Drought Processes in Current and Future Climate and Implications for Irrigation and Resilient Food Systems in Malawi

by

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Confirmation of authorship

The candidate confirms that the work submitted is his own, except where work which has formed part of jointly authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

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This work forms the bulk of Chapter 3. E. Likoya, developed the research idea with contributions from C. Birch, S. Chapman, and A. Dougill. E. Likoya wrote the code for the identification and characterization of austral summer droughts as well as examination of anomalous atmospheric circulation and moisture transport patterns and their links to sea surface temperature anomalies in drought years. E. Likoya led the development of the methodology and conducted the relevant calculations and visualization with guidance from the coauthors. The manuscript was written by E. Likoya with guidance and input from the coauthors. All data sources for this manuscript, the associated chapter, and the rest of the chapters have been cited in relevant sections.

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Abstract

Malawi's climate is no exception to frequent droughts, a characteristic feature of the southern and eastern African climate. The study first examines drought characteristics and associated atmospheric circulation patterns in observations, reanalysis, and present-day climate simulations. Drought climatology is generally uniform across Malawi, but differences is drought timing and simultaneous dry-wet anomalies suggest different drought drivers between the north and south. Different atmospheric circulation patterns during drought years in the two regions highlight the dynamical pathways through which drivers of variability – including El Niňo Southern Oscillation (ENSO) – produce drought conditions in the two regions. CMIP5 models simulate drought processes over Malawi with notable biases in the drought climatology, and inconsistencies in associated mechanisms particularly those linked with ENSO.

The second component of the study examines droughts in climate projections and performs hydrological simulations to examine hydrological responses to climate variability and change, and implications for irrigation across five river basins in the Lake Malawi–Shire River Basin. Drought frequency is projected to increase across Malawi as are drought severity and intensity, reflecting projected changes in temperature and precipitation. Hydrometeorological processes across all five basins show high sensitivity to climate variability and change. High streamflow responses to changes in precipitation means that episodic spikes in irrigation water demand (IWD), resulting from meteorological droughts, usually coincide with hydrological droughts. IWD is projected to increase across all five river basins. The most pronounced increase is in the Shire River basin where a significant reduction in streamflow reliability is also projected.

Finally, the study explores climate risk perceptions in relation to irrigation at the national, local government, and grassroots levels. There is increasing recognition of climate risk in policies, but less attention is drawn to risks for irrigation, although farmer communities appreciate climate risks for irrigation through various encounters. Dominant narratives risk continuous framing of irrigation as immune to climatic shocks but slowly convergent views around climate risks for irrigation and a responsive policy environment provide opportunities for a systematic paradigm shift towards climate-smart irrigation.

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List of Abbreviations

AL	Angola Low
AMMA	African Monsoon Multidisciplinary Analysis
AR	Assessment Report (IPCC)
AVHRR	Advanced High-Resolution Radiometer
CAB	Congo Air Boundary
CDD	Consecutive Dry Days
CDF-t	Cumulative Distribution Function - transformation
CERES	Crop Environment Resource Synthesis
CFSR	Climate Forecast System Reanalysis
CHIRPS	Climate Hazard Group Infrared Precipitation with Station
CMAP	Climate Prediction Centre Merged Analysis of Precipitation
CMIP5	Coupled Model Intercomparison Project phase 5
CORDEX	Coordinated Downscaling Experiment
CRU	Climate Research Unit
DEM	Digital Elevation Model
DHI	Danish Hydraulic Institute
DJF	December January February (season)
DSMW	Digital Soil Map of the World
EMA	Environmental Management Act
ENSO	El Niňo Southern Oscillation
ERA	European Centre for Medium-Range Weather Forecast Re-Analysis
ET	Evapotranspiration
ETCDDI	Expert Team on Climate Change Detection and Indices
FAO	Food and Agriculture Organisation of the United Nations
FGD	Focus Group Discussion
GBA	Green Belt Authority
GBI	Green Belt Initiative
GCM	Global Climate Model
GDEM	Global Digital Elevation Model
GLCC	Global Land Cover Classification
HRU	Hydrologic Response Unit
IMP	Irrigation Masterplan (and Framework of Investment)

IOD	Indian Ocean Dipole
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter Tropical Convergence Zone
IWD	Irrigation Water Demand
JICA	Japanese International Cooperation Agency
JJA	June July August (season)
KGE	Kling Gupta Efficiency (Index)
LMSRB	Lake Malawi - Shire River Basin
MAM	March April May (season)
MCT	Mozambiquan Channel Trough
MGDS	Malawi Growth and Development Strategy
MME	Multi Model Ensemble
MJO	Madden Julian Oscillation
NAPA	National Adaptation Programmes of Action
NASA	National Aeronautics and Space Administration
NCEP	National Centre for Environmental Prediction
NEAP	National Environmental Action Plan
NOAA	National Oceanic and Atmospheric Administration
NRS	National Resilience Strategy
NSE	Nash-Sutcliffe Efficiency (Coefficient)
ODSS	Operation and Decision Support System
PDSI	Palmer Drought Severity Index
PET	Potential Evapotranspiration
PRIDE	Programme for Rural Irrigation and Development
QBO	Quasi-Biennial Oscillation
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RMSE	Root Mean Square Error
SDI	Streamflow Drought Index
SIHP	Southern Indian Ocean High Pressure
SIOCZ	Southern Indian Ocean Convergence Zone
SIOD	Southern Indian Ocean Dipole
SLP	Sea Level Pressure

SO	Southern Oscillation
SON	September October November (season)
SPEI	Standardised Precipitation and Evapotranspiration Index
SPI	Standardised Precipitation Index
SRTM	Shuttle Radar Topography Mission
SST	Sea Surface Temperature
SWAT	Soil and Water Assessment Tool
SWAT	Soil and Water Assessment Tool
TTT	Tropical Temperature Trough
UNFCCC	United Nations Framework Convention on Climate Change
USGS	United States Geological Survey (Department)
VIMD	Vertically Integrated Moisture Divergence
VIMF	Vertically Integrated Moisture Flux
WCRP	World Climate Research Programme
WDF	Wet Day Frequency
WEFE	Water Energy Food Environment (Nexus)
WFD	Watching Forcing Data
WFDEI	Watch Reference Data Applied for ERA Interim
WMO	World Meteorological Organisation
WUA	Water User Association

Chapter 1

Introduction

Droughts are an important feature of the southern and eastern African climate. Their impacts on human systems and ecosystems alike are felt across a range of spatial and temporal scales. For this region, the impacts of droughts are magnified by a range of factors including pre-existing water scarcity, poorly developed economies and livelihoods, and reliance on rainfed agriculture. Malawi's climate is no exception to frequent droughts, the majority of which have had disastrous effects on agriculture and food security over the years. The prospect of increasing drought risk in a changing climate, and increased encounters in recent years, continues to feed the rationale for a climate resilience development agenda, prompting the government and development partners to devise policies and investment plans aimed at galvanizing the agriculture sector through irrigation.

Despite the societal relevance of droughts, and the growing impetus to invest in resilient systems, the understanding of physical drought processes in the region, and Malawi in particular, remains elusive. Over subtropical southern Africa, droughts are mainly attributed to El Niño, while La Niña events are typically expected to produce drought conditions in eastern Africa. However, the non-linearity of the teleconnection between the El Niño Southern Oscillation (ENSO) and rainfall, as well as the influence of other synoptic and local drivers of variability makes the association between droughts and ENSO less straightforward. Malawi's unique geographical location compounds this complexity and presents considerable challenges for drought examination. While previous events have largely been attributed to El Niño, observations in later years indicate the prevalence of a north-south precipitation dipole during El Niño and La Niña. El Niño events are associated with droughts in the south, consistent with patterns noted for subtropical southern Africa, while La Niña conditions are associated with droughts in the north - consistent with patterns in eastern Africa.

Whether incremental or transformational, improved understanding of drought processes has the potential to better the understanding of how well droughts are simulated in Global Climate Models (GCMs). Both the Fifth and Sixth Assessment Reports (ARs) of the Intergovernmental Panel on Climate Change (IPCC) acknowledged limited model evaluation for droughts (Flato *et al.*, 2013; Seneviratne *et al.*, 2021). Model evaluation for droughts is a two-dimensional undertaking. Firstly, the focus of the evaluation is on the drought climatology – defined by the spatial and temporal patterns of a representative weather variable or drought index. In the second instance, emphasis is put on processes that produce drought conditions and how well they are simulated in climate models. In this view, the evaluation ascertains whether a given model reliably simulates drought climatology, and for the right reasons. Regional studies undertaken in recent years (Lazenby *et al.*, 2016; Munday and Washington, 2017; James *et al.*, 2018; Barimalala *et al.*, 2020) have improved the understanding of regional processes and how well they are simulated in GCMs, particularly in the Fifth Phase of the Coupled Model Intercomparison Project (CMIP5) (Taylor *et al.*, 2012) . Notwithstanding these gains, knowledge of model simulation of drought processes remains limited, prompting the need for continuous improved understanding of such processes to improve model performance and make reliable interpretations of climate information for development applications.

Whether short-lived (flash droughts) or long-lived (mega droughts), droughts are slow-evolving phenomena, making them less spectacular as far as their impacts are concerned when compared to other weather extremes such as floods. The nature of processes that govern the propagation of the drought signal through different components of the hydrological cycle makes their examination less straightforward. Such processes can work to produce synchronous or asynchronous water deficits in different components of the hydrological cycle, an essential aspect for examining the potential impacts of a drought. Understanding these relationships is key to navigating assumptions that rainwater deficits will always be offset by irrigation. The potentially paradoxical nature of irrigation-based solutions, especially in a changing climate, is a question that has not received much attention both in research and development.

So far, Malawi has been vigilant in creating plans and policies for drought risk management with the aim of transforming agricultural landscapes from being predominantly rainfed to irrigation based. This is widely perceived as the key route towards achieving resilience of food systems to climate change. Irrigation development is generally predicated on assumptions that water resources to meet irrigation requirements will be available, especially during droughts. However, growing evidence of impacts of climate change on water resources (Conway *et al.*, 2008, 2015; Faramarzi *et al.*, 2013; Adhikari and Nejadhashemi, 2016; Siderius *et al.*, 2021; Bhave *et al.*, 2022) challenges these narratives. Moreover, evidence of maladaptation in the irrigation sector from elsewhere does exist (Caretta *et al.*, 2022), while irrigation sustainability shortcomings in Malawi and other Sub-Saharan African countries (e.g., Ferguson and Mulwafu, 2007; Veldwisch *et al.*, 2009; Gwiyani-Nkhoma, 2011) has been previously highlighted. At the policy level, the acknowledgement of future drought risk is often very superficial at best, stemming from a wide range of factors including the lack of locally relevant projections of future drought risk.

