CLIMATE CHANGE IMPACTS ON MAIZE PRODUCTION AND ASSOCIATED MYCOTOXIN RISK IN MALAWI

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Abstract

Malawi currently suffers from high levels of food insecurity, and its largely rain-fed agricultural sector is susceptible to climatic shocks. Despite this high level of vulnerability, little evaluation has been carried out to determine the quality of climate information available to Malawi or how climate change will impact the quantity or quality of their main food crop, maize.

This research first analysed the ability of currently available climate models to replicate the past climate of Malawi to gain a better understanding of any uncertainty in the models going forward. This research made use of Python to compare observed climatic variables to the outputs of 21 Regional Climate Models (RCMs) from the Coordinated Regional Climate Downscaling Experiment (CORDEX) initiative, as well as six ERA-interim driven RCMs and the 11 General Circulation Models (GCMs) which form their boundary conditions. Through this evaluation it was determined that currently available RCMs and GCMs perform similarly well in replicating the climate of Malawi, but RCMs allow for better spatial analysis due to their higher resolution. It was also clear from this analysis that the performance of RCMs in Malawi is highly influenced by their boundary conditions. This comparison highlighted that currently available climate models replicate trends in Malawi's temperature well, but the outputs for precipitation are highly divergent. This new understanding of the quality of climatic information highlights the risks of maladaptation when using climate projections for adaptation programmes which are sensitive to precipitation, including for the agricultural sector.

Approximately half of all calories eaten in Malawi are from domestically grown rain-fed maize and the quality and quantity of maize produced is highly dependent on climatic conditions. Projecting the existing RCMs into the future, it is possible to see rising temperature trends across the whole country. Keeping the uncertainty of the models in mind, it was also possible to set out three potential precipitation scenarios based on minimum, mean and maximum projected precipitation rates. Using these climatic conditions as inputs to AquaCrop – a public computer-based agriculture model developed by the Food and Agriculture Organisation (FAO), it was possible to determine that the projected yield of maize grown in Malawi's main maize growing region, Central Malawi, could decrease or increase depending on the precipitation scenario applied. Based on the frequency of model results, it is considered likely that that precipitation rates will increase slightly, which would lead to slight increases in maize yields. However, a minimum precipitation scenario - as shown as possible in the model projections - could lead to yields decreasing by up to 93%, highlighting a significant risk to the food supply in Malawi.

Sampling of maize-based food grown and sold in Malawi has highlighted that the crops are often contaminated with dangerous levels of aflatoxin B1 (AFB1), a highly carcinogenic natural toxin. AFB1 is a secondary metabolite of the mould species *Aspergillus flavus* and *A. parasiticus, with A. flavus* a widespread contaminant in arable agriculture. Climatic conditions are known to be key factors in determining the growth and spread of these moulds, and the likelihood of AFB1 production. Using locally calibrated maize crop data, RCM outputs for Malawi, and AFLA-maize – an empirical model developed by researchers at the Università Cattolica del Sacro Cuore in Piacenza, Italy, it was possible to project likely changes in the concentration and distribution of AFB1 contamination on Malawi's maize crops. This analysis found that climate change is projected to make pre-harvest conditions in Malawi more favourable to AFB1 contamination of maize crops, with the risk of contamination moving northwards in a warming climate.

Finally, this research explored the work that is currently being done or is planned in Malawi to tackle the risks posed from food insecurity and aflatoxin contamination in a changing climate. Several recommendations are made to decrease the vulnerability and impact of this risk, while also improving the resilience of the population.

Lay Summary

The population of Malawi currently struggles with unstable and inconsistent access to sustainable and nutritious foods. Their agricultural sector is largely made up of smallholder farms and is almost entirely dependent on rain for irrigation. In the past their food supply has been negatively affected by extreme weather events such as floods and droughts, leaving large parts of the population dependant on international food aid. Despite this high level of vulnerability, there has been little research into how climate change will impact Malawi's main food crop – maize, or how well we understand the changes that Malawi's climate is expected to experience.

While we do not have a crystal ball to *know* what will happen in the future, we can look at the past and see how well currently available climate models can simulate the climatic conditions we know have happened in Malawi. We can then assume that when we run the climate models into the future, they will have a similar level of accuracy and uncertainty as they have had in the past. In this research we have done this by running the climate models over a historic period-of-time and then comparing those outputs to real climate data from weather stations and satellite records. From this analysis we determined that currently available climate models do well in replicating the trends in Malawi's past temperatures, but the outputs for precipitation are less accurate. This new understanding of the quality of climatic information in Malawi highlights the risks of making the wrong choices when using climate projections for adaptation programmes which are sensitive to precipitation, including programmes targeting the agricultural sector.

Approximately half of all calories eaten in Malawi come from domestically grown rain-fed maize and the quality and quantity of maize produced is highly dependent on climatic conditions. Projecting the existing climate models into the future, it is possible to see that the climate in Malawi is expected to get warmer in coming decades. Due to the lack of certainty over using precipitation data from climate models in Malawi, this research instead used a minimum, average, and maximum scenario to consider three possible futures for Malawi. Using these possible future climatic conditions as inputs to a computer-based agriculture model we were able to determine that the amount of maize grown in Malawi's main maize growing region, Central Malawi, could either decrease or increase depending on the precipitation scenario.

Previous studies have tested maize-based foods that are grown and sold in Malawi for a range of toxins. These studies show that the maize grown in Malawi is often contaminated with dangerous levels of a toxin called aflatoxin B1 (AFB1). AFB1 is a naturally occurring substance that is produced by certain moulds that easily grow on a variety of different plants, including maize. Eating maize that is contaminated with AFB1 can cause a range of negative health impacts including stunting the growth of children, cancer and even death. Climatic conditions are known to influence how well these moulds grows and how likely they are to produce AFB1. Therefore, using information that we know about maize varieties grown in Malawi, and the likely climatic conditions going into the future, this research uses a computer model to investigate how the risk of AFB1 contamination will change. This analysis found that climate change is likely to make AFB1 contamination of maize crops at the time of harvest more likely, with the risk of contamination moving northwards in a warming climate.

Finally, this research explores the work that is currently being done or is planned in Malawi to tackle the risks posed from changing maize availability and AFB1 contamination in a changing climate. Several recommendations are made to decrease the impact of this risk.

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Chapter 1 Introduction

1.1. Food Security and the 'Perfect Storm'

Food insecurity poses a significant financial burden on many countries, often compounding the challenges of development. In Africa and Asia, undernutrition has an 11 percent impact on gross domestic product (GDP) annually, which is larger than the impact of the 2008-10 financial crisis (IFPRI, 2016). Food security is also a major concern for a variety of other reasons, causing both direct and indirect impacts on human health outcomes, gender equality, income inequality, education, ecosystems services, climate change, and both intra- and inter-national peace and justice (Lipinski et al., 2013; IFPRI, 2016). While it is understood that attaining food security should be a priority, and that investing in reducing malnutrition has a disproportionally positive impact on the economy, it remains a large challenge for many countries around the world (FAO, 2009; Godfray et al., 2010; IFPRI, 2016).

Over the last century, food production has been increasing steadily to try to keep up with the rise in food demand caused by an ever increasing and more affluent global population (Nellemann et al., 2009; FAO, 2009). However, with the rate of population growth, growing affluence around the world, and a changing dietary preference (e.g. move to more animal products which puts further pressure on agricultural production) the rate and scale of growth in agricultural supply has not been enough to meet the growing demand for food to date, and it is expected that, without significant intervention, this gap will get larger in the future (FAO, 2009; Tester and Langridge, 2010; European Commission, 2019; Fukase and Martin, 2020).

Interest in achieving food security is not new. In 1945 the member states of the United Nations (UN) met in Quebec, Canada to create the Food and Agriculture Organisation of the United Nations (FAO) whose goal it was to *"free humanity from hunger and malnutrition, and to effectively manage the global food system"* (FAO, 2016). Since that time various commitments have been made by the UN and by individual countries in an attempt to tackle this issue. In 1996, at the World Food Summit (WFS) in Rome, the member states of the UN pledged *"... to eradicate hunger in all countries, with an immediate view to reducing the number of undernourished people to half their present level no later than 2015*" (WFS, 1996). This was re-affirmed in 2000 by the UN's Millennium Development Goals (MDGs) which committed to various development targets including Target 1C which stated that, by 2015, the proportion of people who suffer from hunger globally would need to halve compared to 1990 levels (UN, 2016b). The UN's Sustainable Development Goals (SDGs), which supersede the now elapsed MDGs, set forward eight new targets to tackle issues around hunger, food security, nutrition and sustainable agriculture (the Goal 2 targets) (UN, 2016a).

With policies and practices put into place to meet the UN goals, progress has been made in the area. The prevalence of undernourishment, in absolute and relative terms, has decreased in the last few decades (FAO, 2020b). However, food distribution is still not even around the world, and economic downturns, conflict, continually rising populations, changing dietary demands, and increasingly variable and extreme weather conditions are all putting pressures on the agricultural system, undermining efforts to end malnutrition, hunger, and food insecurity (FAO et al., 2020; Fukase and Martin, 2020). Unfortunately, since 2014 the prevalence of undernourishment has been slowly increasing again, with the fastest growth in undernourishment seen in Sub-Saharan Africa (SSA) (FAO, 2020b; The World Bank, 2021b). In 2019, just before the COVID-19 pandemic, it was estimated that, globally, 690 million people were still suffering from undernourishment, and unsurprisingly, the impacts of COVID-19 are expected to exacerbate the issue, making it unlikely that the world will achieve a target of Zero Hunger by 2030 (FAO et al., 2020).

It is also important to note that these figures only consider access to food, they do not consider food safety or the number of people who suffer or die from food-borne diseases. Each year, approximately 600 million cases of illness and 420,000 deaths result from 31 different food-borne diseases, with the highest number per capita observed in Africa (WHO, 2015). A third of all these deaths occur in children under the age of 5, and the World Health Organization (WHO) estimate that at least 33 million years of healthy life are lost each year to the consumption of unsafe food (ibid.).

While it is promising that the UN members are still eager to tackle this issue, achieving these targets will not be easy when considered alongside other global challenges. The world's population is expected to reach 8.5 billion by 2030 and 9.7 billion by 2050[1], with Africa representing the fastest growing region (DESA, 2019). Climate change is projected to put further stressors on food security, through impacts on availability, accessibility, utilisation, and system stability (IDWG, 2008). There will be challenges from volatile food, energy, and commodity prices; changing demand for different types of food, including meat, fish, and dairy; competing demands for land, water, and energy; rising unemployment and underemployment rates; global economic recessions; and political instability (Godfray et al., 2010; FAO et al., 2015). Together these global challenges pose what John Beddington (2009) referred to as the 'perfect storm' of global events, leading to the world not only needing to produce more food, water and energy in an environmentally and socially sustainable manner to meet growing demands, but also mitigate and adapt to a changing climate at the same time.

1.2. Maize: Global Importance and Climate Vulnerability

The maize plant (*Zea mays*) is one of the world's most important crops, providing a source of food, livestock feed, energy, and fibres. Originally domesticated in Mexico, maize has been grown around the world for the last few centuries (Goodman and Galinat, 1988; Tenaillon and Charcosset, 2011; Mir et al., 2013). With many different cultivars bred to grow in a variety of environments, it is said that a crop of maize is maturing in almost every month of the year somewhere on the planet (Encyclopaedia Britannica, 2020). While the nutritional content of maize differs by variety, it is generally considered a good source of starch, fibre, protein, and fat (Ranum et al., 2014). As such, maize has become a staple source of food and feed in many countries; in terms of direct consumption, maize makes up approximately seven percent of the global population's daily calorie intake, however through the consumption of maize-fed livestock products (e.g. meat, eggs, and dairy), and foods containing maize-derived syrup or flour, the calorie share is likely closer to a third (CGIAR, 2016; FAO, 2020a). In much of the developing world, maize is the single largest contributor to daily calorie intake, making up over 50 percent of calorie intake in some countries (ibid.).

With growing populations and high levels of food insecurity, the demand for maize is increasing rapidly (CGIAR, 2016). Maize can be grown in a range of climatic conditions, though the growth, development, and vegetative yield of the plant is strongly influenced by the weather. The optimal growing

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[1] Based on the 2019 medium variant projections by the UN Department of Economic and Social Affairs (DESA) Population Divisions. The projection range is 8.3-8.7 billion for 2030 and 8.9-10.6 billion for 2050.

temperature for maize is higher than many other globally important grain crops, and studies have shown that growth rates and development processes in maize tend to increase as the temperature rises between about 10°C and 32°C (Hardacre and Turnbull, 1986; Stewart et al., 1998; Sanchez et al., 2014). However, the accelerated growth rates and decreased pollen viability associated with higher temperatures lead to smaller kernel numbers and consequentially decreased yields (Gourdji et al., 2013; Lizaso et al., 2018; Zampieri et al., 2019). Higher temperatures are also linked to higher evapotranspiration rates, which increases maize's water demand (Crafts-Brandner and Salvucci, 2002; Zampieri et al., 2019). Decreased water availability has been shown to exacerbate temperature stresses, and has been linked to delays in crop flowering, reduced photosynthesis, and decreased yield, particularly when the water stress occurs early in crop development (Lobell et al., 2013; Zampieri et al., 2019).

With global climate change increasing surface temperatures and changing precipitation patterns, maize yields have already been shown to be changing in many parts of the world. The maize grown in some higher-latitude regions have benefited from the warming, and have shown some increased yields, however maize crops growing in many lower-latitude regions have begun to decline (Mbow et al., 2019). On balance, Lizumi et al. (2018) has shown that between 1981 and 2010, climate change resulted in a net 4.1 percent decrease in potential global mean maize yields compared to a pre-industrial climate. When uncertainties and the impact of increased CO_2 fertilisation and agronomic adjustments were considered, the mean global maize yield impact ranged from -8.5 to +0.5 percent over the same period (using a 90 percent probability interval) (Lizumi et al., 2018). With the global climate projected to warm further, these trends are set to continue into the future, with yields expected to decline the most in South America, Africa, and Asia (Mbow et al., 2019).

1.3. Climate Change and Food Safety: Focus on Aflatoxin B1

Climate change is associated with physical changes to the environment, including rising temperatures, precipitation changes, and changes to the frequency and intensity of extreme events (IPCC, 2018). These physical impacts not only affect the ways in which our food is grown, stored, transported, and prepared, but also the distribution and persistence of a variety of bacteria, viruses, parasites, fungi, and host species, and the diseases which are related to them (Tirado et al., 2010).

Mycotoxins are a group of poisonous chemicals which are produced naturally by certain fungi (moulds) (Food Standards Agency, nd). The moulds which produce the mycotoxins may grow on crops during most stages of the supply chain from while the plant is still growing, during harvest-time, post-harvest handling, processing, or storage (Suttajit, 1989). Multiple criteria impact the type and concentration of mycotoxin which is produced, including the nutritional composition and genetic susceptibility of the host plant, moisture content, humidity, water activity, aeration, temperature, acidity level, fungal population, and physical condition of the crop (e.g. damage due to insects or other stress factors) (Matumba et al., 2014a). However, climatic conditions are thought to be the most important factor in the production of mycotoxins and therefore, climate change is likely to create many changes in the distribution, type, and concentration of mycotoxins (Paterson and Lima, 2010).

While there are several hundred different mycotoxins that have been identified, aflatoxins (AFs) are often the focus of research (WHO, 2018; WHO, 2020). AFs pose a significant risk to human health and represent a substantial burden to the global economy, as AF contamination results in the destruction of 25 percent of the world's food crops annually (WHO, 2018). AFs are colourless to white or yellow in colour, they are flavourless, and their point of fusion and decomposition temperature ranges from 237°C - 320°C meaning they are stable at temperatures commonly used for cooking or preparing food, including boiling, milk pasteurisation and alcohol fermentation (Carvajal-Moreno, 2015). This group of mycotoxins were discovered in the late 1950s and named in the early 1960s after investigation of an epidemic known as "Turkey X Disease" which resulted in the deaths of hundreds of thousands of poultry in England, and was attributed to contaminated groundnut feed imported from Brazil (Blount, 1961).

AFs are a secondary metabolite produced mainly by the *Aspergillus flavus* and *A. parasiticus* fungal species (ibid.). *A. flavus* and *A. parasiticus* can invade a variety of food crops under warm and humid conditions, and therefore are common in tropical and subtropical regions (WHO, 2018). While *A. flavus* are commonly found in soils, their spores are airborne allowing them to easily contaminate a variety of agricultural plants in pre-harvest conditions, including facilities used for storage, processing, and distribution (Gourama and Bullerman, 1995). *A. parasiticus* are more commonly found in rich soil littered with decaying plant material meaning they are more likely to contaminate crops such as groundnuts (ibid.).

There are a variety of AF types although only 4 are known to be naturally synthesized by the moulds themselves – AFB1, AFB2, AFG1 and AFG2 (Carvajal-Moreno, 2015). The other AFs of group M, Q, P and AFL are products of further microbial or animal metabolism of the naturally occurring forms (ibid.). For example, AFM1 – a toxic and carcinogenic form of metabolised aflatoxin, is produced by mammals who have ingested AFB1, and is then excreted through milk (Marchese et al., 2018). AFM1 is therefore found in the human breastmilk and dairy products of mothers and ruminants who have eaten food or feed contaminated by AFB1 (ibid.). The naturally occurring B and G group AFs are so named because they exhibit a blue and yellow-green fluorescent colour respectively when under ultraviolet light (Kensler et al., 2011). Aflatoxins are classified as a Group 1 carcinogen (carcinogenic to humans) by the International Agency for Research on Cancer (IARC, 2002) and AFB1 is one of the most potent naturally occurring carcinogens currently identified (Shan, 2019).

The dose and duration of AFB1 exposure impacts the toxicology, however any exposure has a cumulative effect on the risk of cancer (Dhakal and Sbar, 2020). Long-term exposure to AFB1 is linked to high incidence of liver damage and cancers, and can also be teratogenic[2] and mutagenic[3] (Shan, 2019). Exposure to AFB1 can cause growth restrictions in children and is linked with the development of oedema in malnourished people (kwashiorkor) (Lamplugh and Hendrickse, 1982; Coulter et al., 1986; Soriano et al., 2020). As AFB1 is an immune-suppressant, exposure to it has also been linked to an increased progression rate of Human Immunodeficiency Virus (HIV) infection to Acquired Immunodeficiency Syndrome (AIDS) (Jolly et al., 2013; Jolly, 2014). While most of the human impacts from AFB1 result from low to moderate chronic exposure, toxicity resulting from short term exposure

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[2] A teratogen is a substance that causes physical or functional abnormalities to a foetus following exposure during pregnancy.

[3] A mutagen is anything that causes a change in the DNA within a cell. These changes may lead to harm to the cell and can cause diseases such as cancer.

to high levels of AFB1 contamination, known as acute aflatoxicosis[4], also has serious health implications, with high levels of fatality, particularly amongst impacted children (WHO, 2018; Dhakal and Sbar, 2020). Though relatively rare in humans, cases of acute aflatoxicosis have been documented since the 1960s, with major outbreaks seen mainly in the developing world (WHO, 2018).

Human health is mainly affected by AFB1 through the consumption of contaminated food, although occupational exposure has also been reported in some agricultural and livestock production environments (Wangia et al., 2019). Drought stress, insect damage and poor storage conditions can increase a crop's risk of infection by the mould species (WHO, 2018). Temperature changes and water activity effect gene expression in the *A. flavus* and *A. parasiticus* fungi, influencing AFB1 production (Schmidt-Heydt et al., 2010). Higher temperatures, water stress and enhanced CO_2 concentrations have also been shown to result in enhanced AFB1 production once the crop is infected (Medina et al., 2014).

Only a handful of studies have begun to explore how the risk of AFB1 contamination of maize may change with the impacts of climate change (e.g. Wu et al. (2011) and Battilani et al. (2016)). While it has not been proven how global AFB1 contamination risk may be affected by climate change (Mbow et al., 2019), it is clear that changing conditions will impact the maize crops' susceptibility to be infected with mycotoxin-producing fungal species, the amount of fungal growth that will occur, and whether that fungus goes on to produce dangerous levels of toxins.

1.4. An Overview of Malawi

Malawi is a small landlocked country in SSA with a heterogeneous landscape (see Figure 1.1). Lake Malawi (Lake Nyasa/Niassa), the fourth largest freshwater lake by volume, and ninth largest by area, makes up a quarter of the country's area (Lyons et al., 2011; The World Bank, 2018). The country's topography is mountainous with many plateaus found to the east and west of the Great Rift Valley, which runs the entire length of the country from north to south. The current climate in Malawi is considered sub-tropical (MetMalawi, 2020); Malawi experiences a rainy season between November and April and a dry season between May and October (see Figure 1.2).

There are still gaps in the understanding of localised climate change projections for Malawi. However, projections for SSA as a whole indicate that, over the 21st century, we should expect to see an increase in severe weather events such more erratic rainfall, droughts and floods, increases in average and peak temperatures, and changes in pest and disease spread (Niang et al., 2014). Climate change is expected to exacerbate existing challenges with food security, health, poverty, and development in the region (ibid.). High physical exposure, high levels of poverty, and heavy reliance on a predominantly rain-fed agricultural sector for its economy, employment and food supply mean Malawi is identified as being particularly vulnerable to future climate change (Minot, 2010; Giertz et al., 2015; FAO, 2017).

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[4] Aflatoxicosis has been associated with the consumption of food contaminated with aflatoxins at a concentration of 1mg/kg or higher, and if consumed over a period of 1-3 weeks, AFB1 concentrations of between 20 and 120 µg/kg body weight per day has resulted in acute toxicity and death (WHO, 2018).

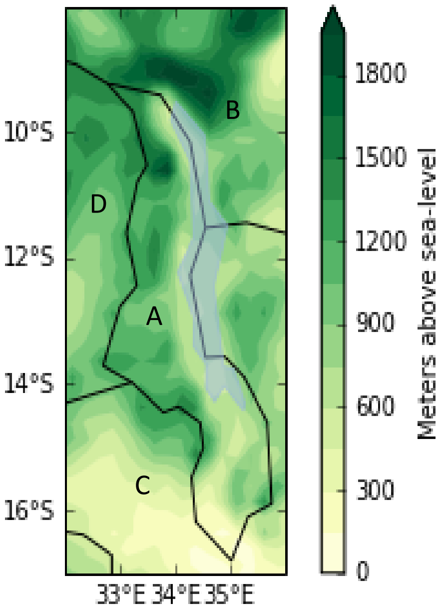

Figure 1.1 Map of Malawi and surrounding area.
Black lines show national borders and the shaded grey-blue area is Lake Malawi. Letters on the map represent different countries; A – Malawi, B – Tanzania, C – Mozambique, and D – Zambia. The colour scale on the map shows elevation data for Malawi in meters above sea-level at a 0.25-degree (approximately 27km2) resolution (JISAO, 2014).

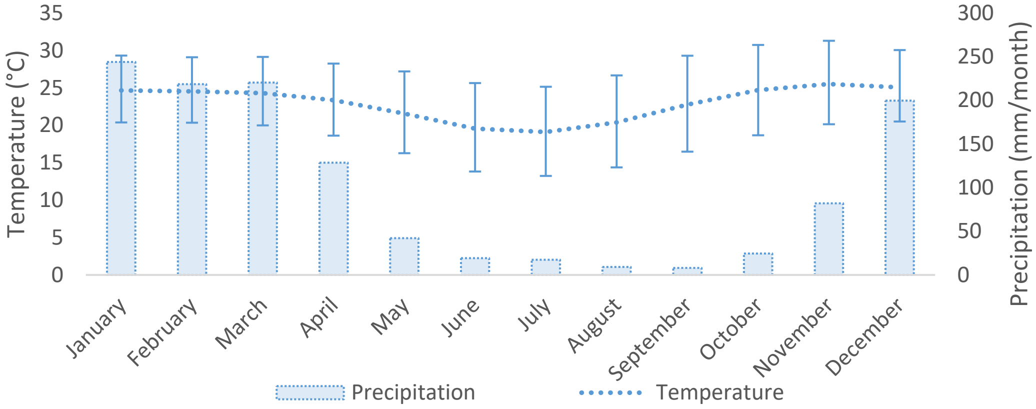

Figure 1.2 Average climate of Malawi based on 1971-2000 period.
The error bars show the minimum and maximum monthly temperatures (Willmott and Matsuura, 2001; Harris et al., 2014; Schneider et al., 2015).

Malawi has seen rapid population growth in recent decades; In 1960, the population of Malawi was just under 3.7 million, but this grew to over 18.7 million by 2019 (The World Bank, 2021a). Annual population growth rate is estimated to be 2.39%, which is within the top 30 fastest growing populations in the world (CIA, 2021a). The population of Malawi is very young, with almost half of the 2021 population under the age of 14, and less than 6% of the country over the age of 55 (CIA, 2021b). Based on the projected risk of poor health and poor education outcomes for children born today, Malawi has one of the lowest Human Capital Index (HCI)[5] ratings in the world (World Bank Group, 2020).

Approximately 70 percent of Malawi's population lives under the international poverty line of USD 1.9 per day (2011 prices) (The World Bank, 2017). While some marginal improvements are expected, severe droughts and floods, combined with political and governance shocks have had a significant

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[5] The Human Capital Index (HCI) is a measure of the amount of human capital that a child born today can expect to achieve by the age of 18. This index considers the risks of poor health and poor education that exists in the country where they live.

negative impact on the country’s economy and poverty levels (The World Bank, 2017; IMF, 2017). There has been some progress in tackling child malnutrition in Malawi, however levels are still high at 37 percent, and in 2013 food insecurity[6] affected 65 percent of all households (84 percent of rural households), up 15 percent from 2010 levels (IMF, 2017). In 2018 an estimated 18.8 percent of the population of Malawi were classified as undernourished, this is down from the peak of 24.7 percent in 2003, but up from the low of 16.9 percent in 2014 (The World Bank, 2021b; FAO et al., 2015).

Over three quarters of the calorific intake in Malawi comes from six crops, with domestically grown maize accounting for half of all calories eaten in the country (FAO, 2013). Maize is the most extensively grown crop in Malawi, grown on approximately a quarter of all cultivated land in 2018 (FAOSTAT, 2020). Due to uncertainty in climate change projections, particularly over future precipitation quantities and distribution, the predictions for the impact on maize yields varies. Looking at rainfed maize crops in the Lilongwe District of Malawi, and depending on timescale and projected precipitation scenario, a range of potential outcomes are predicted for maize yields in Malawi; some projections indicate a net negative impact from climate change on crop yields while others showed that the conditions may be more favourable to maize production (Saka et al., 2012; Stevens and Madani, 2016; Msowoya et al., 2016). However, even the most optimistic of the results suggest that maize production will not be able to keep up with increasing demand from population growth, particularly in the longer term.

The moulds which produce AFs tend to flourish in hot and humid environments, therefore the sub-tropical climate of Malawi creates ideal conditions for growth (Misihairabgwi et al., 2017). Furthermore, erratic rainfall patterns (which are typical in Malawi) and social issues, including theft of food crops before harvest, frequently lead to early harvesting (Matumba et al., 2014a). The crops are then often stored without adequate pre-drying for extended periods of time in facilities with inadequate or non-existent temperature and moisture control, all of which can promote the growth of moulds and so lead to AF production (ibid.).

To date there has not been extensive research into the prevalence of AF contamination in Malawi, although there are a few studies that have been published on smaller scale assessments. Table 1.1 shows dangerous levels of AF present in a range of maize-based foods available for consumption in Malawi. The data in Table 1.1 have been shown in relation to the European Union (EU) regulated levels for AF in these food types as Malawi does not currently have regulations for AF contamination in food sold domestically outside of supermarket environments (Mwalwayo and Thole, 2016).

The exact health impact of aflatoxin exposure in Malawi is largely unknown, however the Partnership for Aflatoxin Control in Africa (PACA, 2020) has estimated that over 2,100 cases of liver cancers occur in Malawi annually due to aflatoxin exposure. This health outcome alone has been estimated to result in 75,400 healthy life years lost annually, representing a cost of USD 393.6 million to the Malawian economy (ibid.). Despite the significant exposure risk and vulnerability of the population, thus far there have been no serious aflatoxicosis outbreaks reported in Malawi (Mwalwayo and Thole, 2016). However, outbreaks have occurred in neighbouring countries with similar climates (ibid.).

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[6] Food insecurity is defined as having access to fewer than 2,100 kilocalories per person per day (kcal/person/day).

With increasing temperatures and even more erratic rainfall predicted, it is likely that climate change will impact the incidences of aflatoxin exposure in this region in terms of their distribution and concentration. These changes pose an additional challenge to existing issues around human health and food security in Malawi, and further research is required to understand the scale of these changes.

Table 1.1: Level of Aflatoxin (AF) contamination in Malawian food commodities.
Aflatoxin (AF) contamination of food commodities in Malawi compared to European Union (EU) regulated levels (European Commission, 2006; Commission, 2010) (table adapted from Misihairabgwi et al. (2017)). NS: Not Stated

Food Commodity	Toxin	Positive samples (%)	Mean (µg/kg) [Range]	EU Regulation (µg/kg)	Source
Maize based beers from Tribal (chewa) rituals and commercial village brewers	AF	89	90 ± 96 [NS]	4	(Matumba et al., 2014c)
Maize Puffs sold in retail markets	AF	75	1.1 [0.3-2.0]	4	(Matumba et al., 2014b)
Instant maize-based baby cereals sold in local markets	AF	100	2.5 [0.5-10.4]	0.1	(Matumba et al., 2014b)
Maize sold in farmsteads and local markets	AF	100	12 [5-20]	10	(Probst et al., 2014)
Maize from rural households	AF	100	8.3 ± 8.2 [0.7-140]	10	(Mwalwayo and Thole, 2016)
	AFB1	45.3	1.71 ± 3.17 [NS]	5	(Matumba et al., 2009)

1.5. Focus of the Thesis

This thesis aims to explore projected climate change in Malawi and the impact that these changes may have on maize yields and the AFB1 contamination risk. Chapter 1 has introduced the subject area in the form of a literature review. From this foundational research, three main research questions were developed, and these are explored in Chapters 2-5. Firstly:

How well do current climate models replicate Malawi's climate?

Before it was possible to determine the scale of climate change impacts Malawi was projected to see, it was necessary to explore how well existing climate models were able to replicate Malawi's past climate. This evaluation was done by downscaling existing data outputs from General Circulation Models (GCMs) and Regional Climate Models (RCMs) over a historic period for Malawi and comparing these outputs to measured climatic data that is known to be relatively accurate. Without this information it would have been impossible to understand the level of uncertainty of using these models for future climate projections. It was expected that existing climate models, which do not have high resolutions or levels of geographical detail for Malawi, would have a high level of uncertainty and a bias in their temperature and precipitation outputs. The details of the methodology applied, and the findings of this analysis are detailed in Chapter 2 of this thesis. Secondly:

What is the impact of future climate change on Malawi's maize production and AFB1 contamination risk?

Once available climate models were evaluated, it was possible to assess future impacts with a better understanding of the level of uncertainty in the climate projections. The hindcasting exercise allowed for the exclusion of inaccurate climate models and the ability to re-baseline projections for improved accuracy. With this better understanding, it was possible to explore the impact of those climate projections might have on maize production in Malawi (Chapter 3) and AFB1 contamination risk on Malawian maize (Chapter 4). These impacts were determined using established computer-based models that have been developed for this purpose. To gather more detail than had been previously explored, these impacts were determined for two different maize cultivars that were planted on different dates within the planting season. Two climate scenarios, Representative Concentration Pathway (RCP) 4.5 and 8.5, and two future periods (to 2035 and to 2055) were explored. It was hypothesized that maize yields in Malawi would be negatively impacted by climate change and that the risk of AFB1 contamination would increase and move northward, expanding the impacted area. Thirdly:

What opportunities and challenges exist for adaptation to Malawi's changing maize yield and AFB1 contamination risk in a changing climate?

With an understanding of projected climate change in Malawi and the knock-on impacts to maize yields and AFB1 contamination risk, Chapter 5 is a review-based discussion on the opportunities and challenges which exist to manage this risk and improve food security in Malawi. This chapter paints a picture of the current and historical strategies employed, as well as discussing some potential future actions in the context of the climate change impacts and uncertainties identified in chapters 2, 3 and 4.

Finally, Chapter 6 provides a summary of the PhD journey taken, the main thesis conclusions, remaining gaps in knowledge and recommendations for future research.

1.6. References

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Chapter 2 Temperature and Precipitation Change in Malawi: Evaluation of CORDEX-Africa Climate Simulations for Climate Change Impact Assessments and Adaptation Planning

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2.1. Abstract

Malawi is highlighted as one of the most vulnerable countries in the world to the effects of climate change. The large uncertainty around future climate change in the region remains a barrier to adaptation planning. Despite this high potential vulnerability, relatively little research has gone into determining how well available models represent this country's climate. This work therefore evaluates the ability of existing General Circulation Models (GCMs) and Regional Climate Models (RCMs) to hindcast climatic variables in Malawi at a resolution appropriate for climate change impact assessment and adaptation planning. We focus on monthly precipitation rate, and mean, maximum and minimum surface air temperature. This assessment compares available observed datasets against the outputs of six ERA-interim driven RCMs and 21 GCM-driven RCMs from the Coordinated Regional Climate Downscaling Experiment (CORDEX) initiative, and the 11 GCMs which form their boundary conditions. It was found that the performance of the RCMs is highly influenced by their boundary conditions. None of the individual or ensemble RCMs or GCMs assessed in this paper correlate well with the observed datasets for any of the assessed climatic variables. While they do simulate the trending change in temperature variables well, the simulated outputs for precipitation are highly divergent. Based on these findings we suggest that either the ensemble RCMs or ensemble GCMs would be suitable for understanding projected temperature trends, with the RCMs providing better spatial resolution. However, none of the assessed models provide certainty over future precipitation trends in Malawi. As such we suggest that impact assessments and adaptation plans in Malawi will need to be designed and tested against a range of future precipitation scenarios. To improve modelling for Malawi it is recommended that regional climate models be improved for higher spatial resolution and inclusion of the impacts from large water bodies, including Lake Malawi.

2.2. Introduction

Sub-Saharan Africa (SSA) has been identified as being particularly vulnerable to future climate change due to its high exposure and low adaptive capacity (Davies et al., 2010; Niang et al., 2014). Climate change is expected to exacerbate existing challenges with food security, health, poverty and development in the region (Niang et al., 2014). The complexity and uncertainty surrounding the impacts of climate change in SSA is one of the main challenges hindering effective adaptation planning (Thornton et al., 2006). While understanding the impacts of future climate change has a level of uncertainty in every region of the world, the levels of confidence are amongst the lowest over SSA due to a lower resolution of available climate models and a lower level of research being conducted (Niang et al., 2014). Therefore, increasing the level of confidence in the projections for this region, or at least quantifying the scale of the uncertainty will be a big step towards providing the certainty required for effective adaptation planning.

Within SSA, Malawi has been highlighted as being especially vulnerable to climatic change due to high levels of poverty, and heavy reliance on a predominantly rain-fed agricultural sector for its economy, employment, and food security (Minot, 2010; FAO, 2017; Giertz et al., 2015). Malawi is one of the poorest economies in the world, with a fifth of the population classified as undernourished, and while progress is being made with treatment and control, there are still high levels of communicable diseases such as HIV/AIDS, tuberculosis and malaria making the population particularly vulnerable (FAO et al., 2015; IMF, 2017; The Global Fund, 2018). Most of the calorific intake of Malawi's population comes from agricultural production within the country's borders (Minot, 2010) and in 2015, 78 percent of Malawi's population was employed in the agricultural sector making it a main source of income (FAO, 2017). The agricultural sector is also a significant contributor to the overall Malawian economy, responsible for 32 percent of the total Gross Domestic Product (GDP) and over 78 percent of the country's total exports in 2016 (CIA, 2017). With much of the agricultural production coming from smallholder rain-fed production, climatic shocks such as floods and droughts have a significant impact on the country's economy and frequently affect its agricultural exports, and food security (FAO, 2010; Pauw et al., 2010; Ministry of Agriculture and Food Security, 2011; Giertz et al., 2015). For example, the 2005 drought led to 40 percent of the population requiring immediate food aid (Giertz et al., 2015).

Climate change is expected to exacerbate existing issues around water availability in Malawi, adding to the vulnerability of wetland and aquatic habitats, and the human systems which rely on them (USAID, 2013). With 96 percent of the country's energy produced through hydropower, water scarcity is already causing energy shortages, and this is expected to worsen (ibid.). While little research exists to prove an explicit link in Malawi, it is also expected that climate change will have negative human health impacts through increased incidence of malaria, cholera and diarrhoea (Irish Aid, 2015). As such climate change is likely to be an additional challenge for achieving various Sustainable Development Goals (SDGs) in Malawi, including the goals for no poverty, zero hunger, good health and well-being, affordable and clean energy, and decent work and economic growth (UN General Assembly, 2015).

To adequately quantify the impact that climate change will have on Malawi, and how the population can best adapt to these changes, a clear understanding of the projected changes is required. While some regional climate modelling has taken place, relatively little research has gone into evaluating how well the available climate models represent this small but heterogeneous country. Multiple studies looking at Malawi's climate vulnerability have highlighted the need for better short-term and mid-term climate projections in Malawi to allow for effective decision making, policy planning, and implementation of adaptation projects and climate services to take place (Nyamwanza et al., 2017; Vincent et al., 2015). While updating the weather and climate observation network would be a large investment for Malawi, research into the impact for Africa as a whole indicates that this money would be more than balanced through avoided losses of infrastructure, productivity, and human life (The World Bank, 2017). Some countries have created nation-specific tools which can help estimate more local-scale impacts and appropriate adaptation responses (UKCIP, 2017; Natural Resources Canada, 2017), 2017). While no such tool yet exists for Malawi a recently approved United Nations Development Programme (UNDP) project, funded by the Green Climate Fund, will provide the opportunity to improve Malawi's climate-information and early warning systems (Green Climate Fund, 2015).

Thus far, General Circulation Models (GCMs) have been used for climate change projections at the regional level for SSA and Malawi more specifically (Osborn et al., 2015; Mittal et al., 2017; Serdeczny et al., 2017). Regional analysis has shown GCMs to be relatively good at reproducing temperature trends, but they tend to overestimate precipitation in all seasons for Southern Africa (Flato et al., 2013; Buontempo et al., 2015). Furthermore, climate projections using GCMs represent changes over a relatively large area, however to carry out context-specific impact and adaptation assessments, a more detailed local understanding is required (Kim et al., 2014).

To achieve a greater level of detail, and improve the accuracy of projections, many studies have started to use regional downscaling methods (Jeong et al., 2016; Nolan et al., 2017; Stratton et al., 2018). With a high level of confidence, Flato et al. (2013) found that Regional Climate Models (RCMs) add value to climate projections particularly in areas with variable topography, and extreme or small-scale climatic processes. Studies by Kalognomou et al. (2013) and Endris et al. (2013) also found that an ensemble of 10 RCMs was able to adequately simulate the distribution and scale of rainfall patterns in Southern and Eastern Africa respectively. Stratton et al. (2018) similarly found that downscaling the Met Office's global-scale Unified Model to the Africa-wide domain allowed for additional detail to be included to the model, particularly higher resolution and convection parametrization. They concluded that the downscaling and improved continent-scale information, particularly the inclusion of convection, allows for improved precipitation simulation during the June-August period.

While RCMs naturally inherit the biases of the GCMs which form their boundary conditions, Buontempo et al. (2015) showed that local climate forcings and the RCM formulation have a larger influence over the results and decrease the impact of these biases in the African region. Some analysis has shown that RCMs are better able to represent annual cycles in Southern Africa and provide finer details to the projections (Nikulin et al., 2012; Buontempo et al., 2015; Dosio et al., 2015). However, it has also been found that the way the RCMs inherit the biases from the GCMs varies for different regions and variables within Africa, therefore it is important for impact assessment studies to re-evaluate the models for suitability before use (Kim et al., 2014).

Our study focusses on evaluating the ability of existing GCMs and RCMs to hindcast climatic variables in Malawi at a resolution appropriate for climate change impact assessment. We focus on the main climatic variables relevant to Malawi's largest exporting and employment sector, agriculture – surface temperature (mean, maximum and minimum) and precipitation rate. We also assess the models' ability to hindcast the frequency and timing of drought events, which are listed as the major environmental risk factor for Malawi's agricultural and hydro-based electricity sector (Giertz et al., 2015; Conway et al., 2017). This analysis provides a basis for future impact and adaptation analysis and an understanding of the limitations and error margins on the use of RCMs and GCMs for this purpose.

2.3. Data and Methods

The most straightforward method to assess the accuracy of climate models is to compare observed climate data with simulated climate outputs (Flato et al., 2013). However, the vast number of variables and timescales which can be considered means there is no standard set of tests which can be applied to a climate model to carry out this comparison (Gleckler et al., 2008). There are many ways in which this comparison can be undertaken, each having its own limitations. Our study is limited to comparing observational data for mean (Tas), maximum (TasMax) and minimum (TasMin) surface air temperature and precipitation rate (Pr) with reanalysed and simulated climate model datasets for Malawi.

2.3.1. Description of Observations

There are few high-quality observational datasets for Malawi's climate at sufficient spatial resolution, and where data does exist there can be discrepancies (Nikulin et al., 2012; Dosio et al., 2015). This limitation is predominantly due to insufficient gauge stations and varied data management techniques; however, it is slightly improved by the introduction of data from satellite measurements (ibid.). While uncertainty exists, studies by Diallo et al. (2014) and Zhang et al. (2013) have shown that there is a good level of agreement between the main datasets over the African region. Therefore, where more than one observed dataset was available, an average was used for comparison purposes and the range of observed data is shown in all temporal assessments. It is acknowledged that the accuracy of the observed data will have an impact on the results of this study and as such is a potential source of error. All the observed data sets used in this study are listed in Table 2.1.

