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Evaluating Temperature and Precipitation Extremes under a 1.5ºC and 2.0ºC Warming Above Pre-Industrial Levels: Botswana Case Study

Master's Thesis

Environmental and Geographical Science Department

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"Nkemelang, T., New, M. & Zaroug, M. 2018. Temperature and precipitation extremes under current, 1.5 °C and 2.0 °C global warming above pre-industrial levels over Botswana, and implications for climate change vulnerability. *Environmental Research Letters*. 13(6):065016. DOI: 10.1088/1748-9326/aac2f8."

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Acknowledgements

Abstract

The United Nations Framework Convention on Climate Change (UNFCCC) noted the need and therefore requested further quantitative research to better inform policy on the potential impacts of further warming to 1.5 and 2.0 °C above preindustrial levels. Climate extremes are expected to become more severe as the global climate continues to warm due to anthropogenic greenhouse gas emissions. The extent to which extremes and their impacts are to change due to additional 0.5 °C warming increments at regional level as the global climate systems warms from current levels to 1.5 and then 2.0 °C above preindustrial levels need to be understood to allow for better preparedness and informed policy formulation. Having realized the lack of research on this front in Botswana, this study investigates the differentiated impacts of climate change on climate extremes under the current, 1.5 and 2.0 °C warmer climates. The dissertation analysed the projected changes in extremes using Expert Team on Climate Change Detection and Indices (ETCCDI), derived from fifth version of Coupled Model Intercomparison Project (CMIP5) projections over Botswana, a country highly vulnerable to the impacts of climate change. Results indicate that (i) projected changes in temperature extremes are significantly different at the three levels of global warming, with hot day and night extremes expected to realise the greatest increases; (ii) drought related indices are also significantly different, and suggest progressively increasing drought risk with shortened rainfall seasons especially in northern Botswana; and (iii) heavy rainfall indices are likely to increase, but are not statistically different at the different global warming levels. The implications of these changes for key socio-economic sectors are explored, and reveal progressively severe impacts, and consequent adaptation challenges for Botswana as the global climate warms from its present temperature to 1.5 and then 2.0 °C.

List of Acronyms

BOPA – Botswana Press Agency
CCCMA – Canadian Centre for Climate Modelling and Analysis
CESM – Community Earth System Model
CMAP – Climate Prediction Centre Merged Analysis of Precipitation
CMIP – Coupled Model Inter-comparison Project
DSF – Dry Spell Frequency
DWA – Department of Water Affairs
ENSO – El Nino Southern Oscillation
ERL – Environmental Research Letters
ETCCDI – Expert Team on Climate Change Detection and Indices
KNMI – Koninklijk Nederlands Meteorologisch Instituut (Royal Netherlands Meteorological Institute)
GCM – General Circulation Model
GDP – Gross Domestic Product
GEV – Generalized Extreme Value
GHG – Greenhouse Gas
GMST - Global Mean Surface Temperature
IPCC – Intergovernmental Panel on Climate Change
IQR – Inter Quartile Range
ISIMIP – Inter-Sectoral Impact Model Intercomparison Project
ITCZ – Intertropical Convergence Zone
MCC – Mesoscale Convective Systems
MDG – Millennium Development Goals
MICE – Modelling the Impact of Climate Extremes
NOAA – National Oceanic and Atmospheric Administration
RCP – Representative Concentration Pathway
SAM – Social Accounting Matrix
SIDS – Small Island Developing States
SRES – Special Report on Emissions Scenarios
TTT – Temperate Tropical Troughs
UN – United Nations
UNFCCC – United Nations Framework Convention on Climate Change
WATCH – Water and Global Change programme
WFDEI – WATCH Forcing Data methodology applied to ERA-Interim reanalysis data
WGCCD – Working Group on Climate Change Detection
WMO – World Meteorological Organization
WPSR – Wilcoxon Paired Signed Rank

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CHAPTER 1. INTRODUCTION AND RESEARCH RATIONALE

Climate change is one of the greatest human made challenges and threats currently faced by the global community, imposing various risks to society and natural systems either directly or indirectly such as risks to infrastructure, health, food and water security (King et al., 2015; ASC, 2016). Having realised the prevailing and imminent negative impacts climate change poses to the world economy and human wellbeing and security, world leaders resolved to increase effort towards reducing the negative impacts by setting global temperature targets in the 2015 Paris Agreement on climate change (UNFCCC, 2015). A goal of keeping global warming below 2.0 °C above preindustrial levels was agreed on, with an ambition to limit the warming to 1.5 °C; the latter being regarded as a much safer option, as a 2.0 °C warmer climate could lead to unchartered territories (Hare et al., 2016). Based on these two temperature targets, shifts in climates of different localities across the globe can then be assessed to determine the extent to which an additional 0.5 °C temperature rise would influence both the mean and the extremes. With some studies proposing that the 1.5 °C warming level could be crossed as early as 2026 (Henley and King, 2017), the need for early action to both reduce emissions, and respond to potential impacts, becomes even more critical.

The climate of any given locality is important in defining livelihoods of communities living in the area. It affects the wider natural ecosystems and socioeconomic activities needed for humanity to thrive. The norm is to define the climate by its mean state, where day-to-day and month to month weather is averaged to calculate long term mean behaviour, and its variance. Though this helps in understanding the general picture, some important aspects such as extremes that could be of significance for defining climate risks to livelihoods can easily be overlooked. Understanding climate extremes becomes relevant in this sense, as it is through climate extremes that many climate change impacts occur (Trenberth, 2012). Therefore, the changing weather and climate patterns due to global warming can be seen in the shifting of the mean, increased variability and the changing of distribution symmetry (Seneviratne et al., 2012). It is the climate extremes that are usually tied to disasters such as floods, droughts and heat waves (Seneviratne et al., 2012).

These disasters are the ones that produce some of the greatest negative impacts on livelihoods and national security such loss of life, damage to infrastructure and food insecurity (IPCC, 2012; McElroy and Baker, 2012; World Bank, 2013). Temperature and precipitation records continue to be broken worldwide as was observed in the years 2016-17, with 2017 being declared the second warmest on record after 2016 (NOAA, 2017; Northon, 2018). Economic losses from natural disasters, most of which were related to extreme climate events amounted to over £175 billion (Munich Re, 2017). Given the continued increase of anthropogenic greenhouse gases into the atmosphere, the global mean surface temperature (GMST) continues to rise, leading to changing regional climate patterns across the globe (IPCC, 2013), and of course, associated climate and weather extremes. This scenario therefore calls for an in-depth look at how these extremes will evolve in the future to allow for informed future planning, as well as to understand the regional and local implications of different global warming targets.

To enable consistent monitoring of extremes across different locations, a set of 27 temperature and precipitation indices were devised by the Expert Team on Climate Change Detection and Indices (ETCCDI) (Zhang et al., 2011). Several studies have shown changes in the historical context of these indices based on observed data (Frich et al., 2002; Alexander et al., 2006; New et al., 2006; Manton, 2010) and reanalysis data (Sillmann et al., 2013a) across the globe. For future climate change, a number of studies have looked at the projected changes in both temperature (Sillmann et al., 2013b; Lewis and King, 2017) and precipitation (Sillmann et al., 2013b) extremes globally. Most of these studies looked at these changes for a particular period in the 21st century following a particular concentration scenario, the current Representative Concentration Pathways (RCPs), e.g. (Fischer et al., 2013; Lewis and King, 2017) or emissions scenario, e.g. (Kharin et al., 2007).

At regional scales, a number of studies have been carried out to assess both the historical, current and future context of temperature and precipitation extremes (You et al., 2011; Monier and Gao, 2015; Dosio, 2016; Razavi et al., 2016; Alexander and Arblaster, 2017; Shi et al., 2017). For Southern Africa, New et al. (2006) investigated the historical context of extremes from observations while Shongwe et al. (2009) and Pinto et al. (2016) looked at the historical and

future projection of precipitation extremes from reanalysis and downscaled climate model outputs. Very few studies have looked at climate extremes in individual African countries (Abiodun et al., 2016; Touré Halimatou et al., 2017). None of the literature reviewed during the course of this research looked at the differentiated impact of 1.5 and a 2.0 °C warming on climate extremes.

Botswana, though highly exposed and vulnerable to the impacts of climate change, is generally poorly researched with regards to climate change, especially on the changes in climate extremes under climate change. Hambira and Saarinen (2015) together with Akinyemi (2017) noted the widespread agreement among policy makers and the general public on the perceived changing climate patterns in Botswana, that there is reduced rainfall, rising temperatures and increased drought recurrence. Even though there is this general consensus, little scientific evidence exists to confirm these views.

This research project therefore intends to assist in reducing these knowledge gaps. It aims to quantify the projected changes in climate extremes in Botswana that can be expected at the global policy agreed in Paris (1.5 and 2.0 °C) relative to both pre-industrial and present day global temperature levels. This work therefore responds to the request from the UNFCCC for studies that provide more information on the relative impacts of the respective warming levels both locally and globally.

This thesis is structured as follows. Chapter 2 presents the literature review; first, literature relevant to the UNFCCC's request to provide a baseline report on the impacts of 1.5 and 2.0 °C warming above preindustrial levels is presented; followed by a review of literature on climate extremes in general, as well as climate extremes in relation to (i) 1.5 and 2.0 °C, (ii) Southern Africa and Botswana; this is followed by a review of literature on climate change vulnerability in Botswana, after which the aim of the study are presented in the light of the review. Chapter 3 presents background information on Botswana's geography and climate and socioeconomic setting. Chapters 4 presents both data and methodology, as presented in a journal article, which is published in Environmental Research Letters (ERL). In Chapter 5 are the results and discussions,

the findings of the study are presented and discussed together with the implications towards climate change vulnerability in Botswana. The results are also presented here as they are in the ERL journal article. Finally, Chapter 6 is the concluding chapter, where the major findings of the study are summarized and the limitations, future work and recommendations are presented.

CHAPTER 2. LITERATURE REVIEW

In the literature review, the reasons behind the United Nations Framework Convention on Climate Change (UNFCCC)'s resolution to limit temperature rise are first explored, followed by a look at both temperature and precipitation extremes. Climate extremes are looked at in general, followed by a summary of studies that tried to find the differentiated impacts of 1.5 and 2.0 °C warming of the climate system. A review of literature on the historical, current and future context of extremes in Africa and Southern Africa then follows. Later on, a review of literature on the state of research relating to climate change vulnerability and how climate extremes are perceived in Botswana is presented, so as to create a basis for the need of research in this area in Botswana.

2.1. 1.5 and 2.0 °C Warming

The Paris Agreement, under Article 2, resolved to keep global warming to below 2.0 °C with an effort to limit the temperature increase to below 1.5 °C above preindustrial levels (UNFCCC, 2015). The aim to limit the warming to 1.5 °C is thought to potentially reduce negative future climate change risks and impacts, especially for Small Island Developing States (SIDS), and other countries with high vulnerability to climate change. Some argue that the 1.5 °C is still insufficient as it undermines the SIDS states whose communities are already being threatened by sea level rise (Tschakert, 2015). These targets have significant policy implications, with most of the upper middle income to high income countries preferring 2.0 °C while the rest are pushing for the lower boundary target (Tschakert, 2015). The uncertainty associated with the time when the climate system reaches the 1.5/2.0 °C temperature warmings coupled with political and technical challenges could make these targets even more difficult to reach (Peters, 2016). Currently, the Nationally Determined Contributions (NDCs) submitted by party signatories to the Paris agreement fall short of the targets to keep below 2.0 °C. The NDCs are estimated to commit the climate system to a 3.2 °C warming above preindustrial levels while current policies actually implemented deliver 3.4 °C of warming by 2100 (Climate Action Tracker, 2017). Huntingford and Mercado (2016) suggest that current greenhouse gas (GHG) emissions have already committed warming to more than the 1.5 °C target while some recent studies suggests there is a chance the

committed warming is still below 1.5 °C (Mauritsen and Pincus, 2017). Another study by Raftery et al. (2017) suggests that if policy interventions are not put into place, there is a very low chance of meeting the 1.5 and 2.0 °C targets by 2100. To meet the 1.5 °C target, stringent emission cuts will have to be put in place in order to limit further GHG emissions (Millar et al., 2017; Su et al., 2017). According to Arnell et al. (2017), between 27 and 62% of impacts could be avoided globally by keeping GMST at 1.5 instead of 2.0 °C above pre-industrial levels. The findings outlined above further add to the pressure that the global community is under to mitigate further GHG emissions. Based on these factors, the Intergovernmental Panel on Climate Change (IPCC) was invited by the UNFCCC to "*provide a special report in 2018 on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways*" (UNFCCC, 2015). The report will provide a scientific basis for the need for stringent mitigation efforts (Hulme, 2016).