1.1 Research aims and objectives.

This project aims to use a combination of approaches to develop a comprehensive picture of drought processes in present-day and future climate scenarios and to determine what the implications for climate change and variability are for irrigation in Malawi. Enhanced knowledge of drought processes will improve drought forecasting, monitoring, assessment, and evaluation of drought risk in future climate. Especially for climate projections, improved knowledge of drought processes will create a basis for evaluating climate models with regards to simulation of drought processes. Simulation of hydrological responses to changes in climate – both mean state and variability – provides a foundation for evaluating impacts of changing climatic patterns on irrigation at the river basin scale. In view of the highly variable hydrological responses to climatic forcings, it is imperative that basin-scale processes are examined in detail to identify the place-based impacts of climate change on irrigation and downstream water user requirements. Improved understanding of drought processes and implications of changes in average and extreme climatic conditions for irrigation has the potential to create a valuable evidence base that supports irrigation management and development. In line with this overarching aim, this project has three objectives.

Objective 1: Develop a comprehensive picture of meteorological drought characteristics and associated atmospheric circulation patterns in observations, reanalysis, and present-day CMIP5 simulations.

Objective 2: Evaluate and characterize the nature and extent of hydrological responses to climatic change and variability and associated influences on irrigation water demand and streamflow reliability in the Lake Malawi-Shire River Basin.

Objective 3: Develop an account of shifting perspectives in policy instruments and diverse climate risk perceptions across multilevel governance structures for irrigation management and development in Malawi.

1.2 Research design

The research design reflects a multidisciplinary approach guided by three specific objectives whose interaction is summarized in Figure 1.1. From a disciplinary point of view, the research has three main components, each with a unique approach grounded on the underlying discipline and associated with each objective. The specific approaches complement each other in addressing the overall research question. The physical climate objective (Objective 1) is addressed using climate data from a range of observed datasets, reanalysis products, and CMIP5 GCMs. Drought indices are computed from precipitation and temperature while diagnostic variables are used to examine atmospheric circulation patterns associated with drought-producing weather and their links to global and regional drivers of variability. The hydrology objective (Objective 2) is based on hydrological simulations performed using the Soil and Water Assessment Tool (SWAT). SWAT uses a range of spatial and climate data described in subsequent chapters. The emphasis of the modelling is both diagnostic and prognostic in the sense that it first builds on examining processes in the current climate to use as a basis for examining future changes.

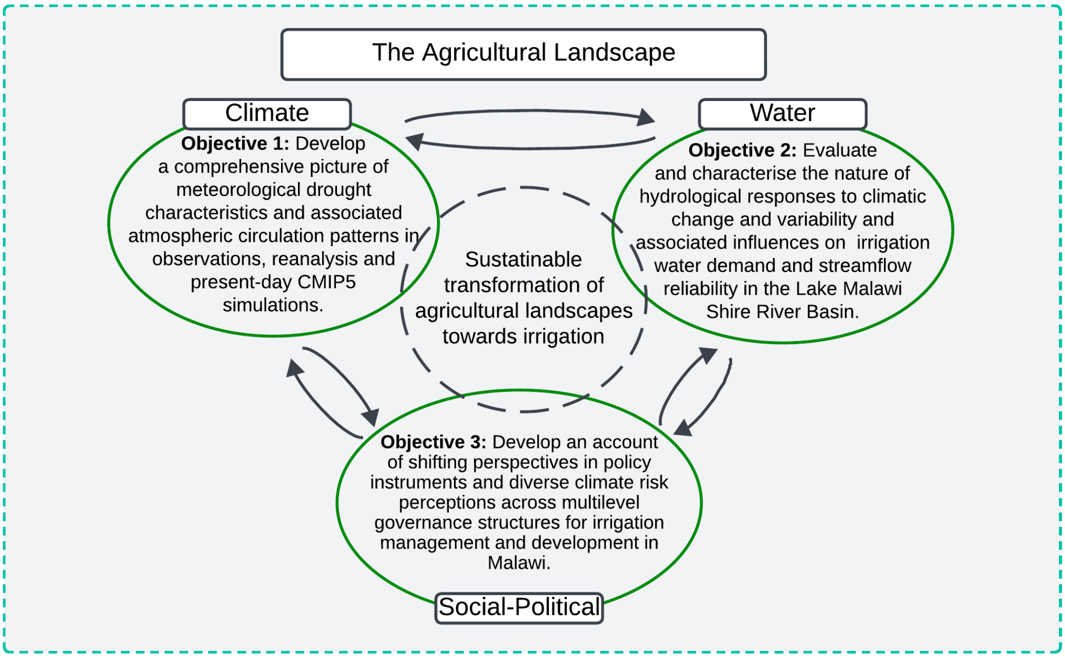

Figure 1.1 | Conceptual framework for the research highlighting the interaction of the three components of the research as a reflection of the three specific objectives in the context of essential dimensions of agricultural landscapes undergoing transformation towards irrigation to build resilience to droughts.

Addressing the social-political objective (Objective 3) relied on data collected from stakeholder workshops and focus group discussions. This is used together with policy narratives to examine how climate-related perspectives have evolved in sectoral and development policies on one hand, and how perspectives around irrigation have evolved in climate change policies. The analysis is focused on a period characterized by a changing climate policy landscape and complemented by grounded empirical analyses of climate risk perceptions for irrigation management and development across different levels of decision making. District stakeholder workshops were conducted in three districts that are situated in the same locations as the modelled river basins. In each of the three districts, focus group discussions were conducted with irrigating and non-irrigating farmers at irrigation scheme level.

While the study is situated in Malawi, the three different components were set for different spatial scales. Smaller scales were carefully selected to reflect broader scales and the complex hydroclimatic and social interactions that influence drought processes across different scales. Examination of drought processes was done at the country level, with a regular grid domain covering latitudes 9-18^{o}S and longitudes 32-36^{o}E (Figure 1.2). Given the underlying research questions, and the attempt to examine meteorological drought drivers, the domain for the examination of diagnostic variables was extended to cover the southern African subcontinent (south of the Equator and parts of the Atlantic and Indian Oceans where relevant atmospheric circulation features are located). Sea surface temperatures were examined across the global ocean basins to include regions of essential processes such as ENSO in the Central and Eastern Pacific Ocean, Indian Ocean Dipole (IOD) in the Indian Ocean, and North Atlantic Oscillation in the North Atlantic Ocean.

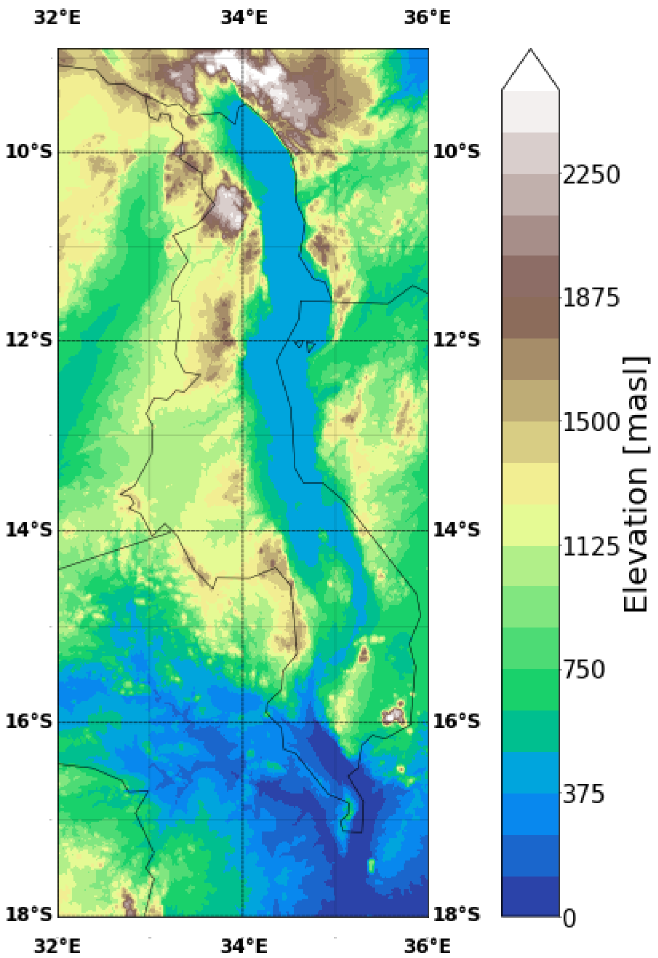

Figure 1.2 | Map of Malawi, the domain over which climate analyses were performed.

Hydrological simulations were performed at river basin scale for five subbasins in the Lake Malawi Shire River Basin (LMSRB). The river basins vary in size and biophysical characteristics including topography, land use and land cover, soil, and climate, details of which are given in subsequent chapters. The third component on irrigation governance is multi-layered. The policy analysis is focused on the national scale. Stakeholder workshops were conducted in Balaka, Karonga and Nkhotakota Districts in south, north and central regions of Malawi respectively. Focus group discussions were conducted with irrigating and non-irrigating farmers at irrigation schemes sampled from irrigation schemes in each of the three districts. In view of these different spatial scales, efforts have been in each corresponding chapter to locate and describe in more detail the study area with reference to the relevant spatial scale.

1.3 Thesis outline

This thesis has six main chapters. A detailed literature review is presented in Chapter 2, which describes the theoretical basis on which the study is found. It provides an overview of recent findings and the general state of knowledge with regards to the different aspects of the research. Specifically, the literature review reflects on drought concepts and regional atmospheric circulation processes – including their drivers – that are relevant for droughts in Malawi. It reflects on the state of knowledge with regards to simulation of these processes in CMIP5 models. The literature review also includes a reflection of hydrological responses to observed and projected climate variability and what it entails for irrigation. A summary of issues around integration of climate change in policies and decision-making processes in the agriculture and water sectors in Malawi is also provided.

Chapter 3 addresses Objective 1 and presents the examination of Malawi's drought climatology, highlighting austral summer drought attributes based on the timeseries of a drought index computed from observed precipitation and temperature. Anomalous circulation in drought years is examined with the aim of identifying circulation patterns associated with droughts in Malawi, paying attention to the unique and shared timings of droughts in the north and south.

