Insurance and also in any other administrative or judicial proceeding associated with that." (Musulin, 1997: 357).

Through Florida's new landscape of interrelated state-sponsored catastrophe risk institutions, modelling was deeply integrated in risk practices. The pricing of the new residual insurer FRPCJUA was informed by modelling, in part through its involvement in the oversight of the Florida Commission. The Commission's role was equally embedded in the public reinsurer, FHCF, which employed model-based calculations and which, since 1998, used instead of one catastrophe model all models that were certified for approval by the Florida Commission (Willis, 2007). Significant changes occurred in the already existing but now transformed FWUA, once its pricing practices were shifted to using catastrophe models. Slightly similar to the NFIP's Special Flood Hazard Areas, the FWUA focused exclusively on coastal areas subject to high risk of wind. It had previously derived pricing from historical data supplied by a central property insurance rating agency, the Insurance Services Office (ISO), which compiled out of the previous 30 years of the state's loss experience an average loss for rate filings (Grossi et al., 2005: 79). Since the ISO's established premiums structure had been shattered by Hurricane Andrew's loss – in hindsight, the "ISO's rate setting process grossly understated the actual risk" (ibid.: 80) – FWUA shifted in 1996 to catastrophe model-based pricing, whose indicated rates projected "several hundred percent rate increases in many areas" (Musulin, 1997: 353).

Parts of the public, especially those in rate-hike affected Miami Dade county (Grossi et al., 2005: 81), and local officials remained opposed to the use of models in fear of negative local economic consequences from higher insurance costs (Weinkle, 2017: 8). From an industry perspective, it was instead argued that by contextualising an over 500% rate increase in wind coverage into an otherwise unaffected homeowner insurance rate and as part of a property tax-including mortgage payment, the actual impact on private households would be minimal (Musulin, 1997: 353). At the same time, it had also been argued that the adjusted ISO rates after Andrew had actually been higher on average than model-informed ones and that regulators had simply approved only lowered rates. It was indicated that "regulators suppressed rate levels generally for both insurers that utilized the ISO loss costs in their rate filings as well as insurers that made independent rate filings" (Grace et al., 2003: 61). Although in the Californian case these struggles unfolded concretely in the concentrated and 'centralised' CEA ratemaking process and hearings, the conflicts themselves over market-societally managing socio-material Anthropocene catastrophe were similar to those in Florida. And for both they eventually, nonetheless, led the states more to follow the promise of model-led risk-based pricing rather than rejecting it.

While these early and reciprocally transformative relationships between catastrophe models and the states of Florida and California had been driven by their acute socio-material situatedness in Anthropocene catastrophe's new high-loss regime, other states followed, albeit less engaged and partly remaining reluctant in embracing these new appropriative dynamics. For instance, Texas initially rejected model-based rates and planned to develop its own regulatory catastrophe model (NAIC, 1995c: 836). While this model had not been built, Texas eventually allowed model-based rates subject to "additional data to determine the reasonableness of the [rate] filings" (Grossi et al., 2005: 107) using modelled catastrophe "as supporting information" (Grace et al., 2003: 59). Louisiana eventually engaged with a smaller modelling firm in setting minimum requirements to be implemented in rate filing questionnaires (NAIC, 1996a). New York, usually embracing market-based solutions (Grace et al., 2003: 69), had already started a study into catastrophe models (NAIC, 1995b: 676), but it remained very sceptical of the direct use of models along with, for instance, New Jersey and Missouri (NAIC, 1995c: 836).

Amidst this discourse – California's Chief Actuary Roth, for instance, suggested that "states should handle this issue individually" while Florida's Insurance Department emphasised "joining forces in the review of catastrophe models" – more concerted approaches despite the dispersed state-level jurisdictions were sought (NAIC, 1995b: 676). The already mentioned Catastrophe Modeling Subgroup of the federal-level NAIC was set out "to identify ways in which state regulators, insurers and the public might benefit from collective or cooperative gathering of information and sharing mutual concerns about the modeling process." (NAIC, 1995c: 835). Especially here, Florida's approach of screening models directly rather than producing more centralised modelled catastrophe as in California's case, was viewed favourably.

One central outcome of this subgroup was the Catastrophe Computer Modeling Handbook published by the NAIC in 2001 (NAIC, 2010). Chaired by a regulatory representative from Florida, the earliest first draft version had been produced for internal review in 1997 (NAIC, 1997: 1358). Already in this early version, it had been established that simply letting insurers disclose where models had been used in ratemaking would entail issues: "Initial attempts by regulators to gain information about catastrophe models resulted in insurers telling the regulators that the information was confidential and could not be disclosed to them. Understandably, the typical regulatory response was to disapprove the filing containing the model results. *Quickly all sides came to realize that the pattern just described was* *unworkable*." (ibid.: 1512; my emphasis). Although the NAIC assured that "it does not take a position as to the ultimate soundness of catastrophe computer simulation models", it was emphasised that "this handbook can be a vehicle to provide the private market level with information about modelling" (ibid.: 1511, 1360). Even more outspokenly advertised, the Handbook was explicitly meant to "help regulators in determining the appropriate pricing for catastrophic insurance, and that certain regulators may also use it for risk analysis of catastrophic exposure." (ibid.: 1032). Consumer groups, and most prominently Selwyn Whitehead of the Economic Empowerment Foundation against their experiences from the CEA ratemaking hearings, affirmed that the NAIC and the Handbook would actively "advocate the use of catastrophe computer simulation modeling" and requested that also "the downside of modeling to be included in the handbook" (ibid.: 1360).

While also critical views had been added to the Handbook, the suggested process of evaluating models and their embedded practices resembled primarily the procedure established by the Florida Commission (ibid.: 1517f), whose statutes explicitly endorsed and encouraged the use of models. Among the supplements of this first version of the Handbook is not only a "Sample Non-Disclosure Notice" to interact with commercial modellers, who were actively sought to consult on the Handbook. Also included were the Florida Commission's "Standards for the Specification of Computer Models for Hurricane Loss Projections" for reference to promote Florida's approach as a template for other states (ibid.: 1519). Using the Commission as a role model was considered "extremely beneficial in that the Florida Hurricane Commission work contains a substantial number of questions and answers about all aspects of the models which would enable the handbook to be as comprehensive as possible." (ibid.). Although the practical every-day significance of the Handbook and the Florida Commission should not be overstated in the overall framework of catastrophe modelling practice by (re)insurers themselves, it does, however, represent the institutionalising of catastrophe modellers' role in the decentralised production of catastrophe for the financial management of Anthropocene catastrophe emerging in the late 1990s. The Commission's process and standards still feature prominently in the second and latest version of the Handbook from 2010. Especially the central section on model validation and updates is "based largely on the Florida Commission on Hurricane Loss Projection Methodology standards" (NAIC, 2010: 17).

The other prominent alternative of a centralised catastrophe production embedded in a CEA-type construct on a national level in form of the NDIC had not materialised. Not in a concrete entity either but instead in form of an institutionalisation of a genre of practices, the proposal from the mid-1990s that the Florida approach of certifying models directly "might be done at a national level" (NAIC, 1995a: 641) had led to the NAIC Handbook. Amidst this new genre, for instance, a year prior to the official release of the Handbook, the Actuarial Standards Board published 'Standard of Practice No. 38' requiring actuarial practitioners to reflect on and explain the use of catastrophe models (Grossi et al., 2005). The NAIC Handbook represents an outspoken acknowledgement of the centrality of commercial catastrophe models and modellers in which reciprocal appropriation is the driving force of producing catastrophe for financial services: "Both regulators and modelers are working to meet the challenge of providing enough disclosure to make informed decisions, while preserving the confidentiality of proprietary details. This handbook is an important step in that process." (NAIC, 2010: 4).

b. Becoming Vendors: Appropriating Experimentality at the 'Fracture of Reality'

At the latest since the second exhibiting of Géricault's Raft of the Medusa, it began to be displayed by more exhibitions; it started 'touring' through England and Ireland and was also sent as a copy to the US for further exhibiting (Riding, 2004). Becoming a hallmark of defining and integrating Romanticism via its appropriation of Neoclassical elements into French art at the time (Dewar, 2020), it was soon picked up by other artists, especially Eugène Delacroix in his Liberty Leading the People. Rather than becoming 'simply' an officiated, staged and delegated historical artefact, such as for instance Anton von Werner's Proclamation of the German Empire, the Raft was central to a becoming genre and to some extent modernism itself. The Raft and its underlying practices and understandings gave birth to a lasting production of works: the genre inspired by the Raft began to get disseminated rather than the singular object of the Raft itself.

For catastrophe modelling, the moment when it became a new 'genre' of risk assessment were the 1990s and some of the most central 'exhibitions', contexts, interpretations and resulting 'pieces of work' of producing catastrophe for financial risk management of Anthropocene catastrophe have been emphasised in this and the previous chapter. On the heels of these developments, the *form* of this new genre emerged and concretised as one of *vending of software devices*. This is the outcome of the complex contexts previously described and in part driven by the favouring of the Florida approach towards models – welcoming and certifying many competing commercial models – over the ones of the CEA and NDIC – choosing and employing a central singular model consultant. It materialised at this point more explicitly, as model user U60 notes, that modellers realised that "they are in the business of selling software, they're not in the business of insurance". While this development was, of course, only one aspect driving the form of vending catastrophe production, it reciprocated with a lasting transformation on the side of modelling firms and the catastrophe analytics market at the time.

"When I meet people for the first time and they ask me what I do, I have so much fun saying, 'I'm a catastrophe modeller', and literally people will actually stop and look at you again and say 'Tell me more! I have never heard of such a thing.'" Hemant Shah, RMS's co-founder tells me that for an RMS team building exercise outside of Zürich, he once used this as an icebreaker: "I said 'Look, so when you enter customs and you have to fill out what your occupation is, what do you fill out?' And some people say, software executive, insurance analyst, etc. […] we had a whole discussion about what it means to be a catastrophe modeller, not just functionally or from a utilitarian perspective, but what does it mean? What is our purpose? What do we do? Why are we here? Why do we matter?" As already discussed in chapter 4, the very form of this was not so much one in the realm of engineering and science-based consulting but *software*: "We approached it as 'Yes, we're doing catastrophe modelling, but we're a start-up software company." And already in the late 1980s, the business plan set up activity on "not just *a* peril [i.e., earthquake], but there's multiple perils". While envisioning servicing for more than one catastrophe type was not unique to RMS, the clear initial formation as a software vendor was. Picking up from the banking and investment field as an "adjacent industry which had their analytical revolution earlier than insurance" and its then already "well-established software companies", RMS adopted especially their "subscription-based business models". This initial format of a software vendor instead of a bespoke analytics consultant (although consulting was and is also part of vendors' services) was accompanied and amplified by transformations of ownership structures and independency from immediate market participants and clients. RMS had previously been financed by venture capital, some of it from the insurance industry, until it sold itself in 1998 to the UK-based media conglomerate Daily Mail and General Trust (DMGT), which had otherwise no ties into (re)insurance (RMS, 2021).

AIR, even though they produced software, was bound to service only reinsurers during its first five years until right after Andrew. AIR's founder Karen Clark remembers that "I wished it would have been a little later though, because we weren't quite prepared for it […] we had that non-compete [agreement] and we didn't have time to develop the software for primary insurers." While Clark's original hurricane model became the basis for the E.W. Blanch Catalyst service for primary insurers (NAIC, 2010: 51), it otherwise separated from the broker and AIR's first own software product had become CATMAP for reinsurance usage, adding eventually primary insurance products during the first half of the 1990s. AIR remained privately owned over the 1990s until it was acquired in 2002 by the Insurance Services Office (ISO) renaming it AIR Worldwide, four years after RMS had been acquired by DMGT. The ISO had been deeply engrained in the US's realm of Anthropocene catastrophe for a long time, since it originated from historic rating bureaus such as the Pacific Fire Rating Bureau (which was once headed by the PML-publicising Karl Steinbrugge discussed in chapter 3) and the National Bureau of Fire Underwriters (which had created the first national building codes in 1905 as mentioned in chapter 2). The ISO was a not-for-profit rating organisation for the US insurance industry and had been officially formed in 1971 to support insurers gather and report data to regulators (SEC, 2017). As such and as mentioned above in the Florida Commission case, it was a quasi-public entity consulting on risk assessment and "providing information to help insurers determine their own independent premium rates" (SEC, 2017: 4) – not unlike catastrophe modellers but without the models. In 1997, however, the ISO converted into a for-profit risk data provider and private rating bureau (NAIC, 1997: 1359), whose acquisition of AIR a few years later was, therefore, in concurrence with AIR's concretising and independent risk model vendor format, organisationally separated from their and the ISO's client base (ISO, 1996a, 1996b, 2002). The ISO would eventually form Verisk Analytics Inc. as a parent holding in 2009 (SEC, 2017), which after series of further acquisitions of data and analytics firms, such as Wood Mackenzie or Maplecroft, is until today one of the world's largest risk analytics corporations.

"Because we needed to get funding to build the models around 1994, EQECAT became a 50-50 joint venture" remembers I64. While AIR had already made itself more independent by moving out of their closer relationship with the broker E.W. Blanch, EQE moved into the broker space by forming EQECAT as its dedicated catastrophe modelling entity together with the broker Guy Carpenter in 1994: "GC threw in the money, and we threw in the technology". Although later than AIR but similar in its rationale, this move followed the sentiment in the early and mid-1990s of "reinsurance brokers [thinking] that they would need to become experts in catastrophe modelling themselves and they had to have their own catastrophe modelling organisation", as I03 tells me. In fact, another large broker, Aon, had engaged in building up catastrophe risk analytics capacities via its unit Impact Forecasting and the consulting firm Towers Perrin's subsidiary Tillinghast, who built models and also started licensing models from RMS in 1998 (e.g. NAIC, 2010). Embedded into brokers' very central position in (re)insurance markets (Jarzabkowski et al., 2015a), Guy Carpenter in a similar way "wanted these models to be used by their clients and our [EQECAT] models' role was to play defence to protect their client-base from going to other brokers who were using other models." (I64).

AIR and RMS were transforming into independent software vendors, broadening their model suites. EQECAT, eventually, decided to do the same: "We had developed earthquake models and were moving into developing wind models [...] And our objective was to basically licence our product to as many clients as possible." EQE took back 100% of EQECAT in 1998 – "to provide a unified approach to the development, sales and support of the suite of EQECAT products" (P&C, 1998) – and it was bought up a year later by ABS Group of Companies, a Texas-based safety, quality and environmental management company. Structurally removed from direct catastrophe market participants, EQECAT had fully settled as a vendor modeller and would eventually be acquired by CoreLogic in 2013, whose name it carries since then. CoreLogic, already a data analytics firm at the time, performed an aggressive expansion into the catastrophe space that year, not only buying EQECAT but also, for instance, real estate data companies and CDS Business Mapping who offer property geocoding for hazard-specific exposure (IJ, 2013). Like Verisk Analytics, CoreLogic expanded its market position within the risk analytics market with their acquisition of a major catastrophe model vendor, while vendors got access to wider proprietary data streams to refine and expand their models.

While modellers built up their software suites and began to compete with one another on their own, brokers realised by the turn of the millennium that they "would be much better off not owning a cat modeller because if you own a cat modeller, everybody assumes you've kind of manipulated the results to suit you as a reinsurance broker because you are trying to sell reinsurance. […] Ownership transformed the whole perspective [and] suddenly that completely shifted the market" (I03). The inherent reference of the etymology of appropriation as 'making something one's own' not only echoes for catastrophe modelling with regards to the proprietary nature of knowledge production materialised in the modules of models, but also in the organisational embeddedness of modelling firms. The mode of brokers' appropriation of catastrophe modelling firms as direct proprietarily owned parts of their business model and development was largely discontinued while they instead continued to increase their literacy in catastrophe modelling. As P02, who had until then worked for Guy Carpenter in the EQECAT joint venture, put it: "Guy Carpenter sold its share on EQECAT because it realised that actually it didn't make much sense for brokers to be aligned with only one cat modelling company. So, they sold their share on EQECAT to EQE and then started licensing other products and I started running a cat modelling team at GC itself". This was driven by the growing acceptance of vendor models and the awareness that outputs and risk levels varied across different models (Grace et al., 2003: 59), a major focus in the following chapters.

"10 years into this race, it was RMS, AIR, EQECAT, probably battling somewhere around 30% market share each" remembers RMS's Hemant Shah. By the start of the new millennium, the mode of socio-material appropriation in catastrophe production for financial risk assessment and management had concretised in the decentralised form of software vendor models and their contextual appropriation of (re)insurance risk practices. A range of vendor modellers, expanding suites of probabilistic simulation models for different catastrophe types, and a growing user base resulted in a multiplicity of proprietary catastrophe across the catastrophe risk space. Throughout that time, as U60 recalls, "there was a pretty big asymmetry [in] the investment in analytical resources on cat between the model vendor versus their users. I remember when I joined [a reinsurer] in 1996, which is one of the largest companies, I was the first scientist they hired to do natural catastrophes, whereas at that time at RMS and AIR, they already had hired *teams* of scientists. [Users] were ok to accept the fact that the models are proprietary".

Between the late 1980s and the early 2000s, against the backdrop of the series of socio-material appropriation acts elaborated above, this epistemic asymmetry had turned the position of catastrophe modelling and models by 180 degrees. P02 notes that at this point, as mentioned at the beginning of the previous chapter, "people actually then sort of adopted it blindly. You know, so it went from 'we don't really know for what and how to use these tools' to 'you *have* to use these tools!' […] Not using them was clearly not an option. And that was all that was offered, you know, all the three modellers that were available at that time were pretty much the same. So to use them blindly was the only choice".

II. Semi-Permeability of Catastrophe Production

What materialised throughout this first phase was the emergence of a *lasting semi-permeable dynamic* of *proprietary catastrophe production in multiplicity,* involving diverse articulations of public and private knowledge. The market-based competitive linkage of both the vendor catastrophe analytics market and the catastrophe (re)insurance markets at this point became a dominant mode in the epistemology of disaster risk. This is primarily due to the way knowledge production at the 'fracture of reality' came to be structured through intimate and entangled socio-material appropriation in the format of vending catastrophe models as proprietary software devices. While the emerging multiplicity of proprietary catastrophe would be exacerbated by more firm-specific contextual appropriation of vendor models by a more model-literate user community from around the 2010s onwards (focused on in the next two chapters), multiplicity of proprietary catastrophe before this shift was mainly driven by the expanding appropriation acts of vendor modellers. As discussed in the previous chapters, catastrophe modellers draw on many sources when building up different submodules of their models.

a. Public Hazard

The proprietary grammars of interaction of catastrophe hinge primarily on the vulnerability module, which derives the consequences from simulated catastrophic phenomena, in the hazard module, interacting with a given socio-material environment and its objects at risk, in the inventory module, e.g., how wind speeds or ground motion interact with a built structure at a specific location. The sources vendors appropriate for the hazard module, discussed in chapter 4, are primarily public ones (Mitchell-Wallace et al., 2017). For instance for tropical cyclone models, data on intensity, size and location of storm systems is usually taken from the HURDAT databases (NOAA, 2020a) and, since 2008, the IBTrACS database (NOAA, 2020b), both administered by the National Oceanic and Atmospheric Administration (NOAA), or, since 2012, the EBTRK data set from Colorado State University (EBTRK, 2020). For earthquake data on intensity, location and probabilities there are, for example, the US Geological Survey data sets in the US, and elsewhere, for instance, the International Seismological Centre (ISC, 2021) or the Japan National Hazard Maps and Catalogues (EIC, 2016).

There is also a range of public catastrophe models that are generally freely accessible. For instance, since 1992, the SLOSH hydrological model (Jelesnianski et al., 1992; NOAA, 2019b), since 1999 the Japanese HERP earthquake model (JISHIN, 2021), or, since 2009 the Global Earthquake Model (GEM, 2021). These models have, however, different foci and goal settings: "[m]any of the governmental models concentrated efforts on hazard […] rather than risk", which makes those models, or parts of them, usable in hazard modules but not as fully-applicable catastrophe loss models for finance (Wyss, 2014: 559). Slightly more involved and a direct outcome of the developments throughout the 1990s is the "HAZUS loss estimation program" introduced in 1997 by the US's FEMA (Grace et al., 2003: 60). HAZUS is the US "federal government's catastrophe model" (Grossi et al., 2005: 237). Its first version in 1997 was an earthquake model until it was extended in 2004 with wind and flood models and subsequently renamed into HAZUS-MH (multi-hazard) (ibid.). However, even though aimed at estimating loss, HAZUS was primarily built for governmental disaster management and research purposes, not for use by financial services or its regulation. But even here, the recursive nature of appropriation in catastrophe production and vendor modellers' central role became evident. For the HAZUS earthquake model the Committee selected RMS to build the earthquake model and EQE International to consult on earthquake model methodologies between 1996 and 1997 and to build a flood model released in 2002 (Schneider and Schauer, 2006: 41f). The HAZUS hurricane model involved the wind-specialised catastrophe modeller ARA. HAZUS has never been commercially used for financial risk assessment directly, but was used occasionally, for instance, along with RMS, EQECAT and AIR models as a test framework due to its more transparent format (Grossi et al., 2005: 83). However, on the side of direct and stand-alone application for risk and loss calculations, "[p]ublicly available or government models had little access to our industry" (Wyss, 2014: 558f).

One notable exception is the "Florida Public Hurricane Loss Model", often referred to as simply the "Public Model" (FPHLM, 2021). After the two Floridian state-insurers, FRPCJUA and FWUA, had been merged into the residual Florida Citizens Property Insurance Corporation in 2003, the Public Model was developed for the Corporation's ratemaking. Apart from a private actuarial consulting firm, it has been developed by public institutions, such as Florida International University and the Hurricane Division of NOAA, and its architecture, assumptions, modules and data are publicly documented (Chen et al., 2009). It is also being reviewed since 2006 by the Florida Commission (NAIC, 2010) and, while private insurers use proprietary models, the Public Model "'serves as a minimum benchmark' for the state's catastrophic residual market" (Weinkle and Pielke, 2017: 553).

Catastrophe modelling brings together the interdependent elements of simulation and socio-material mediation by appropriating numerous different practices, data and devices. Since the production of catastrophe for financial risk management became mainly facilitated by vendor modellers, the proprietary appropriation acts that assemble these elements of modelling created a pivotal position for vendor models in bringing together public and proprietary knowledge. Public sources such as those listed above are important components of every vendor model for generating synthetic history and its extrapolation into the future, in the hazard module, which is essential for, then, simulating damage and loss in the more proprietary vulnerability and loss modules. For instance, as the academic earth and climate researcher, P63, notes: "the HURDAT data, […] is the *gold standard*. All the cat models are built on them". Being 'built on them', however, does not mean a straightforward integration but instead very purposeful, vendor-specific appropriation of this public knowledge. U68, a seasoned model user who worked for (re)insurance brokers and insurance-inked securities investors, explains: "You start with the historical catalogue, HURDAT, which is a public data set that you can download off the Web. And the different vendors will manipulate and clean that data and adapt it […]. They might filter out certain events or certain storms because they think they have evidence that there is a bias in the data set, which is fair." The capacity of entire science teams enables vendors to create an internal community which resides over their interpretation of this 'Other's object' in their individual appropriation of such public artefacts. "This is where opinion counts", continues U68, "You might have three scientists with four different opinions or two different opinions. And so, it [assumption and interpretation] starts already with the basic data."

The interaction of vendor modellers with public knowledge production and sources is a *semipermeable* one. Although vendors were and are involved in public catastrophe analysis activities such as HAZUS, they remain protective of their own core knowledge production. P63 is one of very few academics who are more deeply familiar and interacting with vendors and this very fact, he tells me, is "not saying much about me. It's saying more about the field. There just isn't that much feedback. […] It's not zero, but it's on some level surprising how little it is". At the same time data (such as HURDAT) and components of hazard models (such as SLOSH) as well as personnel and new research from academic projects and publications, are ingested by model vendors, who had built up a considerable but rather exclusive expertise early on. P63 remembers, "I was just shocked at the amount of scientific expertise in the industry. And they're keeping a low profile […] There's quite a bunch of them. They're doing a lot of sophisticated stuff."

This expertise, as already emphasised, is directed not at general research on meteorology, hydrology, seismology or engineering but at knowledge production that enables proprietary financial risk management of Anthropocene catastrophe. This context and goal-setting is driving vendors' expertise in their specific socio-material appropriation of public knowledge. "It's very narrowly targeted compared to how we do research. It's a very small subset of questions, very intently. But on those things, they're incredibly knowledgeable." (P63). Yet, the dynamic is a semipermeable one in that public knowledge is utilised and graduates are hired out of universities: "if you consider their connection to academia, information flows mostly one way", says P63. The vendor I03 notes on interaction with public research: "We sort of work with small projects with universities but actually their time period [long climatological horizons] doesn't work for us, actually. And also commercially, we actually want to do this stuff ourselves." This dynamic enables the vendor-internal expert communities in vendor-specific appropriation acts of public knowledge, as "the information they take in is kind of what they choose to take in […] they're taking what they want and they're defining what they want. And if it was more a two-way conversation, they would be exposed to more information that they might not want" (P63). In other words, 'peer-review' works through vendor-internal communities and the market, rather than through academic channels. Although vendor employees do publish sometimes in academic journals, it is generally rather restricted.

b. Proprietary Damage

While assembling from various sources the components of submodules which enable to simulate, for instance, hurricanes or earthquakes, the most distinctive proprietary and competitive feature of a vendor model is the vulnerability module and its grammars of interaction of catastrophe. U15, a long-term in-house catastrophe modeller and model validator at a very model-literate reinsurer, highlights: "the core research when it comes to hazard, in seismic, in hurricane, is not done at RMS, AIR or CoreLogic, but it's done in Universities, in academia. So they go on and adopt it. Now, vulnerability is one thing that is 100% done by these companies. Vulnerability is essential. Vulnerability is the main source of differences between the vendors, both in methodology as well as in quantification." As already explained, vulnerability modules and their proprietary damage functions are primarily founded on engineering-based equations which disassemble a building into various parameters of building characteristics (such as age, height, construction and material types, occupancy, etc.) and their response to interaction with the intensity of catastrophic phenomena's agencies (such as wind velocity, precipitation, ground motion, water ingress, etc.). The damage functions are the core part of a catastrophe model which bring together catastrophe's two dimensions, occurrence and severity, in what is often called the 'damage ratio', translates damage into loss. They are based on the simulated responses of interaction through series of different individual damage functions which usually derive 'replacement cost value' for the individual components, in which the estimated repair costs represent the modelled loss as a fraction of a building's replacement value, which is the specific "insurance exposure or sum insured" in an insurance policy (Mitchell-Wallace et al., 2017: 14)

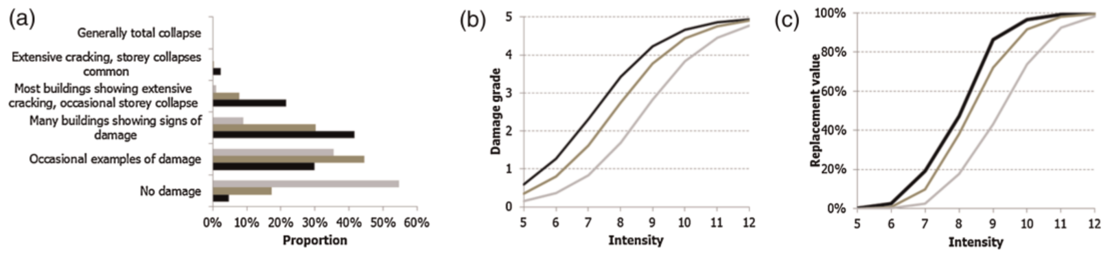

Figure 14: Representations of illustrative vulnerability functions (Mitchell-Wallace et al., 2017: 14)

While damage functions are, of course, also an assemblage of appropriated knowledge from ultimately public sources, the construction and composition of each function is the result of vendor modellers' internal expertise community. "It's a combination of methods", U15 tells me, "One is theoretical, such as engineering practices. Second is lab testing, like putting things in wind tunnels, they find projects from academia and then you [vendor] do it." However, the most critical aspect in constructing and, more importantly, improving damage functions is actualised catastrophe: damage functions feed, so to say, on the moment of consolidation in the 'loop of Anthropocene catastrophe' (introduced in chapter 5).

The ingestion of actualised catastrophe by damage functions materialises in model 'calibration'. Calibration can be informed by various things, such as analytical experimentation on computer or physical models of building behaviour or expert judgements such as elicitation procedures, but the most critical form of calibration is driven by the input of claims data, insurers' socio-materially mediated sensing of actualised Anthropocene catastrophe. In modelling, calibration happens in the space between consolidation and multiplication of catastrophe as the differential of an insurance portfolio's appropriation of a model – actualised exposure – and the appropriation of the same portfolio by a vendor modeller – modelled loss – or in other words: "The differences in what the models predicted and what actually happened provides new opportunities for further fine-tuning damage functions." (Grey, 2020).

c. Market-Shaped Loss

The multiplicity of catastrophe production materialises amidst the duality of vendor and insurer – the loss simulator and the loss sensor – and the duality of both actors' market-driven competitive conditionalities – proprietary models and proprietary data. While vendor models are proprietary and shielded, so are insurers' exposure and claims data. As mentioned especially in chapter 4: at the latest with the Northridge earthquake, the financial socio-material mediation of Anthropocene catastrophe's environment by insurance firms via their claims data had been deemed the most central sensing device, which for strategic, competitive and legal reasons is not shared. "Detailed data for calculating vulnerability, that is, contemporaneous loss and exposure data, are normally proprietary and not publicly available." (Mitchell-Wallace et al., 2017: 226). For building and maintaining catastrophe models, detailed information on the severity dimension of catastrophe is essential but this very "data to calibrate loss models are in general restricted." (Wyss, 2014: 559).

This tension between catastrophe's dimensions of occurrence and severity makes catastrophe production particularly difficult, since in contrast to the public infrastructures of sources on occurrence, detailed data on severity is often private. Although there are public catastrophe loss databases in many countries and to some extent on the international level, they are focused on relief and disaster management aspects, and remain very fractured (Wirtz et al., 2014). "It's a mess", comments the academic researcher P63 and elaborates, "There is no global disaster loss data set that has evolved over years and years of international collaboration with standards and practices, like the World

Meteorological Organization and all that stuff. So, the private sector has much more role play as they've been doing it longer and they know what they're doing. And there's no equivalent. You know, there's no public infrastructure that is adequate". There are more or less comprehensive catastrophe loss databases on a global level which initially emerged between the 1970s and 1980s, two of which are compiled by global reinsurers, Munich Re's NatCatSERVICE and Swiss Re's Sigma, and one is the WHO-supported EM-Dat by the Centre for Research on the Epidemiology of Disasters. The latter focuses "on humanitarian aspects, while the two reinsurers' main interest lies in accurate numbers of material loss" (ibid.: 135ff).

Yet even these reinsurers' publicly accessible databases publish only aggregate- and industry-level data, which is is not sufficient for detailed model calibration. "You need to have policy-level losses", explains U53, a former vendor modeller. "You need to know where they are in order to be able to model at that location level, so you need the entire food chain." And this is the proprietary claims data of insurance firms. "They have a lot of data that nobody else has", says the academic researcher P63, "And it's tough for us because I want to get into modelling. […] But you know, getting data is very challenging, and, you know, HAZUS isn't going to help me. I'd love to model not just the hazard but the impact. And now I can't! I can [only] go and beg these companies for it. […] It shouldn't be that I can only know what hurricane risk is by paying somebody a lot of money." The epistemic significance of claims data is so central, that it is, for instance, considered elementary for eventually enabling a private market for flood catastrophe. There have been repeated calls by now for the NFIP to share their complete claims data with the private sector to enable to forge private insurance products for flood risk: the industry calls for "FEMA to share NFIP information, including claims, elevation, and mapping data, with state insurance regulators, insurers, modelers, advisory, statistical and rating organizations in order for the private market to be able to accurately assess flood risks." (NAIC & CIPR, 2017: 116).

Amidst their semipermeable relationship to the public, vendors emerged in this pivotal position on catastrophe production through their subscription-based client contact at the latest since the mid-1990s: "If you can collect their claims data and exposure data, you can use that for testing all the components of the model. I used to run the modelling here [late 1990s to 2010s] and actually that was a key feature that we would emphasize on going out, working with clients, trying to get hold of their claims data and using that feed-back into the modelling.", explains vendor I03. The critical socio-material point of multiplication of catastrophe on the vendor side is precisely the one of calibration in the face of consolidating catastrophe. The fracturing of 'reality' – as I have quoted I03 before: "there is only the reality of how good a model is" – is mobilised in the calibration of damage functions by proprietary claims data: "the models inevitably are as good as the data going into them in terms of empirical calibration" (I03).[45] Just as much as vendors very individually appropriate public hazard data, they equally do so with proprietary claims data: "we [(re)insurers] don't know whose data they use and what they do exactly with the data", explains the model validator U15.

In these appropriation acts, the *interpretation* of this 'Other's artefact' is potentially even more critical. This is not only because neither the interpretation nor the artefact is accessible outside of vendor-internal communities, but also because of the de- and re-contextualisation of this sensed actualised Anthropocene catastrophe that claims data is. "From the moment I get that claims data, there is a lot of clean up that we have to do, you have to do corrections, you have to account for deductibles, you have to back-track a lot of things. You don't get the claims data in exactly the form you want. And you need to know the business that the company has written" (U15). The issue here is the de-contextualisation of claims data itself, the abstraction of contextually situated damage for the calibration of vendors' proprietary damage functions for future catastrophe. "You need to know the companies behind the claims data that goes into building your vulnerability curves. I give you an analogy: say you want to estimate the height of individuals, ok? And you go to two different associations, one is the NBA and the other is the 'association of jockeys' or whatever. What you gonna find? That the average height for the one is tall and the other is short. You can't just put that data into your statistics without *judging* these averages. You have to adjust this. And the same thing applies to insurance companies. They have their biases, some people do stuff that others don't do". In other words: sensors differ and so does their sensed actualised catastrophe on which basis calibration happens.

The ingestion of claims data for calibration of damage functions is acknowledged to be tricky, as the vendor modeller I03 remarks, reiterating the problematic reality claim of modelling: "we've done the best we can in terms of, sort of, to view this from as many ways of calibrating as possible. But actually, it's going to be imperfect. And with this imperfection, how we judge an imperfection is itself very hard because when you have a real event happening, a big event, then it tests your capability to reconstruct the loss. So again, there is no *reality* here." He continues that, in this way, claims data "is more valuable to us than the results of our models, because the results of our models are conditioned by the assumptions that we build around them". As Pickering has argued, a "given model does not prescribe the form of its own extension." (Pickering, 1995: 56). And the semi-permeability of proprietary knowledge on actualised catastrophe has profound impacts on who can appropriate models with these 'extensions'. Public use is, therefore, limited since the proprietary aspects just described are essential for the epistemology of catastrophe and the key part here is the "calibration of results for the numerous applications. It is important for the public sector to consider that even the best available exposure, vulnerability and hazard model components designed for insurance do not necessarily provide a robust

[45] See also Mitchell-Wallace et al. (2017: 130, 299, 348, 351f).

answer for public sector financial protection or decision-making without the proper calibration of models", which are performed proprietarily (Mitchell-Wallace et al., 2017: 463).

Since the centrality of vendor models became apparent in the late 1990s, the reciprocity between vendors and insurers materialised in vendors' pivotal position as the locus of appropriating simulation and appropriated socio-material mediation.

> "Companies keep this data to themselves because it's commercially very valuable. So, because they are our clients and we have to work with them under different terms as to how we get access to it, it's really important we do access this information. So as a collective, companies have an interest in making sure they're using the best models, so there's an interest in them sharing that [data] with us. But I mean, a major part of our relationships with our clients is this issue. We want them to supply data. What do we have to give back to them to make it worthwhile for them to do that? It is some sort of negotiation." (I03).

Vulnerability modules' damage functions feed on catastrophe's consolidation, but once ingested via proprietary claims data, their calibration by vendors is one of the most central drivers of the market competition-shaped multiplication of catastrophe. The entanglement of proprietary simulation and proprietary socio-material mediation of catastrophe is, therefore, deeply reciprocal in the practice of vulnerability calibration. Since the 1990s, the core of the epistemology of catastrophe risk would, therefore, emerge as semipermeable and become, consequently, inherently market-shaped.

d. Model-Made Catastrophe, Model-Made Markets

In order to write business in catastrophe risk insurance, a complex set of procedures and conditions needs to establish whether it is profitable, in-line with regulation on availability and solvency requirements, and marketable by bearable premiums. In all these aspects, the semipermeable, proprietary production of catastrophe provided by vendors became central in the 1990s. While claims data (post-catastrophe) was appropriated by vendors for maintaining, enhancing and broadening their model suites, users of the models needed time to implement their policies and exposure data (pre-catastrophe) into the licensed models. "Companies bought the models [...] it took them a couple of years to actually get the data in the right format to actually get meaningful numbers out of the model. Then it took a little bit longer to actually then understand the model." (U15). P02 states that, "we built up large bodies of users who were insufficiently knowledgeable about how cat models are built". However, founding the ability to write business in the new high-loss regime of Anthropocene catastrophe on catastrophe modelling led vendors' appropriation of insurance practices already from the mid-1990s on to be perceived as ultimately an enhancement of competitiveness: "premiums can be tailored to more closely match the risk of loss. Thus, insurers find it necessary to use catastrophe modeling for competitive reasons." (NAIC, 1995d: 921).

At the same time, criticism especially from consumer groups remained. One particularly comprehensive critique was formulated by Selwyn Whitehead, which captured the entangled proprietary and semipermeable aspects of the emerging dynamics in catastrophe production: "catastrophe modelers use publicly financed underlying data and, therefore, consumers are paying three times for the use of the models: 1) when the data is developed by public entities; 2) when manipulated data is included in insurer's projected loss costs; and 3) when excessive rates are derived from the use of the model" (NAIC, 1995c: 836).[46] The appropriation of public knowledge by vendors for the appropriation of insurance risk practices and proprietary data was viewed by consumer groups as an unfavourable marketisation of catastrophe for competitive activity. The social consequences would mean an intensification of market imperatives in the management of Anthropocene catastrophe. Whitehead bemoaned that this dynamic would "cede power to those who define the models that generate the forecasts […] Using these models, insurance becomes less a collective function of pooling risks for the overall good of society and more strictly a profit making activity. In this sense insurance is becoming 'privatized,' and the underwriting and rating process are being used to calculate profit and not manage risks." (Whitehead, 1997: 379).

Although risk and profit, of course, have always been deeply entangled in private insurance, the emergence of catastrophe modelling provoked precisely the decisive competitive rationale of appropriating the fracture of catastrophe's 'reality', essentially arbitraging on the experimentality of the epistemic-ontological assemblage that is the market-societal Anthropocene loop of catastrophe: *the financial ontology of Anthropocene catastrophe*. The competition-driven shape of Anthropocene market society was invoked through the purposeful interconnectedness of insurance and Anthropocene environment, especially via real estate and mortgage markets. As opposed to consumer groups' positions, proponents of a market-societal vision of catastrophe management emphasised the promises of model-enabled risk-based pricing: "The consumer effect of models is not all negative, and in fact models may be a great benefit to consumers in the long run by improving the accuracy of pricing and thereby empowering consumers to make intelligent economic decisions about where they live and how they build their homes." (Musulin, 1997: 359).

[46] Of course, this line of critical argument is not unique to catastrophe markets but applies in varying degrees to all economic markets. Pharmaceutical markets are a particularly prominent example where public research, knowledge and data are appropriated for proprietary and commercial products and services.