Assessing the differential impacts of climate due to a 0.5 °C increment in GMST has been found to be very difficult especially when trying to use existing model simulations such as Special Report on Emissions Scenarios (SRES) and RCPs (James et al., 2017). Literature differs considerably in defining the base period for estimating the time when models reach 1.5 and 2.0 °C warming above preindustrial levels. Mitchell et al. (2017) defines a 20 year period of 1861-1880, Schleussner et al. (2016) and Henley and King (2017) used the 1850-1900 period defined by IPCC (2013) while Huang et al. (2017) used the 40 year period 1861-1900. James et al. (2017) acknowledges that there is no optimal base period and defines ΔT_g, "increments of global mean surface temperature increase without reference to baseline" owing to the spread in literature in defining the base period. These differences make uncertain the times at which the climate system reaches the 1.5/2.0 °C warming.

Various approaches have been taken to define the time at which the climate system reaches a GMST of 1.5 and 2.0 °C above temperature at a chosen preindustrial period. Of the studies that considered the use of the fifth version of Coupled Model Intercomparison Project (CMIP5) model outputs, Karmalkar and Bradley (2017) defines the time when the ensemble mean from the RCPs reach the required global temperature warming. Wang et al. (2017) and King et al. (2017) define

a 20 year period following the year a particular ensemble member reaches either 1.5 or 2.0 °C. A more critical look at the various methods currently being employed to extract response of model runs to temperature increments has been carried out by James et al. (2017). The authors here outline both the strengths and weaknesses with four methods discussed namely: Scenario approach, sub-selecting models, pattern scaling and time sampling (James et al., 2017). Descriptions of the methods and examples of studies that applied them are outlined in *Table 2-1*.

Table 2-1: Descriptions with study examples of methods employed to extract the response of model runs to temperature increments (James et al., 2017)

Method	Description	Examples of Studies
Scenario Approach	This method considers a particular RCP or SRES and analysis is made for a specific time interval. It is noted that it is not possible to compare 1.5 and 2.0 °C using this method.	May (2008) Schewe et al. (2011)
Sub-Selecting Models	Only runs within an ensemble from a single scenario that exceed a temperature warming of interest are selected based on the global temperature response. The method cannot be used to distinguish climate of two warming levels.	Clark et al. (2010) Betts et al. (2011) Fung et al. (2011)
Pattern Scaling	This method was initially proposed by Mitchell (2003). It assumes a linear relationship between GMST change and local/regional climate response. Local climate response to a change in GMST is derived from a scale factor between GMST and the regional climate.	Zelazowski et al. (2011) Frieler et al. (2012) Tebaldi and Arblaster (2014)
Time Sampling	This method identifies a date when a model experiment reaches a desired temperature warming. The climatology can then be defined by a period centred at the identified date. The chosen climatology can then be compared with the climatology at other desired temperature increments.	Zaroug et al. (in review) Kaplan and New (2006) Schleussner et al. (2016)

When considering the weaknesses in the above mentioned methods, James et al. (2017) suggested that new approaches to be devised to complement the deficiencies. Some recent studies have come up with the new approaches (Mitchell et al., 2017; Sanderson et al., 2017), proposing that the climate system be allowed to stabilize first before the assessments are made

in order to avoid using results from outputs that are in a transient state. Even though the use of CMIP5 model outputs has been critiqued based on James et al. (2017)'s findings, the current study bases its assessment on the outputs from the CMIP5 project owing to the readily accessible dataset on temperature and precipitation climate extremes. The dataset also has the advantage of using many Global Climate Models (GCMs), providing an ensemble that is useful in spanning key uncertainties, internal climate variability and sensitivities to GHG forcing.

2.2. Climate Extremes

The IPCC defines climate extremes as "the occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable" (IPCC, 2012b). Climate extremes could then refer to extremes of individual atmospheric variables, weather and climate phenomena causing extremes or compounded impacts on the natural environment (Seneviratne et al., 2012). This study focuses on the first category that looks at the individual atmospheric variables namely, temperature and precipitation. To quantify climate extremes, several methods have been proposed, with extreme climate indices being the most popular. The ETCCDI indices (Zhang et al., 2011) have been widely used and accepted by the research community because of their robustness and applicability to any region in the world. These indices were a result of the workshop held by the Working Group on Climate Change Detection (WGCCD) in Morocco aimed at filling data gaps and developing the climate indices for Africa (Easterling et al., 2003). The same indices are recommended by the World Meteorological Organization (WMO) to be used by national meteorological and hydrological services when assessing and estimating climate extremes (WMO, 2009). Some other methods have been suggested including the use of a generalized extreme value (GEV) distribution to study the return period of the climate extremes (Kharin et al., 2007). The IPCC (2013) when describing the indices used in the IPCC fifth assessment report, notes that there are some initiatives being devised to combine indices of precipitation, temperature and other climate variables to investigate the intensity and extent of extremes. The current study only considers ETCCDI extreme indices relevant to climate change vulnerability in Botswana.

2.1.1 Climate Extremes under climate change

Under climate change, changes in the mean climate may not necessarily imply a similar shift in the extremes of a particular climate variable. *Figure 2-1* depict the possible changes in extremes of temperature as a result of climate change. The same could be said of other climate variables such as precipitation (IPCC, 2012c). The possible changes include; *(a)* a shifted mean, *(b)* increased variability and *(c)* a changed symmetry of the entire distribution function of the variable. Most of the studies on extremes project with greater confidence significant changes in temperature extremes under global warming, whereas precipitation extreme changes are reported with a slightly lower confidence level (Seneviratne et al., 2012).

To study climate change, the Coupled Model Inter-comparison Project (CMIP) program has been instrumental in providing the necessary simulations to answer to questions posed by the research community; the fifth version (CMIP5) currently provides the latest model simulations (Taylor et al., 2012). Outputs from the CMIP5 program have been used extensively to study climate extremes both in the historical and future context (Sillmann et al., 2013a;
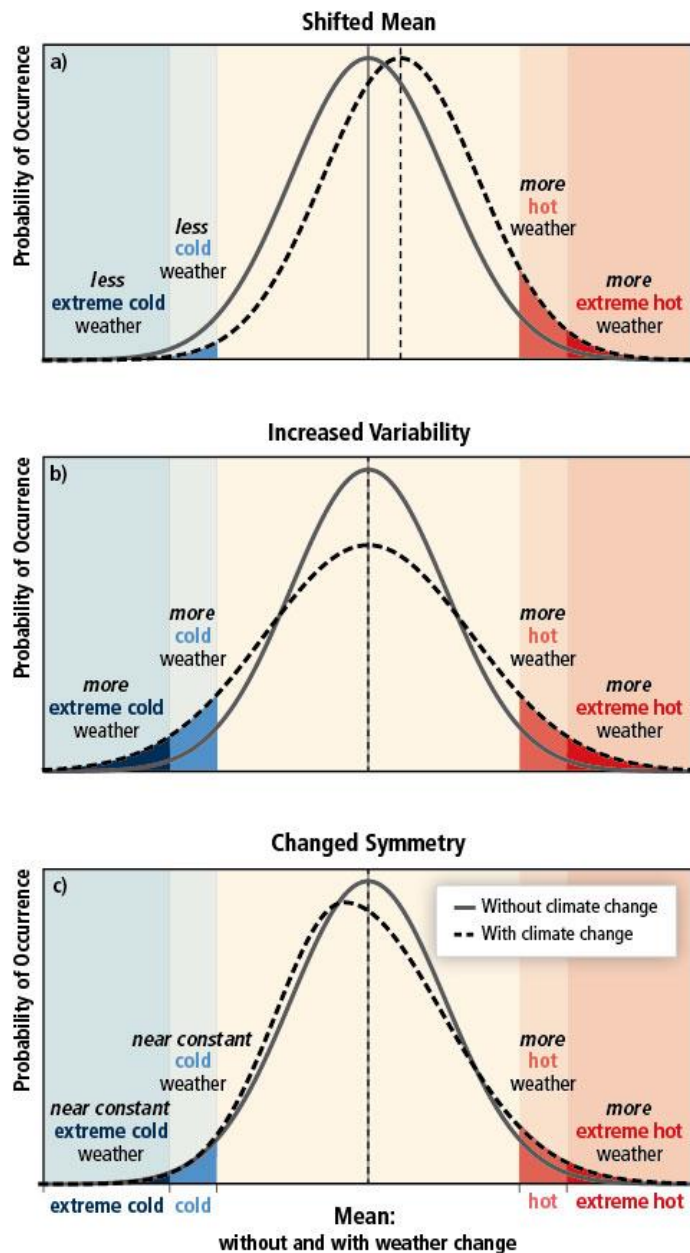
Figure 2-1: Possible changes in temperature distributions under climate change (a) Changed symmetry, (b) increased variability and (c) changed symmetry. Source (IPCC, 2012c)

Sillmann, et al., 2013b; Lewis and King, 2017; Wang et al., 2017). The choice of the RCP followed has been found to have relatively small impact on the changes in the climate extremes (Pendergrass et al., 2015; Shi et al., 2017). Lewis and King (2017) studied the evolution of regional temperature extremes under climate change based on the CMIP5's RCP8.5, an RCP that projects a 8.5 W/m^2 radiative forcing on the climate system by 2100. They describe increases in the ensemble averages of the daily mean (Tmean), maximum (Tmax) and minimum temperature (Tmin) across several regions around the globe. The same study describes an unclear trend in the annual temperature variance with increased variance of differing signs and magnitude at daily timescales further alluding to the changes described earlier by Seneviratne et al. (2012). Fischer et al. (2013), looking particularly at changes in annual temperature maxima and minima (TXx and TNn), five-day accumulated precipitation (TX5day) and number of consecutive dry days (CDD) in precipitation extremes at individual grid points, found a shift towards warming of cold and hot temperature extremes with widespread changes in the precipitation extremes. Razavi et al. (2016) found localized increasing trends in most of the ETCCDI indices including those of precipitation over Hamilton, Canada while Pinto et al. (2016) focusing on precipitation extremes in Southern Africa describes decreases in annual mean precipitation with increases in extreme events. The regional changes in climate extremes, both observed and projected, in literature show the specificity of the changes to different regions. More in-depth analysis at regional and sub-regional spatial scales are therefore needed across the various regions of the world to allow for a more comprehensive understanding of the dynamics in different geographical locations.

2.1.2 Climate Extremes under 1.5 and 2.0 °C warming

More recently, there has been an increased interest on the differential impacts of 1.5 and 2.0 °C warming above pre-industrial levels (e.g. James et al., 2017; Wang et al., 2017). There still exists a gap in assessing these differential impacts, especially at regional or country level scales, and particularly in developing countries. Using the Community Earth System Model (CESM), with simulations that stabilize pathways at GMST 1.5 and 2.0 °C temperatures above preindustrial levels, Sanderson et al. (2017) found the occurrence of global temperature extremes simulated to be 45-55% higher than the 1976-2005 historical levels in a 1.5 °C warmer world compared to

a 70-80% increase in a 2.0 °C warmer world. Precipitation extreme events exceeding the 99th percentile of daily precipitation were found to increase by 7-8% in a 1.5 °C compared to 13-15% in a 2.0 °C warmer climate.