Chapter 4 addresses Objective 2 and examines droughts in future climate based on bias-corrected outputs of CMIP5 model projections. Based on hydrological simulations in SWAT, Chapter 4 provides a comprehensive examination of basin scale hydrological responses to future climatic changes. Impacts of changes in the climatic mean state and variability on irrigation water demand and streamflow reliability to meet irrigation demand are specifically examined and highlighted.

National as well as district and grassroots perspectives in decision-making processes with regards to irrigation management and development in the face of climate change are provided in Chapter 5 (Objective 3). Due to the disciplinary uniqueness of each objective, detailed methodologies, and descriptions of study area in relation to the unit of study in relation to each chapter are provided in respective chapters hence there is no dedicated methodology chapter. Chapter 6 then provides a summary of key findings and recommendations as well as future directions for research.

Chapter 2

Literature review

2.1 Introduction

This literature review provides a theoretical background and context in which the research is grounded. It highlights perspectives that guided the framing and scoping of the study. The first section provides a review of drought concepts, providing the theoretical foundations for drought definition, categorisation, and a summary of drought indices. This is followed by a review of general mechanisms associated with droughts and a summary of the drought climatology for Malawi. This includes a description of circulation patterns that prevail during droughts across southern Africa. Limited work has been undertaken for Malawi hence most of the basis is found on inferences from regional scale perspectives. A summary of drought trends and projections is provided to highlight the latest knowledge of drought risk in a changing climate. This is followed by a summary of climate model evaluation in relation to drought processes to highlight the state of understanding with regards to model reliability in simulating drought processes over southern Africa. A summary of implications for irrigation and socio-political aspects in relation to utilisation of climate information for irrigation development completes the literature review.

Global and regional studies point towards an apparent increase in drought risk due to climate change in both long-term observed climate records (Dai, 2013; Spinoni *et al.*, 2014, 2019) and projections of 21st century climate (Dai, 2013; Trenberth *et al.*, 2014; Ujeneza and Abiodun, 2015; Maure *et al.*, 2018; Naumann *et al.*, 2018; Spinoni *et al.*, 2020). Droughts can occur and affect societies over most parts of the world (Dai, 2011; Seneviratne, 2012; Masih *et al.*, 2014; Botai *et al.*, 2017) but their societal and ecosystem relevance across sub-Sahara Africa is particularly pronounced, owing to preexisting vulnerabilities and water scarcity issues across the region (Calow *et al.*, 2010; Masih *et al.*, 2014).

In Malawi, historical droughts *(1991/1992, 1993/1994, 2004/2005, 2015/2016)* have had disastrous impacts on agriculture and food security (McCarthy *et al.*, 2021) rendering a significant part of the population destitute and needing humanitarian assistance (Pauw and Seventer, 2010; Department of Disaster Management Affairs, 2015). The 2015/16 drought across southern Malawi significantly affected food production and security and exposed the lack of preparedness among farmers (Mkwambisi *et al.*, 2021) while low water levels in the Shire River led to significant reductions in hydroelectric power generation . To that extent, the country's Hazard and Vulnerability Atlas (Department of Disaster Management Affairs, 2015) identifies huge portions of the country as being high at risk of exposure to droughts and their associated impacts (Figure 2.1). The extent of such drought impacts is expected to increase as a result of climate change (McCarthy *et al.*, 2021). The physical exposure to droughts is noticeably the highest in areas around the southern part of the country.

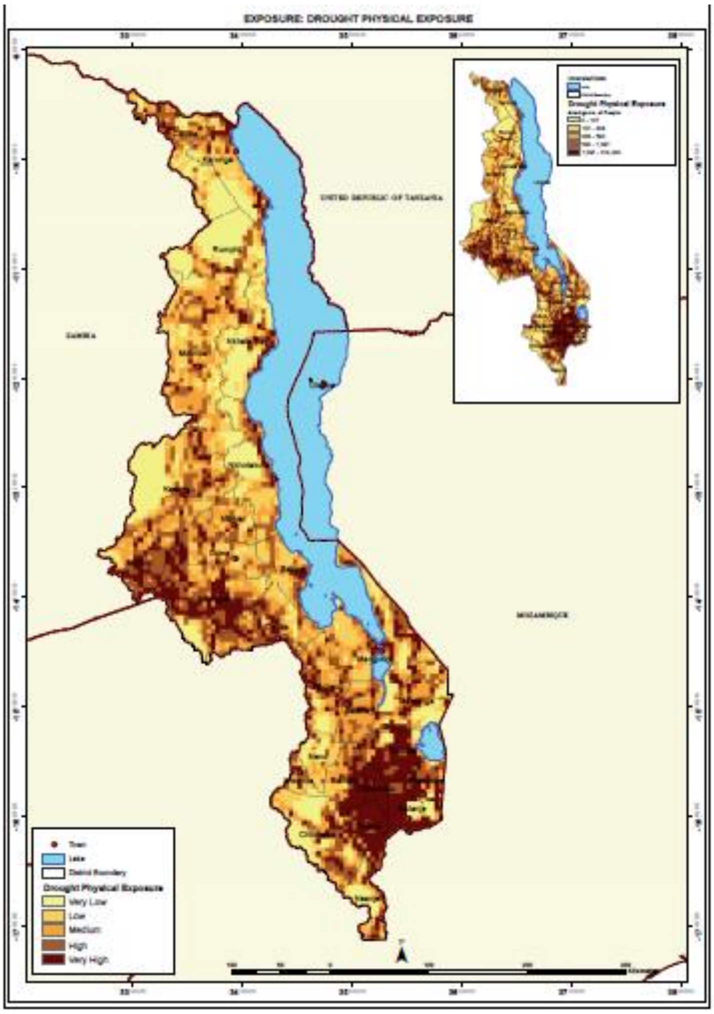

Figure 2.1 | Drought physical exposure map for Malawi indicating high density of very high exposure in the southern Region and in the western part close to the border with Zambia. There is relatively low exposure to droughts with patches of very high exposure in lakeshore areas and to the north close to the border with Tanzania. (Source: Malawi Hazard and Vulnerability Atlas, 2016, Pp 31).

The stress imposed by climate change confronts various sectors including irrigation, conservation, and energy production in unique but interrelated ways (Bhave *et al.*, 2022) and the history (as well as projected scenarios under conditions of climate change) of low lake levels (Bhave *et al.*, 2020) highlight the extent to which drought can confront drainage systems of interconnected nature such as the Lake Malawi Shire River Basin. Competing demands for water resources by various sectors and emerging threats from climate change as shown in the context of Malawi by Bhave *et al.* (2022) present significant development challenges that confront users across various sectors.

Despite the considerable threat that droughts exert on societies and ecosystems in Malawi, understanding of their physical processes remains underdeveloped. Mtilatila *et al.* (2020) provide insights into increasing trends in droughts over the Lake Malawi Shire River basin, consistent with regional trends for Africa (Dai, 2013; Spinoni *et al.*, 2014). This prompts the need for improved understanding of the basin-wide (or countrywide) drought climatology, including their underlying mechanisms and impacts of changes in drought risk on relevant sectors. Especially in the context of climate change, improved understanding of drought processes is essential for examining the extent to which global climate models reliably simulate drought processes and their associated changes in the future.

2.2 A review of drought concepts

Examination of the physical processes that govern droughts is a complicated undertaking, often rooted in concepts laden with contestation. Challenges associated with the practical approaches in evaluating drought processes and deciding best management strategies to cope with their impacts are to an extent rooted in the differences in the conceptual arguments surrounding drought definitions (Lloyd-Hughes, 2014). As a standard, the World Meteorological Office (WMO) defines droughts as a ‘sustained, extended deficiency in precipitation’ (WMO, 1975). In the strictest sense, however, there is no universal definition for droughts owing to differences in hydrometeorological variables and socio-economic circumstances affecting water supply around the world (Mishra and Singh, 2010). In fact, some scholars (e.g., Wilhite and Glantz, 1985; Lloyd-Hughes (2014)) argue that it is almost impractical to have a common, yet objective, definition of drought.

Water deficiency is the common feature towards which all drought definitions converge. Perspectives governing the many different definitions of drought are often based on the component of the hydrological cycle to which reference is being made when examining the water deficiency. Depending on the component being assessed, which also defines the hydrometeorological variable used to define the drought, droughts can be classified as meteorological (related to precipitation deficits), agricultural (related to soil moisture deficits that have an influence on agricultural yields) or hydrological (related to streamflow and reservoir storages (Mishra and Singh, 2010; Dai, 2011; Trenberth *et al.*, 2014; Van Loon, 2015; Mukherjee *et al.*, 2018). Other secondary categories of drought such as ecological drought and socio-economic droughts have also been suggested.

Drought definitions have implications beyond applied statistics of theoretical climatology (Lloyd-Hughes, 2014) and are key to defining the hypotheses for drought studies. Socio-economic implications of droughts present the need for a socio-economically relevant definition that encompasses the hydrometeorological and human aspects of droughts and their associated impacts. In this view, socio-economic drought is defined in the context of demand and supply of water such that a socio-economically important drought emerges when the demand for an economic good exceeds supply because of a weather-related shortfall in water supply. Note should be taken to not mistake this with water scarcity which, as Mukherjee et. al (2018) highlight, could be a result of poor water management rather than physical processes in the climate or hydrological systems.

To predict and monitor droughts, and to evaluate the risk of drought occurrence over long periods of time, it is a prerequisite to define a quantitative variable or indicator with which to measure aspects of drought (Hao *et al.*, 2018). The examination of drought draws from the categorisation of drought definitions as either conceptual or operational (Wilhite and Glantz, 1985; Mishra and Singh, 2010; Mukherjee *et al.*, 2018). On one hand, conceptual definitions outline the basic drought concepts with a general description of the physical processes involved such as shortage of precipitation, soil moisture, water in lakes or streams, and shortage of water for use by society in relation to water management (Mishra and Singh, 2010). On the other hand, operational definitions are those that attempt to identify the onset, intensity, and termination of drought periods (Mishra and Singh, 2010). Operational drought definitions are the basis for early warning systems and drought management decisions (Mukherjee *et al.*, 2018) such that some operational definitions include the estimation of impacts.

2.2.1 Drought indices

Several drought indices have been developed over the years to offer an operational definition of droughts. Drought indices are prime variables used to assess the effect of a drought and define different drought aspects including initiation and termination, duration, severity, intensity, and spatial extent (Mishra and Singh, 2010; Hao *et al.*, 2018). Challenges associated with defining droughts are manifested in the range of drought indices that have been developed thus far. Lloyd-Hughes (2014) indicates that there are over 100 drought indices noting that this only creates further confusion and does little to clarify the definition of drought. The majority of indices are primarily based on precipitation which, in some indices, is used in combination with other hydrometeorological variables depending on the aspects of the hydrological cycle being examined.