Prompting an early market-shaped vision, Hemant Shah recalls his initial idea during graduate school in the 1980s, which would later form the underlying of RMS's value proposition:

> "What we came to understand or hypothesized was that, if you couldn't quantify the risks reliably, financial services companies, whether they were banks, investors or insurers, could not allocate capital to cover the risk. If they couldn't allocate capital to cover the risk, they couldn't extend coverage. If they couldn't extend coverage, people wouldn't buy. And then two bad things happen when there's no coverage provided. One is that you don't have the recovery, so ex post you don't have resiliency. But I think even more fundamentally, ex ante, you discourage resiliency because in many ways insurance monetises the cost of risk, makes it endogenous, and as a result, you create financial incentives to reduce the risk. […] We formulated this kind of thesis, which is, 'Hey, if we want to make an impact knowing something about catastrophe, let's see if we can apply what we know to help quantify risk for insurance companies so they could provide more coverage and etc. etc. etc.' That was our big hairy kind of audacious thought that we can make a contribution."

Or in other words, as he told me in a different conversation, a former colleague of his "coined the term 'model-made markets': you can model the risk, you can monetise the risk, and then market can get creative to manage the risk. You can create economic transaction and then create the underlying incentives to reduce the risks in the first place." This is precisely the contact point where market-shaped, competitive epistemology collapses into ontology – empirically in intended and unintended ways – and explicates a financial ontology of Anthropocene catastrophe.

By growing into the role of software vendors rather than direct and bespoke consultants, catastrophe modellers and their models emerged as the more reliable appropriators of catastrophic 'reality' in the production of situated catastrophe. "While catastrophe modeling is not an exact science, it is dramatically better than having nothing" (NAIC, 1995d: 921). The institutionalised transformation of proprietary models as the objects for appropriating ratemaking and other insurance practices via the screening and certification process in the manner of the Florida Commission endowed the thus transformed appropriation-objects with a kind of legal legitimacy. Issues such as 'model manipulation', for instance, were assumed to be unproblematic if a vendor "controls the model code" since it was argued that in that case "the opportunity for manipulation is significantly reduced and is focused on the insurer's data reported to the modeler and any insurer specific assumptions (unique coverages, etc.) that prompted the modeler to alter its standard product." (Musulin, 1997: 357f) – it is the user's appropriation and to-be-appropriated data that are suspicious here, not the appropriation by the vendors. One suggested (but only informally implemented) precaution was even to require "a formal opinion from the modeler on the proper execution of the model when run by the insurer." (ibid., see also NAIC, 1996a: 756).

Multiple series of appropriation acts had by the early 2000s resulted in a situation in which vendor models were institutionalised and legitimised appropriation-objects whose appropriation of insurance practices and proprietary data by vendor modellers was deemed less partial than its users. While there remains debate, criticism and doubt on the centrality and value of catastrophe modelling, catastrophe model vendors had since the new millennium claimed their position as the core producers of catastrophe for the financial realm. This positioning since then let I03 provide the answer to Hemant Shah's ice breaker questions, "What is our purpose? What do we do? Why are we here?": "insurers and reinsurers would not be considered to have neutral perspectives on risk, and the broker is respected but is not completely, not totally assumed to have a neutral perspective on risk. But a cat model is supposed to be, our business is to be, neutral". Signalling the same but in a more critical tone, AIR's Karen Clark remarks in hindsight that in the late 1990s and over the 2000s "people just started to believe them [models] too much."

Chapter 8. The Era of Catastrophe Modelling Phase 2: Users as Appropriators

From the City of London, inhabiting Lloyd's of London and offices of most large (re)insurers and major vendors, about a one-hour walk along the River Thames to the west you will reach Tate Britain on Millbank. Originally the National Gallery of British Art, the late 19th century gallery became more commonly known as Tate Gallery, after philanthropist Sir Henry Tate. International sugarcane trade since the 18th century had generated sizeable business not just for the growing insurance industry, but also for the former Liverpool grocer Tate, who had entered the sugar business in the second half of the 19th century; sugar trade, in a way, enabled both modern insurance and the Tate. While insurance was primarily struck by the threat of fires at that time, the Tate had to grapple with the threat of flooding. In early 1928, the complex ontology of flood catastrophe unfolded at the Gallery's doorstep: a rapid thaw of heavy snow in Cotswolds and intense precipitation from storms upriver in combination with a coast-side extra-tropical cyclone storm surge and a strong spring tide (intensified by the artificially deepened river channel that allowed larger ships access to London's port) pushed the Thames's level up to its highest-ever record by 5.5 metres, 18 feet (Abbott and Price, 1993). The riverbank across the Tate collapsed and flooded its ground floor galleries – the flood line still marks on its outer wall (Bastock, 2020). Among the partly damaged and hastily rescued pieces of art were also those that were influenced by Théodore Géricault and his Raft of the Medusa. Especially works of William Turner and John Martin were amongst those influenced by the Raft and now rescued from the Thames flood (ibid.).

Figure 15: "The rescue of paintings on the morning of 7 January 1928", © Tate Archive.
(Bastock, 2020)

Although not officially confirmed, the rescued painting seen above in figure 15 is said to be John Martin's 'The Destruction of Pompeii and Heraculaneum', depicting the historic volcanic eruption of Mount Vesuvius, which had premiered in 1822 at the Egyptian Hall in Piccadilly, two years after Géricault's Raft had its central exhibition there and which had influenced Martin in his later works, appropriating them in different ways (Tate, 2021; Dobai, 1977). After the Tate's flooding, Martin's painting was so damaged that it was "effectively written off" until it was eventually restored in 2011 (Tate, 2021). Actualised catastrophe can severely threaten and harm 'modelled' catastrophe, which became eventually apparent also for vendor catastrophe models throughout the new millennium.

In catastrophe risk markets, the moment when the appropriation-object of the catastrophe model and its inscribed practices shifted towards the appropriation by its users rather than its vendors, started to emerge around the second half of the 2000s amidst a second set of socio-material breaking points which continues to drive catastrophe production until today. While 2011 was the year Martin's catastrophe painting received restoration, for catastrophe models 2011 was the year of transformation, the final push into the second phase of catastrophe modelling in financial practice. And just like the first phase, it came on the heels of actualised catastrophe and a series of acts of socio-material appropriation of models and its related practices. This transformation over the 2000s and 2010s, would be central for catastrophe production, exacerbate its multiplicity, and provoke a lasting transformational shift in the appropriation of catastrophe models towards model users as the newly emerging appropriators.

While the two previous chapters on the first phase of applied catastrophe modelling emphasised the multiplicity in catastrophe production driven by the position of vendors as primary appropriators, this and the following chapter on the second phase will emphasise the appropriational shift towards model users. This shift exacerbates the multiplicity in catastrophe production and its proprietary character of 'owning catastrophe', which drives the financial ontology of Anthropocene catastrophe today. The study of this second phase starts (I) with an analysis of Hurricane Katrina, its impact on the catastrophe risk markets, vendor's appropriational reactions and the start of an increased appropriational drive by model users. This is followed (II) by an analysis of the increased embedding of catastrophe modelling into (re)insurance systems and practices. Here, a particular focus lies on the integrational similarities between the Probable Maximum Loss and Value-at-Risk metrics, the Exceedance Probability measure and catastrophe modelling's role in capital modelling, which increased users' appropriational demands. Following this, (III) the foundational role of catastrophe modelling for the emergence and take up of insurance-linked securities is analysed, the emerging position of model vendors as formalised calculation agents, and catastrophe models' roles in catastrophe securities' price discovery. The following chapter will, then, focus on the critical moment of the final push towards users as appropriators and 'owners' of proprietarily produced catastrophe, and arrive at today's state of the financial ontology of Anthropocene catastrophe.

I. Socio-Material Breaking Points and the Rise of Users as Appropriators

"I remember this one meeting in particular, after 2005. At [a major vendor], I was driving the analysis of rates in hurricane models in the US – whether we would go to higher rates, you know, based on short-term type frequencies in hurricanes. And I sat with all those clients who had just lost hundreds of millions of dollars. I explained what we are doing. And a guy on the opposite side of the table says, 'What you're saying is all great but at the end it's my money on the table and I'll do whatever *we think is right*'; so basically: 'I don't care what you're saying'." He laughs noddingly while covering his face with his hand from the Bermudian noon sun – with his formal Bermuda shorts he is clearly better equipped for the temperatures than I, who had just arrived from windy Chicago. U53 had kindly invited me for a tea at the well-attended yet tranquil terrace of the Hamilton Princess – I ended up meeting several interviewees here. A chic and established venue for formal and informal industry meetings amidst wealthy tourists on Pitts Bay Road, 'the Princess' is situated between the offices of major (re)insurance and catastrophe risk specialist firms and Hamilton's inner harbour, not far from the obelisk memorial of former Bermuda Governor and early hurricane researcher Sir William Reid.

U53 has a meteorology PhD and had worked in the early 2000s at one of the large model vendors before he switched to heading risk and modelling departments at major (re)insurance and insurance-linked securities firms from the late 2000s on. He remembers (re)insurers' reactions in his post-2005 vendor client meeting: "I realised that there is no place, like, being at the boundary where you *actually own the risk*. The only way to own the risk is to go into an insurance or reinsurance company. [By being] something in between, vendors just don't own it. What you own is your reputation and trying to get as good as you can with what you deliver, but you don't lose *a dollar* directly when something happens". And at the time when U53 had that vendor client meeting he remembers so well, something had indeed happened and dollars, lives and livelihoods had been lost.

a. Hurricane Katrina 2005

In 2005 on the evening of August 23rd, the US's National Hurricane Center (NHC) designated the birth, or 'cyclogenesis', of Tropical Depression Twelve, 175 nautical miles (about 325 km) southeast of Nassau. Soon after, socio-materially mediated by aircraft reconnaissance and Dvorak satellite image interpretation, it surpassed the critical threshold of 63 km/h, 39 mph one-minute maximum sustained wind velocity, which turns it into a tropical storm and prompted a sinister baptism: on the morning of August 24th, Tropical Depression Twelve was given a name, Katrina. On August 25th, it had turned westwards towards Florida and generated more intense convection until in the evening further measures and estimates had let it breach the threshold of 119 km/h, 74 mph maximum sustained winds.

Katrina had been made a Category 1 hurricane on the Saffir-Simpson Hurricane Scale (SSHS). Interacting with a north-eastern tropospheric flow, Katrina pushed west-southwest gaining 130 km/h, 80 mph and made its first landfall between Broward and Miami-Dade County in Florida at Category 1. It did not disintegrate and mostly maintained its form during its six-hour on-land passage through the peninsular, although Key West and Miami Doppler radars, in a combination of surface observations and estimates, had demoted Katrina back to a tropical storm as they socio-materially mediated a loss in its maximum sustained wind speed, something on-land journeys of tropical cyclones tend to entail. Interacting again with the moist air of the Mexican Gulf's sea surface, Katrina re-emerged as a hurricane in the early hours of August 26th. (Knabb et al., 2005)

Over the following couple of days, Katrina intensified in its transit westwards through the Gulf. Tracked by infrared satellite imagery identifying interchanging formations and deteriorations of eyes of the storm, Katrina expanded heavily and doubled its size with tropical storm-strength as far as 260 km, 160 miles from its centre on the evening of the 27th. By the turn of the day, Katrina had shifted north-westwards and until the evening, aircraft, satellites, radars, stations and ships observations and estimates had picked up windspeeds of 270 km/h, 170 mph, promoting it to the highest Category 5 hurricane strength. Before making its second and third landfalls in Louisiana/Mississippi on August 29th, Katrina had decreased in windspeed to a higher-end Category 3 hurricane with landfall wind velocities of about 200 km/h, 125 mph. Devastatingly, however, it had further expanded with tropical storm-strength winds as far as 370 km, 230 miles from its centre (ibid.). This extraordinary size of Hurricane Katrina would turn its interaction with the socio-material environments at its second and, especially, third landfall locations into what since then became to be known as a super catastrophe or 'Super Cat' (Muir-Wood and Grossi, 2008: 315).

As mentioned in chapter 3 on the development and influence of the SSHS, Hurricane Camille in 1969 had devastated this part of the US's Gulf Coast and prompted development of levees and other structural protection measures alongside environmental alterations in the decades since then. Especially New Orleans and its wider socio-material environment had been subjected to change. Traversed by the Mississippi River, situated between Lake Pontchartrain and the Gulf-side Lake Borgne lagoon, the city lies on average 1.8 m, 6 ft below sea level and its coastwards south is made up of wetlands and marshes. During the decades before the new millennium, especially the wetlands saw considerable reduction due to artificial channel constructions in order to increase shipping on the Mississippi and petroleum exploration across the marshes, with an annual wetlands loss of over 100 km^2, 40 mi^2 by 2000 (Schwartz, 2015: 321). The increased erosion of the wetlands and the flushing out of sediment into the sea had been further increased by storm-surge protecting levees which channelled outflow even more, sanctioned by economic development and the US Army Corps of Engineers (ibid.).

Yet, the marshes and wetlands themselves actually interact with storm surges in an absorbing way so that every three miles of them take up about 30 cm, 1 ft of storm surge water, "acting as mother Nature's insurance policy against hurricanes" (NG, 2012). However, there are of course only Anthropocene 'insurance policies' and they proved to be particularly active components of socio-material catastrophe here, to the extent that "'Katrina' has become shorthand for all that is unnatural about natural disasters" (Schwartz, 2015: 320).

Camille, a major reference point for defence systems in the region, had been a Category 5 hurricane but it was a far more compact storm (Knabb et al., 2005). In contrast, at landfall only Category 3, Katrina's extraordinary size produced a storm surge of 10m, 33ft across the coastlines of Louisiana, Mississippi and Alabama that actually corresponded to a Category 5 on the SSHS (Schwartz, 2015) – the primary reason why the Scale since then excludes flood indication altogether. Upon Katrina's landfall near the Mississippi River mouth, its storm surge was only marginally decreased by the heavily reduced wetlands, and the surge pushed upstream and into Lake Pontchartrain and the Lake Borgne lagoon. The complex socio-material ontology of flooding unfolded on New Orleans with multiple levee breaches and failures, and artificial channels increasing waterflow into the downtown areas, and old drainage canals heightened the runoff of water in low-lying parts of the city (Kelman, 2020; Muir-Wood and Grossi, 2008; Schwartz, 2015; Warrick and Grunwald, 2005). Within a day, 80% of the city were submerged by water of up to 6m, 20ft, and it took many weeks to pump the water out (Knabb et al., 2005). Like Catania in Fabio Giampietro's Thanatos painting (mentioned in chapter 4), Anthropocene environment had turned on itself and produced a socio-material disaster that left 1,833 people dead, displaced 770,000 residents, and destroyed or severely damaged 300,0000 homes (GAO, 2008; USCB, 2015).

Across all affected areas, Katrina produced a total loss of about $125 billion, which is until today the costliest tropical cyclone in global history (Swiss Re, 2020). Since a large portion of the damages incurred by Katrina were flood-related, it infamously wrecked the National Flood Insurance Program's (NFIP) finances, which in 2006 came to be considered by the US Government Accountability Office a "significant fiscal threat to the state", kicking off its long-lasting and politically contested overhaul process (Elliott, 2017: 421). Not including $16.3 billion NFIP loss claims, Katrina amounted for the (re)insurance industry to a $49 billion insured loss (Swiss Re, 2020). The echo of the complex socio-material ontology of floods in the financial epistemology of insurance led to a wave of litigation cases since the devastating destruction of this 'super cat', often leaving only the foundations of homes for inspection, made it particularly difficult to attribute loss to privately insured wind damage versus publicly insured flood damage (ibid.). Epistemic blurriness in loss causation and the seeping-in of non-covered loss into covered loss is known in the industry as 'coverage leakage' and prompted a wave of rewording of contracts and often the henceforth exclusion of any flood damage in such policies (Guy Carpenter, 2015b).

"After the hurricanes of 2005, obviously, a lot of problems were exposed in the models", remembers U60. Of the many issues, the epistemic capture of the ontology of flooding for policy-related loss was a particularly exposing one: "the highly touted computer simulation models […] didn't work as well as some insurers had hoped" (Westfall, 2005). Although secondary peril flooding had been part of the models' hazard modules to varying degrees, its near blanked exclusion from policy covers generally left especially storm surge loss underappreciated. But also beyond coverage exclusions, Katrina exposed models' proprietary grammars of interaction as overemphasising wind damage and underappreciating wind-driven coastal flooding, storm surge and inland flooding: "many assumptions have been incorrect" (Marsh, 2015b). After all, catastrophe production is driven by goal setting and floods were, at least in part, out of scope of those particular goals' 'realities'.

b. Vendors' Appropriation Acts after Katrina

In catastrophe finance's epistemic practices and with reference to both the moment in the loop of Anthropocene catastrophe and the position of the appropriator of models, there is a difference between pre-catastrophe 'modelled loss' and post-catastrophe 'projected loss' (c.f. Muir-Wood and Grossi, 2008). Projected loss are estimates derived from catastrophe produced by vendors as a concrete reconstruction of actualised catastrophe along and immediately after its unfolding – the moment of consolidating 'truth' in the loop of Anthropocene catastrophe. For vendors, these are the moments of 'sticking out your neck' in an unfolding situation, and with Katrina this consolidation was particularly tumultuous. In addition to the simulation aspects of inaccurate assumptions and party unmodelled flooding, the socio-material mediation turned out to be a problem, too.

Projected loss production is based on "rapidly acquired additional information" (Muir-Wood and Grossi, 2008), i.e., the sensing of socio-material aspects used to reconstruct catastrophe's interactions and infer its environment's state. Not per se unusual for landfalling cyclones but to a much larger extent in Katrina's case, most on-land observation instruments and weather stations had been destroyed or damaged by flooding and intense wind speeds (Knabb et al., 2005), whose appropriated readings and estimates are essential for hurricane path and wind speed reconstruction in post-event modelling. Right after Katrina had disintegrated not long after hitting the coast, RMS, AIR and EQECAT's initial projected insured loss estimates had been between $15 and 25 billion, capturing only about one third of what it ended up being, although an update by RMS two weeks later corrected its estimate to about $60 billion (Marsh, 2015a; Westfall, 2005) – in the loop of Anthropocene catastrophe, multiplying catastrophe is socio-materially messy and not at all straightforward, and the same is true for consolidating catastrophe.

In contrast to projected loss, pre-catastrophe or 'modelled loss' is the result of catastrophe modelling appropriating insurance practices, as described in the previous chapters, for instance in rate-setting, risk aggregation or reinsurance buying – catastrophe produced in situated multiplicity before catastrophe actualises. Here, Katrina revealed that model users were indeed not in a stabilised position of an appropriator. A Swiss Re manager observed at the time, that "local [insurers] using the models were off by a factor of two or three […] There is a lot of human error involved." (Westfall, 2005). Unsuccessful appropriation of models was driven primarily by firms struggling to format data correctly for the model-based production of meaningful numbers: the sometimes inappropriate provision of proprietarily sensed socio-material environment in the form inaccurate or low-quality exposure data, "if the data is not correct, it can cause significant problems." (Westfall, 2005). Infamously, for instance, floating casinos had been wrecked by Katrina and catapulted over 1.5 km, 1 mile inland (Belson and Rivlin, 2005), while they had been captured simply as 'casinos' and represented as on-land and structurally sturdy buildings in exposure data files, with the result of heavily underestimated modelled loss (Mitchell-Wallace et al., 2017; Muir-Wood and Grossi, 2008).

Similar to Hurricane Andrew, exposure data quality and provision had been revealed as a central issue in insurance practice, but this time also impacted catastrophe models that had since then been integrated into industry practice. Yet, even beyond data practice, the constantly changing and in-flux Anthropocene environment also emerged as a more pronounced issue for modelling. For instance, as constant new construction and inflation in real estate markets change dramatically, sometimes even over the course of just one year, for RMS model users in Katrina's case this in-flux environment alone led to an understatement of modelled loss of 10% to 15% (Muir-Wood and Grossi, 2008: 313). Overall, due to modelled loss issues many insurers had to significantly raise capital because average annual loss (AAL) had been understated and Katrina's actualisation provoked an up to 10-fold loss (Marsh, 2015a). Across all affected regions and portfolios, models appropriating insurance firms' loss calculations had "underestimated losses by as much as 30 to 60 percent" (Guy Carpenter, 2015b: 10).

With the turn of the millennium, the new high-loss regime continued to unfold over the 2000s and 2010s. Accompanied by the $32.5 billion insured loss terrorism disaster of 9/11 in 2001, catastrophe further provoked ever higher loss in the years to come. Before Katrina, the 2004 North Atlantic hurricane season had already produced nine hurricanes, six of which were 'major' hurricanes (Category 3 and higher), nearly double the 30-year average (NOAA, 2019c). Particularly devastating were Charley, Frances, Ivan and Jeanne, which accounted for the majority share of the season's $61 billion total and $23 billion insured loss (ibid.; Guy Carpenter, 2015a). By the end of 2004, Swiss Re emphasised the season's imperative for using catastrophe modelling in a more integrated way, stating that it had demonstrated how "event-based risk analysis successfully withstood the challenge" (Swiss Re, 2004). A year later, the 2005 season had dwarfed its predecessor by causing a total loss of $171.7 billion of which $58 billion were insured. Katrina had been accompanied by an unprecedented number of 27 named storms, 15 of which made it to hurricane strength. Katrina was one of four Category 5 hurricanes, with the until today most intense Wilma with almost 300 km/h, 185 mph maximum wind speeds.

In addition to the 2004 Indian Ocean earthquake and tsunami (the deadliest disaster on record, but not equally impactful in terms of insurance loss[47]), Pacific typhoons, and a number of tornado-related events in the mid-2000s, Hurricane Ike in 2008 turned out to be another major event for the industry. Hitting across the Caribbean, Texas and Louisiana, it stood out as an extremely long-lasting Category 4 hurricane which, landfalling at Category 2, travelled with damaging high wind speeds and precipitation as far as Pennsylvania (Berg, 2009). Ike caused $38 billion total and $18 billion insured loss (ibid.; III, 2020), and turned out to be yet another major event that materialised loss far outside the range of model-produced catastrophe (Wyss, 2014). Like Katrina, it produced a much more intense storm surge than expected of its category, and due to its long inland travel, it caused damage far deeper inland than thought possible (Willis, 2018). Among the mainly flood-related miscalculations of models, especially the assumption of vendors that constructions had adhered to the latest building codes was proven wrong, which became a major loss driver in its own right (Marsh, 2015b; Mitchell-Wallace et al., 2017).

The concentration of actualised catastrophe throughout the mid-2000s and their complex and long-lasting consolidation periods provoked a series of appropriation acts manifesting in broad and deep adjustments by vendors to their proprietary grammars of interaction. The moments of consolidation in the loop of Anthropocene catastrophe manifest in reflective hermeneutic readings of vendor models by vendors' internal expert communities and result in re-contextualisations of modelled catastrophe within actualised catastrophe and the eventual update of their models. Exacerbating the multiplicity of catastrophe with situated re-contextualisations of grammars of interaction and access to the proprietarily mediated socio-material environment via loss claims, an AIR modeller noted: "[Katrina] will change how modeling is done […] Over the next year, we will collect a lot of claims data, weather data and scientific analysis. It will be interesting to see." (Westfall, 2005).

Often, vendors rank their individual models by the degree of their mission criticality to the functioning of the global insurance industry, and US hurricane always ranks at the top level. While the higher ranks receive more regular internal reviews – "there'd be some facets of them that we may revisit

[47] Despite its excruciating death toll of nearly 230,000, overall catastrophe damages have settled at $8.7 billion (Fenn, 2014), and insured loss projections varied heavily but settled at about RMS's projection of $3 billion plus $1 billion in life, health and travel insurance loss (RMS, 2005).

every year" – the mid-2000s provoked a series of particularly deep changes and adjustments across all vendor models – "if events happen and they give us lots of new information […] there's a process to absorb information which is challenging to what your model currently does" (I03).

Vendor models' performances amidst consolidations of the mid-2000s events brought about multiple appropriation acts by vendor firms to hazard, vulnerability and loss modules of their hurricane models. For instance, EQECAT's hazard module integrated a numerical hydrodynamic model to add storm surge as an interactional dimension to hurricane catastrophe and RMS added finer-grained ground elevation data to its model to better account for potential flood areas (Guy Carpenter, 2015b). All vendors also included high windspeed for further inland locations (Marsh, 2015b). Most crucially, the increased cyclone activity of the 2004 and 2005 seasons provoked modellers to incorporate this apparently patterned variability into a new focus on an ongoing warming trend since the mid-1990s which is connected to the varying sea surface temperatures of the Atlantic with respect to the Atlantic Multidecadal Oscillation (AMO) and the El-Nino Southern Oscillation (ENSO) (Muir-Wood and Grossi, 2008; Swiss Re, 2020). Consequently, vendors adopted the so-called 'near-term view' of tropical cyclone activity based on currently warmer sea surface temperatures, i.e., an elevated frequency probability of hurricane formation. It was integrated to varying degrees in AIR's CLASIC/2 version 8.0, EQECAT's WORLDCATenterprise version 3.8 and, most crucially, into RMS's RiskLink in different forms since its version 6.0 and which drove the near-term view more than any other model vendor – introduced above at the start of this section, U53 referred to this particular change that he explained to vendor clients after 2005. The near-term perspective would become a major and contested aspect in catastrophe modelling over the coming years and would significantly contribute to the final push of shifting users into the position of the appropriator and the transformation of catastrophe modelling in 2011, which will be examined in detail in the following chapter.

Amidst catastrophe's consolidation periods, vendors received a flood of claims data from model subscribers in the aftermath of each of the 2000s events, which led to substantial calibration of the crucial proprietary damage functions in models' vulnerability modules. RMS, for instance, introduced square footage as a new parameter in catastrophe's grammars of interaction, and also added "Floating Structures" as construction and "Casinos" as occupancy classes to account for the miscalculation of damage to the vessel-borne casino loss (Guy Carpenter, 2015b: 11). AIR added a host of new construction types based on different building materials and recent building vintages as well as new occupancy types that had turned out to be particularly vulnerable, such as gas stations, aircraft hangars, and golf courses. The loss modules of vendors were heavily adjusted to incorporate so-called 'demand surge', i.e., the increase in demand for rebuilding and repair services and material, and therefore their availability's contraction, after major disaster events. AIR included demand surge in 2005 and EQECAT in 2008, while RMS added it to their version 2006 model, also including coverage leakage. All these components remain in the most current versions of their models and originated from this period.

c. Model Users as Appropriators

In addition to (re)insurers' heightened exposure to actualising catastrophe, the socio-material dimensions of catastrophe would now also be driven by exposure to the increasing multiplicity of 'views of risk' across counterparties in the industry and, chiefly, by their exposure to changing 'views of risk' in vendor models (Mitchell-Wallace et al., 2017: 123). Especially after 2005 and the very vivid wave of model adjustments, the difference in roles of vendors and users became more apparent. Over another drink at the Hamilton Princess, U53 reiterates, "if you provide a poor model – to some extent we did prior to 2005 in terms of [hurricane] frequency capture – and it goes wrong, you have a scientific obligation to do something right. And so, you feel like you own the risk, but you don't own it as someone who's bonus and money is on the table." (Re)insurance prices increased as a reaction not only to actualised loss, but also to a significant degree connected to "increases in technical pricing due to catastrophe model changes" by about 20% (Guy Carpenter, 2015b: 8). Reinsurers explicitly priced these changes into their contract renewals and modelled increases in annual average loss (AAL) in 2006 along the US's south and southeast to up to 40% (ibid.; Marsh, 2015b: 2).

"It's really after 2005, people were saying: 'What the heck is going on? 2005 after 2004, what's going on?'", remembers U60 during one of my visits to his office in Hamilton where we discuss the mid-2000s series of appropriation acts. "It was scientifically legitimate for them to make the changes because they learned new things. [...] But that prompted that the users felt that they need to understand this better. If I trust that your things are proprietary, at least I need to feel comfortable, but it was that people were uncomfortable with these rapid changes. Doesn't matter if it is the vendors changing it or science changes it. So, I think collectively, the users felt they want to understand this better." Also, U53 describes this situation after having switched from a vendor to the industry side: "at the end, you [(re)insurers] gotta deal with *one number*, you price for it. In the primary [insurance], you have a rate that applies to a policy that's calculated per model […] You have constraints in how regulators look at you. You gotta deal with all of that. You've got a business to run." He explains that model changes have real-world impact in practice and pricing and that vendors' explanations and justifications for model variability after adjustments cannot always bridge into practice: "But in the end, the policy holder pays 1578 bucks, not 1578 plus or minus 200. You've got to transform the uncertainty into a real number. We [(re)insurers] cannot qualify the uncertainty into your [vendors'] sound speech. […] if your analysis is completely wrong, then it goes wrong. It's money, it's not just risk of damage to your reputation […] Of course, as a vendor, you need to grow and a poor model will hurt that, but an event itself is not going to put your belly up".

While the old ways of catastrophe risk assessment and management in (re)insurance had relied mainly on professional underwriting experience and which was initially confronted by vendor modellers after the early 1990s, the mid-2000s proved to model users that models rely on experience as well, if only in a simply more explicitly socio-material way: "Catastrophe models need constant updating based on experience. Even an up-to-date model can miscalculate the potential damage from a storm that behaves in an unforeseen manner – potentially by a significant margin." (Marsh, 2015b: 2). However, in contrast to the socio-material breaking points of the early 1990s and despite the contrast between (re)insurers' monetary and vendors' potential reputational loss, no wave of bankruptcies plagued the industry in the mid-2000s and neither did it hurt vendors' ever centralising position in proprietary catastrophe production. In fact, "[a]lthough Katrina presented insurers with their biggest insured loss of all time […], the hurricane failed to bankrupt a single company", which, despite the unveiled flaws, was accredited to catastrophe models having "passed their first major test in August 2005" (Borscheid et al., 2014: 133). Industry model users' interpretation of models' relative success magnified the perspective of an overall manageability of increasing high-loss catastrophe through the industry, which further animated business. "Instead of ditching the technique, providers of cat modeling are using Katrina as an opportunity to refine or overhaul their programs to account for the powerful storm activity expected to batter the United States for years to come." (Westfall, 2005). By 2009, the rate of usage of catastrophe models in the global industry had risen to over 90% (Grossi and Zoback, 2009: 4).

At the same time, global attention to climate change issues had been risen across the industry throughout the decade, with the IPCC's 2001 and 2007 Assessment Reports, which "heightened insurance and reinsurance concerns and demand for catastrophe modelling" (Mitchell-Wallace et al., 2017: 9). Structurally, both with respect to catastrophe modelling in risk practice as well as vendors' central role across the industry, all major rating agencies, A.M. Best, S&P, Fitch and Moody's, expressed a preference for the newly applied short-term view on hurricane frequency projection, as well as enhanced "accuracy of exposures entered into catastrophe models, insurance to value analysis and geocoding." (Guy Carpenter, 2015b: 9f). Increasingly, rating agencies were also requesting (re)insurers to "explain their choice of which catastrophe model or models they used to represent their view of risk, as well as which options within the models were utilized. Companies were expected to demonstrate that managing catastrophe risk was integrated into their risk management strategies." (ibid.).

The increase in prescribed appropriation of catastrophe modelling by rating agencies provoked a further embrace of models by the industry. Since the links between actualised and modelled loss, risk capital and solvency provision, and price movements appeared to be driven much more than expected by models' appropriation of risk practices, the position of users as the appropriated became increasingly apparent and problematised. "I should not just take the vendor model as it is, I should be able to modify it.", remembers U60 to be the most pressing emerging sentiment at the time. "And there's a buzzword in that phase, it's people say: '*Own your view of risk*'." Conceptually, the etymological backdrop of 'appropriation' serves well here, since it is precisely the mode of 'making something someone's own' that is at the core of what model users started to embark on from the mid-2000s onwards. Just like Turner or Delacroix interpreted Géricault's Raft and his appropriations and techniques, and created their own appropriations of the Raft, catastrophe model users slowly started to do so with vendor models and would switch into the position of the appropriator themselves about a decade later. One important driver of this switch was the industry's embeddedness in macro-level developments around risk measures in the financial sector more broadly and the increasing conceptual and practical applicability of catastrophe modelling within them.

II. Exceedance Probability, Value at Risk and Capital Modelling

"We called it the 'loss exceeding probability' curve, so LEP. And then one of my colleagues, who had previously been in the military, vetoed the term LEP because in military parlay the LEP is the 'least essential personnel'." Hemant Shah and I both laugh while sitting in a start-up incubator office near North of the Panhandle in San Francisco – in 2018, RMS's co-founder had just retired as the firm's CEO, a post he had held since its 1989 founding. "So, we stuck with just 'EP' or 'exceedance probability' curve". While the term exceedance probability had been popularised by RMS, the basic concept was common to all vendor modellers, "we just called it 'loss distribution'" in the earlier models, remembers AIR's founder Karen Clark, and then "RMS invented that language". These concepts emerged out of the vendor context and formed what became a "terminology specific to this industry" (Mitchell-Wallace et al., 2017: 26). Against the backdrop of Mackey and Gillespie's notion of marketing and its role in the shaping of technology (1992: 691), creating concepts and embedding a language around what then becomes a form of demand is a powerful aspect of contextual socio-material appropriation. As an appropriation object, the exceedance probability concept emerged as a central output and market device. Catastrophe modelling's galvanised re-contextualisations of assemblages of different practices and devices produced the exceedance probability curve as one of its most concrete objects in what Taylor interprets as "a new actuarial synthesis" (2020: 1139). As argued in chapter 5, in art as well as in technology there is 'nothing before hybridity' and the assemblage of previously existing elements, not the 'origin' as such, becomes the important aspect in the take up of new practices and devices.

The exceedance probability is of course based on the loss values of model-produced catastrophe. The most basic output of a catastrophe model are the so-called event loss tables, or ELTs, which list the multiple loss results per simulated event to portfolios of specific insured objects. ELTs may vary slightly in terms of the factors they describe but all of them entail a set of central loss statistics per simulated catastrophe: a) the annual occurrence frequency of the event, b) the mean loss produced by the event, c) the standard deviations around the mean loss, and d) the exposure value of the inventory at the location (Mitchell-Wallace et al., 2017: 29ff). Sometimes, ELTs contain all simulated events a model has run for the specific hazard type, area and book, but more often they are sample sets of the overall multiple-10,000-events-strong catalogue to reduce computational demand. In both cases, the event catalogue construction is key to the resulting loss projections (see Weinkle and Pielke, 2017), which is a key competence and, therefore, a hardwired position of epistemic power of vendors. These ELTs are, for instance, the basis on which central metrics such as the average annual loss (AAL) and the risk load are calculated from.

Event ID	Rate	Mean	Sdi	Sdc	Exposure
1	.10	500	500	500	10,000
2	.10	300	400	800	5,000
3	.50	200	300	400	4,000

Figure 16: RMS-style Event Loss Table. (Home and Li, 2017: 31)

The exceedance probability (EP) is usually represented in form of a distribution, the EP curve, and ingests all individual events represented in the ELT. On the most basic level, this involves ordering the mean loss of events in descending order and determining the largest loss event's occurrence frequency as the year's loss exceedance frequency (Mitchell-Wallace et al., 2017: 32f). Combined with a frequency distribution, such as Poisson or negative binomial, the exceedance frequency is used to calculate the probability of a larger loss event happening per year for each individual event in the ELT. In Figure 17, for example, the exceedance probability of the portfolio for $100 million, i.e., the probability of a loss surpassing $100 million in the given year, is 1%. The concept of exceedance probability is the result of re-contextualisations and assemblage of aspects from several different approaches. For instance, while the EP curve feeds on the data of ELTs, part of its conceptual grounding is a somewhat inversion of long established actuarial practice, where annual average loss for insurance policies would be computed "using the conditional average of claim size, given that the claim exceeds the deductible" and the same being applied in reinsurance but for the exceedance of the retention level where the reinsurance cover starts from (Artzner et al., 1999: 223). The focus, so to speak, had here been on the non-breached side of a loss exceeding threshold, or in U15's words: "The concept of EP curves is a typical actuarial thing. That's how actuaries show any curves for non-cat stuff. So insurance was used to this: actually rather the non-exceedance, where they can show the non-exceedance of a particular loss. So that comes from actuarial science". An arguably more impactful aspect that has been appropriated more concretely in the EP concept is that of probable maximum loss (PML).

"The exceedance probability concept [...] started with the notion of a simpler concept called probable maximum loss", notes Shah. As discussed in detail in chapter 3, PML is the maximum outcome of an event ascribed to insured objects in specific areas or portfolios from which the maximum loss is calculated. The PML is then the loss at a probability relative to the event's return period or occurrence probability. PML itself was in part a fusion of earlier insurance risk practices and concepts from earthquake engineering, especially from Cornell's PSHA and the "probability of exceedance" of ground motion above an annual average (McGuire, 2008: 334), and socio-materially in the earthquake engineering realm, for instance, buildings were "designed to the 10% chance of non-exceedance in 50 years" (Shah).

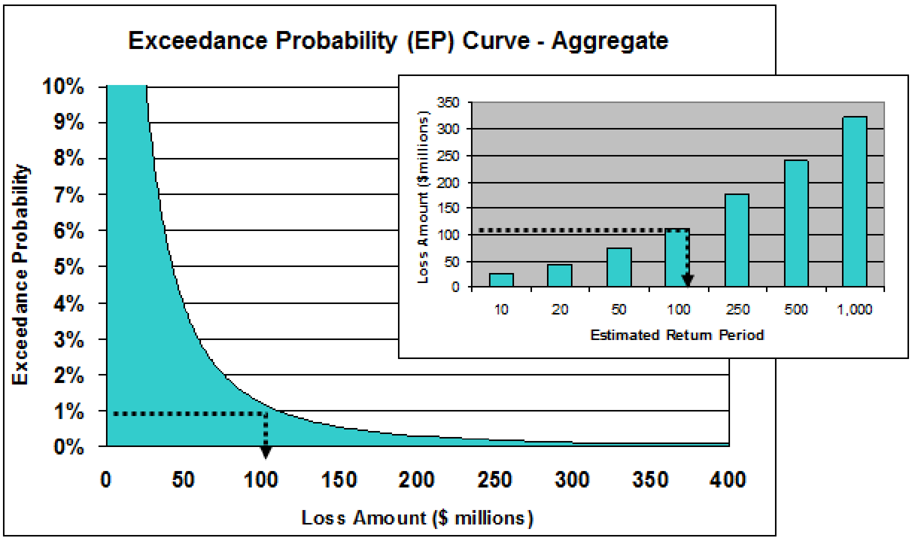

Figure 17: Exceedance Probability Curve (AEP). (Verisk, 2017)

The PML approach was embedded in the EP metric where, mathematically, PML is the inverse EP function (Home and Li, 2017) – in Figure 17, the EP equates to an aggregate PML of 1-in-100 (Verisk, 2017). The EP curve helps to determine by what annual probability any specific loss value will be surpassed, which allows to make risk management decisions in line with a firm's level of acceptability of risk, i.e., which probability of which loss exceedance it wants to tolerate. In this way and as an extension of, for instance, RMS's 'bounded max' approach in the early 1990s (discussed in chapter 4), the EP curve is a fully probabilistic measure of extreme event risk that is, most importantly, applicable across a portfolio and different events. The EP curve accomplishes a cohesive incorporation of different catastrophe events that might impact a portfolio. While traditional PMLs until the 1990s were in practice somewhat limited to individual events, and the 'bounded max' approach only a quasi-probabilistic normalisation across differing probabilities of events across locations, the EP concept would "integrate this across all events [...] [as] a way of managing your [risk] accumulations" (Shah).