Table 2.1: Observed Data

Dataset	Variable Used	Resolution	Time-Period Available	Source	Reference
Climate Research Unit (CRU) version 4.0	Tas, TasMax and TasMin	0.5° Monthly Land Only	1901-2015	Gridded Station Data	(Harris et al., 2014)
	Pr				
University of Delaware (UDel) version 4.01	Tas	0.5° Monthly Land Only	1901-2010	Gridded Station Data	(Willmott and Matsuura, 2001)
	Pr				
Global Precipitation Climatology Centre (GPCC) version 7	Pr	1.0° Monthly	1901-2010	Satellite and Station Data	(Schneider et al., 2015)

2.3.2. Description of Reanalysed and Simulated Regional Climate Models

Here, we make use of data extracts from RCMs produced by many different groups within the Coordinated Regional Climate Downscaling Experiment (CORDEX) initiative. The CORDEX initiative sets a standard grid, domain size, experiment protocols, and data format allowing for direct comparison of the model outputs (Giorgi et al., 2009; Nikulin et al., 2012). Within this framework, only models which were publicly available and provided projections for both Representative Concentration Pathways (RCPs) 4.5 and 8.5 were selected as these are deemed the most useful for further research on future climate change vulnerability and responses. All the RCMs are atmospheric models produced within the defined CORDEX-Africa domain, they provide data on a monthly time scale, and have a 0.44-degree (approximately 50km^2) resolution. All of the models other than CanRCM4_r2 were accessed through The Earth System Grid Federation (ESGF) data index (ESGF, 2017). The CanRCM4_r2 model was accessed through the Canadian Centre for Climate Modelling and Analysis website (CCCma, 2017a).

To better understand the source of any biases within the models, comparisons are made with both RCMs which use GCMs to set their lateral boundary conditions (GCM-driven RCMs) and ERA-interim driven RCMs (ERAINT) which are reanalysed to use observed data for lateral boundary conditions. All the simulated and reanalysed regional models used in this study are listed in Table 2.2 along with the institutions which built them, the conditions which set the lateral boundaries, and the source reference.

Table 2.2: Reanalysed (ERA-interim driven) and Simulated (GCM-driven) Regional Climate Models (RCMs)

RCM	Institution	Lateral Boundary Conditions	Reference
CCLM4-8-17_v1	Climate Limited-area Modelling Community (CLMcom)	ERA-interim	(COSMO, 2017)
		CNRM-CM5 r1i1p1	
		HadGEM2-ES r1i1p1	
		EC-EARTH r12i1p1	
		MPI-ESM-LR r1i1p1	
HIRHAM5_v2	Danmarks Meteorologiske Insitut (DMI)	ERA-interim	(Christensen et al., 2007)
		EC-EARTH r3i1p1	
		NORESM1-M r1i1p1	
RACMO22T_v1	Koninklijk Nederlands Meteorologisch Instituut (KNMI)	ERA-interim	(van Meijgaard et al., 2008)
		HadGEM2-ES r1i1p1	
		EC-EARTH r12i1p1	
RCA4_v1	Sveriges Meteorologiska och Hydrologiska Institut (SMHI)	ERA-interim	(Samuelsson et al., 2015)
		CanESM2 r1i1p1	
		CNRM-CM5 r1i1p1	
		CSIRO-MK3-6-0 r1i1p1	
		GFDL-ESM2M r1i1p1	
		IPSL-CM5A-MR r1i1p1	
		HadGEM2-ES r1i1p1	
		EC-EARTH r12i1p1	
		MIROC5 r1i1p1	
		MPI-ESM-LR r1i1p1	
		NORESM1-M r1i1p1	
REMO2009_v1	Climate Service Centre Germany (CSC) and Max Planck Institut (MPI)	ERA-interim	(Jacob et al., 2012)
		EC-EARTH r12i1p1	
		MPI-ESM-LR r1i1p1	
CanRCM4_r2	Canadian Centre for Climate Modelling and Analysis (CCCma)	ERA-interim	(Scinocca et al., 2016)
		CanESM2 r1i1p1	

2.3.3. Description of Reanalysed and Simulated Global Climate Models

To allow for a fair comparison, we make use of data extracts from the eleven GCMs which are used to form the lateral boundary conditions in the CORDEX RCM models listed in Table 2.2. These models are part of the Fifth Phase of the Coupled Model Intercomparison Project (CMIP5) and the details of these models are found in Table 2.3. All the GCMs are coupled atmospheric-ocean models running historical projections with all forcings being time variable. All the GCM models have monthly data for the atmospheric realm. The resolution of each model is different and listed in Table 2.3 as the distance between adjacent grid points in degrees. The longitudinal resolution is consistent over the whole globe, however the latitudinal resolution listed is that for the equator, and some deviation will exist for high latitudes (ENES, 2016).

Table 2.3: Simulated General Circulation Models (GCMs)

GCM	**Institution**	**Ensemble**	**Resolution**		**Reference**
			Latitude	Longitude	
CanESM2	Canadian Centre for Climate Modelling and Analysis (CCCma)	r1i1p1	2.7906	2.8125	(CCCma, 2017b)
CNRM-CM5	Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique (CERFACS)	r1i1p1	1.40008	1.40625	(Voldoire et al., 2013)
CSIRO-MK3-6-0	Commonwealth Scientific and Industrial Research Organisation (CSIRO)	r1i1p1	1.8653	1.875	(Jeffrey et al., 2013)
EC-EARTH	Sveriges Meteorologiska och Hydrologiska Institut (SMHI)	r12i1p1	1.1215	1.125	(Hazeleger et al., 2010)
	Danmarks Meteorologiske Insitut (DMI)	r3i1p1			
GFDL-ESM2M	National Oceanic and Atmospheric Administration (NOAA)	r1i1p1	2.0225	2.5	(Dunne et al., 2012; Dunne et al., 2013)
HadGEM2-ES	Met Office Hadley Centre	r1i1p1	1.25	1.875	(Collins et al., 2011)
IPSL-CM5A-MR	Institut Pierre Simon Laplace (IPSL)	r1i1p1	1.2676	2.5	(Dufresne et al., 2013)
MIROC5	Atmospheric and Ocean Research Institute (AORI)	r1i1p1	1.4008	1.40625	(Watanabe et al., 2010)
MPI-ESM-LR	Max Planck Institute for Meteorology (MPI)	r1i1p1	1.8653	1.875	(Giorgetta et al., 2013)
NORESM1-M	EarthClim	r1i1p1	1.8947	2.5	(Bentsen et al., 2013; Iversen et al., 2013)

The CanESM2 model was accessed through the Canadian Centre for Climate Modelling and Analysis website (CCCma, 2017a). CNRM-CM5, HadGEM2-ES, IPSL-CM5A-MR, MIROC5 and MPI-ESM-LR were all accessed through The Earth System Grid Federation (ESGF) data index (ESGF, 2017). CSIRO-MK3, EC-EARTH r12i1p1 and NORESM1-M were accessed via the Centre for Environmental Data Analysis

(CEDA) data catalogue (CEDA, 2017). EC-EARTH r3i1p1 was downloaded directly from the Danmarks Meteorologiske Insitut (DMI) servers upon request (DMI, 2016).

2.3.4. Description of Experimental Design

Analysis of the results was performed using a Python interface. Within the interface, the numerical mathematics and graphical plotting were produced using a variety of open-source Python libraries and packages. The code used for each assessment can be found in the author's GitHub repository[7].

The analysis is limited to the time-period in which all the observed data and models overlap. Therefore, the GCM-driven RCMs and GCMs are assessed against observed data over the period of 1961-2005 and the ERA-interim driven RCMs are assessed against observed data over the period of 1990-2008. For the purposes of comparison of relative performance, where all three of the model groups are assessed together and the data are compressed temporally, all data are assessed against observed data over the largest overlapping time-period, 1990-2005.

As the data are associated with 3 dimensions (latitude, longitude, and time), it was necessary to compress them on at least one variable for assessment. Therefore, the assessment has been carried out with the same data over both spatial and temporal scales, where the temporal or spatial variable(s) have been compressed respectively. The model outputs were assessed for annual and seasonal changes and compared with the available observed data sets. The seasons are summer (December, January, February – DJF), autumn (March, April, May – MAM), winter (June, July, August – JJA), and spring (September, October, November – SON). Where more than one observed dataset was available an average of the data was taken. The models were assessed individually, and multi-model average or ensembles of the ERA-interim driven RCM outputs, the GCM-driven RCM outputs, and GCM outputs were also assessed.

While the ERA-interim and GCM-driven RCMs are all in the same resolution, the observed data and GCMs have differing resolutions. To accommodate the differing resolutions, the data in all the models needed to be regridded to match the lowest resolution dataset. For spatial assessment, the models were regridded based on their group, therefore for the ERA-interim driven and GCM-driven RCM spatial assessments, the observed data were regridded to match the ERA-interim and GCM-driven RCM models respectively, which all have the same resolution. For the GCM spatial assessments, all the GCM models and the observed data were regridded to match the GCM model with the lowest resolution (CanESM2). For temporal assessments, all the models and observed data were regridded to match the model with the lowest resolution (GCM CanESM2). Due to this low resolution, and the limitation of using a rectangular boundary, the temporal assessment includes spatial data that are larger than the actual country boundary, as shown in Figure 2.1a. Figure 2.1b also shows the elevation in Malawi, which is useful for understanding some of the results of this research. The elevation map was created using data from the Joint Institute for the Study of the Atmosphere and Ocean (JISAO, 2014).

Spatial assessment was carried out by compressing the data over the previously stated timeframes and plotting both the absolute values and the bias compared to the observed data on a map. Maps were created for each variable in every season and over time. This analysis highlighted the

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[7] Erika Warnatzsch GitHub directory: https://github.com/ErikaWarnatzsch/Malawi-Historical-Climate-Modelling-Assessment

geographical differences in the climatic variables and which areas of the country had higher or lower levels of bias in the model simulations.

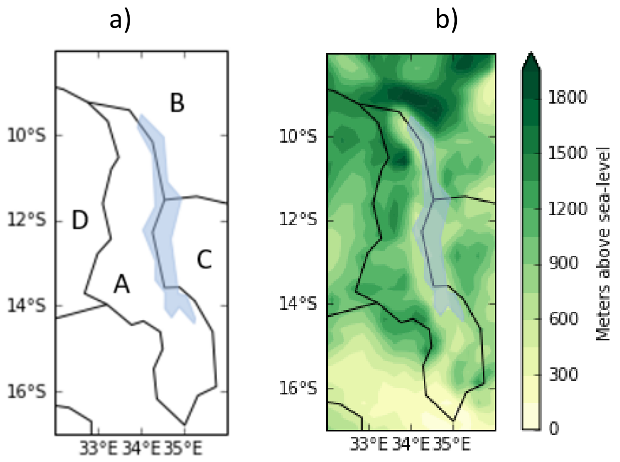

Figure 2.1: Assessment boundary and elevation.
Map a) shows the data boundary used in this assessment. Black lines show national borders and the shaded grey-blue area is Lake Malawi. Letters on the map represent different countries; A – Malawi, B – Tanzania, C – Mozambique, and D – Zambia. Map b) shows elevation data for Malawi in meters above sea-level at a 0.25-degree (approximately 27km2) resolution.

The temporal assessment was carried out by compressing the data over the previously stated latitude and longitude and plotting it over the relevant time-period (e.g., the line graphs showing the model outputs over the 1961-2005 period). This was done by month for all years in the stated time-period, and by year for each season and overall. To assess the data statistically, the spatially-averaged data were assessed using Taylor Diagrams (Taylor, 2001). These provide a succinct statistical analysis of the degree of pattern correspondence between the modelled data and observed data in terms of their Pearson's correlation (shown on the azimuthal angle), root-mean-square error (shown by the internal contours around the 'observed' point), and ratio of their variances (shown on the x-axis). Since its creation, the Taylor Diagram has become a popular and useful tool in the evaluation of climate models (Gleckler et al., 2008; Kim et al., 2014; Loikith et al., 2015).

To determine how well the models were able to replicate droughts, monthly outputs for 1961-2005 were analysed to determine how many months showed precipitation levels that were 1.5 and 2 standard deviations away from the model's own 1971-2000 mean for the same month. This exercise was also carried out for the observed data sets for comparison. The results were then compared with known droughts years from literature (Masih et al., 2014; Pauw et al., 2010) and the number of false positives, false negatives and matches were determined. This methodology is in line with the Standardized Precipitation Index (SPI) (Keyantash, 2018), which is a commonly used to assess drought occurrence (for example Shah et al. (2015), Okpara et al. (2017), and Meroni et al. (2017)).

2.4. Results

2.4.1. Precipitation

As summarized in Table 2.4, the observed data for the period 1961-2005 indicate that Malawi had higher levels of precipitation in the summer months (November – March) with an average of over 225mm in January. In the winter months, precipitation rates dropped drastically, to less than 12mm per month in June – September. The Northern Region, and the western most districts of the Southern Region of the country, received higher levels of precipitation than other areas. Between 1961 and 2005 the country has seen a slight decrease in precipitation levels every decade, from an average of 1140.8mm in 1961-1970 to 1042.4mm in 1991-2000. The annual precipitation varies greatly from year to year (standard deviation 110.9), for example 1989 saw 1317.8mm of precipitation while the next year only received 939.1mm, a drop of almost a third.

Table 2.4: Observed average monthly precipitation in Malawi from 1961 to 2005 (mm per month)

J	F	M	A	M	J	J	A	S	O	N	D
229.3	191.1	186.6	98.2	26.0	11.0	10.3	6.7	6.1	17.7	75.8	178.1

Figure 2.2 shows that the ensemble GCM simulation slightly overestimated precipitation overall (average of +7 percent between 1961 and 2005) and in all seasons except autumn (MAM) which showed an underestimation. Alternatively, the ensemble GCM-driven RCM simulation underestimated precipitation in all seasons (average of -10 percent between 1961 and 2005) except spring (SON), which showed an overestimation. The ensemble ERA-interim driven RCM output underestimated precipitation in all seasons by an average of -34 percent between 1990 and 2005. All the ensembles preformed best in the dry season (May-September).

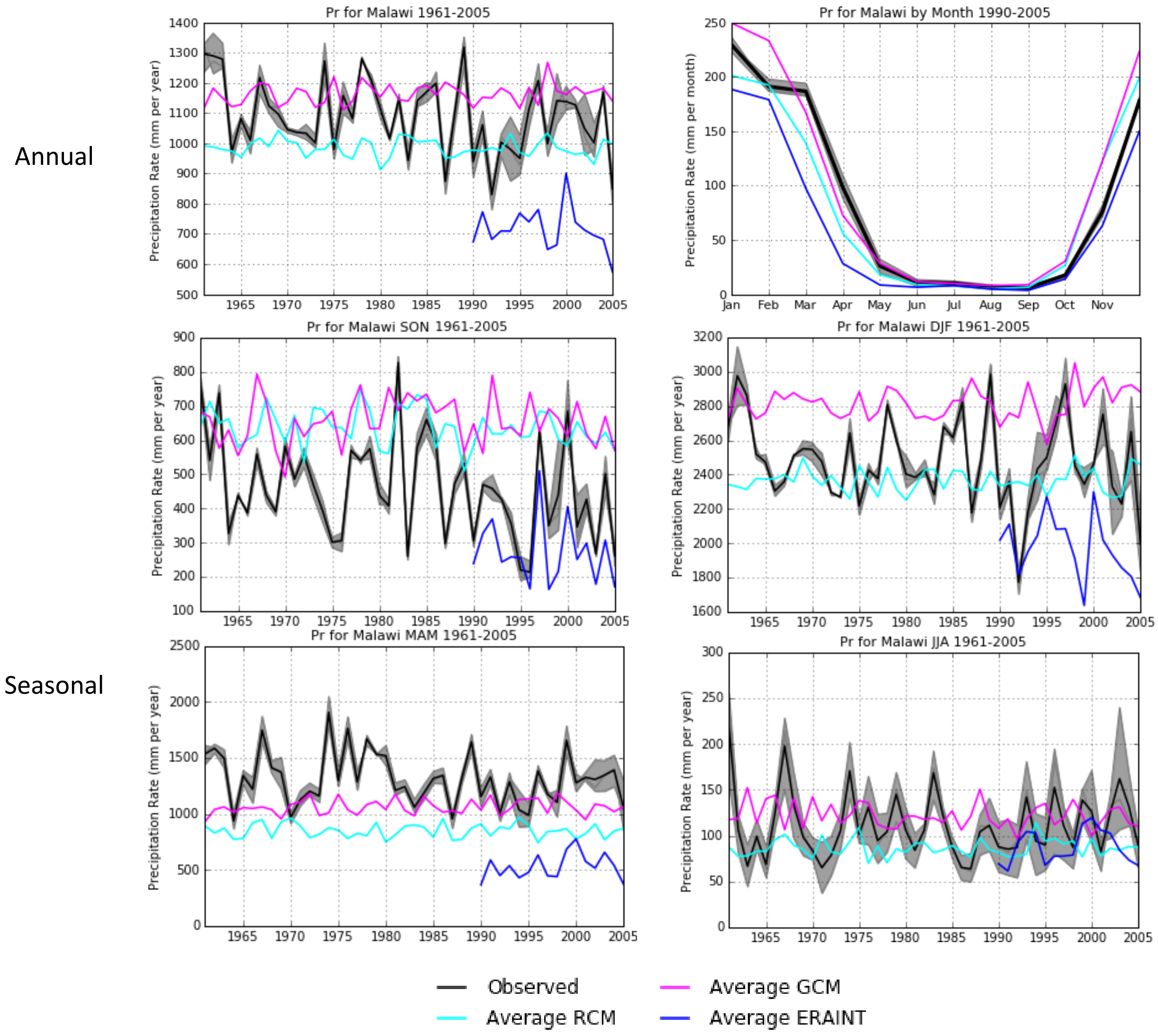

Figure 2.2: Average observed and simulated annual, seasonal, and monthly precipitation in Malawi for 1961-2005 and 1990-2005 respectively.

The grey area represents the range of observed data.

While most of the model outputs were clustered together, one GCM-driven RCM (HIRHAM5_NorESM1-M) was an outlier, greatly underestimating the precipitation in most seasons, particularly the wet season (October-April) (see blue dotted line in Figure 2.3). With this outlier removed the annual ensemble GCM-driven RCM simulation for 1961-2005 comes to within 6 percent of the average observed data trend over the same period, however the correlation is still low.

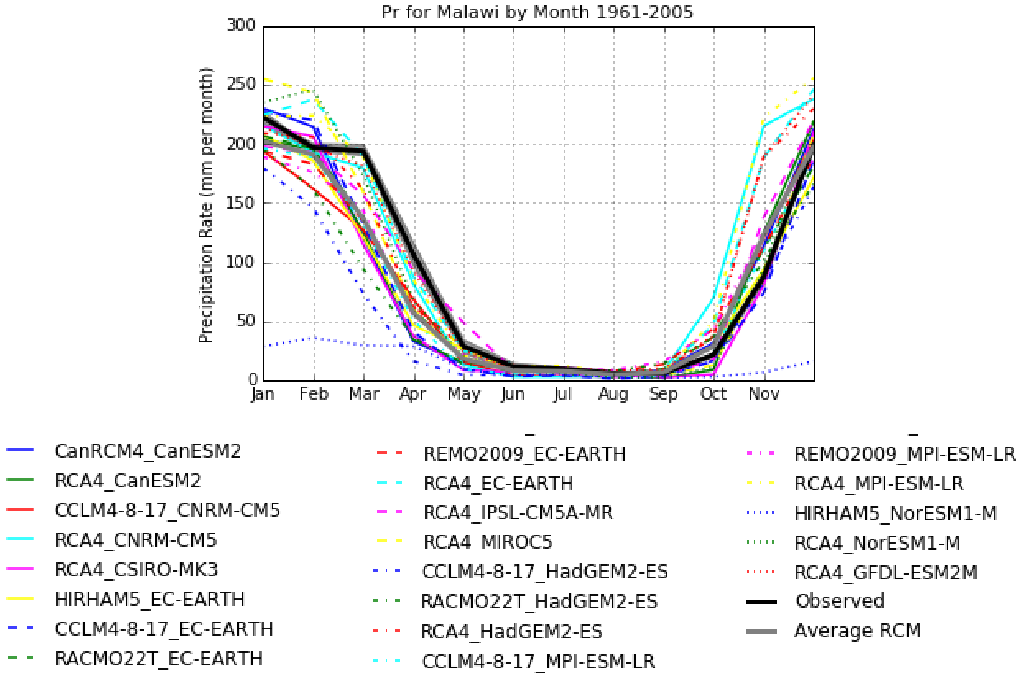

Figure 2.3: Individual and average ensemble GCM-driven RCMs run for average monthly precipitation in Malawi from 1961-2005.

The grey area represents the range of the observed data.

All of the models are able to replicate the seasonal trend in precipitation (i.e. wetter summers and drier winters), however neither the GCM or the GCM-driven RCM simulations replicate the scale of the downward trend in precipitation levels that the observed data show over this period; the trendline associated with the observed data over the period of 1961-2005 has a slope of -2.74mm y^{-1} while the ensemble GCM-driven RCM simulation's trend shows a less steep slope of -0.19mm y^{-1}, and the ensemble GCM shows an increasing trend with a slope of +0.47mm y^{-1}over the same period. Table 2.5 and Table 2.6 show the regression slopes for the observed and individual modelled precipitation rates.

Table 2.5: Regression slope of Precipitation Rate for observed and ERA-interim driven RCMs in Malawi between 1990 and 2008

Dataset	Annual	DJF	MAM	JJA	SON
Observed	5.13	13.83	3.47	0.31	2.80
CCLM4-8-17_v1 ERA-interim	4.12	12.24	4.47	0.14	-0.37
HIRHAM5_v2 ERA-interim	-3.37	-8.14	0.39	-0.38	-5.37
RACMO22T_v1 ERA-interim	-0.50	-1.19	3.91	0.66	-5.36
RCA4_v1 ERA-interim	1.25	-0.51	6.80	-0.66	-0.64
REMO2009_v1 ERA-interim	-1.82	-4.53	-7.55	-0.55	5.34
CanRCM4_r2 ERA-interim	-2.77	-26.66	15.58	0.62	-0.60
Average ERA-Interim	-0.52	-4.80	3.93	-0.03	-1.16

Table 2.6: Regression slope of Precipitation Rate for observed data, GCM-driven RCMs and simulated GCMs in Malawi between 1961 and 2005

Dataset		Annual	DJF	MAM	JJA	SON
Observed		-2.74	-3.83	-3.95	-0.13	-3.36
GCM-driven RCM	CCLM4-8-17_v1 CNRM-CM5 r1i1p1	0.92	2.16	1.03	0.35	0.16
	CCLM4-8-17_v1 HadGEM2-ES r1i1p1	-0.26	-1.34	1.62	0.40	-1.70
	CCLM4-8-17_v1 EC-EARTH r12i1p1	1.27	3.91	0.87	-0.02	0.33
	CCLM4-8-17_v1 MPI-ESM-LR r1i1p1	-0.55	1.45	-1.53	-0.13	-1.99
	HIRHAM5_v2 EC-EARTH r3i1p1	-0.72	-2.09	-0.46	0.12	-0.47
	HIRHAM5_v2 NORESM1-M r1i1p1	0.02	1.36	-0.41	0.36	-1.21
	RACMO22T_v1 HadGEM2-ES r1i1p1	-0.05	2.57	-1.34	0.31	-1.72
	RACMO22T_v1 EC-EARTH r12i1p1	0.96	2.35	1.37	0.23	-0.12
	RCA4_v1 CanESM2 r1i1p1	-1.19	0.44	-2.93	0.24	-2.49
	RCA4_v1 CNRM-CM5 r1i1p1	1.05	3.68	-0.50	0.49	0.54
	RCA4_v1 CSIRO-MK3-6-0 r1i1p1	0.22	-0.64	0.67	-0.26	1.10
	RCA4_v1 GFDL-ESM2M r1i1p1	-0.96	-1.87	-0.81	-0.26	-0.89
	RCA4_v1 IPSL-CM5A-MR r1i1p1	0.21	2.49	-0.40	-0.25	-1.01
	RCA4_v1 HadGEM2-ES r1i1p1	0.49	1.73	0.06	-0.18	0.33
	RCA4_v1 EC-EARTH r12i1p1	0.89	3.03	-2.06	0.59	2.00
	RCA4_v1 MIROC5 r1i1p1	-2.92	-5.77	-1.01	-0.54	-4.37
	RCA4_v1 MPI-ESM-LR r1i1p1	-3.12	-2.07	-4.59	-0.44	-5.37
	RCA4_v1 NORESM1-M r1i1p1	-0.47	-1.77	1.99	0.43	-2.52
	REMO2009_v1 EC-EARTH r12i1p1	-0.38	-0.49	-0.79	0.03	-0.26
	REMO2009_v1 MPI-ESM-LR r1i1p1	1.37	0.74	3.73	0.05	0.96
	CanRCM4_r2 CanESM2 r1i1p1	-0.84	-1.23	-1.23	-0.38	-0.53
	Average RCM	-0.19	0.41	-0.32	0.06	-0.92
GCM	CanESM2 r1i1p1	0.67	1.87	1.88	-0.24	-0.81
	CNRM-CM5 r1i1p1	3.36	2.52	6.35	0.49	4.10
	CSIRO-MK3-6-0 r1i1p1	-0.58	-4.19	2.20	-0.27	-0.04
	EC-EARTH r12i1p1	0.47	1.89	0.82	0.21	-1.05
	EC-EARTH r3i1p1	2.26	6.69	0.28	-0.06	2.12
	GFDL-ESM2M r1i1p1	1.85	7.17	0.89	-1.23	0.57
	HadGEM2-ES r1i1p1	-0.83	-0.47	-2.32	-0.48	2.17
	IPSL-CM5A-MR r1i1p1	-1.28	-2.90	-2.95	0.19	0.56
	MIROC5 r1i1p1	-3.39	-4.63	-4.87	-1.12	-2.94
	MPI-ESM-LR r1i1p1	-0.33	-0.80	1.22	-0.23	-1.49
	NORESM1-M r1i1p1	2.91	6.62	5.69	0.25	-0.91
	Average GCM	0.47	1.25	0.83	-0.23	0.21

The scale of precipitation is not well represented by the ensemble ERA-interim driven RCM, but these models do better at representing variations in extremes from year to year. Both the simulated GCMs and GCM-driven RCMs show much less inter-annual fluctuation, although are on average within the normal range of precipitation for Malawi. The lower inter-annual fluctuations found in the models compared to the observed data, and the lack of correlation between the datasets is supported by the relatively lower standard deviations and low Pearson's Correlation Coefficients shown in Figure 2.4 for the GCM-driven RCM and GCM simulations. None of the individual GCM-driven RCMs or GCMs have a correlation with the observed data greater than +/- 0.57. While the correlations for the ERA-interim driven RCMs are higher, they are still, on average, low overall, and for the summer and winter months in particular. Correlation of the precipitation output of the ERA-interim driven RCMs is relatively good for spring and autumn.

The bias of the models is not equally distributed spatially across the country. The maps shown in Figure 2.5 demonstrate this bias for the average simulations in each group annually and by season. Areas of higher bias can be seen particularly in the ensemble ERA-interim driven RCM and the ensemble GCM-driven RCM simulations in areas of higher altitude (see elevation map Figure 2.1b), particularly around the Shire Highlands in the south (approximately 15.5°S, 35°E); Kasungu National Park and Nyaka National Park, and the area in between in the north (approximately 10.5-12.5°S, 33-34°E); and the area between Dedza-Salima Forest Reserve and the Mozambique border in the centre (approximately 14.5°S, 34°E). The amount of precipitation tends to be overestimated in these areas of higher altitude, while a bias towards underestimating the precipitation is seen around the boundary of Lake Malawi. Getting detail on the spatial distribution of these biases is difficult with the GCMs owing to the relatively low resolution.

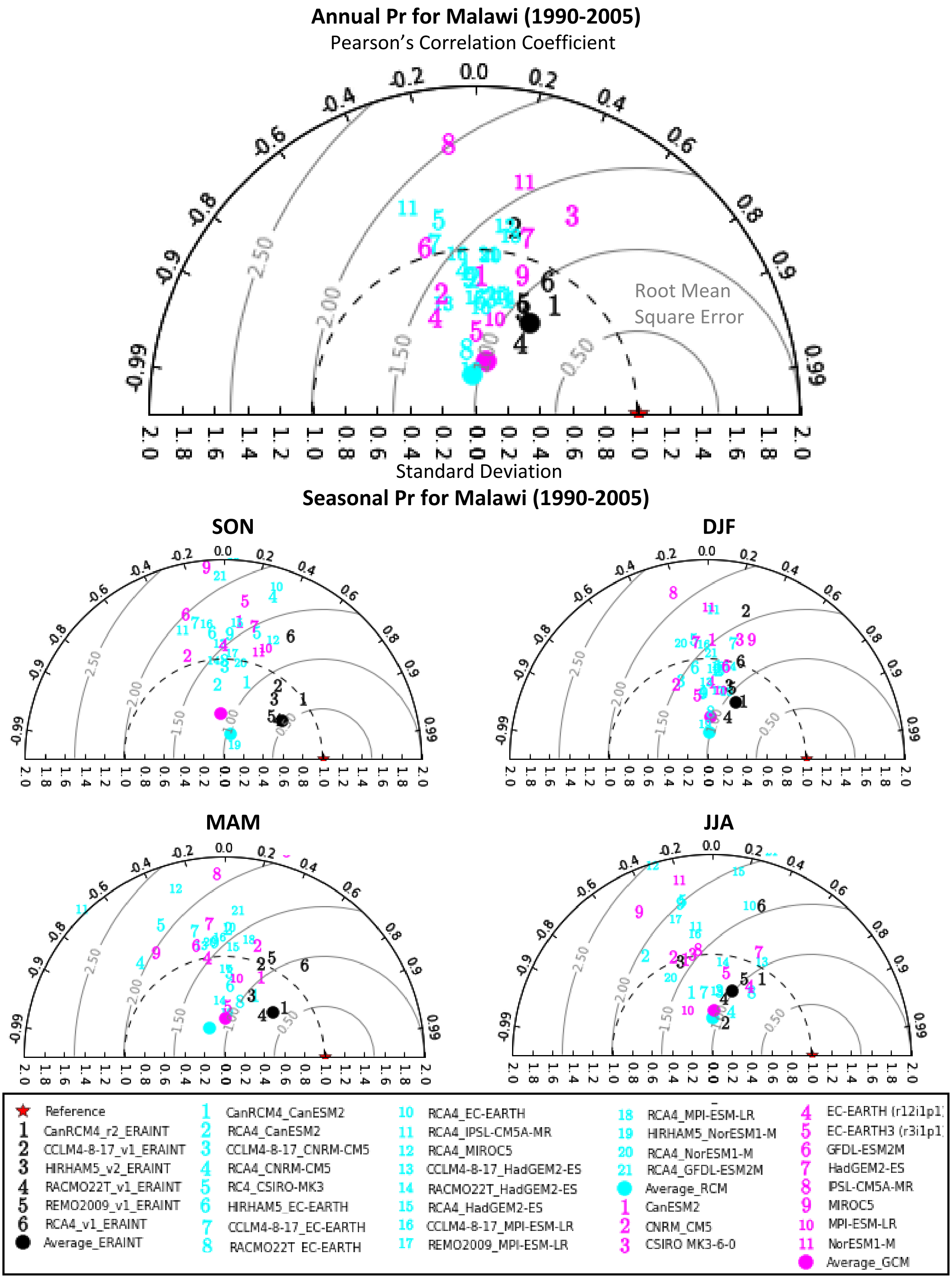

Figure 2.4: Taylor diagrams showing annual and seasonal precipitation for Malawi from 1990-2005. *The red star denotes the observed data for the relevant period, and the individual ERA-interim driven RCMs, GCM-driven RCMs, and GCMs are denoted by black, cyan, and magenta numbers respectively. The ensemble of each group is shown by a circle in the same colour. The Pearson's correlation is shown on the azimuthal angle, the RMS error is shown in the grey contour lines centred around the reference point (red star), and the standard deviation is shown along the x-axis.*

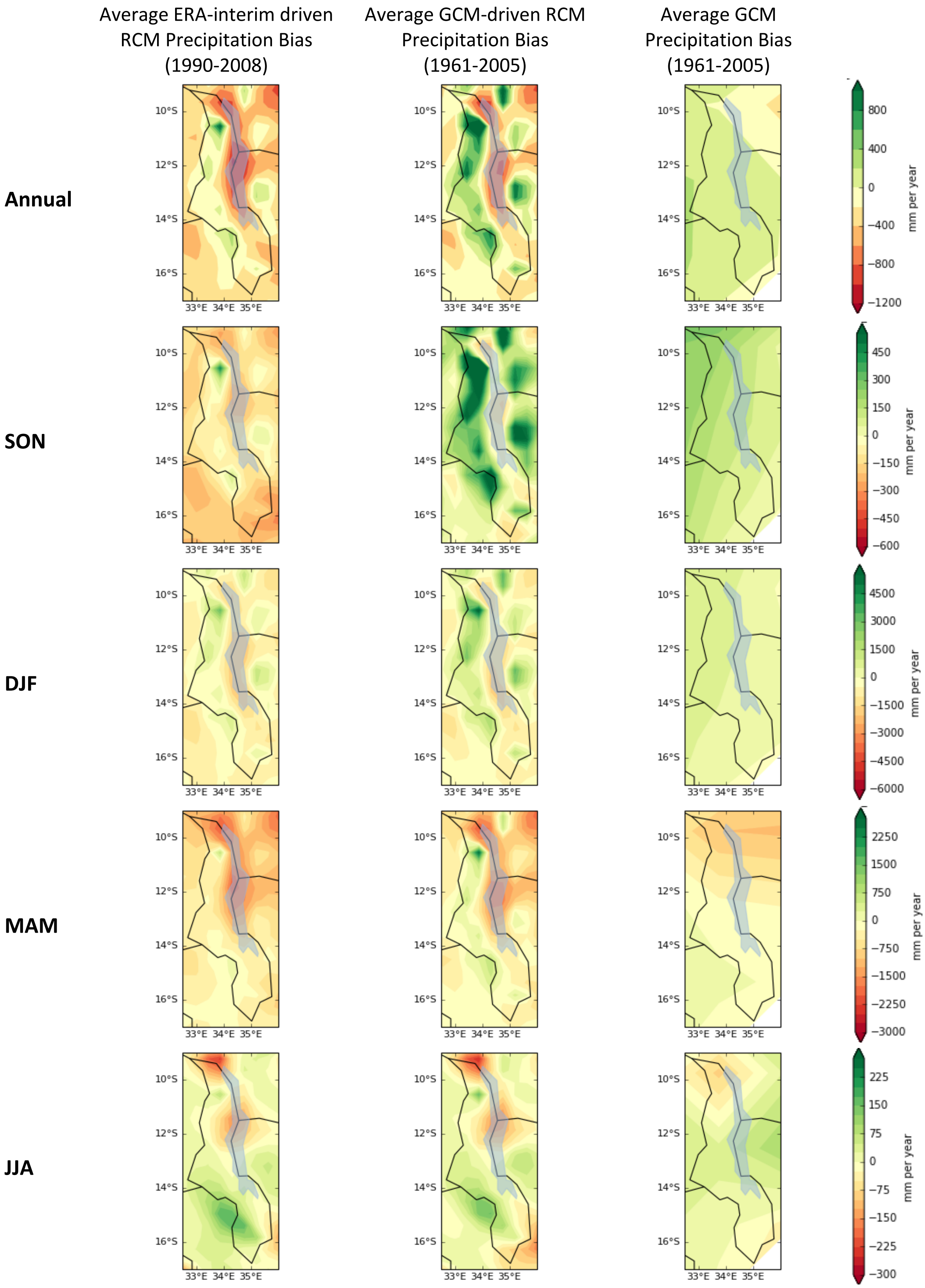

Figure 2.5: Average group simulated bias in Malawi's precipitation annually and by season relative to observed data.

The graphs in the left-hand column are for the time-period of 1990-2005 while those in the central and right column are for 1961-2005. Please note that the colour bar is different for each season and annually.

2.4.2. Droughts

According to the literature, within our assessment period of 1961-2005, severe droughts occurred in Malawi in five calendar years: 1987, 1990, 1992, 2002 and 2005, and five maize crop seasons (November – April): 1986/7, 1991/2, 1993/4. 2003/4 and 2004/5 (Pauw et al., 2010; Masih et al., 2014). Using the SPI method with a standard deviation of 1.5 from the 1971-2000 mean led to far more drought signals occurring in calendar years within the observed datasets (17) as well as most of the RCMs (3-23, average of 13.62; ensemble RCM: 26), and all the GCMs (8-21, average of 15.36; ensemble GCM: 21). This drought bias was also seen when assessing the same data over the maize crop season using a 1.5 standard deviation definition, with 12 drought signals in the observed data, the RCMs showing 2-17 drought signals (average: 10.48; ensemble RCM: 15), and the GCMs showing 8-16 drought signals (average 12.09; ensemble GCM: 12). Using the SPI method with a standard deviation of 2 from the 1971-2000 mean brought the results closer to reality with the observed data sets over a calendar year showing 3 droughts, the RCMs showing 0-7 (average of 2.7l; ensemble RCM: 6) and the GCMs showing 1-6 (average of 3.18; ensemble GCM: 2). Similarly, over the maize crop season, the observed datasets again showed 3 drought signals, the RCMs show 0-6 (average 2.38; ensemble RCM: 4), and the GCMs show 1-4 (average 2.27; GCM ensemble: 2). While the 2 standard deviation definition did not pick up all droughts in the observed dataset, the three which it did signal corresponded to crop seasons where droughts actually occurred (1991/2, 1993/4, 2004/5), and two of the three signalled calendar years with droughts (1992, 2005). The annual precipitation levels in 1987, 1990 and 2002 were 1.7, 1.2 and 0.3 standard deviations below the 1971-2000 mean. Most of the RCMs and GCMs were not able to show any matches with the actual drought years. For the RCMs, seven of the 21 individual models were able to correctly predict one or more drought years in the correct year, using the 2 standard deviation definition. Likewise, four of the individual RCM models were able to correctly predict one or more years of crop season drought using this definition. For GCMs, correct prediction was observed in six and seven of the 11 individual models for calendar year and crop season drought respectively.

2.4.3. Temperature

Table 2.7 summarizes the observed data sets over the period of 1961 to 2005 for mean, maximum and minimum surface temperature. Temperatures were highest in November and lowest in July. The largest difference between the daily maximum and daily minimum temperature was seen in September. Spatially, the temperature was relatively consistent across the country, with temperatures slightly higher in the Southern Region and on the boundary of Lake Malawi. Over the period of 1961 to 2005 a warming trend is seen in Malawi with the mean temperature increasing from an average of 22.0°C in 1961-1970 to 22.6 °C in 1991-2000.

Table 2.7: Observed monthly mean (Tas), maximum (TasMax) and minimum (TasMin) surface temperatures in Malawi from 1961 to 2005 (°C)

	J	F	M	A	M	J	J	A	S	O	N	D
Tas	23.7	23.7	23.5	22.6	20.9	19.1	18.7	20.1	22.4	24.4	24.7	24.0
TasMax	28.8	28.8	29.1	28.2	27.5	26.2	25.6	27.4	29.7	31.2	31.3	29.6
TasMin	19.4	19.4	19.1	17.7	15.5	13.2	12.4	13.8	15.9	18.1	19.5	19.5

The ensemble GCM-driven RCM and GCM simulations show a cool bias underestimating mean and maximum temperature in all seasons, sometimes by over 2°C, as seen in sections i and ii of Figure 2.6. While the ensemble GCM-driven RCM and GCM simulations also underestimate minimum temperature, the simulations are better, usually within 0.5 degrees of the observed data (see section iii of Figure 2.6). The ensemble ERA-interim driven RCM outputs for mean, maximum and minimum temperature are relatively good at recreating both the scale and the variability of temperature in all seasons, predominantly varying within less than 0.5°C of the observed data.

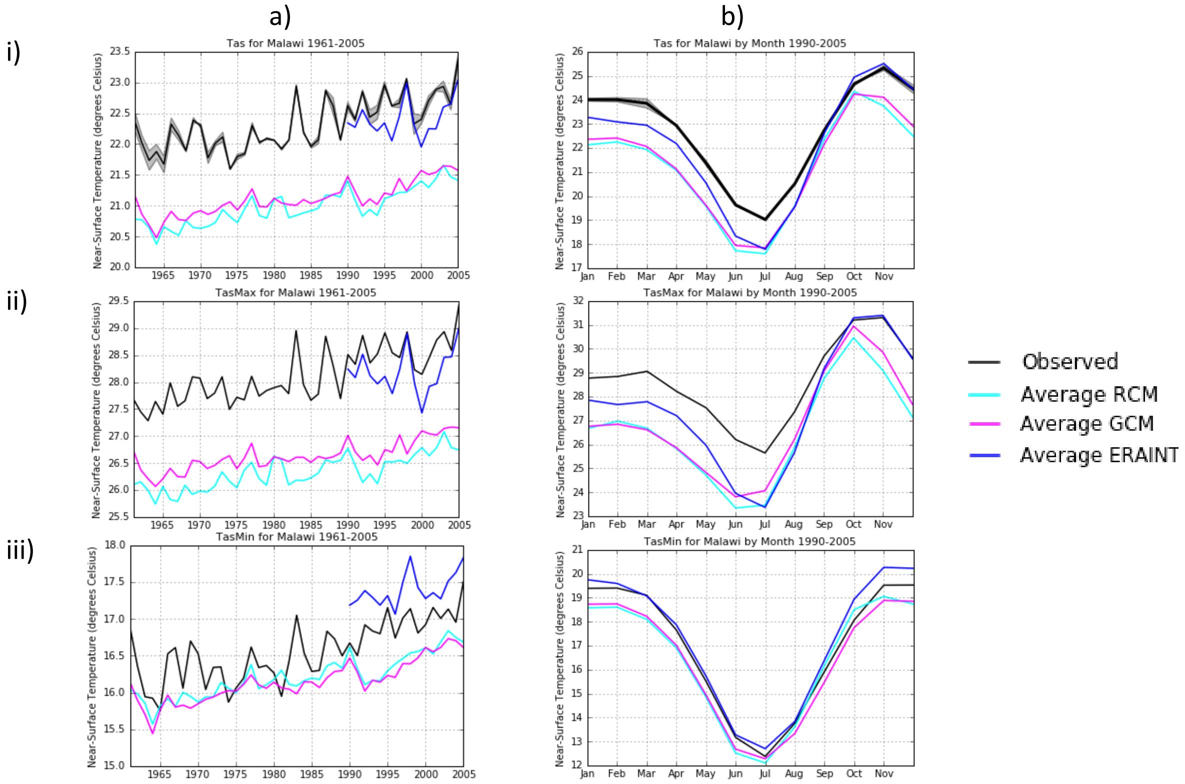

Figure 2.6: Average observed and simulated i) mean, ii) maximum and iii) minimum temperature in Malawi.