Complexities in drought definitions and associated indices are manifested in the lack of a universally agreed upon drought index. Mishra and Singh (2010) note that any ideal drought index should have the capability to quantify the drought for different timescales, the most common of which are yearly and monthly. The utility of the drought examination across the different timescales varies, and different drought indices have shown to be more applicable at certain timescales and, possibly, more relevant for certain drought types than others. Of the many drought indices, the Palmer Drought Severity Index (PDSI) (Palmer, 1965) and the Standardised Precipitation Index (SPI) (McKee *et al.*, 1993; Mckee *et al.*, 1995) are among the most widely used in climate studies. The latter has been modified to include evapotranspiration, creating what is known as the Standardised Precipitation and Evapotranspiration Index (SPEI) (Vicente-Serrano *et al.*, 2010). Drought indices precluding precipitation include the standardised runoff index (SRI), streamflow duration index (SDI) both of which have been developed with the same underlying principles as the SPI but use runoff and streamflow to reflect hydrological drought (Van Loon, 2015).

The choice of index is based on the nature of analysis being sought as well as the underlying objective for those analyses. Different drought indices are known to have different strengths and weaknesses and perform differently under different conditions, depending on the variables used and the climate for which they were originally calibrated (Mishra and Singh, 2011; Trenberth *et al.*, 2014; Touma *et al.*, 2015; Pathak *et al.*, 2016; Mukherjee *et al.*, 2018). Some studies use other proxy indicators such as consecutive dry days to define the risk of drought (Sillmann *et al.*, 2013; Maure *et al.*, 2018). Consequently, the need for multi-index drought assessments has been frequently highlighted, more so in the context of climate change to rid drought evaluations of biases associated with index.

The methodology for any drought assessment therefore must highlight and justify the choice of drought index used in the assessment and be cautious when drawing comparisons with other drought studies which may have used different indices or in cases where the index is sensitive to the type of climate so much so that comparability across spatial and temporal scales is limited. A functional definition of drought in this study is based on the Standardised Precipitation Evapotranspiration Index (SPEI), the justification for which is given in the methodology section in Chapter 3.

2.3 Mechanisms for meteorological droughts

Of the three types of droughts, meteorological droughts are perceived as the primary signal carrier (McNab and Karl, 1991) such that their prediction and monitoring is key for the other categories of drought. The basic variable is rainfall and, as per definition, meteorological droughts are associated with anomalously low rainfall. In this view, the examination of meteorological droughts ought to reflect the precipitation season and account for background aridity so that background dryness is not mistaken for drought (Mukherjee *et al.*, 2018). Anomalous precipitation in drought years can result from a reduced number of wet days or reduced precipitation on wet days. While this is not usually accounted for in drought indices, it is particularly important for understanding the propagation of meteorological droughts into other forms of drought.

Other than rainfall, droughts are also generally associated with low atmospheric water vapour content and drier-than-usual air (McNab and Karl, 1991). Temperature is also important for drought (McNab and Karl, 1991; Mishra and Singh, 2010) through its influence on the climatic water balance through evapotranspiration controls and influence on crop water requirements. The role of temperature in drought processes is particularly important in the context of climate change given the thermodynamic process that govern changes in drought risk (Trenberth *et al.*, 2014; Seneviratne *et al.*, 2021). Changes in temperature have the potential to influence background conditions leading to the high potential for droughts where conditions become more arid (Dai, 2011). The occurrence of drought is a combination of thermodynamic and dynamic processes as is the case with a range of other extreme events (Sillmann *et al.*, 2017). Dynamic processes are essential for explaining drought variability on temporal scales hence their understanding is critical for understanding regional drought climatology.

2.3.1 Anomalous circulation patterns and droughts

Droughts are typically associated with persistent anomalies in atmospheric circulation which create conditions less favourable for rainfall formation (McNab and Karl, 1991; Dai, 2011; Hao *et al.*, 2018). The prevalence of anomalously strong winds from regions of dry air may inhibit the flow of moist air into a region, shifting the zone of moisture convergence and leaving some areas drier and others wetter (McNab and Karl, 1991; Mason and Jury, 1997; Gimeno *et al.*, 2012). Reduced ascent or anomalous subsidence are a typical feature of conditions associated with droughts too (McNab and Karl, 1991; Karl and Young, 2002). The anomalously descending air is adiabatically compressed, leading to increased temperature, and increased atmospheric stability. The increase in temperature resulting from adiabatic compression also leads to a reduction in the relative humidity making conditions even less favourable for rainfall (McNab and Karl, 1991). Furthermore, vertical motion is directly related to the quasi-horizontal pressure-surface patterns, such that dry conditions are associated with positive geopotential height anomalies (McNab and Karl, 1991; Blamey *et al.*, 2018; Mahlalela *et al.*, 2018).

Persistent anomalous circulation associated with droughts is usually driven by anomalous sea surface temperatures (McNab and Karl, 1991; Dai, 2011; Hao *et al.*, 2018). In the tropics and across southern Africa, ENSO is regarded as the major driver of droughts (Mulenga, Rouault and Reason, 2003; Rouault and Richard, 2003; Coelho and Goddard, 2009; Dai, 2013; Ratnam et al., 2014; Wang and Kumar, 2015). Such variations underpin the relevance for regional emphasis in studying drought mechanisms as they often occur in the context of a region's climate system that is influenced by circulation over a larger area. Consequently, understanding the relationship between drivers of anomalous atmospheric circulation and resulting drought conditions is central for drought prediction and monitoring as well as the long-term evaluation of drought risk.

2.4 Basic climatology of Malawi

Malawi's climate is strongly seasonal, with two distinct wet and dry seasons. Mean annual rainfall varies from 800 mm to 1600 mm (Nicholson *et al.*, 2014), but other studies have reported a higher upper bound e.g., 1800 mm (Mtilatila *et al.*, 2020) and 2500 mm (Kumbuyo *et al.*, 2014). Most of the rainfall is received during the austral summer months

– December – February (DJF) (Kumbuyo *et al.*, 2014; Nicholson *et al.*, 2014; Mtilatila *et al.*, 2020). A considerable amount of rainfall, with significant volumes over the northeast, is observed during the March – May (MAM) season. The least amounts of rainfall (typically in the order 10 – 25 mm) are observed in the austral winter – June – August (JJA) (Nicholson *et al.*, 2014), during which time wintery temperatures initiated in May are observed across the country (Kumbuyo *et al.*, 2014). Summer temperatures are observed over the September – November (SON) season, the earlier part of which is considerably drier but wetting towards the end of the season spells the onset of wet season.

Considerable variations in the spatial distribution of rainfall are apparent, exhibiting a pattern that highlights the influence of landscape diversity including topography and proximity to Lake Malawi as evidenced by an east-west gradient with larger rainfall amount towards the eastern part close to Lake Malawi (Kumbuyo *et al.*, 2014; Nicholson *et al.*, 2014; Mtilatila *et al.*, 2020). North-south contrasts in precipitation variability indicated influences by tropical and extra-tropical processes that drive rainfall climatology and variability across subtropical Southern Africa and east Africa respectively (Nicholson *et al.*, 2014). The Inter Tropical Convergence Zone (ITCZ) is the main rainfall bearing mechanism for summer rainfall (Kumbuyo *et al.*, 2014). North-westerly trades from the Congo Basin transport recurved moisture from the southern Atlantic Ocean and contribute significantly to precipitation across the country (McHugh and Rogers, 2001; Kumbuyo *et al.*, 2014). Other key processes include Tropical Cyclones that form in the Indian Ocean to the east of Madagascar as well as in the Mozambiquan channel, usually drawing moisture from the continent but causing extreme rainfall and flooding when they make landfall.

2.5 Drought climatology of the Malawi region

Previous studies have indicated that droughts are not uncommon in southern and eastern Africa (Karl *et al.*, 1998; Nicholson, 2000; Masih *et al.*, 2014; Winkler *et al.*, 2017). Each drought has a unique anatomy (or "signature" as conveniently defined by Rouault and Richard (2005)) defined by its duration, intensity, and spatial extent. Sectoral and economy-wide impacts of drought are influenced by these characteristics as well as the socio-economic factors that determine the adaptive capacity of the affected societies. For instance, the multi-year (2015 – 2018) drought in Western Cape (South Africa) saw that region still gripped by the severe impacts of that drought while the rest of the subcontinent was recovering from a drought that was caused by El Niňo in the 2015/2016 season (Vogt and Barbosa, 2018).

Malawi's drought climatology has not been extensively studied, but recent studies (e.g., Mtilatila *et al.*, 2020; Chikabvumbwa *et al.*, 2022) have provided some context with regards to the spatial and temporal variations in drought characteristics, including trends in indices for different categories of droughts. For instance, Mtilatila *et al.* (2020) note considerable differences in drought attributes between different indicators, highlighting that drought attributes such as duration and severity were relatively more pronounced in indices that integrate potential evapotranspiration. While no significant differences in drought frequency were found, they note that droughts identified for the period 1970 – 2013 typically lasted much longer in the southern part of Malawi.

Regional inferences can be drawn from the work of Ujeneza and Abiodun (2015) which provides a detailed overview of the spatial and temporal structure of drought regimes across southern Africa. The study identifies four main regimes across southern Africa, and parts of eastern Africa, with Malawi sitting between two regimes centred over parts of eastern Africa around Tanzania, and subtropical southern Africa just southwest of the country. The regional picture with respect to the location of the country shows transitional patterns that have been highlighted in latter studies (Kolusu *et al.*, 2019; Siderius *et al.*, 2021) and somewhat indicative of the regional climatic influences highlighted by Nicholson *et al.* (2014) expressing themselves through drought events.

2.5.1 Anomalous circulation and droughts in Malawi

Details of circulation patterns linked to droughts in Malawi are flimsy but there is considerable evidence suggesting that droughts in Malawi are linked to El Niňo conditions (Jury and Mwafulirwa, 2002; Mtilatila *et al.*, 2020). The strong link between regional drought conditions and El Niňo prompts inferences to processes and circulation patterns associated with droughts across subtropical southern Africa. Detailed circulation patterns associated with dry and wet summers are highlighted in Mason and Jury (1997) who offer insights into changes in the frequency, intensity, and duration of largescale weather systems in the context of southern Africa. Variations in such systems are seen as influencing the number of days with high rainfall, rather than the wet day frequency or season longevity.