Regionally, for Australia, King et al. (2017) using CMIP5 projections describes a 26% increment in extreme heat events when moving from a 1.5 to a 2.0 °C warmer climate. They project that coral reef heat stress events that cause widespread coral bleaching will be 22% more frequent in a 2.0 °C warmer climate than in a 1.5 °C warmer climate. On extreme wet precipitation events, the study did not find any significant change, whereas precipitation deficits would become slightly more frequent in a warmer world compared to today. In China, temperature extremes were found to increase significantly as the GMST increases from 1.5 to 2.0 °C (Shi et al., 2017); warm days were expected to increase by 7.5 and 13% at 1.5 and 2.0 °C relative to 1986-2005 levels, while precipitation extremes are expected to also increase by about 7 and 11% at 1.5 and 2.0 °C respectively relative to 1986-2005 levels (Li et al., 2017).

2.1.3 Climate Extremes in Southern Africa

Climate change is also set to increase the frequency of extreme weather events in Africa, thereby increasing vulnerability of those already exposed and sensitive, especially impoverished communities in both rural and urban settings. Heavy precipitation, droughts and temperature variations define most of climate variability observed in Southern Africa (Richard et al., 2001; Kandji et al., 2006). Violent storms bringing heavy precipitation and associated flooding have been studied over the years (e.g., Cook et al., 2004; Reason and Keibel, 2004; Reason, 2007; Manhique et al., 2015; Moyo and Nangombe, 2015), these events had significant negative impacts on the livelihoods of the affected communities. Drought events and high temperature episodes that had widespread impacts in Southern Africa have also been studied (e.g., Richard et al., 2001; Rouault and Richard, 2005). These studies bring to attention the importance of understanding the various weather and climate extremes affecting livelihoods in the region.

Studies looking at the evolution of extremes derived from daily observations of meteorological variables in Southern Africa (New et al., 2006) and the West African Sahel (Mouhamed et al.,

2013) have detected statistically significant warming trends on temperature extremes while precipitation has not shown any statistically significant trends in the late 20th century. Similar sentiments were found by Touré Halimatou et al. (2017) when assessing the historical context of temperature and precipitation extremes in Mali. The IPCC (2013) describes confidence levels on the observed changes in some of the extreme indices across the globe; of the extremes, higher confidence levels are placed on the changes in temperature extremes over Southern Africa, whereas low confidence reported for precipitation extremes. Of the temperature extremes, New et al. (2006) reports a pattern of increasing trends in hot extremes and a decreasing trend in cold extremes with heat waves being observed to be on the increase from 1981-2015 (Ceccherini et al., 2017). The study found that the magnitude of the trend was greater in hot extremes compared to cold extremes. Considering projections of temperature extremes over the African continent, Dosio (2016) found a general increase in the number of warm days and nights towards the end of the 21st century with South Africa expected to see a 50-70% increase in the extremes across all seasons.

Precipitation extremes over Southern Africa as reported by New et al. (2006) did not show any significant trends over most of the stations used in the study. An indication of decreasing annual precipitation accompanied with increased intensity rainfall events was also observed (New et al., 2006). Kruger and Nxumalo (2017) when investigating the evolution of precipitation extremes over South Africa, also showed that most of the stations did not show any significant trends in most of the indices during the 1921-2015 period. The study also found a trend towards increasing intensity of rainfall (Kruger and Nxumalo, 2017).

Pinto et al. (2016) using dynamically downscaled multi-model ensemble projections of precipitation extremes at the end of the 21st century, describes significant changes in the indices with a decrease in total annual mean precipitation but increased magnitude of extreme precipitation events. The findings are consistent with the trends observed by New et al. (2006) as well as Kruger and Nxumalo (2017). The magnitude of change was found to be greater under the RCP8.5 than RCP4.5 pathway where median temperature increases of 2.4 and 4.9 °C above pre-industrial (1850-1875) levels are expected by 2100 (Rogelj et al., 2012).

2.1.4 Climate Extremes in Botswana

There is currently very limited literature on climates extremes and extreme events in Botswana. The African continent has seen an increase in heat waves over the last century (Ceccherini et al., 2017) with some related fatalities in Botswana (China.org.cn, 2016). According to a study by Moses (2017) that looked at the historical characteristics of heat waves in nine of Botswana's synoptic weather stations for the period 1959-2015, there is generally an increasing trend in the frequency and severity of heat waves. The study estimated four heat wave variables namely: mean severity, mean frequency, mean duration, and mean number of heat wave days from daily maximum temperature observations (Moses, 2017). In studying within season (December-February) Dry Spell Frequencies (DSF) over Southern Africa, Usman and Reason (2004) found mean dry spell occurrences ranging between about 3 pentads (5 days with <5mm of rainfall) in the northernmost part of the country to 13 pentads in the southwestern parts of Botswana, the bulk of the country noted as susceptible to summer drought. The study used Climate Prediction Centre Merged Analysis of Precipitation (CMAP) pentad data for the 1979/80 to 2001/02 rainfall seasons; positive trends in DSFs were found over most of Botswana signifiying an increase in the summer drought over the period (Usman and Reason, 2004). The dry climate extremes have generally been associated with El Nino episodes (Nicholson et al., 2001). The increase in droughts and heat wave events has led to increased water shortages, even for wildlife (Williams, 2016). Juana et al. (2014) used a Social Accounting Matrix (SAM) to describe the tendency of drought to decrease economic output in many sectors of Botswana's economy. The highest reduction was found in agriculture and agriculture dependent industries leading to increased vulnerability in many communities as the general welfare decreased (Juana et al., 2014).

Though rainfall deficiencies are the more common form of rainfall extremes in Botswana, flood events do also occasionally occur (Tsheko, 2003; Statistics Botswana, 2016a). In analysing extreme wet and dry rainfall seasons over Botswana, Mberego (2017) found that during the wettest periods, there are two peaks of monthly precipitation with February being the most extreme. A number of extreme wet events studied have been associated with the negative ENSO phase, La Nina and anomalies in the south west Indian ocean (Washington and Preston, 2006).

Some of the most extreme wet events have been associated with individual tropical cyclone events that make landfall over the subcontinent (Dyson and Van Heerden, 2001).

2.3. Climate Change Vulnerability in Botswana

According to ND-GAIN (2016), Botswana is ranked 93rd on the ND-Gain 2016 rankings, and within this overall ranking, is the 64th most vulnerable country. The overall rankings combine a country's vulnerability to climate change and other global changes, together with its resilience potential (Chen et al., 2015). Botswana is therefore among the most vulnerable countries, but has above average resilience potential, and has an urgent need to implement climate change adaptation measures. By 2011, a significant proportion (36%) of Botswana's population lived in rural areas where agro-pastoralism is the main livelihood source (Statistics Botswana, 2016b). With the agricultural sector being the most sensitive to the negative impacts of climate change (Kandji et al., 2006), vulnerability is set to increase as climate change comes in as an additional stressor to the many stressors that affect livelihoods that depend on this sector (Sallu et al., 2010; Bunting et al., 2013). Women in rural Botswana have been found to be the ones most vulnerable to the negative impacts brought in by climate change because of their heavy reliance on arable farming and veldt products that are threatened by climate change (Omari, 2010). Agricultural grain yields are expected to reduce considerably under climate change (Chipanshi et al., 2004). The likelihood of streamflow changes, with implications on surface water supply, is also expected to be affected by changing climatic factors under climate change (Batisani, 2011). In addition, climate change has also been found to impact the health (Tanser et al., 2003) and tourism sectors (Hambira and Saarinen, 2015).

The few regional studies in Botswana assessing vulnerability to climate change have found rainfall deficit, rainfall variability and high temperature extremes to be the main climate factors affecting vulnerability in Botswana (Batisani and Yarnal, 2010; Kgosikoma and Batisani, 2014; Masundire et al., 2016), thereby emphasising the need for an in-depth investigation of the potential changes in these extremes under climate change. This study focuses on extreme indices that relate directly to the factors outlined above.

2.4. **Aim of the Study**

There is indeed an increased interest and need to better understand the potential differentiated impacts of further warming to 1.5 and 2.0 °C above preindustrial levels. The need is even greater for developing countries that are most vulnerable and are already bearing the brunt of current climate change. It is also important that the evolution of climate extremes under climate change are better understood as it is by climate extremes that the impact of climate change is mostly realized. Botswana, as a country highly vulnerable to the impacts of climate change, needs to better understand the implications of further warming so that informed policies can be made to mitigate potential future impacts.

After considering the current socio-economic challenges due to climate variability in Botswana, the potential increase in climate extremes due to climate change and how they continue to negatively impact on the economy; the lack of research in the front of future climate extremes, especially at the different levels of warming above preindustrial levels, this study therefore aims to:

> ➢ Assess the magnitude of changes in temperature and precipitation extremes under different levels of GMST warming above preindustrial and present day levels

CHAPTER 3.   STUDY AREA: BOTSWANA'S GEOGRAPHICAL SETTING

3.1.   Geographical Location and Topography

Botswana is a relatively flat, landlocked country located at the heart of Southern Africa bounded by the 18-27S latitudes and 20-30E longitudes. The country shares borders with South Africa to the south, Namibia to the west, Zambia to the north and Zimbabwe to the north east *(Figure 3-1)*. The population of Botswana is just over 2 million with the majority dwelling along the eastern corridor where most of economic activity takes place because of good transport networks and location of major cities, towns and villages (Statistics Botswana, 2016b).
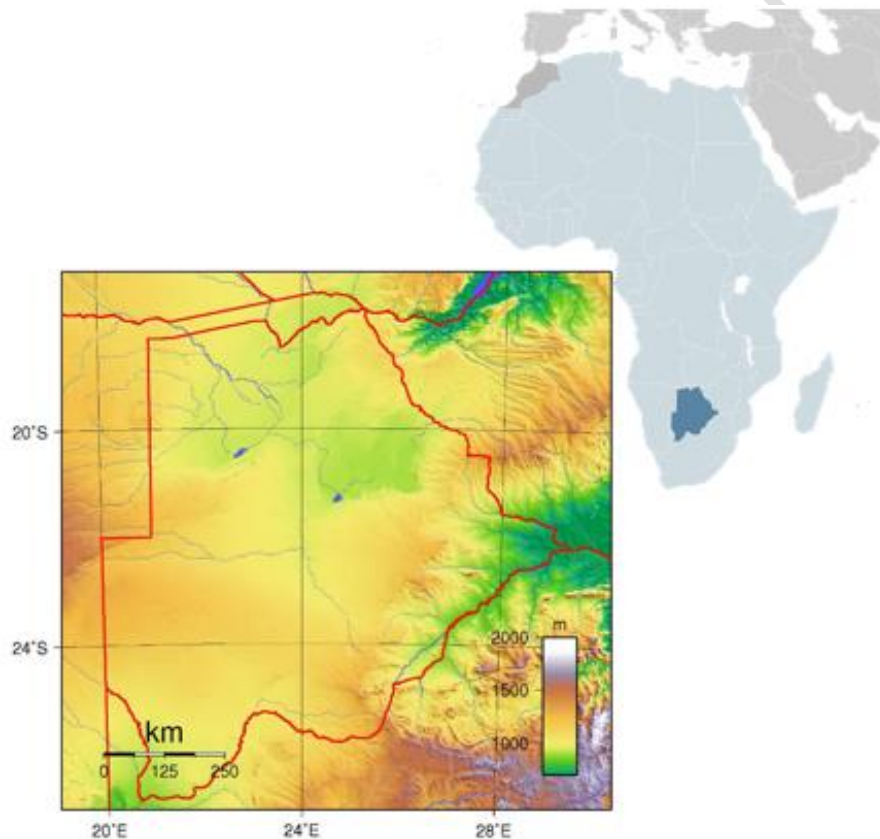