As such, the very practical development of the EP curve accompanied a broader conceptual debate around the coherence of financial risk measures in both academia and financial professions. It was a rather open acknowledgement of performativity of risk measures devices in which the device is necessary to grasp what it is supposed to measure: "the notion of temperature is difficult to conceptualize without a clear notion of a thermometer [...] Similarly, the notion of risk itself is hard to appreciate without a clear idea of what we mean by a measure of risk." (Dowd and Blake, 2006: 198). Here, especially the employment of forward-looking values in random variables, i.e. not purely historic values, as the basis of risk calculation was emphasised (Artzner et al., 1999). This broad interest in risk measures was also motivated by a very practical development throughout the financial industries since the 1980s with the emergence of the Value-at-Risk metric**.**

a. Value at Risk and Probable Maximum Loss

While Hemant Shah and I continue talking about the evolution of the PML measure, I ask him about its roots in insurance from which the geoscientist Steinbrugge picked up on, and whether there are any other links today that connect these measures to financial practices. "Yeah, yeah! I knew Gregg Berman when he ran Risk Metrics Inc. You know, actually, we came to understand that world too". He refers to Risk Metrics, a company that formalised the banking sector's Value-at-Risk measure, or VaR, during the 1990s. It emerged against a backdrop of nearly half a century of developments in financial economics and risk practices in banking, with a similar approach and technique as PML. This similarity would over the 2000s enable catastrophe model users to more actively appropriate vendor catastrophe models and outputs such as EP curves and ELTs in *capital modelling*, a realm in which they were already experts.

Financial economics as a discipline progressed especially due to developments in financial risk analysis and management, most notably in the mid-twentieth century with the creation of portfolio theory (Power, 2007). Starting with Markowitz's paper 'Portfolio Selection' (Markowitz, 1952), risk analysis in finance flourished during the second half of the 20th century. Portfolio theory presupposes risk-averse investment portfolios and attempts, by selecting e.g., specific stocks, to optimise expected returns based on a specific level of market and equity risk. Practically though, Markowitz's original approach proved to be too complex with too heavy data requirements (Allen et al., 2009). Simplified versions were derived for, e.g., pricing assets based on risks (most notably the Capital Asset Pricing Model, c.f. Sharpe, 1963, 1964). Allen et al. state that, after the core assumption was called into question that only market risk[48] would be important for securities pricing (whether it can really tell about actual securities returns), eventually another measure of risk evolved, the Value-at-Risk approach

[48] As opposed to the underlying company risk of e.g., the individual equities in the portfolio.

(2009). Another perspective is presented by Holton, who suggests that Markowitz's approach, and thus all that was based on it later on, was already a form of VaR (2002).[49]

VaR is based on the idea that an investment portfolio of assets holds a present market value with an unknown future market value. The central risk-related question for portfolio management is to figure out "the maximum likely loss over the next trading day" (Dowd and Blake, 2006: 195). The basic principle and common to all VaR variations is drawing on historic or simulated[50] price movements of assets over a set array of time (e.g., 100 or 20 days), whereas the time array defines the inference-statistical confidence interval (e.g., 1 or 5 percent). Here, the strongest decrease in the asset's value over that period becomes the central threshold. In its most basic form, mean variance and standard deviation are calculated while the probabilistic output is the asset's daily loss in value equalling or exceeding the strongest price decrease within the given timeframe denoted by the confidence interval. This is calculated for all the assets in the portfolio and aggregated to derive the overall portfolio's value at risk. It is, thus, in a way a risk assessment towards 'extreme events'[51] of short spans of histories of asset values, whereas, however, everything beyond the exceedance threshold (i.e., the 'tail') is not looked at in a basic VaR measure.

On a practical level, VaR became more commonly used amidst developments in financial markets during the 1970s and 1980s, such as the introduction of asset-backed securities, over-the-counter options, oil and commodities derivatives, and especially the proliferation of leverage in financial instruments (Holton, 2002). With the broader introduction of computers in financial practice, the financial data industry grew and produced datasets of historical price-developments, which were vital for VaR's data requirements. Changes in regulation of financial instruments in 1980 increased market volatility, with VaR being included in capital modelling as a mandatory measure by the US Securities and Exchange Commission, or SEC (Dale, 1996). It was adopted by US security firms and individually modified for internal risk assessments (Holton, 2002). In 1993, the investment bank J.P. Morgan promoted its internal VaR system to the banking industry, but rather than offering it as a distinct software package, J.P. Morgan published their methodology and metrics, convincing software vendors to produce software accordingly. This basic system, named "RiskMetrics" (J.P.Morgan/Reuters, 1996), "was not a technical

[49] While Allen et al. regard VaR as a method, Holton seems to understand VaR more as a broader methodology framework. One rather empirical reason for preferring the methodology perspective is the vast variety of different VaR types in practice today, such as Conditional or Tail Value at Risk (Capiński, 2015; Cossette et al., 2016), or Cash Flow at Risk (Maurer, 2015).

[50] E.g., Lietaer (1971).

[51] However, precisely this has been heavily criticised as a major flaw and short coming in value at risk methodology (e.g. Lockwood, 2014; Rowe, 2013; Taleb, 2008).

breakthrough [...] The important contribution of RiskMetrics was that it publicized VaR to a wide audience" (Holton, 2002: 21). Since the start of the 1990s, VaR had been implemented as a risk measure; e.g. the UK Securities and Futures Authority introduced VaR in 1992, Europe's Capital Adequacy Directive in 1993, and the Basel Committee in 1996 (Holton, 2003).

In hindsight, it is often assumed – especially on the capital markets-side of the catastrophe risk business – that PMLs are a variant of VaR. Historically, however, they seem to have developed rather in parallel, although the influence of financial economics on actuarial science and practice over those decades cannot be denied (c.f. Dowd and Blake, 2006). The fundamental difference between the measures is that PML identifies the maximum or most likely extreme loss while VaR refers to the minimum loss to be exceeded (AIR, 2017) and usually assumes a normal distribution. They are, nonetheless, critically similar in what one can actually *do* with them. Practically, the loss is outputted as a quantile measure based on a probability distribution and the probability of an event p. In this sense, a VaR with p=1% is like a PML at a 100-year return period. A PML is on paper "essentially the same as Value at Risk" (Hochrainer, 2007: 115). U93, a financial risk analyst and catastrophe model user in the insurance-linked securities sector notes that "the EP curve is just a form of Value-at-Risk curve".

The conceptual and practical similarities between PML and VaR socio-materially underpinned the stronger merge of risk practices in natural science, (re)insurance and finance with the introduction of commercial catastrophe modelling. Meanwhile, the economic and political context leading up to these developments was growing global connectedness and liberalisation of markets. With the continuous dismantling of provisions of both the US's 1932 Glass-Steagall Act (separating commercial and investment banking) and its 1956 extension, the Bank Holding Company Act (separating insurance and banking), the Bretton Woods system's failure in the early 1970s, and the liberalisation of OECD markets in the 1980s, global movement of capital accelerated (Borscheid et al., 2014; Werner, 2005). (Re)insurance firms expanded by horizontal integration, i.e., covering the whole value chain of insurance, reinsurance and retrocession, with the advent of stronger shareholder value imperatives and, practically, increasing demands for firms' capital management and modelling. In the 1990s, banking and (re)insurance began to be regarded functionally relatively similar as 'risk-transforming entities' (ibid.). Especially global reinsurance companies since the 1980s did not fundamentally differ from banks when offsetting underwriting risks through their investment strategies and faced the same issues from interest rate and currency fluctuations after the end of Bretton Woods. Derivatives was banks' answer to these fluctuation problems while reinsurers ventured into financial reinsurance. "[R]einsurance companies had to rely on analytical and methodological imports from financial mathematics, as had become customary at banks", and on the asset management side they "learnt from banks how to generate additional income from new financial products […] both applied new financial market and risk models to better control their capital resources" (Borscheid et al., 2014: 224).

These developments led to the eventual adoption of VaR in actuarial practice over the late 1990s and early 2000s (Dowd and Blake, 2006). "This world started sort of crossing over", remembers model vendor veteran I01:

> "Around that time, you started to see in insurance people to come from finance into key risk management roles. So all of a sudden, the chief risk officer you would meet was actually formerly the CRO of the X, Y, Z division at Goldman Sachs. […] So, it wasn't just an insurance actuary or an underwriter. All of a sudden, you had financial services quants playing key roles and what they started asking us was, 'we need a coherent risk management platform. We need to do this consistently. We want to dynamically allocate capacity to underwriting. We want to price not just for the expected loss, but for the marginal contribution of capital. These were all words from finance, not from insurance as much. I mean, now it's all the same concepts and certainly insurance understood these concepts. But that wasn't the prevailing practice of that time because so much of insurance grew up around uncorrelated, diversifiable risks. So much of the capital markets has grown up around quantifying correlated risks in diversification."

Catastrophe model vendors picked up on the intersections of banking and (re)insurance and looked at analytics firms in the established investment industry. Prior to the establishment of catastrophe bonds and the increasing importance of capital markets for catastrophe risk management, RMS, for instance, had consulted on earthquake-related mortgage risk for mortgage-backed bonds of some investment banks: "Because a lot of earthquake risk is uninsured, it's conceivable that you have large scale default and that could undermine the bond. So we sort of got exposed to how you structure bonds and we had meetings with bankers about 'okay, how could our models be applied to that?'", remembers Shah. Especially with respect to measures such as VaR, vendors realised to what extend analytics increasingly drove markets. In investment and banking in the 1990s, there were "established companies that are helping make markets, because they're providing industry-standard analytics. They [the models] helped not only the cost of capital but pricing the deals. And there's analogues in market risk, credit risk, etc. There was Algorithmics up in Canada, there was Risk Metrics and MSCI in New York, there was Barra out of Berkeley. And so I went and talked to those guys [...] 'How do you develop a standard?'". And the EP as a device turned out to become a standard measure for catastrophe risk management in (re)insurance, which was partly built on and connectible to PML and variants of VaR, especially Conditional or Tail Value-at-Risk, which in contrast to VaR refers to loss above the quantile (its exceedance) of the loss distribution and, therefore, concentrates on the extreme end or the 'tail' of the loss.

b. Exceedance Probability Appropriation and Tail Value-at-Risk in Capital Modelling

The mantra to 'own your view of risk' in the (re)insurance industry amidst the socio-material breaking points of the mid-2000s emerged, as framed above, in the mode of socio-material appropriation by model users; 'making something someone's own' against the backdrop of the practical, conceptual and structural assemblages of PML, EP and (T)VaR. This mode was initially motivated not so much by direct rate-setting for catastrophe insurance but more fundamentally by (re)insurers' capital management. "Cat models were thrown at insurance companies, but they didn't know what to do with them. Until they did the link and they figured out, 'ok, I can use them to do capital calculations'. When you start looking at capital you inherently start, you know, in your capital models, you start thinking about TVaR and that kind of thing […] (re)insurance at the latest in 2004 knew about TVaR and VaR because they applied it for capital calculations" (U15). As a reaction to the 2004 and 2005 hurricane seasons, rating agencies stepped up to more concretely incorporate the proliferating risk measures for capital management of (re)insurance firms: "In late 2005, Fitch announced that it would be shifting away from the single-point view of risk, such as the 100 or 250 year loss (or probable maximum loss) and focusing on the Tail Value at Risk (TVaR), which is an average measure of all the modeled losses above a specified threshold. As a result of the new focus on TVaR, combined with the changes to the catastrophe models in 2006, Fitch estimated an increase of 10 percent on average to the overall capital requirements of insurers writing catastrophe risk. [...] New modeled industry curves were released in August 2006, showing significant increases for both U.S. wind and earthquake losses." (Guy Carpenter, 2015b: 10).

Capital modelling is used to determine how much capital a financial company needs to hold to maintain overall solvency and profitability across all its operations. As an established domain and practice in financial institutions, it became a major boundary point for developing a deeper understanding and more active appropriation of catastrophe models. For most of the industry until then, catastrophe models had remained "engineering tools given to insurance people" notes U15. "It took them a while to understand and interpret them. There was a lag until they knew what to do with the output and then VaR and TVaR came into play". Learned through the initial and continuous observation of (re)insurance practices, vendor models had started to produce outputs accordingly, most importantly Occurrence Exceedance Probability (OEP) and Aggregate Exceedance Probability (AEP) (Mitchell-Wallace et al., 2017: 26). While the former, OEP, represents a distribution of a maximum loss and is mainly used to determine the necessary level of reinsurance for an insurer, the latter, AEP, represents a distribution of the annual sum of loss and is fundamental in determining the capital requirements of a (re)insurer. Here, the EP enters directly into capital allocation analyses and companies' capital models, and becomes part of the enterprise risk management, or ERM, in which it becomes an active part of risk-return criteria in overall corporate risk financing strategies (Grossi et al., 2005: 97f). "ERM, that's one big focus" notes U53, "it falls into the environment of the CRO [chief risk officer] – in the indusrty they are often Chief Actuary and CRO – and it's about pricing, it's about reserving, it's about capital management".

The aggregative properties of the EP concept, normalising loss probabilities across perils and portfolios, which made catastrophe risk easier to represent in a TVaR measure, found their ways into setting overall 'risk tolerances' of (re)insurers. As part of these risk tolerances, specific 'catastrophe risk limits' would be set, "defined by a risk metric drawn from the tail of a catastrophe loss distribution [expressed as a] maximum threshold, based on the maximum tolerable impact of modelled losses (at a given percentile) on available capital or regulatory capital" (Mitchell-Wallace et al., 2017: 116f). It was the convertibility of certain catastrophe model outputs, such as the EP curve, the underlying ELTs, and the more specific OEP and AEP metrics, to (T)VaR measures and other analyses in broader capital modelling that further increased catastrophe modelling's centrality. U60 explains to me that "cat models play a very critical role in insurance companies because it is de-facto recognised by the rating agencies: it becomes the model that determines how much capital you need to hold, which is the *real deal*. It's not just a probabilistic exercise".

At the same time, users had found an overarching practice through which it was easier to understand, interpret and, eventually, more actively appropriate vendor catastrophe models on their own terms. For the overall development of catastrophe modelling, the EP concept and its hybridity, both in terms of from where it emerged and its functional integration, marked an important step towards more 'holistic' and more integrated catastrophe risk management. U53 notes: "I'd give a lot of credit to Hemant [Shah], and Karen [Clark] to some extent, in the early days. The *real transformative concept* in cat modelling was to go from account to *portfolio*. And so, did Hemant invent VaR [for catastrophe modelling]? No, but he landed the tools to make that something that you can calculate." This transformative shift conceptually merged even further bottom-up and aggregate modelling approaches in a harmonisation of model use (see Wyss, 2014: 560).

Even though this was done by all vendors, RMS drove this development particularly visibly. "RMS did a better job in putting their product out in the marketplace and faster." remembers I64. Shah tells me about the time towards the shift from individual risk to portfolio-level application and remembers that "we spent a lot of time trying to figure out how to get our modules to scale and also converge on individual risk [...] building analytical models for how to propagate uncertainty, correlation, so you could create the variables, not just the earthquake number, but the analytic quantities that would allow you to measure this. And I think that's when the market started understanding that what they wanted wasn't just a reinsurance model or an underwriting model, they wanted a risk model where they could put their whole book, and [so] that they could underwrite and accumulate and correlate and diversify."

At the same time as these developments further concretised the position of vendors, the user community started to pick up on the new convergence of practices and metrics which increasingly led them to set up their own internal expert communities around catastrophe modelling. "So the desire to own your own view of risk had become more widely desired by the users. […] But the thing is, once you start to do that, that's when you actually see insurance companies start hire scientists themselves" (U60). The mid-2000s saw the beginning of a heavy increase in meteorologists, geophysicists, earthquake engineers, and computer scientists getting hired by (re)insurance firms across global markets, coming either from vendor modelling firms or from academia. At different paces and more at larger firms, modelling departments began to be formed. At one of the early modelling-embracing insurance firms, U53 remembers that at around 2008, "the guys were really involved, interested and understanding the necessity for funding [modelling]. And when I left [in 2013], we had almost across the place – corporate and in the division – we probably had between 40 and 50 people entirely involved in aspects of modelling." U60 recalls that reacting to the 2004 and 2005 hurricane seasons "we started [a reinsurance subsidiary] in 2005. We had two scientists including myself, and we had built a formal science team until 2010. […] So there's people who have no other job, they are focused only on natural catastrophe research, we have eight of those [today] – PhD-level researchers, they don't have any other work".

Towards the end of the 2000s, driven by the socio-material breaking points of actualised catastrophe and a series of appropriation acts by vendors, rating agencies and users, model users had begun to increase their catastrophe model literacy, which would further exacerbate the multiplicity of catastrophe production. With this "new breed of insurance analysts called 'modelers'" (Wyss, 2014: 560), the practical uptake of this 'genre' of risk assessment by (re)insurers themselves would lead to more situated modelling practices. Model users increasingly attempted to appropriate vendor models and insert the interpretations of their emerging firm-specific expert communities. Socio-materially still limited by intellectual property and data infrastructure restrictions imposed by vendors, the interpretations of these 'Other's artifacts' and their re-contextualisations aimed at more individually situating production of catastrophe for financial risk management. "A natural outcome is, once you hire scientists: they want to do different things. They want to say 'ok, I can do better' […] If you have an insurance company guy, this company has three scientists and they think: 'we have a better edge to deal with this one particular problem'. It's quite possible they're better than the vendor models." (U60).

This exacerbating multiplicity of proprietary catastrophe production, now squared across both vendors and more active users as appropriators, remained, of course, fundamentally market-shaped. While providing and further developing proprietary catastrophe production had been a competitive exercise by vendors and their analytics market until the mid-2000s, towards the end of the decade, it emerged as a more direct competitive practice in the (re)insurance market itself in which getting a catastrophe-epistemological 'edge' on others came to be seen as a "competitive advantage" (Wyss, 2014: 561), something that, for instance, U60 values highly: "it is very healthy, which creates a diversity of views in the market, it's great!"

III. Insurance-Linked Securities: Catastrophe Models and Capital Markets

"What's going on in the ILS market is that the world was flat until 1992, '94, and it was discovered not to be flat, discovered to be round in a sense, but it was really triangular." From the rainy streets of New York, I had just been led through an impressive entry hallway and a library to a table in the large dining room of an old private social club in Manhattan's Midtown. U42 sometimes meets clients here, where he now kindly invites me for lunch to talk about the market for insurance-linked securities, or ILSs. ILSs are instruments issued on the capital markets to extend (re)insurance risk capital across financial actors by allowing investor capital access to its risk financing. In this part of the investment industry, U42 is heading a large ILS fund since the late 1990s. What he refers to as a 'flat' world, (put very simplified here) is the idea of spreading risk exposure evenly across geographies and types of catastrophe. Specific to the business of catastrophe reinsurance is that it insures insurers' excess or 'tail' risk, starting or 'attaching' from a loss level which, if catastrophe actualised, could bankrupt the insurer. Before the early 1990s socio-material breaking points around Andrew and Northridge, U42 tells me, "until 1992, '94, the reinsurance market thought it was actually absorbing 99 percent of all the tail risk in the marketplace. Then they had to come to grips with the fact that they're only being able to absorb 10 percent".

As discussed in chapters 4 and 6, the sudden onset of the new high-loss regime of Anthropocene catastrophe had unveiled its socio-material environment to be much more unevenly distributed than expected. The sudden "structural limits to capitalizing re/insurers underwriting in regions with high spatial concentration of 'peak peril' risk" (Taylor, 2020: 1140) produced a previously unknown amount of missing risk capital to cover for the shape of market-societal Anthropocene: "It's a triangle. That's the shape of capitalism", as U42 calls it. The 'flat' world of 'traditional' reinsurance that he refers to hinges on risk management in which there are thresholds to how much risk of one type (e.g., peril and location) a company can and is allowed to take on, expressed in risk tolerances and catastrophe risk limits, as described in the previous section – "there is a max risk limit that's inherent to the system". He notes that "reinsurers want to have what I call a rectangular risk profile, but the problem with the market is that the underlying risk is a triangle. So, we take that excess triangle profile. [...] See, non-normality is the risk, in this sense. If it's normal, it's controllable and it shouldn't pay you a basis point over risk rate. [...] if the risk were 10 times smaller than it is right now, there would be zero need for insurance-linked securities".

The 'triangular' world, perceived here as hardly manageable by the balance sheets of 'traditional' reinsurers alone, is inherently linked to the realisation of catastrophe in capital markets and imperatives of investment practices. Think of the reinsurance tolerances and the overall capital management that is required for reinsurers. The place where this dynamic needs to be managed – exposure vs. capital – is the balance sheet of a reinsurer, which is itself exposed to solvency regulation, rating agencies, shareholders and, ultimately and self-referentially, its listed value that is traded as shares in the capital markets. What makes 'natural' catastrophe risk financially so special is its (assumed) conceptual independence from the usual market dynamics, such as commodities price movements, macroeconomic changes, or financial market shocks – catastrophe risk markets, for instance, stayed famously unimpressed by the 2007/8 financial crisis, "it confirmed that reinsurance and ILSs was truly not correlated to the capital markets. Well, you know, my colleagues on the trading floor were losing their minds and we were just sailing through" (U68).

U33, a former vendor modeller and now chief investment officer at another major ILS fund, explains to me, during another visit to the Hamilton Princess, that the form of capital with which catastrophe risk is backed-up is important. In the business model of a 'traditional' reinsurer, he says, "you take a revenue stream generated by catastrophe insurance, premiums are beautifully uncorrelated from the market, you back it with equity capital, you go public and turn into a stock: and now you've taken it [catastrophe risk] and just correlated it [with capital market dynamics]. Now you're in the capital market, you will go up and down with it, because you correlated it, and you basically destroy a lot of value that that stream originally would have had." ILSs 'de-correlate' catastrophe risk again by financing specific or combined risks not via public or 'rated' balance sheets of stock-listed reinsurance firms, but as different kinds of structured financial instruments with dedicated collateral capital for loss coverage, financed by capital market investors. This risk capital is (theoretically) uncorrelated to other markets and a firm's own stock price, it has a so-called 'low beta' (c.f. Cummins and Weiss, 2009: 498), and is exclusively dedicated to the instrument's specific catastrophe risk. This feature generates the main interest on the investor side, since this de-correlation helps to diversify market risk exposures of investment portfolios. The combination of this feature of catastrophe risk as conceptually uncorrelated to the 'real' economy and the capital markets, and the abundance of catastrophe risk in the high-loss regime of Anthropocene catastrophe is, so to speak, the raison d'être of the ILSs market.

As for 'traditional' (re)insurance markets, catastrophe modelling proved central here: "At the moment that the market realised that it didn't have enough capital allocated to this risk, it was the model that actually could tell us how much capital was necessary" (U42). To account for this newly discovered 'triangular' world – the market-societal shape of Anthropocene catastrophe with its inherent linkage of risk and profit, "capital markets provide triangles, and big ones" – people such as U42 settled into a then young market of insurance securitisation. Catastrophe modelling entered as an appropriation object into the very different space of capital markets and socio-materially enabled this early start of catastrophe (re)insurance securitisation during the 1990s. In turn, this space opened another important stage on which catastrophe modelling was exhibited in a different socio-material shape than in 'traditional' (re)insurance. The emergence of ILSs turned out to add another dimension of reciprocal appropriative effects by and to catastrophe modelling. While catastrophe modelling epistemically and practically enabled the ILS market in the first place, capital markets' practices, structures and rules differed from (re)insurance, broadening catastrophe modelling towards another field in which its appropriation became particularly formalised and technical and further concretised the central position of vendors.

a. Emergence of the ILS market

ILSs developed as an inherent feature of the new high-loss regime from the 1990s onwards. Bermuda had emerged as the home of newly formed reinsurers, firms that became known as very 'technical', such as the industry-renowned Renaissance Re, founded on catastrophe modelling. The hard market, i.e., high prices, and shortage of reinsurance capacity had elevated the Bermuda marketplace to a major hub for new catastrophe reinsurance (Cummins, 2008). U42 notes that, "Bermuda embraced cat models first. London was the opposite of what they wanted to be. Bermuda is like, 'OK, London's got its thing. Our thing is that we're going to use cat models. And then we'll be the best place and centre for catastrophe reinsurance.' And they took that market away from London." Much earlier already, Bermuda had become a haven for so-called 'alternative risk transfer', or ART, vehicles using additional instruments and markets than only the 'traditional' (re)insurance formats of insurance policies and reinsurance or retrocession deals. While ILSs became a more specialised and eventually the dominating arena for risk management and offsetting within the ART space, ART instruments initially were mainly used to reduce the relatively high transaction costs of corporations acquiring insurance covers.

While ART instruments are usually a bridge connecting (re)insurance business with outside capital, they remain within the realm of 'traditional' (re)insurance as so-called 'hybrid' products, such as industry loss warranties (Barrieu and Albertini, 2009). In contrast, ILSs are structured financial market instruments securitising (re)insurance risk with direct access to capital markets. The first such instruments, experimented with directly after Hurricane Andrew in 1992, were catastrophe futures and options contracts introduced by the Chicago Board of Trade. These first attempts of insurance derivatives were initially thought of as a hedging opportunity for (re)insurers to reduce catastrophe-induced profits volatility (D'Arcy and France, 1992). Due to concerns over insurers' hedging expertise, regulatory uncertainties, counterparty credit risk and increased basis risk (Niehaus and Mann, 1992), meaningful interest in these instruments never materialised and they were withdrawn in 2000 (Barrieu and Albertini, 2009). Between the mid-1990s and mid-2000s, several other ILS vehicles emerged, such as catastrophe loss index-based options or Act of God bonds, which all failed to generate any substantial traction (Cummins and Weiss, 2009). However, one instrument that survived this experimentation phase and eventually became widely successful was the catastrophe or 'cat bond', an asset-backed, fixed income instrument, first successfully issued by the reinsurer Hannover Re in 1994 (ibid.; Barker, 2014).

i. Catastrophe Bonds

Securitisation instruments generally are meant to take cash flows and risk off the balance sheet of a company and, thereby, making them more easily transferrable and tradable across capital markets (Fabozzi, 2008). The structure of a catastrophe bond is basically that of most other asset-backed securities in that it is set up in form of a special purpose vehicle, or SPV, which is a standalone economic enterprise and, in the case of ILSs, registered and domiciled most often in Bermuda. Since the purpose of a catastrophe bond is to shift catastrophe risk off-balance sheet for the sponsor, i.e., (re)insurance firms, it acts as another form of additional reinsurance and, therefore, the SPV often carries in its description the addition 'Re', such as 'George Town Re', the bond's name. While the underlying catastrophe risk is 'ceded' from the sponsoring (re)insurance firm, the SPV is managed by a different party, the 'structuring' or 'placement agent', which is often a (re)insurance broker, an investment bank or a large reinsurer who often also act as bookkeepers and, most importantly, market the bond to investors. A trust account is created by the SPV into which the proceeds from the issuance of the bond, i.e., capital from direct initial investors, are transferred into low-risk securities, such as US Treasury notes, as the bond's collateral (Barrieu and Albertini, 2009). After the initial issuance, catastrophe bonds usually exist for three to five years until their 'maturity' date. Over this time, the SPV receives premiums from the sponsoring party, combined with the interest of the collateral account, which is paid out to the bond investors as the bond's coupon. At 'maturity', the collateral account is liquidated and investors receive their share of the principal back, provided that the predefined disaster did not materialise.

Like many other structured securities with a certain level of complexity, especially regarding the underlying risk, catastrophe bonds are only available to so-called 'qualified institutional buyers', defined by a high degree of capitalisation, usually large institutional investors such as pension funds, large investment or hedge funds, or (re)insurance firms' asset management arms. As such, catastrophe bonds in the US, where most of them are ultimately traded, are exempt from certain otherwise more rigid registration and disclosure rules and are instead primarily governed by the SEC's Rule 144A (SEC, 2013).[52] Introduced as an amendment to Rule 144, Rule 144A regulates private (in contrast to 144's

[52] This underlying regulation goes back to the 1933 Securities Act and was meant to prohibit misrepresentation of information about securities.

public) access to US capital markets and is important here since catastrophe bonds are usually first sold to investment banks or broker-dealers on their initial exchanges, most notably the Bermuda Stock Exchange, where these instruments are registered. These initial purchasers then sell them on an 'over-the-counter', or OTC, secondary market in the US where Rule 144A applies. Rule 144A essentially enables this private OTC trading of catastrophe bonds, increasing liquidity in the market and makes buying and selling them easier (Aguilar, 2014; Artemis, 2021d).[53] Although having a rather complex underlying risk, catastrophe bonds are in and of themselves, therefore, generic financial markets securitisation instruments (Cummins, 2005) for which equally generic practices of capital market investing and trading apply, which includes, for instance, negotiating, or 'discovering', the initial offering price and coupon, publishing the 'prospectus', or 'offering circular', and the availability of the bond contract and risk analyses to investors and buyers.

Similar to, for instance, credit securitisations, catastrophe bonds are issued in different 'tranches'. While credit derivatives tranches entail loans with different credit default risks and are, thus, exposed to different potential loss and returns, catastrophe bond tranches structurally resemble the different layers of 'traditional' reinsurance deals.[54] Tranches set up different conditions for a liability attached to different parts of the principal, which are separately rated by rating agencies and represent different risk-return qualities. In a catastrophe bond, different tranches refer to the two fundamental dimensions of catastrophe, occurrence and severity. Tranches can differ in terms of what type of phenomenon and location they refer to and which loss amount and probability the tranche covers. Each tranche, therefore, has a specified range of loss that it covers for which the principal is paid out to the sponsoring (re)insurer if an applicable catastrophe event causes, for instance, a loss above $800 million – the 'attachment point' or 'trigger amount' – and below $1.2 billion – the 'exhaustion point' – from where, for instance, the next tranche starts. Tranches are then divided up in so-called 'classes' of the bond, which are individually bought by investors.

The determining aspect in the definition of a tranche and class of a catastrophe bond is the so-called 'trigger', which is the condition that needs to be met for a loss to occur to the principal, i.e., a loss to the investor (in credit derivatives, this would be somewhat similar to the default of an underlying loan, however here, the principal is transferred to the sponsor, i.e., the (re)insurer, to cover for incurred catastrophe loss). The trigger materialises in specific forms of consolidating future catastrophe which are generally divided into four types: 'indemnity' (the actual loss manifested by accumulated claims to

[53] Rule 144A has been heavily criticised for decreasing market transparency, lack of protection for investors and creating a 'shadow financial market' due to these provisions (Caplinger, 2015).

[54] Important to note is that in contrast to credit derivates, in which the underlying loans are traded via the security as their collateral, catastrophe bonds do not entail and trade the underlying insurance policies.

the sponsoring (re)insurer), 'parametric' (a pre-defined occurrence-dimension characteristic of actualised catastrophe, such as a specific level of wind speed or magnitude of ground motion), 'index' or 'industry loss' (overall loss to the (re)insurance sector from an event, gathered by one of two specialist firms, PCS and PERILS), and 'modelled loss' (the post-event projected loss provided by a vendor) (Barrieu and Albertini, 2009). Until today, the vast majority of catastrophe bonds (in 2021 over 70%) have indemnity triggers (Artemis, 2021a).

While the different types use these different mediation techniques to consolidate actualised catastrophe, common to all is their materialisation in catastrophe bond contracts, most importantly, in form of three key metrics, which define both occurrence and severity of securitised future catastrophe: 'attachment probability' (the probability of loss exceeding a tranche's attachment point), 'exhaustion probability' (the probability of loss exceeding a tranche's exhaustion point), and the 'expected loss' (the anticipated loss as a percentage of the principal within the boundaries of a tranche). These three metrics combined, but of course most dominantly the expected loss, produce catastrophe risk for capital markets, and, as any risk for any security instrument, it is the fundamental element for profit. As the basis of any catastrophe bond, this fundamental element became producible since the 1990s with the emergence of catastrophe modelling. New to the arena of Anthropocene catastrophe, yet another set of actors began to interpret this 'Other's artefact' in what turned out to be, at least in the first decade of catastrophe bonds' existence, a rather detailed hermeneutic reading of this appropriation object, enabling this financial instrument in the first place.

b. Catastrophe Models as Market Devices and Vendors as Formalised Calculation Agents

> "I would say that the sector was enabled by cat modelling. [...] early on investors relied heavily on the models to give them ways to think about riskiness [...] The modelling is what gave investors the confidence to proceed with the bonds. [...] When we did the first Japan earthquake bond, which was Parametric Re in 1997, [...] we felt it necessary to do essentially a half day of due diligence with EQECAT, which did the modelling. Back then, we thought it was incumbent upon us as a dealer to do an alternative check. So, I arranged for us to spend a half day at Lamont-Doherty Earth Observatory of Columbia University and we hired a professor of earthquake science to sit with us and go through the elements of the EQECAT model to study; so that we would have not just looked at it, but so that we would also have a professional basis on which to judge that model adequate. In addition to that, we've had a two-hour session with a lawyer to go through the modelling. And in addition to that, we had a team in Tokyo purchase the Japan [earthquake] fault book – which I still have – to go to Tokyo University and to do the research on the timing and the variability in damage earthquake reporting. So, that level of diligence was done on each of the early cat bonds."

In a brief conversation in New York with arguably one of the most central figures in the early days of the catastrophe bond business, Michael Millette tells me about the first catastrophe securitisations he conducted in the 1990s.

A few years earlier, in 1994, he had been involved in insurers' asset management on behalf of Goldman Sachs, before the continuing reinsurance availability crisis drove the bank to "explore feasibility of insurance securitisation" for catastrophe risk. In 1997, around the same time as the Catastrophe Modelling Handbook was conceived (discussed in the previous chapter), the Valuation of Securities Task Force of the National Association of Insurance Commissioners (NAIC) held a discussion on securitisation possibilities for catastrophe risks. While the issue was brought up of how "regulators get comfortable with the modeling of these securities", Michael Millette had been invited and presented the "modeling used for catastrophe-linked securities [which] is very intensive and requires a great deal of time and resources" and for capital markets use would involve specific "disclosure issues that the investment banking firm would have to follow, as dedicated by the current securities law" (NAIC, 1997: 1032). While the feasibility of these instruments for (re)insurance was discussed at the NAIC, Millette already spoke from experience since less than a year earlier, as is famously known in the ILSs market, "by the end of 1996, we completed the first Rule 144A securitisation ever completed, which was George Town Re".[55] In these early days of catastrophe risk securitisation, investor-mandated due diligence and SEC rules required investment bankers, such as Millette, to go to substantial lengths to understand catastrophe models since they set the basis for the price 'discovery' of the to-be-issued notes. For instance, for the Parametric Re Japan earthquake bond mentioned above, "Mike Millette became terrific on the roadshow because he got the famous Japanese historical catalogues [the Japan earthquake book Millette still has today], and rumour was he'd put it under his pillow at night. He knew about *every* historical earthquake", remembers I64, then at EQECAT who was the bond's modeller.

"The fact that the nature of the risk itself is modellable, that's very important [...] You can actually make an argument that cat models helped create the ILS market", U42 tells me over the remainders of our risottos in the Manhattan club. "They were the means of exchange of information. When you and I agree on a risk transfer contract that has a three percent probability loss, it's through this third-party model." Those who have ever seen a bond contract will know that it extends over hundreds of pages, most of them disclaimers, in which, however, also very detailed information is given on, amongst many other things, the underlying risks and their calculation as the basis for what is usually called the 'technical price' of a bond. While structures of financial securities vary, the basic principle of risk versus return is common to most, on which basis price and coupon are negotiated and which is most dominantly driven by the capital markets' 'cost of capital', i.e., the availability of capital eager (or

[55] See also Artemis (2021b).

not) to be exposed to this specific risk-return dynamic. This determines both the initial issuance price and coupon as well as trading price much more directly than the underlying 'technical' risk-return. In this basic dynamic, there is somewhat of an agnosticism towards the kind of risk involved, as long as it is expressible in relation to return. In less complex instruments, this risk is often calculated by direct participants in the transaction, such as a dealer-broker or the seller, while in more complicated transactions, such as complex credit derivatives, this role is assigned to a third party with sufficient expertise and independence (c.f. Fabozzi, 2008: 183). This role of a so-called 'calculation agent' is a common and formalised one in securitisation procedures (PWC, 2021).

i. Vendors as Calculation Agents

This was the world into which catastrophe models as appropriation objects would enter from these early catastrophe securitisations in the 1990s onwards: they enabled to express the risk against which a return can be constructed and on which basis catastrophe's cost of capital would be determined. And they entered this realm via vendors' newly emerging risk transaction role, who were endowed as the formalised 'calculation agent' for ILSs. On this new stage, catastrophe modellers found themselves in a different contextual environment with different epistemic power dynamics. "A lot of investors initially were very sceptical of the validity of the models", tells me I64. As an early structuring agent, U71 confirms this, too, and notes "the amount of attention paid to diligencing the model in that early period was incredible. People did not take the model on faith, they thought that they needed to look at each and every step that existed. [...] So, now we have former modellers that work in the industry and for the investor base, but in those days the investors would commonly engage an expert to vet the modellers". U42 also tells me, that "in the old days, investors actually needed clarity [...] There's clever enough people in the investment side who understand that. Don't throw a bunch of PhDs at me and say, 'you've got it!' You've got to tell me what's the core insight of this model and why is that core insight stable."

At the same time, vendors were confident enough to be exposed to this level of confrontation, since they saw themselves as science- and engineering-driven outsiders to the generic modelling in financial markets. The socio-material reference of Anthropocene catastrophe, in their perspective, endowed them with a legitimacy lead ahead of financial modelling. Over a drink at the Hamilton Princess again, U33, who entered the ILSs space as a former vendor modeller, remembers from his initial exposure to this world:

> "In finance, there are things they call 'laws' that an engineer would not. You know, as an engineer when you say something's a law, like gravity, it works every time. In finance, they're a lot more loosely. They say something's a law but it's not a law, it's an observation. So, on the one hand, that made me feel a lot better about engineering and science. [...] to have more confidence in 'I might get the things wrong but we're not gonna get it *that* wrong' [...] It was

> more like, 'I know this from engineering, how things are built, and I know what level of precision and accuracy we can get to' – which is not great in engineering – but when you compare this to finance you're like 'holy smokes! We're like ages ahead!' Because in engineering, you're dealing with nature, you're dealing with things [...] and that is no innovation, the laws of physics don't change with evolution of people's thinking. But in finance, things change. I mean, somebody invents reverse mortgage, somebody invents this and that, and suddenly the laws you thought you knew go out the window."

Therefore, going into capital markets did only strengthen his view on catastrophe modelling, "it just brought me to realise that, what I did know about catastrophe modelling was that it is fairly uncertain, there is a lot of variability around your estimates, but, a) it might not be as bad as forecasting that people do in finance, and b), you know your foundations are a lot more solid than in finance theory."

Although the scrutiny of the new appropriation objects was deep, vendors were emboldened by their 'science-stance' in their interaction with investors, but also by capital markets' very own epistemic power dynamics: "they [investors] said, 'did [a leading investment bank] have anything to do with this model?' and we said, 'absolutely, absolutely not!'. I basically said, 'there are three modelling companies in this business and none of these models were developed on Wall Street. These are independent of Wall Street.' And the investors said, 'we like that'" (I64). This perceived independence from 'Wall Street' helped vendors to stage their appropriation object precisely because, not despite, the heightened investigation (i.e., hermeneutic reading) of models by investors and structuring agents – "we actively recreated parts of the model internally to ensure that we weren't just accepting a model on faith" (U71).