The graphs in column a) represent annual data and those in column b) monthly data for 1961-2005 and 1990-2005 respectively. The grey area represents the range of observed data.

Most of the model outputs were quite closely grouped together, however, like the precipitation simulations, one GCM-driven RCM simulation was an outlier for the temperature datasets; HIRHAM5_NorESM1-M greatly overestimated the mean, maximum and minimum temperature in all seasons. As the ensemble GCM-driven RCM simulation is already underestimating temperature, removing this outlier makes the bias even greater.

While the scale of the temperature output from the ensemble GCM-driven RCM and GCM simulations was underestimated, they were both able to replicate the rate of change seen in the observed datasets for mean and minimum temperature of approximately +0.02°C y^{-1} over the 1961-2005 period. The ensemble GCM-driven RCM and GCM simulations also replicated an upward trend in maximum temperature, however the models only showed an average increase of +0.02 °C y^{-1}over the 1961-2005 period, while the observed data indicate that this increase is occurring faster, at an average rate of +0.03 °C y^{-1}over the same period.

Similar to the precipitation results, the ERA-interim driven RCMs have a relatively high correlation with the observed datasets, while the GCM-driven RCMs and GCMs do not. Unlike the precipitation analysis. The standard deviations for the observed, reanalysed, and simulated datasets are similar. These statistics are shown graphically in Figure 2.7.

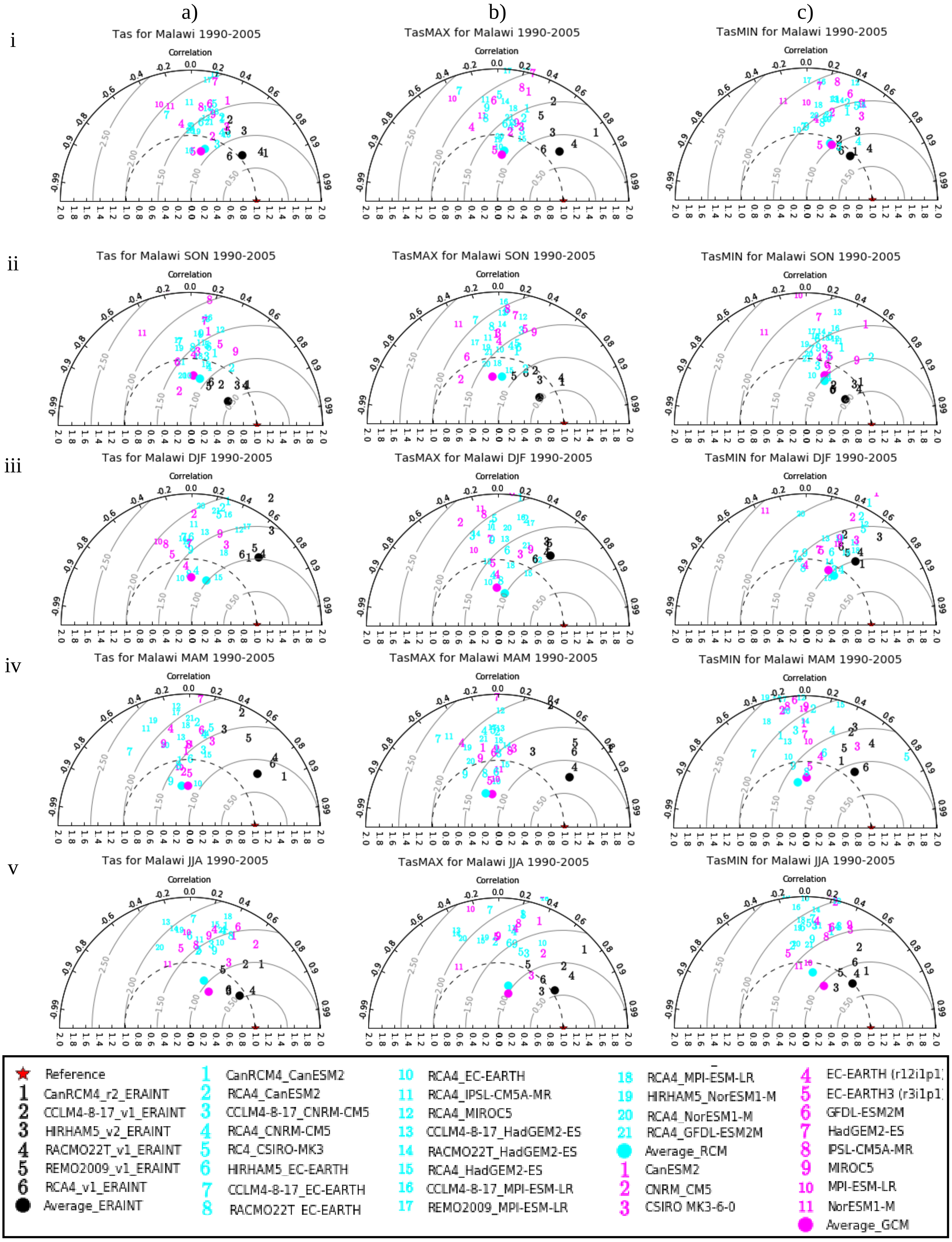

Figure 2.7: Taylor diagrams showing annual and seasonal temperatures for Malawi from 1990-2005. *Taylor diagrams showing annual (i) and seasonal (ii=SON, iii=DJF, iv=MAM, v=JJA) a) mean, b) maximum, and c) minimum temperature for Malawi from 1990-2005. The red star denotes the observed data for the relevant period, and the individual ERA-interim driven RCMs, GCM-driven RCMs, and GCMs are denoted by black, cyan, and magenta numbers respectively. The ensemble of each group is shown by a circle in the same colour. The Pearson's correlation is shown on the azimuthal angle, the RMS error is shown in the grey contour lines centred around the reference point (red star), and the standard deviation is shown along the x-axis.*

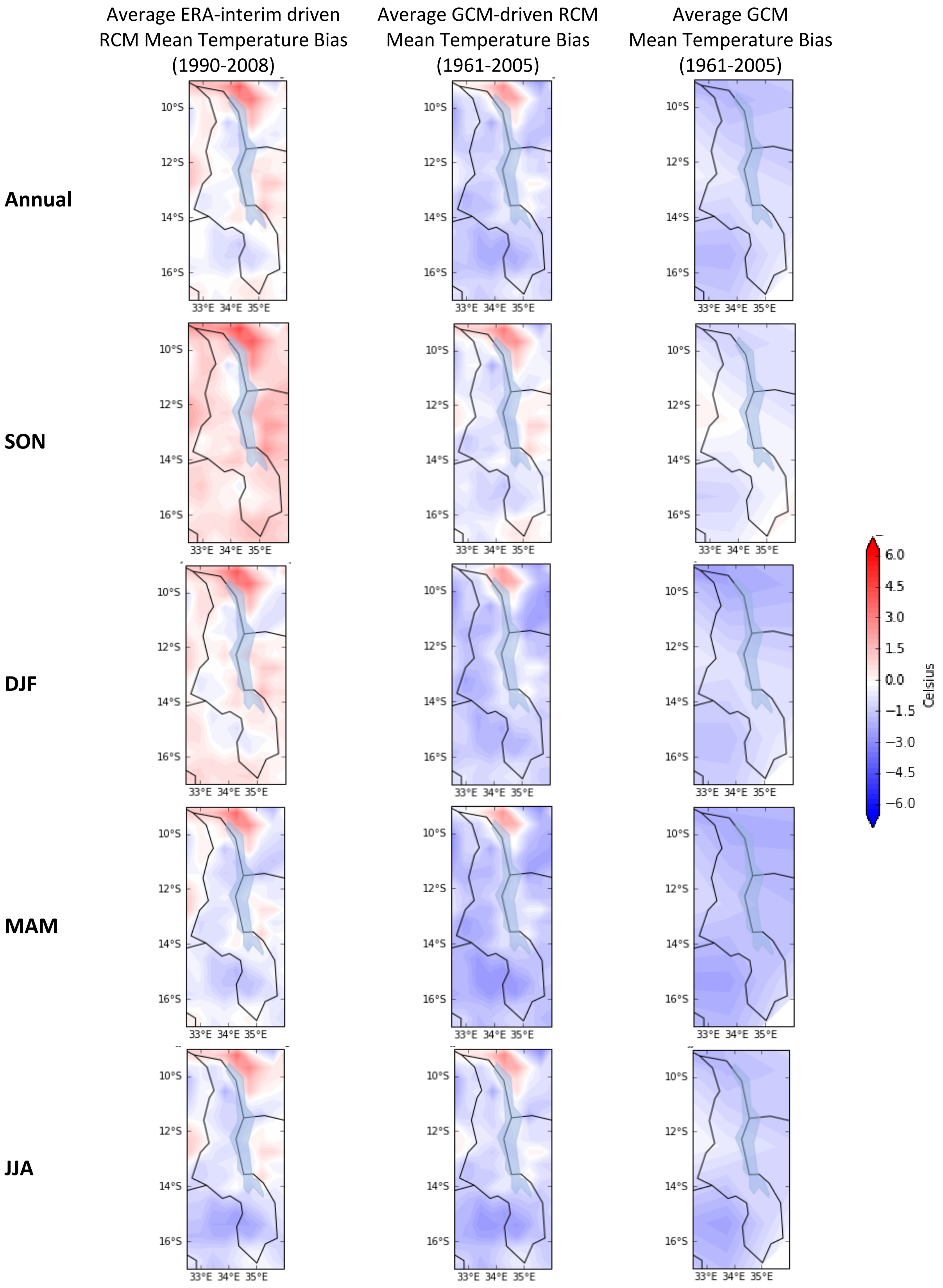

Figure 2.8: Average group simulated bias in Malawi's mean temperature annually and by season relative to observed data.

The graphs in the left-hand column are for the time-period of 1990-2005 while those in the central and right column are for 1961-2005

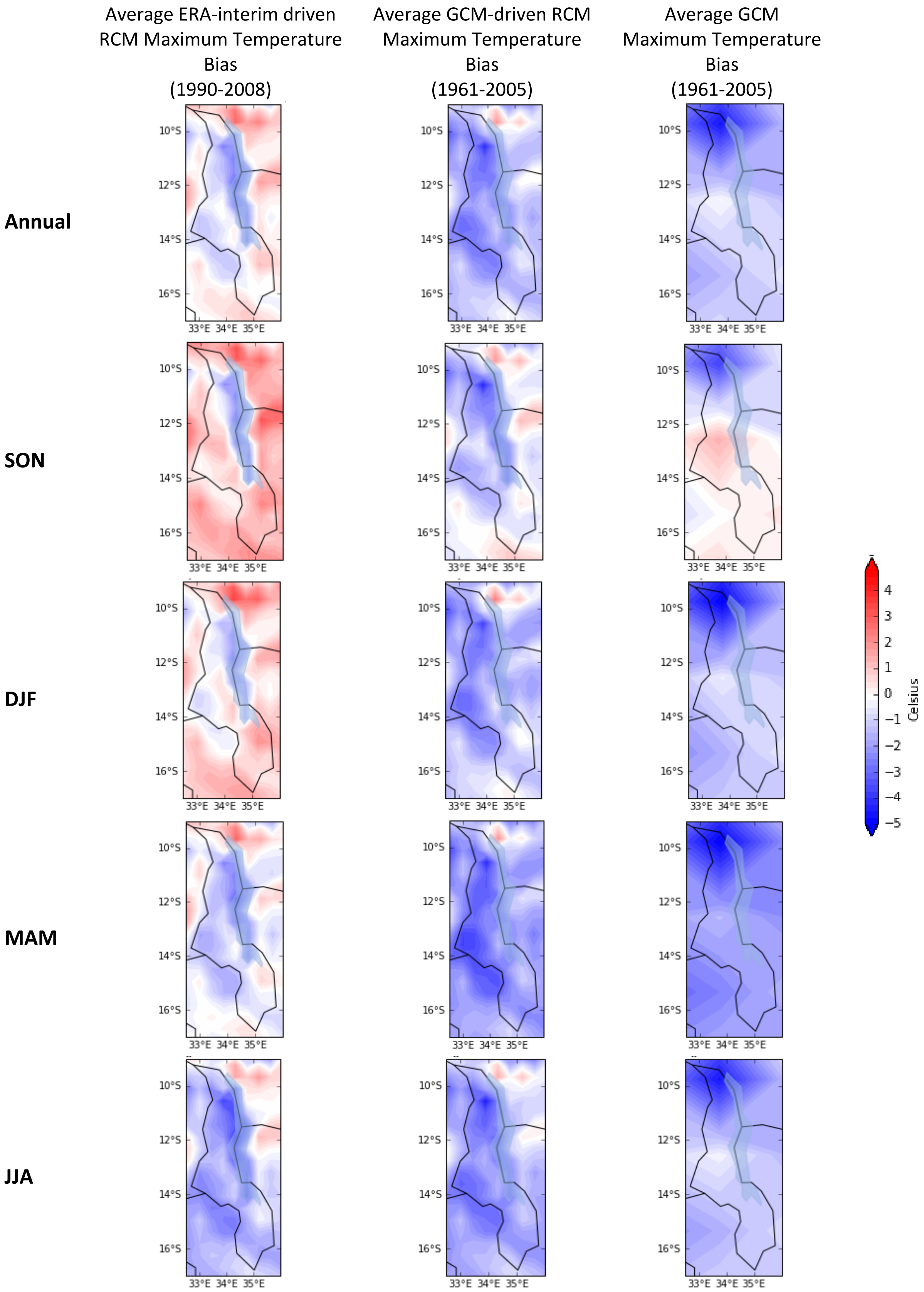

Figure 2.9: Average group simulated bias in Malawi's maximum temperature annually and by season relative to observed data.
The graphs in the left-hand column are for the time-period of 1990-2005 while those in the central and right column are for 1961-2005

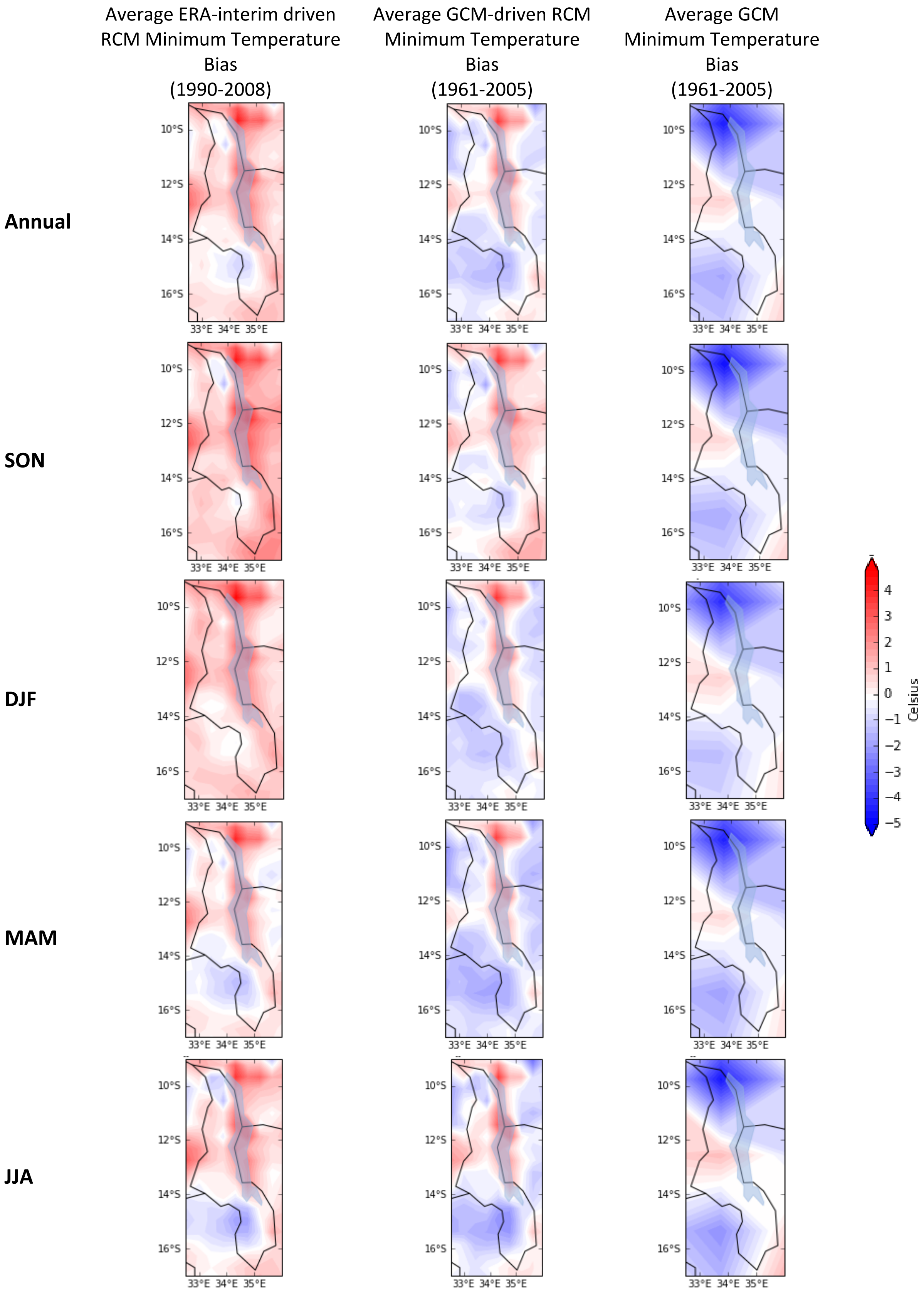

Figure 2.10: Average group simulated bias in Malawi's minimum temperature annually and by season relative to observed data.
The graphs in the left-hand column are for the time-period of 1990-2005 while those in the central and right column are for 1961-2005

Like the bias seen in the precipitation models, the largest temperature biases in the models were seen in areas of higher altitudes and around the boundary of Lake Malawi (see elevation map Figure 2.1b and Figure 2.8, Figure 2.9 and Figure 2.10 for mean, maximum and minimum temperature bias maps respectively). Overall, the direction of the bias (either cooler or warmer than the observed) was fairly consistent spatially in all seasons for the ensemble GCM-driven RCM simulations. The ensemble ERA-interim driven RCM outputs showed some spatial variation in the direction of the bias, particularly in summer. Again, getting detail on the spatial distribution of these biases is difficult with the GCM models owing to the relatively low resolution.

2.5. Discussion and Conclusions

Understanding the impact of climate change on Malawi's agricultural sector requires robust projections of a variety of factors, including precipitation and temperature, to design appropriate adaptation plans (Reddy, 2015). Domestically-grown rainfed maize is the main source of calories for the Malawian population (FAOSTAT, 2018), and those studies which have assessed maize crop models around the world for sensitivity to precipitation and temperature change have highlighted the importance of these climatic variables in determining future productivity and yield (Knox et al., 2012; Bassu et al., 2014; Zhang et al., 2015; Stevens and Madani, 2016). Notably, Challinor et al. (2016) found that a warming climate could lead to reduced crop durations for maize in SSA, with implications both for yields of current maize varieties and the traits likely to be required in new, more climate-resilient varieties.

Similarly, studies assessing the impact of climate change on Malawi's hydrological cycle, and in particular hydropower generation in the region, have also found temperature and precipitation to be key determinants (Kumambala and Ervine, 2010; Hamududu and Killingtveit, 2016). Changes in the timing and intensity of precipitation, together with enhanced evapotranspiration rates at higher temperatures, pose a potential risk to the commercial viability of current and planned hydropower installations, especially the run-of-river schemes common to Malawi (Kaunda and Mtalo, 2013; Kachaje et al., 2016). For example, the late rainy season and prolonged dry spells of 2015 reportedly reduced energy generation by two-thirds for hydroelectric plants on Malawi's Shire river (Sanje, 2015).

With the vast majority of the domestic energy in Malawi produced through hydropower (USAID, 2013) and the majority of the food supply, employment, and income depending on rain for irrigation (Minot, 2010; FAO, 2017; Giertz et al., 2015), it is important to understand the uncertainties around Malawi's climate modelling if these projections are to be successfully used in impact and adaptation planning.

Our analysis indicates that the boundary conditions greatly influence the performance of the RCMs. While the ERA-interim driven RCMs provide a reasonable correlation with the observed data for both precipitation and surface temperature (mean, maximum and minimum), the GCM-driven RCMs and GCMs do not. Furthermore, while the RCMs and GCMs do reasonably well at determining the frequency of drought events, particularly when assessing the data for the maize crop season only (roughly corresponds to wet season) rather than the whole calendar year, they do not do well at determining which years those droughts occur in. Therefore, these models, using the SPI method for drought, would have been less useful for predicting specific annual events or informing short-term adaptation responses over this historical period. For example, the 2005 drought is clearly visible in the observed data, with only 849.7mm of precipitation falling over the country (21% percent less than, and 2 standard deviations below the 1971-2000 average). While most of the ERA-interim driven RCM outputs, and the ensemble of these, do indicate a downturn in precipitation in that year, neither the ensemble GCM-driven RCM or ensemble GCM predict the severe drought that was experienced. It is worth noting that the observed precipitation datasets and inferred droughts (using the SPI method with a sensitivity of 2 standard deviations from the 1971-2000 baseline) did not match with all reported droughts in the study period. As such, it is possible that either the drought definition (2 standard deviations below the mean) or the chosen baseline for the SPI assessment are not always appropriate for defining a drought in Malawi. This also highlights the limitations of using the SPI method for drought impact assessment as droughts are not only caused by the absolute amounts of precipitation but also the timing of precipitation events, evapotranspiration rates and runoff (Trenberth et al., 2013).

In the last few decades, Malawi has experienced multiple severe droughts and flash flooding events which have had a significant impact on the country's overall development, including energy provision, infrastructure, and food security (Pauw et al., 2010; MRCS and IFRC, 2015). Over the last half century both the number and extent of floods and droughts have increased sharply (ActionAid, 2006). It will be important for Malawi to create adaptation plans to minimise the impact of future climatic shocks, but it is also important for planners to understand the limitations that climate models have for predicting the timing and frequency of these events, and the scale of the uncertainty around precipitation patterns more generally.

A lack of correlation between the models and the observed data is not a barrier to use in itself; climate models are not used to predict a specific weather event which may occur in any one year, but rather the trend in climatic change. Both the GCM-driven RCMs and GCMs recreate the trending change in the temperature variables with reasonable accuracy, however this is not true for precipitation where a clear signal is not seen. The projections for precipitation are highly divergent across the models assessed here. Furthermore, the scale of the simulation outputs shows a bias for all variables, to a lesser or greater degree. While this analysis can only state that this uncertainty exists for the simulations of the past, we suggest that this would also be true for future projections. As such, we find that these models, as they are, cannot easily be used to understand future changes in precipitation, but may have more utility for temperature projections, particularly if used for understanding the scale of change in temperature rather than absolute values.

Further improvements may come from better representation of topography and large climate-relevant features, such as Lake Malawi. Lake Malawi makes up over three-quarters of the eastern border and about one fifth of the country's total area (Eccles, 1974). The Great Rift Valley passes through the country from north to south causing elevations to rise from 37 meters above sea level where the Shire River meets the border of Mozambique, to 3003 meters above sea level at the peak of Mulanje Massif in the Shire Highlands (WorldAtlas, 2018). This diversity in Malawi's geography makes climate modelling difficult. When this heterogeneity is coupled with the relatively low resolution of the GCMs (used as is, or as boundary conditions in the RCMs), providing spatial analysis which would be useful on the scale of a local (e.g., <25km^2, UKCIP09) climate change impact assessments is not possible.

Impact assessments, including those using crop models, generally require higher spatial resolution inputs than those provided by GCMs (Niang et al., 2014). Kim and Yoo (2015) looked specifically at crop yield modelling in Korea and the impact that different spatial resolutions had on uncertainty levels of the meteorological inputs. It was found that the higher the spatial resolution the smaller the uncertainty, however the degree of uncertainty varied depending on the climatic variable in question (ibid.). Kim and Yoo (2015) also highlighted that the impact of this uncertainty would be more problematic for drawing conclusions from the models associated with those crops most sensitive to small changes. Their study compared climate models with 1km^2 and 12.5km^2 spatial resolution. Based on this, we suggest that the climate models currently available for Malawi would have even higher levels of uncertainty due to their lower spatial resolution (approximately 50km^2 for RCMs, and 124km^2 to 310km^2 for GCMs).

Kim and Yoo (2015) also reported that there were higher levels of uncertainty in climatic variables in the area near the ocean. While Malawi is landlocked, Lake Malawi, the ninth largest lake in the world (Makwinja et al., 2017), is likely to have a significant impact on the local climate. Studies from many regions of the world have shown large lakes to have a significant impact on the local water and energy cycles (Long et al., 2007; Samuelsson et al., 2010; Wen et al., 2015). As such, the inclusion of large bodies of water, including lakes, creates a significant improvement in the outputs of simulations for local temperature, evaporation and precipitation, compared to models which do not consider the lake effect (Long et al., 2007). The likely influence of Lake Malawi on the local climate is supported by our spatial analysis of the degree of bias in both the precipitation and temperature variables, with high levels of bias seen in areas closest to the lake boundary. As the RCMs assessed here are atmospheric models, they will not include the full complexity of the climatic interaction with Lake Malawi. Expanding the RCMs into coupled atmospheric-lake models would likely improve the accuracy of the outputs. This suggestion is supported by the findings of studies that found that coupling a freshwater lake model to a RCM improved the performance of the model for simulating precipitation and temperature over the African Great Lakes area and Malawi more specifically (Thiery et al., 2015; Diallo et al., 2017).

In line with other studies which have assessed the performance of African CORDEX models (Nikulin et al., 2012; Kalognomou et al., 2013; Endris et al., 2013; Kim et al., 2014), this study shows that the multi-model average, or ensemble simulation, generally outperforms individual model simulations for both precipitation and temperature variables. We suggest that future studies can use either the ensemble RCMs or ensemble GCMs analysed in this paper to understand the trends and degree of change seen in Malawi’s future temperature, however the RCMs do allow for greater spatial understanding and should therefore be preferentially used. It should be noted that the absolute temperature that these models predict is likely to be less accurate, particularly for mean and maximum temperatures. With respect to precipitation and frequency of meteorological droughts, the authors suggest that any current impact and adaptation plans consider a range of potential outcomes, including the maximum, minimum and average projections from the models, as well as a business-as-usual projection. This uncertainty highlights the need for further development in climate modelling for Malawi and suggests that impact assessment and adaptation planning would benefit from being designed and tested against a range of future scenarios.

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Chapter 3 Assessing Climate Change Projections and Impacts on Central Malawi's Maize Yield: The Risk of Maladaptation.

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3.1. Abstract

Malawi is listed as a Low-Income Food-Deficit Country (LIFDC) by the United Nations (UN), with high levels of poverty, malnutrition, and undernutrition. The maize grown in the Central Region of Malawi represents approximately a quarter of the total Malawian population's calorie intake, is a large source of local income, and a significant contributor to the country's Gross Domestic Product (GDP). While maize has been shown to be more resilient to climatic changes than many other grain crops, the predominantly rain-fed maize grown in Central Malawi has experienced many shocks from severe weather events in the past. Using the ensemble mean of 20 Regional Climate Models (RCMs), this study shows that temperatures in Central Malawi are projected to increase from the 1971-2000 baseline by between 1.4 and 1.6°C by 2035 and 1.9 and 2.5°C by 2055 under Representative Concentration Pathways (RCPs) 4.5 and 8.5 respectively, but precipitation projections are more uncertain. Using the United Nations Food and Agriculture Organization's (FAO) AquaCrop model, this study assesses the impact of future warming and three precipitation scenarios on two cultivars of maize planted on three separate dates in Central Malawi's summer planting season. The results (see example of some in Figure 3.1) indicate that if precipitation levels follow the ensemble average or maximum projection, then moving to a later planting date and a slower-developing cultivar may result in increasing yields compared to the baseline scenario. However, under a minimum precipitation projection, the results are less positive, with decreasing yields seen for both cultivars and all planting dates. The uncertainty around future precipitation therefore poses a significant risk of maladaptation and highlights the need for more robust precipitation projections in the area before climate model outputs are used as a primary driver for decision-making in Central Malawi's maize cultivation.

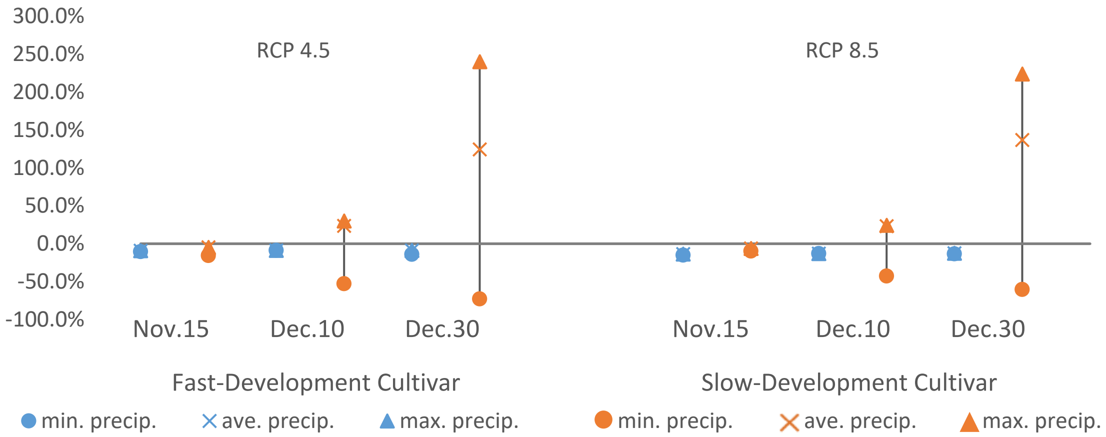

Figure 3.1 Changes in yield of two maize cultivars in the Central Region of Malawi in 2055 for three planting dates and precipitation scenarios (compared to 1971-2000 baseline)

3.2. Introduction

Globally maize provides almost seven percent of the world's calorific intake by way of direct consumption (FAOSTAT, 2018a), but as it is also the largest source of livestock feed grain, it is indirectly responsible for much more (CGIAR, 2016). It is the staple crop for many food insecure populations, and an important source of calories for people living on less than US $2 per day (ibid.). With an ever-increasing global population, and the consumption of animal-based food products and biofuels on the rise, the demand for maize is expected to double by 2050 (Hubert et al., 2010). However, recent studies suggest that climate change will lead to declining maize yields and price volatility, exacerbating existing challenges around food security, poverty, and malnutrition (Tigchelaar et al., 2018; Zampieri et al., 2019).

Table 3.1: The main food crops by calorific intake in Malawi.
The calorie intake, production, import and export data reflects 2013 data (FAOSTAT, 2018a) while the current yield data is from 2017 (FAOSTAT, 2017).

Crop	**Calorie Share (%)**	**Share Produced Domestically (%)**	**Production**	**Export**	**Import**	**Current Yield**
			1000 tonnes	1000 tonnes	1000 tonnes	tonne/ha
Maize	47.5	98	3640	2	61	2.0
Potatoes	10.5	100	4536	1	0	18.4
Cassava	6.2	100	4814	0	0	21.4
Pulses	4.3	100	381	10	0	0.48 – 1.71 [a]
Wheat	3.7	0	2	2	195	1.2
Sugar	3.4	43	309	176	2	1 07.6
Groundnuts	3.0	81	267	51	51	1.0

[a] depends on variety

Like much of the developing world, maize is currently, and has historically been, the main food crop in Malawi (see Figure 3.2), and it is grown by 97% of smallholder farmers (NSO, 2005). Almost half of the calorie intake in Malawi is met by the direct consumption of maize and maize products (see Table 3.1), the majority of which is domestically grown in the Central Region using rain-fed production (Arya et al., 2005). Agriculture is the main source of income in Malawi, with over three-quarters of Malawi's population employed in the sector, and over a third of Malawi's Gross Domestic Product (GDP) related to agricultural activity (FAO, 2017; CIA, 2018). Within this sector, maize has been the largest contributor to Malawi's gross agricultural production value in 37 of the last 56 years (1961-2016), coming second 16 times, and third only three times (FAOSTAT, 2018b).

While the Malawian government and many food aid organisations have been concentrating on improving domestic agricultural production and food security in the country for more than a decade (IFPRI, 2018), the Food and Agriculture Organisation of the United Nations (FAO) still classifies Malawi as a Low-Income Food-Deficit Country (LIFDC) (FAO, 2019). Climatic, political, and governance shocks have had a negative effect on developmental progress and resulted in minimal poverty alleviation, particularly in rural areas (IMF, 2017). Severe droughts such as those experienced by the region in 1992, 1994, 1997, 2001, 2005 and 2016 have had a significant negative impact on the country's economy, food supply, and poverty levels (see Figure 3.3) (The World Bank, 2016; The World Bank, 2017). The relative lack of diversity in the calorie share, the share of economic and household income from agriculture, and the vulnerability of that agriculture to climatic changes has meant that Malawi is often reliant on high levels of international aid. For example, crop losses due to the 2005 drought meant that 40 percent of the population required immediate food aid (Giertz et al., 2015).

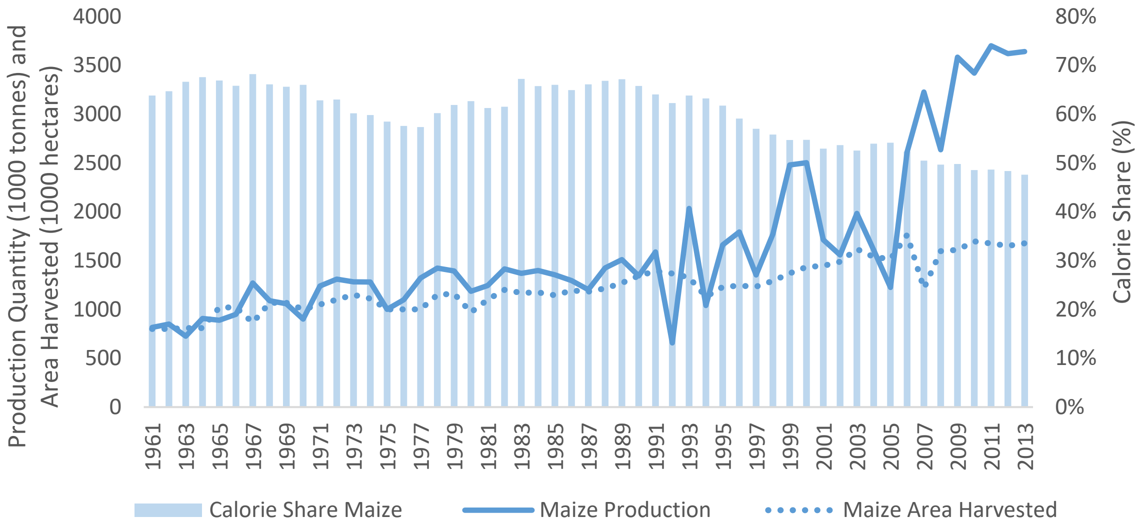

Figure 3.2: The importance of Maize in Malawi.
Malawi's 1961-2013 production of maize (1000 tonnes) and area harvested for maize (1000 hectares) shown on the left hand axis, and calorie share met by maize shown on the right hand axis (FAOSTAT, 2018a; FAOSTAT, 2019).

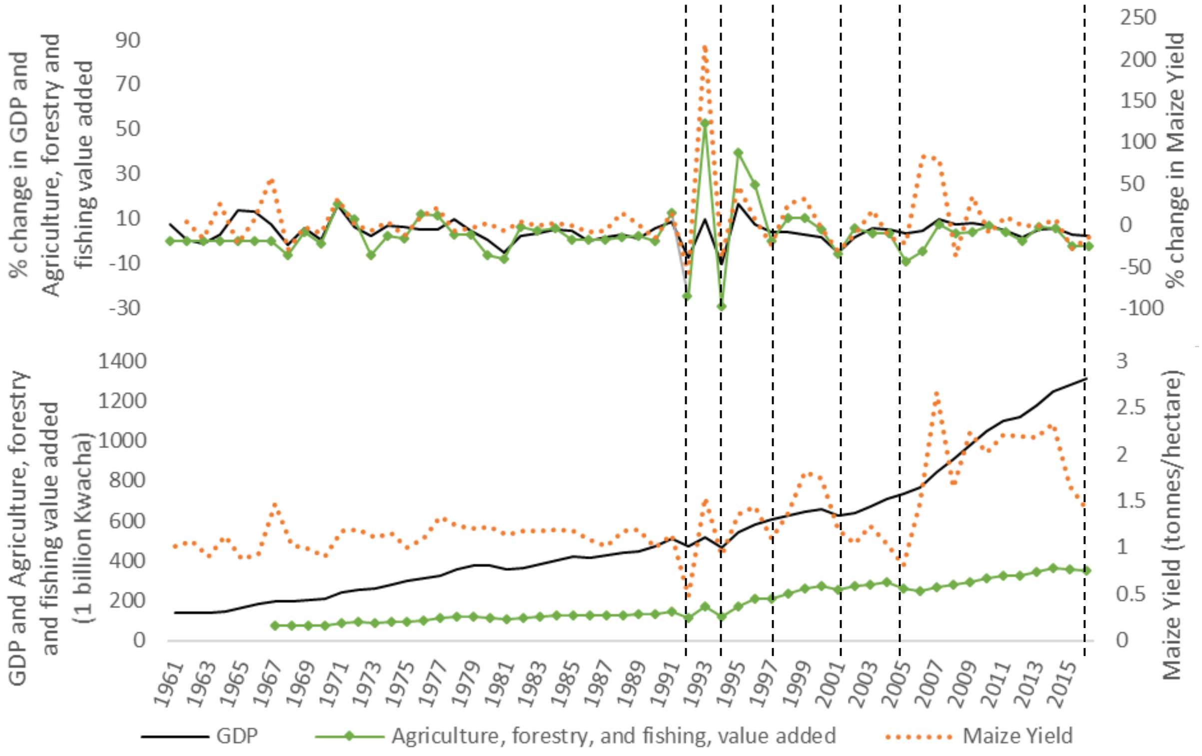

Figure 3.3: Climatic Shocks.
The top chart shows Malawi's percent annual change in Gross Domestic Product (GDP) and Agricultural Value added (The World Bank, 2018) shown on the left hand axis, and percent annual change in Maize Yield (FAOSTAT, 2017; The World Bank, 2018) shown on the right hand axis. The bottom chart shows the same parameters in absolute values. The vertical dashed lines denote notable drought years.

The Malawian government introduced the Farm Input Subsidy Programme (FISP) after the 2005 drought which helped increase crop production and improve national food security mainly through improved access to fertilisers, however it is unlikely that this measure alone will be able to maintain food security in a changing climate (Msowoya et al., 2016). With limited finances and technology to cope with changes, and much of the economy, employment, and food supply reliant on a predominantly rain-fed agricultural sector, Malawi is highlighted as being particularly vulnerable to future climate change (Minot, 2010; Giertz et al., 2015; FAO, 2017).

Under all future climate projections, the surface temperatures in Malawi are expected to rise, but precipitation projections are less certain (Mittal et al., 2017; World Bank Group, 2019). While maize has an optimal growing temperature range that is higher than many other globally important grain crops (Sanchez et al., 2013), it is still sensitive to changes in maximum daily temperatures (Lobell et al., 2013; Tebaldi and Lobell, 2018). Upper temperature threshold exceedances result in reduced photosynthesis and increased evapotranspiration[8] rates, and therefore increased water demand (Crafts-Brandner and Salvucci, 2002; Zampieri et al., 2019). Furthermore, higher temperatures hasten the transition between phenological phases and reduce crop yields (Tebaldi and Lobell, 2018). Maize is particularly vulnerable to temperature anomalies during the flowering and yield formation stages of development, as higher temperatures decrease pollen germination and lead to shortened kernel filling and yield development (Gourdji et al., 2013; Zampieri et al., 2019). Maize is also drought sensitive, particularly early-on in crop development. A lack of water in early development can cause delays in crop flowering, reduced photosynthesis and decreased yield (Zampieri et al., 2019). Furthermore, low soil moisture tends to exacerbate the temperature stresses described above (Lobell et al., 2013).

Based on climate change projections for Sub-Saharan Africa, various studies have indicated vulnerability for maize's future crop productivity in the region, with maize yields expected to decrease in the 21st century (Challinor et al., 2014; Gachene et al., 2015). For Malawi more specifically, some previous research has gone into quantifying the impact that climate change will have on domestic maize yields (Saka et al., 2012; Zinyengere et al., 2014; Fiwa, 2015; Msowoya et al., 2016; Stevens and Madani, 2016; Olson et al., 2017). The results from these studies vary significantly, with some projecting a decrease in maize yield of up 14% and others a projected increase of up to 25% by 2050. The wide range in results stems from the assumptions made, both in terms of future climate and in crop modelling. Most of the studies used models calibrated for one cultivar of maize with one planting date. Fiwa (2015) assessed the impact on three different cultivars (early, intermediate, and late maturing), but only one planting date and highlighted the need to research the impact of changing planting dates on the crop yield under future climate scenarios. Zinyengere et al. (2014) on the other hand looked at one cultivar and two planting dates but only under one climate projection. All these previous studies highlight the importance of understanding the variables that will impact maize's yield response to climate change, as making choices on incomplete information poses a risk of maladaptation. This paper therefore aims to determine the impact of projected climate change on the yield of two different maize cultivars planted on a variety of dates during the summer planting season in the Central Region of Malawi, and to examine the utility of this in informing cultivation practices and potential risks of maladaptation. The Central Region produces the majority of the food in Malawi

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[8] Evapotranspiration refers to the process which transfers water from the land to the atmosphere through evaporation of water from the soil and other land surfaces and by transpiration from plants.

and this boundary represents over a quarter of the Malawian population's calorie intake (Arya et al., 2005; FAOSTAT, 2018a).