Figure 3-1: Botswana's geographical positioning in Africa (top right) and topography. Source (Mapsland, 2017)

3.2. Climate

Botswana's climate is largely semi-arid to arid with the Kalahari Desert covering over 80% of all land area. Aridity generally increases from the southwest to the north of the country. The southwestern parts of Botswana receive mean annual rainfall accumulations of below 250mm up to 650mm in the northernmost parts, and a secondary maximum of 550mm in southeast Botswana (Bhalotra, 1987). The rainy season occurs in austral summer (mainly November to March). Temperatures in Botswana are lowest during the austral winter and highest during the austral summer. In winter, the occasional passing of westerly cold frontal systems can cause minimum temperatures to fall to below freezing resulting in frosts over most parts of the country (Andringa, 1984). The lowest of temperatures are experienced in the southern most parts of the country while the northern most parts of the country have slightly warmer winters. Moses (2017), using temperature data from 1959-2015, found mean summer daily maximum temperatures to be 31.1-33.0 °C for synoptic weather stations in the northernmost parts of Botswana, 30.9-31.3 °C in central Botswana and 33.0 °C in southwestern Botswana (cf. *Figure 4-2*). Summer temperatures are characterised by occasional heat waves with temperatures reaching over 42.0 °C and lasting up to 10 days on average in some places; trends in the various heat wave variables investigated to date were positive indicating an increase over the period 1959-2015 (Moses, 2017). In 2016, several maximum temperature records were broken with temperatures reaching up to 44.0 °C in Maun (BOPA, 2016).

The subsiding limb of the Hadley cell defines most of the climate in Botswana, with a semi-permanent high pressure system (Botswana high) persistent over the region (Driver and Reason, 2017). Botswana's inter-annual climate variability is mainly driven by ENSO, where El-Nino events are associated with dry conditions (Nicholson et al., 2001) and La Nina events are associated with wet years (Mason and Jury, 1997). Rain bearing weather systems affecting the country include among others temperate tropical troughs (TTT) (Williams et al., 2007) and mesoscale convective systems(MCCs) (Blamey and Reason, 2012). These systems are mainly convection driven and associated with the southward movement of the Intertropical Convergence Zone (ITCZ) in the austral summer months (mainly November to March) (Bhalotra, 1987). Tropical depressions that

form in the Indian Ocean also occasionally penetrate the subcontinent from the east, bringing along heavy precipitation (Reason and Keibel, 2004; Reason, 2007). Some heavy precipitation events could be a combination of various weather systems such as westerly troughs (cold fronts), tropical lows and ridging anticyclones creating a conducive environment for such events (Crimp and Mason, 1999). Cut off lows are also a common occurrence over the region, and tend to bring along heavy precipitation episodes that can cause flooding in some places in Southern Africa including Botswana (Singleton and Reason, 2007; Favre et al., 2013; Molekwa, 2013). Cut off lows also tend to be associated with extreme rainy days that fall outside of the normal rainy season (Favre et al., 2013).

As discussed earlier, dry spells within the rainy season are also a common occurrence in Botswana (Vossen, 1990), being more frequent during ENSO warm phases and over the south-western parts of the country (Usman and Reason, 2004). The national average annual rainfall trends (1971-2015) over the entire country show a decreasing trend, signifying a general drying over the country (Statistics Botswana, 2016b).

3.3. Botswana's Social and Economic Setting

A large percentage of Botswana's population is located in the eastern, less arid, parts of the country where most of the urban centres and major villages occur. Because of the relatively flat landscape, all of Botswana's major dams are located in the eastern parts of the country in the Limpopo river basin, the only area where topography allows for suitable dam sites (DWA, 2013). The bulk of the rural population therefore relies on underground water sources (Omari, 2010b). Though over 60% of the population dwell in the urban and major villages, small scale agriculture is still the main source of livelihoods for the majority of the rural population and major village dwellers accounting for about 70% of the population's livelihood (Setshwaelo, 2001; Omari, 2010b). Large scale commercial agriculture is still at its infancy although some areas have been identified as potential hubs for commercial farming. The Pandamatenga farms in the Chobe (north of the country) are the biggest in terms of land allocated, followed by the Borolong and Ngwaketse farms in the southern district (Statistics Botswana, 2015). Low rainfall and poor soils

make arable farming unviable over the western half of the country. The dominant economic activities in this area are therefore agro-pastoralism and tourism with large chunks of land being reserved for national parks and game reserves. Even though small stock farming in the south west accounts for only 2% of the total small stock population in Botswana (Statistics Botswana, 2015), it still remains the main source of livelihood in the region (Kgosikoma and Batisani, 2014).

Tourism is mainly confined over the northernmost parts of the country which is endowed with abundant wildlife. The Okavango Delta in the north west of the country is the main tourist attraction. The delta receives most of its water from the Okavango River that has its catchment over Angola. Though there is abundant water supply in the region, agricultural activity is limited mainly because of human-wildlife conflicts (Moswete and Dube, 2013). Water abstraction from the delta is also restricted to villages around the delta making commercial irrigated farming difficult (DWA, 2013).

Botswana has performed relatively well in efforts to meet the Millennium Development Goals (MDGs) (United Nations, 2015). Significant progress was made in the goal to eradicate extreme poverty and hunger, access to universal primary education, child mortality reduction and combating HIV/AIDS, malaria and other diseases by the year 2015. Of interest is the slowness of the country to integrate principles of sustainable development into country policies, with limited awareness on the subject of global warming by both the public and the private sector leading poor uptake of policies promoting sustainable development (United Nations, 2015).

CHAPTER 4.   DATA AND METHODOLOGY

This section has been directly cut from the equivalent section of the journal article published in ERL. The paper is attached as an Appendix. The section presents the data used in the study, how the data was processed and the methods used to analyse the data.

4.1.   Data

The expert Team on Climate Change Detection and Indices (ETCCDI) temperature and precipitation extreme indices derived from the fifth version of the Coupled Model Intercomparison Project (CMIP5) program participating models were analyzed. A total of 24 CMIP5 Global Climate Model (GCM) outputs developed by Sillmann et al. (2013a) *(Table S1),* were downloaded from KNMI Climate Explorer website database, https://climexp.knmi.nl (Trouet and Van Oldenborgh, 2013). Where a model had more than one ensemble member, only the first member of the ensemble is chosen. The impact of internal variability of the individual participating models is therefore not captured in the current analysis. All the indices are available re-gridded to a common spatial resolution of $2.5^0 \times 2.5^0$ from their native model resolutions (Sillmann et al., 2013b). Historical simulations (1861-2005) combined with the high emissions scenario Representative Concentration Pathway that projects an 8.5 W/m^2 radiative forcing on the climate system by 2100 (RCP8.5) (Taylor et al., 2012) are chosen for analysis. This RCP is chosen as the forcing is sufficiently intense to guarantee all models reach a warming of 2.0 °C by the end of their simulations. Furthermore, it is most representative of current forcing trends (Lewis and King, 2017). As described below, we analyze indices from individual models at the time they reach specific global temperature targets (1.0, 1.5 and 2.0 °C), so the forcing scenario is not particularly important. Additionally, Pendergrass et al. (2015) and Shi et al. (2017) have shown that, in general, changes in climate extremes are indistinguishable across different RCPs when using multi-model ensembles; although Wang et al. (2017) shows that differences in regional aerosol emissions do produce differences in projected changes over high emission areas (not Southern Africa).

This study focuses on extreme indices that relate directly to climate change vulnerability in Botswana *(Table 4-1)* as determined from a review of vulnerability to climate in semi-arid countries of Southern Africa (Spear et al., 2015). Rainfall deficit, rainfall variability and high temperature extremes have been found to be the main climate factors driving vulnerability (Batisani and Yarnal, 2010; Omari, 2010; Kgosikoma and Batisani, 2014; Masundire et al., 2016). PRCPTOT relates to annual rainfall deficits, R99P, R95P, RX1DAY, RX5DAY, R20MM and R10MM, ALTCWD heavy rainfall extremes and ALTCDD dry periods. For temperature derived indices, the WSDI is used to relate the potential impact of continuous high temperature instances (heat waves as defined by Moses (2017)). The TN90P, TN10P, TX10P and TN10P are also included to help in defining the potential impact of individual hot and cold events (Klein Tank et al., 2009).

Table 4-1: Temperature and precipitation climate extreme indices relevant to vulnerability assessment in Botswana. The indices are available from the KNMI Climate Explorer website [http://climexp.knmi.nl]

Symbol	Name	Units
Precipitation Indices		
PRCPTOT	Annual Total Precipitation in Wet Days	mm/yr
ALTCDD	Maximum Number of Consecutive Days Per Year with Less Than 1mm of Precipitation	days
ALTCWD	Maximum Number of Consecutive Days Per Year with At Least 1mm of Precipitation	days
RX1DAY	Annual Maximum 1-day Precipitation	mm/dy
RX5DAY	Annual Maximum 5-day Precipitation	mm/5dy
R99P	Annual Total Precipitation when Daily Precipitation Exceeds the 99th Percentile of Wet Day Precipitation	mm/yr
R95P	Annual Total Precipitation when Daily Precipitation Exceeds the 95th Percentile of Wet Day Precipitation	mm/yr
R20MM	Annual Count of Days with At Least 20mm of Precipitation	days
R10MM	Annual Count of Days with At Least 10mm of Precipitation	days
Temperature Indices		
TX90P	Percentage of Days when Daily Maximum Temperature is Above the 90th Percentile	%
TN90P	Percentage of Days when Daily Minimum Temperature is Above the 90th Percentile	%
TX10P	Percentage of Days when Daily Minimum Temperature is Below the 10th Percentile	%
TN10P	Percentage of Days when Daily Minimum Temperature is Below the 10th Percentile	%
WSDI	Maximum Number of Consecutive Days Per Year when Daily Maximum Temperature is Above the 90th Percentile	days