Thus formed the new role of the calculation agent for catastrophe bonds and the dedicated and formalised position of vendors in the capital markets as independent and 'neutral' parties for catastrophe production for investment risk assessment. "If they want to use our model to issue a cat bond, they would *need* to involve us because we need to document actually the modelling and the calibration to show that it's appropriate to be used in this way." (I03). In contrast to the never fully materialised role of vendors as 'judges' on proper model use by (re)insurers (as mentioned in the previous chapter), in the capital market realm they became the central judges on the 'technical risk' of investment instruments. "We act as an independent expert", tells me I38, a large model vendor's ILSs manager, while we are going through a matured catastrophe bond contract and he explains to me where the modelling comes in. "We actually sign a letter that we're putting our name out there as an expert on this transaction, such that rule 144A is met in that certain disclosure levels and due diligence is performed on behalf of the initial bank that underwrote the transaction before they go to market with it." Here, it is them who judge against the backdrop of their expertise and their contextualisation of their own models, "We have an obligation to put what we think is *our* best view of risk forward, not *all possible* views of risk".

This formal and central position complements the epistemic dynamics of market-shaped Anthropocene catastrophe production in that vendors inhabit the pivotal position for proprietary financially sensed environments, since the underlying 'technical' risk of ILSs instruments remains that of socio-material catastrophe. While in 'traditional' markets insurers will give the reinsurer granular exposure data, "they won't do that in a cat bond", tells me U42. "It happens via the modelling firm itself. The modelling firm will get the granular data and then use that for modelling, so they have the best data to do their modelling and pass on the results to us, the investors". I38, the ILS model manager of the large vendor, explains, "[sponsors] give us detailed exposure information, the address and the value, the limit deductible, the building characteristics […] it's very detailed. And that's what makes these reports so valuable and robust. They're based on the best possible quality data." This sensing, however, hinges on the subscription-based relationships with (re)insurers socio-material mediation of Anthropocene environments and is now detached from the buyer of the bond, "we're just disclosing what was given to us [by the sponsor]. So, if that differs from reality, the investor would need to figure that out."

ii. Appropriation of Models in ILSs Market Making

While being not the only means in 'traditional' (re)insurance, as highlighted by Jarzabkowski et al. (2015a), catastrophe models became a central element of catastrophe risk management with different appropriative dynamics and contexts (rate setting, risk aggregation, capital management, reinsurance buying, solvency regulation, etc.). In ILSs markets, however, although formalised as legally necessary calculation agents to catastrophe bond deals, vendors' appropriation object did not enter into practice by appropriating capital markets actors' practices but had been instead appropriated by capital market actors from the very start of the emergence of ILSs. This is because in contrast to (re)insurance's catastrophe risk management context, it is rather the cost of capital that is the dominant dynamic in capital markets, and here the catastrophe model is appropriated solely as a starting point for the generic 'price discovery'. I38 tells me that when he gets started working on the modelling for a bond deal, there is an "urgency in which the bankers need from us to get these numbers. They know that this is going to drive the conversation, this expected loss value. But it isn't the end all be all."

Before going on roadshows, where both the structuring agent and the calculation agent of a bond 'pitch' a deal to investors, a pricing guidance is produced. The starting point of this guidance is the model-produced 'technical risk' enacted by attachment point, exhaustion point, and expected loss, which are specific tranche-contextual representations of exceedance probabilities (EP), where, preconditioned by attachment and exhaustion of the tranche, "expected loss dominates by far the conversation" (U42). Depending on the structuring agent's view on the current cost of capital in the market, the pricing guidance is usually a range of a multiple of the technical risk, such as 550 to 625 basis points (5.5 to 6.25%) return for an expected loss of 1.36% (e.g. Artemis, 2021b). "There is dollars and cents on the money-side of it, but on the risk-side you need something, so you need a model" (U33).

This is the place of the act of catastrophe model appropriation, the risk-return dynamic before the bond goes to market. Yet, its role ends here for this is when 'price discovery' and the cost of capital take over. I38 reports from the roadshows and what happens after, where the structuring agents tell investors: "'So here is the first time you're seeing this bond. This is the risk. This is what we think the appropriate return is. Let's discuss.' Now they go to market and they say, 'Oh, you know, we only have 125 million to sell and we now, after talking to all the different investors, we now know there's 250 million dollars of interest, there's more supply than demand [of capital], so price [i.e., return for investors] goes down. So now investors are saying, 'Well, I'll take it for 500 basis points' or 'I'll take it for 450'. And all of a sudden, that competition drives down the pricing guidance." This is, of course, a very different dynamic and context than catastrophe risk management, "actually this year I think, there was a bond where the return was lower than the expected loss. Because the market demand was so high. So there are factors that definitely trump both model output and trump sound underwriting practices that pre-date [catastrophe] models".

In this mode, not only the direct appropriation of catastrophe models is used as a vehicle for nudging 'market forces', but also the underlying sensed Anthropocene environment and its proprietary epistemic quality which depends on its embeddedness in financial services. For instance, the investors' appropriation of model data uncertainty. If the underlying proprietary exposure and calibrated potential loss data are deemed coarse, which would be the case for regions other than, for instance, the US or Europe, the coupon paid out to investors might be higher. "The expected loss is 0.92%. Maybe the coupon return is 4%. If this is based on very coarse information and there's a lot more uncertainty around it, maybe 4 percent isn't appropriate. You'd say, 'Oh well, I'll still buy it, but because I think it's more volatile, I want 8% return. So that's how you translate that into these numbers." But overall, as U42 tells me, by now over a tea after our lunch, "in the end, it really just comes down to market forces, supply of capital versus demand. [...] These models are useful for us to haggle and get the price discovery faster. [...] It's not price discovery itself." Using catastrophe models and their vendors as formalised independent calculation agents became the standard in the 1990s. "It's an agreement. They said, 'I don't want asymmetric information. I don't want you to have a better model to me. Let's just agree on a model so that now we can actually come closer to where the price should be and then we'll let market forces, supply-demand, determine where in the range it settles. And that's how you build markets."

Albeit appropriated in this rather different way, catastrophe models became the means to greater disclosure on catastrophe risk from the investment side of the business. While (re)insurance firms would not disclose to their shareholders, for instance in annual reports or at shareholder meetings, the concrete expected loss of their policy portfolios, the world of structured financial instruments appears different: “We [ILSs fund] are not required to do it either [to disclose a portfolio’s expected loss] but if you don’t do it, they just don’t invest.” (U60). This disclosure, within the framework of over-the-counter capital markets investment practices, involves the offering circular in which the vendor explains the model’s methodology and data in the Expert Risk Analysis Annex, sometimes somewhat similar to what is published through the Florida Commission. In other words, vendors accepted a closer reading and appropriation of their appropriation object in exchange for a solidified and formalised position of catastrophe producers for the capital markets.

“The model was valuable as a means of risk transfer in the context of a market that discovered that its tail risk was ten times larger than it had thought” (U42). From the mid-1990s on, the ILSs market had thus started to emerge and catastrophe modelling appropriation (in a market-specific switching between appropriating and being appropriated) had enabled additional proprietary epistemic dynamics throughout the ‘traditional’ (re)insurance space. “The arrival of the modelers and their models is eroding the comparative information advantage of insurers and reinsurers and opening the door to new players. […] the stage has been set for an unbundling of insurance products with insurers retaining marketing underwriting and settlement services and risk bearing by-passing the reinsurance industry and being provided more directly from the capital market.” (Doherty, 1997).

In line with U42’s assessment, the new high-loss regime of Anthropocene catastrophe had deemed the ‘old’ capacity of risk coverage and financing too little. For instance, the old and established Insurance Services Office (ISO) suggested in 1996 that “[w]hile reinsurance and other pooling mechanisms can help, they are not sufficient – access to outside capital is required to fund these risks […] There is a concerted, ongoing effort to educate traditional financial investors about insurance risks and to develop mechanisms (e.g., insurance futures, catastrophe bonds, etc.) that can facilitate the application of capital market capacity to catastrophe risk management.” (Davidson, 1996: 178). In NAIC discussions around additional capital inflow from capital markets, the Reinsurance Association of America “expected that the market will continue to try to find more attractive ways to spread risk” (NAIC, 1995a: 640).

Over the second half of the 1990s, reinsurance capacity had grown due to the socio-material breaking points earlier that decade, which had opened up widely the market for catastrophe reinsurance. After the new, catastrophe model-fuelled and mainly Bermudian reinsurers had taken hold in the markets, this, counter-intuitively, produced a ‘soft market’ (i.e., lower prices) for catastrophe reinsurance since for a few years then no major catastrophe struck this space. ILSs already on the market had a slow start in terms of market share since it was hard to compete with the relatively low cost of reinsurance cover towards the end of the decade. "Some insurers who support securitization […] are praying for a major catastrophe as the only way to bring the market to its senses and stiffen reinsurance prices", and an investor pondered in 1999, "'Somebody else's earthquake would suit me just fine'" (Sherriff, 1999).

Their prayers would be heard and from the mid-2000s onwards, prices hardened and ILSs propelled into a lasting wave of issuance. Amidst these developments, large and established reinsurers, such as Swiss Re or Munich Re, driven by their longer-standing modelling capacities and early involvement in ILSs markets, further developed their excess of loss, or 'XL', business (Kyrtsis, 2016; Wyss, 2014: 556). "[The] assessment of natural catastrophes […] was combined with sophisticated financial management and the fine-tuning of financial innovations […] the combination of catastrophe forecasting with financial instruments. This meant also a shift from innovative internal accounting and the distribution of risks among various insurance and reinsurance organizations [i.e., 'traditional' (re)insurance], towards distributing risks through the financial markets. Instead of spreading risks through networks of organizations, the risks were placed in a wide variety of portfolios. This doesn't mean that all the old reinsurance services and traditional practices had been totally abandoned. The various elements constituting the palette of products and services now appeared in different configurations." (Kyrtsis, 2016: 169).

"I walked into [a Bermuda-based ILSs fund] two days after Katrina. It was my first day in the office", remembers U33 laughingly. "It felt like the worst luck ever. And it actually was quite good timing, but it didn't feel like that at the moment. That was like 'fuck, I convinced my wife to move here...!' But it turned out to be alright." The second set of socio-material breaking points of the mid-2000s, its loss and subsequent hardening of the 'traditional' (re)insurance markets benefitted the by then a decade-old ILSs market, at this point by far dominated by catastrophe bonds, and propelled the market to a near-mainstream status (Lane and Beckwith, 2008). However, in comparison with other asset-backed securities, the ILS market remained relatively small, even compared only to the general reinsurance market alone (Michel-Kerjan and Morlaye, 2008), and it would only years later have a more structural effect on catastrophe risk (re)insurance. While investment banks had been critical in establishing the structural formats of insurance-linked instruments – "they basically created the legal and structured finance framework" (U42) – large reinsurers had also established themselves as structuring agents of catastrophe bonds. At the same time, (re)insurance brokers as the established intermediaries who had since the new millennium parted ways with owning vendors and instead increased their in-house modelling expertise (Wyss, 2014), more forcefully entered the ILSs space since not doing so was perceived a threat to their central position in the overall market. Over the 2000s, "what happened was that the reinsurance brokers, like Aon, Guy Carpenter, they recognised, very smartly, this is a very secular threat to their business. They basically formed their own securities divisions to do cat bonds at very low costs, subsidised by their main reinsurance business. [...] This is strategic investment to protect their business, whereas Goldman Sachs has to make an investment-bank profit margin. If you look at it today, all the cat bond issuance is totally dominated by the big brokers' securities arms." (U60).

By the end of the 2000s, the socio-material appropriation of catastrophe models had effected a by then established ILSs market that was there to stay (Artemis, 2009; Barrieu and Albertini, 2009). While, other than in the 'traditional' markets, these appropriation acts had left catastrophe models' structural architectures and features largely unaffected, i.e., the material objects themselves, the reciprocal appropriation acts had further elevated catastrophe models' centrality all the way into capital markets practices. These appropriative developments had also further centralised model vendors on yet another stage: as formal calculation agents for structured financial instruments. Once more sophisticated investors and ILS fund managers, similar to (re)insurers but in a shorter period, started to build up internal modelling expertise, this further exacerbated the multiplicity of proprietary catastrophe production across a widened scope of financial practices. While catastrophe production had been 'squared' by an increasing number of model-literate (re)insurance users, the emergence of the ILSs markets added users in the capital markets, and proprietary catastrophe production, in this sense, was now 'cubed'.

What is often termed the 'convergence' of the 'traditional' and the alternative risk markets (Cummins and Weiss, 2009), however, does not necessarily mean an overall takeover by capital markets practices but, rather contrary, seems to involve the seeping-in of reinsurance practices into capital markets. Over the 2000s, catastrophe bonds were not the only ILSs instrument but were followed especially by 'collateral reinsurance', which is essentially a bespoke 'traditional' reinsurance contract but backed-up by a collateral account instead of a reinsurer's balance sheet, i.e., similarly 'de-correlating' catastrophe risk from the wider capital markets as catastrophe bonds (Cummins and Trainar, 2009). Large ILSs funds, such as those of U33, became not only catastrophe bond investors and traders but also very active collateral reinsurers over the 2000s. Compared to 'traditional' reinsurers, he says, "the only difference that we have is how we face the market. We buy and sell reinsurance, we buy and sell cat bonds, we sell insurance now. The way we interact with the market is the same, the only real difference is what is the capital behind you." Although the capital structure is by no means trivial, collateral reinsurance is a combined appropriation of catastrophe models in the 'traditional' sense and of capital markets structures for somewhat generic (re)insurance risk management, essentially extending the market-reach of the financial ontology of Anthropocene catastrophe.

Even though ILSs' role and influence in Anthropocene catastrophe is one that deserves much more attention in its own right, for instance excellently done by Taylor (2020), it escapes the scope of this thesis. While the ILSs space plays an increasing role in financial services' catastrophe risk management, it remains relatively small in terms of its market size. Also, for instance the trading of catastrophe bonds in the secondary markets has so far not developed into aggressive hedging or arbitrage practices, "Trading cat bonds is like watching paint dry." (U68). ILSs most dominant influence, against the backdrop of the discussion above, is primarily in the realm of converging practices and capital from (re)insurance and capital markets where the principles of diversification and de-correlation are the driving elements for both investment and catastrophe risk underwriting. Its role in the financial ontology of Anthropocene catastrophe, therefore, is not so much that of an agent of change or disruption but more that of a catalyst, which exacerbates the multiplicity of catastrophe production and carries it over to the capital markets. Letting capital markets' generic price discovery lead the pricing of catastrophe risk in catastrophe bonds and, by now more importantly, simply extending the balance sheet for catastrophe risk to capital market investors via collateralised reinsurance,[56] reproduces and intensifies rather than disrupts the way market societies conceptualise, manage and financially realise catastrophe in the Anthropocene.

[56] Collateral reinsurance as an ILSs instrument has since 2013 overtaken catastrophe bonds as the dominant source of coverage and financing capacity in the ART markets (Wheatley, 2015).

Chapter 9. The Era of Catastrophe Modelling Phase 2: Owning Catastrophe

The majority of the appropriations of Géricault's Raft of the Medusa are paintings, 'modelled' catastrophe materialised in paint on canvas. But its influence also inspired the medium of sculpturing, such as the works of Rachel Kneebone[57] or Frank Stella[58] (see figure 18). While paintings' spatial environment in an exhibition is important for its staging, this aspect becomes ever more central for the medium of sculptures. The added dimension in this medium of art, as anyone who has ever been to places such as the Noguchi Museum[59] can attest to, brings about the importance of space and plasticity that allows – or forces – to inspect the object, its elements, *and* its position in space, the environment in which it is placed, in a much more intense way. It endows the onlooker as well as the artist with more room, more angles, for and of interpretation, while the space around it (in Kneebone's case, for instance, the windows and the ceiling's stucco, or in Stella's case the ventilation system and industrial roofing), its socio-material context, becomes part of the artwork itself. The contextual placing, however, might come in hindsight and not necessarily exclusively installed and placed by the artist themselves. And while alteration of a finished and dried painting necessitates a huge amount of delicate work, altering a sculpture can mean 'simply' putting it in a different spatial setting, adding to or removing from one of its many material elements, or choosing to inspect and interpret it from only certain angles.

Figure 18: left: Rachel Kneebone, Raft of the Medusa, 2015, porcelain; right: Frank Stella, Raft of the Medusa Part 1, 1990, oil and enamel on etched honeycomb aluminium with steel pipes, beams, and other metal elements.

[57] See https://foundlingmuseum.org.uk/events/raft-of-the-medusa/

[58] See https://www.artsy.net/artwork/frank-stella-raft-of-medusa-part-i

[59] See https://www.noguchi.org/

If catastrophe modelling before 2011 might be seen more as appropriation via the medium of painting, its appropriation after 2011 could be seen more similar to that of sculpturing. Catastrophe models as appropriation-objects received a fundamental shift in terms of their socio-material staging after 2011, with, similar to sculpturing, added plasticity and dimensionality of reciprocal appropriative effects by and to the practices and the devices of catastrophe modelling. Against the backdrop of this shift's onset in chapter 8, over the 2010s catastrophe modelling would get both more problematised and more appropriated – the dynamics of socio-material appropriation inherently encapsulate problematisation as an increase of these dynamics rather than a reduction or elimination of appropriation of an appropriation object since it provokes further, if more critical, appropriative interpretation. Another series of socio-material breaking points in the early 2010s, heavily connected to and conditioned by the ones of the 2000s, provoked a series of lasting appropriation acts that would let catastrophe production emerge in greater plasticity and user intervention. So while Martin's disaster painting in need of rescue after the Thames flood received restoration in 2011 (mentioned in chapter 8), catastrophe modelling in need of rescue after the early 2010's breaking points received, more drastically, transformation similar to the one from painting to sculpturing: a form of catastrophe production, in which the object's contextual environment is inherent and where inspection is intensified via increased dimensionality and for which much more direct appropriation is enabled by both contextual installation and by adding or removing elements of different material media to or from the object.

This chapter first (I) focuses on the developments that delivered the final push towards the shift of model users as the primary appropriators of proprietary catastrophe production. It analyses the height of the most dominant vendor, RMS, and their momentous and problematic version 11 hurricane model update, which provoked model users to fully embrace the notion of 'owning their own view of risk'. Regulatory influences as well as the appropriational dynamics in consolidating actualised catastrophe are also discussed. The further exacerbated level of multiplicity of proprietary catastrophe production by the heightened and by now mandated appropriation of models by users represents the current state of catastrophe modelling and is analysed in the last section (II), where formalised and normalised processes of appropriation acts by users and the competitive role of proprietary catastrophe production are focused on. Finally, the socio-material appropriation framework is revisited against the backdrop of this and the precious chapters and how their results constitute a financial ontology of Anthropocene catastrophe.

I. 'Owning a View of Risk' and Normalising Multiplicity

"How are an insurance salesperson, an underwriter and an actuary driving a car?", starts a (re)insurance broker an apparently common industry joke at a risk modelling conference I am attending in 2020. "The salesperson is pressing their foot on the gas, the underwriter is pressing their foot on the break, and the actuary on the backseat is looking out of the rear-view window telling each of the others separately the directions where to go.” The joke did only yield moderate laughter but seemed rather appropriate for the dilemma the conference attendees were facing, since the conference focused on cyber risks, a growing field in (‘human-made’) catastrophe with infamous modelling difficulties (McMullan, 2017; Wheatley et al., 2021; Xu and Hua, 2017). The inherent message of this joke was that, in contrast, for ‘natural’ catastrophe risk the industry had advanced and was indeed looking out of the front windscreen. At a different catastrophe modelling conference in 2018, one keynote speaker reminded attendees of their position as catastrophe model users: “in the early 2000s, producing numbers at all was the major task. Now, working out the right analytics is the main task in cat modelling”, it was the move from “merely processing data to actual analysis” that users underwent, something cyber risk modelling had not achieved yet.

These developments in catastrophe model usage over the course of the 2010s were brought about by a previously increasing centrality of vendors and models, an increasing modelling literacy of users in both (re)insurance and ILSs markets, and an increasing integration of catastrophe production from underwriting to capital management to investment management. ‘Owning a view of risk’ as the emerging mode of catastrophe production and management across the industry had slowly started to materialise in form of internal modelling teams towards the new decade, further integration of modelling practices, and especially brokers’ established role as proficient and critical model users.

Driven by their ever-centralising position, vendors for their part, had also started to take a lead on professionalising catastrophe modelling as a yet-to-be officiated occupation on its own. With the increased hiring of experts on the user side, vendors became a form of cadre training facility for future industry modellers, similar to consultancies such as the Boston Consulting Group (BCG) or McKinsey in broader business sectors. Most industry catastrophe modellers then and today would have spent at least a few years at a vendor, learning the trade, before switching to the industry side – most industry modellers I spoke to have a PhD and a vendor modeller in their professional biography. P63, the academic modeller confirms, “yes, they [vendors] have really become the BCGs here”. And most of the time, as with business consultancies, modellers stay in the industry after this initial transfer, “We only go one way and never come back” (U15). As still a rather niche profession, the number of catastrophe modellers globally, although grown over time, is estimated at the lower thousands (in contrast, the number of actuaries is around 40,000) (Mitchell-Wallace et al., 2017: 124), which makes them very sought-after specialists.

As the most dominant actors in the field of catastrophe production, vendors also started offering modelling training programmes for industry professionals from the mid-2000s on. In contrast to the established and formalised certifications of actuaries, formal 'faculties' or 'associations' of catastrophe modellers do not exist. Even before most manuals and guides were published by professional bodies (e.g. ABI, 2011; ASB, 2011), the two major model vendors introduced certified programmes, RMS with its "Certified Catastrophe Risk Analyst" training since 2005 (RMS, 2021) and AIR with its AIR Institute's "Certified Catastrophe Modeler" programme since 2006 (AIR, 2006), which are creditable towards, for instance, certificates of the Chartered Insurance Institute, the American Institute of Chartered Property Casualty Underwriters or the American Academy of Actuaries (Mitchell-Wallace et al., 2017: 124). The perspective of the 'hermeneutic reading' of catastrophe models and their practices for those mainly actuarial professionals completing these programmes would, however, then "reflect the views of the commercial [vendor] organizations" (ibid.), which, for then, anchored vendors' epistemic and appropriative position since "models incorporate many areas of informed judgement" (NAIC, 2010: 11).

Thus staffed with more and more user proficiency, the (re)insurance industry and the growing ILSs markets entered the 2010s amidst another series of socio-material breaking points as the new decade proved vested in actualised catastrophe. Among them was the infamous Haiti earthquake in 2010 which, although particularly devastating and deadly, did not yield considerably significant insured loss – the inverse relationship between economic/insured loss and loss of lives was particularly gruesome in Haiti ($8.8 billion economic loss, <$800 million insured loss, >200,000 dead) compared, for instance, with the similar magnitude-Christchurch New Zealand earthquake a year later ($36 billion economic loss, $28 billion insured loss, 185 dead) (Swiss Re, 2018a). More events did hurt the industry considerably, especially the Chile 'Maule' earthquake in 2010, the Japan 'Tohoku' earthquake and tsunami, the Thailand flooding, and a high number of US tornados in 2011, and Hurricane Sandy in 2012 (Marsh, 2015b; Munich Re, 2011, 2012b). While 2011 events globally yielded a then record of $380 billion total and $105 billion insured loss (both higher than 2005) (Munich Re, 2012a), Hurricane Sandy a year later cast a long shadow of damage and loss from both flood and wind across the socio-material environments it interacted with, ranking at the time as the third-costliest hurricane after Andrew and Katrina with $70 billion total and $22 billion insured plus $7 billion NFIP loss (Allianz, 2013; Swiss Re, 2013).

These events prompted vendors to change and update their models (Mitchell-Wallace et al., 2017; Wyss, 2014). For instance, earthquake models needed updating on the so far unknown fault underneath the city of Christchurch and the soil conditions' liquefaction effects; or incorporation of underground structures and electrical grid exposure to secondary peril storm surge in hurricane models and the integration of new flood data from FEMA after Sandy (Marsh, 2015b; Powers, 2015). What actualised catastrophe had 'revealed' was, then again, ingested in models in multiplicity, "There's a constant conversation going on around those questions. [...] 2011, a whole lot of things happened which weren't necessarily in the models", tells me vendor modeller I03. "And so, it was really important that we had a research agenda leading to product innovation focused around tsunami modelling or magnitude 9 earthquakes or liquefaction or something, which all came out of some of the lessons of 2011." It was a series of appropriation acts similar to the ones after 2004/2005. Along these events of actualised Anthropocene catastrophe, however, one other event stood out and it would provide the final push for model users as the more active appropriators of catastrophe models. Amidst the tensions between actualised and model-produced catastrophe, which drive the financial ontology of Anthropocene catastrophe, a disaster materialised exclusively inside the financial realm, endemic to the practice of catastrophe production in multiplicity and its appropriative dynamics throughout the markets it involves: the RMS model 'Version 11' update in 2011.

a. RMS's Market Leadership

"[In ILSs markets] they're using different models, different bankers, different modelling firms behind them [...] So, we couldn't, for example, recreate AIR's view [the calculation agent of specific bonds]. But we could say, 'here's a *consistent* view'. So you can actually add up these risks and then the Miu software platform lets you essentially roll up and measure the accumulation across different deals. [...] Miu is the Japanese word for a cat" – "The animal?" – "Yeah, yes, haha!" We laugh as Hemant Shah explains to me how in the late 2000s, RMS had built and started offering a portfolio analytics software called Miu for ILSs market users that re-modelled deals on the back of RMS's own model suite to make, for instance, several catastrophe bonds comparable on their risk metrics for investment portfolio analysis. Across this growing palette of vendor products, catastrophe modelling by then had been in use from insurance underwriting all the way to investment portfolio analytics, in line with a growing convergence of (re)insurance and ILSs business models and a host of mergers and acquisitions (Borscheid et al., 2014). "All of these use cases were [now] connected, i.e., issuing a cat bond is related to managing a portfolio is related to allocating capacity and line of business is related to an underwriting decision. You need models that can support that end-to-end process in a consistent way. And that's when RMS started to break out."

Their initial focus on software and the industry-wide integration of model suites into different forms of software, enabling contextualised catastrophe production for different financial practices and functions, helped RMS to eventually dominate the vendor market throughout the 2000s. "I think the biggest detriment […] was that we probably didn't have the best people doing the software development [...] So over time, RMS began to become the leader", remembers I64. P02 explains that it was "like a VHS-Betamax type of situation where, well, people want one type of solution, one type of technology. [...] Once it became clear that they [RMS] were dominant, that domination was going to perpetuate because the market would support them." Shah clarifies, "Our view was, that we need to deliver a modelling platform that can span this across enterprises. So we may not be as precise as EQE on an individual building for earthquake. We might not be as easy to use and computationally efficient as AIR on a portfolio. But our models can support both in a credible way that is coherent. So you could actually measure things in relation to one another and actively manage a book of business risk by risk by risk".

Also, quite materially, RMS's models' data format had become the practical industry standard. Vendors build their software on proprietary platforms, which includes not only their own application programming interface but also the underlying data infrastructures and applicable data input and output formats. Adherence to these data formats is especially critical on exposure data formatting (input) and results formatting (output) when running catastrophe models, and these formats differ by vendor and are often incompatible (see e.g. Fulcher et al., 2006). "Data standards were created around each of these modelling firms, so this is a real barrier to creating choice. So what happened was, people said, 'we have to use one format for AIR, one format for RMS, one for EQECAT. If we are only using one, then I can use just that.' [...] That data standard that RMS had created for themselves, once it became dominant it became very hard to compete with it." (P02).

Concretely, RMS's EDM (exposure data module) and RDM (results data module) (Fulcher et al., 2006) got integrated across the industry and "RMS didn't call what they have a standard - but it *is* the data standard in cat modelling in the industry" (P02). Model users needed to build up data-infrastructural interfaces, often including cumbersome manual data cleansing and reformatting, to allow for systematic data import and export between their data systems and vendor models. U68's department at a large institutional investor had then moved from AIR to RMS "not so much on the basis of 'one modelling methodology is better'. It was more a question of the actual software implementation." "RMS is strong because they were able to enter all the systems, everything is based on RMS." (I13). "It'd be kind of like Excel spreadsheets. [...] If you use a non-Excel spreadsheet, you can open it as an Excel spreadsheet, but what about that one percent of the time where there's an incompatibility and the cell shows a blank because it can't be rendered. So there's a huge effect like that for RMS, their data files are actually the industry standard. [...] [They] really built up the data structures to really embed themselves in the industry such that it's almost impossible to get rid of them." (U42). In other words, vendors and their models applied particularly material appropriation acts to (re)insurance data infrastructures, cementing even more their central position in catastrophe production in financial services over the 2000s, with RMS as the definitive leader by the turn of the decade.

By the start of the 2010s the industry felt as if RMS "were the only game in town" (U42) along with RMS's rather ambitious marketing and positioning in the catastrophe risk space. Although in principle being based on the same structures and techniques, "it's the same science [...] [RMS] cost more, they had higher prices" (I35). AIR's Karen Clark notes on this, "I thought [then] lower prices were better but actually [...] it's total psychology". Major vendors in general had increased model prices, "we had an oligopoly and oligopolies mean [...] you drive up price. [...] increasingly they'd [users] be looking at this and going 'what? How much are we paying? That's ridiculous! I want to negotiate that down' and then they realise, they can't, they have no choice" (P02). The vendor I64 remembers asking a former RMS manager they had hired, "'RMS continue to raise their prices on their product and thereby sucking up the budgets that reinsurers have for running models. Why is RMS doing that?' And [his] answer was 'because we can'". "Top clients [of RMS] are paying 12 million a year [$ US]", tells me U42, and this price narrative developed together with the perception of models becoming increasingly complex. Amidst the increased literacy of users, confronted with regular model updates and new features, I35 summarises RMS's stance at that time as following: "'Our models are more sophisticated, so they're better. Our models cost more, so they're better.' They got more clients, they got bigger, 'We're bigger, we have more scientists, so we're better'. That's how RMS got there."

But subscription price increases had not only marketing reasons but the expansion of vendors also necessitated higher returns to compensate for growing bodies of staff and research. RMS in particular "had grown *dramatically*. […] end of the 90s, RMS was about 30 million in revenue. At the end of the 2000s RMS was like 200 million dollars in revenue, so almost 10-fold growth. They'd gone from 50 to 100 people to […] 1200 people", tells me Shah. Especially the consistency approach across different types of catastrophe from underwriting to investment management complicated model development and increased models' complexity. "And it wasn't, you know, six people building a model [anymore]. You'd have dozens of people working on *a single* model update. And the model teams got very large. The problems became somewhat siloed: 'Ok, we have one team working on the wind field of that new construction [type], one team working on the parameterisation of the storms, another team working on the re-characterisation of the vulnerability curves.' [...] we were very focused on building these broad platforms".

This was also driven by developing public as well as proprietary knowledge and data, "in the late 2000s, with more and more granularity, the science was getting more refined, there was more data available", says Shah. In other words, while catastrophe production by vendors became more complex with an increasingly siloed internal expert community – think of a set of connected sculptures containing more and more elements pieced together by an increasing number of different artists – the user community had grown and broadly integrated especially RMS models into their activities – the sculpture installation became placed in a host of different environments, which interpret them from various different angles with appropriative dynamics around different meanings. Although there are several aspects in the assumptions of the increasingly newly added elements in catastrophe models, one in particular became both dominant and problematic in this more complex reciprocal appropriative staging of catastrophe models: the so-called 'near-term view' in hurricane frequency projection.

b. The 'Near-Term View'

A central element in the forming of tropical cyclones is the deferential between sea-surface temperature and air temperature: the higher the sea-surface temperature in contrast to air temperature, the better conditions for tropical cyclones to form (AOML, 2006; Gray, 1998). Upper-layer ocean water temperatures vary and, for instance in the Atlantic, do so on a patterned, multi-decadal scale. There are decades-long phases in which more or less continuously the sea-surface temperature is warmer than in other, colder phases which alternate in the Atlantic Multidecadal Oscillation or AMO (AOML, 2005). While there is no doubt around an observable patterned change in sea-surface temperatures, there is increasing scientific debate around whether this pattern is a 'natural' variability independent of broader phenomena such as climate change, i.e., whether it is indeed an actual 'internal' oscillation such as the El Niño–Southern Oscillation (e.g. Clement et al., 2015; Frankcombe et al., 2018; Haustein et al., 2019; Trenberth and Shea, 2006; Zhang, 2017). Fairly strong indications, for instance, point to an increase of hurricane activity after the capping of sulphate aerosols emissions from fossil combustion in the 1970s. Their wider climatic effects had previously led to a cooling of parts of the planet, decreasing sea-surface temperatures and hurricane formation. After its emissions gradually declined towards the 1990s, hurricane activity increased again (Mann et al., 2021). This is important for projections of future hurricane formation patterns, for instance, as these 'external' and for the future potentially unknown anthropogenic factors can vary more or less than the assumed 'internal' oscillation of the thus problematised AMO.

Although debated scientifically more today, there had already been discussions and indications in the 2000s (Mann and Emanuel, 2006). Yet, although catastrophe model vendors were aware of this debate, vendors and most decisively RMS started to take the AMO more systematically into account after the 2004 and 2005 hurricane seasons. Regardless of its explanation, Atlantic sea-surface temperatures had indeed been in a warmer phase since the 1990s and highly contributed to the high-loss regime of Anthropocene catastrophe. Until 2005, catastrophe model vendors, including RMS, applied the so-called 'long-term' view on hurricane frequencies, including both warm and cold phases in occurrence frequency calculation (St John, 2010; Weinkle and Pielke, 2017). However, especially the 2004/2005 seasons had clearly materialised in a warm phase, making formation of tropical cyclones much more likely and stronger. On this basis, the so-called 'near-term' view emerged, in which only warm year simulations are used, appreciating the higher probability of hurricanes forming, otherwise averaged out in the long-term view. Amidst its market-leading position, RMS became the most active proponent of an adoption of the near-term view in hurricane model updates.

The near-term view was justified in so-called 'elicitation' procedures (Weinkle, 2019). Elicitation involves the forming of an independent scientific expert group organised by vendors which functions as a proprietary peer-review consortium whose results are used to calibrate but mainly to legitimise model changes. Vendors' elicitation processes around the adoption of the near-term view are a particularly resourceful, public and politicised form of the appropriation of public science, as Weinkle demonstrates: "The end result of the process was a new "Near Term" event catalog that provided an increase in hurricane frequencies by 21 percent for category 1 and 2 storms and 36 percent for category 3–5 storms compared to the existing long-term catalog. RMS and the broader insurance industry touted the Near Term event set as a great technological achievement representing the very best of scientific knowledge." (ibid.: 7).

Especially rating agencies quickly adopted the near-term view, already in 2006, "Like A.M. Best and S&P, Moody's moved to a short-term frequency event set for the industry exceedance curves" (Guy Carpenter, 2015b: 10). In Florida, the debate around the near-term view was particularly contested since it provoked higher hurricane rates and risk in model outputs, resulting in higher insurance premiums (Weinkle, 2019). Despite the 2006 changes in its own regulation - "advances in science or technology […] [may lead to] develop new standards or revise exiting standards to reflect these advances" (NAIC, 2010: 188) – the Florida Commission initially rejected the RMS approach after which a workshop on the short-term view was scheduled and, eventually, RMS's model was accepted under the 2008 standards (ibid.: 228). This overall adoption process during the late 2000s yielded an industry-wide acknowledgement of the near-term view's legitimacy, and all three major vendors had started offering it, although RMS had done so in the most integrated way while others still highlighted more openly the usefulness of alternative views (AIR, 2015; Dailey et al., 2009; Marsh, 2015b; Weinkle and Pielke, 2017). While hurricane risk became, therefore, higher over time not because of a repetition of the 2004/2005 seasons towards the end of the 2000s but due to the adoption of the near-term view (Swiss Re, 2020), model users became accustomed to more regular model updates framed around new scientific insight, "people had gotten used to that and they think it's about the science." (I35). These series of appropriation acts by vendors culminated, however, in 2011 when the epistemically and infrastructurally dominant RMS rolled out its major model update RMS RiskLink Version 11.0 Hurricane & Windstorm Model.

c. 'V11'

"You know, for us, we knew we had made a terrible mistake as soon as we released" tells me I01, a former manager involved in the RMS Version 11 release. The socio-material appropriative dynamics around catastrophe production had until this point perpetuated the position of vendors as the primary appropriators of ever-increasing modelling practices and cemented the catastrophe model as the central appropriation object mobilising the industries' epistemic and infrastructural devices and practices of catastrophe production. 'V11', as many in the industry refer to it, however, marked the moment where a vendor lost appropriative control over their appropriation object, a device whose appropriation of the industry's catastrophe production became now socio-materially so consequential that it transcended the environment for which it was designed. "I think it was a combination of a degree of arrogance and a degree of rapid growth and the culmination of one way of thinking about how we built and calibrate models that, you know, it almost took a bit of a catastrophe to change the culture and the models".

As discussed in earlier chapters, model updates follow the calibration of elements in different submodules of the overall model. Calibration can be driven by the appropriation of theoretical or experimental insights and from actualised catastrophe. Also the socio-material breaking points of the 2000s had produced a flood of new public and proprietary data, prompting a host of appropriation acts especially around hurricane models. As a socio-material activity, catastrophe model construction and calibration have also a critical organisational dimension, which involves a form of bricolage or 'curating' (Kob, 2020) as to fit together different components to form an overall piece of work, where various elements, data, devices and knowledges are appropriated and re-contextualised. In these newer and more complex model updates with changes to the various submodules, modelling-produced catastrophe, to use the illustration of art works again, started to appear like a sculpture installation entailing various objects positioned in a three-dimensional space in which the different elements stand in relation to one another and in which the overall web of relations and objects form the overall installation. In the case of the fast-grown RMS, as noted above, most sub-modules would have dedicated calibrating specialist teams whose individual objects, then, need to be integrated and set into relation with all other components forming the overall model.

"RMS for new versions, they would bring in new engineering and new science teams, and they would allow them a blank slate. They would be like, 'Ignore the past. I want you with fresh eyes to look at this'. [...] When RMS does this, their model is very well known for having volatility that way on model updates. And they're proud of that, they say: 'that's evidence that we're not just on autopilot and just taking the past up and tweaking it - we're taking a fresh look at it'. And they're right. But [with V11] they just went too far." (U42). Although not entirely unique, approaching model updates this way stems from

RMS's initial modelling culture, as Shah explains to me, "RMS when it's at its best, was deeply bottom-up in its thinking. It came out of that culture. […] You know, RMS is a hundred and something people with doctorates, I mean, like a large university. […] it has this deep commitment to this granular science and engineering-based construction of models." U42, who has himself a science background, a lot of interaction with vendors and hired a number of former vendor modellers, confirms, "what they'll do is that they let all the engineers and all the geophysicists and everything do their thing", a more and more siloed division of labour. Putting these sub-modules into interdependent relations to one another, the curation of different elements into an overall installation, is, then, all the more critical work to produce modelled catastrophe and which is often referred to as 'integrated calibration'.

Organisationally, this involves a function which sits above the individual modellers ensuring an overall socio-material curational process in updating a model. "They'll assemble all the modules in a radically new model version, slam them all together, and run some basic benchmarks. So, for example, the classic one is, 'how much is a 1-in-100-year Florida hurricane in terms of industry loss?' And let's say that number is now hovering around 110 billion dollars. So they run that number again under the new model and if it jumps to 210 billion dollars, they'll pause and say, 'Ok, we know what happened'" (U42). The 'curators' then engage with the teams, identify new elements in their submodules and look at the risk-contributing factors, which due to the stochastic nature of the modelling are often ranges around a mean rather than a single number. Here, for instance, a new roof type of a building adds to the sub-module's damage function an additional 5-20% of potential loss, which, to be conservative, would have been set to 20% by the specialist team for the initial overall model run. The 'curators' contextualise this individual element and might, for example, nudge this factor down as it affects other sub-modules and the overall dynamic of the model, "If we made that, like, 14%, would you be ok with that?' 'Yeah, sure, that's noise. Fine.' And [the 'curators'] just run around and talk to everybody like this. And then they rerun the model. And instead of a 210 billion dollars in all industry loss, its 135. And they're like, 'that's fine'" (U42). Although this procedure is to differing degrees common to all vendors, this curation is sometimes perceived by more sophisticated users as if "in the end the individual component might not be right […] they are counting on errors to cancel each other out" (U60).