Precipitation variability across southern Africa draws from the complex physical characteristics and their interaction with local, regional, and remote processes essential for the region's weather variability as summarised in Figure 2.2. Southern Africa is a peninsula-shaped land mass surrounded by a warm Indian Ocean to the east and a cold Atlantic Ocean to the west (Mahlalela *et al.,* 2018). The contrasting oceanic surroundings and the steep topography are conducive for extreme events and high interannual variability in the hydrological cycle (Mason and Jury, 1997; Dube, 2002; Gimeno *et al.*, 2016). The principal oceanic moisture sources for summer rainfall are the tropical western Indian Ocean and the subtropical southwest Indian Ocean. The southeast Atlantic Ocean is an important secondary moisture source (Gimeno *et al.*, 2014, 2016), which is modulated by the Angola low pressure system (AL, Figure 2.2) that develops in the austral spring (SON) and persists until late autumn (Gimeno *et al.*, 2016). Moisture inflow from the Indian Ocean is mainly modulated by the Southern Indian Ocean High Pressure system (SIHP) (S. Ind High, Figure 2.2), and tropical cyclones that form to the east of Madagascar and along the Mozambiquan Channel.

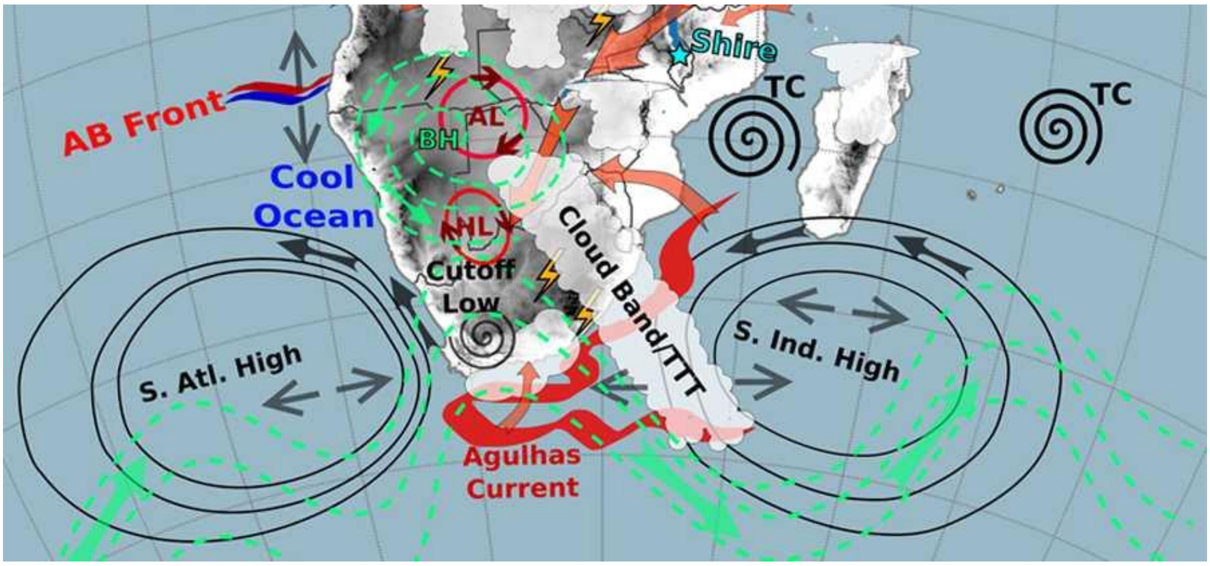

Figure 2.2 | Schematic of southern African climate features and processes. The red arrows represent low level flow indicating the role of the tropical western and southwestern Indian ocean as the principal moisture source through north-easterly and south-easterly flows. Features of importance include the tropical cyclones in the Mozambique channel and to the east of Madagascar; Anticyclones to the southeast (in some literature, the south Indian Ocean high pressure system is also referred to as the Mascarene High) and southwest; the Angola and Namibian (Kalahari Lows); as well as the Tropical Temperate Troughs which constitute the South Indian Ocean Convergence Zone. Features represented by green arrows represent upper-level flow. (Source: (Reason, 2017))

Tropical-temperate troughs (TTT), cut-off lows, tropical cyclones and midlatitude cyclones are among the prominent weather systems whose variability in intensity, frequency, and duration is essential for summer rainfall variability over the region. TTTs and associated cloud bands (Cloud Band/TTT in Figure 2.2) are a significant contributor to summer rainfall (Mason and Jury, 1997; Todd and Washington, 1999). They form when a tropical low is coupled to a temperate westerly wave via a subtropical trough, resulting in a northwest-southeast cloud band on the leading edge of the westerly trough.

In the absence of the tropical low-westerly wave coupling, the tropical low can still provide significant rainfall northwards of 20 degrees south but prolonged, heavy rainfall is more likely when the coupling occurs. The amount of rainfall for each cloud band is dependent on atmospheric moisture availability, atmospheric (in)stability, upper level divergence and the speed of the trough itself. Gimeno *et al.* (2016) note that there is a distinction in TTTs for wet and dry years. In wet years, a prominent Angola Low acts as the regional source for the TTTs. For dry years, however, the prevailing anticyclonic conditions are associated with a weaker Angola Low, such that the TTTs shift eastwards towards the southwestern Indian Ocean. Furthermore, the TTTs that occur over land in dry years are generally weaker in contrast to those that occur in wet years.

Tropical cyclones (TC in Figure 2.2) off the Mozambican coast are also associated with dry conditions over inland southern Africa. Tropical cyclones in the Mozambique channel (the oceanic region between Madagascar and continental southern Africa) reduce the north-easterly flow of moisture on to the continent, and continental dry conditions prevail. In the subtropics, the SIHP (S. Ind. High in Figure 2.2) has a significant influence on rainfall over the subcontinent given its influence on north-easterly inflow over the east coast. The anticyclone is typically weaker than normal in dry years, effectively diminishing the north-easterly inflow (Matarira and Jury, 1992; Mason and Jury, 1997; Dube, 2002), which is often the case during droughts (Gimeno *et al.*, 2016).

Dry summers are generally associated with changes in atmospheric circulation patterns relative to moisture sources and preferred locations of convection. Such longitudinal changes in the preferred locations of convection are typified by drying over southern Africa that is compensated by wetting in eastern Africa (Mason and Jury, 1997; Giannini *et al.*, 2008). In general, dry summers are dominated by confluent upper winds that suppress convection over the subcontinent. Over the subcontinent, higher geopotential heights indicate a weaker subtropical trough and dominance of temperate circulation which is anomalously situated further north than its preferred location. This is often accompanied by an eastward shift in the preferred location for summer convection. Observations of outgoing longwave radiation indicate this shift in the preferred location of summer convection such that drier conditions over the subcontinent coincide with wetter conditions to the east in the southwest Indian Ocean.

Longitudinal shifts in the preferred locations of convection trigger a response in the Hadley circulation which is characterised by a convection dipole that produces different precipitation responses over the subcontinent. In dry years over southern Africa, the Hadley circulation is weakened over the region leading to a reduction in rainfall (Lindesay, 1988; Mason and Jury, 1997). A simultaneous strengthening of the Hadley cell-mass is apparent to the east of the subcontinent, thus creating wetter conditions. The opposite is expected when there is enhanced Hadley circulation and a subsequent increase in rainfall over southern Africa. Circulation shifts of the Indian Ocean arm of the Walker circulation (east of the subcontinent) are evident in wet and dry years and indicate a convective dipole that further underpins the convection location preferences governing interannual variability (Giannini *et al.*, 2008).

Analyses for Malawi suggest that circulation patterns associated with dry years are consistent with circulation patterns associated with dry summers across the subcontinent. Evaluation of dry-year composite anomalies for Malawi, for the period between 1962 and 1995 (based on a composite of five particularly dry years within that period) (Jury and Mwafulirwa, 2002), indicated that negative SST anomalies prevail in higher latitudes of the Atlantic and Indian Oceans. This is in addition to negative SST anomalies in the tropical Atlantic around 10 ^{o}S, 0 ^{o}E and a large area of positive SSTs in the west Indian Ocean centred at 10 ^{o}S, 70 ^{o}E (Jury and Mwafulirwa, 2002). Negative precipitable water anomalies are found in the Mozambique Channel extending into the subcontinent with a northwest orientation and positive anomalies over western Congo, extending eastward to a centre of action in the west Indian Ocean (20 ^{o}S, 70 ^{o}E). A narrow axis of enhanced westerlies at 500 hPa was also identified to occur along the -15^{o} latitude in a 5-year composite for the period between 1964 and 1995. This analysis revealed similar patterns highlighting eastward shifts of zones of preferred convection during dry years noted through an axis of convection eastwards of Madagascar and one subsidence over southern Africa with associated cooler SSTs near Angola. The distinction in dry years between the north and south of Malawi is however not adequately reflected with no recent work indicating any efforts to study the regional variations in droughts occurrences between the north and south of Malawi.

Nicholson *et. al* (2014) highlight significant spatial variability and identify four clusters with the spatial-temporal homogeneity in precipitation. Spatial variability is controlled by both remote and local forcings including orography and proximity to Lake Malawi. While they note quasi-similar patterns in terms of the seasonal distribution of rainfall across the four clusters, larger volumes are noted in the later months of the rainy season (i.e., March-April-May) for clusters in the north. A consistent break in rainfall at the end of the December-January-February (DJF) period signals a shift in the dominance of regional controls, signifying an influence of mechanisms for precipitation in both southern and eastern Africa.

2.5.2 Drivers of anomalous circulation during drought conditions

ENSO is widely viewed as the main driver of interannual rainfall variability and droughts in southern Africa (Mason and Jury, 1997; Dube, 2002; Mulenga *et al.*, 2003; Giannini *et al.*, 2008; Gimeno *et al.*, 2016; Blamey *et al.*, 2018). The El Niňo Southern Oscillation is a naturally occurring atmosphere-ocean mode of variability that impacts weather and climate globally. The ocean component is characterized by recurring anomalous warm (El Niňo) and cold (La Nina) events in the tropical central and eastern Pacific Ocean that form the link with anomalous global climate patterns (Trenberth, 1997, 2020). Referred to as the Southern Oscillation (SO), the atmospheric mode of ENSO is essentially a global-scale see-saw in atmospheric sea level pressure (SLP) that involves an exchange of air between the western and eastern hemispheres centred in the tropical and subtropical latitudes Indonesia and the Tropical South Pacific near Tahiti being the centres of action (Trenberth, 2020). This is characterised by inverse variations in pressure anomalies at Darwin (12.4°S, 130.9°E) in northern Australia and Tahiti (17.5°S, 149.6°W) (Trenberth, 2020). The SLP tends to be higher (lower) than normal at Darwin (Tahiti) during El Niňo and vice versa during La Nina hence ENSO is used to describe these ocean-atmosphere interactions. Such alterations disrupt global wind patterns essential for moisture transport.