4.2. Methodology

A 40 year (1861-1900) base period for the preindustrial era was defined from which the changes in extreme indices are compared following Huang et al. (2017). The years at which each participating model reaches 1.0, 1.5 and 2.0 °C global warming above preindustrial levels is defined using a time sampling method initially used by Kaplan and New (2006) and applied by Zaroug et al. (in review). The 1.0 °C temperature warming above preindustrial is used to represent the current climate (warming to date, from preindustrial) given the GMST reached 1.1 °C in 2016 (WMO, 2017). A 31-year running mean is applied to the entire time-series for each model ensemble member. The climatology at a given GMST warming above pre-industrial is defined by a 30 year period centred at the year the running mean reaches the GMST of interest. *Figure 4-1* shows the spread of the years the participating models reach 1.0, 1.5 and 2.0 °C warming above preindustrial levels.
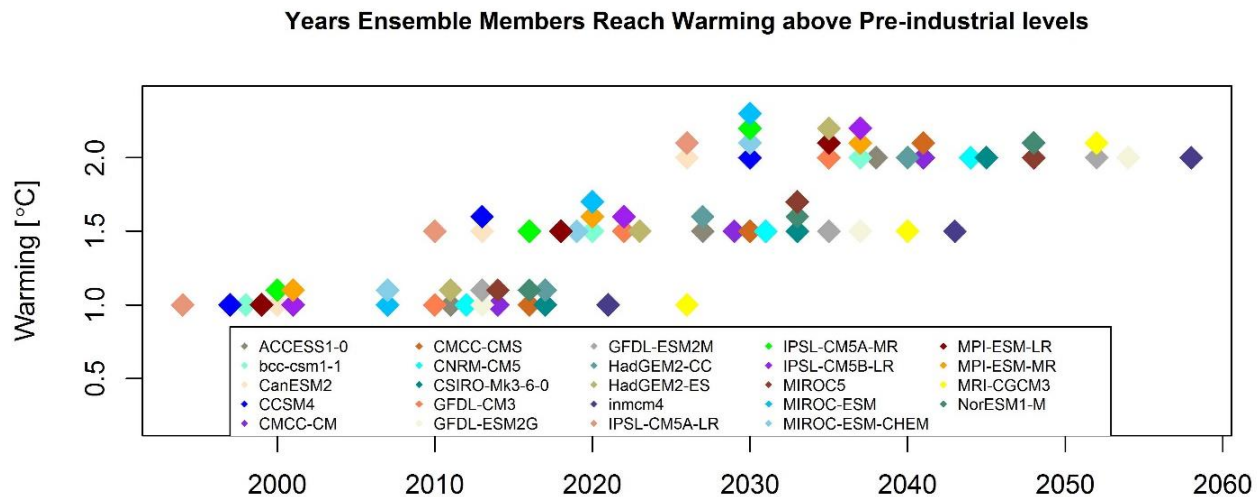
Figure 4-1: Timing of when participating ensemble members reach GMST of 1.0, 1.5 and 2.0 °C warming above the 1861-1900 preindustrial baseline period following the RCP8.5 emissions scenario pathway

Monthly means of observed climate for 1979-2013 from the WATCH Forcing Data methodology applied to ERA-Interim data (WFDEI) (Weedon et al., 2014) was used to cluster Botswana into 3 regions of homogeneous rainfall *(Figure 4-2)*. The WFDEI dataset was found to simulate precipitation well over southern Africa (Li et al., 2013) and has been used in a number of studies in Sub Saharan Africa (Andersson et al., 2016; Nkiaka et al., 2017). Shapefiles of Botswana and the three regions were created using ArcGIS and used to extract the gridded sub-sets of the indices over each region, and the whole country.
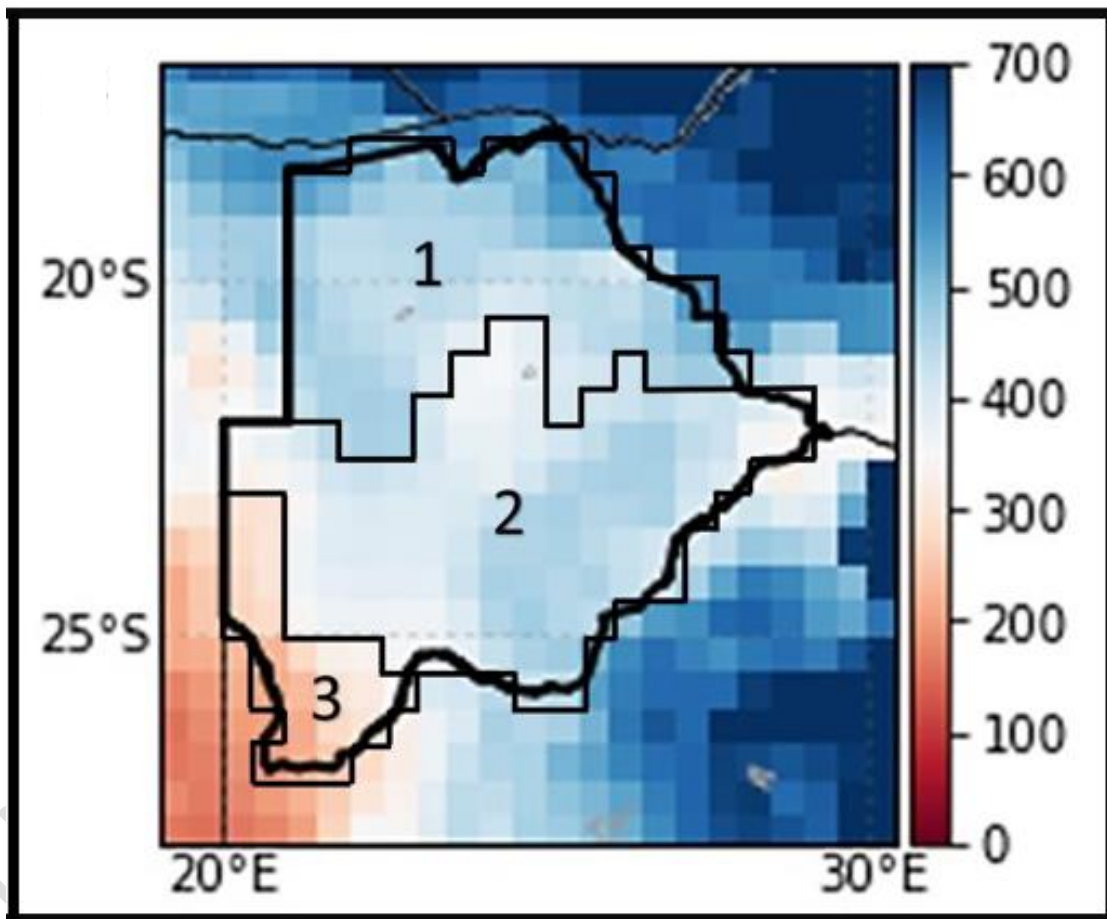
Figure 4-2: Mean annual precipitation (1979-2013) in mm over Botswana derived from the WFDEI dataset and the 3 regions of homogeneous monthly rainfall in Botswana (Region 1, 2 and 3)

Area-weighted average climatological means of the indices at a given GMST warming above pre-industrial levels were calculated within the subsets and used to determine the change relative to pre-industrial levels. For all the 24 members, the change for each extreme index relative to preindustrial levels is calculated as;

$$\Delta I = I_n - I_0 \tag{1}$$

where $I_n, n \in \{1.0, 1.5 \text{ and } 2.0\}$ represents the area averaged climatological mean calculated from the 31-year period surrounding the date of GMST, and I_0 is the area averaged climatological mean of the index of interest for 1861-1900 preindustrial times. Box-and-whisker plots of the absolute changes for each climate extreme index are plotted spanning the 24-member ensemble for each for the 3 regions and over the country areal average.

The non-parametric Wilcoxon Paired Signed Rank test (WPSR) is applied to test if the distributions of ensembles of the indices at 1.0, 1.5 and 2.0 °C are statistically significantly different from preindustrial levels, and from each other. This test has been used in previous climate studies looking to determine the significance of changes in various climate indices/variables at different warming levels (Kharin et al., 2013; Sillmann et al., 2013b). To determine whether the models agree on the sign of change, a criterion that at least 75% of the members need to agree on the sign was adopted (Sillmann et al., 2013b; Pinto et al., 2016).

CHAPTER 5. **RESULTS AND DISCUSSION**

This section is taken from the results section of the paper published in ERL. The paper is attached as an appendix.

Results are presented in box-and-whisker plot format representing the ensemble spread for the change in the indices relative to the preindustrial baseline period. Changes are presented first for precipitation extreme indices followed by temperature extreme indices. From the plots, the ensemble median, interquartile range (IQR) and the outliers are represented. Ensemble member values that exceed 1.5xIQR are considered to be outliers. The box-and-whisker plots are made for each of the 3 regions *(Figure 4-2)* and the country average. Results obtained from testing model agreement on the sign of change are summarized in *Table S2* while *Table S3* summarizes the median [IQR] changes in both of the precipitation and temperature indices relative to preindustrial levels. WPSR test results are presented using p-values.

5.1. **Precipitation Extremes Changes**

Changes in the precipitation indices at 1.0, 1.5 and 2.0 °C GMST warming above preindustrial levels indicate a progressive drying across Botswana, accompanied by an increase in heavy precipitation events, reduced wet spell events and increased dry spells *(Figure 5-1)*. The country average ensemble median change for total annual precipitation, PRCPTOT at 1.0, 1.5 and 2.0 °C GMST warming above preindustrial levels indicate a reduction of 13.4, 33.4 and 63.4 mm/yr with the most extreme reductions (0th percentile) at 175.0, 187.0 and 192.0 mm/yr respectively *(Figure 5-1a)*. Of the 3 regions, Region 1 representing the northern and wettest parts of the country has the largest median reduction across the 3 warming periods with reductions of 20.2, 55.1 and 75.9 mm/yr respectively (these are also the largest relative reductions, compared to preindustrial mean precipitation; see *Figure S1a*). This region, as opposed to the rest of the country tends to be the one that receives most of its rainfall when the ITCZ shifts south in austral summer. The stabilizing and equatorial-ward shifting of the mean position of the ITCZ under climate change could therefore be the reason behind the reduction (Giannini et al., 2008). Region

3 has the least reductions (10.0-43.0mm) in total annual precipitation, because of its already low annual precipitation totals *(Figure 4-2)*; relative reductions are much larger *(Figure S1a)*. When testing for model agreement on change of sign, the change in PRCPTOT at 2.0 °C is the only one that shows consensus among models with >75% of the ensemble members projecting a reduction across all regions. Taking the country average, 58.3% of the models project a decrease in PRCPTOT at 1.0 °C, 62.5% at 1.5 °C and 83.3% at 2.0 °C GMST above preindustrial levels *(Table S2)*. WPSR test results show that the change in PRCPTOT between the three levels of warming is statistically significant across all regions, except for 1.0 versus 1.5 for a couple of the regions. An additional 0.5 °C increment in GMST from 1.5 and 2.0 °C therefore has significant impacts on the annual precipitation across the country. We note that PRCPTOT is not strictly a climate extreme, but it is included in climate extreme studies as total annual precipitation is a measure of interannual drought, and has implications on various economic sectors especially in water stressed countries like Botswana.

Changes in the number of consecutive dry days (ALTCDD) *(Figure 5-1b)* show statistically significant increases across all regions for all warming levels. ALTCDD median increases of 7.2, 13.5 and 18.7 days for the 1.0, 1.5 and 2.0 °C warming levels respectively are projected for Region 1, these being the largest of the changes. On average, Botswana is projected to realise median increases of 5.7, 10.4 and 17.8 days in ALTCDD under the respective warmings. There is general consensus on the sign of change of ALTCDD across ensemble members with more than 80% of members depicting an increase across the three warming periods over the entire country. The increases in ALTCDD imply longer dry seasons with late onsets and early cessation of rainfall as pointed out by Pinto et al. (2016), the same having been noted by Sillmann et al. (2013b). Median changes in the number of consecutive wet days (ALTCWD) are generally very small in magnitude *(Figure 5-1c)*. Relative to preindustrial levels, median changes at 1.0 °C warming are for a decrease of 0.21 days (approximately 5 hours) in Region 1 while Region 2 and 3 show median increases of up to a couple of hours. On average, an additional 0.5 °C warming to 1.5 and 2.0 °C reduces ALTCWD by about half a day. The reductions in ALTCWD may be small in magnitude but are very significant given the short-lived and convective nature of rain bearing weather systems

in Botswana. The shorter rainfall seasons described by increases in ALTCDD coupled with potentially shorter wet-spells will have serious implications on various economic sectors with the agricultural sector set to suffer the most.

For the heavy precipitation indices, the projected ensemble median changes in total accumulated precipitation from heavy (R95P) and very heavy (R99P) precipitation days are a small, but generally non-significant increase as the climate system warms further *(Figure 5-1d,e)*. For R99P, the changes are mostly significant between the three warming levels in Regions 1 and 2, but not in Region 3. The ensemble spread generally disagrees on the sign of change for R95P, but there is more agreement for R99P, especially at the 1.5 and 2.0 °C warming levels.