Although RMS's flagship RiskLink US Hurricane & Windstorm Model is updated annually, major updates had last been released in 2003 and 2006 (Lloyd's, 2012). With V11, RMS released the next major model update, entailing various bigger and smaller methodological changes to a number of existing, and introducing some new, components. Apart from, for instance, incorporating additional territories outside the US, a rebuilt wind model and related damage functions, or updates on roof construction types, three major changes would turn out to be particularly impactful: near-term hurricane frequencies, so-called 'inland filling' rates and a new storm surge model (ibid.; Marsh, 2012).

For the new near-term hurricane frequencies ('medium-term' in RMS terminology), RMS used so-called 'forecast activity rate models', which project five-year annual average landfalling probabilities by automatically adjusting to the current sea-surface temperatures, whereas the individual rate models are weighted against each other (Lloyd's, 2012). For V11, RMS had abandoned its elicitation procedure, in which the weighting would have been discussed and decided on, and instead applied a historical back-testing approach, so-called 'hindcasting', to assign the weights automatically (ibid.). This change in near-term frequency methodology caused the overall model to project an almost doubled loss factor for near-term Category 3-5 hurricane landfalls compared to the 2010 version (ibid.).

The second major addition was a component that modelled the so-called 'inland filling' of hurricanes, which refers to the decay of the storm's intensity upon landfall (ibid.). In part based on the experiences from Hurricane Ike, RMS extended the severity of storms moving further inland which would increase loss estimates from this element of catastrophe by up to 200% (Weinkle, 2019). A third component was a newly added storm surge model, a reaction primarily to hurricanes Katrina and Ike's flood loss experience. It incorporated an additional loss factor by increasing potential flood surge loss and assumed 'coverage leakage' from flood into wind damage policies. It increased the flood element of hurricane catastrophe by a factor of 4 compared to the 2010 version and accounted for about 18% of the overall loss estimate, double of the 2010 version (Lloyd's, 2012).

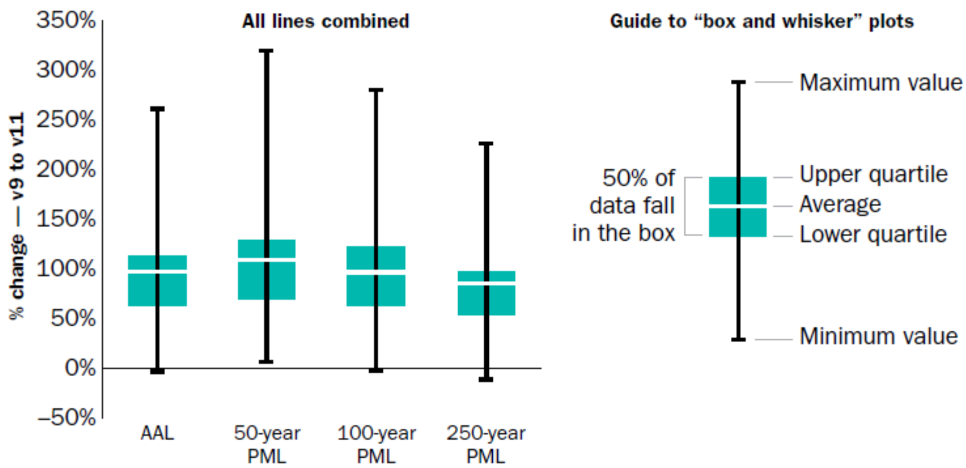

Figure 19: RMS RiskLink 11.0 change in % from version 9.0. (Source: Towers Watson via Lotz and Schmiesing, 2012)

"2011 the whole [modelling] industry changed by a 100%" tells me I35. RMS's US hurricane model was and remains until today the most important model of their suite as it pertains to the financially most critical arena of global catastrophe risk markets. "A little tiny change can make a big change at high resolution level. So it happens all the time, this volatility, and it's just noise, it's not new science. [...] So, I don't want to say there is never any new science, but [does] this new science indicate that your losses should be higher or your losses should be lower? That should be stated before you even do the update, because that is the point of the model". Although model updates always come with documentation flagging updates' implications, V11's role-out immediately changed firms' applied model loss estimates, for instance very critically for annual average loss (AAL) in variations between -4 and +279% (c.f. Lotz and Schmiesing, 2012). (Re)insurance firms' solvency ratings would have drastically changed, prompting expensive capital increases. Also, 16 catastrophe bonds, whose calculating agent was known to be RMS, were placed on negative credit watch by S&P, six of them with ultimately lowered ratings (ibid.).

In mid-2012 at the latest, the industry had fully implemented V11 into catastrophe production with "the effect of significantly increasing aggregations and the amount of capital insurers need to have at hand. RMS v11 has been considered to be equivalent of a $25 billion to $35 billion capital event in the property market" (Marsh, 2012: 3). "For twelve months, at least a year, users could not figure out why their numbers changed. [...] There was board-level angst because the models were so important. My capital, my RoE [return on equity] is dependent on my PML that comes out of the model. So if my PML doubles, either I have to raise twice as much capital or my RoE goes down immediately. I told my investors, 'I was making 15%. Well guess what, I'm only making 7,5% now.' That is huge!" (I35). Hemant Shah, in an attempt to get ahead of the curve while also trying to own up to V11's implications, published a statement in mid-2012 titled 'A Paradigm Shift', invoking the 'accidental ecosystem' of reciprocal appropriational dynamics in catastrophe production:

> "The present modelling ecosystem, from the development and release of models to how re/insurers operate them, organise and roll-up the results, and disseminate and act on their implications, appears to many as a Rube Goldberg-like contraption – a somewhat accidental, over-engineered and creaky machine. [...] Instead of models helping users to become more deeply risk-aware, the opposite can occur. Indeed, some now feel more vulnerable to a change in model versions than to the very catastrophes that these models were intended to mitigate. [...] We all became too complacent. While models can help optimise a book of business, an overreliance on models can lead to fragile portfolios that are prone to surprises, whether from Mother Nature or from the models themselves." (Shah, 2012: 16).

Model user proponents, such as P02, had long criticised the power and centrality of the dominating vendors and saw in V11 a justification to increase appropriation by users: "Basically [Shah] was saying 'we got it all wrong'. And the reason why they got it wrong partly was because with version 11 [...] people were very surprised about those changes – and they shouldn't have been surprised, right? Because we're talking about natural uncertainty in those products, right? And they were surprised, and they blamed RMS, and they were surprised because they understand these models." Although this might sound paradoxical, it actually points to the shifting appropriative dynamic since precisely *because* users understood catastrophe production better, their more active appropriative reading of the appropriation object yielded a problematised interpretation that prompted a call for more appropriative agency in the process of proprietary catastrophe production. V11 magnified the central position of vendors as appropriators in producing catastrophe and catastrophe models as active appropriation objects placed amidst individual user contexts. However, on the concrete socio-material level of the model update itself, V11 revealed the central issue at the calibration of updating models, the 'curation' of the relational components in the appropriation object's assemblage.

The socio-material curatorial complexity of V11 became especially strained with the novel storm surge model adding a considerable load of 'new' risk to the outputs. Katrina and Ike's huge flood loss led to a number of court cases in the mid- and late 2000s on whether existing hurricane policies would be liable for flood surge damage claims. "The wind policy was forced to pay for all those homes. You see, normally those are excluded. [...] The clients complained to RMS and said 'your model is crap. We had huge losses from the water, what your model did not pick up on. And I'm hopping mad at you. I'm blaming you guys. So I want you to fix it.'" (U42). The then introduced flood surge model was meant to represent these more relevant aspects in the financial ontology of Anthropocene catastrophe by the new decade. This model's huge loss projections had at least two sources. First, it highlighted flood surge loss as a significant financial contributor to hurricane catastrophe: "The storm surge model was too aggressive. [...] It's biblical. It just takes out everything for like twenty miles inland." (U42). Second, the legal environment around 'coverage leakage' had since changed in more specific policy language and a number of post-Katrina insurance litigation rulings determining that wind coverage does not cover flood damage (Cohen and Rosenberg, 2008). Yet, RMS had decided to leave the assumption of intense coverage leakage from wind to water in the model (Lloyd's, 2012). The primary reason for this seemed to be to protect a number of previously complaining but large clients, to which RMS's rection was to, "say to the user, 'Well, you can dial it back if you want to. But just to be conservative, in a sense, we want to overstate the losses. We can let the customer understate them. And now we don't get yelled at by the client.'" The socio-material entanglement of these two aspects, the pronounced loss from the flood simulation and the goal-driven overstated coverage leakage, remained unresolved by the curation of V11, "because project management was so complex, when it rolled out, you couldn't roll back the storm surge loss." (U42).

Steep growth of RMS, increased siloed structures around model components, and the ever-intensifying interconnected range of use cases had made the 'curational' practice of model calibration much more important to keep the appropriation object 'in check', and it had failed with V11.[60] Failed

[60] For confidentiality reasons, I cannot disclose the exact succession and position of managerial failure in this 'curational' process. However, the overall dynamic described should serve the argument to the degree necessary,

internal curation overall led to a very different installation of catastrophe, in which "there wasn't enough attention to [...] make sure that when the results come out the end, it's not just 'you add all the components together and you get an answer'. […] the whole can't just be the sum of the parts, because you have a lot of integrated calibration." (I01). I35 confirms, "These are models, they are based on science and every scientist has to make assumptions because there is very little data and these models are very complex, and there are many places where they can go wrong, and there can be mistakes, and there can just be bad computer code in there, etc.". When RMS had introduced V11, the lack of comprehensive socio-material curation started to become more obvious across the user community, "It got out of control!" (U42). Having been placed into numerous individual contextual places in (re)insurers' operations, a too centralised yet shielded and, ultimately, unsuccessful curation of proprietary catastrophe production revealed its expanded dimensionality across applied financial risk management.

The epistemological and socio-material issue of a catastrophe model being more than the sum of its parts is not only a vendor-internal appropriational node but always extends into the realm of usage, which became much more pronounced with V11. The question RMS should have asked itself but had not, according to I01, was "Are you iterating your calibration to ensure that the end result is reasonable?", by which he means not simply scientific reasonableness but reasonableness for the environment in which the output is meaningful. As with sculpture installations, the contexts and spaces into which such objects are placed matter as much to the objects' meaning and interpretation as the object itself. It became clear that internal critical inspection to the degree necessary was not living up to the contextual consequences of such complex socio-material installations that had become operationally so critical to catastrophe risk markets.

> "So even though there was an argument to be made, there was a lot of new science between the new hurricane model and the older hurricane model, introducing it in one big step function is not healthy or helpful because there's now a market trading on this information, it's not a research function anymore, it's actually: capital gets measured, you know, rating agencies have a view, reinsurance is structured in part on it, cat bonds are triggered or not triggered. And as a result, even if the science changes this much and the [risk/loss] number needs to be higher or lower, it's better to have a more continuous [updating]" (I01).

More than with earlier instances of model issues, users' contextual interpretation of RMS's appropriation object V11 yielded a critical appreciation of the complex environment of proprietary

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since the crucial work of assembling the overall model from relational components was the definitive source of the main issue with V11.

catastrophe production. Not only the performative qualities of models and their updates but also the inherent goal-settings of vendors became more pronounced as appropriational consequences of vendors' competitive business strategies for model performance. "About how much of this was really done on deep, sincere scientific thinking as opposed to sort of more the commercial consequences of this? […] We were always sceptical that it wasn't suddenly stunning new science but it was that they were doing things that the market perhaps wanted to hear as opposed to what they believed in and so they would turn the models one way or the other. But then sometimes they did things that shocked the market, and we couldn't understand that either." (I64). While, for instance, the introduction of the flood surge model had catered to what key clients 'wanted to hear', RMS had also led the market's focus on near-term hurricane rates, while they, now, had shocked the market with the socio-material culmination of epistemic *and* commercial appropriation acts materialised in V11.

In market environments, appropriative dynamics entail tensions around goal-setting for knowledge production and market competition, which was magnified by V11. "One of the problems about RMS or AIR: they are in the business of selling software [...] providing the best science and selling software, there's no guarantee that both are [always] in sync [...] Let's say, even if RMS were correct in jacking up the [frequency] rates [...] even if they had been [scientifically] correct, then they still would have lost business" (U60). These dynamics have a material impact on realising catastrophe in financial services, since knowledge production as a pillar for competition is not about finding viable truths, as already argued, but about enabling business not only for (re)insurers but, of course, also for vendors, as vendor veteran I64 confirms, "we learned early on that being true to your technical heart is not necessarily giving you a lot more business". Even rather 'forgiving' users such as U68 were taken aback by the swift reaction of RMS ultimately walking back some of their model changes: "Either sticking to your guns saying, 'We've used the best science available; this is what we believe in and we're going to stick to it.' But then they're running a business and there were a lot of pressures for them to reverse course. [...] there was a lot of criticism thrown at RMS, which I don't think was warranted [...] But the flip-flopping, that didn't help them." U60 describes a similar confusion, "So ever since, you see RMS [risk] numbers going down for the first time. It isn't easy because, is it because they have caught up the science or is it because they have a new business strategy? Nobody knows."

d. Institutionalising an 'Own View' of Catastrophe Risk and Normalising Multiplicity

In the catastrophe analytics market, by then understood as a 'duopoly' (Nasdaq, 2018), one rather immediate consequence of V11 was that the other major vendor, AIR, gained significant market share. "AIR got a lot of business after that. [...] At a conference, I heard someone saying, 'AIR salesperson of the year [award] went to Hemant Shah'" (I35). But the socio-material position of catastrophe models as infrastructurally deeply integrated appropriation objects throughout the market meant that RMS by no means faltered fatally in the medium-term. “In my opinion, [RMS] could probably do anything, they’d still have a strong hold. To change your exposure databases, your process and stuff, it’s a lot more complicated than simply ‘changing a model’ [...] all your systems are built around that” (I13). Also on a governance level, there were provisions in place to prohibit ‘model shopping’, as U60 tells me, “Rating agencies would say: ‘since you licensed the RMS model, you can’t change models just because they raised the numbers’” (U60). For new or renewing business, however, the heavy dominance and market share of RMS declined. “The entire industry almost fired RMS. AIR suddenly got business like they never dreamed of [...]. And so, at a minimum, what happened now is that everybody has both RMS *and* AIR.” (U42)

V11 and its aftermath over the first half of the 2010s prompted an increased balance between the two major vendors in the risk analytics market with an overall uptake in subscription.[61] In the catastrophe risk market itself, however, this entirely virtual catastrophe yielded a tilt of appropriative agency in proprietary catastrophe production towards the thus far appropriated user community practices and devices, exacerbating the sentiment of ‘owning one’s view of risk’. “It reinforced the user community should own their own view of risk, you can’t rely on the vendor models to be your own view.” (U60). “What has been happening [after V11] is that people believe they have to have their own view of risk, so either modify the model or they blend models or whatever”, tells me I35 and continues, “You know AIR and RMS [say], ‘Oh, near-term is up by 20, it’s down by 3, it’s up by 15’. I mean these are all just assumptions and the client has to choose, ‘Well, do I want 17% or do I want -3%?’ What if you wanted 2% or 3%, you know? […] So let’s say the range is +20% to -20% and anything in between. What people have now is they have AIR picking a number and RMS picking a number. So [users] got two numbers inside there, that’s all they have. Why shouldn’t they be able to test the whole range?” (I35).

In other words, multiplicity of catastrophe became the most critical focus in proprietary catastrophe production moving forward and RMS’s acknowledgement of inevitable change promised reformation in this now to be exacerbated multiplicity:

> “Products should offer a broad view into alternative perspectives on risk, and allow re/insurers to seamlessly penetrate the interdependencies between their exposures and the ranges of modelled output. And re/insurance companies must have the power to take control of the key model assumptions that drive those outputs. [...] Doing this the right way requires a modelling environment in which models are constantly used [...] It’s not about ‘running the model’ and then ‘generating the report.’ [...] In fact, this new approach will yield a range of models. The ‘same’ exposures will look different to different companies, as they should, and strategies will

[61] EQECAT had already before settled on a distant third rank.

be driven by explicit choices that each re/insurer makes on how to interpret and control key assumptions [...] [B]y having multiple dimensions from which to view risk and the ability to systematically and consistently interpret what the deltas [differences] mean, companies can [...] deliver multiple perspectives on risk." (Shah, 2012: 17).

Apart from the earlier uptake of catastrophe modelling practices and metrics by rating agencies, emerging standards and regulatory frameworks would now, in the 2010s and with the appropriational shift towards users, exacerbate the dynamics of multiplicity in proprietary catastrophe production. Standards frameworks were, amongst others, the ASOP 38 by the US's Actuarial Standards Board, and TAS D and TAS M by the UK's Financial Reporting Council (Mitchell-Wallace et al., 2017: 124). On the regulatory side, however, one of the most impactful ones was the long-prepared EU Solvency II Directive, which came into force in 2016 but had a long integrational onset since the early 2000s throughout the affected markets and indirectly other regions in which those markets wrote business (e.g. van der Heide, 2019). Solvency II aims at harmonising insurance regulation across the EU, including the UK even after Brexit, and in terms of risk modelling and management focuses primarily on firms' internal capital models, with direct implications for the use of catastrophe models in the industry.

Catastrophe modelling here is seen as integral to risk management and operations and is treated by default as an internal practice and part of the overall 'internal capital model'. "'[R]esponsibility for all components of an Internal Model lie with the company itself.' [...] Under Solvency II, companies must be able to demonstrate that they have appropriate in-house understanding of model selection and model change." (ABI, 2011: 9f).[62] This means that the appropriational position that Solvency II attempts to install for users of catastrophe models is the one of the appropriator who needs to demonstrate deep understanding of their appropriation object. This pertains, for instance, ensuring that models accurately reflect risk profiles (Article 120), models undergo systematic validation procedures, sensitivity tests and data assessment (Article 124), assumptions, mathematical and empirical underlying are justified and documented (Article 125), and if external vendor models are used that the responsibility for the above still lies with the firm itself and not with the vendor (Article 126) (EU, 2016: L 335/57-59). The hermeneutic reading of the 'Other's object', so to speak, is mandated to the reader, which is supposed to make it 'one's own' object, or as I13, vendor modeller and member of the Directive's expert groups, explains to me, "Solvency II is telling you '*You* own the risk'".

However, while it does so, Solvency II also means that any change from one model to another requires a detailed justification just as much as blending different models' outputs or benchmarking

[62] The Association of British Insurer's guidance on catastrophe modelling with a particular focus on complying to Solvency II includes out of 19 authors six from the three major model vendors.

across different models requires to demonstrate deep literacy of all models involved. While this in principle discourages employing more than just one or only a few models, it implicitly encourages to appropriate and re-contextualise more intensely the models that one does use, "you modify one model to accommodate your own view of risk. [...] Some people because they are convinced it is the right one, and others because they have to because their boss that they had 10 years ago decided that it works and then they have to invent new stuff around it". From a regulatory perspective, multiplicity in proprietary catastrophe production is, therefore, at least implicitly encouraged, conditioned by sufficient user model literacy of the 2010s.

Amidst vendor-driven infrastructural, material and intellectual property-related limitations still in place, users' increased model literacy would further grow to yield socio-material agency over vendors, "you don't agree with the models anymore, but it's so difficult to change [the model vendor], so what you start doing is changing the model. Because now a lot of people know about models [...] you can change your results and adapt them." (I13). The industry more systematically and confidently, "dug even deeper to derive their own view of risk, incorporating independent scientific research on hazard and vulnerability and other methods of validation into their investigations." (Guy Carpenter, 2015b: 13). To use the illustration of appropriation art and sculpture installations, users demanded appropriative share in rearranging, adding, removing individual elements and their relationships within the overall installation and in endowing different meanings to the piece of work by more contextually placing it into different environments. In other words, users demanded to become appropriation 'artists' of catastrophe themselves, moulding proprietary catastrophe by appropriating different vendor models into an object whose environment would be theirs and whose appropriative agencies they wanted to control.

After V11 as a market-endemic socio-material breaking point, the 'fracture of reality' between actualised and modelled catastrophe became a lot more blurred, since V11 emphasised the deep financial ontological relationality between the two. The weight that proprietary catastrophe production had gained seemed to have superseded that of actualised catastrophe as the imperative in catastrophe risk management – "a model revision can now alter prices more than a catastrophe" (Muir-Wood, 2016: 143). 'Owning one's own view or risk', therefore, has since become the central mantra in proprietary catastrophe production – the appropriational position that had finally become actively captured by model users. This is not to say that on a micro level the switching between positions of appropriator and appropriated did not keep permeating in everyday practice, since, as mentioned above, vendors still hold crucial socio-material sway over what can and what cannot be done with, and known about details in, vendor models. But on the macro level, the shift towards an overall appropriating position of users had materialised by the early to mid-2010s by the increased and normalised usage of multiple models and model vendors amidst the grown model literacy of model users: “Utilizing multiple models, blending one or more catastrophe models and/or adjusting catastrophe modeling output started to become the industry norm, and this trend continues to the present day.” (Guy Carpenter, 2015b: 13).

e. Socio-Material Appropriation in Consolidating Actualised Catastrophe

While the appropriation-driven growth in multiplicity of catastrophe production had become the norm, consolidating catastrophe once it has actualised is not free from appropriation either. An important sensing mechanism of Anthropocene catastrophe, as already discussed, is that of insurance claims against exposure databases, the mediation of actualised catastrophe. As competitively valuable data, sensed actualised catastrophe is not publicly available on a granular basis. Even within catastrophe risk markets, vendors act as epistemological intermediaries to derive and learn from actualised catastrophe. On a much less granular level, however, two firms collect loss data from (re)insurers to maintain so-called ‘industry loss indices’, PCS for mainly North American events and PERILS for mainly European events. These indices are used to maintain a market-level perspective on the severity dimension of catastrophe and are used, for instance, to activate industry-loss triggered (re)insurance products when a certain threshold of loss is breached. And although Munich Re with its NatCat and Swiss Re with its Sigma provide semi-public aggregate-level catastrophe loss repositories , they are not used for products themselves. Socio-materially mediating actualised catastrophe, however, is not without socio-material appropriation. Munich Re’s and Swiss Re’s industry loss repositories, for instance, can vary considerably on individual events (Waisman, 2015: 20).

On the level of the contextually situated insurer as the primary catastrophe ‘sensor’, an increased expansion of sensing devices has emerged, supposed to support the consolidation of actualised catastrophe. For instance, satellite services are used by insurers for geospatial surveillance of socio-material environments (Catapult, 2018). Parametric insurance products fundamentally hinge on specific sensor networks, for instance for hail damage (Artemis, 2019a). Sensor networks from the internet of things are also used for catastrophe-related products (OECD and ADB, 2020), such as water damage sensing in buildings (Munich Re, 2020). Vendors, too, have enlarged their sensing capacities to mediate socio-material environments of actualised catastrophe. For instance, Verisk Analytics, AIR’s parent company acquired in 2017 Arial Imagery, a “multi-spectral aerial photographic services with expertise in offering digital photogrammetric and remote sensing data for mapping and surveying applications.” (SEC, 2017: 5).

But even more institutionalised processes of socio-material mediation of actualised catastrophe are subject to appropriation acts, which renders Anthropocene catastrophe multiple by socio-material appropriation not just on the side of proprietary catastrophe production. This is important, since catastrophe’s moment of ‘truth’, the counterpart to its market-shaped multiplication at the ‘fracture of reality', also appears as an appropriatively active component in realising a financial ontology of Anthropocene catastrophe. An (arguably extreme) example for this is the case of the FONDEN catastrophe bond and hurricanes Odile and Patricia. The MultiCat Mexico Series 2012-1 catastrophe bond was issued via Swiss Re for the sovereign Fund for Natural Disasters of Mexico (FONDEN), covering earthquake and hurricane disasters in specified areas until its maturity date in December 2015. The Class C notes of the FONDEN series was a $100 million tranche featuring a large zone on Mexico's Pacific coast. The trigger type was parametric, i.e., coverage is determined by a sensed feature of the hazard phenomenon, defined in two intervals of millibar central storm pressure:[63] if a hurricane during landfall in this zone has a central pressure between 932mb and 921mb, the bond is triggered to pay out 50%, i.e. $50 million, of its collateral; if the central pressure is 920mb or less, the bond is completely triggered and pays out the full collateral of $100 million of this tranche.

Vendor modeller AIR was the calculation agent for this bond. As such, it has primarily a twofold role: it helps to establish the trigger threshold that is, via its modelling, associated with a certain degree of loss which the state of Mexico deems problematic enough for it needing additional funds. At the same time, it calculates and supplies the three main risk probability factors, expected loss, [64] attachment and exhaustion probability, that are the basis for the technical price for the bond's price discovery (see previous chapter), which in this case was a coupon of a very lucrative 8.75 – 9.10% based on S&P's rather high-risk level of "B-" (Artemis, 2016). This, of course, is already a socio-material appropriation act, since, for instance, the riskiness level perceived here by the rating agency S&P is more determined by the structure of the bond's tranche than by the fact that between 1949 and 2004 only two hurricanes actually produced such low central pressure (ibid.). Another appropriative dynamic lies in the more general sensing of Anthropocene environment, since before 1949 the central pressure of cyclone systems at least for this coastal area had not yet been measured (c.f. NOAA, 2019a) and are therefore in principle 'non-existent' – only after sensing devices deployed to measure central pressure, this facet of catastrophe (and the environment more generally) had been socio-materially realised.

Odile made landfall as a Category 4 hurricane (205 km/h, 125 mph) on September 14th, 2014 near Cabo San Lucas. Research planes off the coast had previously flown through the hurricane eyewall dropping probes measuring the central pressure at 923mb and winds at 240 km/h, or 150 mph (Muir-Wood, 2017). The strong gusts around the storm system had eradicated all measuring stations on land

[63] Central pressure is a measure projecting the intensity of a storm. The lower the central pressure of a storm system, the stronger and potentially more devastating it becomes (NHC, 2019).

[64] Expected loss was 4.36%, i.e. anticipated loss as a percentage of the principal, which is an inherently fictional number since the loss can in reality only either be 0% or 50% or 100% for this tranche, but it is used as a relative factor in the pricing and rating of the bond as it expresses the overall risk of loss in general (Artemis, 2016).

in the area three hours before landfall. For these geographical areas, the US National Hurricane Center (NHC) serves as the dedicated and qualified 'sensor' for such financial instruments, "A lot of pressure on the NHC guys. They probably rather not have this responsibility", tells me P63, the academic modeller. At this point the NHC had interpolated from the last plane measurements an estimated landfall central pressure of less than 932mb, which would have triggered the lower pocket of the Class C tranche and released $50 million to FONDEN. Meanwhile, professional storm hunter and journalist Josh Morgerman stayed at a hotel close to the city and measured central pressure right after landfall at 943mb and submitted it to the NHC (NHC, 2015: 7). Subsequently, the Center adjusted its landfall estimate to 941mb, which pushed the parameter out of the AIR model's trigger scale tranche C and prevented triggering of the bond altogether. Hurricane Odile, nonetheless, produced $1.2 billion of insured loss and left about 10,000 people homeless (Muir-Wood, 2017).

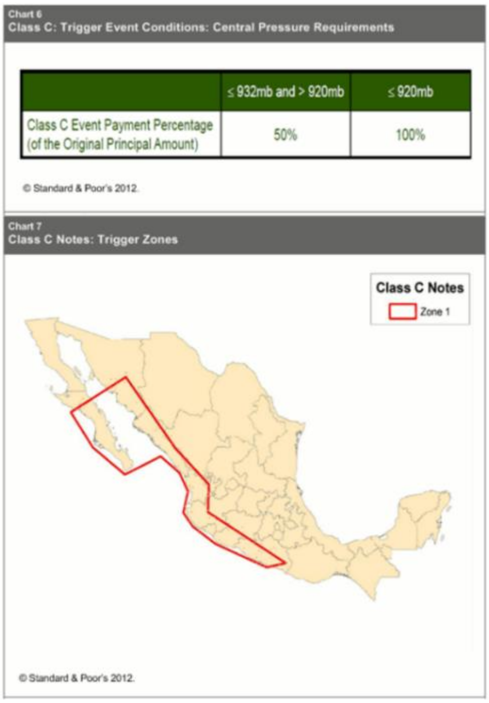

Figure 20: Trigger event & hurricane zone for Class C MultiCat Mexico 2012-1. (Source: S&P via Artemis, 2016)

A rather similar incident occurred a year later with Category 5 Hurricane Patricia. Pre-landfall measurements were at a very low 896mb and landfall central pressure was subsequently estimated by the NHC at 920mb, which would have triggered the upper $100 million pocket of the tranche – this hurricane has so far been the strongest Pacific hurricane in history (NHC, 2016). Again, Morgerman was present a few miles inland from landfall and measured central pressure at a much higher 937mb (Morgerman, 2015), i.e. outside the trigger scale, which contradicted the NHC's projections. As a consequence, the bond's triggering remained in a state of limbo for months (Artemis, 2015) until recordings of an automated weather station on a private biosphere reserve, not too far from Morgerman's position, were recovered and which recorded pressure at 934mb (NHC, 2016). This measurement led the NHC in early 2016 to readjust its interpolation to 932mb (ibid.), which indeed triggered the lower pocket of the tranche and released $50 million to the Mexican state. It should be added that Hurricane Odile, even though a less intense storm system, resulted in a much more devastating disaster since the area it hit most was much denser populated, while Hurricane Patricia hit a less inhabited area (Muir-Wood, 2017). Given the actual damage and loss incurred, in hindsight Odile would have necessitated a triggering and not Patricia. This contradiction ties the issues of sensing, knowledge infrastructure and fact production back to the socio-material assemblage that is catastrophe.

Although socio-material appropriation in consolidating actualised catastrophe is organised and materialises differently than the appropriation of catastrophe production in multiplicity, it is important to note that appropriation acts take place along the meditation processes involved, be it the definition of what constitutes in the financial realm a specific, contextual catastrophe by setting the trigger parameter or the mediation via extrapolation, direct sensors or public estimation models. In this way, socio-material environment is in permanent becoming on the backdrop of socio-materially mediated information. By the appropriational interlocking of these many processes and devices and humans and nonhumans, the financial framework for which context a socio-material environment is sensed becomes part of realising Anthropocene catastrophe. This is, of course, essential for subsequent proprietary catastrophe production since it is the backdrop that resulted from disassembling catastrophe into individual building blocks and is fundamental, in turn, for reassembling catastrophe in simulation. In this way, consolidating catastrophe is one of the central appropriational aspect for vendors' pivotal position in calibrating models and explicating multiplicity in the grammars of interaction of produced catastrophe.

II. Owning Catastrophe

"Mother Nature is full of surprises. [...] The next event is not going to be in your model" says a Head of Operations of a major Lloyd's syndicate in his keynote speech. About a 20-minute walk from the Monument in the City of London we are gathered at one of the major annual catastrophe modelling and risk management industry conferences at a slick convention centre in 2018. About 200 practitioners from (re)insurers, brokers, regulators and vendor modellers mingle on the extensive lower ground floor level of the centre as if we were sheltering away from the host of Anthropocene catastrophe of the previous year. 2017 had wreaked havoc in many places around the globe, but especially across the Americas. Most prominent was the 'HIM' cluster of three Category 4 and 5 hurricanes, Harvey, Irma and Maria, with landfalls in the Caribbean and the US, accompanied by massive wildfires in the west of the US and Canada, and major flood events in Texas, Nepal, India and Bangladesh. Overall, 2017 broke all records with global insured loss reaching $144 billion and total economic loss amounted to nearly $340 billion or about 0.44% of global GDP, almost double the 10-year average (Swiss Re, 2018b). Yet, no (re)insurance company got severely impaired and ILS products generally fared well (Economist, 2018).

a. Today's Proprietary Catastrophe Production in Competitive Multiplicity

"We had four very earnestly working groups of scientists that did the best job they could possible to work out the cost of pure premium across that certain region. And if you look at the answers, there is a *huge range* of answers." The moderator of a panel discussion refers to the preceding session in which a practice took place that has become rather customary since the mid-2010s at such conferences: model comparison exercises (e.g. Waisman, 2015). In these exercises, expert model users prepare a framework of specific objects at risk in a specific geographical region that is subject to a specific type of hazard and a number of benchmark scenarios for which different vendors prepare their models' loss estimates, which are, then, presented and compared in front of attendees – these sessions are particularly popular and well-attended.[65]

In this case, it was a comparison exercise on the most developed 'flagship' models for US hurricanes. The underlying hypothetical portfolio was based on public data and applied the objects at risk (43% buildings, 29% contents, 29% business interruption) and deductibles (1.4%) across the data set at more than 500,000 locations, taken from public geospatial location repositories (Stanford University's EarthWorks project and US Geological Survey's HSIP Freedom 2010 project). Four US regions were differentiated with different weights in terms of numbers of locations: Gulf area (32% of all objects at risk), Florida (9%), Southeast (19%), and Northeast (40%); within those, three more granular and socio-materially riskier 'Bay Areas' were more specifically focused on: Tampa (1.5%), Savannah (0.3%), and New York/New Jersey (5%).

Two large and two smaller vendors had been asked to run this hypothetical portfolio on their latest 2017/2018 update versions and prior to the presentation of results a representative of each vendor briefly explains the main features of their models. For instance, one explicates their model's emphasis on the importance of wind speeds and their non-linear relationship with damage in vulnerability functions, which take account of changing building codes on roof construction types and factors in neighbouring houses' roofs as sources of debris in the model's damage functions. Another highlights their model's large location-level claims data library with 20,000 validated field observations. Yet another stresses their model's combination of hurricane, storm surge and inland flood hazard components which offer access to parameters of correlation of secondary uncertainty, allows users to

[65] Three of the four industry conferences I have attended between 2018 and 2020 featured model comparison exercises.

change vulnerability settings, local digital terrain models and defence assumptions at an up to 10-meter footprint resolution.

After these introductions, but before going through the results, detailed specifications of the models are compared by the expert model user who runs the exercise. For instance, all four models use in-house adapted variations of HURDAT's historical data sets, they all take tidal effects into account, and all use the US Geological Survey's NED geospatial surface elevation datasets. Differences are, for instance, that only one model entails a full inland flood model, or that only one model applies a two-second peak wind gust measure while the others apply three seconds. These differences can play important roles in application, for instance applying two instead of three second peak wind gust can have an effect for risk products with a parametric trigger, i.e., were coverage hinges on an event breaching a certain wind-speed instead of a loss threshold. Another major difference is that one model applies a Poisson distribution for occurrence frequency while the others use Negative Binomial distributions. While the expert model user goes through these details, audience members sometimes comment on them amongst themselves. For example, a well-respected and seasoned catastrophe modeller from a large European reinsurer sitting close by leans over to people next to him and comments, "Sometimes shit happens and usually it hits the fan… Because you have mild, loss-free periods but then you have 2005, 2011, 2017 and this needs to be included in the models – this is not a Poissonian process, severe losses are not Poissonian. That we have to accept."

This is followed by a session presenting, explaining and discussing the results and their differences between the four models. Although a seemingly dry presentation, this is a moment where attendees spend particular attention, users and vendors alike. The expert model user meticulously goes through various benchmarks and output metrics on several granularity and location levels and highlights for which types and paths of simulated hurricanes which loss amounts are outputted (severity) at which return periods (occurrence). For instance, while there is agreement among all models on the projections for which of the four regions will experience higher or lower numbers of annual hurricane landfall frequencies (e.g., Gulf region as highest and Northeast as lowest), there is disagreement on frequencies within some of the regions, especially comparing near-term versus long-term projections. Average Annual Loss (AAL) projections overall from two of the models are double the projections of the other two, while there is agreement on Florida and the Gulf as the regions with the highest loss projections. Exceedance probabilities (EP) also vary across the different models where the only agreement is on EPs for more frequent and less severe events in the New York/New Jersey and Savannah 'Bay Areas'. Flood surge loss projections also vary considerably across the four models between 7% and 22% of overall loss contribution. A specific element of comparison exercises runs models on historical scenarios as a back-testing benchmark where the actual unfolding and loss are already known. Here, ten historical events had been run by the four models, including hurricanes Andrew (1992), Katrina (2005), and Sandy (2012). The models display the least differences on Hurricane Andrew with a loss spread of 80%, because it remains to be the most researched event and it is also the benchmark point for the Florida Commission. The most significant disagreement amongst the models is on Hurricane Sandy with a loss spread of 942%.

Now vendors are given the chance to explain and justify their models' results. Here, the different representatives highlight, for instance, that the primary source of difference are vendors' proprietary damage functions and one vendor stresses that their much larger and granular calibration datasets change their damage curves in comparison to other vendors. One vendor notes that they assume a bias on wind speeds in the underlying HURDAT datasets and, therefore, use not velocity but air pressure data from these sets. Another emphasises that in the historical benchmark for Katrina, their model applied the 2018 flood defence structures which lowered significantly the loss projection: in 2018 Katrina would be primarily driven by wind loss and not flood. Overall however, these differences are not seen as fundamentally problematic by both the exercise participants and the audience, and the expert model user notes the absence of any systematic biases in the models and concludes, "Knowing the strengths and limitations of the underlying assumptions and data is most essential for the users of catastrophe models".

This particular exercise took place not far from where the Egyptian Hall exhibited Géricault's Raft in 1820 and just as much as appropriations of the Raft have come a long way, so has catastrophe modelling whose appropriations are now exhibited in such industry gatherings. Although model comparison exercises serve no formal function, they embody the appropriational dynamic and status quo of today's catastrophe production in financial services. With the appropriational shift of owning a view of risk during the 2010s, catastrophe modelling appears in greater plasticity through which its hermeneutic reading is magnified. Model comparison exercises can be thought of as a form of staging appropriation-objects in user-curated exhibitions in which, as in sculpture displays, the objects can be viewed from various angles and perspectives and where the relationships between different elements and entire installations are inspected, interpreted and critiqued. The creators are given the chance to explain and justify their choices and provide intentions and interpretations of their work, but they are now to a much lesser degree the ones whose opinions count. 'Beauty is in the eye of the beholder', which is not only true for art but also for catastrophe production since the situated contexts of users are the primary loci of judgement in owning catastrophe today.

i. Model Evaluation

While model comparison exercises are a rather informal practice, a much more formal process is model evaluation at (re)insurance companies. Model evaluation, often also synonymously called model validation or even 'developing a view of risk', is a by now fairly formalised set of measures in an "overall process including adjustments to models, incorporation of non-modelled risk and implementation" as well as determining "whether the external catastrophe model provides a valid representation of catastrophe risk for your portfolio" and regulatory model validation procedures (Mitchell-Wallace et al., 2017: 390). Although not the same as model comparisons, model evaluation processes treat the concrete models and practices in a similar way as they are meant to inspect as deeply as possible the properties, inherent assumptions, differences and contextual consequences of different vendor and internal models for the individual company. This includes measures such as sensitivity testing, stress testing, profit and loss attribution, benchmarking, model functioning tests, or evaluating non-modelled risk (ibid.: 398).

In contrast to model comparison exercises, model evaluation and other measures of a formalised and implemented 'view of risk' process, in this sense, take the exhibition of catastrophe an important step further, a step that formalises and exacerbates the multiplicity of proprietary catastrophe production. Internal model evaluation appears here as the most crucial appropriation act by users on a micro level as the object is placed into their own situated and contextual environment – putting a sculpture installation into ones own contextual spatial setting can fundamentally change the piece's meaning.