El Niňo conditions have been strongly linked to droughts in subtropical southern Africa while wetter conditions are typically expected during La Nina (Fauchereau *et al.*, 2003; Mulenga *et al.*, 2003; Manatsa *et al.*, 2008; Blamey *et al.*, 2018; Pomposi *et al.*, 2018;

Kolusu *et al.*, 2019) although the relationship is not perfectly linear (Ujeneza and Abiodun, 2015; Gaughan *et al.*, 2016; Blamey *et al.*, 2018). Several indices have been developed to identify and characterise ENSO but the Nino3.4 is the most widely used. Based on the Nino 3.4 index, El Niňo years are clearly identifiable in years including 1982–1983, 1986–1987, 1990–1995, 1997–1998, 2002–2003, 2004–2005, 2006–2007, 2009–2010, and 2015–2016 (Santoso *et al.*, 2017; Trenberth, 2020), and most recently in 2023, some of which coincide with the most pronounced droughts in Malawi (e.g., 1991/1992, 1993/1994, 2004/2005, 2015/2016, and 2023) (Pauw and Seventer, 2010; McCarthy *et al.*, 2021; Mkwambisi *et al.*, 2021) and the southern African region. The ENSO-rainfall teleconnection is particularly pronounced during the December to March period (Lyon and Mason, 2007; Gaughan *et al.*, 2016) which, for Malawi, happens to be when most of the rainfall is received and most agricultural activities take place.

During El Niňo, unfavourable conditions occur over southern Africa owing to anomalous circulation patterns that lead to less moisture uplift, convergence, and instability (Giannini *et al.*, 2008; Blamey *et al.*, 2018). Anomalous heating in the eastern Pacific leads to an increase in the average tropospheric temperature hence stabilisation occurs (Chiang and Sobel, 2002; Neelin *et al.*, 2003). The stabilisation resulting from the increase in tropospheric temperature affects convection leading to a tropical precipitation teleconnection during El Niňo, patterns of which are illustrated in Figure 2.3. However, the teleconnection is modified regionally depending on a region’s underlying surface, regional tropical SSTs, the land-atmosphere coupling, and aspects of regional circulation patterns (Lyon, 2004). A reversal in the global El Niňo-precipitation teleconnection, highlighted in Figure 2.3, is expected, and usually observed during the opposite (i.e., La Nina) phase the nature of which varies from region to region.

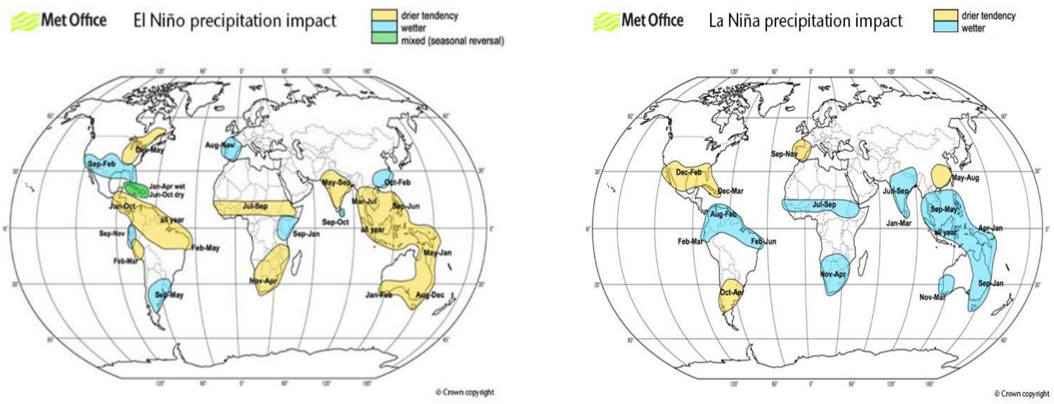

Figure 2.3 | World ENSO-Teleconnections indicating the impacts of El Niňo and La Nina on precipitation globally. In each case, orange indicates areas where negative precipitation anomaly is experienced while blue indicates areas where a positive precipitation anomaly is experienced. (Source: UK Met Office, Accessed 10th April 2019).

During El Niňo, circulation patterns over southern Africa are usually associated with dry summers over Southern Africa, as illustrated in the rainfall anomalies in Figure 2.4, for two strong El Niňo events (1982/83 and 2015/16). Pomposi *et al.* (2018) investigated the differences in rainfall responses across subtropical southern Africa (south of 15 ^{o}S) based on the strength of El Niňo and established that rainfall is reduced by as much as 0.88 standard deviations for strong El Niňo and the likelihood for rainfall reduction was about 80%. For moderate-to-weak El Niňo , rainfall reduced by about 0.44 standard deviations and the likelihood for below normal rainfall was about 60%. Like other previous studies (Ashok *et al.*, 2007; Ratnam *et al.*, 2014; Blamey *et al.*, 2018), they also highlight that the ENSO teleconnection is influenced by where, in the Pacific, the SST anomaly is situated.

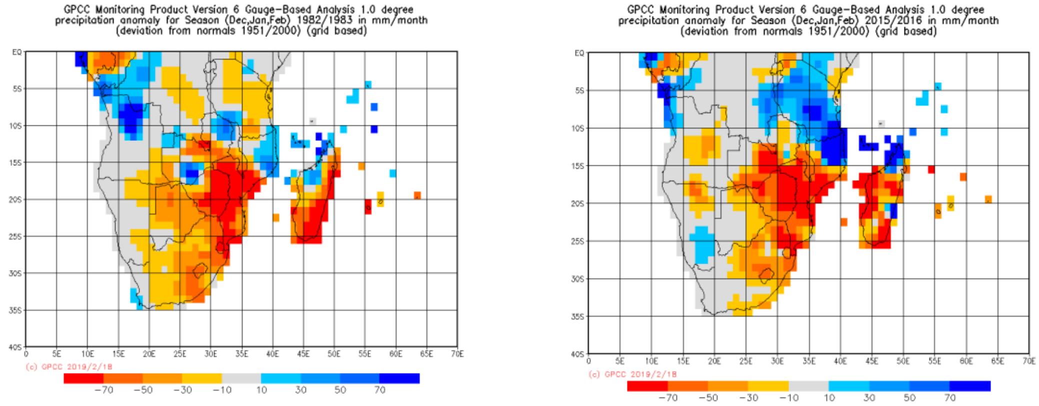

Figure 2.4 | Southern Africa rainfall anomalies in the DJF season for 1982/83 and 1997/98 indicating widespread reduction in rainfall in Southern Africa and wetter conditions in eastern Africa [plotted with Global Precipitation Climatology Centre visualiser available at *https://kunden.dwd.de/GPCC/Visualizer*) and the legend represent percent deviation from DJF climatology].

Despite these notable relationships between the ENSO and southern African rainfall, the mechanisms by which El Niño influences southern Africa precipitation are not well understood (Ujeneza and Abiodun, 2015; Blamey *et al.*, 2018; Pomposi *et al.*, 2018; Gore *et al.*, 2020). This is emphasised in the fact that even the strongest of El Niño events do not always lead to droughts in the region and not all droughts are caused by El Niño (Ujeneza and Abiodun, 2015; Blamey *et al.*, 2018). A notable example is that of the 1997/98 El Niño which, despite being one of the strongest on record, did not lead to dry conditions over southern Africa as would be typically expected. Blamey *et al.* (2018) note significant differences in circulation patterns and moisture fluxes for this and two other El Niño events with similar intensity (strength of SST anomaly) but different precipitation anomalies and remarkably different atmospheric circulation patterns as shown in Figure 2.5.

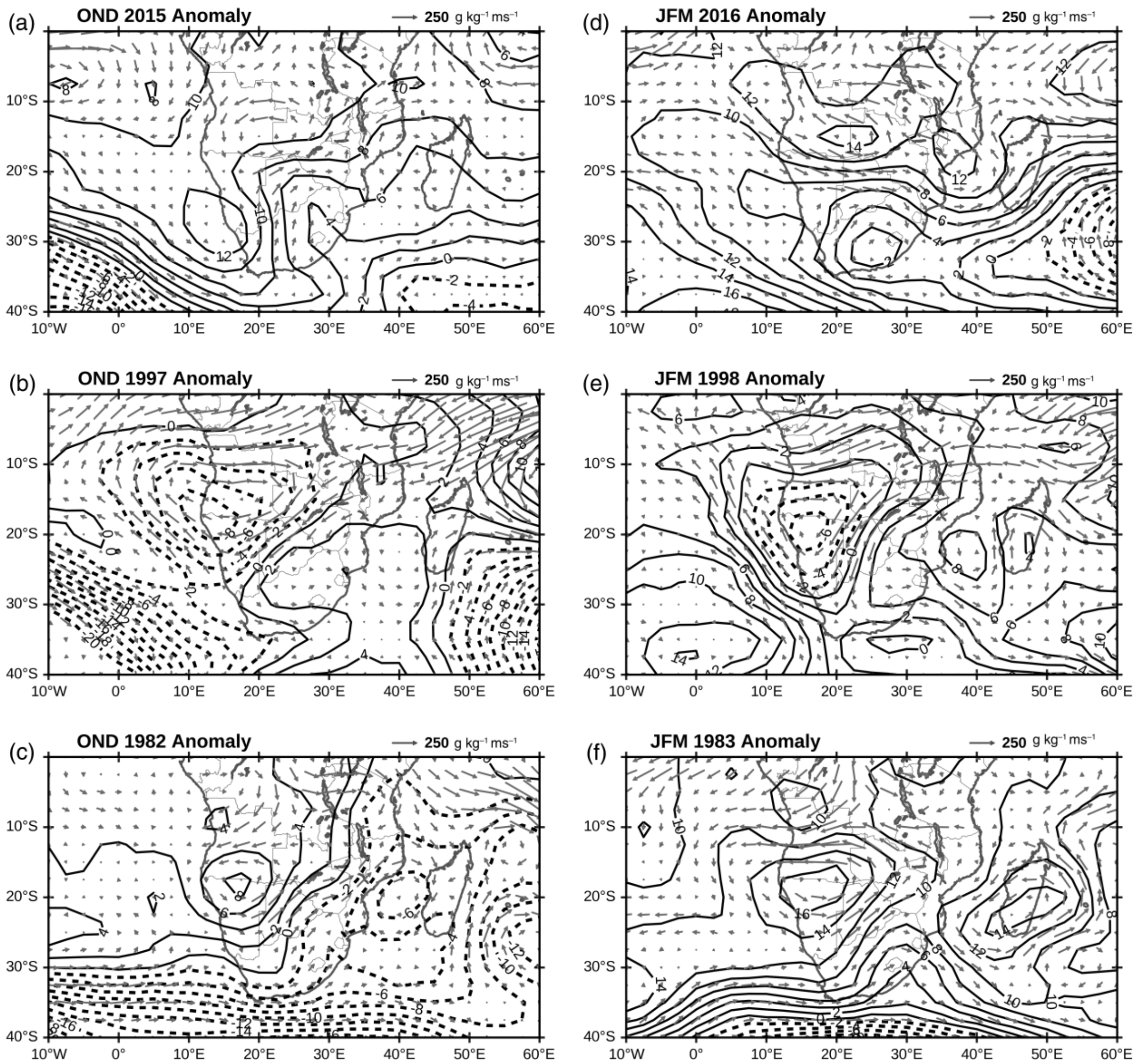

Figure 2.5 | Differences in regional circulation patterns exhibited through differences in geopotential height and moisture flux anomalies coinciding with El Niňo events of almost similar strength but different precipitation impacts. (Source: (Blamey *et al.*, 2018)**).**