3.3. Climate Change Projections

To understand the impact of climate change on maize yields in Central Malawi, it is first important to get a clear understanding of how the climate is currently predicted to change. Here we assess the change in projected temperature, precipitation, and evapotranspiration rate for the 2035 (2020-2049) and 2055 (2040-2069) climates. These time horizons have been chosen as they are both short-term enough to be relevant to current farmers, consumers, and policy makers, and long enough to allow for adaptation to take place.

3.3.1. Climate Modelling Methodology

To project Malawi's climate into the future, we make use of 20 RCMs produced by different organisations within the Coordinated Regional Climate Downscaling Experiment (CORDEX) initiative (see Table A.1, found in Appendix A). The CORDEX initiative sets a standard grid, domain size, experiment protocols, and data format allowing for direct comparison of the model outputs (Giorgi et al., 2009; Nikulin et al., 2012). Within this framework, only models which were publicly available and provided projections for Representative Concentration Pathways (RCPs) 4.5 and 8.5 were selected[9]. All the RCMs are atmospheric models produced within the defined CORDEX-Africa domain, they provide data on a daily time scale, and have a 0.44-degree (approximately 50km^2) resolution.

An evaluation of the ability of these RCMs to hindcast minimum, maximum and mean temperature (TasMin, TasMax, and Tas respectively) in Malawi found that they are not able to adequately simulate absolute temperatures, however the trending change in temperature correlated well (Warnatzsch and Reay, 2019). To take this into consideration in this study, the method used by UKCP09 was applied to re-baseline the temperature and precipitation data (UKCP, 2014). This methodology involves using a 30-year average from station and satellite observed data, in this case 1971-2000, and adding to that the difference between the climate variable output for the time-period of interest and the hindcasted 1971-2000 average from the CORDEX models. The observed data used for this re-baselining are detailed in Table A.2 (Appendix A).

The CORDEX-Africa models do not have an output for reference evapotranspiration, and an adequate observed database for historical reference evapotranspiration rates could not be found for Malawi. As such, the historic and projected reference evapotranspiration data were determined through calculation. To calculate the reference evapotranspiration data, the FAO's Penman-Monteith (FPM) method was applied (Allen et al., 1998a; Allen et al., 1998b). Full details of the calculations applied can be found in the Appendix B. This methodology was tested for application in Malawi by Wang et al. (2011) and Southern Malawi by Ngongondo et al. (2012) and deemed to be appropriate for use.

While half of the models use a 366-day calendar (include leap-days), seven use a 365-day calendar and three use a 360-day calendar (assumed all months are 30 days). To create the daily profiles used here, it was necessary to make all the calendar formats the same. There is no standard method to do this, however the crop model used requires a 365-day year. Therefore, we took the decision to add a

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[9] At the time of writing there was one additional RCM available that met these criteria, HIRHAM5_NorESM1-M, however this model has been excluded from this study. Based on the findings of Warnatzsch and Reay (2019), this RCM is a major outlier and does not simulate Malawi's temperature or precipitation well.

31st day to May, July, August, October, and December for the 360-day calendars and remove February 29th from all the 366 and 360-day models. No 31st day was added for January or March, as the extra days from February accounted for this. The data for these additional days were created by using an average of the data from the five days before and five days after the missing date.

Limited by the resolution of the models, and the need to use a rectangular boundary, the assessment includes spatial data that are larger than the actual geographical boundary of the Central Malawi region, as shown by the grey shaded areas in Figure 3.4.

Analysis by Warnatzsch and Reay (2019) found that the RCM model outputs for precipitation are highly divergent and not well correlated to observed precipitation levels. As such, we recommended that a range of future precipitation scenarios be used for impact assessment and adaptation planning for the future food supply chain in Malawi. The current study will therefore assess impacts using three future scenarios based on the ensemble maximum, minimum, and mean projections for precipitation rate in Malawi. Warnatzsch and Reay (2019) also found that the ensemble average better represented the temperature records of Malawi than individual model simulations. Therefore, these three precipitation scenarios will be used in combination with ensemble average mean, minimum and maximum daily temperature projections, and calculated reference evapotranspiration rates. Analysis of the results was performed using a Python interface. Within the interface, the numerical mathematics and graphical plotting were produced using a variety of open-source Python libraries and packages. The code used for each assessment can be found in the author's GitHub repository[10].

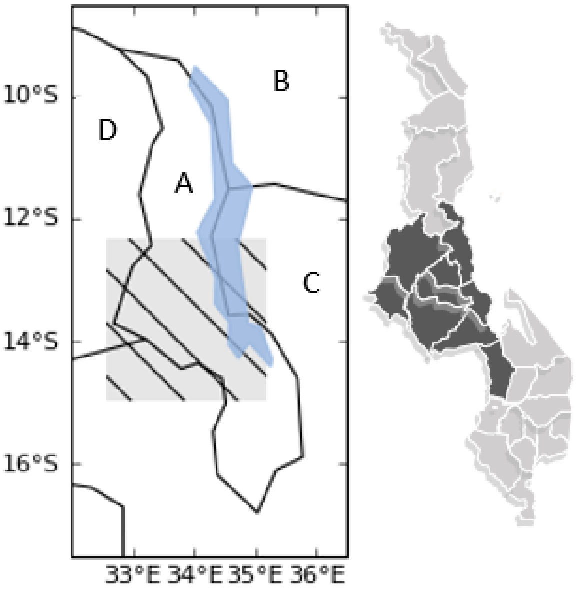

Figure 3.4: Assessment Boundary.
The map on the left shows the data boundary used in this assessment indicated by the grey hatched area (32.5 to 35.5 degrees East and -15 to -12 degrees South). Black lines show national borders and the solidly shaded blue area is Lake Malawi. The map on the right shows the actual land boundary for the Central Region of Malawi shaded in dark grey, the white lines show the district borders.

3.3.2. Climate Change Projection Results

Malawi's climate is classified as sub-tropical and has distinct seasons: a warm and wet season from November to April and a cooler, dry season from May to October. This seasonality is projected to continue under both RCP 4.5 and RCP 8.5, although all seasons are expected to get warmer with annual average temperatures increasing by 1.4 and 1.6°C by 2035 and 1.9 and 2.5°C by 2055 (see Table 3.2 for details). For both time periods and scenarios, the temperature increase is seen to be largest in

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[10] Erika Warnatzsch GitHub directory: https://github.com/ErikaWarnatzsch/Malawi-Future-Climate-Modelling-Assessment

the autumn months (March-May), as seen in Figure 3.5. Overall, based on the calculation methods, annual reference evapotranspiration rates in Central Malawi are projected to remain relatively stable, only showing a slight increase from the 1971-2000 baseline in both future time periods and RCP scenarios (Table 3.3).

Three scenarios were run for projected precipitation: minimum projection, ensemble mean and maximum projection (Table 3.3). The minimum RCM projection has annual precipitation decreasing by approximately half from the 1971-2000 baseline, while the ensemble mean shows a much smaller decrease of only 3-4%. The maximum RCM projection has precipitation increasing by between a fifth and a quarter compared to the 1971-2000 baseline. Figure 3.5 show that there is largest agreement in the models for precipitation during the dry season, with larger variation in the wet season in both time periods and scenarios.

Table 3.2: Malawi's annual historic near surface temperatures and the projected future changes.
The adjusted hindcasted annual mean, minimum and maximum surface air temperatures in Central Malawi for the 1971-2000 period, and the RCM ensemble mean projected increases in temperature for the 2035 (2020-2049) and 2055 (2040-2069) climates under the RCP 4.5 and 8.5 scenarios.

	Temperature (°C)	**RCP 4.5 - Change in Temperature (°C)**		**RCP 8.5 - Change in Temperature (°C)**	
	1971-2000	2020-2049	2040-2069	2020-2049	2040-2069
TasMin	16.6	1.4	1.9	1.6	2.5
Tas	22.1	1.4	1.9	1.6	2.5
TasMax	27.8	1.4	1.9	1.6	2.5

Table 3.3: Malawi's annual historic evapotranspiration and precipitation rates, and the projected future changes.
The hindcasted and projected annual evapotranspiration rates, and the adjusted hindcasted annual precipitation rate (mm/year) in Central Malawi for the 1971-2000 period, and the RCM ensemble minimum, mean, and maximum projected precipitation rates for 2030 (2020-2049) and 2050 (2040-2069) climates under the RCP 4.5 and 8.5 scenarios.

	1971-2000	**RCP 4.5 (% change from baseline)**		**RCP 8.5 (% change from baseline)**	
		2020-2049	2040-2069	2020-2049	2040-2069
Evapotranspiration Rates (mm/year)	1226.0	1265.4 (3.1%)	1283.3 (4.5%)	1272.1 (3.6%)	1301.4 (5.8%)
Minimum Precipitation Rate (mm/year)	1081.37	743.48 (-45%)	735.89 (-47%)	721.53 (-50%)	694.87 (-56%)
Ensemble Mean Rate (mm/year)		1044.55 (-4%)	1036.73 (-4%)	1052.56 (-3%)	1044.41 (-4%)
Maximum Precipitation Rate (mm/year)		1399.31 (23%)	1404.64 (23%)	1369.47 (21%)	1423.74 (24%)

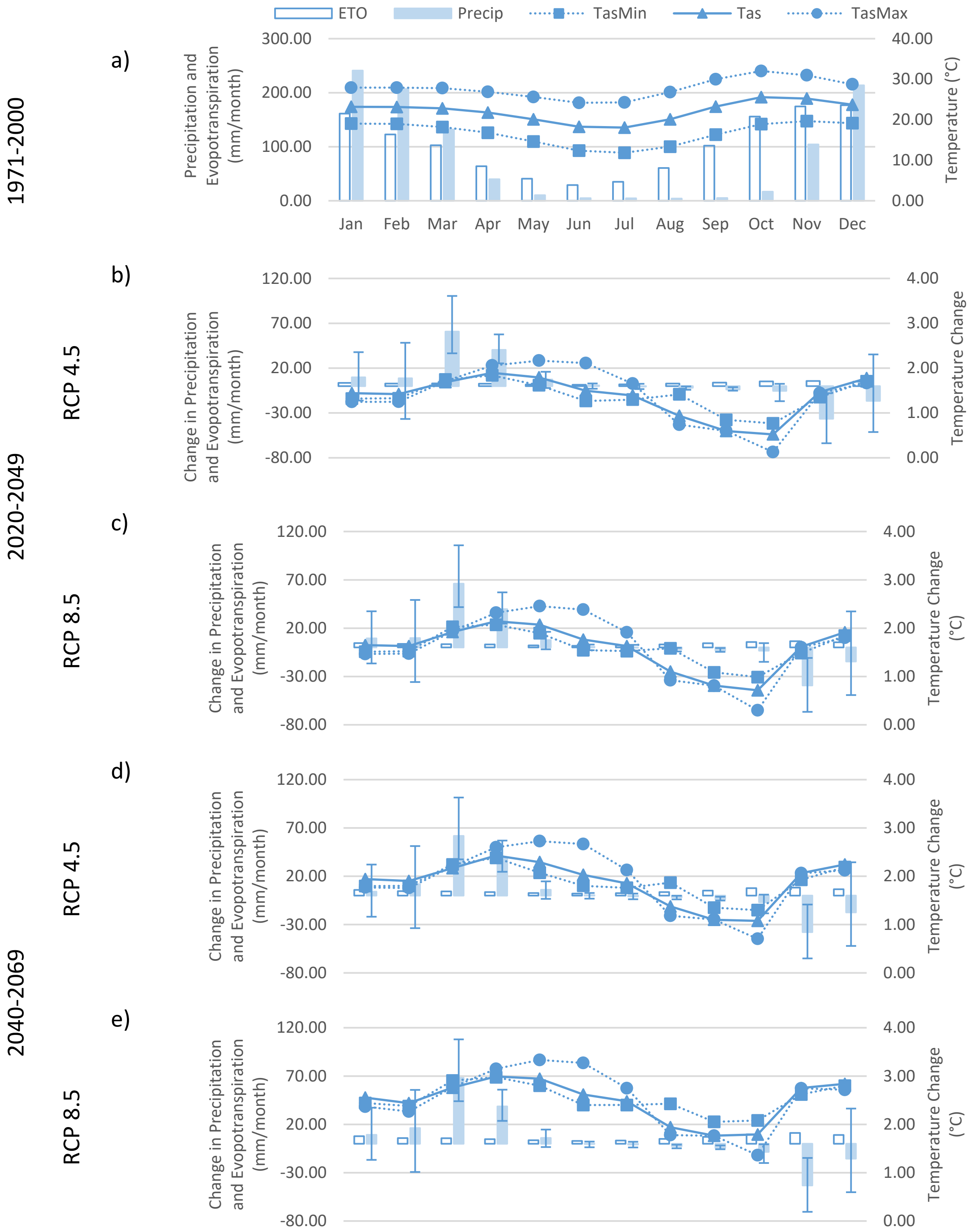

Figure 3.5: Malawi's historic seasonal climate and projected changes.

Historic and projected future temperature, evapotranspiration, and precipitation for the Central Region of Malawi. The absolute historic climatic data are shown in graph a), while the projected changes from the 1971-2000 baseline climate are shown in graphs b) through e). Graphs b) and c) represent the projected changes in the climatic variables from this baseline in the 2020-2049 period (2035 climate) for RCP 4.5 and RCP 8.5 respectively, and d) and e) show the projected changes for the 2040-2069 period (2055 climate) for RCP 4.5 and RCP 8.5 respectively. The bars on the relative change in precipitation reflect the three precipitations scenarios: the height of the bar represents the change in the average precipitation projection, and the upper and lower bars represent the change in the maximum and minimum precipitation scenarios respectively.

3.4. Impact on Maize Yield

There are multiple crop models available, each with their own characteristics and applications (Di Paola et al., 2015). While the use of crop models does have limitations, they are still useful tools for determining the likely impact of specific changes on a crop (Boote et al., 1996). In this study we are interested in determining the impact of various potential future climate scenarios on the yield of two maize cultivars in Central Malawi. For this purpose, we have chosen to use the FAO's crop growth model, AquaCrop. Analysis by Steduto et al. (2009) found that when compared to other crop simulation tools, AquaCrop is amongst the most intuitive in terms of usability, and has achieved a good balance of accuracy, simplicity and robustness, making it perfect for users who are not familiar with crop physiology.

AquaCrop is a crop growth model which is specifically built to evaluate the yield response of a variety of crops to different environmental factors and crop management techniques (FAO, 2018). While there are many variables that can be altered and calibrated for local specificity within the model, it is also possible to leave some aspects as 'default' to focus in on the impact of changing one variable or category, in our case, the climatic conditions. This ability to both calibrate the model where necessary (e.g., the climatic, crop and soil characteristics), but also keep the complexity to a minimum makes AquaCrop an ideal tool for the purposes of this study.

Various studies have assessed AquaCrop's sensitivity to climatic changes and its suitability for use in modelling yield response at a regional scale for rainfed maize (for example, Mebane et al. (2013), Akumaga et al. (2017), and Mibulo and Kiggundu (2018)). It was not possible to carry out region-specific data collection or site calibration as part of this study. However, the model has been assessed for use in Malawi before. Fiwa (2015) assessed the ability of AquaCrop to simulate yield of rainfed maize in Central Malawi specifically and found a good correlation between observed data and simulated outputs. Stevens and Madani (2016) also evaluated AquaCrop's ability to simulate yields for maize in Central Malawi and found that, while the model overestimated yields in their study, it was still suitable for assessing relative change. As such, this model is deemed appropriate for use in examining the potential effects of climate change on maize yields in Central Malawi, particularly if using relative change in yield rather than absolute values.

3.4.1. Crop Modelling Methodology

AquaCrop has been developed to be used at both the field- and regional-scale (FAO, 2018). When used at the regional scale, as is the case in this study, a variety of climatic and environmental parameters must be identified for input into the model. These inputs help to calibrate both the crop and environmental factors to be as specific as possible to the region in question. The crop, soil, and climate files used in this study can be found on the author's GitHub repository.

A total of 13 climate scenarios were created to test the impacts of climate change on maize yields in Malawi (see Table A.3 found in Appendix A). These scenarios were created using the models and data described in Section 3.3. above. The historical climate represents the 1971-2000 period using daily data adjusted from hindcasted ensemble RCM outputs for: minimum and maximum near-surface temperatures; minimum, mean, and maximum precipitation rates; and calculated reference evapotranspiration rates. This historical climate used the default Mauna Loa CO_2 concentrations file that is provided by the AquaCrop Model. To represent future climate change, 12 climate scenarios were created. Half of the future climate scenarios use projections for RCP 4.5 and the other half RCP

8.5. For the CO_2 concentrations, these future climate scenarios use the AquaCrop IPCC RCP 4.5 or 8.5 files respectively. Within each of the two RCP scenarios, two time-periods were assessed, the 2035 climate (2020-2049) and the 2055 climate (2040-2069). The appropriate time-period and RCP scenario was used with adjusted ensemble RCM daily minimum and maximum temperatures, and calculated daily evapotranspiration rates. For each of these four future climates (two RCPs and two time-periods), three potential climate scenarios were created using ensemble minimum, ensemble mean and ensemble maximum precipitation rate projections.

To ensure that we were only analysing the impact of changing climate, rather than any other human-induced factors, we have assumed that no irrigation and no field management is used. The authors acknowledge that this will mean that the absolute output data will be biased by the assumed lack of human management, and that the relative changes will therefore only reflect the impact of climatic change on the crops (in reality, some degree of management change is inevitable). According to Chavula (2012) the depth of the water table in Central Malawi is 15-25 meters below the surface. As this is too deep to influence crops, no groundwater is considered in the AquaCrop model. The soil in the majority of Central Malawi is described as a Sandy Clay Loam (Saka et al., 2003) so the analysis used the AquaCrop 'Sandy Clay Loam' file as a base to calibrate a new source file specific for Central Malawi. The calibration of this file is based on analysis carried out by Fiwa (2015) and is described in Table 3.4. It is worth noting however that, when tested for sensitivity, this soil calibration did not create a significant change to the yield simulations in the historic climate scenarios, or any of the average or maximum precipitation scenarios. The calibration did however have a significant impact on the output of some of the minimum precipitation scenarios and as such is a potential source of error (see Table A.4, Table A.5 and Table A.6, found in Appendix A).

Table 3.4: Calibration of soil file for Central Malawi based on data collected by Fiwa (2015) for Lilongwe in Central Malawi

Parameter	AquaCrop Default for Sandy Clay Loam	Calibration for Central Malawi	Source/Notes
Soil Thickness (m)	4	2.1	(Fiwa, 2015)
Permanent Wilting Point (vol. %)	20	14.9	
Field Capacity (vol. %)	32	25.8	
Saturation point (vol. %)	47	44.1	
Saturated Hydraulic Conductivity (mm/day)	225	360	
Depth Groundwater Table below soil surface (m)	4	10	Maximum model allows

The majority of maize grown in Central Malawi is rainfed and produced by smallholder farms for own use (Arya et al., 2005; FAO, 2015). The maize is planted via direct sowing with most of the maize in Central Malawi planted in the summer between the 15th of November and the 31st of December (Arya et al., 2005; FAO, 2010; Fiwa, 2015). For this analysis, three planting dates within this period were input into the AquaCrop model for analysis: November 15th, December 10th, and December 30th. AquaCrop provides a default maize model and this has been shown to be effective at simulating yield changes to various climatic stresses (Heng et al., 2009). However, to better reflect the characteristics of the maize grown in Central Malawi, data from studies conducted in the area were used to better calibrate the model (see Table 3.5 and Table 3.6). As such, two maize crop models were calibrated to represent short and long growth cycle (fast- and slow-development) maize varieties that are typically grown in Central Malawi. The calibration of the crop files does create a significant impact on the output of the model and as such is also a potential source of uncertainty (see Table A.7, found in Appendix A). For comparison purposes, the two varieties were given shared characteristics, with the times taken to reach each growth stage being the only differences. Table 3.5 shows the shared characteristics and Table 3.6 shows how the two varieties differ. These tables only show changes that can be input into AquaCrop, there are also some differences in characteristics that AquaCrop automatically calculates based on these inputs.

Table 3.5: Common calibration of both maize varieties compared with AquaCrop default values.

Parameter		**AquaCrop Default**	**Calibrated Maize**	**Source**
Initial Canopy Cover	Initial Plant Density (plants/ha)	75 000	47 000	(Wiyo et al., 1999)
Canopy Development	Maximum Canopy Cover (%)	96	75	(Fiwa, 2015)
Root Deepening	Maximum effective rooting depth (m)	2.3	0.6	
Harvest Index	Hio (%)	48	40	
Air Temperature Stresses	Base temperature (°C)	8	13	(Benson et al., 2016)
	Upper temperature (°C)	30	32	
Soil Salinity Stress - Salt tolerance	ECe lower threshold (dS/m)	2	4	adapted from (Benson et al., 2016)
	ECe upper threshold (dS/m)	10	9	
Crop response to soil fertility stress	Crop response to soil fertility stress	Not Considered	Considered	(Fiwa, 2015)
	Biomass Production (%)		69	
	Canopy Decline in Season		medium	
	Reduction of Canopy Expansion (%)		7	
	Average decline in Canopy Cover (%/day)		0.1	
	Reduction in water productivity (%)		47	

Table 3.6: Calibration of individual maize cultivars (Sutcliffe, 2014) compared with AquaCrop default values.

Parameter (in degree days)	AquaCrop Default	Fast-Development	Slow-Development
Emergence	80	60	98
Max Canopy	705	684	720
Senescence	1400	1008	1715
Maturity	1700	1332	2267
Length building up to Harvest Index (HI)	750	636	1140
Duration of flowering	180	132	220
Degree-Days for Flowering	880	636	1078
Time to maximum rooting depth	1409	1120	1722

3.4.2. Crop Modelling Results

Based on the findings of Stevens and Madani (2016), this report does not concentrate on absolute yield outputs from AquaCrop and instead concentrates on relative change in maize yield due to the impacts of projected climate change. However, the absolute yield outputs for the two cultivars for each planting date have been provided in Table 3.7 to demonstrate the difference in yield potential for the two cultivars under historic climate conditions. Due to uncertainty within the model output for absolute values, these number should only be used to assess the scale of the yield output for each of the two cultivars and to assess the impact of planting date. The results show that under historic climate conditions, the slow development cultivar has a substantially higher yield output than the fast development cultivar. For the slow development cultivar, planting mid-season results in marginally better yield output, whereas the fast development cultivar results in higher yields with later planting.

The relative results of the assessment of projected climate change on maize yield from AquaCrop indicate that maize yields are highly dependent on the precipitation scenario for both the slow- and fast-development cultivars, with the changing planting date giving mixed results (see Table 3.8). Both cultivars show a decreasing yield in all future climate scenarios with minimum precipitation. While the fast-development cultivar generally shows a smaller yield decrease under the minimum precipitation scenarios with later planting dates, the reverse is true for the slow-development cultivar which shows larger yield decreases with later planting dates under a minimum precipitation scenario. Under the average or maximum precipitation scenarios, the future climates show a small increase or decrease in yield depending on planting date and cultivar. For the earliest planting dates, the maximum precipitation leads to a better yield outcome than the average precipitation scenario in all future scenarios, but for later planting dates, the yield outcome is the same for both the average and maximum precipitation scenarios. Under the average or maximum precipitation scenarios, the fast-development crop acts differently than under a minimum precipitation scenario, and the yield outcome is generally better when the crop is planted earlier in the season. Contrary to the minimum precipitation scenario, the slow-development crop has the best yield outcome with the latest planting date in all future scenarios with average or maximum precipitation.

Table 3.7 Absolute maize yield (tons/ha) outputs from AquaCrop for two maize cultivars planted on different dates within the historic climate period (1971-2000)

Planting Date	Slow Development	Fast Development
15 Nov	12.052	7.383
10 Dec	12.861	7.961
30 Dec	12.249	8.243

Table 3.8: Change in AquaCrop outputs for Dry Yield Production (tons/ha) using the historical and projected climate scenarios and a variety of crop calibrations.

The baseline historical climate uses calculated evapotranspiration rates and adjusted hindcasted temperature and precipitation data. The projected climates have three precipitation scenarios, ensemble mean temperature, and calculated evapotranspiration projections for the 2035 (2020-2049) and 2055 (2040-2069) climates and RCP 4.5 and 8.5 scenarios.

Cultivar	RCP	Planting Date	2020-2049			2040-2069		
			Min. Rain	Ave. Rain	Max. Rain	Min. Rain	Ave. Rain	Max. Rain
Slow-Development	**4.5**	**15 Nov**	-54.4%	-0.6%	-1.5%	-60.2%	-0.2%	1.9%
		10 Dec	-79.1	0.8%	0.8%	-78.8%	-4.2%	-4.2%
		30 Dec	-93.5%	11.8%	11.8%	-93.4%	8.6%	8.6%
	8.5	**15 Nov**	-68.5%	0.6%	3.1%	-63.9%	-2.4%	0.2%
		10 Dec	-78.1%	0.0%	0.0%	-73.5%	-5.2%	-5.2%
		30 Dec	-92.8%	8.8%	8.8%	-89.6%	3.4%	3.4%
Fast-Development	**4.5**	**15 Nov**	-77.3%	3.0%	7.6%	-81.8%	0.7%	5.8%
		10 Dec	-6.9%	1.3%	1.3%	-23.9%	-0.8%	-0.8%
		30 Dec	-14.7%	1.8%	1.8%	-20.0%	-1.0%	-1.0%
	8.5	**15 Nov**	-81.6%	0.9%	6.9%	-86.1%	-5.6%	0.7%
		10 Dec	-18.7%	0.0%	0.0%	-31.9%	-5.5%	-5.5%
		30 Dec	-16.4%	0.0%	0.0%	-16.2%	-5.1%	-5.1%

Due to the timing of precipitation and planting, the three precipitation scenarios do not impact the amount of water available to the crops in all stages of development proportionally - as shown in Figure 3.6 for the slow-development cultivar (the equivalent figure for the fast-development cultivar is shown in Figure A.1, found in Appendix A). As maize has a different sensitivity to water availability in each development stage, the timing of the precipitation has a large impact on the crop development and yield formation. Additionally, the change in precipitation scenario does not cause directly proportional changes in the water content of the soil at the effective root zone of the plant, which further explains the yield response. This may be due to the type of soil in the region, timing of the precipitation, relatively stable evapotranspiration rates, response of the plant to rising temperature, and water uptake of the plant at different stages of development. For both the fast- and slow-development cultivars, the crop is exposed to less water availability in the effective root zone under the minimum precipitation scenario as compared to the baseline period in all stages of growth and future time periods. For both cultivars, under the minimum precipitation scenario, the largest decrease in water availability occurred for the middle planting date for the emergence and vegetative stages. However, the earliest planting date saw the largest decrease in water availability during flowering and yield formation. The average and maximum precipitation scenarios generally result in an increase in the water availability in all stages of the development for both cultivars, with more availability under the maximum precipitation scenario than the average. It should be noted that in the water-sensitive flowering and yield producing stages (Manivasagam and Nagarajan, 2018), the increase under the average and maximum precipitation scenarios compared to the baseline period was generally largest with later planting dates, particularly for the slow-development cultivar, which may explain why the yield increases were largest in these scenarios.

To test how much of the yield change was a result of precipitation and how much was due to temperature, the crop model was run again using the same crop and soil calibration but using historic climatic data for all variables except either precipitation or temperature respectively. The results of these test runs are shown in Table 3.9 and Table 3.10. These indicate that, for both cultivars of maize, precipitation is the predominant factor in changing yields. Increasing temperature plays a small positive role for most planting dates in 2035 but, by 2055, the higher increase in temperature results in a negative yield influence in all but one scenario. The crop yields are more favourable under RCP 4.5 scenarios than RCP 8.5, and generally improved with planting at the latest time rather than the earliest. This is consistent with an analysis of the number of days which exceed the maximum temperature threshold for crop development, with only the earliest planting date showing exceedances, and the number of exceedances increasing for the high warming RCP scenario (see Table A.8 in Appendix A).

Overall, our analysis finds that Malawi's climate is expected to warm by around 2^{o}C by the middle of the century, but that projections for precipitation are highly divergent. Modelled maize yields identified some potential yield increases for a slow-development cultivar under average and high precipitation scenarios by 2055, while yields of a fast-development cultivar decreased in all but two climate and planting date scenarios over this same period.

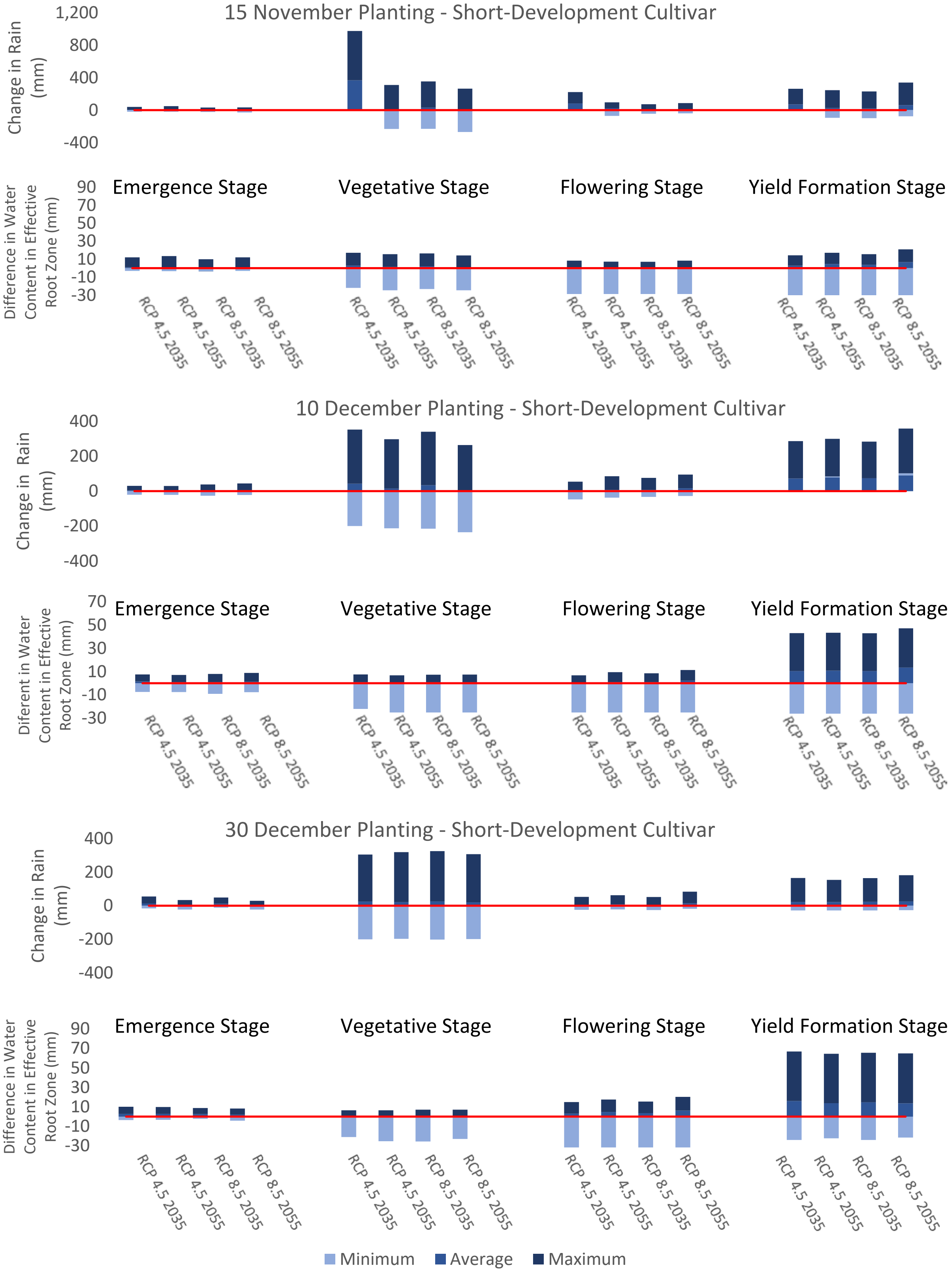

Figure 3.6: Change in total precipitation (mm) and water content in the effective root zone (mm) by developmental stage of the slow-development cultivar maize grown in Central Malawi for the three planting dates as compared to the baseline 1971-2000 period (red line).

This data is shown for the ensemble mean temperature, calculated evapotranspiration, and the three precipitation scenarios: minimum (palest), average (medium shade) and maximum (darkest) precipitation, for the two RCP scenarios and time periods.

Table 3.9: Yield impacts from three projected precipitation scenarios.

AquaCrop outputs for change in Dry Yield Production (tons/ha) using the historical and projected precipitation scenarios and a variety of crop calibrations. The historical climate is using calculated evapotranspiration rates and adjusted hindcasted temperature and precipitation data. This was compared to a test scenario where temperature and evapotranspiration rates are kept the same as the historical run, but three precipitation scenarios are projected for the 2035 (2020-2049) and 2055 (2040-2069) climates and RCP 4.5 and 8.5 scenarios.

Cultivar	RCP	Planting Date	2020-2049			2040-2069		
			Min. Rain	Ave. Rain	Max. Rain	Min. Rain	Ave. Rain	Max. Rain
Slow-Development	**4.5**	**15 Nov**	-54.0%	0.8%	3.0%	-58.3%	1.0%	3.0%
		10 Dec	-77.6%	0.0%	0.0%	-78.8%	0.0%	0.0%
		30 Dec	-93.8%	8.8%	8.8%	-92.5%	8.8%	8.8%
	8.5	**15 Nov**	-69.4%	0.5%	3.0%	-62.8%	0.8%	3.0%
		10 Dec	-78.1%	0.0%	0.0%	-77.8%	0.0%	0.0%
		30 Dec	-92.9%	8.8%	8.8%	-91.3%	8.8%	8.8%
Fast-Development	**4.5**	**15 Nov**	-78.6%	1.9%	6.8%	-80.6%	2.3%	6.8%
		10 Dec	-8.7%	0.0%	0.0%	-18.3%	0.0%	0.0%
		30 Dec	-15.8%	0.0%	0.0%	-18.0%	0.0%	0.0%
	8.5	**15 Nov**	-81.6%	0.9%	6.8%	-83.9%	1.4%	6.8%
		10 Dec	-18.5%	0.0%	0.0%	-18.5%	0.0%	0.0%
		30 Dec	-16.4%	0.0%	0.0%	-12.9%	0.0%	0.0%

Table 3.10: Yield impacts from projected temperature changes.

AquaCrop outputs for change in Dry Yield Production (tons/ha) using the historical and projected temperature scenarios and a variety of crop calibrations. The historical climate is using calculated evapotranspiration rates and adjusted hindcasted temperature and precipitation data. This was compared to a test scenario where precipitation and evapotranspiration rates are kept the same as the historical run, but the ensemble mean temperatures are projected for the 2035 (2020-2049) and 2055 (2040-2069) climates and RCP 4.5 and 8.5 scenarios.

Cultivar	RCP	Planting Date	2020-2049	2040-2069
Slow-Development	**4.5**	**15 Nov**	-1.4%	-1.0%
		10 Dec	0.8%	-4.2%
		30 Dec	2.1%	1.2%
	8.5	**15 Nov**	0.0%	-2.7%
		10 Dec	0.0%	-5.5%
		30 Dec	-0.1%	-0.8%
Fast-Development	**4.5**	**15 Nov**	0.7%	-1.2%
		10 Dec	1.3%	-0.8%
		30 Dec	1.8%	-1.0%
	8.5	**15 Nov**	0.1%	-6.0%
		10 Dec	0.0%	-5.5%
		30 Dec	0.0%	-5.1%

3.5. Discussion

Both the scale of relative change in the ensemble RCM mean precipitation rate and the large discrepancy between model outputs that we have found in the RCMs are consistent with the findings of other climate change projections for Malawi and Sub-Saharan Africa more broadly (e.g. Niang et al. (2014) and Mittal et al. (2017)). Mittal et al. (2017) used 34 of the latest General Circulation Models (GCMs) for their projections of Malawi's climate and found that almost half showed changes in rainfall to be less than +/-5% by 2040, with the other half in disagreement as to whether the climate in Malawi will become wetter or drier. According to their study, the ensemble average of the GCMs showed a slight decrease in precipitation of around 2-4% by 2040, with a larger drying out seen in later time periods. This uncertainty in the projections highlights the need to assess multiple potential future precipitation scenarios, but also suggests that the extreme minimum and maximum precipitation scenarios used in this report are unlikely, with reality more likely to be closer to the average precipitation scenario.

The climate in the Central Region of Malawi is changing, and this is expected to have a mixed impact on maize yields in the coming decades. Under a minimum precipitation scenario, both cultivars show a large decline in yield under all future climate scenarios and planting dates. For the average and maximum precipitation scenarios, the direction of yield change is more reliant on the cultivar, time-period, RCP scenario, and planting date.

Through isolating the climatic variables in the crop model, it was possible to determine that future temperature levels play little role in the yield outcome of both maize cultivars in the short term. However, by 2055, the extent of the warming does start to play a larger negative role, particularly for earlier planting dates. Conversely, a reduction in precipitation does have a large negative impact on yields, while the increasing precipitation of the average or maximum scenarios only showed slight improvements in yield.

While our study suggests that planting later in the season and using slower developing cultivars may help improve yield outcomes in a warmer climate, these increasing temperatures will not happen in isolation. Importantly, other factors and their interactions with climate variables must also be considered before any planting advice is developed and certainly before it is applied. For example, Cairns et al. (2013) found that while the development of more climate resilient maize cultivars could lead to improved yield outcomes in Sub-Saharan Africa, this would not be successful without improved management systems and farmers gaining access to the necessary seeds. Switching from cultivars based on development length may also have other consequences, including changing the timing of and magnitude of climatic stresses, the absolute size of the yield, the uptake of soil nutrients, and vulnerability to pests and disease, all of which need to be considered. Without access to technological solutions such as irrigation, the uncertainty around precipitation levels may also make any change between these two varieties futile.

Cherry-picking a single future prediction and basing future planting decisions on this may lead to unintended negative outcomes due to uncertainty in the climatic projections and simplicity in the crop modelling. The importance of assessing a variety of crop types and planting dates, as well as the challenge of addressing the sensitivity of the soil and crop calibration in the models is highlighted by the high degree of variation found in the results of this and other studies (Saka et al., 2012; Challinor et al., 2014; Zinyengere et al., 2014; Gachene et al., 2015; Fiwa, 2015; Msowoya et al., 2016; Stevens and Madani, 2016; Olson et al., 2017). Previous studies indicate that maize yields may decrease by as much as 14% or increase by up to 25% under a changing climate, with the main differences between the studies being the cultivar calibration, climate scenario and planting date. The range of outcomes seen in these previous studies is echoed in our results although, due to the use of more extreme minimum and maximum precipitation scenarios and not just an ensemble average, the lower end of the range is more extreme. Furthermore, our results and the results of most previous studies base their findings on just one crop model type that is calibrated for a specific situation. Crop models, while very useful, do have limitations and these should be considered when determining the usefulness of their outputs for the research and policy community in Central Malawi and any other region they are applied to (Boote et al., 1996; Di Paola et al., 2015). In this case AquaCrop was deemed appropriate for use in examining the potential climate change impacts on two maize cultivars grown in Central Malawi, however these results do not necessarily translate into climate-smart application at an individual farm level. Changes in the crop model choice and calibration could cause the results to vary widely, and as such, crop models should be tested for applicability, and more local calibration will be required to develop and recommend robust climate change adaptation options. Real world application would also need to consider key interactive effects, such as soil fertility and management practices, which are not assessed in this paper.

Likewise, the projected impact of climate change on the volume and timing of precipitation in the studied region is highly uncertain and this too may lead to maladaptation when choosing maize planting dates and cultivars. This risk is echoed by Sutcliffe et al. (2016) who found evidence of potential maladaptation already taking place in parts of Southern Malawi, with farmers already switching maize cultivars due to perceived changes in rainfall. The disparity in future precipitation projections, combined with the more certain temperature projections, results in either a greatly negative or greatly positive impact on final maize yields. The sensitivity of Malawi's main food source to precipitation highlights the need for more locally calibrated crop models and higher resolution climate modelling to better inform adaptation measures. In the interim, improved access to short-term weather forecasting and early warning systems for extreme events, such as floods and droughts, is required, but this would not address the need for long term agronomic solutions and adaptation.

In the face of such uncertainty, technical solutions, such as the use of irrigation, could reduce the impact of changing precipitation patterns, particularly if the climate follows a scenario of declining precipitation. This could target soil moisture deficits in the more vulnerable growth stages of the maize to help improve yield outcomes. However, special care must be taken to ensure that future practices consider the whole system and do not waste already limited water and energy resources (USAID, 2013) or contribute to the land degradation and declining soil fertility already challenging the area (Vargas and Omuto, 2016).

In this study it was not possible to determine the impact of climate change on the yield of other main crops such as potatoes or cassava, or on a larger range of maize cultivars, or the growth of any of these crops in differing soil conditions, as the information required to effectively calibrate the crop model is not readily available. Diversifying the crops grown by smallholders in Malawi is highlighted as a significant and viable option for improving food security (Mango et al., 2018). Crop diversification could make the agricultural sector more stable and provide improved dietary diversity and nutrition (ibid.). However, there has been very little research into how climate change will impact other food crops in Malawi, and this will need to be understood to avoid farmers investing in potentially more vulnerable crop types or cultivars.

Assessing how climate change will impact the availability of food is key to determining future opportunities and risks. However, the vulnerability of the food system does not stop with yields. To get a more complete picture, further examination of the three other dimensions of food security and how they interact with climate change is required, namely: how the price of food will change the purchasing power (PP) of the population and therefore change access to the food; how food-borne diseases, pests and post-harvest food losses (PHL) will impact the safety and utilisation of food crops; and how interactions between ecosystems, transboundary impacts (e.g. water abstraction in Tanzania) and the socio-economics of the agricultural sector threaten the wider stability of the system (Campbell et al., 2016; FAO, 2008).