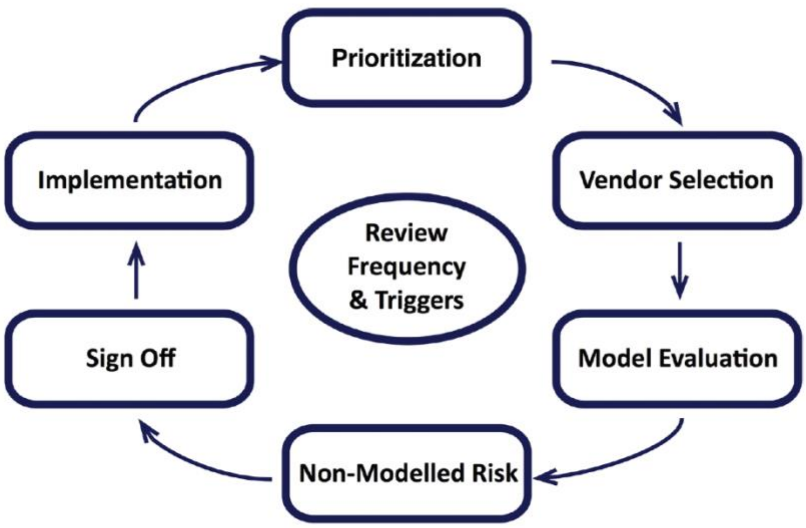

*Figure 21: A conceptualization of the view of risk process". (*Mitchell-Wallace et al., 2017: 396)

Market participants today have implemented to differing degrees these processes around catastrophe models and use "ideally more than one. And ideally, you have gone the extra step where you understand what comes out and why, and you have your own judgment on the risk. [...] A lot of the more advanced shops today will do research, understand the models and adjust them", tells me U53 over another drink at the Princess. An increasing number of sophisticated actors in the market not only appropriate vendor models but also construct their own proprietary in-house catastrophe models, “You’re going to build the views of risk, build new models where there is no model, these kinds of things. So that’s the primary task of modelling – [corporate] scientists are well equipped for that.” Arguably among the most sophisticated of such ‘shops’ is, for instance, Swiss Re which has a long history of dedicated research around catastrophe risk and employs today over 45 scientist-grade catastrophe experts running, managing and developing a global suite of several catastrophe models, including larger and smaller vendor and proprietary in-house models, on their internal platform, CatServer, with a unified front end application, MultiSnap (which goes back to their first model applications in the late 1980s, as U15 tells me). All relevant corporate functions, e.g., underwriting, risk aggregation management, or capital management, have integrated access to this platform, its systems and tools (Zbinden, 2020).

There is a growing tendency to grant more weight to catastrophe modellers and risk analytics units in the underwriting process today, as U52, the Head of Catastrophe Pricing at a large, globally active Asian reinsurer, tells me in his Bermuda office.

> “So the submission from the market [insurer] would come in and it would hit the cat modelling team first. We would assess the risk, modelling the risk through whatever models we are licensing, RMS, AIR, EQE, internal models […] So when a deal would be priced, the analytics team would do the full pricing of the deal. So we would do the modelling, we would build up the financial modelling of the structure, so the reinsurance terms and conditions, and then we would apply any outputs, calibrate the model and produce the results. And from there, the underwriting team basically would take that and then from there they would determine how much or if they want to write any of this risk. [...] That’s a core pillar of our strategy. […] The pricing team here has a lot of influence over whether we’re gonna write a deal or not. So when we complete the quantitative assessment of the risk, the underwriters don’t have flexibility to adjust that. That’s an internal policy.”

This active appropriational position of model users in owning catastrophe here stretches deep into the ‘risk appetite’ of the company, as the capacity of proprietary catastrophe production is directly influencing the focus of underwriting, “Our preference is more homeowners, residential-type business where we believe there’s less volatility in the cat models and we have better grasp on the risk”.

The in-house curation of elements of catastrophe production is by now a high-ranking position within companies, such as U60’s executive role at another, globally active Bermudian firm. Although he holds a science PhD, his role is not to conduct scientific research, “users, like myself, I’m not an applied scientist, I never pretend that I invent new science because that’s not my job. But it is my job to know where the best science is and use it for risk taking. The difference in top priorities is a key factor why I truly believe that companies need to have their own view of risk”. This centrally involves active interpretation of Anthropocene environments and differentiating against vendor modellers even if this means having to offer higher prices than peers, “RMS is pretending we’re in a cold phase now [Atlantic sea-surface temperatures in 2018]. Our scientists have told us that it is not the case and we’re not changing our rates, that means we’re less competitive to those who purely use RMS”, whereas “I think there is a very limited number of players out there just taking the model vendor outputs and accept the black-box nature and ‘yeah, whatever the model says’. Nobody does that anymore.” However, this doesn’t mean that one would not actively appropriate such vendor models, especially for vendors’ pivotal position on proprietary calibration data, “We believe RMS and AIR have the economy of scale to collect raw data of the underlying science and the underlying data for all perils in the world. We need that. [...] We’re buying their raw data they’ve collected. So our agreement with the vendor modellers is: ‘We buy your data, you don’t tell us it’s proprietary, otherwise, we’re not buying. We’re buying your data, we don’t even care to use your software.’” This appropriational position of users in proprietary catastrophe production exacerbates the multiplicity of catastrophic ‘reality’ which now exists socio-materially within each firm (whether they perform these tasks themselves or have model-savvy brokers to support them in these processes).

In line with these appropriational shifts, true appropriational agency is by now believed to require not only these processes but a proprietary catastrophe modelling ‘platform’, something that arguably very advanced firms such as Swiss Re already have. This has socio-material reasons within the production of catastrophe, “For example, if you are an insurance company, you have so much claims data, you believe for this particular house the building should respond instead of what the vendor says. How do you let the model let the building behave the way you want it without essentially having an open access to the platform: it is impossible for you to do. [...] It’s not only people want to own their view of risk, people want to own their platform.” (U60). As a reaction to these increasing demands from the user community and V11’s aftermath, vendors have started over the 2010s to integrate their model suites into often cloud-based platforms with overarching proprietary APIs, such as RMS(One), AIR Touchstone or CoreLogic/EQECAT’s RQE, which are meant to open up, for instance, modelling functions, assumptions or data access, “they would share that information, making it easy for teams like ours to just, you know, go to the backend and extract data and manipulate that ourselves.” (U68). However, while vendors attempt to balance out the current appropriational dynamics and positions by offering more open but vendor-controlled platforms of their many appropriation-objects, essentially enshrining them into second-order appropriation-objects that are their platforms – “the software platform is so rigid that they [users] are only able to make very limited changes” (U60) – the user community as a whole has since actively begun to install their own, collective second-order appropriation-object with the Oasis Loss Modelling Framework.

ii. Oasis

"One of the things that the main, large cat modelling firms have done so well is to use their multidisciplinary skillset to build a series of useful, functional tools for nearly 30 years. But it seemed that there was a desire to create something new, and so we decided to do that" says Oasis's director Dickie Whitaker on the stage facing an audience of (re)insurance and vendor practitioners and industry journalists. Minutes before, on a chilly evening in 2014, we stood queuing in front of the Lloyd's of London headquarter, a bowellist building designed by Richard Rogers which looks almost like an oil refinery, since all service components, such as stairs and piping, are visible on the outside. Walking inside, it suddenly looks like the outside of modern glass and steel office buildings with wide open and transparent spaces and visibility of the insides of individual offices. We took the escalators downstairs, which are also transparent, and on the sides and on the bottom the mechanics and greased metal chains are exposed behind thick glass. Hidden amidst all the technical surroundings on the lower ground floor, we were led into what feels like the antithesis of the building's genre, the 'Old Library', a windowless and wood-fitted room that was remodelled after the library of the original Lloyd's building that had grown out of Edwards Lloyd's coffee house over the last centuries. In the front above the stage where Whitaker spoke to us are wooden carvings and images of ship anchors and sextants referring back to the initial marine risk origins of the insurance business and the Lloyd's market. Here, I attended (fortuitously[66]) the initial launch event of the Oasis Loss Modelling Framework.

Oasis had been formed a few years before as a not-for-profit industry initiative around the issues of catastrophe modelling, especially V11's socio-material breaking point. Then founded and funded by the Lloyd's market and 20 other mainly large (re)insurers and brokers as well as the EU's climate initiative Climate KIC, it had by 2014 an additional 36 associate members which were not only industry institutions but also smaller vendors, consultancies, IT sector firms and universities with catastrophe research foci such as Columbia, Imperial College or UCL (Oasis, 2014a). Oasis was meant to provide a model-agnostic platform enabling to plug-in components of catastrophe models of all origins, i.e., internal and vendor models, primarily hazard and vulnerability modules as well as exposure and policy data. Oasis's platform is built around a kernel that combines an open-source loss module, proprietary loss data and an open-source financial module (ibid.). Although it also provided at its official launch in 2014 at least nine catastrophe models for flood, earthquake, tsunami and bush fire hazards, it is primarily meant for members to "put their own models into the framework [...] They are also able to develop models for sale or license to other users" (Oasis, 2014b: 2). This includes academic and other non-industry modellers as well, "there are more flood models that are outside of some of these main [vendor] firms than there are inside these firms. And I think that's perhaps a sign of the potential

[66] All credit goes to Martha Poon for inviting me to this event that inspired my focus on catastrophe risk markets.

diversity of supply that we can get embedded in this and other areas", notes Whitaker at the launch event.

While model evaluation processes are the most important appropriation acts by users on the micro level, Oasis is arguably the most crucial appropriation act on a macro level. While model evaluation places the appropriation-objects into firm's own contextual environments, like placing a sculpture installation in the company lobby, Oasis attempts and has partly by now already accomplished to erect and organise a socio-material gallery of appropriation-objects, a permanent workshop of catastrophe production. Oasis provides an open C++ API with direct access to its platform, a library with resources around catastrophe modelling and a repository of open Python-based code and collaborative projects on different modules for users and development teams (Oasis, 2021). Oasis is a catastrophe modelling ecosystem rather than a provider of models, where any model that is built on or compatible with the Oasis API gets integrated and its workings and results can be compared to others in the ecosystem. Another rather infrastructural element is Oasis's development of Open Data Standards (ODS) which are supposed to enable interoperability between different data systems of users and all models in the markets, which so far has been dominated by RMS's data standards. OED (Open Exposure Standard) and ORD (Open Results Standards) are meant to translate with a data converter proprietary formats such as RMS's EDM and RDM or AIR's CEDE.

In this way, Oasis stylises itself socio-materially as an advocate of sound modelling practices and the representative of the model user community. Oasis is present at every major industry event and organises free-of-charge conferences in the manner of vendor modellers' client meetings and conferences. Community-building here serves as an active form of lobbying by socio-material means. At the 2018 industry conference mentioned above, Oasis's Whitaker was present, too, and pushed their agenda, "we're doing this as a community effort not only as an Oasis thing, practically let's just try and sort of say, 'We want to make that happen.' And if everybody in this room says, 'We'll support this actively', then actually we won't have this conversation [about black-boxed vendor models and incompatible data standards] in ten years because we have done something about it."

Strengthened by the appropriational shift towards users in proprietary catastrophe production, smaller and new model vendors have more robustly entered the catastrophe risk analytics market over the course of the 2010s such as KatRisk, ARA, JBA or Impact Forecasting, and have enabled compatibility with the Oasis formats and API, joined more recently also by CoreLogic. AIR by now is also an Oasis partner and has converted its CEDE exposure data standard more generally into an open standard in 2020 (AIR, 2021), while RMS remains officially not a partner of Oasis and has instead issued its own Risk Data Open Standards (RDOS) (RMS, 2021).

Even though both larger and smaller (re)insurers are participating and using Oasis, it is set to especially enable the smaller ones with less research and development capital to appropriate catastrophe production to a higher degree. The socio-material appropriational setup of Oasis, the increased diversification of the analytics market and the aim at enabling smaller (re)insurers in model appropriation adds to the increased level of multiplicity in catastrophe production today. At the same time, regulation such as Solvency II, for instance, has increased the burden of documentation and formal model approval procedures for users. Over a coffee at Oasis's offices in Southwark, purposefully on the opposite Thames side from the City of London, Dickie Whitaker, by now the initiative's CEO, tells me in 2018, "to change one part of one output for one model, one company said, 'That'll take us a year to get a real approval of that process.' That's a year of work, new documentation, new tests, new controls. [...] These processes cost millions. [...] The unintended consequences of Solvency II are a lack of use of multiple models". Although this threatens modelling "knowledge to trail off", he explains that for smaller firms Oasis presents an option to partly resolve this issue, while larger firms are able to cope due to their larger research budgets which enable to build their own in-house platforms, "that's one version of modelling-Nirvana, that's the best thing you can do". Keeping modelling-hindering effects at bay while further increasing the level of users' appropriational position, Oasis further enables an exacerbated multiplicity of proprietary catastrophe production in owning catastrophe by continuously extending its member base, which entails by now most (re)insurers in the market (e.g. Artemis, 2021c).

iii. Embracing Multiplicity

"Now, I'm not being critical, I'm just saying that four groups of experts, their best opinions have got a huge range. [...] How do you cope with that level of uncertainty?", asks the moderator a panel of (re)insurance practitioners at the 2018 industry conference after the model comparison exercise. The sentiment in the market, contrary to social and political science perspectives (e.g. Weinkle and Pielke, 2017) and the early days of catastrophe modelling use in the 1990s (see chapter 6), is that divergences across different catastrophe models on their 'views of risk' is an important and a positive rather than a problematic or questionable aspect. "I mean, I consider the differences actually as a positive thing," replies the Head of Catastrophe Management and Underwriting of a large Swiss insurer on the panel. The positive perception of multiplicity of catastrophe in both vendors' and users' catastrophe production, conditioned on the active appropriational position of users, is based on at least three elements.

First, it is seen as a driver for increased and critical hermeneutic reading of the concrete appropriation-objects, "differences, in a way, are a good starting point, so let's try to understand those", continues the panellist. Another panellist, Head of Catastrophe Research of a large Bermudian Reinsurer, agrees, "At a 100-years [return period] there was a factor of 1.6 difference in the models. [...]

We should also ask the providers of the models to give us more information about where are the key sensitivities. [...] Every single vendor model provider, every [user] modeller has to make shortcuts. And these shortcuts are where expert judgement comes in, and these shortcuts are not bad, they're just necessary, because we don't know everything. We've got limited data and we have to make expert option and include that. So I see this as a good thing." Understanding the 'Other's object', or even one's own, increases one's appropriational position for contextual and situated catastrophe production in multiplicity. Another panellist, a Science and Insurance Pricing Manager at another large Bermudian insurer and reinsurer, highlights, "once you understand the ranges that the models can produce and why they produce them, you then start digging into what's the reasoning behind them choosing this assumption or that assumption. And you can actually make informed decisions based on your own portfolio, I would say, about where you would like to sit, because, as people have said before, all of the assumptions are valid, but some might be more valid for your specific book and knowing that helps you to choose between these results."

Second and more technically, multiplicity in catastrophe production is seen as a shield against epistemological bias and, therefore, against systemic risk across financial markets, "convergence is a scary thing, especially when it comes to extreme events", exclaims one of the panellists. A few weeks later in a café in London, I13 explains to me the merits of diverging model outputs, "at least, you know, the whole industry is not going to fall apart if something happens, because you have different views of risk. The problem is when you are using exactly the same one and you are modifying it exactly the same way and you are doing exactly the same tests everyone does, you are not giving any room for variability." Dickie Whitaker, as an argument for Oasis's multiplicity-driving mission made the same point in 2014 at the launch event by reminding of the reasons for multiple and even unconventional projections to avoid missing improbable but possible 'Super Cats', "One of the best examples is the [2011] eastern Japanese quake, where this sort of perceived wisdom, whatever that means, and the best science, whatever that means, say that it's not probable to get quakes above the magnitude 8 on the subduction zone on the east coast of Japan. But actually, of course, it happened".

More generally, increased multiplicity in catastrophe production is perceived as moving away from overreliance on the 'duopoly' of AIR and RMS as the primary producers of catastrophe. "The oligopolistic nature of markets with large economies of scale, allows the few players to be more authoritative as central source of knowledge, than justified by the quality of their models alone. Unfortunately, the more the industry tends to rely on a single source of knowledge, the smaller the upside when it gets things right and the greater the downside when it gets things wrong (as, one day, it inevitably will)." (Beale and Goldin, 2015: 10). In this light, the user community sees its by now solidified appropriational position also as a service to society as a whole, as another panellist at the 2018 conference underlines, “when I’ve had conversations with regulators, they’re saying, ‘Oh it’s terrible, all these different outputs from the models!’ I always say that, ‘That’s the service we provide to society as an industry.’ Mother Nature is going to be different in the next five to ten years with all the hurricanes and earthquakes and floods and fires that happen, and we’re willing to take that risk to help business carry on. So, shouldn’t we get praised for the fact that it’s uncertain and tricky because we’re actually taking that risk off business and the regulator.”

Third, and most importantly, multiplicity is perceived as a fundamental prerequisite and consequence of agency in competitive market environments promising to earn a profit from owning catastrophe, the fundamental driver of catastrophe for market-shaped Anthropocene catastrophe. The perspective of California’s Chief Actuary Roth in the mid-1990s that “insurers find it necessary to use catastrophe modeling for competitive reasons” (NAIC, 1995d: 921) has evolved, nearly 30 years later, into a fundamental feature of catastrophe production. A pronounced socio-material appropriative position towards catastrophe modelling enables to perform in the market, “take all the [vendor] models, buy all the underlying data and then work out your own model, and then you have as perfect knowledge as you can against the marketplace and then you use that to arbitrage against other people” (P02).

At an advanced reinsurer he worked for in the mid-2010, U53 tells me that sophisticated contextual model use “you need to do it for survival, to show your edge, and that you’re ahead of others”. Active appropriation entails by now the ability to adapt, add or remove elements and data of the appropriation-object, “it is a tool and the flexibility around the tool is what makes a tool usable from a competitive standpoint”, as U53 continues. However, the very fact that the appropriational dynamics have shifted towards users which entails the expectation that sellers and buyers in a catastrophe risk transaction of any kind accept catastrophe models as their contextual appropriation-object, leads market actors, such as U33, to interpret that “catastrophe modelling is like currency.” U53 argues in a similar way, “You know, at the end a tool works if it’s a currency and it’s why it works and it’s used in the market. You get a number from someone else and to the extent that you know what they turned on [specific parameters in the models] you know what you’re getting. And that’s the currency aspect of it.” To clarify, what is meant by ‘currency’ here is the fact that catastrophe models are accepted and appropriated by all parties in a deal and where the competitive practice is to work out what one’s own and the other parties’ produced catastrophe versions can tell about one’s own profitability of the deal.

In the catastrophe risk market, the level of multiplicity around catastrophe production appropriated in these ways generates considerable competitive advantages, as U33 tells me, “Companies start understanding that there’s the competitive aspect of it. If you take the model and you really understand it, you can actually go and make the estimate for decisions in the market. [...] you can actually go to the market and have such an advantage that sometimes you can price a deal knowing that you are basically making money just by buying the deal because the [counterparty's] model is so off and the other guys they may not understand.” The contextualisation into one’s own situated environment also highly depends on one’s goal setting and interpretation of the socio-material environment in question, “the sophistication often comes in not just in understanding the model, the model might be perfectly right. But seasonality.” U53 explains that, “we were doing some work on seasonality of winter storm where we would say, ‘okay, so the expected loss in that model is 10% on a climatology basis. But you know what? The next three months is completely different’. And so you’re going in the market where the currency is the model. But in reality, because of the knowledge that you have of climatology, which is probabilistic in nature, but still, you know that the likelihood in the next three, four months is much different, and you can leverage that in making decision”. Since owning catastrophe overall means, in a rather Callonian way as discussed in chapter 2, to integrate catastrophe into an economic context, it entails also fusing ‘financial reality’ with ‘catastrophic reality’ beyond catastrophe production itself, financially binding these realms within the financial ontology of Anthropocene catastrophe in financial practices of competitively valuing deals, “At the end of the day, there are other risks that are involved in reinsurance contracts, in cat bonds, that are not technical in nature, contract risk, for example, counterparty risk, that sort of thing, which could overshadow, you know, whatever you think of model output.”

This aspect of financially conceptualising Anthropocene catastrophe has been particularly pronounced in the ILSs markets where ‘owning a view of risk’ had also more broadly been adhered to. Structurally, this particular part of the catastrophe risk market had changed over the 2010s in that its over-the-counter (OTC) trading in the US on the secondary market since 2014 was mandated to be made available on the platform of the Financial Industry Regulatory Authority (FINRA, 2014). Here, although Rule 144A eases the disclosure and documentation standards, the initial information on trades of ILSs, such as catastrophe bonds, are available to eligible market participants, and information on deals, including Offering Circulars and risk analytics, are more readily available in more detail primarily on the content management Intralinks platform (Intralinks, 2020). Here, as discussed in chapter 8, risk pricing is dominated by the financial markets’ price discovery rather than the ‘technical price’ of catastrophe modelling-based risk analytics. However, the currency aspect weighs even more in this part of the market since it represents the basis on which price discovery starts off. “I know all three numbers for AIR, RMS and CoreLogic on every deal”, tells me U42.

At the same time the competitive advantage of proprietary catastrophe production by now yields considerable potential to gain an edge over peers where disagreement with the formal calculation agent, i.e., vendor modellers, has become the norm as U33 tells me. Vendor modellers’ risk assessments for catastrophe bonds, for instance, are perceived by firms such as U33’s rather as a rating agency on the technical risk of a catastrophe risk instrument, "we don't want to insult anybody but we think we're better than a rating agency". The appropriational agency especially in the ILS market, which by now includes many large (re)insurance companies, seems to be particularly pronounced today, questioning the central and dominant appropriational position of vendors, "the RMSs in the world, they conflated the money, the outrageous money that they were making before V11, with their central primacy in the market for price discovery" (U42). "I think a lot of investors start to share that view. They're sophisticated enough that they by now, you know, in their experience with other asset classes, too, that they know that a [vendor] model is just a guide and that's all it is." (U68).

While, as argued in the previous chapter, catastrophe production got 'squared' by model-literate (re)insurance users, and 'cubed' with the growth of ILS markets, the shift towards user appropriation on a broader scale after V11 with institutionalised model evaluation procedures, regulation, a host of new vendor entries into the market, and Oasis, proprietary catastrophe production now and lastly has become 'quartet' with its competition-driven multiplicity – metaphorically speaking, proprietary catastrophe production has added the most forceful and now fully-fledged 'fourth dimension', that of market competition, in realising Anthropocene catastrophe.

b. The Financial Ontology of Anthropocene Catastrophe

Generating a profitable business model that successfully appropriates Anthropocene catastrophe is about *owning catastrophe*. As discussed throughout the preceding chapters, it means being active in both proprietarily producing catastrophe, i.e., owning a view of risk, and underwriting, i.e., owning risk, amidst competitive market environments. If we revisit the conceptual sketch of socio-material appropriation laid out in chapter 5, we have now arrived in a time in which the multiplication of situated catastrophe is actively socio-materially accomplished not only by vendors but also, and in practice more dominantly, by users in catastrophe risk markets. Not only are market participants driven by their portfolios' exposure to actualised catastrophe but also by their exposure to a variety of views of risk, first and foremost those of vendor modellers, that have to be explicitly rendered as not their own anymore. The appropriational shift towards users meant the normalisation and institutionalisation of continuous and even required appropriation acts by users to the appropriation-objects of proprietary catastrophe production in multiplicity, which had yielded continuous reciprocal transformations of appropriators, appropriated and appropriation-objects until today.

As lined out conceptually in chapter 5 and now played out empirically throughout chapters 6 to 9, the financial ontology of Anthropocene catastrophe is one emerging in a competitive arena in which the confluence of socio-material mediation of Anthropocene environment and simulation of modelled catastrophe is active in realising very 'real' worlds of catastrophe. It was shown that, with any situated appropriation act, contexts and views of risk multiply and appropriational dynamics accelerate, while positions of appropriated and appropriators switch on a micro and macro level and that this switching determines and is determined by the distribution of socio-material agency. Over time, design and use of catastrophe modelling folded into one another with continuous appropriation acts experimenting between actualised and modelled catastrophe, between socio-material environments and portfolios, with a multiplicity of proprietarily produced, situated yet equally in-flux versions of modelled and actualised, 'virtual' and 'real' catastrophe. Once in use, the mode of socio-material appropriation of catastrophe modelling reciprocally transformed many aspects of the two elements of realising catastrophe – socio-material mediation and simulation – thus, actively engaging in the in-flux experimental state of Anthropocene catastrophe. The semi-permeable nature of mediating and simulating catastrophe via public sensing, data and knowledge infrastructures ('public hazard'[67]) and proprietary damage-sensing and model calibration with claims and exposure data ('proprietary damage'[67]), accelerates both 'multinaturalism' of mediation and 'multirealism' of simulation at the appropriational intersection of vendors and users of catastrophe modelling.

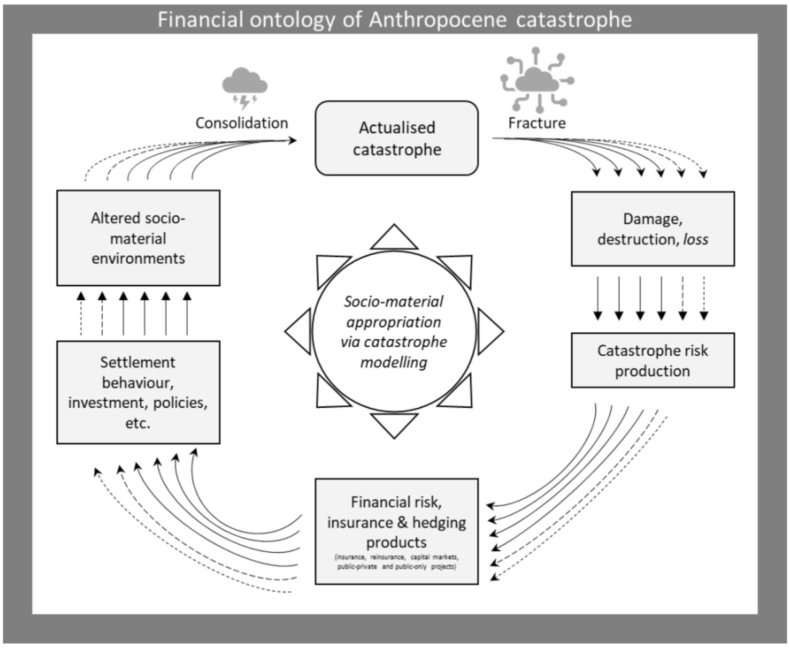

Figure 22: The loop of Anthropocene catastrophe.

These appropriational interactions that produce catastrophe in multiplicity are driven primarily by competitive market dynamics, which accelerate appropriational imperatives and, therefore, multiplicity of catastrophe, whether it is gaining an edge over competitors (in the analytics, (re)insurance, and ILSs markets), internal risk and capital management, or complying with market regulation. Here, socio-material appropriation's primary location is, as argued before, at the margin between modelled and actualised, multiplied and consolidated catastrophe, the 'fracture of reality', where the loop of Anthropocene catastrophe ends and starts again. Socio-material environments of

[67] As discussed in the last section of chapter 7.

actualised catastrophe are sensed proprietarily and fed into multiple calibration processes whose updated models are again used to produce situated proprietary catastrophe in competitive multiplicity in the successive loop. The fracturing of catastrophic 'reality' here is accomplished precisely by myriad acts of socio-material appropriation in situated mediation and simulation, while the consolidation of catastrophic 'reality' is equally subject to similar acts of appropriation. Neither consolidation nor multiplication are, thus, realms of epistemological truths but those of market-shaped financial risk management ('market-shaped loss'[67]).

As argued in chapters 2 and 5, assigning risk to specific socio-material environments and objects is a way of distributing agency throughout the Anthropocene, where appropriation of catastrophe modelling emerges as an active agency-distributing practice. The reciprocity between finance and socio-material environments remains not untouched by this but through the fundamental functions of distributing and insuring capital for economic activity and consumption the conditions for, and thus the ontological foundation of, Anthropocene catastrophe are rendered actual. The relationships between finance, real economy and society, though, are not at all straightforward and subject to explicit and implicit struggles. While, for example, Floridian beachfront real estate development is politically, at least to a certain degree, desired and (re)insurance is put to use to enable it amidst an 'age of catastrophe' (c.f. Taylor, 2020; Ubert, 2017; Weinkle and Pielke, 2017), in Germany, a country without compulsory catastrophe insurance, insurers are, for instance, excluding certain objects from catastrophe coverage in areas that have been inhabited for centuries but only now emerge as potentially disaster-prone, decreasing incentive for new settlements but leaving already existing ones exposed (GDV, 2021; Krüger, 2021).

The very fact that (re)insurance for disaster-prone areas is available enables socio-material catastrophe and its environment to exist and grow (c.f. Kelman, 2020; Keucheyan, 2014; Taylor and Weinkle, 2020), while its absence in other disaster-prone areas increases exposure to loss (c.f. Elliott, 2018; Jarzabkowski et al., 2018). A thorough analysis of these concrete socio-material relationships and interactions remains outside the scope of this thesis where it goes beyond the financial realm of catastrophe production in risk markets. However, the very deep and central integration of insurance and financial services in economic and overall societal activities, its ultimately agency-distributing function, is arguably an almost foundational character of today's market societies. To lesser or greater, unintended or deliberate degrees, this enabling position of catastrophe risk finance impacts on economic and societal activities as part of socio-material environments of Anthropocene catastrophe. The ontological actualisation of catastrophe is, therefore, actively shaped by market-competitive financial risk management – *owning catastrophe* – based on the socio-material appropriation of activities such as catastrophe modelling.

The notion of ‘owning catastrophe’ not only refers to the appropriator position of (re)insurers and ILSs as the ones owning a view of risk, i.e., making catastrophe’s epistemological-ontological realisation their own, but it also pertains the political and societal question of responsibility for socio-material Anthropocene catastrophe. Although an assessment would go beyond this thesis’s scope, it should remain questionable whether also private households or small businesses should become themselves somewhat appropriators of catastrophe production and ‘own their own view of risk’ in an individualistic vision of self-entrepreneurship – as we have seen, enabling catastrophe loss is not an individual failure of rational action but the result of a wide, decentralised, networked system of distributing socio-material agencies. The debate around who owns catastrophe at the end of the day, such as Elliott’s sociology of loss (Elliott, 2018), is one that needs to be more actively tabled in political processes. In today’s market societies, the boundary between how much market mechanisms, earnings-oriented risk management and proprietary knowledge production can yield financial value and how much society, states, businesses and individual households and their socio-material environments need to rely on the profitability of such business models while at the same time paying premiums *and* taxes to make up for loss needs to be more actively engaged. How much can catastrophe be kept a profitable realm in order to sustain ‘the market’ as our societies’ primary risk manager, especially in times of climate crisis? The big task is to critically table the discourse of the extent to which proprietary catastrophe production needs to be kept proprietary and market-based in order to yield mitigation of vulnerability, loss and destruction – who should and can be in positions of appropriators and appropriated not just of catastrophe modelling but of the market for catastrophe risk as a whole - in an age of Anthropocene catastrophe.

Chapter 10: Conclusion

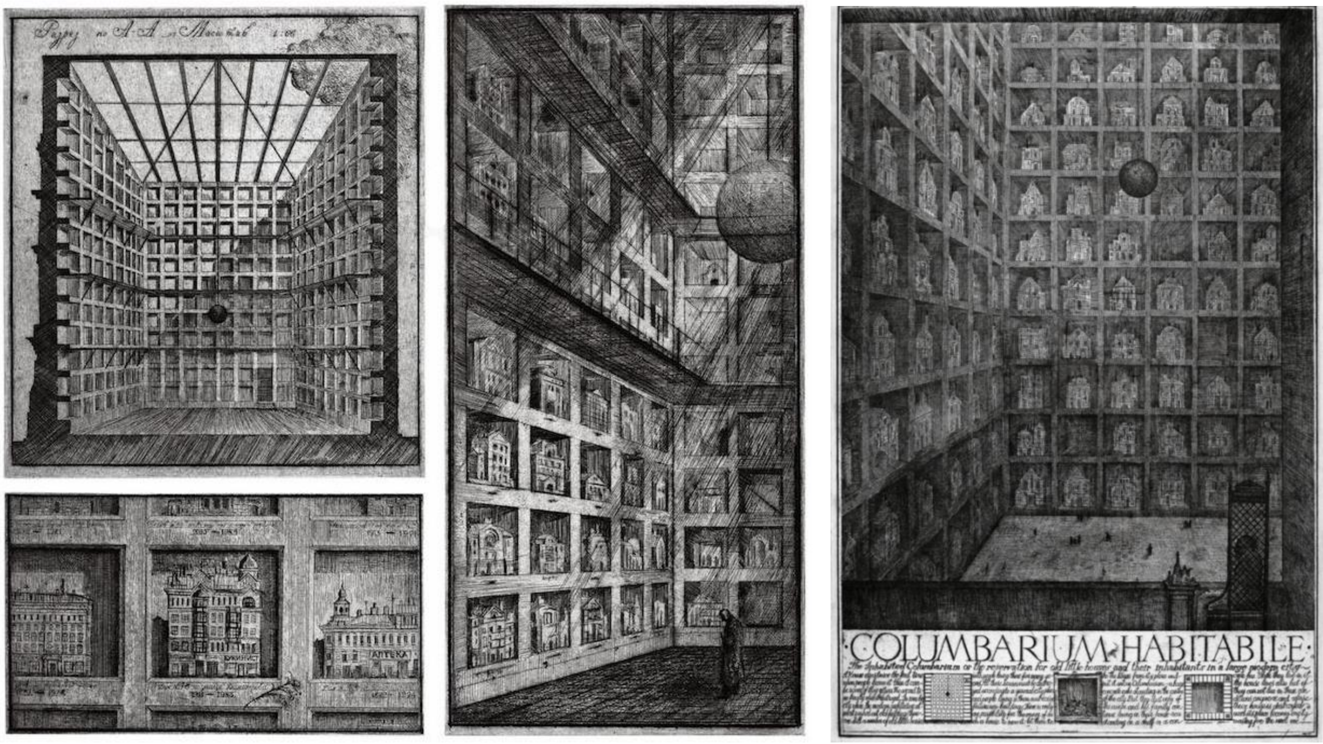

Figure 23: Left: Brodsky & Utkin, Columbarium Architecturae, 1990, etching; right: Brodsky & Utkin, Columbarium Habitabile, 1990, etching. (Onion, 2015)

The introduction of this thesis started with a framing of its underlying question on the influence and role of epistemic disaster projections on the ontological conditions of the 'real' world. It did so by drawing inspiration from Baudrillard's notions concerning catastrophe and simulation but analytically approached the question instead from a pragmatist perspective. Having presented the analysis of the financial ontology of Anthropocene catastrophe, an earlier quote from Baudrillard in the thesis's introduction chapter appears surprisingly graspable now:

> "in the absence of a real catastrophe it is quite possible to trigger one off by simulation, equivalent to the former, and which can be substituted for it. One wonders if this is not what fuels the fantasies of the 'experts' […] isn't every system of prevention and deterrence a virtual locus of catastrophe? Designed to thwart catastrophe, it materializes all of its consequences in the immediate present. Since we cannot count on chance to bring about a catastrophe, we must find an equivalent programmed into the defence system." (1992: 196).

The epistemic practitioners of catastrophe risk finance seem to have embraced this encompassing notion of simulation activities in an applied way. Robert Muir-Wood, Chief Science Officer at RMS, imagines, for example, a future in which the ubiquity of catastrophe modelling is so vast and institutionalised that it has exhausted all possibilities of actualised catastrophe. Here, catastrophe can be managed by identifying in the archive of produced future catastrophe, for instance, an earthquake "as simulation disaster number 6843" (2016: 276). Like the 'paper architecture' project Columbarium Architecturae or Museum of Disappearing Buildings by Alexander Brodsky and Ilya Utkin in figure 23 above, there is an idea of a vast repository of representations of recontextualised environments; an exhibition that in catastrophe's case hosts, instead of buildings, all variants of disaster, providing, however, only limited access to the public. While Brodsky and Utkin's "proposal for an impossibly large archive parodied the reality of the dilapidating and neglected historical cities of the Soviet Union" (Weizman, 2012), rather than parodying, Muir-Wood's vision inspires the vast projections of catastrophe as the means of financial risk management of future reality, of Anthropocene cities and environments that are yet to be confronted with erosion. Answering how this is actually attempted and what consequences it has for the realisation of catastrophe was the purpose of this thesis.

I. Summary

This dissertation has investigated the relationship between the epistemic financial risk practices of catastrophe modelling in disaster risk markets and the ontological condition of 'natural' catastrophe in market societies. It has conceptualised catastrophe as socio-material interaction between phenomena such as hurricanes or earthquakes and contextual environments of the Anthropocene, in whose shaping financial practices are active. It has argued that knowledge production in the form of simulation-based risk modelling of future Anthropocene catastrophe in the insurance, reinsurance and securitisation of disasters enables the financial risk management and economisation of disaster and, by so doing, has an impact on the ontological realisation of actualised catastrophe. Finance's contribution to this realisation manifests in a market environment driven by proprietary epistemic practices and competitive economic imperatives and, thus, engenders a 'financial ontology of Anthropocene catastrophe' by epistemic and risk managerial means.

By extending a socio-material and ontologically 'flat' understanding of distributed human and non-human agency from actor-network theoretical approaches, the thesis has extended perspectives on the Anthropocene with social studies of finance and science and technology studies approaches on market devices, performativity and calculative practices. It has further drawn on a combination of concepts from appropriation art practices and approaches of technology use to develop the notion of 'socio-material appropriation' as a lens to analyse epistemic, socio-material and power shifts in uses of catastrophe risk models across model creators and model users in finance – a mode of technology use in which devices such as catastrophe models but also users and creators of devices both appropriate each other and are themselves appropriated in modes of financial risk management.

The thesis found that the emergence of a financial ontology of Anthropocene catastrophe is characterised by two fundamental elements of catastrophe modelling. First, aspects of hazard-prone environments (such as geophysical and meteorological specificities, buildings and their material features, etc.) need to be 'sensed' by various processes and practices of socio-material mediation (such as environmental sensor networks, public data collection on built environment, and, chiefly, databases of insurers) to produce multiple proprietary exposure repositories, resulting in what, in chapter 2, I called a 'multinaturalism' in representing the world. Second, future catastrophe is produced by simulation in various modelling practices and devices with multiple grammars of interaction of catastrophe as proprietary understandings of how phenomena such as hurricanes interact with the represented worlds of exposure repositories, resulting in a 'multirealism' of possible contextual disaster. Actual, insured environments are financially managed on this basis of proprietary catastrophe production in multiplicity, who eventually experience actualised disaster events. Here the multiplicity of produced catastrophe is consolidated by practices of mediation and afterwards multiplied again in refined but new versions of simulated future catastrophe for continued financial risk management. This cyclical and reciprocal relay of multiplication and consolidation characterises a 'loop of Anthropocene catastrophe' in which finance conditions actual environments to certain degrees via modelled and actualised catastrophe in continuous feedback loops.

While from the early 1990s these epistemic practices were dominated and catastrophe risk management socio-materially appropriated by commercial catastrophe modelling companies (the creators of models), this dominance shifted towards (re)insurance practitioners (the users of models) with a growing sophistication of their appropriation of models since the early 2010s. These appropriational dynamics of proprietary catastrophe production have an influence on actual socio-material environments via the crucial role of insurance in market societies' risk management by attributing risk to its objects, for instance, by prescribing or discouraging how and where buildings can be built or maintained. While finance's influence on the shape of environments in this way is a complicated one and characterised by calculative, material, social, economic and political struggles around adhering to such prescriptions, actual disaster and its environments are themselves appropriated by these forms of proprietary epistemic and financial risk management practices. The result is a financial ontology of Anthropocene catastrophe in which financial institutions are key in proprietarily 'sensing' disaster environments in multiplicity, and in which both users and creators of models produce proprietary catastrophe projections. These activities' purpose is not the uncovering of any singular truth but multiple, contextual versions of projected yet performative catastrophe for profitable financial risk management of, thus, market-shaped socio-material environments.