Some studies indicate the possibility of uncharacteristic atmospheric circulation patterns during some El Niňo events that have coincided with wetter conditions as opposed to the rather widely expected drier conditions as was the case for 1997-1998 event (Lyon and Mason, 2007, 2009; Pomposi *et al.*, 2018). This not only highlights the importance of considering other sources of drought predictability, for example Darwin Sea Level Pressure anomalies highlighted by Manatsa *et al.* (2008), but also the association between drivers and mechanisms for evaluation of drought risk and impacts in the current climate and in future as the risk of drought changes in response to changes in driving mechanisms. The role of SST over adjacent oceans is also highlighted by Blamey *et al.* (2018); Mahlalela *et al.* (2018); Pomposi *et al.* (2018).

Distinguishing characteristics of dry years that coincide with ENSO from those that do not would add value towards understanding of droughts and their associated driving mechanisms. Analyses for Malawi show correlation patterns indicative of drier summers during El Niňo consistent with the rest of the subcontinent. However, the correlation diminishes going farther north close to the borders with Tanzania to an extent indicating that this is a transitional region for the teleconnection dipole pattern complemented by a wetter eastern Africa (Goddard and Graham, 1999; Jury and Mwafulirwa, 2002). Figure 2.6 highlights this division for the most recent strong El Niňo event and subsequent drying in the southern region and across southern Africa (not shown).

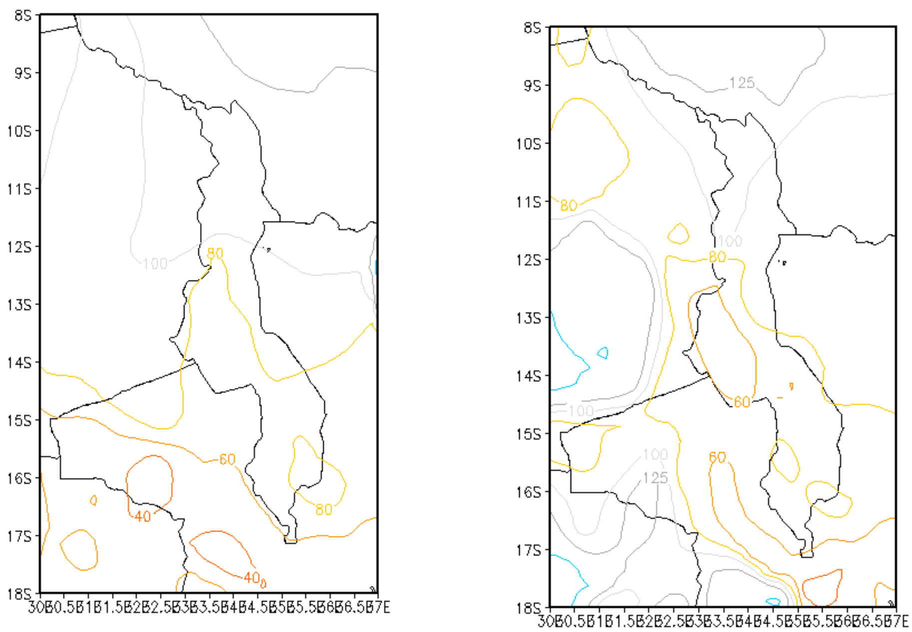

Figure 2.6 | GCPC precipitation anomalies (percent of normal precipitation) for DJF and MAM during the 2015/2016 El Niňo event indicating a consistently drier south (consistent with the rest of southern Africa) and wetter north.

2.5.3 Drivers other than ENSO

The influence of the Quasi-Biennial Oscillation (QBO) on circulation patterns leading to wet or dry conditions in the region has been highlighted (Mason and Lindesay, 1993; Mason and Jury, 1997). QBO events are a stratospheric phenomenon characterised by two phases: westerly and easterly. When the warm phase of ENSO coincides with the easterly(westerly) phase of the QBO, the influence of ENSO is much drier (wetter). The QBO is thought to interact with the Indian arm of the Walker circulation as the lower stratospheric easterly zonal winds provide upper tropospheric wind stress in the easterly QBO phase. This enhances Walker cell overturning with a descending limb over southern

Africa and a rising limb eastwards over the ocean. A reversal of the process occurs during the westerly phase of the QBO.

SSTs in the adjacent oceans also tend to influence rainfall variability over the subcontinent. Warmer SSTs in the tropical western Indian Ocean lead to changes that may favour convection over the ocean, at the expense of convection over the continental land mass. Such variability in Indian Ocean SSTs can act independently or in concert with Pacific Ocean SSTs (Black, 2005). The South-West Indian Ocean Dipole (SIOD) is an apparent SST dipole observed between the subtropical western Indian Ocean to the southeast of Madagascar, within the Agulhas region, and the subtropical eastern Indian Ocean off western Australia (Behera and Yamagata, 2001; Reason, 2001; Gaughan *et al.*, 2016). Its association with interannual precipitation variability is investigated by Behera & Yamagata (2001), and Reason (2001). The positive phase, characterised by warmer SSTs on the western side and colder SSTs on the eastern side off the western Australian coast, is typically associated with wetter conditions across the southern Africa (Behera and Yamagata, 2001; Reason, 2001). Evaporation is enhanced around the warmer pool leading to a moister marine airmass which is advected westwards towards the southern African subcontinent. This enhanced moisture convergence leads to a statistically significant increase in the precipitation over land during the austral summer months when the SIOD is in its positive phase.

2.5.4 Beyond Southern Africa

Given the transitional nature of Malawi's geographical position in relation to the teleconnection between ENSO and precipitation across southern and eastern Africa, a reflection of processes associated with precipitation variability linked to droughts in east Africa is worthwhile. Eastern Africa comprises subregions of unimodal and bimodal precipitation (Nicholson, 2017). The bimodal region comprises northern Tanzania, Kenya, Somalia, Rwanda, Burundi, and southern Ethiopia and most of Uganda. The two rainfall seasons occur in the March to May (MAM) and October to December (OND) and are conveniently referred to as the long and short rains respectively. This context is essential for understanding patterns and drivers of variability in the region.

Irrespective of the disparity between the unimodal and bimodal regions, interannual variability over eastern Africa is mainly associated with ENSO whose influence is mainly experienced during the short rains (Nicholson, 2017; Palmer *et al.*, 2023). The short rains demonstrate high interannual variability despite the associated mean rainfall being relatively less than that observed during the long rains (Black, 2005; Gamoyo *et al.*, 2015). Consequently, the focus of most of studies drawing the relationship between ENSO and precipitation has been the OND when ENSO has a more pronounced effect (Nicholson, 2017) but there is some indication that ENSO also influences variability in the long rains (MAM) (Gamoyo *et al.*, 2015). The ENSO teleconnection is different from that observed in southern Africa such that La Nina is typically associated with abnormally drier seasons and vice versa for El Niňo, effectively creating a northeast – southwest precipitation dipole between the two regions (Lazenby *et al.*, 2016; Kolusu *et al.*, 2019). The north-south contrast in the rainfall over Malawi during El Niňo/La Nina draws from such regions but the nature of the underlying processes has not received much attention in previous work.

The Indian Ocean Dipole (IOD) (Saji *et al.*, 1999) is another key feature of east African rainfall variability (Black, 2005; Gamoyo *et al.*, 2015) while it also exerts some influence on southern African rainfall (Manatsa *et al.*, 2008; Gaughan *et al.*, 2016). The positive phase of the IOD is characterised by strong positive SST anomalies in the tropical western Indian Ocean (50^0E-70^0E, 10^0S-10^0N), and negative SST anomalies in the southeastern Indian Ocean (90^0E-110^0E, 10^0S-Equator) (Yamagata *et al.*, 2003). The teleconnection is characterised by a precipitation dipole between southern and eastern Africa where the positive phase is associated with wetter conditions across eastern Africa and drier conditions in southern Africa, and vice versa for the negative phase (Black, 2005; Manatsa *et al.*, 2008; Gamoyo *et al.*, 2015; Gaughan *et al.*, 2016). Evidence suggests that the occurrence of the IOD events, whose pick is observed during the austral spring (SON) season, and their influence on precipitation can be triggered by ENSO or occur independently (Black, 2005; Manatsa *et al.*, 2008, 2011; Schott *et al.*, 2009; Mbigi and Xiao, 2021; Kolstad and MacLeod, 2022). The IOD may therefore create antecedent conditions which may work to modulate the ENSO-rainfall teleconnection across eastern and southern Africa.

The short rains demonstrate strong coupling to a vertical circulation cell referred to as the Walker cell or Walker-type circulation (Schott *et al.*, 2009; Gamoyo *et al.*, 2015; Palmer *et al.*, 2023), potentially explaining the dynamical pathway through which the IOD exerts its influence on east African rainfall (Figure 2.7). The Walker cell is characterized by westerly winds at the low level and easterly winds at the upper levels (around 200 mbar) with ascent in the east and subsidence in the west, near eastern Africa, completing the cell. Dynamics associated interannual variability are associated with zonal circulation linked to this cell and low-level westerlies from the Congo Basin (Nicholson, 2017; Finney *et al.*, 2020; Walker *et al.*, 2020) where the westerlies are enhanced during the positive phase of ENSO (El Niňo) and IOD, and vice versa for La Nina and the negative phase of the IOD.