Median changes in one day and five-day maximum precipitation (RX1DAY and RX5DAY) show a general increase across all regions as the models progress to warmer climates. These changes are generally statistically significant over the wetter and semi-arid Regions 1 and 2, but not in Region 3 *(Figure 5-1f,g)*. These results slightly contradict the findings by Sillmann et al. (2013b) who concluded that there is a general decrease (though statistically insignificant) in RX5DAY in Southern Africa when looking at the changes for the period 2081-2100 relative to 1981-2000. Pinto et al. (2016)'s findings using downscaled projections over Southern Africa are consistent with our results, though they looked at the changes for 2069-2098 relative to the 1976-2005 period. Changes in the frequency of very heavy (R20MM) rainfall events do not show any significant changes, while the frequency of moderately heavy rainfall events (R10MM) show statistically significant decreases across all regions *(Figure 5-1h,i)*.
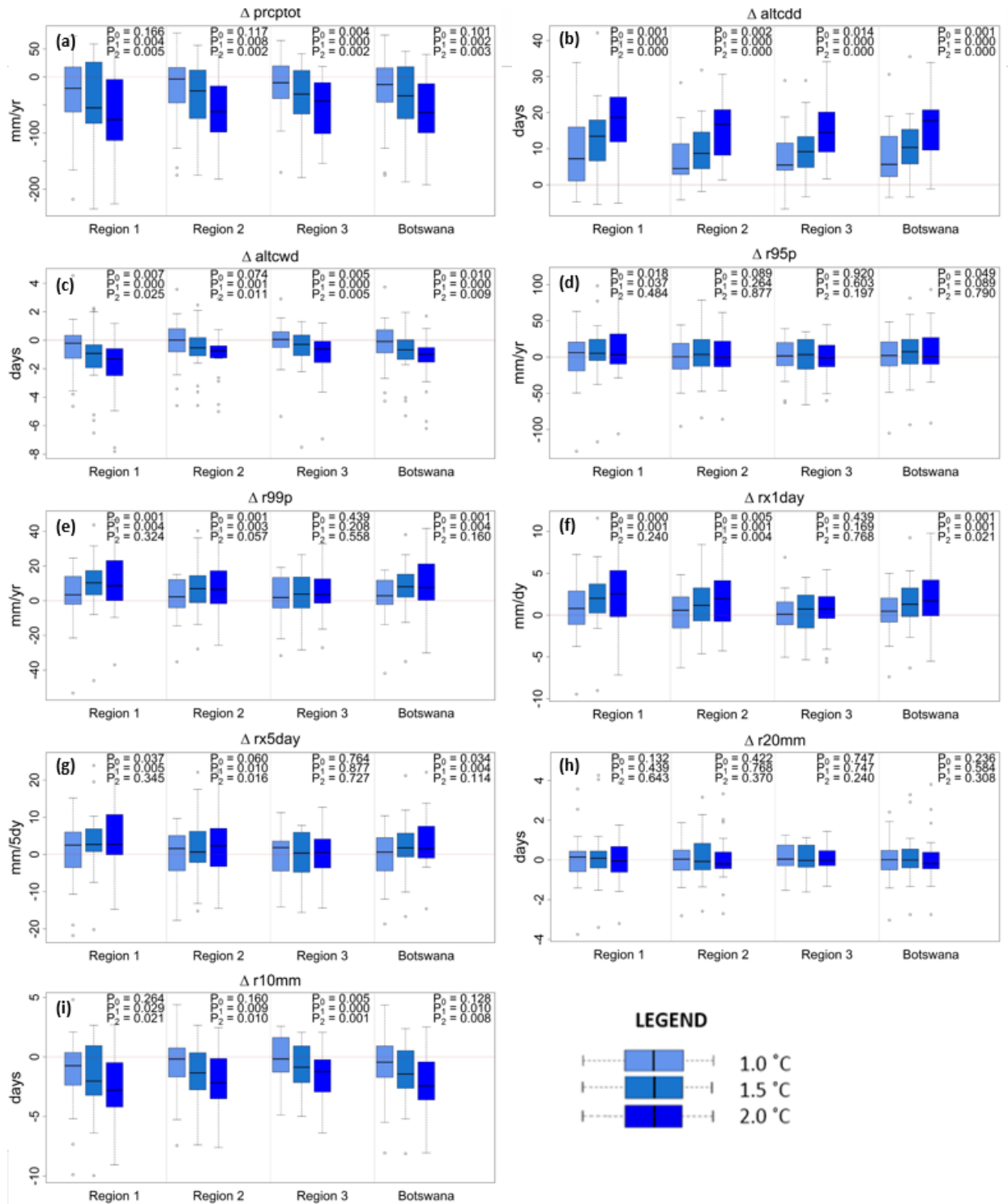
Figure 5-1: Box and whisker plots showing the changes in extreme precipitation indices across an ensemble of 24 participating model members. The changes are at 1.0, 1.5 and 2.0 °C above preindustrial levels (1861-1900). P-values from the WPSR test are shown: P_0, P_1 and P_2 compares the ensemble spread of 1.0 to 1.5°C, 1.5 to 2.0 °C and 1.0 to 2.0 °C warmer climate regimes respectively

To investigate whether biases inherent in climate models especially in simulating accumulated precipitation may influence the results, box-and-whisker plots of percentage changes in the total annual precipitation (PRCPTOT), one day maximum precipitation (RX1day) and the five day maximum accumulated precipitation (RX5DAY) relative to industrial levels are also plotted *(Figure S1)*. Similar results to those obtained using absolute changes were found. An exception was that P_0 for PRCPTOT in Region 2 decreases from 0.117 when using absolute changes to 0.097 when using percentage changes *(Figure S1a)*. The difference suggests that the change in PRCPTOT between the current climate and 1.5 °C are significantly different in Region 2. This could be because of the aridity in Region 2 meaning small percentage changes in total annual precipitation make a significant difference.

5.2. **Temperature Extremes Changes**

The changes in temperature indices agree strongly on the signs of change across the all indices *(Figure 5-2 and Table S2)*. P-values for temperature derived indices obtained from the WPSR test are all very small (<0.001) across all regions and warming levels above preindustrial levels. The p-values here imply that the changes in these indices are statistically significant across all warming levels.

Of the percentile based indices, the hot day and hot night extremes, TX90P *(Figure 5-2a)* and TN90P *(Figure 5-2b)* show the greatest changes, though the change is more pronounced for TN90P especially over Region 1. TX90P is projected to increase by 30% above preindustrial levels on average in Botswana when the climate system reaches 2.0 °C, an increment of 10% from 1.5 °C levels. For TN90P the average increase at 2.0 °C is even higher, at 35%. Decreases in cold day and night extremes, TX10P *(Figure 5-2c)* and TN10P *(Figure 5-2d)*, occur over the entire country with minimum temperature based extremes showing the larger reductions. Hot nights and mild winters are therefore expected to become a common occurrence with a warming climate leading to a decrease in frost occurrences. An increase in warm spells (heat waves; WSDI) are projected across all regions, by 80 days compared to preindustrial levels at 2.0 °C for Region 1, and by 65 and 62 days for Region 2 and 3 *(Figure 5-2e)*. Relating to findings by Moses (2017), the increases

in TX90P and WSDI suggest a significant increase in heat wave events across the country. We note here the need to look at these indices seasonally as an opportunity for further investigation (Sillmann et al., 2013b); we further note that the WSDI does not consider the intensity of heat waves, as pointed out by Dosio (2016).
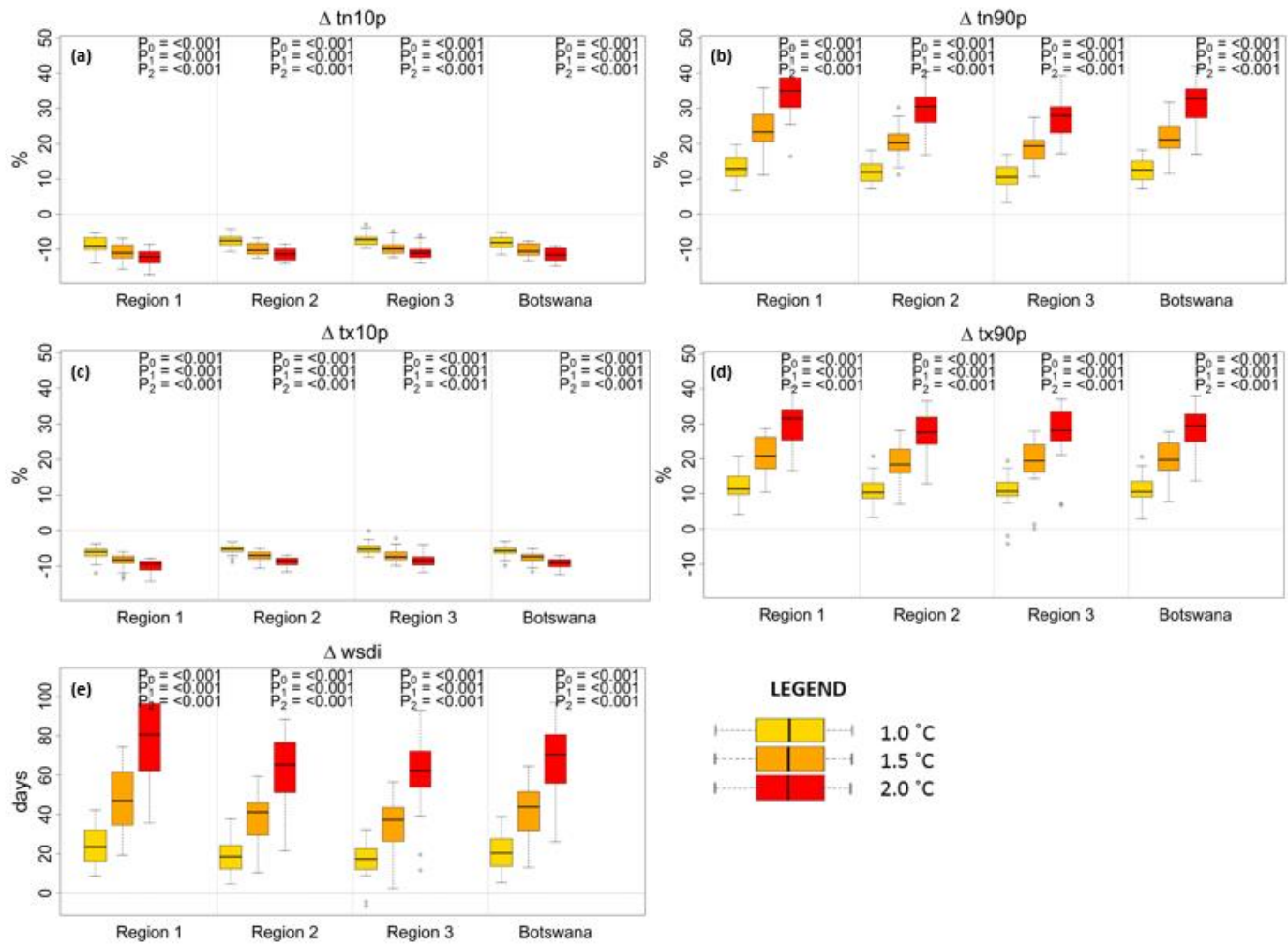

Figure 5-2: Box and whisker plots showing the changes in extreme temperature indices across an ensemble of 24 participating model members. The changes are at 1.0, 1.5 and 2.0 °C above preindustrial levels (1861-1900). P-values from the WPSR test are shown: P0, P1 and P2 compares the ensemble spread of 1.0 to 1.5°C, 1.5 to 2.0 °C and 1.0 to 2.0 °C warmer climate regimes respectively

5.3. Implications for Vulnerability to Climate Change in Botswana

This section is taken from the equivalent section of a paper under consideration with ERL journal. It discusses the potential implications of the changes in the climate extremes to key sectors that are expected to be highly impacted. The agricultural sector is set to be the one to suffer the most followed by the water and the health sectors. The implications are discussed first for the agricultural sector, followed by the water sector and finally the health sector.