II. Limitations and Contributions

While this thesis tried to be as technically and historically detailed as possible, it necessarily had to be selective. A major result of this (not unconscious) selection is the exclusive focus on developments in market-based catastrophe finance in the West, with a particular tilt towards the US. Although this is a reflection of the major developments in catastrophe modelling, it underrepresents modelling advances, for instance, in Japan and China. A more problematic omission caused by this is the lack of reference to disaster in regions other than the US and other western countries. While the analysis of the major developments in catastrophe modelling practices necessitates the focus on 'mature' (re)insurance markets, without which models have no user market, this political and economic disadvantage for catastrophe knowledge production in 'developing' countries and regions necessitates a problematisation that this thesis could not deliver due to its limited scope. Also, while postulating the impact of financial risk management on 'real' environments, this thesis did not deliver, for instance, analysis, case studies or more systematic review of insurance and financial intervention in socio-material spaces 'on the ground'. Among the surely more numerous shortcomings of this thesis, both these points are urgent topics for future research building on the back of the results and framework of this study.

Despite its selectiveness and omissions, this thesis hopes to produce several points of scholarly contribution. For one, it provides a thorough historical account of the practice of catastrophe modelling based on original empirical research, which, to my best knowledge, does not exist elsewhere in this detail. It also provides an overarching framework through which the relationship between finance and Anthropocene environment can be thought and analysed. As such, the thesis adds a backdrop, both historically and potentially conceptually, to excellent studies on this relationship and finance's socio-material influence on environments and social arenas of disaster and climate change (e.g. Elliott, 2019, 2021; Grey, 2020; Taylor, 2020; Taylor and Weinkle, 2020; Ubert, 2017). It also extends actor-network theory and Latour's work on the Anthropocene in particular (e.g. Latour, 2014a, 2017a) towards the incorporation of finance in the scholarly debate, and, at the same time, inserts the socio-materiality of catastrophe and the Anthropocene into the fields of the social studies of finance and economic sociology. As such, the thesis also adds to the study of the financialisation of nature (e.g. Keucheyan, 2018; Kill, 2014; Sullivan, 2013) and more broader financialisation scholarship (e.g. Chiapello, 2015; Mader et al., 2020) the case of catastrophe finance not just as a field of turning disaster into a financial object, but also how this activity imprints on the realisation of catastrophe itself, pushing the boundaries of financialisation of social spheres towards the materiality of disasters and the Anthropocene.

Beyond academia, the thesis also delivers a conceptual and empirical framework on the financial aspects of a political discussion that has recently been dubbed 'NND', or 'no-natural disasters' (NND, 2021; ShelterBox, 2021). Against the backdrop of discourses around the human causal position in natural catastrophe (see e.g. Horowitz, 2020; Kelman, 2020; Smith, 2007), it postulates that disaster cannot be understood as 'natural' but always as human-made, primarily due to lack of mitigation, adaption and defence measures and their neglect in economic and political imperatives, and that there is, therefore, no natural but always human-made disaster. While this rather political discussion is by now pushed not only by activists but, fortunately, also by the UN, especially within its Sendai Framework, and the Red Cross (Medlicott, 2021; UNDRR, 2021), this thesis provides a detailed social-scientific account and theorisation of this notion for the financial role in the production of disaster. It can, thus, deliver a conceptual underpinning of this political discussion for the implications of financial practices in an Anthropocene epoch.

Beyond catastrophe, this thesis also offers a conceptual lens through which the broader issue of climate crisis and finance's position in it can be thought through and analysed. Originally a chapter, my deeper discussion and analysis of the currently emerging field of climate finance can be found in Appendix A to this thesis, due to the word count constraints of a PhD thesis. There, by extending the argument towards climate crisis, I argue that although financial catastrophe risk practices are active in Anthropocene ontological becoming, they do not follow a concerted interventional programme. In contrast, the emerging field of climate finance, which is based on catastrophe modelling and related epistemic practices, seems to deploy instead a purposeful and teleological programme to intervene in global climate change. This extension of the analysis suggests that the field of climate finance currently emerges as another form of appropriation of such performative epistemic practices as a way to actively manage the climate crisis, steering towards an even more encompassing 'financial ontology of the Anthropocene'.

The interconnectedness of catastrophe and climate crisis also provides some learnings from catastrophe risk finance for climate finance. For instance, the proprietary production and availability of certain forms of disaster and climate data (private sensing processes of socio-material environments), appear to hinder a broader and more transparent stocktaking of the Anthropocene condition. This has epistemic consequences not only for knowing about disaster environments but also for the equally crucial construction and calibration of models and the consequential knowledge on catastrophe's grammars of interaction. Catastrophe knowledge in such a privatised format curtails public manoeuvrability in the face of disaster. While these dynamics are established in the realm of Anthropocene catastrophe and require critical socio-political review, looming climate crisis and its vastly expansive consequences cannot afford to fall into a similar topography of knowledge production. While the belief in finance's capacities to manage both catastrophe and climate crisis effectively is one that needs to be scrutinised both scientifically and politically, the socio-material conditions that such belief produces are already actualising. These already emerging linkages between epistemic activities and socio-material ontologies must also be analysed and debated and must not be stalled by the political debate for or against finance's delegated position in the appropriation of the Anthropocene. The position this thesis takes sits rather squarely to this debate.

III. Reflection

By flagging the character of proprietary catastrophe production in multiplicity and postulating that such competition-driven and decentralised knowledge production in market environments bends Anthropocene catastrophe into a market-based shape, this thesis prepares the ground for the rather political question of what a market-shaped multiplicity of catastrophe and climate crisis means for societal reality. Rather than asking whether catastrophe finance has helped to curb or contribute to loss, this thesis suggests to acknowledge that finance should neither be viewed in 'non-material' isolation nor as ontologically separate from the Anthropocene condition in the first place. Finance is a part of social and material reality, whether we like it or not, and so are both its presence (co-production of disaster environments) and its absence (financial protection gap and structural lack of catastrophe knowledge) integral to the ontology of the Anthropocene.

This becomes especially important when finance is attempted to be mobilised as an active intervenor in climate change (see Appendix A): the question of whether finance is able or unable to solve socio-environmental problems undermines the ontological condition of the Anthropocene of which finance has always been an important part. In light of the concept of socio-material appropriation, the question for both catastrophe and climate crisis is not whether or not finance should be part of intervention, but (1) on a macro level whether either finance or broader society are becoming the socio-material appropriators of climate crisis, and (2) on a micro level, to what extent concrete appropriation acts of performative epistemic practices and tools tilt the appropriational power balance on the macro level in the long run towards one side or the other. In other words, finance is always both a cause of and an intervention in catastrophe and climate crisis, but the crucial role that knowledge production in finance has in these realms needs to be acknowledged politically first and appropriational positions explicitly negotiated before we put finance into use to purposefully contribute to solutions to socio-environmental problems.

Currently, the debates around climate finance do focus also on the already active and proposed concrete epistemic practices and tools in the field, but these debates remain largely technical rather than political. In catastrophe risk markets, too, the political debate around catastrophe models seems to have largely faded. This thesis has shown that the technical debates around concrete practices and tools bear considerable societal and political relevance for the virtual and actualising futures that finance produces for market societies. Like the cartoon in figure 24 by the artist Bernd Thuns, with whom I had numerous discussions leading to this drawing, it seems that societal and political debate takes proprietary catastrophe production as a given. We wander in a world as an exhibition space for catastrophe and crisis and even when they actualise, finance's performative representations evade our attention. We should look at them more carefully.

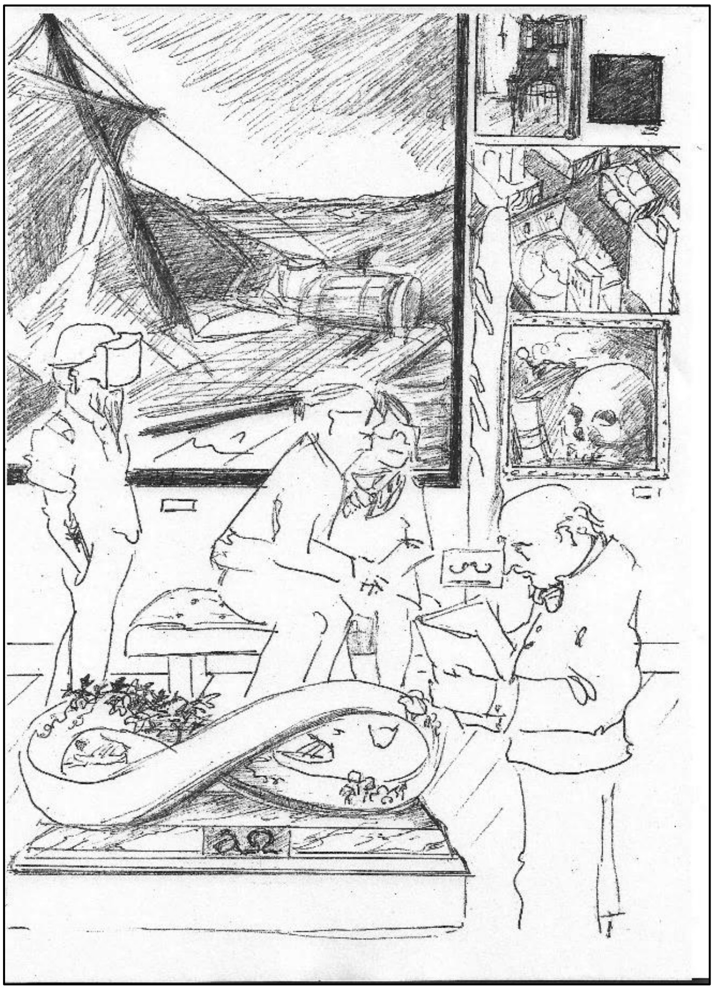

Figure 24: Bernd Thuns, Onlooking is not the same as acknowledging (Betrachten ist nicht gleich Beachten), 2021, ink on paper. Curtesy of Bernd Thuns

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Appendix A: Epilogue – Climate Crisis and the financial Ontology of the Anthropocene

“The reality of the external world is used for illustration and proof, and so comes to serve the reality of our mind.” (Dali, 1997: 240).

“Architecture – the imposition on the world of structures it never asked for and that existed previously only as clouds of conjectures in the minds of their creators.”
(Koolhaas, 1994: 246)

“... while others debate the theory, you deal with the reality. [...] You peer into the future [...] a time machine, shining a light not just on today’s risks, but on those that may otherwise lurk in the darkness for years to come. [...] By managing what gets measured, we can break this tragedy of the horizon.”
(Carney, 2015)

Figure 1: Interim Flood Protection bulwark towards the East River, Manhattan Seaport District, New York City. Photos taken by J. Kob, 2019

If you want to get a quaint and relaxed view of the Brooklyn Bridge, you might want to choose a spot in Lower Manhattan’s Seaport District, right at the shore of the East River, which is actually not a river but a saltwater tidal estuary of the Atlantic. If you choose so, similar to Hamburg’s fish market case, you might sometimes find your shoes soaked on even normal days. On catastrophic days, however, you should steer clear of the area. In the face of 2021’s Hurricane Ida, New York City found itself overwhelmed with water, especially flooding of underground spaces such as the subway system, whose passengers got trapped in stations and wagons, some of them did not survive (CfDP, 2021). While these consequences of Ida’s socio-material interactions are reminiscent of Hurricane Sandy in 2012, the ontological unfolding was different. Sandy unleashed an intense storm surge from the sea, including from the East ‘River’ which infamously devastated Seaport District, while Ida approached on land and produced torrential rainfall pouring more than 7.5cm (3 in) of fresh water per hour across most parts of the city. Sandy since 2012 had provoked a lot of changes in the socio-material makeup of the city, such as permeable architecture, including rain gardens and green roofs, modern pumps and drainage pipes as well as bulwarks, which all affect flood interaction (Crownhart, 2021). So-called 'pluvial' flooding by excessive rainfall such as Ida's, however, cannot be solved by this alone and especially not by coastal protection. It is, instead, even more the result of socio-material Anthropocene environments such as sealed ground by concrete buildup and lack of surfaces for water to sink into – on Lower Manhattan's East River shore in Seaport District in 2019 where I was gazing over the Brooklyn Bridge, a bulwark had been set up against storm surge flooding, while the paths around it were covered by water from rainfall unable to sink into the ground (see figure 1). Spurred by Ida's socio-material environment but with all future situations of more broader climate interactions in mind, an urban planner bemoaned, "'The way we've developed New York City has caused the flood problem' [...] 'We need to literally *redesign* the city to solve the problem'" (ibid., my emphasis).

2021 was a year of Anthropocene catastrophe. Amidst the hope for a gradual, vaccine-induced taming of the global Coronavirus pandemic – of course also a catastrophe and excruciatingly difficult to model (Kob, 2020) – 2021 is already ripe with actualised catastrophe and about to go down as an extraordinarily loss-intense year. Until the end of June, the first half of the year produced several events which caused a currently estimated $74 billion total loss of which $40 billion were insured (IJ, 2021). En route to become one of the costliest winter storms in recorded history, the January US winter storm Uri affecting primarily Texas produced a currently estimated $15 billion insured loss (ibid).[1] In June, European thunderstorms, hail and tornadoes caused about $4.5 billion insured loss, and extreme heat in Canada and the US caused large wildfires (ibid.). The second half of the year started off with heavy rainfall-induced European floods in July, affecting primarily Germany, sweeping away entire towns along the rivers Ahr and Erft and causing an estimated $7.5 billion insured loss, marking it the costliest 'natural' catastrophe on German record (GDV, 2021). Also rain-caused Chinese floods, particularly in Henan province, produced about $1.7 billion insured loss (IJ, 2021). Greek and Turkish wildfires are set to add to the loss of 2021's second half, although no estimate exists at the moment – wildfires are particularly difficult to model due to the complex socio-material interaction of the "engineered ecosystem" of forests, vegetation and built environment, as a wildfire modeller at an industry conference in 2019 told me. Meanwhile in August, Haiti had been struck by a 7.2 magnitude earthquake destroying over 135,000 homes and killing 2,200 people (UNOCHA, 2021).

Amidst an above-average projected hurricane season (Klotzbach et al., 2021), as of mid-September 2021, there were 14 named storms in the North Atlantic basin, 5 of which (Larry, Ida, Henri, Grace, Elsa) reached hurricane strength (NOAA, 2021). Especially Ida, Category 4 at landfall with 240 km/h (150 mph) maximum wind speed and sustaining considerable strength over hours after coming ashore, seems to yield particularly high loss this season. Causing flooding in Venezuela, ripping through Cuba and landfalling in the US on August 29th, the same day as Katrina 21 years ago, Ida is expected to have produced about $95 billion total loss in the US alone (CfDP, 2021), although the modelled loss, i.e., previously modelled proprietary catastrophe productions for an event as Ida, had been set 2.5 times higher (Dizard, 2021). Wrestling with the critical moment of preliminarily consolidating 'truth' of projected loss production post-event – the moment to 'stick out one's neck' – insured loss from Ida is

[1] This winter storm might even top Hurricane Katrina as the costliest weather-related event in recorded history, for which at the time of writing only estimates are available but which project a total loss between $150-200 billion (Insurance Journal, 2021; Perryman Group, 2021).

estimated by RMS as of early September at between $25 and $35 billion and by AIR at between $17 and $25 billion (AIR, 2021; RMS, 2021). Both vendors' projected loss estimates, however, do not include at this point any precipitation-induced and other flood loss in the US's Northeast, and will be added "once the full extent of damage is known" (RMS, 2021) – estimating these parts of Ida's Anthropocene catastrophe seem to be particularly difficult as neither of the vendors had updated their estimates in the weeks after issuing their initial ones.

Several catastrophic loops have come to an end and start anew again this year, as so many others have before. All of them are Anthropocene catastrophes, and most of them are tied in one way or the other to the socio-material Anthropocene issue of climate change. Many of the ones that are expected to follow, as an early-released part of the International Panel on Climate Change or IPCC's Sixth Assessment Report on climate change projects, will become more erratic and violent in the decades to come (IPCC, 2021a). While the climate crisis has been mentioned implicitly along the lines of the preceding chapters – climate change is an important inherent feature of this study's Anthropocene concept but not its exclusive perspective – this additional chapter embeds the climate crisis within the mode of financial knowledge production and ontological becoming of a financial Anthropocene.

What will follow should, however, be understood rather as a discussion of current developments in the space that is emerging as 'climate finance' rather than a thorough analysis, since the field is currently heavily in flux and the level of preliminary experimentation only allows for a broader reflection and an attempt of sense-making. The here presented argument and future perspective for research from this study will position the non-teleological arena of the financial ontology of Anthropocene catastrophe towards the purposefully deployed, indeed teleological, programme of financially managing the climate crisis, realising a financial ontology of the Anthropocene. It hinges, structurally different but epistemic-ontologically similar, on the market-societal shape of socio-material appropriation, mediating and simulating socio-material environments' interactions with various potentially catastrophic phenomena in multiplicity. What has been tabled at the latest since the 2015 Paris climate agreement as an attempted financial management of the global climate crisis is rooted at least to a significant degree on a conceptual and practical level in the realm of the market-based financial management of catastrophe. To engage in the currently exploding plethora of research into climate-related finance (c.f. Jayaram and Singh, in press; PRI, 2021), at least sociological and social studies of finance research agendas need to account for financial Anthropocene catastrophe, representing both the theoretical and empirical relevance of this study, before taking on the financial (Anthropocene) climate crisis.

I. Financial Anthropocene Climate Crisis

Precipitation patterns, rising sea levels, droughts, heatwaves, wildfires, storms etc., are subject to wider climatic dynamics whose severity and occurrence are set to increase along with growing socio-material environmental makeup such as continued urbanisation, growing populations, and expansion of economic activity – Anthropocene catastrophe will inevitably keep actualising and more intensely so (IPCC, 2021a). The acknowledgment and the intensified knowledge production around climatic change and anthropogenic contributions to them over the last decades problematises the Anthropocene condition as a mounting crisis on material and social levels. While the conceptual understanding of the socio-material Anthropocene of this thesis goes beyond (or rather starts before) climate crisis – it includes geophysical phenomena such as earthquakes as well – most catastrophe manifests in the realm of climatic factors.[2] The fundamental driver of climate change in this regard is, of course, the rise of global temperatures. Even though non-anthropogenic factors contribute to global temperature changes, such as the planet's orbital changes (Milankovitch cycles), volcanic activity, fluctuations in solar output or the El Niño Southern Oscillation, the largest influence is the amount of greenhouse gasses or GHGs in the atmosphere (IPCC, 2015). Solar short-wave radiation reaches through the planet's atmosphere to its surface, is absorbed by it and released back as long-wave radiation of which some passes back into space and some is absorbed by GHGs in the atmosphere resulting in warming of the planet. Gasses such as CO2 or methane occur naturally in the atmosphere and the greenhouse effect is in principle a normal and important one – without it, the planet would be quite frosty. However, the massive increase of GHG emissions by human activity, since the industrial revolution and especially the Great Acceleration, and the adding of synthetic gasses, such as chlorofluorocarbons (CFCs), have caused a so-called 'anthropogenic radiative forcing' of the atmosphere resulting in an average global temperature rise since the mid-18th century of 2.3 C°, not only warming on-land temperatures but also oceans, including reduction of icesheets resulting in sea-level rise of 0.19 meters over the course of the 20th century, and changes in air streams, ocean currents and precipitation patterns (ibid.). The inevitable but still uncertain consequences of these indeed *socio-material* interactions could, in analogy to this thesis's framework, be called Anthropocene climate crisis.

While Anthropocene catastrophe is a problem of the ontology of socio-material events, the Anthropocene climate crisis is a problem of the socio-material ontological condition in and of itself. Although Anthropocene catastrophe to a large degree is an inherent part of it, Anthropocene climate crisis – the rise of global temperatures – more explicitly renders all socio-material environments' interactions with agencies of the earth system as ontologically inseparable – Latour's 'critical zone' and all its agencies. Anthropocene catastrophe's financial realisation, in its present form enabled by the appropriative dynamics of catastrophe modelling, is at its core an epistemological adaption of financial practice to Anthropocene catastrophe. Although it is active in realising socio-material environments, its locus of appropriational transformation is finance itself – purposefully it is only concerned with owning its 'own' catastrophe and only in relation to this specific ownership the consequences for socio-material environments are subject to its ontological realising and management.

Anthropocene climate crisis escapes this 'ownership structure'. So, while the proprietary production of catastrophe enables a financial ontology of Anthropocene catastrophe and is able to realise its socio-material environments, (re)insurance markets' own epistemic-ontological reach in this regard somewhat evades the ontology of climate change. Instead, Anthropocene climate crisis requires, to borrow and universalise the words of the New York urban planner quote above, to "literally redesign" the Anthropocene, a purposeful intervention on socio-material interactions throughout the 'critical zone'. The primary goal of this intervention is, of course, the limiting of global temperature rise, and its main access point is the reduction of the excess of GHGs in the

[2] The causal relationship between climate change, extreme weather and actualising catastrophe is sought by the cumbersome work of so-called attribution science, most prominently by the World Weather Attribution initiative (WWA, 2021). For instance, climate-change induced alterations in the Jet Stream seems to have contributed significantly to the North American heatwave, Turkish and Greek wildfires and European floods in 2021.

atmosphere. GHG emissions, temperature rise's main signal, have become somewhat of an unofficial 'currency' of climate change at the latest since the 1997 Kyoto Protocol and have been endowed with their own accounting standards, most notably the GHG Protocol established in the early 2000s (WBCSD and WRI, 2004). While academic climate science, often embodied by the IPCC, produce and use overall estimates via modelling and instrument readings of the atmosphere's GHG concentration (public sensing), their anthropogenic emissions originate primarily in the economic activities of companies whose emissions attribution can be calculated by them via standards such as the GHG Protocol using physical or economic output factors, such as CO2e[3] per kWh of energy use or per dollar of revenue (private sensing) (ibid.). The sensing of the Anthropocene here, beyond catastrophe, is, therefore and for now, also performed by market actors.

Anthropocene climate risk, in this sense, is a derivative of GHG concentration in the atmosphere, and by localising its emissions the socio-material intervention since the Kyoto Protocol means the reduction of such emissions. In the genre of economic risk, this has been translated into two categories, 'physical' and 'transition risk', which relate differently to GHG emissions (this translation will be discussed in more detail in the following sections) (TCFD, 2017). Physical risk represents the consequences from global temperature rise for the earth system. Here, simply the total amount of GHG emissions in the atmosphere counts, irrespective of its sources, and how it impacts on systems such as the Jet Stream, the Gulf Stream, ice sheets, air and sea surface temperatures, etc. (IPCC, 2015). These consequences are the realm of Anthropocene catastrophe, such as tropical cyclones, various forms of weather-related floods or wildfires (so-called 'acute' hazards), and more long-term conditions such as more erratic heatwaves or flooding from sea level rise (so-called 'chronic' hazards) (TCFD, 2017). Transition risk, in contrast, represents the social, economic and political consequences of the intended socio-material intervention in the Anthropocene – the 'transition' to low carbon and environmentally more sustainable economies and societies – primarily and ultimately via the reduction of GHG emissions in the atmosphere via regulation and economic (dis)incentives, but also adaption measures to materially deal with actualising physical risk.

Physical climate risk is essentially the underlying of transition risk: while transition risk is an expression of self-inflicted intervention, physical risk is its socio-material and conceptual raison d'être. In analogy to the New York urban planner pressed by Ida mentioned above, physical risk is the acknowledgment of actualising Anthropocene catastrophe in specific localities, while transition risk represents the cost and socio-material consequences of the 'redesign' of the Anthropocene. Economic risk here is represented by assets' susceptibility to physical and transition climate change impact, i.e., climate risk, whose value is therefore exposed to potential decline manifesting in climate-related potential loss. The market-societal rendering of climate-induced financial loss is paired with its transposition into profits, so-called 'climate opportunities', which are earnings stemming from mitigating and reducing risks, for instance by investing in the production of 'climate-friendly' technologies or switching to renewable energy supplies.

[3] GHGs comprise several gasses, with CO2 as the most ubiquitous one. This is why GHGs are denoted usually as carbon dioxide-equivalent or CO2e and gasses other than CO2 are transposed into the CO2e unit.

While the financial management of Anthropocene catastrophe, due to its 'ownership structure', operates on the various actualised *symptoms* of the Anthropocene condition, the management of Anthropocene climate crisis, while including and ingesting the symptoms, attempts to operate on its *causes*. Yet, it seems this endeavour will also be pursued, at least to a substantial degree, by mobilising finance's epistemic-ontological market dynamics: appropriative financial knowledge production via socio-material mediation and simulation of experimental interactions within Anthropocene environments. And while socio-material appropriation in the realm of Anthropocene catastrophe, as argued in the this thesis, has arrived in the mode of 'sculpturing' – enhanced dimensionality granting the interpreting observers and curators more agency over the object rather than that of the creators – socio-material appropriation in the wider realm of Anthropocene climate crisis seems to emerge in a more encompassing, purposeful and interventional mode. This mode constitutes the focus of this additional chapter, sketching out the potential scope of this thesis's underlying concept, the financial ontology of the Anthropocene.

II. Architectural Mode

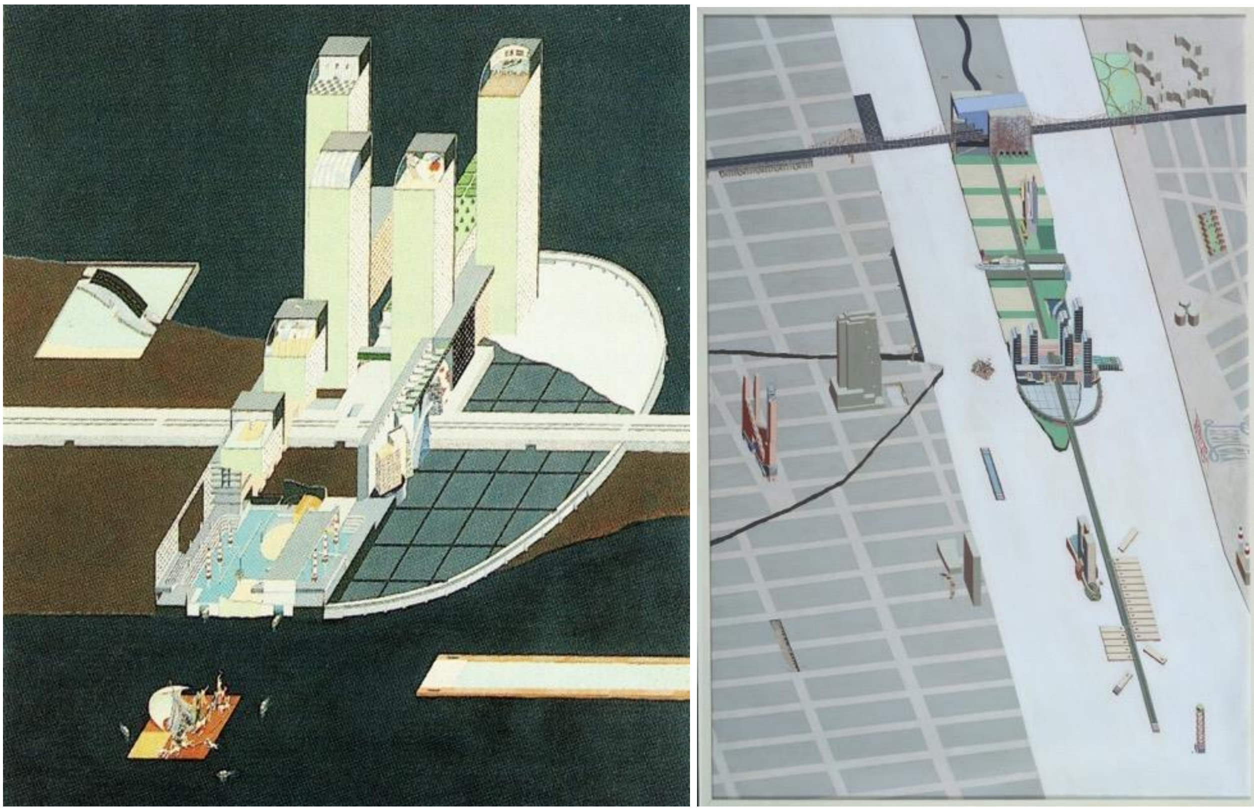

Figure 2: left: Koolhaas & Vriesendorp, Welfare Palace Hotel Project (cutaway axonometric), 1976, gouache on paper; right: Koolhass & Zenghelis, New Welfare Palace Project (aerial perspective), 1975-76, gouache on paper. (Koolhaas, 1994)

From where you could gaze over the Brooklyn Bridge, a short and scenic public ferry ride from Seaport District up the East 'River' (you haven't left the Atlantic), you will reach Roosevelt Island, a slender piece of land between Manhattan's East Side and Queens's Dutch Kills and Astoria, connected by Queensboro Bridge. The southern stretch of the island still inhabits the historic Smallpox Memorial Hospital and a public park with great views on the UN Headquarters. If the architect and urbanist Rem Koolhaas's conceptual projects of a new 'Manhattanism' had been realised, though, you would lounge on the terraces of the Welfare Palace Hotel, gazing over a giant, swimming sculpture reproduction of Géricault's Raft of the Medusa – you would have been able to take a hotel 'lifeboat' to circle around it and apply your interpretative perspective from any angle you would have seen fit.[4] Yet another appropriation of the Raft, already dimensionally enhanced as sculptured and not on canvas anymore, but now envisioned as an element of urban architecture, about to finally spill over into realised socio-material environment itself – incidentally in the very body of water in which the actual marine disaster actualised two centuries ago, across the Atlantic off the African coast.

Like the appropriation of the Raft in Koolhaas's urban architecture concept, the attempted financial management of Anthropocene climate crisis ingests Anthropocene catastrophe and makes it a fundamental part of itself – "a symbol of Manhattan's metropolitan agonies providing both the need and the impossibility of 'escape'" (Koolhaas, 1994: 306). In a way as its conceptual raison d'être, it builds an encompassing system of socio-material appropriation around it that supersedes catastrophe to the extent that it almost fades into the background – today, climate's 'transition risk' is a much more immediate concern for markets than climate's 'physical risk' (WEF, 2021). While this piece of art illustrates metaphorically well the current coming together of catastrophe modelling and (financial) climate modelling in the attempted 'redesign' of the Anthropocene (as will be shown in more detail below), Koolhaas's underlying conceptual and practical understanding of architecture serves here on a more fundamental level as a mode of grasping these current developments in Anthropocene climate crisis.

(Re)designing socio-material environments in general, of course, can also be seen as a mode of socio-material appropriation and here architecture in particular is a field that encapsulates as much material and social engineering as it requires art. While contemporary catastrophe modelling could be seen as appropriation in the mode of 'sculpturing', the developments that can be observed currently in the field of (financial) climate modelling resemble a mode of 'architecture'. As noted in chapter 9, the staging of sculptures, in contrast to paintings, inherently encapsulates their situating into an environment as an act of appropriation. It aims primarily at the object of art and weaves into it, successfully or not, the space it is placed in. While sculptures are, in this sense, more self-centring and *transforming themselves through their environments* (they are in principle materially mobile), architecture could be seen as doing the opposite (its objects are materially immobile), that is radiating outwards and *purposefully transforming its environment*. This is demonstrated well by the work of Koolhaas and his Office for Metropolitan Architecture, whose urbanism and architectural theory and projects can be seen both in realised structures, such as the Casa da Música in Porto, the Seattle Central Library or the Dutch Embassy in Berlin, and in conceptual pieces of art in galleries such the Museum of Modern Art in New York. Architecture can be the locus where art spills over into the Anthropocene and realises manifested socio-material environment.

Architecture's appropriative dynamics are, therefore, arguably less subject to environments' appropriative grip on architecture's own object but, instead, architecture subjects its environment to its object's appropriative claim to transform the socio-material space it is placed in and designed for. This is important for an illustration of the contrast between the financial management of Anthropocene catastrophe and of Anthropocene

[4] The little boats can be seen circling around the giant Raft on the left schematic in the bottom-left corner in Figure 2.

climate crisis. Sculpturing's appropriative reach concerns primarily its own object, similar to catastrophe finance's focus on its own transformations – the aim is to stage catastrophe in contextual 'exhibitions' by (re)insurers. In contrast, the attempted financial management of Anthropocene climate crisis seems to set focus on socio-material environment's transformation, similar to how architecture's appropriative reach concerns primarily its environment: the aim is to make socio-material environment the ultimate exhibition space to stage within it contextual climate crisis – both 'climate finance' and architecture hold an explicit transformative programme for their socio-material situatedness. While the mode of 'sculpturing' means realising an active ontological proxy of socio-materiality with 'real' consequences, so to say, the mode of 'architecture' has an ontological claim and ambition and promises the socio-material means to actively realise it.

With the mode of architecture in realising socio-material worlds, we arrive at a point where the mere rhetorical and conceptual illustration of socio-material appropriation of modelling might become a 'real' thing. Beyond the metaphorical merit of the Welfare Palace Hotel, Koolhaas's conceptual work will serve as an orientation to explicate the 'architectural' mode of the financial management of Anthropocene climate crisis along two elements: (a) methodologically, to illustrate and present the conceptual and practical relationships between catastrophe modelling and what is emerging heavily in flux as financial climate modelling as socio-material appropriation; and (b) programmatically, to illustrate and discuss the programmatic difference and interrelations of catastrophe markets as non-teleological and climate finance as a teleological manifesto for an active financial ontology of the Anthropocene.

II. Method: Practice of Socio-Material Appropriation

"The big, the really big thing is to apply this thinking to climate change [...] It's very hard for people now to understand the relation between actions to mitigate risks and manage risk and the economic benefit of that. [...] If we can better understand the risk of climate change over long time scales, we can create new financial services [...], we heavily monetise those risks and then create financial products to manage those risks and start to actually *cause* those risks, which are right now seen as exogenous, to bring them into the economic system so that people have incentives to manage them, so that the cost isn't just 20, 30, 50 years from now, [but] so that there's actual cost today. Because what you're doing is trying to hedge that risk and that costs you something today, which means it gives you an incentive today to actually manage it." In my first conversation with Hemant Shah in 2014, we had also talked about the issue of climate change. RMS at the time had just contributed to a study that had been conducted and published that year by the 'Risky Business' project. "It was a study to quantify the economic risks of climate change in the US economy and we provided the catastrophe modelling for that. It talks a lot about how we can take these concepts of risk and risk management and apply them to the problem of climate change [...], to use our catastrophe models to estimate how the exceedance probability curves would change over time, conditional to that climate loss – so sea level rises, sea surface temperatures changes, etc., and the likelihood of hurricanes, floods happening, and so on."

The Risky Business project had been initiated by Michael Bloomberg, the founder of the financial software and data provider Bloomberg and former mayor of New York City, and other prominent financial individuals in 2013 (Risky Business, 2021). It financed a large report published in 2014, which was the result of a collaboration between the economic research firm Rhodium and a group of academic researchers from Rutgers University, University of Chicago and UC Berkeley who formed the Climate Impact Lab, and RMS (Risky Business, 2014). The report was called the American Climate Prospectus (Rhodium Group, 2014), "the sort of Stern Report for the United States, that was the way it was framed", tells me O84 in his office in 2019, who is one of the report's academic authors. It is a combination of physical climate projections using, for instance, data and projections from the IPCC's AR5 and the US's NCA3 report and Global Climate Models (GCMs) from the World Climate Research Programme's Coupled Model Intercomparison Project (CMIP), especially its CMIP5 models projections, econometric analysis of climate change impacts on a range of economic sectors in the manner of classic work such as Nordhaus's and Cline's (1992; 1991), and sector and asset-specific regional risk modelling from RMS and Rhodium's energy sector model. Applied catastrophe modelling appears here as one component, leveraging not only its hazard modules but also its pivotal and proprietary "building-level exposure dataset" for deriving loss from physical damage (Rhodium Group, 2014: 7). Conceptually, the overall analysis and the bringing together of different model and sub-models follows physical risk assessment methodologies for economic and financial aspects employed so far commercially primarily by catastrophe modelling: physical climate projections and catastrophe models' detailed hazard models act as a form of climate hazard module, econometric research and detailed sectoral models (incl. average annual loss by county from RMS) as climate vulnerability modules, and the integrated economic analysis as a climate exposure database and loss module.

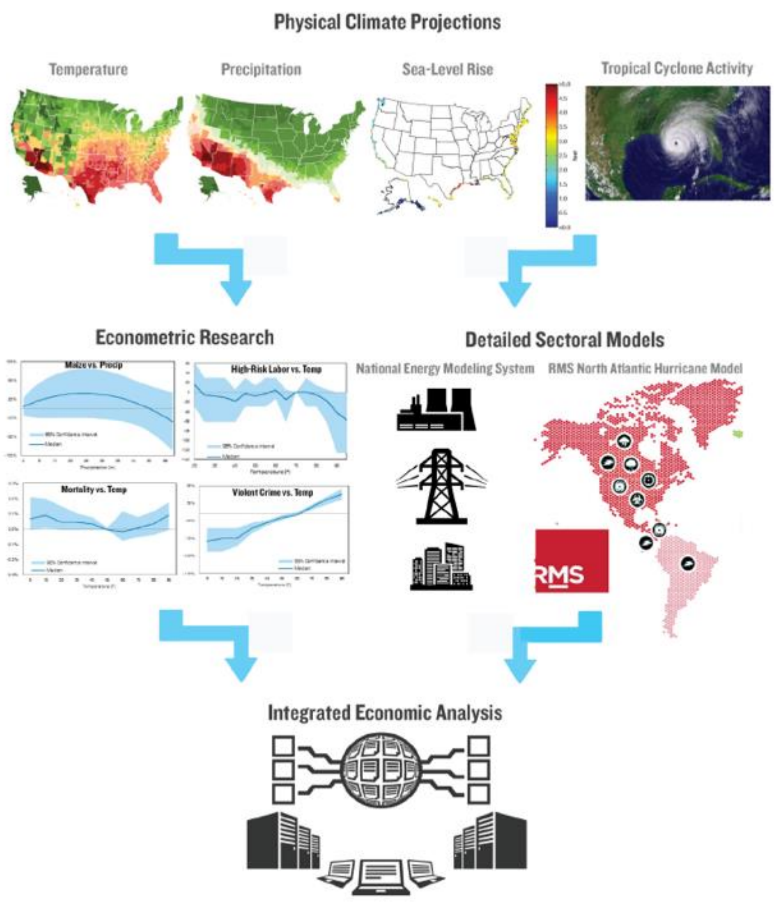

Figure 3: Spatial Empirical Adaptive Global-to-Local Assessment System (SEAGLAS). (Rhodium Group, 2014: 6)

"Effectively, what we're doing is cat modelling, but we're not really thinking of it in that way. [...] We're using big data approaches, econometrics, historical records to estimate relationships [between climate and impact] [...] We're doing a large statistical approach. We're not doing a building-level analysis like in engineering" (O84). The core problem that cascades through the entire approach of climate impact modelling (whether financial or otherwise) is a similar one as in catastrophe modelling: the problem of insufficient empirical history. But because of the ontological difference between Anthropocene catastrophe and Anthropocene climate crisis, it yields different solutions in modelling. Although there is data on historic climate variability, the anthropogenic influence on global temperature rise is unprecedented. This necessitates to even more embrace the practice of simulation, but less a probabilistic one. Instead, simulation is enacted via drawing up a number of different scenarios. Catastrophe markets are also sometimes utilising catastrophe scenarios for cases where catastrophe models do not exist, "If I don't have a cat model […] I create a single [deterministic] event as a [catastrophe] scenario", as U15, the (re)insurance model validation, tells me. In contrast, climate scenario projections are at the centre of any climate analysis, whether public or commercial, and they entail a host of assumptions and different combinations of sub-models. Projection-type scenarios are often Global Climate Models (GCMs, and more specialised ones from the CMIP5 suite such as GFDL-ESM2M, MIROC5, or IPSL-CM5A-LR), Regional Climate Models (RCMs), or Earth System Models which simulate various future climates based primarily on greenhouse gas emissions, their influence on rising temperatures and consequences for different parts of the Earth system (SENSES, 2021). They are not only dependent on the combination of models' inherent sub-models but also on input from emissions projections. Emissions projections, in turn, need to be produced on outlook scenarios of different future levels of anthropogenic GHG emissions, primarily produced as the IPCCs Representative Concentration Pathways or RCPs (IPCC, 2021b), which are subject to different potential political, social and economic developments, produced as Shared Socioeconomic Pathways or SSPs, which are hosted by the International Institute for Applied Systems Analysis (IIASA, 2021).