3.6. Conclusions

Malawi currently faces large challenges with food security, and interventions will be required, with or without further climate change, to deal with issues around a lack of enough calories and a lack of sufficient diversity in nutrients (IFPRI, 2018). Climate change represents a further risk multiplier for an already-vulnerable agricultural sector and food supply system. Our study shows that use of existing climate projections coupled with a widely used crop growth model (AquaCrop) has limited utility in terms of informing future maize growing decisions at the local scale in Central Malawi. Indeed, our analysis highlights the potential for maladaptation, where uncertainties in projected climate variables (especially precipitation) and lack of local scale model calibration could result in a choice of investment into maize cultivar breeding and research and large infrastructural projects that reduces climate change resilience instead of enhancing it.

We recommend that investment be made into higher resolution climate modelling alongside greater accessibility of outputs, particularly around precipitation. This would allow for the projected climate impacts and associated uncertainties to be better incorporated into decision-making by policy makers, extension service providers, and the farmers themselves. More locally specific studies on the climatic sensitivity of multiple cultivars of the main food crops for a variety of soil and farm management conditions are also required. This information could allow the creation of context-specific ‘no regret interventions’, targeted investments, and education programmes to allow both commercial and subsistence farmers to make sound and sustainable adaptation decisions in a changing climate.

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Chapter 4 Climate Change Impact on Aflatoxin Contamination Risk in Malawi's Maize Crops

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4.1. Abstract

Malawi is one of the poorest countries in the world, with high levels of malnutrition and little domestic mycotoxin regulation. Domestically grown maize is the largest single source of calories in the country and a large contributor to the economy. This research uses Regional Climate Models (RCMs) to determine the climatic conditions in the three regions of Malawi (Northern, Central and Southern) in 2035 (2020-2049) and 2055 (2040-2069) as compared to the baseline climate of 1971-2000. This climatic data is then used as inputs to the Food and Agriculture Organization's (FAO) AquaCrop model to assess the impact on the growth cycle of two maize varieties grown in each region and sown at three different times during the planting season. Finally, AFLA-maize, a mechanistic model, is applied to determine the impact of these projected changes on the aflatoxin B1 (AFB1) contamination risk. We find that Malawi's climate is projected to get warmer (by 1-2.6°C) and drier (reduction of 0-4% in annual rainfall levels) in all regions, although some uncertainty remains around the changes in precipitation levels. These climatic changes are expected to shorten the growing season for maize, bringing the harvest date forward by between 10 and 25 days for the short-development variety and between 25 and 65 days for the long-development variety. These changes are also projected to make the pre-harvest conditions for Malawian maize more favourable for AFB1 contamination and risk maps for the studied conditions were drawn. Exceedances of EU safety thresholds are expected to be possible in all regions, with the risk of contamination moving northwards in a warming climate.

4.2. Introduction

Food crops are an ideal substrate for fungal mould growth, and this is a major cause of spoilage in the food supply chain (Adeyeye, 2016). These moulds can impact both the quality and quantity of the crop yield, and can contaminate the edible part of the crops with toxic secondary metabolites called mycotoxins (Bhat and Miller, 1991; Magan et al., 2011). Exposure to mycotoxins, either through skin contact, inhalation, or ingestion can cause a range of symptoms and illnesses in humans, both acute and chronic, ranging from cold and flu like symptoms to immune deficiency, organ failure, cancer and even death (Peraica et al., 1999; Hussein and Brasel, 2001; Udomkun et al., 2017). The young, elderly and those with compromised immune systems are more vulnerable to the negative health effects of mycotoxins (Bennett and Klich, 2003). While early estimates from the Food and Agriculture Organization (FAO) suggested that mycotoxin contamination effected 25% of global crops, more recent estimates show that this may be as high as 60-80% (Eskola et al., 2019).

The main food crops grown in Malawi are unfortunately not safe from mycotoxin contamination (Misihairabgwi et al., 2017) and with much of the population reliant on un-regulated subsistence farming, and no regulation on levels of mycotoxins found in domestically grown food sold in local markets (Mwalwayo and Thole, 2016), the population is at risk of dangerous levels of mycotoxin exposure. Furthermore, high levels of malnutrition and incidence of communicable diseases such as

HIV/AIDS, tuberculosis and malaria (IHME, 2018), make the population of Malawi particularly vulnerable to the adverse health effects of mycotoxin exposure.

The moulds which produce mycotoxins tend to flourish in hot and humid environments, therefore the sub-tropical climate of Malawi creates conditions conducive to growth (Misihairabgwi et al., 2017). Multiple drivers impact the type and concentration of mycotoxin which is produced, including the nutritional composition and genetic susceptibility of the host plant, moisture content, humidity, water activity, aeration, temperature, acidity level, fungal population, and physical condition of the crop (e.g. damage due to insects or other stress factors) (Matumba et al., 2014a). However, meteorological conditions are the most important factor in the production of mycotoxins and therefore, climate change is likely to induce significant changes in the distribution, type, and concentration of mycotoxins (Paterson and Lima, 2010).

Little research has so far examined the effect future climate change may have on mycotoxins in Africa as a whole, let alone in specific nations such as Malawi. However, some assessment of current prevalence and impact of mycotoxins in Malawi has been made. The majority of these studies concentrate on aflatoxins due to their significant health impacts and the relative ease of detection (Chipinga, 2014). Aflatoxins are a group of mycotoxins produced primarily by *Aspergillus flavus* and *A. parasiticus*, with *A. flavus* a widespread contaminant in arable agriculture (Payne and Brown, 1998; Santini and Ritieni, 2013). While there are many different types of aflatoxins, studies often concentrate on aflatoxin B1 (AFB1) as it is the most toxic of the compounds[11], and is a known carcinogen, causing liver cancer, growth suppression, immune system modulation, and malnutrition in both humans and livestock (Payne and Brown, 1998; Rushing and Selim, 2019). Due to its ability to suppress the immune system, AFB1 exposure is also believed to be linked with the increased HIV viral load in those infected, and faster progression of the HIV infection to AIDS (Jolly, 2014). While data on the exact impacts of aflatoxin exposure in Malawi are unknown, the Partnership for Aflatoxin Control in Africa (PACA, 2020) estimates that over 2,100 cases of liver cancer and 75,400 healthy life years are lost annually in Malawi due to aflatoxin exposure. In addition to the main health concerns for people involved, this causes an annual loss of up to USD 393.6 million to the local economy (ibid.)

The few studies available that explore the current prevalence of aflatoxin contamination in Malawian food have highlighted a worrying situation. Analysis of a range of locally processed maize-based foods sold in popular Lilongwe markets found multiple incidence of aflatoxins, including AFB1, at concentrations which exceeded EU health safety levels, including in all 36 samples of locally processed maize-based baby foods (Matumba et al., 2014b) (see Table C.1 in Appendix C). With infants being particularly susceptible to the negative effects of aflatoxins, and cereal based foods forming a significant part of many infants' diets, these findings are very concerning.

The presence of different mycotoxins and the levels of mycotoxin contamination differ by climatic region in Malawi. A study by Chipinga (2014) found that the Southern region, which tends to be warmer in all seasons (Met Malawi, 2006), has more incidence of mycotoxin contamination in general, with samples more likely to contain fumonisins, aflatoxins, deoxynivalenol, and/or ochratoxin, while incidences were lower in the relatively cooler Central region, and the contaminant more likely to be zearalenone. These findings are in line with Matumba et al. (2014c) who found that 75% of samples

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[11] AFB_1 has a median lethal dose (LD_{50}) for mice in laboratory testing which ranges from 9-60mg of AFB_1 per kg of body weight (Almeida et al., 1996).

taken from hotter regions of the country were contaminated with at least one mycotoxin, whereas cooler zones had a much lower incidence of mycotoxin contamination at 17%. These studies highlight that the climatic conditions not only have an important role in whether mycotoxin-producing moulds will be present, but also which species will grow and how prolific they will be.

With increasing temperatures and more erratic rainfall predicted (Warnatzsch and Reay, 2020; Mittal et al., 2017), it is likely that climate change will impact mycotoxin occurrence in Malawi in terms of their type, geographic distribution, and concentration. These changes may negatively impact the quality and quantity of food grown, and therefore raise key issues for human health, food security, and climate change adaptation. This paper aims to quantify the current and future risk of pre-harvest AFB1 contamination of maize in the three main growing regions of Malawi.

Aflatoxin contamination is a concern in Malawi, and it could become even more serious in the future; predictions highlight an increase in maize contamination in Europe (Battilani et al., 2016), therefore suggesting possible critical scenarios for aflatoxin contamination of maize in other geographic areas. Domestically grown maize represents 48 percent of the calorie intake of Malawi's population, with 32, 54, and 14 percent of that maize grown in the Southern, Central and Northern regions respectively (Arya et al., 2005; FAOSTAT, 2018). A change in contamination risk could therefore have large impacts to food security and safety at regional and national levels and may require anticipatory actions (Battilani et al., 2016). The modelling approach is a crucial tool for policy makers and farmers to support strategic decisions and reinforce aflatoxin management, both aimed to prevent human and animal exposure to this compound with acute and chronic toxic effects.

In each of the three regions of Malawi, two varieties of maize were chosen for assessment, one slow- and one fast-developing. Three different sowing dates, early, medium, and late, were also assessed.

4.3. Methodology

To assess the potential impact of climate change on the risk of pre-harvest AFB1 contamination of maize crops over time and geographic spread, it was first important to understand how the climate is projected to change in the three regions of Malawi: Southern, Central and Northern. Here we first assess the baseline climate of each region as the 1971-2000 period, and two future time periods representative of the 2035 (2020-2049) and 2055 (2040-2069) climates under Representative Concentration Pathway (RCP) 4.5 and 8.5. These two future time horizons were chosen as they are long enough to allow for adaptation measures to be implemented, and short enough to be relevant to current farmers, consumers, and policy makers.

As an assortment of maize cultivars are grown in Malawi and planting occurs during a 'season' rather than on a specific date, this assessment considers the changes in pre-harvest AFB1 contamination risk on two varieties of maize, one with a slow-development and one with a fast-development period, which are sown on three separate dates within the main summer growing season, November 15, December 10 and December 30 (Warnatzsch and Reay, 2020).

A modelling approach was used to predict the risk of AFB1 contamination of each variety of maize in each time-period and region depending on sowing date. The model applied was AFLA-maize, a mechanistic weather-driven model which determines the daily risk of *A. flavus* infection and AFB1 contamination of maize from silk emergence through to harvest (Battilani et al., 2013). Other models exist to predict AF contamination in maize (e.g. Dowd (2004); Chauhan et al. (2008); Battilani et al. (2008); Chauhan et al. (2015); Damianidis et al. (2018)), however AFLA-maize is currently the only peer-reviewed mechanistic model available. As this study is investigating the risk for a region rather than a site, and as limited local calibration data was available, it was deemed preferential to use a mechanistic model rather than an empirical model or semi-mechanistic model which requires much more specific calibration.

This model has been shown to be effective in predicting aflatoxin contamination in maize crops grown in Italy (Battilani et al., 2013), it was effectively used to assess the impact of climate change on mycotoxin risk in Europe (Battilani et al., 2016), and recently the model was successfully adapted to predict AFB1 occurrence in pistachio-nuts in Greece (Kaminiaris et al., 2020). A site-specific validation for Malawi was not managed as part of this study; however, mechanistic models, such as AFLA-maize, are designed to consider the cause-effect relationship between variables and no calibration is required when used in different geographies (De Wolf et al., 2003; Camardo Leggieri et al., 2013).

To run the AFLA-maize model it was necessary to obtain daily climatic data for each time-period and RCP scenario, as well as information on the crop development, namely the sowing date, emergence date, and harvest date. The methodologies for determining these model inputs, and the process for utilizing the model are described in the sections below.

4.3.1. Climate and Environmental Conditions

The daily temperature, precipitation and relative humidity data used in this assessment were output from a set of atmospheric Regional Climate Models (RCMs) from the African domain of the Coordinated Regional Climate Downscaling Experiment (CORDEX) initiative (see list of RCMs in Table C.2 in Appendix C). Within this initiative, all currently publicly available models which provide projections for both RCP 4.5 and 8.5 were selected, with one exception[12].

Limited by the resolution of the models[13], and the need to use a rectangular boundary, the assessment includes spatial data that are larger than the actual geographical boundary of the three Malawi regions, and some overlap in the three regions also exists, as shown by the shaded areas in Figure 4.1.

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[12] At the time of writing there was one additional RCM available that met these criteria, HIRHAM5_NorESM1-M, however this model has been excluded from this study. Based on the findings of Warnatzsch and Reay (2019), this RCM is a major outlier and does not simulate Malawi's temperature or precipitation well.

[13] All the RCMs used have a 0.44-degree (approximately 50km^2) resolution.

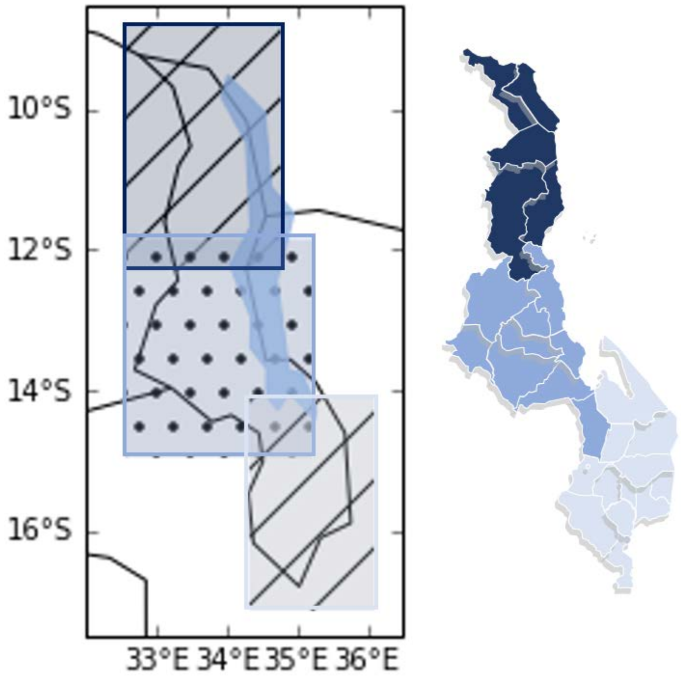

Figure 4.1: Assessment Boundary. *The map on the left shows the data boundary used in this assessment. Northern Malawi is indicated by the hatched area at the top (32.5 to 35 degrees East and -8.5 to -12.5 degrees South), Central Malawi is indicated by the dotted area in the centre (32.5 to 35.5 degrees East and -11.5 to -15 degrees South), and Southern Malawi is indicated by the hashed area at the bottom (34 to 36.5 degrees East and -14 to -17.5 degrees South). Black lines show national borders and the solidly shaded grey-blue area is Lake Malawi. The map on the right shows the actual land boundary with Northern Malawi in the darkest shade, Central Malawi in the mid-shade, and Southern Malawi in the lightest shade. The white lines show the district borders.*

Direct comparison of individual CORDEX model outputs is possible as the initiative sets a standard grid, domain size, experiment protocols, and data format (Giorgi et al., 2009; Nikulin et al., 2012). However, the CORDEX initiative does not dictate the calendar format resulting in some of the RCMs using a complete 366-day calendar (includes leap-days in relevant years), while others have a 365-day calendar or a 360-day calendar (assumes all months are 30 days). Before any direct comparisons or ensemble means could be calculated from the daily data outputs, it was necessary to make all the calendar formats the same. There is no standard method to do this, however the models used in this assessment require either a 365-day year (for AquaCrop) or 366-day year (for AFLA-maize). Therefore, in order to make the calendar formats comparable the methodologies established by Warnatzsch and Reay (2020) were applied.

The ability of these RCMs to hindcast daily mean temperature in Central Malawi was evaluated in a previous study. It was found that, while they are able to replicate relative changes in temperature well, they are not able to adequately simulate absolute temperatures (Warnatzsch and Reay, 2019). To account for this modelling bias, the temperature and precipitation projections were re-baselined using methods applied by the Met Office's United Kingdom Climate Projections (UKCP18) (Met Office, 2018) and the observed datasets detailed in Table C.3 (Appendix C) (Warnatzsch and Reay, 2020). An adequate observed database for historical relative humidity could not be found for Malawi and as such, the relative humidity data have not been re-baselined and the authors acknowledge that these data are a source of uncertainty.

As reference evapotranspiration (ETo) is not a climatic variable, the CORDEX-Africa models do not have an output for it. The reference evapotranspiration data for each time period were therefore determined using the FAO's Penman-Monteith (FPM) method (Allen et al., 1998a; Allen et al., 1998b), details of which can be found in the Appendix B. This methodology was tested for application in Malawi (Wang et al., 2011) and Southern Malawi more specifically (Ngongondo et al., 2012) and deemed appropriate for use.

Data for leaf wetness, an important variable for determining mycotoxin risk, were also not available for any region or time frame in Malawi. As such, an established empirical model to simulate leaf wetness was applied. This model assumes that if relative humidity was greater than or equal to 90%, or there was any precipitation (≥ 0mm) during that day, the leaf wetness would be equal to one (1), otherwise it was assumed to be zero (0). Evaluation of this model in various parts of the world has found that, in the absence of measured data, this empirical model performed better than other methods, although some over or under estimation was observed (Sentelhas et al., 2008). While the authors acknowledge that this is a source of uncertainty, Battilani et al. (2016) carried out a sensitivity analysis which found that the model accuracy was not significantly affected by adjusting leaf wetness within a realistic range.

Previous analysis on the performance of climate models to simulate precipitation in Malawi have found the model outputs to be highly divergent and not well correlated to observed precipitation levels (Mittal et al., 2017; Warnatzsch and Reay, 2019). However, in both the Warnatzsch and Reay (2019) and Mittal et al. (2017) a clustering of model outputs was seen around the ensemble mean, making this scenario more likely than either a minimum or maximum scenario. Based on these findings, the current study assessed future impacts on Malawi's three regions using an ensemble mean precipitation scenario. With regards to temperature, Warnatzsch and Reay (2019) found that the ensemble average adequately represented the temperature records of Malawi once adjusted for the bias, as described above. Therefore, our impact assessment was based on climatic scenarios built upon the bias-adjusted ensemble average outputs for daily precipitation rate and temperature, the ensemble mean relative humidity rates, and calculated reference evapotranspiration and leaf wetness. The full details of these climate scenarios can be found in Table C.4 and Table C.5 (Appendix C).

All data were formatted and output from the RCMs using a Python interface and a variety of open-source Python libraries and packages. The code used for each assessment can be found in the author's GitHub repository[14].

4.3.2. Crop Development

A crop model (AquaCrop) was used to determine the emergence date and the harvest date of two varieties of maize (slow- and fast-development) under the different climatic conditions (set out in Section 4.3.1) and initial sowing dates in each region of Malawi. The calibration of AquaCrop in this analysis was based on earlier calibration carried out by Warnatzsch and Reay (2020). Full details of the calibration for the two crop models is given in Table C.6 and Table C.7 (Appendix C).

With a broader geographic range, the calibration of AquaCrop for soil in this study differed slightly from Warnatzsch and Reay (2020). The dominant soil texture in Malawi is classified as sandy clay loam, accounting for over two thirds of the soil distributed across the country (Li et al., 2017). Li et al. (2017) found that the Northern Region also had a sandy loam texture in a tenth of the soil, while the Central Region had just under a tenth of its soil texture described as sandy loam. Other soil textures were found to account for only a small proportion of the soils. Therefore, the AquaCrop model was run using the sandy clay loam, sandy loam, and sandy clay default AquaCrop soil models. However, the soil choice was found to have no impact on the crop development dates in any region.

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[14] The author's GitHub directory can be found at: https://github.com/ErikaWarnatzsch/Maize-Aflatoxin-Risk

4.3.3. Aflatoxin Contamination Risk Assessment

The mechanistic model, AFLA-maize, was used to predict AFB1 contamination risk of two different maize varieties grown in the three regions of Malawi using crop development dates and the climate scenarios created using the methodology described in Sections 4.3.1 and 4.3.2 above. The original AFLA-maize model required hourly meteorological data input (Battilani et al., 2013), however this was not available for Malawi. Therefore, the methodology applied by Battilani et al. (2016) to adapt the model to work with daily meteorological data was used in this analysis. The sensitivity of the AFLA-maize model to this adaptation was tested by Battilani et al. (2016, supplementary material) and the results were found to be comparable.

4.4. Results

4.4.1. Projected Climate Change in Malawi

Malawi's current climate is classified as sub-tropical (Met Malawi, 2006). It has two distinct seasons: a warm and wet season in the spring and summer (October to April) and a cooler, dry season in the autumn and winter (May to September). Historic trends in Malawi's climate are shown in Figure C.1 (Appendix C). Temperatures fluctuate by an average of 11°C over the course of the day, with a larger range in the winter months than the summer. On average, the Northern Region of the country is the coolest, and the Southern Region is the warmest. Precipitation levels vary by region and season, with almost no rain in any region during the autumn and winter months (April – October). During the spring and summer months (November - March), the Northern and Central Regions tend to see more rainfall than the Southern Region. With reference evapotranspiration linked to temperature, a similar trend is seen for this variable; overall reference evapotranspiration is higher in the spring and summer, and lower in the autumn and winter. As temperatures decrease with latitude, reference evapotranspiration rates are highest in the Southern Region, and lowest in the Northern Region. Relative humidity levels are also tied to temperature and precipitation, although the annual trend shows a lag response, with the highest rates in February and lowest in October.

The seasonality that Malawi experiences is expected to continue under both RCP 4.5 and RCP 8.5 for the 2020-2049 and 2040-2069 periods. However, temperatures are set to increase in all regions and scenarios (see Table 4.1).

Table 4.1: Malawi's annual historic near surface temperatures and the projected future changes by region.

The historic annual mean, minimum and maximum surface air temperatures (Tas) in the three regions of Malawi for the 1971-2000 period, and the Regional Climate Model (RCM) ensemble mean projected change (Δ) in temperature for the 2035 (2020-2049) and 2055 (2040-2069) climate periods under the Representative Concentration Pathway (RCP) 4.5 and 8.5 scenarios.

		Southern			**Central**			**Northern**		
		Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Tas (°C)	1971-2000	17.9	23.4	29.3	16.6	22.1	27.7	15.4	21.0	26.9
Δ (°C)	2020-2049	1.4	1.4	1.0	1.4	1.4	1.4	1.4	1.4	1.4
RCP 4.5	2040-2069	1.8	1.8	1.4	1.9	1.9	1.9	1.9	1.9	1.9
Δ (°C)	2020-2049	1.6	1.5	1.1	1.6	1.6	1.6	1.6	1.6	1.6
RCP 8.5	2040-2069	2.5	2.5	2.0	2.5	2.5	2.5	2.6	2.5	2.5

With increasing temperatures, rates of reference evapotranspiration are also projected to increase slightly in all future time periods and regions (see Table 4.2). The ensemble mean shows a small decreasing trend in precipitation rate and relative humidity in all future scenarios and regions. The small change in precipitation (±5%) is supported by around half of the model projections, with a larger number projecting a reduction rather than an increase in precipitation in all future scenarios and regions.

Table 4.2: Malawi's annual historic precipitation rate, reference evapotranspiration rate (ETo) and relative humidity, and the projected future changes by region.
The historic precipitation rate, reference evapotranspiration rate (ETo) and relative humidity in the three regions of Malawi for the 1971-2000 period, and the Regional Climate Model (RCM) ensemble mean or calculated projected change (Δ) in these variables for the 2035 (2020-2049) and 2055 (2040-2069) climate periods under the Representative Concentration Pathway (RCP) 4.5 and 8.5 scenarios.

			Southern	**Central**	**Northern**
Precipitation (mm/year)	Absolute	1971-2000	1048	1085	1111
	Δ (%) RCP 4.5	2020-2049	-2%	-3%	-2%
		2040-2069	-2%	-4%	-3%
	Δ (%) RCP 8.5	2020-2069	-1%	-3%	-3%
		2040-2069	0%	-4%	-3%
ETo (mm/year)	Absolute	1971-2000	1301	1221	1198
	Δ (%) RCP 4.5	2020-2049	1%	4%	4%
		2040-2069	2%	5%	5%
	Δ (%) RCP 8.5	2020-2069	2%	4%	4%
		2040-2069	4%	11%	7%
Relative Humidity (%)	Absolute	1971-2000	67%	66%	67%
	Δ (%) RCP 4.5	2020-2049	-2%	-2%	-2%
		2040-2069	-3%	-3%	-3%
	Δ (%) RCP 8.5	2020-2069	-2%	-2%	-2%
		2040-2069	-3%	-3%	-3%

4.4.2. Changes in Crop Development

Projected climate change for the 2020-2049 and 2040-2069 periods, as described in Section 4.4.1, is not expected to have a significant impact on the date of emergence of either the fast- or slow-developing maize varieties considered here; shifting the date forward by an average of one day (maximum 2 days). However, the impact on the date of harvest is larger. Both maize varieties show little difference between the two future time horizons examined in either absolute or relative terms. However, the RCP scenario does impact the results for both varieties and all sowing dates with RCP 8.5 scenario leading to a shorter development time than the RCP 4.5 scenario in the same time period (see Table C.8 and Table C.9 in Appendix C for full results).

Figure 4.2 shows the absolute (top panel; (A)) and relative (lower panel; (B)) change in the number of days between sowing and harvest for the two varieties of maize in the three regions. For all future scenarios in all three regions and sowing dates, the time to harvest for the slow-development variety of maize shortens by a larger number of absolute days than the fast-development variety. However, on relative terms, the impact that future climate change has on the time to harvest depends on sowing date and variety. The slow-development maize variety shows a smaller relative advance in harvest timing with later sowing dates in the Northern and Central regions, but this trend is not followed in the Southern region. For the fast-development maize variety, the relative impact on the development time to harvest is smaller with earlier sowing dates in all regions.

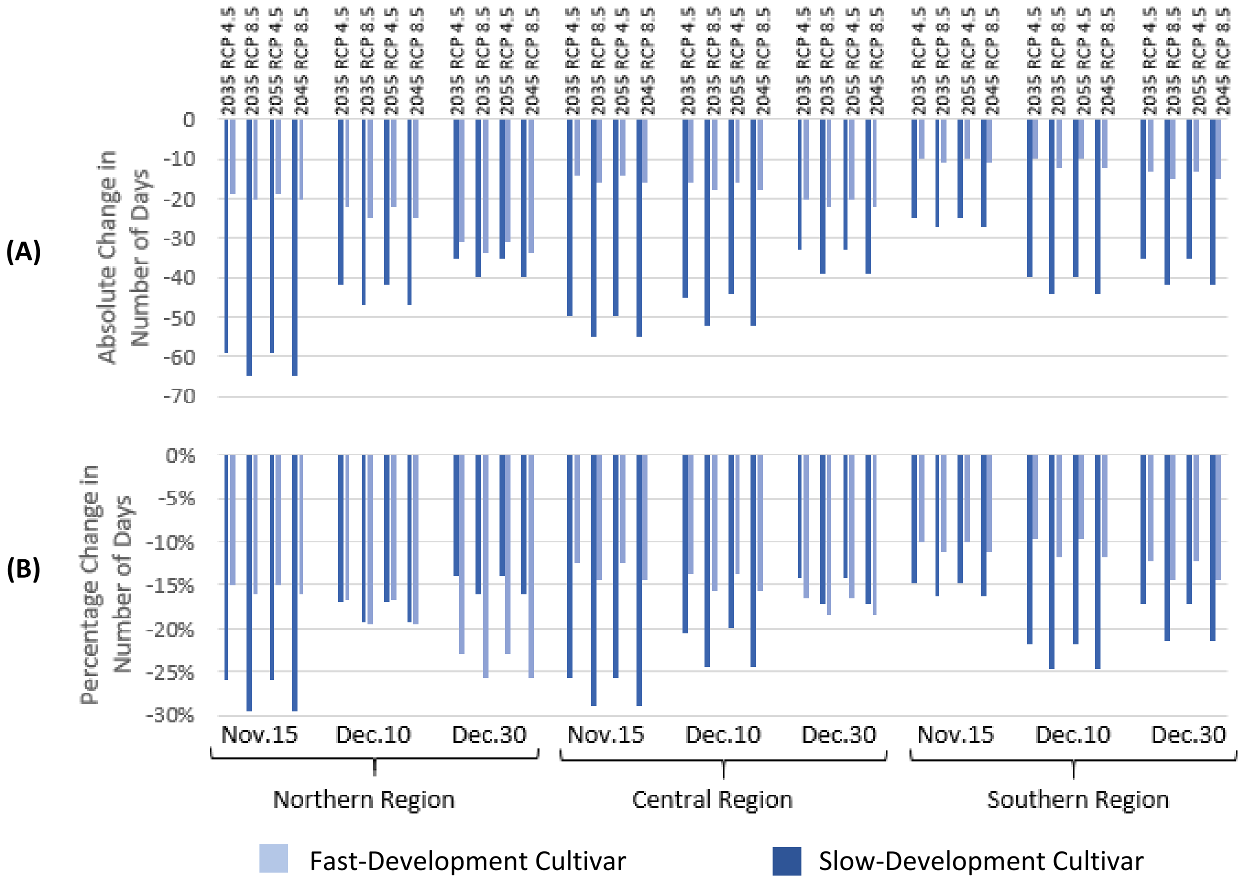

Figure 4.2: Impact of projected climate change on maize development.
Absolute and relative change in number of days between sowing date and harvest date for two maize cultivars under future climatic conditions compared to baseline period (1971-2000) by sowing date and region. The light blue and dark blue bars represents the results for the fast-development and slow-development cultivars respectively.

4.4.3. Changes in Aflatoxin B1 Contamination Risk

The primary output of the AFLA-Maize model - the aflatoxin risk index (AFI) - indicates the cumulative risk of AFB1 contamination in the crop during its development pre-harvest (Battilani et al., 2016). The AFI is calculated daily throughout the growing season of maize, although this study assesses the AFI at the point of harvest. If AFI = 0 this indicates that conditions are such that no interaction between the *A. flavus* and the maize crop was possible, and as such no AFB1 contamination risk is possible. Where the AFI result is larger than zero, then a host interaction is possible, which indicates that AFB1 contamination is also a risk. An AFI ≥ 95 is considered consistent with an AFB1 contamination equal to or greater than the current European threshold for legal AFB1 contamination, 5 µg per kg (EU, 2006; EU, 2010; EU, 2014). The results of the AFLA-maize analysis are shown in Figure 4.3 and Figure 4.4 (the numerical data is presented in tabular and graphical format in Table C.10 and Figure C.2 in Appendix C)

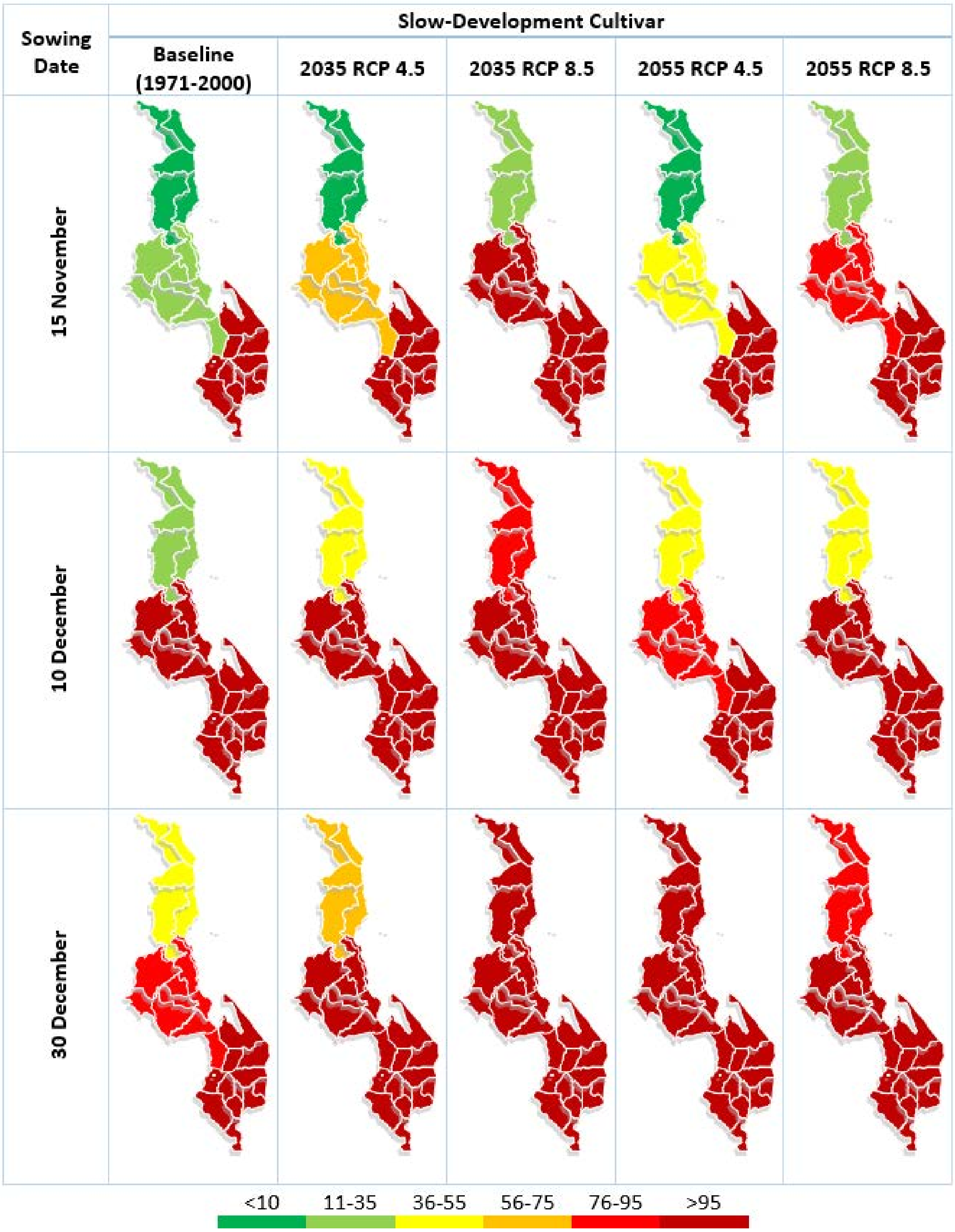

Figure 4.3: AFI risk for slow-developing maize cultivar in each region of Malawi under differing climatic conditions and sowing dates.

The first of the five columns represents the AFI risk under the baseline climate condition (1971-2000), the second and third column represent this risk associated with the 2020-2049 climate under Representative Concentration Pathway (RCP) 4.5 and 8.5 respectively, and the final two columns represent this risk associated with the 2040-2069 climate under RCP 4.5 and 8.5 respectively. The three rows represent the different sowing dates assessed: 15 November, 10 December and 30th of December. The index at the bottom places the AFI results into colour bands, with the deepest red indicating AFI levels which are consistent with exceedances of the EU threshold for AFB1 contamination in food.

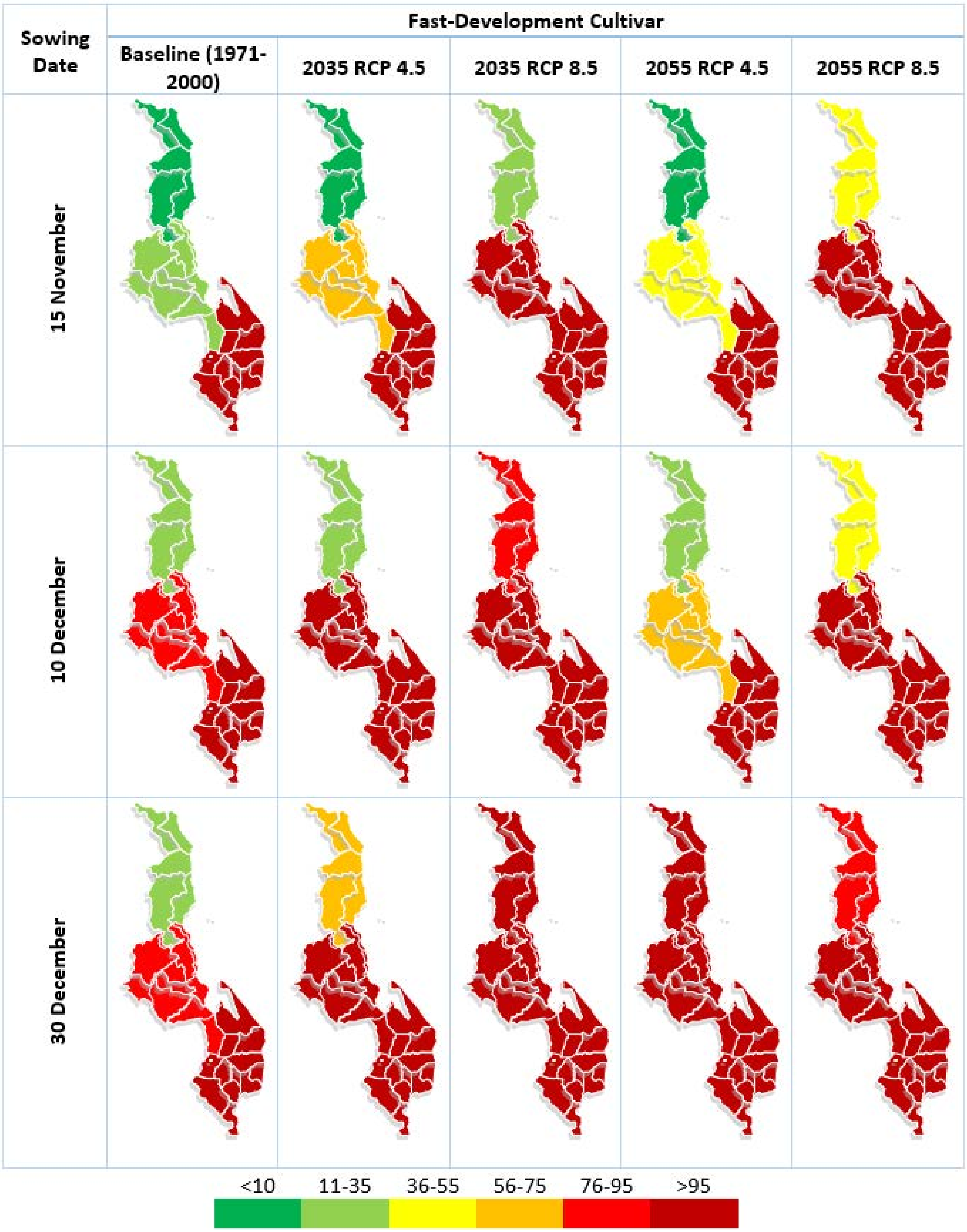

Figure 4.4: AFI risk for fast-developing maize cultivar in each region of Malawi under differing climatic conditions and sowing dates.

The first of the five columns represents the AFI risk under the baseline climate condition (1971-2000), the second and third column represent this risk associated with the 2020-2049 climate under Representative Concentration Pathway (RCP) 4.5 and 8.5 respectively, and the final two columns represent this risk associated with the 2040-2069 climate under RCP 4.5 and 8.5 respectively. The three rows represent the different sowing dates assessed: 15 November, 10 December and 30th of December. The index at the bottom places the AFI results into colour bands, with the deepest red indicating AFI levels which are consistent with exceedances of the EU threshold for AFB1 contamination in food.

Use of the baseline climate (1971-2000) indicates AFB1 contamination risk in both maize varieties to be possible (AFI>0) in all regions of Malawi, with the AFI lowest in the Northern Region and highest in the South. The model indicates that the EU legal threshold of 5μg AFB1 per kg is likely to be exceeded in the Southern Region regardless of sowing date or variety of maize, and some exceedances are possible in the Central region. Risk of EU legal threshold exceedances in the Northern region is low under these baseline climate conditions. For both maize varieties, later sowing dates in the Northern and Central regions largely result in higher contamination risk than earlier sowing dates, although this trend is not consistent in the Southern region.

In the future climate scenarios examined both varieties of maize show the same general trends: higher concentrations of AFB1 contamination and the risk of exceeding the EU legal threshold moving northward. The trend of later sowing dates resulting in higher contamination risk continues in the Northern and Central region under the future climate scenarios. However, there is still no consistent trend in the Southern region, where sowing date plays a smaller relative role in the changes observed. The only scenario where the maize shows a lower risk of contamination in a future climate relative to the baseline is in the Northern region with the earliest sowing date. This decrease in risk is linked to the shortened development time, which means the *A. flavus* does not have enough time to grow and produce high levels of AFB1 before the crop is harvested. This is also the reason the future climates under RCP 8.5 do not always show higher contamination risk than the RCP 4.5 climate in the same period; while the future climatic conditions are often more conducive to AFB1 contamination, the crop development is accelerated and therefore the toxin has less time to accumulate.

Similar levels of contamination risk are seen in both varieties of maize under the same climatic and sowing conditions, with no consistently strong trend seen in the Southern or Central regions between varieties. However, in the Northern region, the slow-development maize variety did show slightly higher levels of contamination risk than the fast-development maize variety which again is due to longer periods of time for the toxin to be produced before the time of harvest.

4.5. Discussion and Conclusion

Currently, the majority of maize is grown in the Central region of Malawi, with trade between the regions (FAOSTAT, 2018). We find that future climate change can be expected to increase the risk of pre-harvest AFB1 contamination in maize in all regions of Malawi. The risk of dangerous contamination levels (i.e., above EU legal thresholds) is expected to continue in the Southern region while also expanding northwards into the Central and Northern regions.

Our results are consistent with the findings of previous research which has shown that increasing temperatures, particularly when combined with lower precipitation levels during the early growing season, lead to higher levels of aflatoxin contamination (Battilani et al., 2008; Magan et al., 2011; Medina et al., 2014; Medina et al., 2017; Stepman, 2018). However, with significant uncertainty remaining around future precipitation rates, further analysis should be carried out with a range of precipitation scenarios to develop a more robust, higher resolution likelihood assessment for AFB1 contamination, and so avoid risks of maladaptation. With higher resolution climate models, it would also be possible to more confidently assess risk at a more granular level, such as using the six established agro-ecological zones of Malawi. This more detailed assessment would better align the risk assessment with regional agricultural strategy development.