The projected changes in both temperature and precipitation extremes under warming climates are expected to have significant negative implications on the agricultural sector The majority of Botswana's population is highly reliant on rain-fed agriculture for livelihoods, so these changes in extremes are likely to produce severe impacts, especially on the most vulnerable, women (Omari, 2010a). Many crops suffer sharp drops on yield after periods of cumulative heat stress (e.g., Schlenker et al., (2010)). The large increases in temperature extremes projected for Botswana, as one moves from 1.5 to 2.0 °C, suggest potentially large, and growing impacts on crops that are currently farmed, such as maize (Barnabás et al., 2008), significantly reducing yields. Previous studies show that Botswana's crop production will be among the most impacted of the countries in Africa (Chipanshi et al., 2004; Schlenker and Lobell, 2010). These impacts will be exacerbated, particularly for rain-fed agriculture, with the projected decreases in mean rainfall and longer dry spells causing plant water stress, crossing the tipping point between good and average harvests, and complete agricultural failure (Batisani and Yarnal, 2010). More intense rainfall will potentially cause crop damage and lower soil moisture. These multiple impacts warn of a growing adaptation challenge as the climate warms, requiring more heat- and drought-tolerant varieties to be developed or adopted. The options for expanding irrigated agriculture are small, apart from perhaps the North West of the country in the Okavango basin, but this would involve trade-offs with biodiversity conservation and ecotourism in this unique wetland system. Livestock production is also likely to be negatively impacted as increased dry spells will

reduce pasture productivity (Setshwaelo, 2001; Mberego, 2017), compounded by inadequate adaptation strategies (Kgosikoma and Batisani, 2014).

Water resources are also likely to be heavily impacted negatively by the reduced total precipitation and increased intensity and longer dry spells, and greater evaporation under more extreme temperatures. Water stress is already a challenge with various economic sec- tors competing for the scarce resource; drought in 2014–2016 led to water-supply failure in the capital city, Gaborone (Siderius et al., 2018). For Region 3, in the south-western parts of the country where rain- fall is already low (annual accumulations of less than 300 mm), further reductions in rainfall imply increased pressure on the already stressed water sources (Siderius et al., 2018). The likelihood of streamflow changes with implications on surface water supply is also expected to be affected by changing climate extremes under climate change (Batisani, 2011). The increasing RX5DAY imply potential increase in very heavy rainfall events that could cause flooding and lead to economic losses (Tsheko, 2003). Though this is the case, some of these heavy rainfall events could come as a relief, replenishing stressed water resources. An example of such a case is the heavy downpours that came with post cyclone Dineo in February 2017 filling up the Gaborone dam that had run dry the previous year.

Looking at the health sector, climate sensitive diseases such as malaria will also be affected by the changes in climate extremes. As malaria epidemics thrive on wet and warmer climates, a general drying of the climate and shorter rainy seasons could lead to a reduction in the extent of the disease (Tanser et al., 2003). Tanser et al. (2003) also note that though for drier climates climate change leads to a reduction in malaria incidences, epidemics can rise during times of heavy precipitation in these generally dry climates (Huang et al., 2017). Based on the reasoning above, epidemics of malaria cases could also become a challenge as the climate systems warms to 2.0 °C. Other implications for health include increased chances of heat related mortalities as heat waves become a common occurrence, malnutrition due to reduced food supply as the agricultural sector is negatively impacted and direct mortalities and injuries from floods (McMichael et al., 2006).

These changes in extremes present a growing adaptation challenge between 1.5 and 2.0 °C for key economic sectors in the country. Rain-fed agriculture is already marginal, and the combined changes in heat extremes and decrease in moisture may well make current agricultural practices unviable at 1.5 or 2.0 °C warming. Botswana is already water-stressed and the projected decreases in mean annual rainfall, as well increased dry spell length, will escalate stress, leading to more frequent water shortages in today's urban and agricultural supply systems. While further work is needed to better quantify the impacts, and resultant costs of adaptation, at these different levels of global mean warming, our results suggest that, for a climate-stressed country such as Botswana, even small increments in global mean temperature have serious societal consequences that will demand progressively more radical adaptation responses.

CHAPTER 6. CONCLUSIONS

There is limited understanding on the potential differentiated impact further warming to 1.5 and 2.0 °C above preindustrial levels will have on the natural environment, socio economic activities and ultimately on human livelihoods. Vulnerable communities in developing countries including Botswana are expected to suffer the most from continued climate change due to global warming. Given that climate extremes are key drivers of vulnerability to climate change impacts and are expected to increase as the climate system warms further, in this study, the evolution of precipitation and temperature extreme indices relevant to climate change vulnerability in Botswana are investigated under current, 1.5 and 2.0 °C warming above preindustrial levels. The main findings of the study are outlined below.

6.1. Key Results

Botswana is projected to experience significant increases in both temperature and rainfall extremes as GMST increases from 1.0 °C through 1.5 to 2.0 °C above preindustrial levels. The changes are particularly strong for temperature extremes; for each increment of global warming, temperature extremes are statistically different, indicating markedly different future regional climates over Botswana. Similarly, there is a statistically significant decrease projected for mean

rainfall and dry-spell length at each global temperature level. In contrast, although intense rainfall indices do show ensemble median increases, the spread in model results means that changes at each increment are not statistically distinguishable. The findings are consistent with studies that showed statistically significant increases in projected temperature derived extreme indices over Southern Africa (Sillmann et al., 2013b; Dosio, 2016) and significant decreases in annual precipitation and drought related indices while heavy precipitation indices show increases that are statistically insignificant (Sillmann et al., 2013b; Pinto et al., 2016).

This study aimed to quantify the relative difference in projected changes in climatic extremes under progressive warming from current to climate policy targets of 1.5 °C and 2.0 °C above preindustrial levels agreed on in the Paris accord of 2015. Changes in climate extreme indices relevant to climate change vulnerability in Botswana were investigated. The indices were obtained from an archive that derived them from models that participated in the CMIP5 project. Findings from this study reveal that Botswana is projected to experience a significant increase in climate extremes especially those of temperature. A significant decline in annual precipitation and shortening of the rainfall season is expected in Botswana as the climate system warms from the current 1.0 °C to warmer 1.5 and 2.0 °C GMST above preindustrial levels. The northern most parts of the country will see the greatest reduction in annual precipitation and increase in the length of the dry season. Very heavy precipitation incidences are projected to generally increase in a 2.0 °C warmer climate compared to the current and 1.5 °C though the increase has been found to be generally statistically insignificant especially over the Kgalagadi region which receives the least annual rainfall accumulations. Heat waves are projected to increase significantly over the entire country as WSDI increases with further warming above current levels. As has been concluded by various studies looking at the evolution of climate extremes, changes in temperature extremes are more pronounced compared to precipitation extremes. The changes in the extremes have been found to have significant implications on various socioeconomic sectors in Botswana with the agricultural and the water sector set to be the most affected.

6.2. Limitations, Future Work and Recommendations

This study uses outputs from GCMs that are of low spatial resolution (of order 2.5 degrees latitude and longitude). This therefore does not allow for the inclusion of local topographical features and processes that could influence the evolution of the extremes, and for precipitation, does not resolve some dynamical meteorological processes that cause extremes, such a tropical depressions and convection. Time constraints made it difficult to employ downscaling methods which could have been of added value to the outcomes of the study.

The study also only looked at extremes at annual timescales which limits the depth of understanding in the projected changes of some of the indices, as noted by Sillmann et al. (2017). More detailed analysis could evaluate extremes on a seasonal basis, although this requires accessing and processing of CMIP5 daily data, which was again not possible within the time limits of this research project. The use of CMIP5's RCP8.5 model outputs means that the climates at 1.5 and 2.0 °C warming are realised in a transient warming phase that could have an influence on the results compared to if an equilibrium state were attained (Sanderson et al., 2017). Comparison of results obtained from the different equilibrium states could help ascertain the credibility of the results obtained in this study.

This study has been conducted using GCM derived data without any background analysis of the current state of climate extremes in Botswana. An analysis of the historical context of climate extremes, derived from either observations, re-gridded or reanalysis datasets in Botswana is recommended. It is also recommended that the study be expanded and conducted at finer temporal and spatial resolutions by applying downscaling methodologies and estimating the indices at sub-annual timescales. This recommendation is conferred given that most climate extremes happen at seasonal, monthly and daily to sub-daily timescales (Sillmann et al., 2017) and that some are season dependent (Dosio, 2016).

The use of climate impact models that incorporate together climate, population, economic and socio economic projections have been found to provide more useful and sector relevant results that can be used to provide better policy advice (Schiermeier, 2012). A possibility of expanding

this study to use impact models could be fitting to provide a sector-oriented impacts of the climate extremes at the respective warming levels above preindustrial levels. Examples include: hydrological models for impacts of potential increased flooding events and water flow into dams; crop models to simulate crop responses to drought, flood and heat extremes; models that can simulate impacts on human health (heat stress, advances in climate related diseases such as malaria) would be a welcome development. Examples of such projects include the Modelling the Impact of Climate Extremes (MICE) project undertaken in the European Union (Hanson et al., 2007) and the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) project (Frieler et al., 2017).

The projected increase in climate extreme indices does have some serious implications for some of Botswana's key socio-economic sectors. Since the agricultural and water sectors are expected to suffer the most, this study recommends a call for different stakeholders in Botswana to work towards adapting to the current and expected challenges. It is noted that concerted efforts need to be made to increase adoption of Climate Smart Agriculture practices, strategic planning for future water security, encouraging water saving measures as well as looking to promote rain water capture as measures to mitigate future impacts. It is further recommended that investments in climate change research be intensified to increase the country's knowledge base on climate change thereby promoting informed policy formulation.

CHAPTER 7.   REFERENCES

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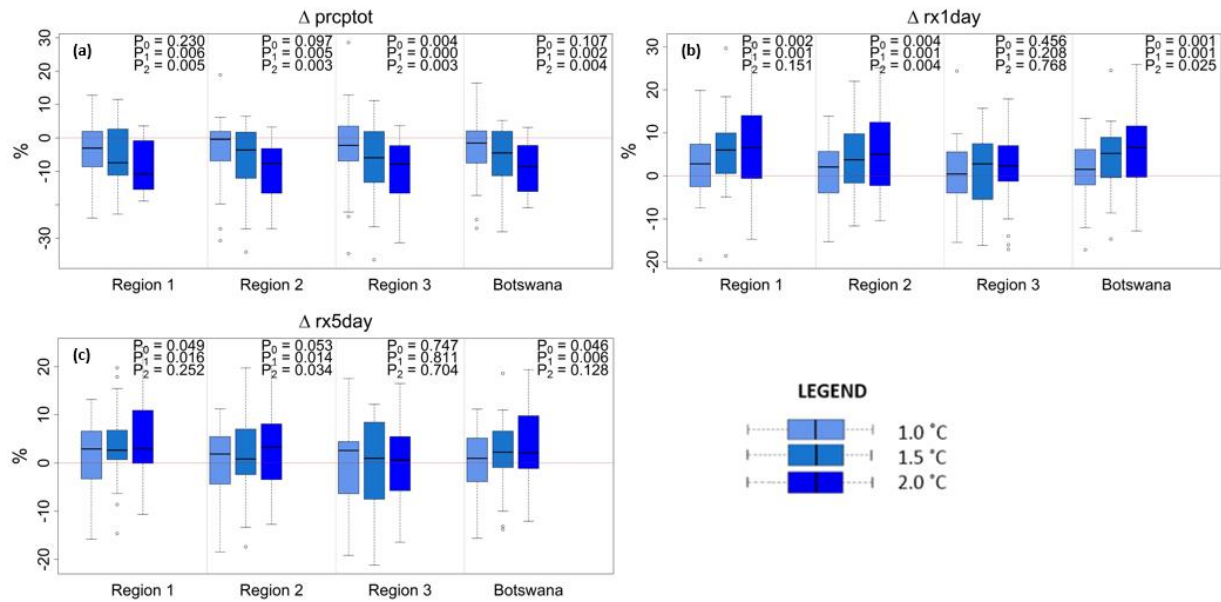
CHAPTER 8. **APPENDICES**