Climate risk modelling, similar to catastrophe modelling, hinges, therefore, on the appropriation of various public knowledge sources, infrastructures and devices already on the 'hazard' level and, much more than catastrophe modelling, needs to digest a lack of history, which spurs multiplicity as different combinations of scenarios and differing emissions projections yield interpretative room for hosts of climatic futures. On the 'exposure' level, this becomes an even bigger problem. Projects such as the American Climate Prospectus represent an 'early' version of broad but fairly granular sectoral climate impact analysis and modelling and remains until today a public one, similar to the EU-financed PACTA Climate Scenario Analysis Program by the think tank 2 Degrees Investing Initiative (2DII, 2021), and they rely primarily on public data. Commercial providers of climate modelling, who used to be focused on catering the thematically broader but until recently rather niche space of 'sustainable finance'. Yet, since the 2015 Paris climate agreement, these firms' services have experienced a huge demand wave and have, hence, been acquired by mainstream financial intelligence companies. Firms such as Carbon Delta (now part of MSCI), South Pole's Climate Division (now part of ISS), Trucost (now part of S&P Global), or Jupiter Intelligence, like the catastrophe vendors in the 1990s, hinge on the ability of appropriating various public domain devices, data and knowledge. They are equally dependent on receiving asset data from their clients, not only to produce analyses for them, but chiefly to calibrate their proprietary climate models and build up exposure databases of investee companies and other assets, their so-called 'universes'. This data, however, is at the moment rarely available to the clients themselves, since unlike (re)insurers' policy portfolios, investment portfolios do not hold much data on the socio-material situatedness of their assets. C94, a climate modeller and former academic catastrophe modeller from one of the emerging but already leading climate analytics vendors tells me about catastrophe modelling and physical climate modelling in 2021, "the real difference there is really that in one case you have the data [catastrophe modelling] and in the other case you have to do with public data [physical climate risk modelling]. So, yeah, the approaches are slightly different in terms of the granularity and, you know, the shortcuts that you have to take." They appropriate, for instance, satellite-based night imagery to estimate assets and population density from light distribution. "It is not about being the most granular for that specific region, for that specific building. But otherwise, it's the same stuff."

The epistemological core distinction between catastrophe modelling and climate modelling is, however, their spatial-temporal horizon. "The difference between cat modellers and what we're doing is that cat modellers mostly don't care about what happens beyond 2050. Very few of their clients care about what happens beyond 2020", tells me O84, the academic climate modeller, in 2019. While Anthropocene catastrophe, even if affecting larger areas, is in principle a local or regional issue, climate change, although with regional differences, is a global one. And while Anthropocene catastrophe actualises in rather sudden extreme events, Anthropocene climate crisis unfolds only slowly and over long time horizons. This spatial and temporal socio-material difference marks both the structural distinction and linkage between modelling for catastrophe and modelling for climate since extreme events are a stock-taking in the grand scheme of looming climate crisis. This is also interrelated with catastrophe's and climate crisis's management. While the former is managed primarily by local and national governments with temporally limited electoral cycles and (re)insurance's rather short-term renewing products and an often similarly shaped transformation of socio-material environments, climate crisis requires a management over decades, whose long onset, however, is supposed to be influenced by a continuous socio-material transformation of the Anthropocene by emissions reductions and the so-called 'green' or 'climate-aligned transition' of the global economy.

In contrast to physical climate risk, the less descriptive but more performative component is, therefore, climate transition risk. Transition risk represents what Hemant Shah at the start of this section referred to as 'actually causing' climate risks to bring what for now lurks in the distant future into the financial present to produce costs today. Shah is already used to this way of thinking in 2014 since it marked the initial value proposition around modelling in catastrophe markets, but on short time horizons and against the backdrop of series of actualised events and loss. For the very different spatial-temporal scope of climate crisis, however, what is modelled but also frequently realised catastrophe loss in catastrophe markets needs to be simulated entirely for climate loss in wider financial and economic markets due to the lack of present actualisation. Transition risks are the socio-material consequences of a both politicly and market-based "transition to a lower-carbon economy [which] may entail extensive […] changes to address mitigation and adaption requirements related to climate change" (TCFD, 2017: 5). It is based on anticipated climate-focused changes to legal and policy demands (e.g., implementation of costlier carbon pricing mechanisms, constraining harmful activities such as producing and using fossil fuels, or climate-related litigation by civil movements and NGOs), technological changes (e.g., replacing less climate friendly technologies with newer friendlier ones and the disruptive potential to existing systems), market changes (e.g., changes in consumption preferences and patterns or the risk of owning so-called 'stranded assets'), or reputational issues (e.g., consumer perceptions of activities that harm environments) (ibid.).

Although the actual 'hazards' here are brought into the presence primarily by policy and market developments, their transition risks are brought about through simulation modelling. In a way, where physical climate risk's practical complexity ends, transition risk's complexity starts, that is with emissions projections. Emissions projection scenarios rely on assumptions around the future socio-material states and changes of the Anthropocene, so-called 'pathway scenarios', and their potential to emit more or less GHGs. They are mitigation and adaption scenario simulations driven by particular visions or 'narratives' of specific aspects of socio-material future developments such as energy technology development, for instance the International Energy Agency's Energy Technology Perspectives or the 2021 Net Zero Scenario, land use development such as the PRELUDE, or climate policy development such as the UN Principles for Responsible Investment's Inevitable Policy Response scenario. Each of those aspect-specific scenarios are based on what could be understood as specific 'grammars of interactions' of the socio-material domains they focus on and are, therefore, themselves assemblages of underlying devices, data and variables. Particular pathway scenarios are brought together through combinations of projection scenarios, mainly SSPs and RCPs, by Integrated Assessment Models (IAMs). IAMs actively assemble different versions of those specific socio-material interactional aspects for particular foci of future developments – "they combine different strands of knowledge to model human society alongside parts of the Earth system" (Evans and Hausfather, 2018). They assemble factors such as GDP, labour, consumption, investments, energy, emissions, etc. from those different sources and enact their interactional interdependencies to model, for instance, what happens if a universal carbon price would be set up from 2022 onwards. IAMs are usually too complex for individual organisations to build, and instead a suite of publicly accessible models, such DICE, RICE, IMAGE, GCAM, or REMIND, with different sectoral applicability are used (UNFCCC, 2021).

Other than catastrophe modelling, transition risk for specific financial portfolios and positions in various economic sectors, therefore, heavily depends and fluctuates depending on the chosen scenarios, pathways, IAMs, SSPs and RCPs, and they necessarily rely on much more 'speculative' assumptions and less extrapolation from empirical data than even physical risk assessment. Transition scenarios are mostly "a statement not so much about the CO2 in the atmosphere, but a statement about how each sector is going to evolve, the mitigation strengths and pressures on all sectors", as the commercial climate risk modeller C94 tells me. Due to the much broader scope of financial climate modelling and the excessively rapid growth of demand for it, commercial vendors, financial institutions and public entities much more than in the catastrophe space scramble to appropriate various emerging models, components and data from commercial and public sources for both physical and transition risk. Devoid of an internal model core, such as RMS's initial IRAS model, AIR's CATMAP or Swiss Re's SNAP, it is, at least for now and for most actors, much more about recontextualising and repurposing existing components in a proprietary way, such as the public domain catastrophe model CLIMADA by a former Swiss Re catastrophe modeller turned-academic at ETH Zürich, specific CMIP5 models, IPCC and IEA scenarios, EM-Dat exposure data, licensable financial data from Bloomberg, FactSet or S&P Capital IQ, etc. – "The analysis here is really trying to do the best we can with what we have", says C94. This socio-material appropriation on a micro level emerges on the back of an appropriational dynamic on a macro level, in which various actors, not just commercial outfits but NGOs (such as WWF, WRI, or Greenpeace), think tanks (such as 2Dii or ClimateWise) and international organisations (such as UNEP FI, UN PRI or UN Global Compact), appropriate various elements to enable financial climate modelling in this way.

Such practices in the field are at the moment heavily in flux with new frameworks, models, scenarios and data emerging in parallel and a proper analysis of it would go beyond this chapter's scope. However, what is already observable is an intensified 'multinaturalism' and 'mulitrealism' spawning from these appropriative acts and at the same time a similar emergence of appropriative modelling practices and appropriative dynamics between vendors and financial institutions as in the early days of catastrophe modelling. Vendors are in need to apply hermeneutic readings of their clients' financial practices, this time primarily in investment portfolio management and risk assessment, while financial institutions are more and more eager to adjust their practices to appropriative imperatives. These imperatives are, however, not as much driven by vendors this time than by the overall emerging regime of climate finance, which is set to appropriate risk practices to induce socio-material change in the Anthropocene and its environments. Different climate futures are started to being produced by financial institutions in multiplicity who situate their investment assets with contextual Anthropocene projections, whose risk management requires, at least in principle, to either change portfolio compositions which diverts capital to certain investee companies and away from others or necessitates to use their ownership relationship to press companies to change activities that lower their climate risk. In this way, financial institutions are envisioned as enforcers of market-based climate policy, appropriatively to steer and redistribute agencies in order to change socio-material makeup and interactions throughout the Anthropocene.

Especially because of the longer time horizon, this is about more active but also more speculative future-making than in catastrophe markets, and at the same time it is an extended, outwards-reaching form of appropriation since this future-making explicitly includes a re-shaping of the real economy, 'owning' and thereby realising parameters of projected futures. In this way, the emerging climate finance regime, spurred by scenario-driven modelling, resembles Koolhaas's image of architecture as applying one of the most purposeful forms of artistic appropriation: socio-materially adapting, reinterpreting, recontextualising social and spatial elements as well as design concepts and physical substances, all, of course, realised in, and implicitly or explicitly as, Anthropocene settings – think of Bawa's 'tropical modernist' architecture and its reciprocal appropriational dynamics between human and nonhuman agencies (design, concrete, plants, etc.) mentioned in chapter 5. Architecture, in this way, can be seen as a programme of distributing socio-material agencies,[5] much like the emerging practice of climate risk modelling.

At its core, Koolhaas likens architecture to what Salvador Dali developed in art practice as 'Paranoid-Critical Method' or PCM, a process which seeks to "create systematic objectifications of the delirious connections made by the unconscious [...] the fabrication of facts to evidence an unprovable worldview" whose facts are inserted into reality by artistic practice (Buchanan, 2018). Without going into the deeper theoretical discussions

[5] For instance controversially shown for the case of urban planner Robert Moses's 'low-hanging overpasses' in New York's Long Island as 'political artifacts' (Winner, 1989).

around Dali's method and surrealism's use of psychoanalytical concepts (c.f. Lacan, 1992; Breton, 1972), what is important to Koolhaas are its implications for architecture, both conceptually and practically, which are reminiscent of what has been laid out in this thesis as socio-material appropriation in risk modelling: "the delirium of interpretation" as an "intense – if distorted – relationship with the real world" that is practically characterised by "conceptual recycling [...] fabricated evidences can be generated simply through the act of interpretation", the appropriative hermeneutic reading, and, importantly, the "subsequent grafting of this evidence on the world" (Koolhaas, 1994: 238, 241). The intensified socio-material appropriational reach, in contrast to sculpturing, lies here in the elementary ambition of realising socio-material 'reality' itself, grafting transformation onto its environment rather than the other way around. Modern architecture, in this view, embodies the imperative of "otherworldliness" (ibid., 246) and is about appropriatively realising purposefully performative projections of future worlds, which the currently developing practices of the emerging regime of climate finance seems to be set out to do, too. What one can learn from Koolhaas's architectural concepts for the grasping of climate finance will become clearer when focusing on the programmatic aspects of both expressions of modern architecture and political visions of the roles of catastrophe finance and, more encompassing, finance in general in Anthropocene climate crisis.

III. Programme: Manifesto for a Financial Ontology of the Anthropocene

Koolhaas received wider architectural attention initially not through realised structures but with a conceptually and empirically rich, ambitious, and polemic (re)interpretation of the modern architectural becoming of Manhattan: Delirious New York, published in 1978. In it, he looks back at Manhattan's architectural history and formulates 'retroactively' a manifesto for Manhattan's architectural metropolitan genre which he calls 'Manhattanism'. Koolhaas sees it, in retrospect, as a product of the 'Paranoid-Critical Method', "Architecture is inevitably a form of PC activity" (Koolhaas, 1994: 246) – an explicitly socio-material appropriative mode of architecture. Non-metropolitan 'reality' is superseded here by an experimental playground in form of the grid-system of streets and rectangular plots of land in Manhattan, dividing the island into blocks within which anything goes and whose contents are constantly changing – especially by means of the concept of the Manhattan skyscraper, 'reality' (i.e., socio-material space) is multiplied with each additional floor, stacking the block and its realisations within itself, only constrained by the guardrail of the grid. Architecture, in this understanding, is the epistemic-ontological crossover of appropriation as an art practice into realised and actualised socio-material environment. Koolhaas's subsequential identification of multiplicity in a "culture of congestion", both the enabler and consequence of Manhattanism, emerged based on what is elsewhere often seen as the indisputable coming of the market-societal Anthropocene, the industrial and post-industrial developments and the 'Great Acceleration' (discussed in chapter 2) (c.f. Deamer, 2014). In this sense, the culture of congestion is, of course, inherently driven by market-societies' socio-material distribution of agency. While Koolhaas sees the culture of congestion as founded on and spurred by the mode of the grid system, it can be seen as an expression of global capital flows which are founded on and spurred by the mode of decentralised markets in market-society, the guardrail of socio-economic activity and an important format of the distribution of socio-material agency in the Anthropocene.

Koolhaas sees Manhattanism as something that emerged without any particular programme, theory or defined genre, and he somewhat ironically does not see it realised to its fullest extent. For him, it lacks an explicit declaration which is why he provides his 'retroactive manifesto' of the concept of Manhattanism in hindsight (Koolhaas, 1994: 10f), almost like a Foucauldian genealogy or a Benjaminian 'piecing-back together'.[6] He finishes his Manhattanist manifesto on a series of architectural and urbanist concepts, headed by its most encompassing piece, The City of the Captive Globe, and accompanied by potential elements of it, such as the Welfare Palace Hotel and its appropriation of the Raft of the Medusa. Polemically, these concepts offer a metropolitan agenda for a 'second coming' of Manhattanism, providing blueprints for an indeed teleological programme with an "explicit manifesto" to fully realise this surreal metropolitan exuberance: "It is the capital of Ego, where science, art, poetry and forms of madness compete under ideal conditions to invert, destroy and restore the world of phenomenal Reality. Each Science or Mania has its own plot. [...] a conscious doctrine whose pertinence is no longer limited to the island of its invention" (ibid.: 293f).

Figure 4: Zenghelis & Koolhaas, The City of the Captive Globe, 1976, gouache on paper. (Leydecker, 2014)

Retroactive (re)interpretation is, of course, also an appropriative act, which folds Koolhaas's architectural mode into his 'reading' of Manhattanism and enables to produce its 'manifesto' in the first place. Admittedly doing something similar here too, I would argue that this 'Koolhaasian' act of appropriation, its layered appropriational claims and the speculative practical and socio-material outcomes of a retroactive and then extrapolated but enhanced manifesto, is something that happened explicitly in 2015 with the Paris climate agreement and the establishment of the Task Force on Climate-related Financial Disclosure (TCFD) by the Bank for International Settlement's Financial Stability Board (FSB), embodied in a by now well-known speech two months before the Paris summit would commence.

[6] Koolhaas came into personal contact with Michel Foucault when they met at Cornell University in 1972 (Patrão, 2020). There are also clear influences on his work from Walter Benjamin, especially the Arcades Project (Hsu, 2016).

"Alongside major technological, demographic and political shifts, our very world is changing. Shifts in our climate bring potentially profound implications for insurers, financial stability and the economy" (Carney, 2015). Mark Carney, then the FSB's chairman and Governor of the Bank of England and since 2020 the UN's Special Envoy for Climate Action and Finance, spoke in September 2015 to a room of financial executives. Although what he addressed with his "Breaking the tragedy of the horizon" speech would be the gloom of climate crisis for the global financial system and by its agency-distributing reach also for the global economy, he had sought an audience he could flatter in this context: (re)insurers at the Lloyd's of London, which hosted the speech. "Since 1688 Lloyd's has, in the great tradition of the City [of London], served both the UK and the world, providing protection against the perils of the age [...] the Lloyd's market has evolved constantly to meet the needs of a rapidly changing world. [...] Modern catastrophe cover was born with your decision to stand by policyholders after the [1906] San Francisco earthquake." In his plea for climate-related intervention by the financial markets and its professions, it was (re)insurance's knowledge and proprietary catastrophe production that he invoked as exemplary for financial services, "Lloyd's underwriters were the first to use storm records to mesh natural science with finance [...] Events like Hurricanes Andrew, Katrina and Ike have helped advance catastrophe risk modelling [...] Your [catastrophe] models were validated, claims were paid, and solvency was maintained." By doing so, he also explicitly evoked the sometimes problematic epistemic-ontological properties, "Insurers' rational responses to physical risks can have very real consequences […] storm patterns render [householders] unable to get private cover, prompting mortgage lending to dry up, values to collapse and neighbourhoods to become abandoned."

He turned to the asset management side of (re)insurers and extended the insurance-endogenous impact of physical climate risk, i.e., Anthropocene catastrophe, towards the so-far exogenous state of climate change in financial investments, "Physical risks from climate change will also become increasingly relevant to the asset side of insurer's balance sheets. While the ability to re-price or withdraw cover mitigates some risk to an insurer, as climate change progresses, insurers need to be wary of cognitive dissonance within their organisations whereby prudent decisions by underwriters lead to falls in the value of properties held by the firm's asset managers – where the underwriting side moves quickly, and the investing side moves more slowly. And that dynamic highlights the transition risk from climate change." Bringing future risks into the presence to manage and change, or rather create a different, future, is the core aspect of transition risk here as he addresses the investment industry as a whole, "once climate change becomes a defining issue for financial stability, it may already be too late [...] As [climate] risks are a function of cumulative [GHG] emissions, earlier action will mean less costly adjustment. [...] Risks to financial stability will be minimised if the transition begins early and follows a predictable path, thereby helping the market anticipate the transition to a 2 degree world." The underlying market-shaped configuration with knowledge production as a competitive asset in catastrophe (re)insurance was invoked as a key dynamic for performing this anticipation, "Your motives are sharpened by commercial concern as capitalists and by moral considerations as global citizens. And your response is at the cutting edge of the understanding and management of risks arising from climate change." At its core, he saw the pivotal epistemic driver of catastrophe modelling (history is 'not enough') as the underlying of financial management of Anthropocene catastrophe, "Your genius has been to recognise that past is not prologue and that the catastrophic norms of the future can be seen in the tail risks of today."

Given the unprecedented nature of climate crisis, the application of this 'genius' on a broader scale means the prompting of a climate finance regime in which "'green' finance cannot conceivably remain a niche interest over the medium term" and the agency-distributing properties of finance are actively and purposefully embraced to manage the climate crisis, "Capital should be allocated to reflect fundamentals, including externalities". However, because global financial stability would be essential for market societies to remain afloat, the transition must not come too sudden, for market actors need to be given time to transform themselves to transform market-shaped Anthropocene, "an abrupt resolution of the tragedy of horizons is in itself a financial stability risk." Rather, it is about empowerment by policymakers, regulators and the market to "help the market itself to adjust efficiently" and at the core sits knowledge production around climate-situatedness and enabling the financial market beyond (re)insurance to develop ownership of a view of climate risk, to produce "better information to allow investors to take a view". It is this performative aspect of knowledge that let Carney invoke the production of financial climate knowledge as the driver of the potential financial management of the Anthropocene, "supply [of climate information] creates demand [for investment]". Yet, it is about the prescription of the appropriation of knowledge production, not about prescribing a universal view of risk or even a climate crisis-acknowledging view, "The right information allows sceptics and evangelists alike to back their convictions with their capital" – a multiplicity of financial climate futures is the desired format of future-making for the emerging climate finance regime and market-shaped Anthropocene. Consolidation of climate crisis, on the other hand, evades into the future and needs to be retracted via virtual feedback loops of market performance through knowledge production of financial institutions' situated climate futures and their emissions data, which would "allow feedback between the market and policymaking, *making climate policy a bit more like monetary policy*" (my emphasis). In closing, Carney reiterated the laudable achievements of (re)insurance as pioneers of future-making – "You peer into the future, building your defences against a world where extreme events become the norm" – and the yet to be explicated model function of (re)insurance's appropriational position and capacity in catastrophe production and their assumed potential for 'climate production', "Others will need to learn from Lloyd's example in combining data, technology and expert judgment to measure and manage risks."

a. Emerging Climate Finance Regime and an 'own view of climate risk'

Two months after this speech, COP21 commenced and ended with the formulation and signing of the Paris climate agreement entailing in Article 2.1c, of course not by Carney's decree, the objective of "Making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development", one of the three overall pillars of the agreement (UNFCCC, 2015). Conceptually, like Koolhaas's 'Manhattanism', Carney's 'climate finance' has turned an "unformulated theory" into an "explicit doctrine" (Koolhaas, 1994: 10f). Even though there had been considerations of utilising more actively the properties of catastrophe markets in the context of climate change, for instance as early as the mid-1990s in enquiries by then US Vice President Al Gore to the US (re)insurance community (NAIC, 1995: 640) or recently the OECD (OECD and ADB, 2020), there has never been an actual, concerted vision or effort to apply catastrophe finance's epistemic-ontological reach to programmatically shape the Anthropocene – like Manhattanism before its programmatic formulation, explicitly appropriating finance as a teleological means to 'redesign' the Anthropocene would have been "so ambitious that to be realized, it could never be openly stated" (Koolhaas, 1994: 10). Like Koolhaas's 'retroactive manifesto' for

Manhattan, Carney's address to the Lloyd's of London in 2015 can be understood as a retroactive reading and (re)interpretation of catastrophe modelling and catastrophe finance, a somewhat "speculative reconstruction" through which its "successes and failures [can] be read" (ibid.: 11). Carney sketched out in his speech a teleological reformulation – an act of conceptual appropriative hermeneutic reading – to construct a speculation on financial Anthropocene catastrophe's formative and conceptual extension towards the Anthropocene as a whole, to explicate in principle what the new, prospective 'manifesto' of climate finance seems to be: realising a financial ontology of the Anthropocene.

Concretised cornerstone of this manifesto became in parallel of COP21 the foundation of the Task Force on Climate-related Financial Disclosure or TCFD in 2015. Reporting to Carney as the chairman of the FSB, TCFD then and until today is chaired by Michael Bloomberg, whose Risky Business Project initiative (discussed above) had materialised the American Climate Prospectus a year earlier. Formed as a consortium of a number of executives and managers mainly from financial sectors (FSB, 2016), the TCFD is focused on the establishment of a disclosure standard for climate-related risks that sets out a framework for publicising climate risks and emissions footprints of portfolios in analogy of standard financial disclosure of publicly listed companies (TCFD, 2017). It formally defines climate risk and its distinction into physical and transition risks. Financial institutions have to take stock of the GHG emissions and physical susceptibility to climate change of their portfolio assets. As such, it is meant to instigate what Carney in his speech referred to as providing 'better climate information' on which basis financial institutions can produce their situated and contextual climate futures. It stages financial climate scenario analysis as its primary practice to perform this contextual climate production as a prescription of socio-material appropriation, "The idea is to challenge conventional wisdoms about the future." (ibid.: 7) – financial climate knowledge production is here similar to "Manhattanism as conjecture" (Koolhaas, 1994: 11).

TCFD, and equally the later established but broader Sustainable Finance Disclosure Regulation of the EU (EU, 2019), therefore, are starting on the 'sensing' side of the financial Anthropocene, which is supposed to instigate an appropriative uptake of climate future-making in contextual and proprietary simulation: "With better information as a foundation, we can build a virtuous circle of better understanding of tomorrow's risks, better pricing for investors, better decision by policymakers, and a smoother transition to a lower-carbon economy" (Carney, 2015), the multiplication of climate futures to redesign the Anthropocene. Here, Anthropocene socio-material environments are primarily sensed by the emitting companies themselves based on carbon accounting standards and practices that had already been established since the start of the millennium but are still in a process of emergence. Emissions are (not yet fully mandatorily) reported via companies' Corporate Social Responsibility reports and otherwise enabled and enforced, for instance, by the Carbon Disclosure Project (CDP, 2021) or the Carbon Trust (2021). For now, these emissions data – the sensing of 'portfolio emissions' and their Anthropocene situatedness – are collected, adjusted, often modelled (where there is insufficient data), and provided to financial institutions by climate analytics and modelling vendors such as MSCI or Trucost. Against this emerging market-based regime of climate finance, there are various (and sometimes competing) frameworks and organisations to establish standards on what is currently a heavily in flux situation that seems to focus on enabling financial institutions to develop from the get-go their 'own views of risk' to build up capacity and become active appropriators of both the climate finance regime and the Anthropocene itself, rather than appropriated by, for instance, vendors and models.

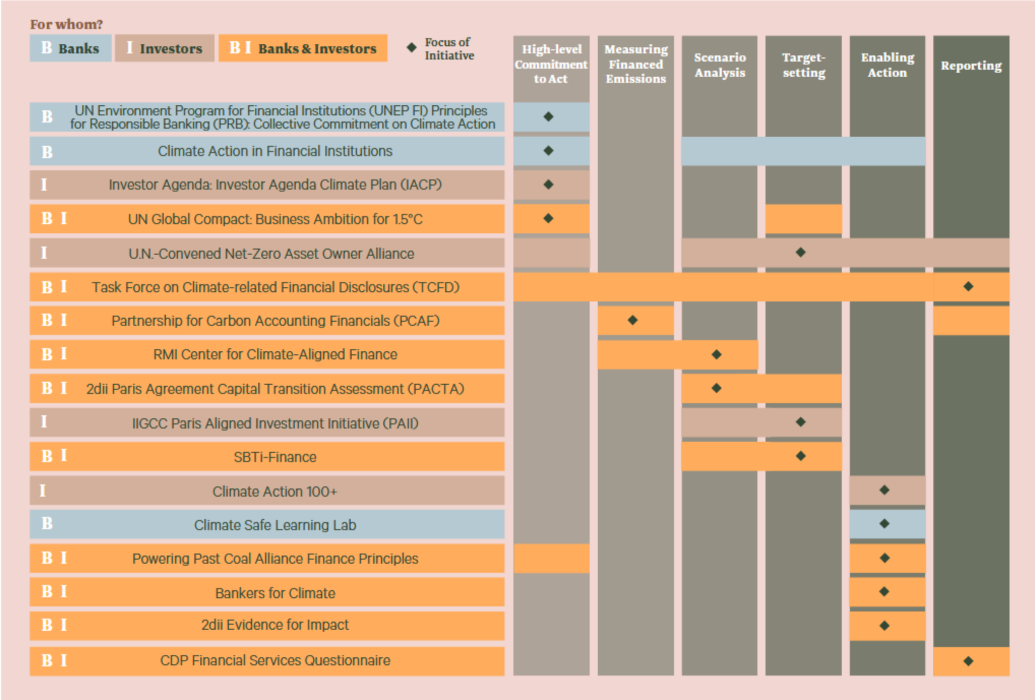

Figure 5: Cluster of Climate Initiatives. (PCAF, 2020: 14)

While financial climate production, in this way, follows similarly socio-material mediation and simulation in multiplicity, its consolidation remains in a starker way than in catastrophe finance in a state of appropriation. Since there is no actualising event in the same way as Anthropocene catastrophe – the moment of consolidating 'truth' – Anthropocene climate crisis as a combination of physical and transition risk needs to be entirely mediated and simulated in forms of appropriative modelling. The consolidation mode here can be seen as the equally simulation-based feedback-loop of climate futures run against benchmark futures of officiated climate scenarios provided primarily by the IPCC, IEA and, especially for finance, the newly formed scenarios of the central banks' Network for the Greening of the Financial System, whose scenarios are already the foundation of the Bank of England's 2021 CBES, the first applied financial climate stress testing exercise ever (BoE, 2021; NGFS, 2021). At the same time what has been since called 'climate alignment' and 'climate target setting' for portfolios and financial institutions perform an additional attempt of consolidating multiplicity of Anthropocene climate crisis, although, equally as in Anthropocene catastrophe, not to reach a universal truth but to set market-societal boundaries for the financial management of climate crisis in multiplicity – the guardrails of market-based Anthropocene climate as part of a 'grid' as in Manhattanism. Here, market initiatives such as the Net Zero Asset Owner Alliance, NGO-fuelled frameworks such as the Science-based Targets initiative alongside with the UN Environmental Programme Finance Initiative and its Principles for Responsible Investment appear as various points for consolidation efforts, to tie back multiple proprietarily simulated climate futures towards 'corridors' of futures that are deemed politically appropriate (SBTi, 2021; UNEP FI, 2021).

b. Realising a Financial Ontology of the Anthropocene

Koolhaas formulated the manifesto for 'Manhattanism' as a polemic, but climate finance is set to realise its manifesto in sincere benevolence. Carney explicitly, and implicitly the wider emerging climate finance regime, suggest the appropriation of Anthropocene catastrophe's 'unwritten theory' to bring about a universalised 'second coming' of it but now with an intentional, teleological manifesto of extended concern – including NGOs aiming at extensions towards fields such as biodiversity or ocean conservation (TNFD, 2021; WWF & PWC, 2020; WWF et al., 2018). In it, it declares catastrophe risk in a widened sense as 'physical risk' and invokes the genre of 'transition risk' as the appropriative method to manage physical risk by means of produced climate crisis, a purposefully self-inflicted 'virtual' ontology of its unfolding in market-shaped multiplicity – like a purposeful and continuous V11 incident – something that is supposed to yield not only market-societal transformation, but more fundamentally the transformation of Latour's 'critical zone' to realise a financial ontology of the Anthropocene.

Extended to climate crisis as a whole, the 'loop of Anthropocene catastrophe' gets folded into itself. Without the active and political recognition by COP21 of the active socio-material nature of the financial ontology of the Anthropocene, the long onset of climate crisis in an epistemic-ontological confluence would allow two alternative morphologies of the loop. Either, to stretch the loop so far into an ellipse that it appears as a flat line with an anticipatable and singular teleological point of ultimate climate impact: a final cumulation of permanent and omnipresent 'apocalyptic' climate catastrophe against which there is not much to do. Or the multiplied simultaneity of micro-loops devoid of concerted consequences that essentially equate to a denial of systemic climate change because isolated individual events are attributed to climate variability. Yet, with the Paris climate agreement the financial shaping of an Anthropocene ontology has, in a way, both been politically ratified and, even more importantly, with TCFD and it's structurally emerging consequences been turned into a proliferated strategic solution to redistribute socio-material agencies through financial markets and practices to steer market society towards a 'sustainable' planetary system: the attempt, for better or worse, to financially redesign the Anthropocene.

Here, the loop of Anthropocene catastrophe folds into itself precisely through the financial mode of knowledge production that has been at the centre of the this thesis. The feedback aspect of the loop, that is the materialisation of the reference point by mediated, yet actualised, catastrophe, folds into what at this very moment is becoming the yet to be defined '*loop' of Anthropocene climate crisis*. What in Anthropocene catastrophe's case had already been an important practice in consolidating actualised catastrophe, becomes in the case of Anthropocene climate crisis the only driver of feedback whatsoever: socio-material appropriation of mediation and simulation. Appropriating not just catastrophic futures but Anthropocene futures as the driver of Anthropocene ontologies serves as the entire nature of a loop that has little actualised ontology to work with due to the shape of the long onset of climate crisis – instead of having too little 'real' history, as in the case of catastrophe, we have close to none for the case of climate crisis. The anticipated 'reality' of climate crisis, which has not yet fully materialised, is attempted to being realised in the multiplicity of myriad knowledge productions by financial actors and their prescribed contextual situating of their portfolios in Anthropocene futures: the ontological becoming of a market-shaped financial Anthropocene.

Devoid of enough actualised climate catastrophe but instead enriched by mobilised knowledge production of how it *could* play out, the feedback loop of Anthropocene climate crisis is driven by a yet-to-be established consolidation mode of permanent recalibration of financial climate models and modelling practices against unconsolidated mediated socio-material environments. Here, it is, again, inventories of exposed assets (now, however, everything from material objects, business operations and plans all the way to entire economic, political, environmental and social systems), hazards (now the interaction between emissions levels and global warming and how warming interacts with the climate system and socio-material environments), and vulnerabilities as the grammars of interaction of physical manifestations (now everything from disaster events to lasting socio-material shifts in environments, such as droughts and sea level rise) and self-inflicted transitional manifestations (the more immediate economic consequences of emerging regulative and market programmes to mitigate climate change). Climate loss appears here as a proxy for potential but not yet fully actualised damage within the Anthropocene, and as such as a product of a 'better' or 'worse' management of its realisation.

What Koolhaas retroactively attributed to New York as 'Manhattansim' famously shocked surrealists such as Salvador Dali. A historical fact but framed in Koolhaas's narrative of Delirious New York, Dali failed in his initial plan to 'shock' Manhattan upon his first arrival on the island in 1935 by presenting himself on the docks with a 2.5-meter loaf of bread on his shoulder as a surrealist artistic act. However, the welcoming New York journalists did not react to it because Manhattan, as Koolhaas puts it, was already 'surreal'. Admittedly illustratively exaggerated, the currently emerging regime of financially managing the climate crisis is reminiscent of trying to shock surrealism: to already socio-materially realise environments which can withstand the shock of a climate crisis already in motion and about to land on the global islands of market societies. One seems to get a glimpse of what a realisation of the manifesto of a financial ontology of the Anthropocene could conceptually look like as a mode of architectural appropriation if one takes literally Koolhaas's City of the Captured Globe. Financial actors, each one block to realise in multiplicity their situated climate futures, graft their socio-material appropriative reach onto the Anthropocene as enforcers of a permanently shifting consolidation of how we want and can envision our market-shaped climate futures: "all these Institutes together form an enormous incubator of the World itself; they are breeding on the Globe. Through our feverish thinking in the Towers, the Globe gains weight. Its temperature rises slowly." (Koolhaas, 1994: 294). The socio-political question now is, to what extent we and 'the market' are prepared to leave it to the financial 'Institutes' to appropriatively breed on our Globe, and the ontological question, that will long remain unanswered, is how slowly the Globe's temperature can rise because of it.

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Appendix B: List of Interviewees

Synonym	Location	Org. Type	Profession	Date (int. 1)	Date (int. 2)
C94	Online	Vendor	Modeller	06.05.21	
Dickie Whitaker	London	Industry Initiative	CEO	18.08.14	28.03.18
Hemant Shah	Online/ San Francisco	Vendor	CEO	26.07.14	22.05.18
I01	San Francisco	Vendor	Modeller	23.05.18	
I03	London	Vendor	Modeller	12.09.14	20.03.18
I13	London	Vendor	Modeller	29.03.18	
I14	London	Vendor	Modeller	27.07.18	
I18	London	Vendor	Modeller	29.03.18	
I29	London	Broker	Modeller	12.10.18	
I35	Boston	Reinsurer	Underwriter	05.04.18	
I37	London	Vendor	Modeller	29.03.18	
I38	Boston	Vendor	Modeller	06.04.18	
I64	San Francisco	Vendor	Modeller	21.05.18	
Karen Clark	Boston	Vendor	CEO	05.04.18	
Michael Millette	New York	ILS Fund	CEO	30.05.18	
O75	New York	Bank	Risk Analyst	21.05.19	
O84	New Jersey	Academic	Modeller	15.05.19	
O87	New York	Asset Manager	Risk Analyst	08.05.19	
O89	Boston	Academic	Modeller	13.05.19	
O91	Online	Broker	Risk Analyst	16.11.18	
P02	London	Consultancy	Risk Analyst	18.08.18	
P30	London	Consultancy	Modeller	28.03.18	
P31	London	Consultancy	Consultant	28.03.18	
P32	London	Consultancy	Risk Analyst	28.03.18	
P63	New York	Academic	Modeller	14.05.19	
U10	Edinburgh	Asset Manager	Portfolio Manager	01.03.18	
U11	London	Broker	Modeller	19.03.18	
U12	London	Insurer	Risk Manager	12.03.18	11.09.18
U15	London	Reinsurer	Modeller	27.03.18	11.09.18
U16	San Francisco	ILS Fund	Modeller	22.05.18	
U28	Brighton	Trade Press	Journalist	22.03.18	
U33	Hamilton	ILS Fund	CIO	14.05.18	15.05.18
U34	New York	Insurer	Underwriter	17.05.19	
U39	New York	Reinsurer	Underwriter	10.04.18	
U40	New York	Insurer	Underwriter	30.04.18	
U42	New York/ Connecticut	ILS Fund	CEO	27.04.18	10.05.19
U43	San Francisco	ILS Fund	CIO	22.05.18	

U44	Chicago	ILS Fund	Portfolio Manager	07.05.18	
U45	Online	Bank	Portfolio Manager	22.01.19	
U47	Chicago	ILS Fund	Risk Analyst	08.05.18	
U48	New York	ILS Fund	CEO	25.04.18	
U51	Hamilton	Reinsurer	Underwriter	10.05.18	
U52	Hamilton	Reinsurer	Risk Analyst	11.05.18	
U53	Hamilton	Reinsurer	CRO	10.05.18	
U55	Chicago	ILS Fund	Modeller	07.05.18	
U59	San Francisco	ILS Fund	Risk Analyst	22.05.18	
U60	Hamilton	ILS Fund	CEO	14.05.18	16.05.18
U61	Hamilton	Reinsurer	CRO	15.05.18	
U68	Hamilton	Asset Manager	Portfolio Manager	16.05.18	
U71	New York	ILS Fund	Portfolio Manager	30.05.18	
U72	Hamilton	Reinsurer	Risk Analyst	15.05.18	
U93	New York	Asset Manager	Risk Manager	31.05.18	
U93	Online	ILS Fund	Risk Analyst	28.05.19	

Appendix C: List of Observations

Type	Location	Date (To ensure anonymity, only years for industry events are given.)
Industry Initiative launch event	London	07.02.2014
Observation at a vendor	London	12.09.2014
Industry conference	London	2018
Industry conference	London	2018
Annual shareholder event of a (re)insurer	Omaha	2018
Observation at catastrophe risk consultancy	London	28.03.2018
Observation at a reinsurer	New York	09-10.04.2018
Observation at an ILS fund	Chicago	07-08.05.2018
Observation at a reinsurer	New York	09-10.04.2018
Industry workshops	London	12.09.2018
Observation at a reinsurer	New York	09-10.04.2019
Observation at an ILS fund	Connecticut	10.05.2019
Industry conference	London	2019
Industry conference	Online	2020