Our research does suggest that changing to a faster developing variety of maize may limit the risk of AFB1 contamination at the time of harvest in parts of the country. However, this is not a solution for most of the maize growing areas and even where it is, it may not lead to lower contamination risk at the point of maize consumption. This study only looks at the cumulative risk index up to the point of harvest, however if *A. flavus* is present on the crop at the time of harvest or becomes contaminated with spores post-harvest, it is likely to keep growing and metabolizing toxins, particularly if storage conditions are not optimized (Mahuku et al., 2019; Channaiah and Maier, 2014; Neme and Mohammed, 2017). Erratic rainfall patterns, which are typical for Malawi, and social issues including theft of food crops before harvest, often lead to early harvesting (Matumba et al., 2014a). The crops are then frequently stored before adequate drying for extended periods of time and in facilities with inadequate or non-existent temperature and moisture control. When grain is stored with humidity and temperature suitable for fungal activity, these factors promote the further growth of moulds and leads to mycotoxin production. Aflatoxin synthesis is very rapid when grain humidity is lower than 28-30% (Payne et al., 1988; Giorni et al., 2016), and these conditions are consistent with the common water content of post-harvest maize without adequate drying. The issue of post-harvest contamination in a changing climate is therefore one that requires urgent examination in Malawi.

In addition to the need for research to be expanded to include post-harvest phases, research is required to understand how climate change will impact the contamination risk of other mycotoxins on maize, as well as the impact on other food crops. Despite the significant exposure risk and vulnerability of the population, AFB1 and other mycotoxin contamination does not yet appear to be a high priority from a public health policy standpoint in Malawi. While regulations limiting aflatoxins concentrations in food stuffs do exist, they only apply to products being exported or sold in supermarkets, and no regulation currently exists for other mycotoxins (Mwalwayo and Thole, 2016). Strict mycotoxin regulations do however exist in most developed countries which means that only the least contaminated crops can be exported, and the more contaminated foodstuffs are kept for local consumption (Mwalwayo and Thole, 2016; Matumba et al., 2015; Misihairabgwi et al., 2017).

Regulation on its own may not solve this issue as it would be likely to have little impact on the large quantity of subsistence-based farming in Malawi. Only 20 percent of maize farmers produce enough to sell their produce, with the remaining farmers only producing enough for their household's needs (Mwalwayo and Thole, 2016; Denning et al., 2009). Ambler et al (2017) found that farmers who reported their crop to be damaged (loss of quality) predominantly did not dispose of it, but instead diverted the crop from sale and seed to instead use for their own consumption. The underlying food security and poverty issues in Malawi are compounded by undiversified diets, and an inadequate or incomplete knowledge on the risks associated with mycotoxins in the general population. A study by Matumba (2016) found that while 88% of the population understood that moulds posed a risk to human health, few understood what that danger was, and half believed that any toxins would be destroyed by cooking, which is generally not the case (Bullerman and Bianchini, 2007). Therefore, with insufficient knowledge on the impacts of ingesting mouldy food, and most farmers selling their best product, the food remaining for household consumption is often the grain with the lowest quality and the highest probability of mycotoxin contamination (Mwalwayo and Thole, 2016).

Thus far there have been no serious mycotoxicosis[15] outbreaks reported in Malawi, possibly due to the limited reporting of cause of death and the difficulty of assigning causality to some aflatoxin affects, like immunosuppression, to the toxic ingestion. However, outbreaks have occurred in neighbouring countries with similar climates (Mwalwayo and Thole, 2016), and studies indicate that the Malawian population is already consuming contaminated food (Doko et al., 1996; Matumba et al., 2009; Monyo et al., 2012; Matumba et al., 2014b; Matumba et al., 2014d; Probst et al., 2014; Matumba et al., 2015; Mwalwayo and Thole, 2016). Worryingly, Malawi has very high rates of cancers which are known to be linked to mycotoxin exposure (Ferlay et al., 2014). However, while the correlation exists, no systematic study has been carried out to determine the causal factors or fully explore links with mycotoxin exposure and incidence of cancer or other health issues in Malawi (Mwalwayo and Thole, 2016).

Our study finds projected climate change is expected to cause the main food crop in Malawi, maize, to become more contaminated, with dangerous levels of AFB1 at the point of harvest in regions of the country that have not historically faced this challenge. Unless adaptation or mitigation measures are put in place to improve or change storage, consumption, and legislative conditions, this will likely lead to higher levels of toxins to be present in foods at the point of consumption. From a risk assessment perspective, the results of this paper represent a communication tool for stakeholders, including policy makers, to highlight the need for education and awareness of this risk. The approach followed in this study can significantly support emerging countries like Malawi to reduce local population exposure to aflatoxins, and therefore improve human and livestock health. Future research is required to explore what mitigation and adaptation measures are available and appropriate for use in Malawi, and the impact these may have on AFB1 contamination risk of Malawian maize crops. Further analysis of post-harvest contamination of maize, as well as the impact of climate change on other mycotoxins and food crops is now also urgently required.

4.6. References

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[15] Mycotoxicosis is poisoning caused by exposure to mycotoxins.

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Chapter 5 Opportunities and Challenges for Reducing Aflatoxin B1 Contamination Risk in Malawi's Maize Crops in a Changing Climate

5.1. Introduction

Over the past decade, research has begun to highlight the important link between health and climate change. The majority of research to date has focused on direct impacts from changing weather conditions and extreme events, and acute vector-borne illnesses such as malaria, dengue or tick-borne encephalitis (Watts et al., 2018). However, very little research has been published to investigate the important climate change, health, and food security nexus, and specifically the impacts on acute and chronic health conditions linked to food safety in developing nations such as Malawi. This is despite the Foodborne Disease Burden Epidemiology Reference Group (FERG) reporting that foodborne disease is estimated to have a health burden on the same scale as HIV/AIDS, malaria or tuberculosis, and 98% of the impact occurs in low- and middle-income countries, disproportionately affecting children (WHO, 2015).

While progress is being made to tackle issues of food security, Malawi still struggles with high levels of malnutrition, undernutrition and childhood stunting (Global Nutrition Report, 2019). The impact of these food-related issues are compounded by high incidence of communicable diseases in the population (FAO et al., 2015; IMF, 2017; The Global Fund, 2018).

Malawi is one of the most maize-dependent countries in the world with almost half of the Malawian diet, in terms of calories, met by this one crop (FAOSTAT, 2019). Maize is grown by 97% of smallholder farmers (Denning et al., 2009), who are responsible for 90 percent of all maize produced in the country (Lindsjö et al., 2020). Maize also plays a crucial role in the local economy, contributing between 5 and 10 percent of the country's annual Gross Domestic Product (GDP) over the last few decades (NSO, 2005; Arya et al., 2005; CIA, 2018; FAOSTAT, 2018). The vulnerability of maize to weather-based disturbances and the high dependency of the population on this single crop has led to multiple food shortages and economic shocks in recent years (Giertz et al., 2015).

The research presented in Chapters 3 and 4 of this thesis has shown that, with no adaptation measures taken, climate change is expected to impact both the quantity and quality of maize produced in Malawi, with potentially decreasing yields and increased risk of more widespread contamination by aflatoxin B1 (AFB1) (Warnatzsch and Reay, 2020; Warnatzsch et al., 2020). AFB1 is one of the most dangerous mycotoxins to human health, as it has carcinogenic, mutagenic, teratogenic, and immunosuppressive effects (Bbosa et al., 2013). Chronic exposure to dangerous levels of AFB1 can lead to aflatoxicosis with symptoms that include gastrointestinal haemorrhage, acute liver damage, oedema, impairment of digestion, and death (Sarma et al., 2017). Even low-level exposure to AFB1 can cause congenital malformation, impaired digestion, and childhood stunting (ibid.). The health impacts from AFB1 can arise from occupational exposure, but most commonly occur from direct consumption of contaminated food (Wangia et al., 2019). AFB1 is already known to be found at dangerous concentrations in the Malawian food chain (Matumba et al., 2014b; Mwalwayo and Thole, 2016), however the full extent of current AFB1 exposure in the food supply is not well understood. Estimates by the Partnership for Aflatoxin Control in Africa (PACA, 2020b) suggest 75,400 healthy life years[16] are lost annually due to liver cancers associated with aflatoxin exposure in Malawi, representing a USD 393.6 million loss to the local economy. This impact is significant, but it is important to remember that liver cancers are just one potential health outcome; the true impact of AFB1 contamination in the Malawian food supply chain has never been fully assessed. In addition to health implications, aflatoxin contamination also poses a major constraint on access to highly profitable export markets (Gichohi-Wainaina et al., 2021).

The combination of decreasing domestic maize supply, growing risk of dangerous AFB1 exposure, little domestic regulation on mycotoxin levels in food stuffs produced, sold, and consumed in the country, and high levels of existing vulnerability, is likely to have dire consequences for Malawi. This chapter sets out to discuss existing measures in place to improve food security and control AFB1 risk in Malawi in a changing climate, and some of the opportunities and challenges that the research community, policy makers, consumers and producers of maize in Malawi have when it comes to meeting this challenge.

5.2. Existing General Food Security Measures

Malawi is classified as having a 'high commitment' in the Hunger and Nutrition Commitment Index which ranks governments on their political commitments to tackle hunger and undernutrition (HANCI, 2020). In the early 2000s the country experienced severe droughts which resulted in large-scale food shortages affecting millions of people (Chinsinga, 2004). These climatic events were a tipping point for an already struggling agricultural sector, marred by a soil fertility crisis and relying on traditional low-technology rain-fed farming systems (Mango et al., 2018). These events sparked high level debates at various levels of national and local government and culminated in the creation of the Farm Input Subsidy Programme (FISP) in 2005 (Kawaye and Hutchison, 2018). FISP aims to increase resource access for smallholder farmers, including fertilisers and high quality seeds (Ministry of Agriculture Irrigation & Water Development, 2018a). In 2010 the Agriculture Sector Wide Approach (ASWAp) was introduced to build upon FISP to boost maize production, reduce on-farm postharvest losses and improve food security (Ministry of Agriculture Irrigation & Water Development, 2018b). ASWAp directed investments towards improving access to production inputs, on-farm storage technologies and facilities, and promoting good agricultural practices (ibid.). Within ASWAp, arrangements were made for the establishment of a Technical Working Group (TWG) for Food Security and Risk Management, and a TWG for Commercial Agriculture and Marketing (MAPAC, 2013). These TWGs would have relevance in the control of food safety in crops for domestic consumption and export respectively, however, to date, no publicly available information on their status or remit is apparent.

As part of Malawi's Growth and Development Strategy (MDGS), the agricultural sector has been highlighted as one of the key priority areas requiring targeted investment in order to meet the various domestic and international development frameworks which Malawi has committed to, including the Sustainable Development Goals (SDGs) (UN General Assembly, 2015), the pan-African Agenda 2063

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[16] The years of life lost (YLL) is a recognised measure of the impact of premature mortality on a population. According to the WHO (2006) this measure considers not only the number of people who have died, but also the age at which death occurs and a standard life expectancy at the age at which the death occurred. The healthy years of life lost, also known as the Disability Adjusted Life Years (DALY) extends the YLL concept to also include the impact of disease or disability on the number of 'healthy' years a person has lost (WHO, 2006).

goals (African Union Commission, 2015), the Vienna Programme of Action (VPoA) (UN, 2014), the Istanbul Programme of Action (UN, 2011), amongst others.

Now in the third phase, MDGS III (2017-2022) is targeting investment for climate change adaptation of the agricultural system and improved water resource management. The specific aims of the MDGS III relevant to these key areas, as well as the summary of costs per strategy, are listed in Table 5.1. A breakdown of the costs by year can be found in Annex 5 of the MDGS III strategy document (Government of Malawi, 2017). Note that the total 5-year expected cost for this programme is 985 227 million Malawian kwacha (MK) which, using an exchange of 1MK = 0.0013USD (accurate on the 11th January 2021 (XE, 2021)), equates to 1 263.11 million USD.

Table 5.1: Outcomes and Strategies for Agriculture, Water Development and Climate Change Management, and associated 5-year total costs (2017-2022) in millions of Malawian kwacha (MK) (Government of Malawi, 2017)

	Outcome	**Strategy**	**5-year total cost (mill. MK)**
AGRICULTURE	Increase agricultural production and productivity	Promoting and strengthening agricultural extension and rural advisory services	11 502
		Supporting inclusive agricultural innovation systems for research, technology generation, and dissemination	18 110
		Increasing agricultural mechanisation	3 189
		Promoting infrastructure investments for large scale irrigation schemes	66 001
		Facilitating and supporting improved coordination and capacity as well as infrastructural development for improved agricultural service delivery	62 361
		Promoting reforms of agricultural institutions and programmes to make them more sustainable and cost effective	1 283
	Increase land under irrigation	Developing areas with irrigation potential	77 219
		Conducting and promoting research and use of appropriate technologies in irrigation	1 467
		Enhancing technical and institutional capacities in irrigated agriculture	1 583
	Increase agricultural diversification	Promoting diversified crop, livestock production and utilization	5 379
		Promoting and encouraging sustainable fisheries management and commercial aquaculture development	18 845
	Improve nutrition and food security	Fostering adequate market supply of diverse and nutritious foods	15 293
		Promote technologies that reduce post-harvest losses in storage, preservation, and food processing	23 032
		Promoting private sector investments in production, processing, and marketing of high-quality nutritious foods, including complementary foods	187
		Promoting bio-fortification and fortification of major staple foods	21 237
		Promoting food and nutritional education for all	963

		Promoting education and research into use, propagation and conservation of indigenous Malawian food	1 340
	Increase agriculture market development, agro-processing and value addition	Promoting regional and global exports of value-added agricultural commodities	1 701
		Supporting improvements in quality standards and grading systems for all agricultural commodities	2 016
		Promoting the development of efficient and inclusive agricultural value chains	46 397
		Facilitating the creating of new structured markets, especially in oilseeds, sugarcane, livestock, and animal feed and fisheries products	1 642
		Strengthening and harmonising agricultural market information systems	2 726
		Ensuring transparency in trade policies and regulations	784
		Promoting agricultural value addition and agro-processing	1 035
		Coordinating and strengthening agricultural marketing	67 295
	Enhance agricultural risk management	Promoting climate-smart agriculture and sustainable land and water management	4 572
		Promoting integrated soil fertility management.	23 529
		Promoting sustainable irrigation in crop production	102 410
		Promoting integrated conservation and utilisation of Malawi's rich agro-biodiversity	3 862
		Promoting market risk management	1 047
		Harmonise key messages and incentives on climate-smart agriculture	1 034
		Promoting integrated pest and disease management	Unknown
	Increase empowerment of the youth, women, persons with disabilities and vulnerable groups in agriculture	Promoting establishment of cooperatives	2 690
		Promoting access to, ownership and control of productive resources	570
		Promoting agricultural education and technical training for women, youth, and vulnerable group	3 880
		Promoting access to finance for women, youth, and vulnerable groups in agriculture	2 110
WATER DEVELOPMENT	Increase access to water resources	Improving efficiency and sustainable use of water in all irrigation schemes	35 050
		Supporting integration of irrigation in power generation in sustainable water management investment	116 744
		Enhancing rainwater harvesting, conservation, and utilization	21 795
		Improving water supply in rural and urban areas	101 220
		Promoting empowerment of local communities to properly develop and manage catchment areas	2 640
	Enhance integrated water resource management at all levels	Institutionalising practical Operations and Maintenance (O&M) framework at all levels	820
		Promoting community-based management of rural water supply facilities	428
		Strengthening monitoring and evaluation system for water utilization and management	1 295
		Promoting scientific research and investigation	585

CLIMATE CHANGE MANAGEMENT	Improve weather and climate monitoring for early warning, preparedness, and timely response	Promote effective and efficient generation analysis and utilisation of reliable, responsive, high quality, up to date and time climate service	1 815
		Improving spatial by area and agro-ecological zone) weather and climate monitoring and prediction systems through automation and other IT advances	47 940
	Strengthen policy operating environment for climate change and meteorological services	Harmonizing climate change related policies	582
		Developing and enforcing legal and regulatory framework in climate change management	519
		Mainstreaming climate change issues in sectoral policies, plans and programmes	2 760
	Enhance community resilience to climate change impacts	Promoting the adoption of low carbon emission development strategies	1 510
		Improving adoption of climate change adaptation and mitigation measures	975
		Implementing a comprehensive national climate change investment plan	22 502
		Enhancing cross sectoral coordination of climate change programmes	687
		Improving access to domestic bilateral and multilateral climate financing and private sector investment	404
	Enhance climate change research and technology development	Promoting research, technology development and transfer in climate change and meteorology	26 665

This third phase of the MDGS does broaden the focus of investment on food security significantly, however it still concentrates mainly on food availability and access, with some actions targeting food stability, but little or no attention paid directly to food safety. Many of the actions highlighted in Table 5.1 could indirectly help address mycotoxin risks and improve food safety, such as education programmes, irrigation technologies, research, and infrastructure improvements, however without the details on how these strategies will be implemented it is not possible to assess the impact these may have. In addition, strategies proposed under the remit of the other key MDGS III sectors could have wider indirect impacts on food safety, including via reducing gender inequality, improving education, improving transportation infrastructure, increasing health care provisions and general health research (Government of Malawi, 2017).

Malawi's so-called "Green Revolution" has been generally praised, with maize yields showing improvements that have been attributed to these policies (Kawaye and Hutchison, 2018). Acknowledging the importance of the agricultural sector to the Malawian economy and overall population welfare, average public expenditure on food and agriculture between 2006 and 2017 represented 20 percent of total public budget (see Figure 5.1). This makes Malawi one of the few countries who have exceeded the Comprehensive Africa Agriculture Development Programme

(CAADP)[17] commitment of spending at least 10 percent of its national budget on agriculture (OSAA, nd.; Mwabutwa, 2017). However, actual spending for improvements within the sector have been volatile and, whilst a large portion of the financing over this period was allocated to trade and market infrastructure (e.g. road development and rehabilitation), investment into transport and storage services, inspection facilities and information systems was low (FAO, 2015). There has also been criticism of how the policies have concentrated mainly on maize inputs (seeds and fertilisers), with this one crop type receiving an average of 50 percent of all public expenditure in the agriculture sector between 2005 and 2013 (ibid.). This focus has been considered a hindrance to the diversification of agricultural production, and a distraction from more long-term investments into other required public goods (e.g., research, irrigation, and other risk management tools) (ibid.). Possibly due to these shortcomings, this high level of expenditure has not resulted in a steady growth of value from the agricultural sector; between 2006 and 2017 agricultural value growth has been below the CAADP target of 6 percent (OSAA, nd.), averaging only 2.6 percent (The World Bank, 2020a) (see Figure 5.1).

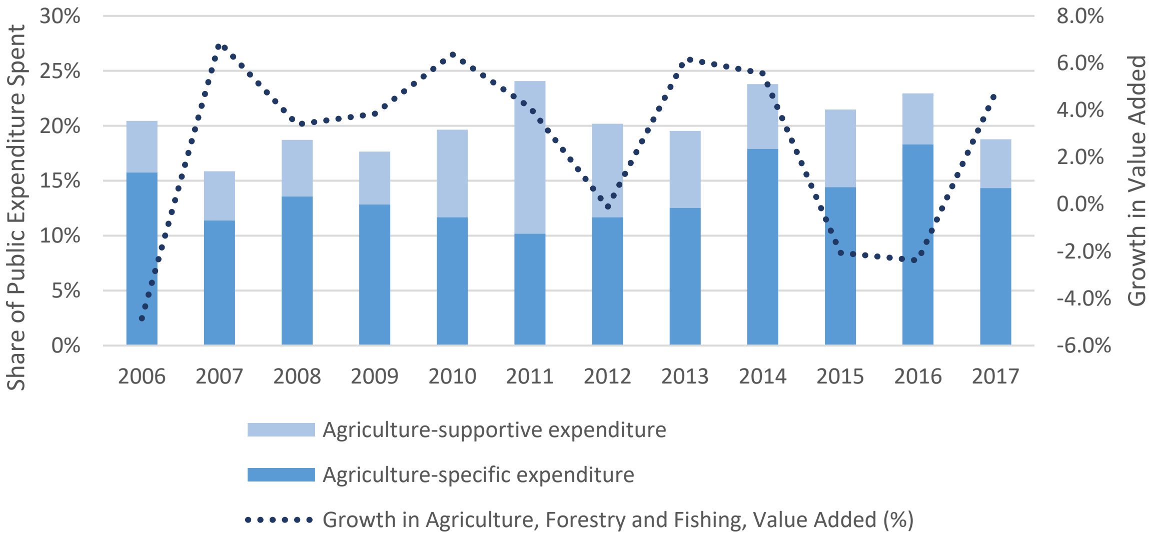

Figure 5.1: Share of public expenditure and growth value added from the Agricultural Sector. *The primary vertical axis (left) shows the share of total public expenditure in Malawi allocated to the food and agriculture sector (FAO, 2020b), while the secondary vertical axis (right) shows the change in agricultural, forestry and fishing value added (The World Bank, 2020a) by year (2006-2017). The agriculture-specific expenditure includes payments to producers, consumers, processors, traders, and transporters of agricultural goods, as well as general support of the food and agriculture sector. The agriculture-support expenditure includes spending on the rural agricultural sector, including rural education, rural health, and rural infrastructure (including roads, water and sanitation and energy).*

Malawi is arguably making good progress on improving food security; however, the situation is still dire. The prevalence of under-fives stunting - a measure of chronic malnutrition - has dropped from 47 percent in 2010 to 37.1 percent in 2017, but is still fifth highest in the Southern Africa Development Community (WFP, 2019). While the government has made efforts that have resulted in increasing maize yields over the past two decades, the increases achieved are modest when compared to global improvements in maize yields, in both absolute and relative terms (see Figure 5.2). The population is

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[17] CAADP is a programme designed to boost investment and stimulate growth in Africa's agricultural sector to stimulate economic growth, create benefits for smallholder farmers, increase food production and end hunger across the continent.

frequently reliant on food aid as the supply of food is still very sensitive to shocks. 2020 has been another challenging year for Malawi due to diminished harvests from flood and drought impacts through the first part of the year, COVID-19 restrictions, and a high number of refugees coming from the Democratic Republic of Congo and Burundi (USAID, 2020a). In addition to these domestic challenges, due to high demand for maize from neighbouring countries who have experienced drought, the price of maize has nearly doubled compared to the five-year average, limiting the purchasing power of poor households (ibid.). The situation going into 2021 has not improved. On January 26th, 2021, the Government of Malawi issued a press release stating that food aid and cash assistance was required for 2.6 million people who face immediate severe food insecurity due to lower crop production related to weather conditions, and lower purchasing power as a result of the on-going COVID-19 pandemic (Government of Malawi / World Food Programme, 2021).

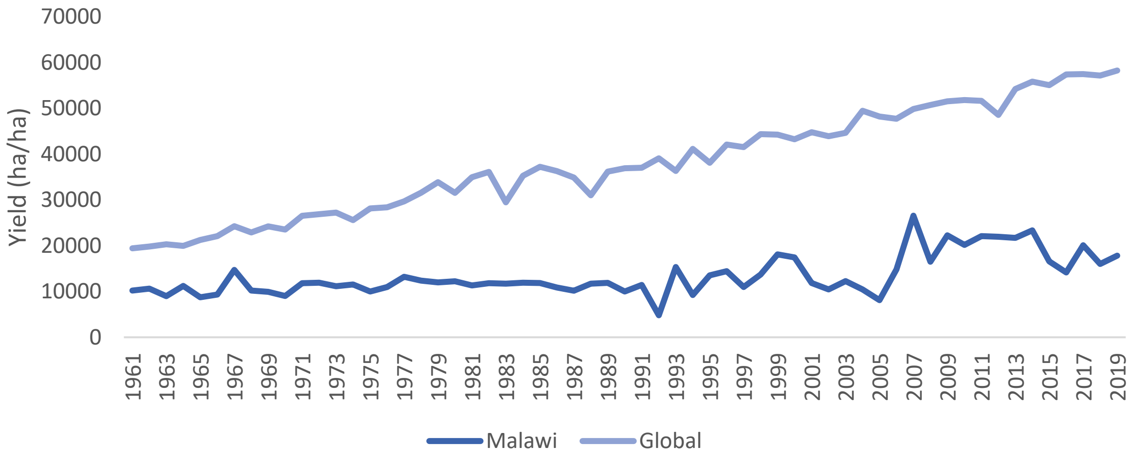

Figure 5.2: Changes to global and Malawian maize yield in hg/ha (1961 - 2019) (FAOSTAT, 2020)

5.3. Existing AFB1 Contamination Risk Control Measures

Based on extensive database and literature searches, there appears to be limited publicly available material to allow a full understanding of historical policy development and determine the current status of aflatoxin contamination controls in Malawi. Available materials tend to be rather dated and some of the documents contradict each other on simple aspects such as the year in which actions took place. Despite attempts to contact key personnel in the Malawian Government and Partnership for Aflatoxin Control in Africa (PACA) to ascertain whether more recent aflatoxin control measures have been put in place, no response has been forthcoming. The following section therefore summarises the best available public information on the historical and current aflatoxin controls in Malawi. This information is based on all currently available information in the public domain and is intended to provide a baseline for exploring future actions. Unless a different reference is given, it should be assumed that all of the information in the following sub-section of section 5.3 has been sourced from a Malawi Programme for Aflatoxin Control (MAPAC, 2013) report entitled "Advancing Collaboration for Effective Aflatoxin Control in Malawi".

5.3.1. Development of the Malawi Programme for Aflatoxin Control (MAPAC)

In 2011 the Malawi Ministry of Industry and Trade (MoIT), with the support of USAID, set out to assess what barriers existed to expanding export of Malawi's agricultural products. As part of this assessment, aflatoxin mitigation, management, and control (particularly associated with groundnuts) was highlighted as one of the top four issues needing to be addressed to support export growth. Following on from this, a consultative process was initiated to develop an aflatoxin control programme to improve groundnut exports. Through this consultation process, stakeholder recommendations were made, and the initial programme scope was expanded from its trade focus to also include domestic food safety. The Malawi Programme for Aflatoxin Control (MAPAC) was established in 2012 with the goal of improving collaboration and coordination of aflatoxin control in the country. MAPAC's key objective is the development of Malawi's capacity for effective aflatoxin control, and they aim to achieve this through three primary actions:

- Strengthen testing, standards, and policies
- Mainstream good practices and technologies into key value chains; and,
- Create public awareness, advocacy, and consumer education (Dakamau, 2016).

It is unclear what exact investment has been made into each of these three strategies, although the 2013 MAPAC report and a 2016 presentation from the second PACA Partnership Platform Meeting in Entebbe, Uganda indicates the scale of proposed investment for a variety of actions. The initial estimates for required investment for AFB1 intervention ranged from 820,000 to 1.03 million USD (MAPAC, 2013), while the later PACA presentation estimated 1.48 million USD for the 2017-18 MAPAC budget for AFB1 interventions (Dakamau, 2016).

While MAPAC is the main domestic initiative for aflatoxin control, they are not working alone, and they work to bring alignment of domestic actions with global and regional initiatives. MAPAC have received funding support from the Standards and Trade Development Facility (STDF), the UK Department for International Development (DFID), USAID and several others. There is also information and support that can be drawn on from regional initiatives such as the Partnership for Aflatoxin Control in Africa (PACA, 2020a) and global initiatives such as the World Bank's Global Food Safety Partnership (GFSP, 2020), the USAID Southern Africa Trade and Investment Hub (SATIH) (USAID, 2020b) and the Agricultural Productivity Program for Southern Africa (APPSA) (CCARDESA, 2020). MAPAC has also sought partnership and collaboration with other domestic organisations to tackle aflatoxin risk, including the National Smallholder Farmers' Association of Malawi (NASFAM) and the Ministry of Agriculture, Irrigation and Water Development.

Through MAPAC and their partners, a variety of actions have been taken to control aflatoxin contamination in the food supply for domestic consumption and export from Malawi. These actions are described in the following sub-sections.

5.3.2. Regulating, Policing and Quantifying the scale of contamination and exposure of population:

Various academic studies have been undertaken to determine current levels of aflatoxin contamination in the Malawian food chain (e.g. Monyo et al. (2012), Matumba et al. (2014c), Mwalwayo and Thole (2016) and Njoroge (2018), among others). These have concluded that there is widespread contamination of foodstuffs sold and consumed in Malawi at concentrations of aflatoxin above CODEX international food safety levels. The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and Kamuzu Central Hospital collaborated to expand the scope of testing to determine the level of exposure within the Malawian population. In their study, blood samples were taken from locals living within various districts in Malawi and tested for biomarkers which indicate aflatoxin exposure. Samples of groundnuts and maize from the households of the study participants were also tested for contamination to help determine the likely source of any exposure. This study is complete and found biomarkers indicating exposure to AFB1 in 67% of blood samples. AFB1 was also found in 91% of groundnut and 70% of maize samples in the participants homesteads. The results of this study can be found in Seetha et al. (2018).

The Malawian Bureau of Standards (MBS) has the legal responsibility of providing testing of domestic and imported commodities. The 2013 MAPAC report highlights that confidence in MBS's capabilities has been low. Therefore, while building confidence in government laboratories, investment has also been made into improving the testing capacity of Malawi's private laboratories for providing low-cost testing for aflatoxin contamination in maize. This includes investment support from the Bill and Melinda Gates Foundation (Bill and Melinda Gates Foundation, 2009). It is unclear whether investment in this type of test development or provision is still on-going, although more recent statements by the Bill and Melinda Gates Foundation indicate that investment has been broadened to move away from specific aflatoxin control to a "more holistic view of food systems and multiple pathways for spurring change, including by empowering women" (Bill and Melinda Gates Foundation, 2020).

As part of the improvements in testing capacity, the Chitedze Agricultural Research Station (CARS), was established to carry out various tests including testing of aflatoxin contamination in maize. Unfortunately, during a 2011 external audit, deficiencies were highlighted at both MBS and CARS and as a result accreditation of these laboratories by the Southern Africa Development Community Accreditation Service (SADCAS) was not possible at the time. With the assistance of the United Nations Development Programme (UNDP) and with European Union (EU) funding, MBS was able to make the necessary improvements and achieve accreditation for robust internationally-recognised aflatoxin testing in November 2018 (UN Industrial Development Organisation, 2018). With funding support from the United States (US) Government, CARS similarly underwent updates and improvements (Aflasafe, 2019), however their current accreditation status is unknown. In recent years, research organisations including ICRISAT have also developed testing capacity using quick, low-cost and user-friendly technologies (ICRISAT, 2019).

Regulation for aflatoxin contamination exists in Malawi for maize (3 ppb), in-shell nuts (10 ppb) and nut kernels (3ppb). However, these regulations are not well monitored or regulated, particularly for food grown and consumed domestically. The MAPAC (2013) report also makes reference to the intended creation of a roadmap for the development of a Food Safety and Quality Policy (FSQP) and Food Safety and Quality Bill (FSQB), however no publicly available information has been found on the progress of these roadmaps or documents.

5.3.3. Aflatoxin control measures

Academic research has been undertaken in Malawi and internationally to assess how different processes and technologies can be used to control initial aflatoxin contamination or decontaminate maize already contaminated with aflatoxin. In their 2013 report, MAPAC has stated that they endeavour to develop the research capacity of the National Agricultural Research System (NARS) through international collaboration. This includes piloting and validating emerging technological solutions and seeking investment to pilot the use of a biological control (*Aflasafe*) on Malawi's crops. MAPAC also outline a range of agronomic and postharvest management techniques that can be implemented to reduce contamination risk in groundnuts, however some of these are applicable to aflatoxin control in maize as well (see Table 5.2).

Table 5.2: Range of intervention strategies proposed for aflatoxin management/control in Malawian groundnuts (MAPAC, 2013)

Pre-Harvest	• Development of aflatoxin-resistant varieties • Quality seed and planting varieties suited to agro-ecological conditions • Early planting • Property planting densities • Fertilisation / including soil amendments • Pest controls • Irrigation (or water retention practices (tied ridges)) • Crop rotation • Cultural practices that reduce weed growth, lower the incidence of soil insects, mites, and nematodes • Application of biological controls
Harvest	• Proper harvesting (avoid early lifting) – harvest the groundnuts at full physiological maturity • Shake the groundnut plant after lifting to remove excel soil from pods • Avoid mechanical and physical damage to pods at all stages of harvesting • Remove and destroy all dead plants. Do not mix immature pods and damage gleanings with main produce
During Drying	• Dry harvested pods to moisture levels of 6-8% • Slow drying in a well-ventilated environment • Clean and dry containers for transporting nuts from either the field to storage or from storage to markets to avoid contamination
In Storage and Transportation	• In-shell storage • Only store nuts that are properly dried • Storage in a dry and ventilated environment protected from insects • Use clean and dry bags and stack them on pallets or poles • Make sure stacks of good sizes are made, i.e. up to 10 bags high. Use of propylene bags is not recommended • Periodically check stored groundnuts for mould growth and insect infestation • Shift from manual to mechanical shelling • Avoid water addition during manual shelling and/or previous to marketing for enhance weight • Groundnut pods and kernels should be carefully sorted and graded • Defective (mouldy, discoloured, rancid, decayed, shrivelled) nuts must be removed • Blanching nuts (large processing) / Physical treatment in combination with sorting
Dietary and Food Processing Interventions	• Diversification of consumption (reduce dependency of maize) • *Novasil* clay for decontamination of animal feed
Health Related	• Vaccination against Hepatitis B.

It is unclear what progress has been made on all the above-mentioned suggestions or how these translate to maize crops in the country, however some information is available on a few of the points. With regards to the pre-harvest stage, some good progress has reportedly been made on bio-controls. After a three year trial period, two *Aflasafe* biocontrol products have been launched in Malawi to reduce aflatoxin contamination during crop production and post-harvest (IFPRI, 2019). *Aflasafe* MW0MZ01 (regional) and MW02 (Malawi-specific), when applied directly to crops in the pre-flowering stage, produce locally native strains of the fungus *Aspergillus flavus* that do not produce aflatoxin and out-compete and displace the toxin-producing strains (IITA, 2020). Through this process these two bio-controls have been shown to reduce aflatoxin levels in both groundnuts and maize by over 80 percent (ibid.). They were approved for more widespread application by the Malawi Agricultural Technical Clearing Committee (ATCC) in December 2018 and the Pesticides Control Board (PCB) in 2020 (IFPRI, 2019; IITA, 2020). As of April 2020, it is understood that a commercialization strategy is being produced for the *Aflasafe* bio-control products to allow for more widespread uptake and use (IITA, 2020). As of January 2021, the *Aflasafe* website lists Malawi as a registered country, but does not yet list the products as on sale or available (Aflasafe, 2020).

For the harvest and processing stages, a paper by Matumba et al. (2014d) investigated the effectiveness of hand sorting, flotation/washing, dehulling (and combinations of these processes) to decontaminate mycotoxin contaminated white maize in Sub-Saharan Africa (SSA). They found that some of these techniques could reduce contamination of ingested food, with hand sorting having the greatest impact. It is unclear how or if this information has been disseminated to the Malawian maize farmers or consumers.

With regards to action by the health sector, proposals to improve Hepatitis B vaccination while also controlling aflatoxin exposure could have a great impact on the health impact of AFB1 exposure within the population. Hepatocellular carcinoma (HCC) is the most common type of liver cancer, accounting for 85-90 percent of all primary liver cancer diagnoses (NORD, 2017). While relatively rare in some parts of the world, globally hepatocellular carcinoma (HCC) is the sixth most common type of cancer, with incidence rates increasing year-on-year (Kew, 2012; Hamid et al., 2013). The prognosis of patients with HCC is not good; it has the highest 12-month fatality ratio of any human tumour (93-96 percent) (Kew, 2012). The exact causes of HCC are not fully understood, but HCC incidence in the developing world has been shown to occur primarily in people who suffer from chronic liver diseases, such as cirrhosis, secondary to infection by the Hepatitis B virus and/or exposure to AFB1 contamination (Magnussen and Parsi, 2013; Mayo Clinic, 2021). Further analysis of cases has shown that people exposed to both Hepatitis B virus and aflatoxins are 30 times more likely to develop HCC than people exposed to aflatoxins alone (Magnussen and Parsi, 2013). An established vaccine is available for Hepatitis B which has been shown to be safe and effective (Mansoor and Salama, 2007; Plymoth et al., 2009). The Hepatitis B vaccine has been part of the routine childhood vaccination schedule in Malawi since 2002, with a 93% uptake of all three required doses (Stockdale et al., 2018). While immunisation of adults against Hepatitis B is also effective, there is no publicly available information on uptake of the vaccine by the adult population in Malawi. It is hoped that, moving into the future, with continued high infant uptake and improved aflatoxin controls, incidence of HCC will decline in Malawi.

Using the FAO/WHO food control system assessment tool (FAO and WHO, 2019), a participatory assessment of the national food control system was also carried out in Malawi in 2017-18 (FAO, 2021c). A national food control system *"ensures that food available within a country is safe, wholesome and fit or human consumption, conforms to food safety and quality requirements and is honestly and accurately labelled as prescribed by law. As such, food control systems protect the health and safety of consumers and help assure the safety and quality of food being traded both nationally and internationally"* (FAO, 2021b). This assessment provided a more up-to-date and in-depth understanding of Malawi's national food control system and has created a baseline for future food policy development (ibid.). This process also included training workshops on assessment of mycotoxin risks and microbiological risk management (FAO, 2019). Following on from these learnings and activities, the Government of Malawi signed a new Technical Cooperation Project (TCP) with the FAO to help strengthen the national food control system in Malawi. This TCP will run until the end of 2022 (FAO, 2021c).

5.3.4. Education and awareness

MAPAC has produced a communication and education strategy to increase awareness of the risks of aflatoxin contamination amongst farmers in Malawi. A study by ICRISAT in 2008-9 found that existing awareness of the risks in the Malawian farming community was low (65% nationally) (Monyo et al., 2012). The study highlighted the use of radio programmes, extension officers, and neighbouring farmers as effective channels for communication on the subject.

A publicly available PowerPoint presentation from the second PACA Partnership Platform Meeting in Entebbe, Uganda, indicates that between 2014 and 2016 MAPAC produced a communication and awareness strategy, a skills development plan, and educational communication materials including brochures and posters (Dakamau, 2016). It was not possible to find public copies of the strategy or plan, and it is unclear whether MAPAC are tracking the impact of these campaigns.

Through funding from the McKnight Foundation, a video on the risk posed by aflatoxins found in groundnuts was produced and translated into 10 African languages, including Chichewa, one of Malawi's major languages, spoken by over half of the population (PAEPARD, 2017b). This video was made freely available and downloadable online (Stepman, 2018). A second short video developed by the government of Malawi was produced in 2017 to educate the population on the causes, risks, prevention and control of aflatoxins (PAEPARD, 2017a). This video featured leaders from the public sector, consumer rights bodies, farmers' organisations, research instructions and other key stakeholder groups (ibid.). The video was aimed at the public and aired on various TV stations in Malawi (ibid.).

A study by Anitha et al. (2019) found some marginal improvements after training of farmers in three of Malawi's districts on recommended pre- or post-harvest aflatoxin control measures; after training, knowledge and implementation of the practices was marginally improved, and the level of aflatoxin contamination in their maize crops had decreased from 83.6 to 55.8 ppb, however no significant change in behaviour was seen when it came to consuming their own unsellable low-grade crops that may be high in contamination. More recently, a study by Gichohi-Wainaina et al. (2021) carried out surveys to understand the state of knowledge and the understanding of aflatoxin contamination risk amongst a range of Malawian stakeholders, including: agriculture extension workers, frontline health workers, and small holder farming households. This study found that frontline health workers had the best understanding of domestic management of aflatoxin contamination and the impact of aflatoxin exposure to childhood development and general health, but relatively little understanding of the practices to avoid aflatoxin exposure or the impact on crop and income losses. Perhaps unsurprisingly, the opposite was found among smallholder faming households who showed the highest knowledge on issues around loss of income due to aflatoxin contamination. Despite what the data suggests, the study by Gichohi-Wainaina et al. (2021) found that overall public perception of the risks posed by aflatoxins was low; over half of the survey participants considered aflatoxin contamination severity to be low in Malawi, and over half did not think that this was a problem that could be controlled. This study therefore highlights a knowledge gap in the Malawian population, and a suggests that communication of the risks posed by aflatoxins, and opportunities available to manage this risk, is still lacking.

5.4. Future Adaptation Challenges

Malawi faces a wide range of challenges that have impeded the nation's economic development and food security, including: land degradation; natural resource depletion; over-reliance on one weather dependent sector; lack of diversity in agricultural sector; price volatility in crops; multiple health shocks; high levels of illiteracy; high levels of poverty; high population growth; young population; inconsistency in planning; high levels of corruption; and an underdeveloped financial sector (Government of Malawi, 2017). In addition to these overarching development challenges, tackling AFB1 contamination in Malawi is made more difficult due to incomplete transparency of current and past planning and actions, which creates a risk of inefficiency, duplication of action or mismanagement. This issue is raised by MAPAC in their 2013 report, but so far, the challenge does not seem to have been adequately tackled, with very few publicly available updates made on progress since.

Morse et al. (2018) analysed some of the challenges that Malawi's food safety sector faces. In their paper they describe 15 directorates within six ministries of the Government of Malawi who have oversight over food safety issues. With no overarching policy on food safety, this has led to a lack of clarity on who has authority over which issues, unconsolidated databases, confusion and frustration amongst stakeholders, an overlap in enforcement, and inconsistent messaging. Without an integrated approach, significant and sustainable progress on tackling food safety issues will remain a challenge.

While many countries around the world have been successful in limiting the AFB1 contamination of maize consumed by their population, this has been predominantly achieved through large-scale integrated approaches, where aflatoxins are controlled at each stage from field to fork (WHO, 2018). These schemes often involve specialised breeding or genetic engineering of the crop seed, use of bio-controls, adequate drying and storage, and chemical decontamination of any already affected foodstuffs (ibid). While these actions have been shown to be successful, they are also laborious, time consuming, and sometimes expensive (ibid.) making them more difficult to implement in a resource poor and subsistence-based farming system such as Malawi's. Social factors such as the risk of theft directly from the field also form disincentives for farmers to follow mycotoxin-limiting crop management suggestions, and result in crops commonly being harvested and stored before adequate drying can take place (Matumba et al., 2014a).