Figure S1: Box and whisker plots showing the relative changes in extreme accumulated precipitation indices across an ensemble of 24 participating model members. The changes are at 1.0, 1.5 and 2.0 °C above preindustrial levels (1861-1900). P-values from the WRS test are shown: P_0, P_1 and P_2 compares the ensemble spread of 1.0 to 1.5°C, 1.5 to 2.0 °C and 1.0 to 2.0 °C warmer climate regimes respectively

Table S1: CMIP5 Models used in the study

Model Name	Abbreviation
Australian Community Climate and Earth-System Simulator	ACCESS1-0
Beijing Climate Center Climate System Model, version 1.1	BCC-CSM1-1
Second Generation Canadian Earth System Model	CANESM2
Community Climate System Model, version 4	CCSM4
Centro Euro-Mediterraneo per I Cambiamenti Climatici Climate Model	CMCC-CM
Centro Euro-Mediterraneo per I Cambiamenti Climatici Stratosphere-resolving Climate Model	CMCC-CMS
Centre National de Recherches Météorologiques Coupled Global Climate Model, version 5	CNRM-CM5
Commonwealth Scientific and Industrial Research Organisation Mark 3.6.0	CSIRO-MK3-6-0
Geophysical Fluid Dynamics Laboratory Climate Model, version 3	GFDL-CM3
Geophysical Fluid Dynamics Laboratory Earth System Model with GOLD component	GFDL-ESM2G
Geophysical Fluid Dynamics Laboratory Earth System Model with MOM, version 4 component	GFDL-ESM2M
Hadley Centre Global Environment Model, version 2 - Carbon Cycle	HADGEM2-CC
Hadley Centre Global Environment Model, version 2 - Earth System	HADGEM2-ES
Institute of Numerical Mathematics Coupled Model, version 4.0	INMCM4
L'Institut Pierre-Simon Laplace Coupled Model, version 5A, low resolution	IPSL-CM5A-LR
L'Institut Pierre-Simon Laplace Coupled Model, version 5A, mid resolution	IPSL-CM5A-MR
L'Institut Pierre-Simon Laplace Coupled Model, version 5B, low resolution	IPSL-CM5B-LR
Model for Interdisciplinary Research on Climate, version 5	MIROC5
Model for Interdisciplinary Research on Climate, Earth System Model	MIROC-ESM
Model for Interdisciplinary Research on Climate, Earth System Model, Chemistry Coupled	MIROC-ESM-CHEM
Max Planck Institute Earth System Model, low resolution	MPI-ESM-LR
Max Planck Institute Earth System Model, medium resolution	MPI-ESM-MR
Meteorological Research Institute Coupled Atmosphere–Ocean General Circulation Model, version 3	MRI-CGCM3
Norwegian Earth System Model, version 1 (intermediate resolution)	NorESM1-M

Table S2: Summary of model agreement on sign of change, percentage number of participating models projecting a negative (decrease) change for the different climate extreme indices.

	% Number of Members Projecting Negative Change											
	REGION 1			REGION 2			REGION 3			Botswana		
Warming Level	1.0 °C	1.5°C	2.0°C	1.0 °C	1.5°C	2.0°C	1.0 °C	1.5°C	2.0°C	1.0 °C	1.5°C	2.0°C
Index	**PRECIPITATION**											
PRCPTOT	62.5	66.7	75.0	58.3	62.5	79.2	54.2	58.3	83.3	58.3	62.5	83.3
ALTCDD	16.7	8.3	4.2	12.5	8.3	0.0	16.7	4.2	0.0	12.5	4.2	4.2
ALTCWD	62.5	79.2	79.2	50.0	66.7	79.2	45.8	62.5	75.0	54.2	75.0	79.2
R95P	37.5	37.5	41.7	41.7	50.0	50.0	45.8	45.8	50.0	41.7	41.7	50.0
R99P	29.2	20.8	25.0	41.7	25.0	29.2	45.8	41.7	37.5	33.3	20.8	25.0
RX1DAY	37.5	20.8	29.2	37.5	33.3	37.5	50.0	37.5	37.5	33.3	25.0	25.0
RX5DAY	41.7	20.8	25.0	41.7	41.7	33.3	45.8	50.0	50.0	45.8	25.0	33.3
R20MM	45.8	45.8	58.3	50.0	50.0	58.3	45.8	50.0	50.0	50.0	50.0	58.3
R10MM	62.5	66.7	75.0	58.3	62.5	79.2	66.7	62.5	79.2	58.3	62.5	79.2
	TEMPERATURE											
TN10P	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
TN90P	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TX10P	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
TX90P	0.0	0.0	0.0	0.0	0.0	0.0	8.3	0.0	0.0	0.0	0.0	0.0
WSDI	0.0	0.0	0.0	0.0	0.0	0.0	8.3	0.0	0.0	0.0	0.0	0.0

Table S3: Median changes in the precipitation and temperature indices (top figures) and the inter-quartile ranges of the ensemble spread of the changes (bottom figures). NOTE: The red colored figures show negative changes

		MEDIAN AND INTERQUARTILE RANGE											
		REGION 1			REGION 2			REGION 3			Botswana		
	Warming Level	1.0 °C	1.5 °C	2.0 °C	1.0 °C	1.5 °C	2.0 °C	1.0 °C	1.5 °C	2.0 °C	1.0 °C	1.5 °C	2.0 °C
Index	Units	PRECIPITATION											
PRCPTOT	mm/yr	-20.2 -0.6, 16.2	-55.1 -82.1, 25.8	-75.9 -113.0,-6.8	-3.6 -44.8,15.9	-24.7 -72.8,12.2	-61.7 -97.7,-18.3	-10.0 -37.9,17.90	-30.4 -64.28,11.1	-43.0 -100.4,-11.4	-13.4 -42.1,15.1	-33.4 -74.0,18.4	-63.4 -98.8,-12.6
ALTCDD	days	7.2 1.2,16.0	13.5 7.0,17.9	18.7 12.0,24.2	4.5 3.0,10.8	8.7 4.7,14.5	16.6 8.3,20.5	5.5 4.1,10.8	9.2 4.9,13.3	14.5 9.2,19.7	5.7 2.4,13.4	10.4 6.1,15.3	17.8 9.8,20.4
ALTCWD	days	-0.2 -1.3,0.3	-0.9 -1.9,-0.3	-1.3 -2.4,2.6	0.0 -0.7,0.8	-0.5 -1.9,0.2	-0.7 -1.2,-0.5	0.1 -0.5,0.5	-0.3 -1.1,0.3	-0.6 -1.4,-0.1	-0.1 -0.9,0.6	-0.7 -1.3,-0.1	-1.0 -1.5,-0.5
R95P	mm/yr	6.2 -17.9,20.3	5.2 -4.2,24.4	3.4 -9.2,30.7	0.3 -15.3,19.0	3.6 -12.5,23.1	-0.1 -12.6,21.5	1.6 -11.3,19.7	3.4 -16.1,23.0	-0.8 -12.9,16.0	2.1 -9.4,20.3	7.3 -9.6,24.2	0.7 -9.9,26.0
R99P	mm/yr	3.5 -1.3,13.9	10.3 3.9,17.3	8.7 0.1,22.7	2.2 -4.0,12.1	6.9 0.3,14.4	6.6 -1.3,17.0	1.9 -4.1,13.0	3.8 -3.6,13.6	3.6 -1.4,12.1	2.9 -1.7,11.7	8.0 2.7,15.2	7.7 0.6,20.4
RX1DAY	mm/dy	0.8 -1.1,2.6	2.0 0.3,3.7	2.5 0.1,5.3	0.6 -1.4,2.2	1.2 -0.6,3.2	2.0 -0.7,4.0	0.1 -1.1,1.4	0.7 -1.3,2.4	0.7 -0.4,2.1	0.1 -0.7,2.0	1.3 0.0,3.2	1.7 0.0,4.0
RX5DAY	mm/5dy	2.5 -3.5,5.7	2.7 1.0,6.8	2.7 -0.1,10.6	1.6 -4.3,4.8	0.7 -2.0,6.1	2.31 -2.8,6.7	1.8 -4.4,3.6	0.4 -4.7,5.7	0.5 -3.4,3.9	0.6 -4.2,4.5	1.8 -0.3,5.7	1.6 -0.9,7.3
R20MM	days	0.1 -0.6,0.4	0.1 -0.4,0.4	-0.1 -0.6,0.6	0.0 -0.5,0.5	-0.1 -0.5,0.8	-0.2 -0.4,0.4	0.0 -0.2,0.7	0.0 -0.4,0.7	0.0 -0.3,0.4	0.0 -0.5,0.5	0.00 -0.4,0.5	-0.2 -0.4,0.4
R10MM	days	-0.7 -2.2,0.4	-2.0 -3.1,0.9	-2.8 -4.1,-0.9	-0.2 -1.7,0.6	-1.3 -2.6,0.3	-2.2 --3.4,-0.2	-0.2 -1.2,1.5	-0.9 -2.1,0.9	-1.2 -2.8,-0.3	-0.4 -1.7,0.9	-1.4 -2.4,0.5	-2.4 -3.6,-0.6
		TEMPERATURE											
TN10P	%	-9.1 -10.1,-6.7	-11.0 -12.5,-8.8	-12.2 -13.7,-10.8	-7.5 -8.8.8,-6.5	-10.3 -11.4,-8.4	-11.4 -13.0,-10.0	-7.3 -8.6,-6.7	-9.9 -11.13,-8.7	-11.0 -12.3,-10.1	-8.1 -9.5,-6.7	-10.6 -11.6,-8.4	-11.6 -13.2,-9.7
TN90P	%	12.9 10.8,16.0	23.3 10.7,28.2	35.0 30.3,38.7	12.0 9.5,14.2	20.3 18.3,22.6	30.6 26.1,33.2	10.5 8.6,13.2	19.4 18.3,22.6	28.0 26.1,33.2	12.6 9.8,14.8	21.1 18.9,24.8	32.8 27.9,35.4
TX10P	%	-6.0 -7.0,-5.4	-8.2 -9.0,-7.2	-9.3 -11.0,-8.6	-5.2 -5.9,-4.3	-7.0 -7.9,-6.1	-8.6 -9.5,-7.8	-5.3 -6.2,-4.3	-7.4 -8.1,-6.1	-8.5 -9.7,-7.4	-5.7 -6.2,-4.9	-7.4 -8.2,-6.7	-9.0 -9.9,-8.2
TX90P	%	11.4 9.9,14.8	20.9 17.8,26.1	31.6 25.4,33.9	10.5 8.9,13.1	18.4 16.2,22.5	27.6 24.4,32.7	10.8 9.5,13.3	19.5 16.3,23.9	28.1 25.1,33.3	10.7 9.2,13.6	19.8 17.1,24.3	29.5 24.9,32.7
WSDI	days	23.5 16.3,32.0	47.0 34.7,61.2	80.7 62.3,96.4	18.6 12.6,24.3	41.2 30.1,45.5	65.4 52.6,76.5	17.4 12.7,22.4	37.3 26.7,43.5	62.4 54.3,72.1	20.5 14.2,27.6	43.9 33.0,51.0	70.6 57.5,80.3