Large scale testing and regulation has been successful in some countries, but regulation and the financing of large-scale testing is not easily done in Malawi since most of the maize grown and consumed is done at subsistence level (Matumba et al., 2014a). In order to maximise food access and monetary gain, subsistence farmers in Malawi have been shown to keep low-quality grain for home consumption, selling the higher quality grain to market in order to get the best return (Mwalwayo and Thole, 2016). Due to this behaviour, much of the grain, particularly the grain that is damaged and more likely to be contaminated, will never have the chance to be tested.

The consequence of aflatoxin exceedances of regulatory thresholds in most developed countries is to throw out the affected food (WHO, 2018), but this is not an option in Malawi; Even if testing were implemented, and quick, affordable testing was widely available, food access remains an issue in Malawi (Botha, 2020) which means that throwing out affected food could lead to further undernutrition or starvation in the immediate term. Although not Malawi specific, a study by Otsuki et al. (2001) also found that while the impact of applying more stringent European Union (EU) level regulation on aflatoxin levels in African foodstuffs would provide some health benefits, it would also have a large-scale negative impact on the export economy in the region, highlighting the important need to consider and balance acceptable levels of risk and trade standards.

In theory, farmers tend to be incentivised to invest in technologies and practices which reduce AFB1 contamination risk if they are confident that they can sell their agricultural products at a higher price than similar produce with a higher or unknown level of contamination (Grace et al., 2015). However, market-based approaches to incentivising aflatoxin control have not been shown to be successful in developing countries, particularly in poorer countries, such as Malawi, whose food supply chain tends to be largely informal and made up primarily of smallholders operating largely outside of government control (ibid.). Although a study in Kenya has shown that there may be a marginal increase in the willingness to pay of some consumers for aflatoxin tested maize (Hoffman and Mwithirwa Gatobu, 2014), the risk remains that even with market incentives, the most vulnerable segments of the population will not be able to afford the lower risk products (Grace et al., 2015).

5.4.1. Climate Change Risk

While measures to control AFB1 contamination in Malawi's maize crop are important, the scale of the actions should be proportionate to the risk. Chapter 3 and 4 of this thesis have attempted to determine the effect of climate change on future Malawian maize yields and the associated pre-harvest AFB1 contamination risk. However, the insufficient resolution and clarity on future climate change highlighted in Chapter 2 creates uncertainties in these projections.

Confidence in the climate models currently available for Malawi is strong for trends in temperature, however the projections for precipitation are highly divergent and uncertain (Warnatzsch and Reay, 2019). The sensitivity of maize grown in Malawi's largest maize growing region, Central Malawi, to changes in temperature, precipitation, and planting date was analysed in Chapter 3. This evaluation found precipitation to be the dominant factor in determining changes in yields; depending on precipitation scenario, the maize yield in Central Malawi, could either decrease, increase or stay the same by mid-century (Warnatzsch and Reay, 2020). This analysis looked at both the ensemble mean and the two extremes in projected precipitation. Based on the frequency of model projections, it could be inferred that it is more likely that precipitation scenarios will track closer to the mean scenario, however this is still largely uncertain (Mittal et al., 2017; Warnatzsch and Reay, 2019). While the sensitivity of AFB1 contamination risk to differing precipitation scenarios was not assessed in our analysis, previous studies have shown that the fungi who produce AFB1 are highly sensitive to changes in precipitation trends (Cotty and Jaime-Garcia, 2007; Obonyo and Salano, 2018). The scale and distribution of precipitation, the timing of those precipitation events in the growing cycle, and the combination of those precipitation events with higher temperatures, all have a big impact on the concentration of aflatoxin produced (Cotty and Jaime-Garcia, 2007). Therefore, the low spatial resolution of the models, combined with poor precipitation projections pose a very large challenge in determining the best way to tackle this issue, and these large uncertainties leave room for potentially significant maladaptation.

5.5. Future Risk Management

While more information is still required, it is clear that food insecurity remains a large issue in Malawi, and dangerous levels of AFB1 contamination are present on maize crops in the food chain. As such, it is important that Malawi continues to implement measures to reduce these risks. Effectively managing the impact of any risk requires actions to target three elements: understanding and managing the hazard, reducing the vulnerability of the population or infrastructure, and reducing the level of exposure to the hazard (Crichton, 1999). A range of strategies exist to manage these three elements of risk as related to food security and AFB1 contamination in Malawi’s maize crops. In terms of understanding and managing the hazard, actions range from policy and regulatory interventions; public health and education campaigns; research, development, and technological solutions; international aid and finance; and autonomous adaptation. Even without these changes, Malawi’s resilience would be improved, and the vulnerability of the population to the effects of food insecurity and AFB1 exposure would be greatly reduced through general improvements in Malawi’s development. Progress on the Sustainable Development Goals (SDGs) in Malawi would lead to higher levels of education, health, equality, and financial stability, and reduced levels of poverty and corruption. And finally, improved food security and reduced exposure to AFB1 contamination could be achieved through education campaigns, and interventions to promote more diverse agricultural cultivation and dietary mix.

5.5.1. Capacity Building and Knowledge Exchange

The MDGS III (2017) and MAPAC (2013) reports go a long way to outline the types of actions that should be explored and implemented in Malawi in particular to reduce the risks faced by the population from food insecurity and AFB1 contamination. These interventions target all three aspects of the risk triangle, and strategies the government has set to address their SDG targets will further improve the resilience of the population. However, from publicly available information, and as outlined in Sections 5.2 and 5.3 of this Chapter, it appears that progress on some of these strategies has been slow and not well communicated to the public. Without clear communication, effective capacity building and knowledge exchange will not be possible.

To understand how to address issues of food-borne disease or crop losses, it can be useful to look for examples from elsewhere in the world. Similar to Malawi, Bangladesh’s economy and employment is largely dependent on the agricultural sector, with the majority of farms categorised as small-scale subsistence farms (CGIAR, n.d.-b). Bangladesh has high levels of poverty, childhood malnutrition, and food insecurity (WFP, 2021) which is exacerbated by climatic shocks (CGIAR, n.d.-b). To help address the vulnerability of food crops to climatic disasters, the World Bank has helped finance the construction of modern public grain storage silos for rice and wheat in various Bangladeshi districts (The World Bank, 2020b). These public silo complexes are linked to a Food Stock and Market

Monitoring System (FSMMS) which can help fill food shortages after natural disasters and also create local jobs, particularly for women (ibid.) In addition to the public silos, this funding was expanded to cover the manufacturing and distribution of 800,000 household-level silos which are air- and water-tight (ibid.). These projects help reduce post-harvest food losses by at least 50 percent and extend the nutritional value of the grains from 6 months under previous storage systems, to 2 years (ibid.).

Looking more specifically at reducing aflatoxin contamination in the food supply, the World Health Organisation (WHO) has highlighted the use of biological controls as an approach that has shown promising results (WHO, 2018). *Aflasafe* biocontrol products have been used for aflatoxin control on crops in SSA since 2014. Nigeria was the first country to register *Aflasafe*, followed by Kenya in 2015, The Gambia and Senegal in 2016, Burkina Faso in 2017, Ghana, Zambia and Tanzania in 2018, and Mozambique in 2019 (CGIAR, n.d.-a). The results of a 10-year study on the impact of *Aflasafe* in Nigeria, found that groundnut and maize fields treated with *Aflasafe* had a greater than 80 percent reduction in aflatoxin contamination compared to control fields, with more than 90 percent of the maize grains harvested having less than 4 ppb of total aflatoxin contamination (Bandyopadhyay et al., 2019). In 2018, the use of *Aflasafe* in Nigeria was also shown to increase the income of smallholder maize farmers by an average of 11.5% compared to untreated maize farmers (CGIAR, n.d.-a).

As discussed in Section 5.3.3, the use of biocontrol products is a strategy that is being developed in Malawi. Once implemented, careful analysis will be needed to track the uptake and effectiveness of this control in practice. The WHO (2018) also emphasised that for successful management of aflatoxins, an integrated approach, with control at all stages from farm to table is necessary. With very fragmented food production, this type of integration may be harder to implement in Malawi, however improved transparency and infrastructure for small-holder farmers and market operators would improve the lines of communication and improve collaboration. Furthermore, the WHO (2018) emphasize that actions by consumers to carefully select and store food from trusted sources can have a big effect on risk mitigation, and promotion of a varied and diverse diet is recommended to reduce the risk of consuming high levels of contamination, while also improving nutritional intake.

Learning from international experiences is important, but Malawi will need a tailored approach to ensure the success of any adaptation programme. While the impacts of food insecurity in Malawi have clear economic impacts at a national level, the brunt of the impacts are felt at the individual and community level. Therefore, while national-level initiatives will go a long way, regional and community level strategies which consider the specific needs and conditions of the various farming communities and local populations are optimal. Research by the Global Centre on Adaptation has found that local action on climate change provides critical benefits for improved climate resilience including providing more appropriate response to the local impact; higher social, environmental and economic returns; more equitable outcomes; a more holistic solution; and amplified local knowledge (Mfitumukiza et al., 2020). A Malawi-specific study using nationally representative sample of households in 2011, also found that: the farming practices chosen by farmers are related to the local climate change impacts they are experiencing; adaptation in farming practices has led to positive yield results; the adaptive capacity of the households is linked to both household and community level factors; and, there are substantial barriers to adaptation through farming practice selection (Asfaw et al., 2014). As such, more research and localised investigation is required to ensure the best outcomes of any adopted adaptation strategies.

An example of a successful programme of community level agronomic knowledge exchange is the FAO's Malawi Farmer-to-Farmer Agroecology Project (MAFFA) which took place in 2016 (FAO, 2016). This project worked in two different areas of Malawi: Lobi region of Dedza District, Central Malawi and Ekwendeni region in Mzimba District, Northern Malawi (ibid). The farmers who participated in the MAFFA project received a range of services, including: training on agroecological principals, nutrition and social equity issues; access to materials and information for diversifying their crops and improving soil fertility; and support for experimenting with agroforestry (Bezner Kerr et al., 2016). In addition to community wide support in these areas, MAFFA implemented a farmer-to-farmer educational approach; this approach involved the nomination of a man and woman from households in each village to join the Farmer Research Team and receive additional training (ibid.). These local farmer research teams then act as a community link for the research team as well as a mentor within the community. This project has resulted in participating farmers achieving a range of successes, including improvements in maize yields, crop and dietary diversity, soil fertility, seed sovereignty, food security, household gender relations, and climate resilience (ibid.).

In addition to MAFFA, the FAO has facilitated various training programmes and projects to help increase the knowledge and skills of extension workers in Malawi to carry out climate smart agriculture, improve food security, and enhance community resilience of vulnerable households. These include:

- implementation of the Farmer Field Schools;
- development of Village Action Plans;
- piloting Social Support Programmes which are shown to reduce barriers to adoption of climate smart agriculture (FAO, 2020a), including School Meals Programmes, Social Cash Transfer Programmes, Public Works Programmes, and Microfinance and Village Savings and Loans schemes;
- implementation of training activities and capacity building actions at community and individual level;
- implementing nutritional education programmes to improve childhood nutrition;
- procurement of vehicles to support nutrition sensitive agriculture flagship programmes; and,
- deployment of a communication strategy (FAO, 2018a; FAO, 2018b; FAO, 2021a; FAO, 2021d).

Along with the bottom-up strategies which target food insecurity and AFB1 contamination risk from the local level, top-down frameworks are also essential to verify, monitor and ensure progress (E3G, 2010). Enhanced accountability and transparency is imperative at all levels to ensure the best outcome of past and existing strategies, and of any future research. With this increased transparency, efficiencies and collaborations would be made possible, and links with other campaigns and development actions could be better integrated to find win-win solutions. This transparency will also reduce the risk of inefficiencies and potential corruption.

5.5.2. Climate Services

In addition to targeting the issues that are currently present, it is important that Malawi adapts and manages this issue in a way that is sustainable in a changing climate. With crop performance and aflatoxin contamination levels clearly tied to climatic conditions (Perrone et al., 2020), there is an imperative to improve climate projections and communication to the community to ensure that the most appropriate actions and investments are taken. Malawi is highlighted as being particularly vulnerable countries to climate change (Minot, 2010; Giertz et al., 2015) and yet the country, and wider African continent, has very weak access to and use of climate information and services (Vincent et al., 2015); According to H.E. Vera Songwe, the Under-Secretary-General and Executive Secretary of the United Nations Economic Commission for Africa: "the limited uptake and use of climate information services in development planning and practices in Africa is due in part to the paucity of reliable and timely climate information" (UN Climate Change, 2020). Without higher definition in the models, the uncertainty, particularly around precipitation, remains far too great to make effective and reliable adaptation programmes. Furthermore, the currently best available resolution does not allow for enough granularity to understand local trends.

Climate modelling has been improving around the world (James et al., 2018); various countries have built upon existing global and regional climate models to create high resolution and locally specific projections upon which they can design appropriate adaptation frameworks. The United Kingdom (UK) was amongst the first countries to create a nationally specific climate model. In 1991, the UK generated their first national climate change scenario, with updates in 1998, 2002, 2009 and most recently in 2018. Each subsequent version has become more detailed with increased computing power, has integrated new scientific understandings, and has considered the needs of a growing number of stakeholders (Bowyer, 2009). The newest iteration (UK Climate Projections 18 or UKCP18) provide updated probabilistic projections for four potential future representative concentration pathways (RCPs) with a spatial resolution of 12km^2 (Met Office, 2019). Users of UKCP18 have access to numerous web-based tools that can be used to access the raw data and key outputs of the models as well as a clear and transparent public website containing detailed reports and guides for understanding and using the data. This climate modelling gives users the most certainty possible with current science and computing power, while also making the information accessible to users at a range of technical levels. This increases uptake in the use of the information and the ability for businesses, policy makers, communities, and individuals to make the robust adaptation plans. Other examples of national and regional investments in climate knowledge sharing and local climate communication include the Danish Climate Atlas (MED/EPA, 2021), the Climate Atlas of Canada (Prairie Climate Centre, 2021), the US's Climate Explorer (U.S. Climate Resilience Toolkit, 2021), California's Cal-Adapt (California Energy Commission, 2021) and Climate Ireland (Climate Ireland, 2021). Programmes like these require a significant financial investment, evident by their development thus far occurring exclusively in rich countries/regions of the world. However, evidence has shown that projects which strengthen early warning systems have the highest benefit to cost ratio of any adaptation approach (Global Commission on Adaptation, 2019) and are therefore a good investment.

Climate information across Africa remains low resolution (James et al., 2018). The African continent is geographically very heterogenous and the climate is highly influenced by convection processes and remote ocean basins which are challenging to simulate (ibid.) The continent is therefore often impacted by finer scale climatic events than current resolutions allow, even if they were properly considered (ibid.). A consortium of the UK Met Office and other leading UK and African institutions has set up the 'Improving Model Processes for African Climate' (IMPALA) project. The aim of the IMPALA project is to improve climate modelling information for the African continent to gain the high-quality climate information required for effective decision making in the region (Met Office, n.d.) . This project has received £20 million in funding from the UK government-funded Future Climate for Africa (FCFA) initiative, a joint programme of the Department for International Development (DFID) and Natural Environment Research Council (NERC) (ibid.). However, due to the complexity of systems and geography influencing the African continent’s climate James et al. (2018) argue that there should be no “one size fits all” approach for improving climate modelling on the continent; the sub-regions and countries within Africa will each need their own approach to improving model performance.

In parallel with improved climate information, investment is required into communicating that information effectively to the various stakeholders. Without an effective mechanism for disseminating information to individuals, communities, businesses, and policy makers, it will be impossible for effective adaptation plans to be made. To ensure the successful use of climate information, it will not only be important for the information to be communicated at a range of expertise levels, but also to a wide audience.

Early warning systems are an important adaptive measure, helping communities appropriately prepare for hazardous climate-related events, and helping local policy makers implement the best possible measures, saving them money in the long run and stabilising economic systems (UN, n.d.). Investment has been made by many countries around the world to improve climate communications and early warning systems. The UNDP’s Signature Programme was established to “[strengthen] climate information and early warning systems for climate resilient development and adaptation to climate change” (UNDP, n.d.-b). They invest in projects “across Africa, Asia and the Pacific in order to help them respond to both short-term/rapid onset climatic hazards (e.g., cyclones, floods and storms), as well as long-term/slow onset hazards (e.g., droughts and long-term climate change)” (ibid.). As part of this project, between 2013-2017 Malawi received 4 million USD of funding through a Global Environment Facility (GEF) grant, and an additional 11.3 million USD in co-funding to strengthen their climate information and early warning systems, in order to improve climate resilience (GEF, n.d.-b). The project officially closed in July 2019, and targeted two main outcomes as outlined in Table 5.3.

Table 5.3 Key Outputs of the UNDP project to strengthen the climate monitoring capabilities, early warning systems and available information for responding to climate shocks and planning adaptation to climate change in Malawi (UNDP, n.d.-a)

Outcome 1: Enhanced capacity of national hydro-meteorological (NHMS) and environmental institutions to monitor extreme weather and climate change.	Output 1.1 Procurement and installation or rehabilitation (in case of existing) of approximately 10+ hydrological monitoring stations with telemetry, archiving and data processing facilities.
	Output 1.2 Procurement and installation or rehabilitation of approximately 40 meteorological monitoring stations with telemetry, archiving and data processing facilities.
	Output 1.3 Procurement and installation or rehabilitation of radar for monitoring severe weather.
	Output 1.4 Procurement and installation or rehabilitation of upper air monitoring stations
	Output 1.5 Procurement and installation or rehabilitation of satellite monitoring equipment to receive real time climate and environmental information.
	Output 1.6 Training of at least 3-5 officers to maintain and repair equipment, computer infrastructure and telecommunications, including cost-effective technologies to interface with existing equipment/software (approx. $150,000).
Outcome 2. Efficient and effective use of hydro-meteorological and environmental information for making early warnings and long-term development plans.	Output 2.1 NHMS capacity to make and use climate forecasts (on daily to seasonal, as well as medium- to long-term timescales) is strengthened by training at least 4 forecasters. (approx. $150,000)
	Output 2.2 Tailored sector-specific early warning products that link climate, environmental and socio-economic information on a range of timescales are developed, based on identified user needs.
	Output 2.3 National capacity for assimilating forecasts and monitoring into existing development planning, PRSPs and disaster management systems is built, including coordination with systems and warnings developed by other initiatives (approx. $390,000)
	Output 2.4 Communication channels and procedures for issuing warnings (through both governmental and non-governmental agencies) are enabled (e.g., radio, newspapers, mobile phones, television etc).
	Output 2.5 Plan for sustainable financing for the operation and maintenance of the installed EWS developed and implemented, including public and private financing options (approx. $150,000)

After the project completion a terminal evaluation report was compiled to assess the success of the project. This evaluation report found that the project objective has only partially been achieved. While the severe weather forecasting system was strengthened and technical equipment to facilitate early warning dissemination was provided, the implementation of the early warning system, the community-based delivery of this system, the manual local water readings, and planning for climate change adaptation were only partially achieved. The review also found little evidence to show improvements in risk knowledge or appropriate response capacity. While the majority of the budget was spent, the review found the effectiveness of the project implementation to be 'moderately unsatisfactory' and the cost-effectiveness of the project was deemed 'unsatisfactory'. The main shortcoming highlighted by the review was that the project underestimated the cost to operationalise the project. The donor-funding was based on securing expensive technology and equipment which are standard in developing countries. However, no financing was secured for the operation or maintenance of this equipment or the programmes which support them, and as such the project was always going to fall short. This highlights the importance of working with communities and local individuals in making adaptation plans to ensure their success. It is highly recommended that future projects aiming to strengthen climate services in Malawi are designed with the input from a range of stakeholders and with an understanding of the human and financial costs associated with their sustained success.

There is evidence that projects to improve early warning systems and climate information in developing countries can be successful. A UNDP project carried out in Uganda, with similar goals to improving climate information and early warning systems between 2014-2018 resulted in many successes. This project received the same 4 million USD GEF Project grant, although a larger amount of co-financing (20.3 million USD) than the Malawian project (GEF, n.d.-a). The Terminal Evaluation Report did still highlight a few issues around securing uninterrupted bandwidth for the short-term weather forecasting systems, some issues of delay, theft and vandalism of equipment, and an a need for further facilitation of adaptation planning and resource management all of which demonstrate the need for a second phase to the project (Sobey and Mbogga, 2018). However, the project has resulted in many positive impacts, including large improvements in the country's climate information quality and the public communication of that information to stakeholders (ibid.)

5.6. Conclusions

Over the last decade Malawi has made some large positive steps towards improving and understanding food security, including food production and food safety. Various studies have been carried out that help to paint a picture of the scale of some of these issues, although many gaps in our understanding remain. While the government has outlined some strategies to address these knowledge gaps and the already highlighted issues, there remains a clear lack of transparency. This not only hinders the ability to assess progress but is also likely to lead to inefficiency and misuse of resources. Compounding issues of tackling current food security challenges is the uncertainty around climate change projections in the country. Without improved climate information and climate communication the risk of maladaptation is high.

In combination with efforts to improve general sustainable development progress in the country and build resilience, direct action is required to tackle food shortages, aflatoxin risk, and gaps in knowledge and knowledge dissemination in Malawi. To establish appropriate, equitable, affordable, and effective adaptation programmes that can be sustainably implemented to tackle issues of food security, an integrated approach must be adapted. Knowledge transfers are useful, and programmes should learn from the successes and failures of technologies and programmes implemented internationally. However, community level engagement is necessary and locally tailored solutions must be designed.

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Chapter 6 Concluding Remarks

6.1. The Research Journey and Main Findings

The initial research proposal for this PhD was centred on determining the climate change impacts on post-harvest spoilage in Malawi, and the knock-on effects to human health from mycotoxins, and greenhouse gas emissions. However, the goal of the project changed slightly as the research progressed. The direction of research was very much led by the findings at each stage with the intent of creating a cohesive research narrative. In this section I present the journey that was taken, the main findings, and the reasoning behind the choices made.

Through initial research to determine the projected climate change impacts in Malawi, it became clear that little investigation had taken place to understand how well the models were replicating the climate of this small and heterogenous country. This resulted in a decision to take a step back from projecting into the future, to first understand the efficacy of existing climate models in replicating Malawi's historic climate. This analysis would allow for judgements to be made on the scale of uncertainty associated with any future projections. To further understand the source of any biases found, a decision was taken to assess not only a large range of Regional Climate Models (RCMs), but also the General Circulation Models (GCMs) which form their lateral boundary conditions and the ERA-interim models which use observed data for their lateral boundary conditions. The decision was taken to concentrate on two climatic variables most directly linked to our intended research focus - agricultural and myotoxicity models – surface temperature (daily minimum, mean and maximum) and precipitation rate. From this investigation it became clear that, while modelled temperature trends could be used with a reasonable level of confidence, the levels of uncertainty in current precipitation trends were too large for useful adaptation planning. The results were comparable for the GCMs and RCMs, however the RCMs provide higher resolution which can make them better suited to adaptation planning. Boundary conditions were shown to have a large impact on RCM performance and, in line with previous research on the performance of African climate models (Nikulin et al., 2012; Endris et al., 2013; Kalognomou et al., 2013; Kim et al., 2014), the ensemble means of the model outputs generally outperformed individual model simulations.

With the limitations of available climate modelling data in mind, the project re-focused on Malawi's projected future climate change and the potential impacts on their food security position. Maize makes up almost half of all calories eaten in Malawi (FAOSTAT, 2021), therefore a decision was taken from the start that this crop would be the focus of the project. The initial proposal focused on post-harvest losses and the associated emissions associated with these, however it became clear through literature review that only a small portion of crops were lost due to post-harvest conditions (Ambler et al., 2017). While post-harvest conditions are responsible for the reduction in quality of crops in Malawi, it was found that most crop loss occurred at the point of harvest, and that the majority of crops harvested are consumed, even if damaged; Only extremely damaged crops are disposed of, and most low-quality and damaged crops are kept by small-holder farmers for domestic consumption, with higher quality crops sold on to market (ibid.). Therefore, while reducing post-harvest losses and improving the quality of the post-harvest conditions is still an important topic of research, a decision was taken to focus this research on understanding how climate change may impact food access and the pre-harvest conditions related to food quality and safety, concentrating on aflatoxins.

Before it was possible to look at future crop performance and safety, it was first necessary to understand what changes are projected to occur in the local climate. Keeping the uncertainty that was determined via hindcasting in mind, the second paper of this project set out to model a range of future climate scenarios for Malawi's main maize growing region, Central Malawi (Arya et al., 2005). With over half of the domestically grown maize cultivated in Central Malawi, this boundary was significant, however the choice of spatial research boundary was also limited by the availability of good quality local data to effectively calibrate crop models. This resulted in six future climate scenarios comprising two representative concentration pathways (RCPs) using an ensemble mean of temperature projections in each, and a minimum, mean, and maximum precipitation projection for the region. Each of these scenarios were projected to two future time periods (2035 and 2055) for relevance to different adaptation planning horizons and were compared to a 1971-2000 baseline. The modelling projected an increase in Central Malawi's temperatures of between 1.4 and 1.6°C by 2035, and 1.9 and 2.5°C by 2055 under Representative Concentration Pathway (RCP) 4.5 and 8.5 respectively. As was expected from investigation into the historic model performance, the projections for future precipitation were found to be highly divergent. The ensemble mean showed a slight decrease of 3 to 4% compared to the baseline period, but the minimum and maximum projections showed that precipitation could either decrease by half or increase by up to a fifth. These projections are in line with climate change projections described by Mittal et al. (2017), with the mean precipitation scenarios showing a larger consensus between models, and a closer replication of historic trends.

While some investigation into the projected impacts of climate change on Malawian maize yields have already been published (Saka et al., 2012; Zinyengere et al., 2014; Fiwa, 2015; Msowoya et al., 2016; Stevens and Madani, 2016; Olson et al., 2017), there were few data available to understand the yield sensitivity of different crop types, or the yield sensitivity to differing precipitation scenarios or planting dates. Therefore, using an existing FAO crop model calibrated to represent two locally grown varieties of maize, the impact on yield was evaluated for three different planting dates within the current average planting season in Central Malawi - this used six climate scenarios for two future time periods. It was found that the maize yield could increase or decrease due to projected climate change, depending on which precipitation scenario was considered. Furthermore, advice on whether to plant at a different time, or invest in adaptation strategies such as irrigation or changing crop variety, would also be highly dependent on the precipitation scenario. As such, this research highlights a significant risk of maladaptation due to the limitations of currently available climate information.

With a better understanding of climate projections and the impact of climate change on maize yields, the project shifted towards food safety. The initial research proposal had a focus on human health impacts from mycotoxin exposure, and this was a topic I was keen to understand more. Literature review highlighted mycotoxin contamination to be a concern for the Malawian food supply, but there were many gaps in the available information. One such gap was how climate change could impact mycotoxin contamination in the country. In fact, very little research has been published in this area globally. However, expertise was found at the Università Cattolica del Sacro Cuore in Piacenza, Italy; Professor Battilani and her colleague Dr. Marco Camardo Leggieri have published a few articles in this area and developed a mechanistic model to test the impact of changing climatic conditions on the concentrations of a particularly dangerous mycotoxin, aflatoxin B1 (AFB1), produced on maize crops.

While their model had never been used for application outside of Europe, through discussions with Professor Battilani and Dr Camardo Leggieri, it became clear that their model was not geographical specific and instead reliant on inputs related to the development cycle of local maize and the climatic conditions in the geography of cultivation. It was therefore possible to use their AFLA-maize model to determine how AFB1 contamination of maize grown in Malawi may be impacted by a changing climate. The decision was taken to broaden the assessment back out to the full country of Malawi, as it was hypothesised that the climate change impact would not only be on concentrations of the toxin, but also the distribution of the contamination. This hypothesis was upheld by our analysis which found that not only is AFB1 contamination of maize at the time of harvest expected to increase in all regions of the country, but the distribution of the risk is expected to spread to the colder regions of the country, where the risk is currently low.

The journey to this point gave a better understanding of Malawi's currently available climate information, future climate projections, and the resulting impact on future yields and AFB1 contamination on the main food crop, maize. This research highlighted potentially significant associated impacts and vulnerability to the Malawian population. Therefore, the final chapter of the thesis aimed to bring these themes together and explore what is being done to address these challenges, and what further steps are required to best manage these risks. This assessment was done as a desk-based exercise and relied on publicly available information. While the literature review showed that progress has clearly been made in Malawi to address many issues of food security and climate resilience, the data still show a difficult situation. Current and historic actions target a range of measures, but there is a lack of transparency making it difficult to get a clear picture of specific on-the-ground activities, or of the results of implementation. This analysis showed that further action is required to build up the resilience of the Malawian agriculture sector and address many of the knowledge gaps, including those around climate information and services. Without this knowledge, as well as clear and effective dissemination of the information to key stakeholders, it will not be possible for Malawi to make effective, appropriate, and sustainable adaptation plans to tackle issues around food security and safety in a changing climate.

6.2. Research Implications and Knowledge Gaps

This research has provided new information for climate change adaptation in Malawi, however – and possibly most importantly – it also highlights important gaps in our current understanding. At the time of research, the best available GCMs were all part of the fifth phase of the Coupled Model Intercomparison Project (CMIP5). However, since publication of the research detailed in Chapter 2 of this thesis, the project has entered a sixth phase (CMIP6) and the models have been updated and improved in line with new scientific capabilities and understandings (WCRP, 2021). While the CMIP6 models are still very new, some analysis has been published indicating that the newer models do perform better than their predecessors when it comes to simulating spatial patterns and temperature extremes (Fan et al., 2020). A comparison of projections using CMIP5 and CMIP6 models for Africa also show higher warming trends than previously thought and a mixed result for precipitation depending on the region of Africa in question (Almazroui et al., 2020). As such, a new analysis should be undertaken to get an updated picture on the current uncertainties around climate modelling quality for Malawi and the impact of the new projections on maize yields and AFB1 risks. Based on this new analysis, targeted local modelling improvements should be made to ensure Malawi's climate information has sufficient resolution and certainty for making sustainable adaptation plans.

In parallel to improving climate information, it will be important for research to be carried out to understand the best way to disseminate information to key stakeholders within households, communities, businesses, and government agencies across Malawi. The strength of climate information is irrelevant if the right people do not have access to it, or do not understand it sufficiently to allow for sustainable, affordable action to be planned and implemented.

Diversifying the agricultural sector and the local diet is a key recommendation for improving food security and nutrition in Malawi. Therefore, future research needs to build upon the findings of this project to expand our knowledge of the impact of climate change on other crops and to understand which varieties and species may be best suited to the future climatic conditions in Malawi. When considering new crops, any future research will also need to investigate the interactions between the timing of planting and key crop development stages with changes to temperature and precipitation patterns. These studies will need to not only look at what plants will grow well in a changing climate but how the nutritional content of the crop is impacted by the climate, and whether their agricultural output will be safe for consumption, and free from aflatoxin risk, as well as other mycotoxins, pests, and diseases. While this research concentrated on pre-harvest conditions, it is also important to note that the risks of crop damage remain in post-harvest conditions, and as such future research should also be expanded to consider the full supply chain from field to fork.

While AFB1 is highlighted as a particularly dangerous mycotoxin, there are many others which have severe health implications, and are already known to be found in dangerous concentrations within the Malawian food supply, including: fumonisins, ochratoxins, deoxynivalenol and zearalenones (Doko et al., 1996; Matumba et al., 2014; Probst et al., 2014; Chipinga, 2014; Mwalwayo and Thole, 2016). Based on previous studies, it is likely that climate change will impact the life cycle of a range of mycotoxin-producing moulds, influencing the host's resistance to infection, the distribution of growth, the host-pathogen interaction, as well as the concentration and type of mycotoxin produced (Perrone et al., 2020). In addition to the health implications from AFB1 which are discussed in this thesis, Malawi also currently has higher than average levels of cancers, such as oesophageal cancer, that are linked to exposure to other mycotoxins (Msyamboza et al., 2012; Misihairabgwi et al., 2017). However empirical studies to determine the link between a range of mycotoxin exposures and the high incidence rates of chronic health issues are lacking, as is research to understand the impact of climate change on the contamination levels and distribution of these other mycotoxins in Malawi. These are both key areas of required further research.

Studies on the scientific options for adaptation and risk reduction are important, but these adaptation opportunities must also consider local preferences, and the willingness of the local population to grow, buy, cook, and eat the foods that are suggested. The co-dependencies of actions and outcomes across a range of categories must also be considered. For example, how any changes would impact, price, food choice and access, water quality, soil fertility and biodiversity.

While this study has concentrated on specific aspects of food availability and safety in Malawi, Campbell et al. (2016) highlights that there are actually four main aspects of food security. Therefore for Malawi to fully understand the impacts of climate change on their food security, it will be important to expand the research to not only determine how changes in the yield of food crops will impact the availability of food, and how food-borne diseases and food losses will impact the safety and utilisation of food crops, but also important to investigate how the price of food impacts the purchasing power (PP) of the population and therefore changes access to the food, and how interactions between ecosystems and the socio-economics of the agricultural sector threaten the stability of the system (FAO, 2008). Only by understanding all four of these aspects will we be able to understand the impact that climate change will have on food security.

Even with gaps remaining and further research required, food insecurity in Malawi remains an important known issue that has clear interactions with climate change. There are many actions that could be taken now to improve food availability, safety, utilisation, access, and stability; human and livestock health; exports and trade; and the local economy. Careful local consideration must be taken to ensure the sustainability and affordability of actions and minimise the risk of maladaptation. However, a range of systemic changes will be required to deal with not only the current issues of fluctuating maize yields and AFB1 contamination, but to address larger developmental issues and build resilience in the population and food system.

6.3. References

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Appendix A Supplementary Information to Chapter 3

Table A.1: Regional Climate Models (RCM) sources.

All of the models other than CanRCM4_r2 were accessed through The Earth System Grid Federation (ESGF) data index (ESGF, 2017). The CanRCM4_r2 model was accessed through the Canadian Centre for Climate Modelling and Analysis website (CCCma, 2017).

RCM	Institution	Lateral Boundary Conditions	Original Calendar	Reference
CCLM4-8-17_v1	Climate Limited-area Modelling Community (CLMcom)	CNRM-CM5 r1i1p1	365-days	(COSMO, 2017)
		HadGEM2-ES r1i1p1	360-days	
		EC-EARTH r12i1p1	366-days	
		MPI-ESM-LR r1i1p1	366-days	
HIRHAM5_v2	Danmarks Meteorologiske Insitut (DMI)	EC-EARTH r3i1p1	366-days	(Christensen et al., 2007)
RACMO22T_v1	Koninklijk Nederlands Meteorologisch Instituut (KNMI)	HadGEM2-ES r1i1p1	360-days	(van Meijgaard et al., 2008)
		EC-EARTH r1i1p1	366-days	
RCA4_v1	Sveriges Meteorologiska och Hydrologiska Institut (SMHI)	CanESM2 r1i1p1	366-days	(Samuelsson et al., 2015)
		CNRM-CM5 r1i1p1	366-days	
		CSIRO-MK3-6-0 r1i1p1	365-days	
		GFDL-ESM2M r1i1p1	365-days	
		IPSL-CM5A-MR r1i1p1	365-days	
		HadGEM2-ES r1i1p1	360-days	
		EC-EARTH r12i1p1	366-days	
		MIROC5 r1i1p1	365-days	
		MPI-ESM-LR r1i1p1	366-days	
		NORESM1-M r1i1p1	365-days	
REMO2009_v1	Climate Service Centre Germany (CSC) and Max Planck Institut (MPI)	EC-EARTH r12i1p1	366-days	(Jacob et al., 2012)
		MPI-ESM-LR r1i1p1	366-days	
CanRCM4_r2	Canadian Centre for Climate Modelling and Analysis (CCCma)	CanESM2 r1i1p1	365-days	(Scinocca et al., 2016)

Table A.2: Observed data sources

Dataset	Variable Used	Resolution	Time-Period Available	Source	Reference
Climate Research Unit (CRU) version 4.0	Tas, TasMin, TasMax and Pr	0.5° Monthly Land Only	1901-2015	Gridded Station Data	(Harris et al., 2014)
University of Delaware (UDel) version 4.01	Tas and Pr	0.5° Monthly Land Only	1901-2010	Gridded Station Data	(Willmott and Matsuura, 2001)
Global Precipitation Climatology Centre (GPCC) version 7	Pr	1.0° Monthly	1901-2010	Satellite and Station Data	(Schneider et al., 2015)

Table A.3: List of data sources for the 13 climate files used in the crop models.
Note that all RCMs referred to in this table are listed in Table A.1 and the observed data referred to in this table are from the sources listed in Table A.2.

File	Time Scale	RCP	Temperature	Reference Evapotranspiration	Precipitation	CO_2 concentration
1	1971-2000	N/A	Mean of observed monthly data for minimum and maximum temperature	Calculated using methodology described in Section 2	Observed monthly data for precipitation rates	AquaCrop Mauna Loa CO_2
2	2020-2049	4.5	Projected ensemble mean daily minimum and maximum temperature		Projected ensemble min. precipitation rate	AquaCrop IPCC RCP 4.5
3					Projected ensemble mean precipitation rate	
4					Projected ensemble max. precipitation rate	
5		8.5			Projected ensemble min. precipitation rate	AquaCrop IPCC RCP 8.5
6					Projected ensemble mean precipitation rate	
7					Projected ensemble max. precipitation rate	
8	2040-2069	4.5			Projected ensemble min. precipitation rate	AquaCrop IPCC RCP 4.5
9					Projected ensemble mean precipitation rate	
10					Projected ensemble max. precipitation rate	
11		8.5			Projected ensemble min. precipitation rate	AquaCrop IPCC RCP 8.5
12					Projected ensemble mean precipitation rate	
13					Projected ensemble max. precipitation rate	

Table A.4: Absolute AquaCrop output data for historic 1971-2000 climate using three different soil types

Cultivar	Planting Date	AquaCrop Default Soil	AquaCrop Default Sandy Clay Loam Soil	Calibrated Sandy Clay Loam Soil
Slow-Development	**15 Nov**	12.293	12.05	12.052
	10 Dec	12.861	12.861	12.861
	30 Dec	13.323	12.834	12.249
Fast-Development	**15 Nov**	7.727	7.384	7.383
	10 Dec	7.961	7.961	7.961
	30 Dec	8.243	8.243	8.243

Table A.5: Absolute AquaCrop output data for projected climates under RCP 4.5 using three different soil types

Cultivar	Soil Type	Planting Date	2020-2049			2040-2069		
			Min. Rain	Ave. Rain	Max. Rain	Min. Rain	Ave. Rain	Max. Rain
Slow-Development	AquaCrop Default Soil	**15 Nov**	9.781	12.15	12.229	8.142	12.197	12.284
		10 Dec	9.024	12.958	12.958	7.615	12.324	12.324
		30 Dec	4.682	13.699	13.699	4.324	13.299	13.299
Fast-Development		**15 Nov**	6.162	7.844	7.947	5.691	7.683	7.81
		10 Dec	7.894	8.065	8.065	7.613	7.901	7.901
		30 Dec	8.388	8.388	8.388	8.093	8.157	8.157
Slow-Development	AquaCrop Default Sandy Clay Loam Soil	**15 Nov**	5.502	11.985	12.229	4.628	12.021	12.284
		10 Dec	3.031	12.958	12.958	2.994	12.324	12.324
		30 Dec	0.995	13.699	13.699	1.004	13.299	13.299
Fast-Development		**15 Nov**	1.716	7.611	7.947	1.431	7.435	7.81
		10 Dec	7.419	8.065	8.065	6.344	7.901	7.901
		30 Dec	7.391	8.388	8.388	6.957	8.157	8.157
Slow-Development	Calibrated Sandy Clay Loam Soil	**15 Nov**	5.497	11.984	12.229	4.800	12.025	12.284
		10 Dec	2.683	12.958	12.958	2.725	12.324	12.324
		30 Dec	0.792	13.699	13.699	0.804	13.299	13.299
Fast-Development		**15 Nov**	1.675	7.601	7.947	1.344	7.433	7.810
		10 Dec	7.410	8.065	8.065	6.060	7.901	7.901
		30 Dec	7.032	8.388	8.388	6.596	8.157	8.157

Table A.6: Absolute AquaCrop output data for projected climates under RCP 8.5 using three different soil types

Cultivar	Soil Type	Planting Date	2020-2049			2040-2069		
			Min. Rain	Ave. Rain	Max. Rain	Min. Rain	Ave. Rain	Max. Rain
Slow-Development	AquaCrop Default Soil	**15 Nov**	8.337	12.317	12.423	4.884	11.962	12.077
		10 Dec	8.44	12.863	12.863	8.615	12.186	12.186
		30 Dec	5.013	13.324	13.324	5.191	12.667	12.667
Fast-Development		**15 Nov**	5.604	7.749	7.891	4.218	7.284	7.433
		10 Dec	7.635	7.962	7.962	7.15	7.527	7.527
		30 Dec	8.206	8.244	8.244	7.775	7.819	7.819
Slow-Development	AquaCrop Default Sandy Clay Loam Soil	**15 Nov**	3.771	12.112	12.423	3.548	11.747	12.077
		10 Dec	2.91	12.863	12.863	3.299	12.186	12.186
		30 Dec	1.112	13.324	13.324	1.509	12.667	12.667
Fast-Development		**15 Nov**	1.413	7.448	7.891	1.107	6.963	7.433
		10 Dec	6.602	7.962	7.962	5.6	7.527	7.527
		30 Dec	7.249	8.244	8.244	7.172	7.819	7.819
Slow-Development	Calibrated Sandy Clay Loam Soil	**15 Nov**	3.799	12.121	12.423	4.352	11.759	12.077
		10 Dec	2.816	12.863	12.863	3.402	12.186	12.186
		30 Dec	0.878	13.324	13.324	1.275	12.667	12.667
Fast-Development		**15 Nov**	1.358	7.449	7.891	1.029	6.970	7.433
		10 Dec	6.473	7.962	7.962	5.421	7.527	7.527
		30 Dec	6.895	8.244	8.244	6.905	7.819	7.819

Table A.7: Absolute AquaCrop output data for historic (1971-2000) and projected climate under RCP 4.5 and 8.5 using the default Maize crop file and calibrated sandy clay loam soil file.

Soil Type	Planting Date	1971-2000	RCP	2020-2049			2040-2069		
				Min. Rain	Ave. Rain	Max. Rain	Min. Rain	Ave. Rain	Max. Rain
Calibrated Sandy Clay Loam Soil	**15 Nov**	14.24	4.5	13.92	14.27	14.33	13.88	14.27	14.33
			8.5	13.90	14.25	14.33	13.72	14.24	14.33
	10 Dec	14.33	4.5	14.26	14.33	14.33	14.22	14.33	14.33
			8.5	14.21	14.33	14.33	14.18	14.33	14.33
	30 Dec	14.49	4.5	14.49	14.49	14.49	14.48	14.49	14.49
			8.5	14.49	14.49	14.49	14.49	14.49	14.49

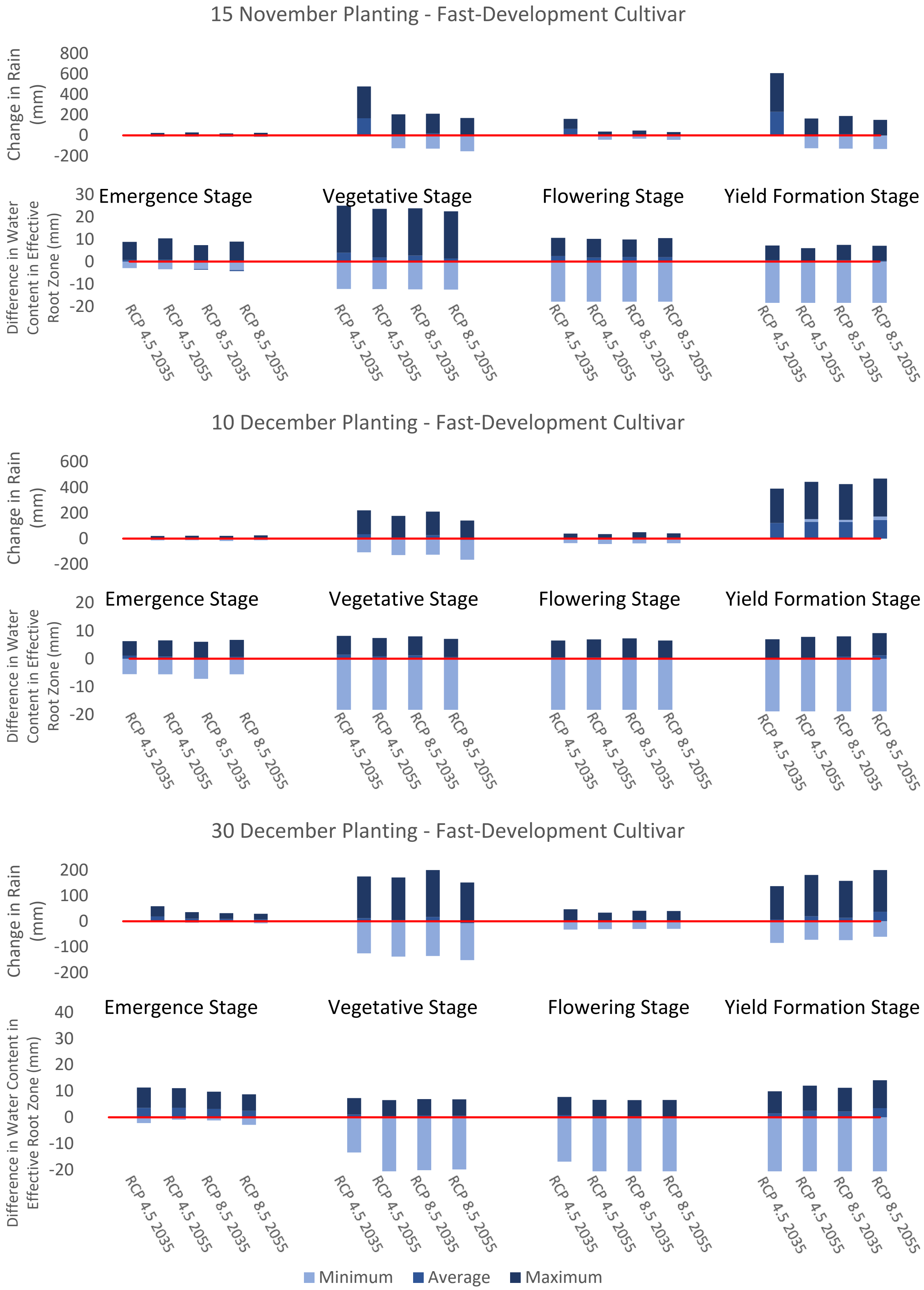

Figure A.1: Change in total precipitation (mm) and water content in the effective root zone (mm) by developmental stage of the fast-development cultivar maize grown in Central Malawi for the three planting dates as compared to the baseline 1971-2000 period (red line).

This data is shown for the three precipitation scenarios: minimum (palest), average (medium shade) and maximum (darkest) precipitation, for the two RPC scenarios and time periods.

Table A.8: Number of days exceeding the maximum temperature threshold (32 degrees Celsius) by development stage for each cultivar

	Planting Date	**Stage**	**Historic**	**RCP4.5**		**RCP8.5**	
				2035	**2055**	**2035**	**2055**
Slow-Development Cultivar	Nov. 15	Emergence	8	6	8	8	7
		Vegetative	1	0	2	1	10
		Flowering	0	0	0	0	0
		Yield Formation	0	0	0	0	0
		Total	**9**	**6**	**10**	**9**	**17**
	Dec. 10	Emergence	0	0	0	0	0
		Vegetative	0	0	0	0	0
		Flowering	0	0	0	0	0
		Yield Formation	0	0	0	0	0
		Total	**0**	**0**	**0**	**0**	**0**
	Dec. 30	Emergence	0	0	0	0	0
		Vegetative	0	0	0	0	0
		Flowering	0	0	0	0	0
		Yield Formation	0	0	0	0	0
		Total	**0**	**0**	**0**	**0**	**0**
Fast-Development Cultivar	Nov. 15	Emergence	5	5	5	5	5
		Vegetative	4	1	5	4	12
		Flowering	0	0	0	0	0
		Yield Formation	0	0	0	0	0
		Total	**9**	**6**	**10**	**9**	**17**
	Dec. 10	Emergence	0	0	0	0	0
		Vegetative	0	0	0	0	0
		Flowering	0	0	0	0	0
		Yield Formation	0	0	0	0	0
		Total	**0**	**0**	**0**	**0**	**0**
	Dec. 30	Emergence	0	0	0	0	0
		Vegetative	0	0	0	0	0
		Flowering	0	0	0	0	0
		Yield Formation	0	0	0	0	0
		Total	**0**	**0**	**0**	**0**	**0**

A. 1. References

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Appendix B Methodology for Calculating Reference Evapotranspiration

To calculate evapotranspiration, the FAO Penman Monteith (FPM) model was applied (Allen et al., 1998a).

Equation 1 $$ETo = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

Where:

- ETo is the reference evapotranspiration (mm day^{-1})
- R_n is the net radiation at the crop surface (MJ m2 day^{-1}),
- G is the soil heat flux density (MJ m-2 day^{-1})
- T is the mean daily air temperature (°C)
- u_2 is wind speed at 2 m height (m s^{-1})
- e_s is the saturation vapour pressure (kPa)
- e_a is the actual vapour pressure (kPa), see Equation 10
- $e_s - e_a$ is the saturation vapour pressure deficit (kPa)
- Δ is the slope vapour pressure curve (kPa°C^{-1})
- γ is the psychrometric constant (kPa °C^{-1})

It is not possible to get data for all of the above variables for Central Malawi, either from observed data of the past, or from climate models used to hindcast the past or forecast future climates. Therefore, temperature-based calculation methods were applied for climatic variables with no primary data available (Allen et al., 1998b). This methodology has been tested for Malawi by Wang et al. (2011), and for South Malawi by Ngongondo et al. (2012) and deemed to be appropriate for use.

B.1. Net Radiation at the Crop Surface

R_n is the net radiation at the crop surface (MJ m2 day^{-1}) and can be calculated as follows:

Equation 2 $$R_n = R_{ns} - R_{nl}$$

Where:

- R_{ns} is the net incoming shortwave radiation (MJm-2 day-1) and can be calculated as follows:

  Equation 3 $$R_{ns} = (1 - \propto)R_s$$

  Where:

  - ∝ is the albedo or canopy reflection coefficient, which is 0.23 for the hypothetical grass reference crop
  - R_s is the fraction of the solar radiation not reflected from the surface (MJm-2 day-1) and can be calculated as follows:

    Equation 4 $$R_s = k_{Rs}\sqrt{T_{max} - T_{min}}\,R_a$$

    Where:

    - K_{RS} is adjustment coefficient. For inland regions not influenced by large bodies of water, $K_{RS} = 0.16$; for coastal regions, or regions where the air mass is influenced by a large nearby water body, $K_{RS} = 0.19$. Since Central Malawi is highly influenced by the presence of a large water body (Lake Malawi). K_{RS} is considered to be 0.19 in this study.
    - T_{max} is the maximum air temperature (ºC)
    - T_{min} is the minimum air temperature (ºC)

        - R$_a$ is extra-terrestrial radiation (MJm-2 day-1) and can be calculated as follows:

          Equation 5 $$R_a = \frac{24(60)}{\pi} G_{sc} d_r [\omega_s \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \sin(\omega_s)]$$

          Where:

            - G_{Sc} is the solar constant = 0.0820 MJm^{-2}min^{-1}
            - d_r is the inverse relative since earth-Sun (rad) which can be calculated as follows:

              Equation 6 $$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right)$$

              Where:

                - J is the number of days in the year between 1 (1 January) and 365 or 266 (31 December). J at the middle of each month = 30.4M-15 where M is the month number
            - ω_s is the sunset hour angle (rad) which can be calculated as follows:

              Equation 7 $$\omega_s = \arccos[-\tan(\varphi) \tan(\delta)]$$

              Where:

                - φ is the latitude (rad)
                - δ is the solar declination (rad) which can be calculated as follows:

                  Equation 8 $$\delta = 1 + 0.409 \sin\left(\frac{2\pi}{365} J - 1.39\right)$$

- R$_{nl}$ is in the net outgoing longwave radiation (MJm-2 day-1) and can be calculated as follows:

  Equation 9 $$R_{nl} = \sigma \left[\frac{T_{maxK^4} + T_{minK^4}}{2}\right] \left(0.34 - 0.14\sqrt{e_a}\right) \left(1.35 \frac{R_s}{R_{so}} - 0.35\right)$$

  Where:

    - σ is the Stefan-Boltzmann constant [4.903 x 10^{-9} MJ K^{-4} m^{-2} day^{-1}
    - T$_{max,K}$ is the maximum absolute temperature during the 24-hour period [K = °C + 273.16],
    - T$_{min, K}$ minimum absolute temperature during the 24-hour period [K = °C + 273.16],
    - e$_a$ actual vapour pressure [kPa], which can be calculated as follows:

      Equation 10 $$e_a = e^o(T_{dew}) = 0.6108 \exp\left(\frac{17.27 T_{dew}}{T_{dew} + 237.3}\right)$$

      Where:

        - T$_{dew}$ is the dew point temperature. T$_{dew}$ is near the minimum temperature (T$_{min}$) when the relative humidity is nearly 100%. In semi-arid regions, T$_{dew}$ is estimated by subtracting 2°C from T$_{min}$. As Central Malawi's humidity is typically under 90%, the T$_{dew}$ can be calculated as follows:

          Equation 11 $$T_{dew} = T_{min} - 2$$
    - R$_s$ is the solar radiation [MJ m-2 day-1], see Equation 4.
    - R$_{so}$ is the clear-sky solar radiation [MJ m-2 day-1], which can be calculated as follows:

      Equation 12 $$R_{SO} = (0.75 + 0.00002(h))R_a$$

Where:

- h is the elevation above sea level (m)
- R_a is extra-terrestrial radiation, (MJm-2 day-1), see Equation 5.

B.2. Soil Heat Flux Density

G is the soil heat flux density (MJ m-2 day^{-1})

- For daily assessment, G is assumed to be zero (0) as the soil heat flux is relatively small

  Equation 13: $\boldsymbol{G_{day} = 0}$
- For monthly assessments,

  Equation 14: $\boldsymbol{G = 0.07\ (T_{month,i+1} - T_{month,i-1})}$

  Where:
  - $T_{mon,\ i-1}$ is the mean air temperature of the previous month (°C)
  - $T_{mon,\ i+1}$ is the mean air temperature of the next month (°C)

B.3. Mean Temperature

T is the mean daily air temperature (°C), which can be calculated as follows:

Equation 15: $\boldsymbol{T_{mean} = \frac{T_{min}+T_{max}}{2}}$

Where:

- T_{max} is the maximum air temperature (ºC)
- T_{min} is the minimum air temperature (ºC)

B.4. Wind Speed at 2m height

u_2 is wind speed at 2 m height (m s^{-1}). We can use a default value of 172 km day^{-1} which is the average value over different weather stations around the globe. This was recommended by Allen et al. (1998). To convert to the correct units for the equation above (m s^{-1}) we can do the following:

Equation 16: $\boldsymbol{\frac{172km}{day}\ x\ \frac{day}{24\ hours}\ x\ \frac{hour}{60\ minutes}\ x\ \frac{minute}{60\ seconds}\ x\ \frac{1000\ meters}{km} = \frac{172{,}000\ meters}{86{,}400\ seconds}}$

B.5. Vapour Pressure

To calculate ETO, various vapour pressure variables are required, including the saturation vapour pressure (e_s), the actual vapour pressure (e_a) and the slope vapour pressure curve (Δ).

- e_s is the saturation vapour pressure (kPa), it can be calculated as follows:

  Equation 17: $\boldsymbol{e_s = \frac{e^o(T_{max})+e^o(T_{min})}{2}}$

  Where:
  - $e^0(T_{max})$ is the vapour pressure at maximum temperature, and can be calculated as follows:

Equation 18: $e^o(T_{max}) = 0.6108exp\left(\frac{17.27T_{max}}{T_{max}+237.3}\right)$

Where:

  - T_{max} is the maximum air temperature (ºC)

- $e^0(T_{min})$ is the vapour pressure at minimum temperature, and can be calculated as follows:

Equation 19: $e^o(T_{min}) = 0.6108exp\left(\frac{17.27T_{min}}{T_{min}+237.3}\right)$

Where:

  - T_{min} is the minimum air temperature (ºC)

- e_a is the actual vapour pressure (kPa), see Equation 10
- Δ is the slope vapour pressure curve (kPa°C^{-1})

Equation 20: $\Delta = \frac{4098\left[0.6108exp\left(\frac{17.27T}{T+237.3}\right)\right]}{(T+237.3)^2}$

Where:

- T is the mean air temperature (°C), see Equation 15
- exp[…] 2.7183 (base of natural logarithm) raised to the power […]

B.6. Psychrometric Constant

γ is the psychrometric constant (kPa °C^{-1}), it can be calculated as follows:

Equation 21: $\gamma = \frac{C_pP}{\varepsilon\lambda}$

Where:

- C_P is the specific heat at a constant pressure, C_P = 1.013 x 10^{-3} MJ kg^{-1} °C^{-1}
- P is atmospheric pressure (kPa), which can be calculated as follows:

Equation 22: $P = 101.325(293 - 0.0065(h))^{5.25588}$

Where:

- h is the altitude above sea level in meters (m)
  - For Central Malawi, the average altitude above sea level (h) is 948.1944444m (determined using data from JISAO (2014))
- ε is the ratio molecular weight of water vapour / dry air, ε = 0.622
- λ is the latent heat of vaporization, λ = 2.45 MJ kg^{-1}

B.7. References

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Appendix C Supplementary Information to Chapter 4

Table C.1: Aflatoxin (AF) contamination of food commodities in Malawi.

Aflatoxin (AF) contamination of food commodities in Malawi compared to European Union (EU) regulated levels (European Commission, 2006; Commission, 2010) (table adapted from Misihairabgwi et al. (2017)). NS: Not Stated

Food Commodity	Toxin	Positive samples (%)	Mean (µg/kg) [Range]	EU Regulation (µg/kg)	Source
Maize based beers from Tribal (chewa) rituals and commercial village brewers	AF	89	90 ± 96 [NS]	4	(Matumba et al., 2014b)
Maize Puffs sold in retail markets	AF	75	1.1 [0.3-2.0]	4	(Matumba et al., 2014a)
Instant maize-based baby cereals sold in local markets	AF	100	2.5 [0.5-10.4]	0.1	(Matumba et al., 2014a)
Maize sold in farmsteads and local markets	AF	100	12 [5-20]	10	(Probst et al., 2014)
Maize from rural households	AF	100	8.3 ± 8.2 [0.7-140]	10	(Mwalwayo and Thole, 2016)
	AFB1	45.3	1.71 ± 3.17 [NS]	5	(Matumba et al., 2009)

Table C.2: Regional Climate Models (RCM) sources the original calendar format, and the climatic variables used.

All of the models other than CanRCM4_r2 were accessed through The Earth System Grid Federation (ESGF) data index (ESGF, 2017). The CanRCM4_r2 model was accessed through the Canadian Centre for Climate Modelling and Analysis website (CCCma, 2017).

RCM	Institution	Lateral Boundary Conditions	Climatic Variable	Original Calendar
CCLM4-8-17_v1 (COSMO, 2017)	Climate Limited-area Modelling Community (CLMcom)	CNRM-CM5 r1i1p1	Tas, Pr	365-days
		HadGEM2-ES r1i1p1		360-days
		EC-EARTH r12i1p1		366-days
		MPI-ESM-LR r1i1p1		366-days
HIRHAM5_v2 (Christensen et al., 2007)	Danmarks Meteorologiske Insitut (DMI)	EC-EARTH r3i1p1	Tas, Pr, Hurs	366-days
RACMO22T_v1 (van Meijgaard et al., 2008)	Koninklijk Nederlands Meteorologisch Instituut (KNMI)	HadGEM2-ES r1i1p1	Tas, Pr, Hurs	360-days
		EC-EARTH r1i1p1		366-days
RCA4_v1 (Samuelsson et al., 2015)	Sveriges Meteorologiska och Hydrologiska Institut (SMHI)	CanESM2 r1i1p1	Tas, Pr, Hurs	366-days
		CNRM-CM5 r1i1p1		366-days
		CSIRO-MK3-6-0 r1i1p1		365-days
		GFDL-ESM2M r1i1p1		365-days
		IPSL-CM5A-MR r1i1p1		365-days
		HadGEM2-ES r1i1p1		360-days
		EC-EARTH r12i1p1		366-days
		MIROC5 r1i1p1		365-days
		MPI-ESM-LR r1i1p1		366-days
		NORESM1-M r1i1p1		365-days
REMO2009_v1 (Jacob et al., 2012)	Climate Service Centre Germany (CSC) and Max Planck Institut (MPI)	EC-EARTH r12i1p1	Tas, Pr	366-days
		MPI-ESM-LR r1i1p1		366-days
CanRCM4_r2 (Scinocca et al., 2016)	Canadian Centre for Climate Modelling and Analysis (CCCma)	CanESM2 r1i1p1	Tas, Pr	365-days

Table C.3: Observed data sources

Dataset	Variable Used	Resolution	Time-Period Available	Data Source
Climate Research Unit (CRU) version 4.0 (Harris et al., 2014)	Tas, TasMin, TasMax and Pr	0.5° Monthly Land Only	1901-2015	Gridded Station Data
University of Delaware (UDel) version 4.01 (Willmott and Matsuura, 2001)	Tas and Pr	0.5° Monthly Land Only	1901-2010	Gridded Station Data
Global Precipitation Climatology Centre (GPCC) version 7 (Schneider et al., 2015)	Pr	1.0° Monthly	1901-2010	Satellite and Station Data

Table C.4: List of data sources for the climate files used in AquaCrop.

Note that all RCMs referred to in this table are listed in Table C.2 and the observed data referred to in this table are from the sources listed in Table C.3. Note also that a version of each of these climate files was created for the three regions of Malawi: Northern, Central and Southern. All climate data used in AquaCrop used a 365-day calendar averaged over the relevant time period.

File	**Time Scale**	**RCP**	**Temperature**	**Reference Evapotrans-piration**	**Precipitation Rate**	**CO_2 Concentration**
1	1971-2000	N/A	Mean of observed monthly data for minimum and maximum temperature	Calculated using methodology described in Section 2	Observed monthly data for precipitation rates	AquaCrop Mauna Loa CO_2
2	2020-2049	4.5	Projected ensemble mean daily minimum and maximum temperature		Projected ensemble mean precipitation rate	AquaCrop IPCC RCP 4.5
3		8.5				AquaCrop IPCC RCP 8.5
4	2040-2069	4.5				AquaCrop IPCC RCP 4.5
5		8.5				AquaCrop IPCC RCP 8.5

Table C.5: List of data sources for the climate files used in AFLA-maize.
Note that all hindcast and projected data referred to in this table are from the RCMs listed in Table C.2 and the observed data referred to in this table are from the sources listed in Table C.3. Note also that a version of each of these climate files was created for the three regions of Malawi: Northern, Central and Southern. All climate data used in AFLA-maize used a 366-day calendar with daily results for each date and year (i.e. 365/366 days (depending on leap year) x 30 years for each scenario).

File	Time Scale	RCP	Temperature	Relative Humidity	Precipitation Rate	Leaf Wetness
1	1971-2000	N/A	Mean of observed monthly data for minimum and maximum temperature	Hindcasted ensemble mean daily relative humidity	Observed monthly data for precipitation rates	Calculated using methodology described in main paper (Section 4.1)
2	2020-2049	4.5	Projected ensemble mean daily minimum and maximum temperature	Projected ensemble mean daily relative humidity	Projected ensemble mean precipitation rate	
3		8.5				
4	2040-2069	4.5				
5		8.5				

Table C.6: Calibration of individual maize varieties (Sutcliffe, 2014) compared with AquaCrop default values.

Parameter (in degree days)	AquaCrop Default	Fast-Development	Slow-Development
Emergence	80	60	98
Max Canopy	705	684	720
Senescence	1400	1008	1715
Maturity	1700	1332	2267
Length building up to Harvest Index (HI)	750	636	1140
Duration of flowering	180	132	220
Degree-Days for Flowering	880	636	1078
Time to maximum rooting depth	1409	1120	1722

Table C.7: Common calibration of both maize varieties compared with AquaCrop default values.

Parameter		**AquaCrop Default**	**Calibrated Maize**	**Reference**
Initial Canopy Cover	Initial Plant Density (plants/ha)	75 000	47 000	(Wiyo et al., 1999)
Canopy Development	Maximum Canopy Cover (%)	96	75	(Fiwa, 2015)
Root Deepening	Maximum effective rooting depth (m)	2.3	0.6	
Harvest Index	Hio (%)	48	40	
Air Temperature Stresses	Base temperature (°C)	8	13	(Benson et al., 2016)
	Upper temperature (°C)	30	32	
Soil Salinity Stress - Salt tolerance	ECe lower threshold (dS/m)	2	4	adapted from (Benson et al., 2016)
	ECe upper threshold (dS/m)	10	9	
Crop response to soil fertility stress	Crop response to soil fertility stress	Not Considered	Considered	(Fiwa, 2015)
	Biomass Production (%)		69	
	Canopy Decline in Season		medium	
	Reduction of Canopy Expansion (%)		7	
	Average decline in Canopy Cover (%/day)		0.1	
	Reduction in water productivity (%)		47	

Table C.8: Development Dates for the fast-development maize variety.

The date of emergence and harvest dates are listed for each climatic scenario and time period, as well as the number of days after planting (DAP) those dates occur. The difference (Δ) between the development of the crop under historic climatic and future climatic conditions is also listed.

Sowing Date	**Region**	**Climate Scenario**	**Emergence**			**Harvest**		
			Date	**DAP**	**Δ**	**Date**	**DAP**	**Δ**
15 Nov.	Northern	1971-2000	21 Nov.	6	N/A	09 Apr.	145	N/A
		2020-2049 RCP 4.5	20 Nov.	5	-1	20 Mar.	126	-19
		2020-2049 RCP 8.5	20 Nov.	5	-1	19 Mar.	125	-20
		2040-2069 RCP 4.5	20 Nov.	5	-1	20 Mar.	126	-19
		2040-2069 RCP 8.5	20 Nov.	5	-1	19 Mar.	125	-20
	Central	1971-2000	20 Nov.	5	N/A	22 Mar.	127	N/A
		2020-2049 RCP 4.5	20 Nov.	5	0	07 Mar.	113	-14
		2020-2049 RCP 8.5	20 Nov.	5	0	05 Mar.	111	-16
		2040-2069 RCP 4.5	20 Nov.	5	0	07 Mar.	113	-14
		2040-2069 RCP 8.5	20 Nov.	5	0	05 Mar.	111	-16
	Southern	1971-2000	20 Nov.	5	N/A	04 Mar.	109	N/A
		2020-2049 RCP 4.5	20 Nov.	5	0	22 Feb.	99	-10
		2020-2049 RCP 8.5	20 Nov.	5	0	21 Feb.	98	-11
		2040-2069 RCP 4.5	20 Nov.	5	0	22 Feb.	99	-10
		2040-2069 RCP 8.5	20 Nov.	5	0	21 Feb.	98	-11
10 Dec.	Northern	1971-2000	17 Dec.	7	N/A	12 May	153	N/A
		2020-2049 RCP 4.5	16 Dec.	6	-1	19 Apr.	131	-22
		2020-2049 RCP 8.5	16 Dec.	6	-1	16 Apr.	128	-25
		2040-2069 RCP 4.5	16 Dec.	6	-1	19 Apr.	131	-22
		2040-2069 RCP 8.5	16 Dec.	6	-1	16 Apr.	128	-25
	Central	1971-2000	16 Dec.	6	N/A	22 Apr.	133	N/A

		2020-2049 RCP 4.5	15 Dec.	5	-1	05 Apr.	117	-16
		2020-2049 RCP 8.5	15 Dec.	5	-1	03 Apr.	115	-18
		2040-2069 RCP 4.5	15 Dec.	5	-1	05 Apr.	117	-16
		2040-2069 RCP 8.5	15 Dec.	5	-1	03 Apr.	115	-18
	Southern	1971-2000	15 Dec.	5	N/A	02 Apr.	113	N/A
		2020-2049 RCP 4.5	15 Dec.	5	0	22 Mar.	103	-10
		2020-2049 RCP 8.5	15 Dec.	5	0	20 Mar.	101	-12
		2040-2069 RCP 4.5	15 Dec.	5	0	22 Mar.	103	-10
		2040-2069 RCP 8.5	15 Dec.	5	0	20 Mar.	101	-12
30 Dec.	Northern	1971-2000	06 Jan.	7	N/A	14 Jun.	166	N/A
		2020-2049 RCP 4.5	05 Jan.	6	-1	13 May	135	-31
		2020-2049 RCP 8.5	05 Jan.	6	-1	10 May	132	-34
		2040-2069 RCP 4.5	05 Jan.	6	-1	13 May	135	-31
		2040-2069 RCP 8.5	05 Jan.	6	-1	10 May	132	-34
	Central	1971-2000	05 Jan.	6	N/A	20 May	141	N/A
		2020-2049 RCP 4.5	05 Jan.	6	0	29 Apr.	121	-20
		2020-2049 RCP 8.5	05 Jan.	6	0	27 Apr.	119	-22
		2040-2069 RCP 4.5	05 Jan.	6	0	29 Apr.	121	-20
		2040-2069 RCP 8.5	05 Jan.	6	0	27 Apr.	119	-22
	Southern	1971-2000	04 Jan.	5	N/A	28 Apr.	119	N/A
		2020-2049 RCP 4.5	04 Jan.	5	0	14 Apr.	106	-13
		2020-2049 RCP 8.5	04 Jan.	5	0	12 Apr.	104	-15
		2040-2069 RCP 4.5	04 Jan.	5	0	14 Apr.	106	-13
		2040-2069 RCP 8.5	04 Jan.	5	0	12 Apr.	104	-15

Table C.9: Development Dates for the slow-development maize variety.

The date of emergence and harvest dates are listed for each climatic scenario and time period, as well as the number of days after planting (DAP) those dates occur. The difference (Δ) between the development of the crop under historic climatic and future climatic conditions is also listed.

Sowing Date	**Region**	**Climate Scenario**	**Emergence**			**Harvest**		
			Date	**DAP**	**Δ**	**Date**	**DAP**	**Δ**
15 Nov.	Northern	1971-2000	25 Nov.	10	N/A	28 Aug.	286	N/A
		2020-2049 RCP 4.5	24 Nov.	9	-1	29 Jun.	227	-59
		2020-2049 RCP 8.5	24 Nov.	9	-1	23 Jun.	221	-65
		2040-2069 RCP 4.5	24 Nov.	9	-1	29 Jun.	227	-59
		2040-2069 RCP 8.5	24 Nov.	9	-1	23 Jun.	221	-65
	Central	1971-2000	24 Nov.	9	N/A	18 Jul.	245	N/A
		2020-2049 RCP 4.5	23 Nov.	8	-1	28 May	195	-50
		2020-2049 RCP 8.5	23 Nov.	8	-1	23 May	190	-55
		2040-2069 RCP 4.5	23 Nov.	8	-1	28 May	195	-50
		2040-2069 RCP 8.5	23 Nov.	8	-1	23 May	190	-55
	Southern	1971-2000	23 Nov.	8	N/A	27 May	193	N/A
		2020-2049 RCP 4.5	22 Nov.	7	-1	01 May	168	-25
		2020-2049 RCP 8.5	22 Nov.	7	-1	29 Apr.	166	-27
		2040-2069 RCP 4.5	22 Nov.	7	-1	01 May	168	-25
		2040-2069 RCP 8.5	22 Nov.	7	-1	29 Apr.	166	-27
10 Dec.	Northern	1971-2000	21 Dec.	11	N/A	26 Sep.	290	N/A
		2020-2049 RCP 4.5	20 Dec.	10	-1	14 Aug.	248	-42
		2020-2049 RCP 8.5	20 Dec.	10	-1	09 Aug.	243	-47
		2040-2069 RCP 4.5	20 Dec.	10	-1	14 Aug.	248	-42
		2040-2069 RCP 8.5	20 Dec.	10	-1	09 Aug.	243	-47
	Central	1971-2000	20 Dec.	10	N/A	01 Sep.	265	N/A

		2020-2049 RCP 4.5	19 Dec.	9	-1	17 Jul.	220	-45
		2020-2049 RCP 8.5	18 Dec.	8	-2	10 Jul.	213	-52
		2040-2069 RCP 4.5	19 Dec.	9	-1	18 Jul.	221	-44
		2040-2069 RCP 8.5	18 Dec.	8	-2	10 Jul.	213	-52
	Southern	1971-2000	18 Dec.	8	N/A	21 Jul.	223	N/A
		2020-2049 RCP 4.5	18 Dec.	8	0	10 Jun.	183	-40
		2020-2049 RCP 8.5	18 Dec.	8	0	06 Jun.	179	-44
		2040-2069 RCP 4.5	18 Dec.	8	0	10 Jun.	183	-40
		2040-2069 RCP 8.5	18 Dec.	8	0	06 Jun.	179	-44
30 Dec.	Northern	1971-2000	10 Jan.	11	N/A	14 Oct.	288	N/A
		2020-2049 RCP 4.5	09 Jan.	10	-1	08 Sep.	253	-35
		2020-2049 RCP 8.5	09 Jan.	10	-1	03 Sep.	248	-40
		2040-2069 RCP 4.5	09 Jan.	10	-1	08 Sep.	253	-35
		2040-2069 RCP 8.5	09 Jan.	10	-1	03 Sep.	248	-40
	Central	1971-2000	09 Jan.	10	N/A	23 Sep.	267	N/A
		2020-2049 RCP 4.5	08 Jan.	9	-1	20 Aug.	234	-33
		2020-2049 RCP 8.5	08 Jan.	9	-1	14 Aug.	228	-39
		2040-2069 RCP 4.5	08 Jan.	9	-1	20 Aug.	234	-33
		2040-2069 RCP 8.5	08 Jan.	9	-1	14 Aug.	228	-39
	Southern	1971-2000	08 Jan.	9	N/A	26 Aug.	239	N/A
		2020-2049 RCP 4.5	07 Jan.	8	-1	21 Jul.	204	-35
		2020-2049 RCP 8.5	07 Jan.	8	-1	14 Jul.	197	-42
		2040-2069 RCP 4.5	07 Jan.	8	-1	21 Jul.	204	-35
		2040-2069 RCP 8.5	07 Jan.	8	-1	14 Jul.	197	-42

Table C.10: AFI for slow- and fast-developing maize varieties in each region of Malawi under differing climatic conditions and sowing dates.

The bold red text indicates AFI levels which are consistent with exceedances of the EU threshold for AFB1 contamination in food.

	Sowing Date	Region	Baseline (1971-2000)	2035 RCP 4.5	2035 RCP 8.5	2055 RCP 4.5	2055 RCP 8.5
Slow-Development Maize Variety	15 Nov.	North	5.62	5.90	28.06	0.44	32.02
	10 Dec.		21.08	38.02	90.07	45.40	54.15
	30 Dec.		35.75	60.19	**101.57**	**169.69**	83.42
	15 Nov.	Central	31.46	60.43	**116.33**	47.80	93.21
	10 Dec.		**97.63**	**103.05**	**146.55**	94.04	**129.55**
	30 Dec.		81.98	**151.65**	**165.21**	**167.04**	**215.79**
	15 Nov.	South	**178.01**	**235.61**	**247.04**	**210.21**	**232.87**
	10 Dec.		**179.40**	**251.67**	**244.28**	**234.12**	**197.55**
	30 Dec.		**147.21**	**238.50**	**247.30**	**265.58**	**282.81**
Fast-Development Maize Variety	15 Nov.	North	4.14	3.43	21.85	0.00	45.61
	10 Dec.		17.20	30.68	75.75	30.32	44.53
	30 Dec.		31.57	64.15	**96.19**	**139.86**	81.83
	15 Nov.	Central	22.27	55.07	**124.70**	39.69	**110.78**
	10 Dec.		84.62	**111.70**	**127.55**	74.40	**110.26**
	30 Dec.		89.86	**156.09**	**168.65**	**154.72**	**209.15**
	15 Nov.	South	**178.60**	**231.56**	**240.76**	**215.12**	**236.56**
	10 Dec.		**185.92**	**251.83**	**243.54**	**235.35**	**180.24**
	30 Dec.		**156.20**	**238.02**	**250.55**	**268.90**	**247.19**

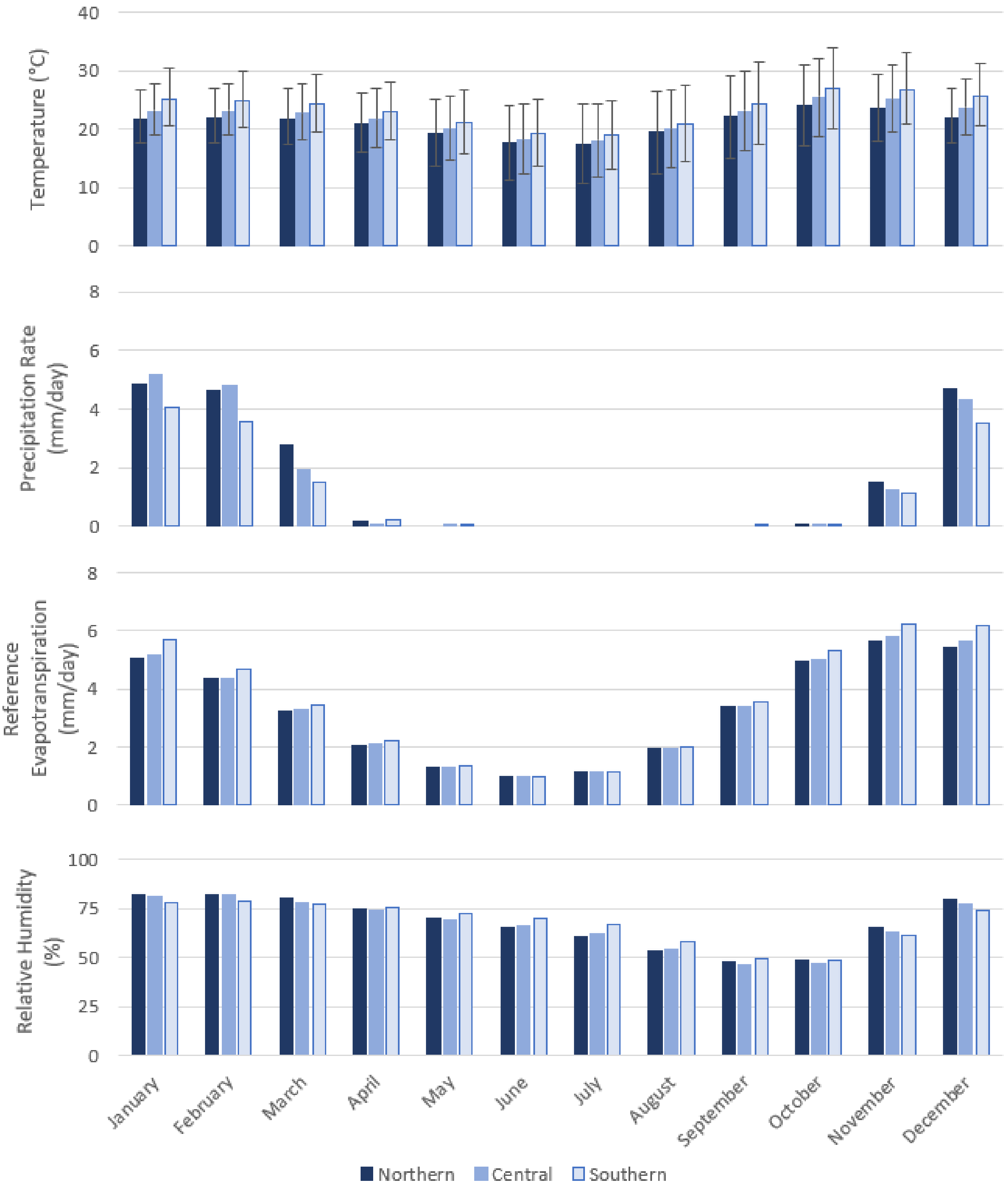

Figure C.1: Malawi's historic climatic conditions (1971-2000).

The top panel shows daily temperatures, the height of the bar indicates the average mean daily temperature during the relevant month over that 30 year period, with the whisker bars indicating the average daily minimum and maximum temperatures. The second, third and fourth panels down show average daily precipitation, average daily reference evapotranspiration and average daily relative humidity respectively. All four panels show this data for the three regions of Malawi in the 1971-2000 period, with the darkest blue representing the Northern Region, the middle blue representing the Central Region and the lightest blue representing the Southern Region.

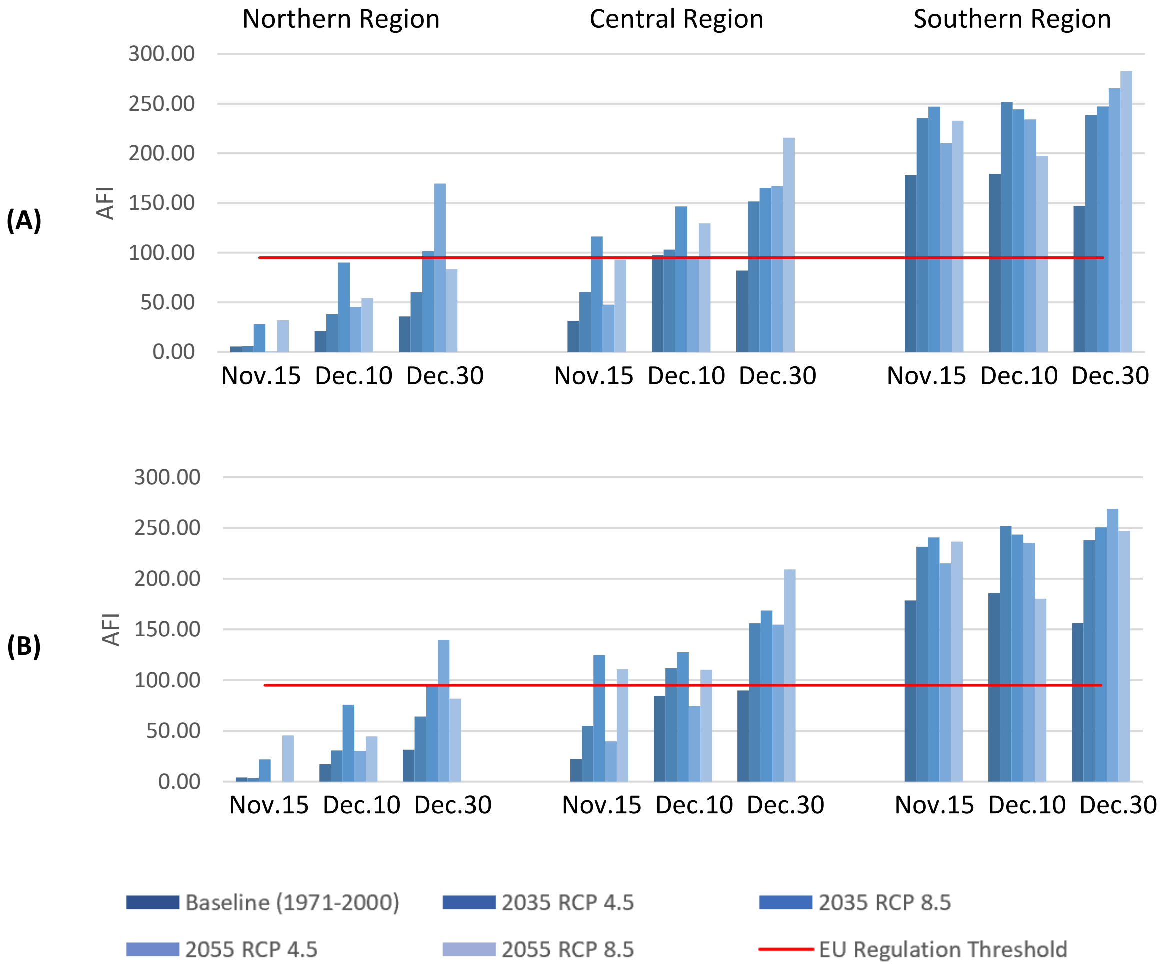

Figure C.2: AFI for slow (A) and fast (B) development maize varieties in each region of Malawi under different climatic conditions and planting dates.

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