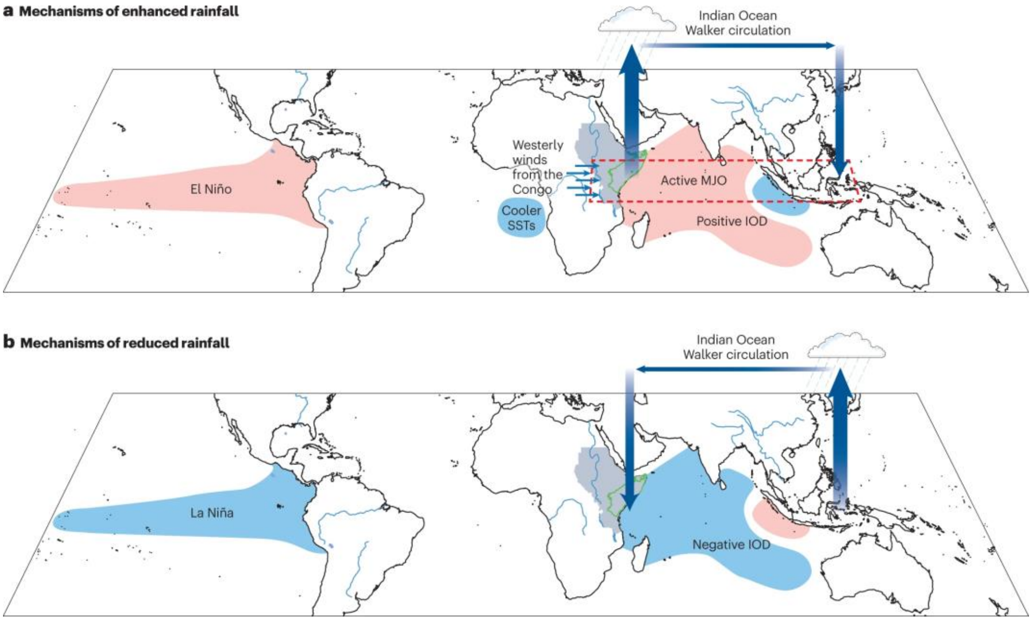

Figure 2.7 | The Walker circulation dynamic pathway through which IOD and ENSO lead to wet and dry conditions in eastern Africa. The green contour delineates the bimodal rainfall region of eastern Africa. Orange and red represents warmer and colder than normal SSTs during El Niňo (and positive phase of IOD) and La Nina (and negative phase of IOD) respectively. (Source: (Palmer *et al.*, 2023)**).**

Land-sea contrasts have also been highlighted as a key driver of precipitation variability at interannual to decadal timescales over eastern and southern Africa (Zhang *et al.*, 2015; Nicholson, 2017) creating a dipole mode that situates Malawi in the transitional zone between the two regions. Zhang *et al*. (2015) note that, the dipole index for this mode is highly correlated to the land-sea contrast along the east coast of Africa. When the land-sea thermal strengthens, the onshore easterly flow becomes stronger. This, coupled with topographic controls and surface heating, leads to low-pressure circulation anomalies over land areas southwards of the maximum easterly flow anomaly, consequently leading to more rainfall across southern Africa. At decadal timescales, the pattern is modulated by an SST-dipole across the Indian Ocean characterised by warmer (colder) SSTs across the central (west) Indian Ocean. The colder SSTs in the western Indian Ocean further act to enhance the land-sea temperature contrast while influence through SST-cloud coupling (and associated feedbacks) was also noted (Zhang *et al.*, 2015). These relationships were also noted to be related to ENSO-like patterns responsible for low-frequency variability across southern Africa characterised by onshore(off-shore) anomalies responsible for moisture transport from the Indian Ocean onto the subcontinent (Reason & Rouault, 2002) which are in and out of phase to modulate the wet/dry anomalies.

Elsewhere in Africa, the influence of land-atmosphere interactions on droughts (McNab and Karl, 1991; Trigo *et al.*, 2012) has been highlighted. Notably, land-atmosphere coupling through moisture recycling is particularly important for heat waves and droughts (Fischer *et al.*, 2007; Trigo *et al.*, 2012). A detailed case study is presented by Nicholson (2000) for Sahel region of Africa and shows how the land surface can prolong the effects of drought. Such influences are, however, localised and can modify the influence of large-scale controls (Nicholson, 2000). Land-atmosphere interactions are regarded as less important than ENSO and SST anomalies for three reasons (Mason and Jury, 1997; Nicholson, 2000; Masih *et al.*, 2014): (1) the areal extent of the soil-moisture anomaly is typically smaller than SST anomalies, (2) land-surface anomalies are less persistent as compared to SST anomalies, and (3) the substantial moisture content and weak vertical stability over oceans favours the redistribution of the SST anomaly over a thick layer of the atmosphere, enhancing the global effect of the SST anomaly.

2.5.5 Drought characteristics and driving mechanisms: potential links

Mulenga et al (2002) analysed dry summers over northeast South Africa and their associated circulation patterns, compositing El Niňo years and non-El Niňo years. While noting that both categories of dry summers exhibited substantial to severe drying (defined based on the magnitude of the standard deviation of summer rainfall), they established that El Niňo dry summers were generally because of tropical circulation patterns that suppressed convection and led to conditions less favourable for the development of TTTs. For non-El Niňo dry summers, dry air advection from the south Atlantic, like that observed in El Niňo years, was apparent but largely driven by mid-latitude rather than tropical processes. Studies indicated a positive relationship between the strength of El Niňo and drought intensity and spatial extent (Pomposi *et al.*, 2018), nonetheless one which is influenced by regional circulation patterns not well understood. Understanding the mechanisms associated with droughts has the potential to improve drought predictability and monitoring (Manatsa *et al.*, 2008, 2017) as well as improve critical evaluation of climate models while making the most of what they project in terms of future drought risk (Mccrary and Randall, 2010; Taylor *et al.*, 2012).

2.6 Anthropogenic climate change and risk of drought

2.6.1 Observations

It is widely anticipated that climate change will enhance the risk of drought through the twenty-first century (Dai, 2011, 2013; Trenberth *et al.*, 2014) owing to enhanced evapotranspiration, changes in convective storms and changes in atmospheric circulation patterns that affect moisture transport (Trenberth et al., 2014). Observed trends in droughts vary globally but there is *medium confidence* that parts of Africa have experienced increasing drought intensity and duration (Seneviratne *et al.*, 2021). This is based on indicators for meteorological, agricultural, and hydrological droughts. Trends based on meteorological drought indices indicate an increase in drought frequency and severity over southern Africa (Spinoni *et al.*, 2014) but changes are generally not uniform. Observed changes in drought indicators show the influence of choice of drought indicator and temporal variations marked in the period over which the examination is done and the season of interest (Spinoni *et al.*, 2014; Thoithi *et al.*, 2021). Thoithi *et al.* (2021) show in the context of southern Africa that trends in dry spells in DJF exhibit two strong gradients (meridional and diagonal) both of which are characterised by spatial variability with regards to the direction and magnitude of change in summer dry spell frequency between 1981 and 2019.

Drying trends have also been observed across east Africa especially during the long rains (March - May) but the short rains exhibit a wetting trend (Palmer *et al.*, 2023). The drying trend in the long rains is against the expectation that the season will be wetter in future climate as seen from projections (Palmer *et al.*, 2023), essentially creating what is known as the East African Paradox (Rowell *et al.*, 2015; Nicholson, 2017). Anomalously wet long rains in 2018 and 2020 may be an indication of a recovery of some sort (Palmer *et al.*, 2023) but successive failures have been noted for the short rains (October - December) in 2018 and long rains in 2019, which led to droughts in parts of east Africa, reinforcing the view that the risk of drought over east Africa is increasing with increasing average global temperatures (Wainwright *et al.*, 2021). Additionally, successive below normal rainfall events during the short rains in 2020, 2021, and 2022, as well as the long rains in 2021 and 2022 plunged the great horn of Africa region into its worst drought for forty years, the risk of whose occurrence has been attributed anthropogenic influences (Kimutai *et al.*, 2023). Such extremes highlight the need for improved understanding of drought processes and how they change in future climate and against changes in the background climatology.

In Malawi, trends in hydrometeorological variables relevant for water balance variables indicate growing risk of drought in the latter half of the twentieth century (Ngongondo *et al.*, 2015; Kambombe *et al.*, 2021). Ngongondo *et al.* (2015) also noted significant positive trends in mean annual temperature and potential evapotranspiration in both observations and simulations, coupled with negative trends in mean annual precipitation, actual evapotranspiration, and runoff albeit with low statistical significance. The directions of changes of these hydrometeorological parameters indicate the prospect of increasing drought risk. This is reinforced by increasing trends in meteorological droughts identified from examination of meteorological drought indices (Mtilatila *et al.*, 2020; Chikabvumbwa *et al.*, 2022) and hydrological drought indices reflecting trends in relation to water levels in Lake Malawi.

2.6.1 Projections

Future projections of drought risk are primarily based on global climate models (Burke and Brown, 2008; Dai, 2011; Trenberth *et al.*, 2014; Liu *et al.*, 2018) some of which have been downscaled, most notably through the Coordinated Regional Climate Downscaling Experiment (CORDEX) (e.g. Maure *et al.*, 2018b; Nikulin *et al.*, 2018) by the World Climate Research Programme (WCRP). The emphasis of such evaluations is placed on meteorological droughts as the basis for future drought risk evaluation as opposed to other forms of drought such as hydrological or agronomical.

Overall, GCM projections for drought risk indicate an increase in the spatial extent of droughts over southern Africa and other parts of the world (Touma *et al.*, 2015). Pronounced changes in indices that integrate the influence of evapotranspiration (Touma *et al.*, 2015) indicate the evident effect of potential evapotranspiration on drought risk in a warmer climate. Spinoni *et al.* (2020) highlighted from an ensemble of CORDEX RCMs that dry spells are likely to increase in both frequency and duration over the course of the twenty-first century in both RCP4.5 and RCP8.5 emission scenarios, consistent with findings from high-resolution convection permitting models (Kendon *et al.*, 2019). The projected changes are more pronounced in indices that incorporate the indirect influence of temperature through potential evapotranspiration (Spinoni *et al.*, 2020). Such effects of evapotranspiration potentially signify the relevance of the underlying mechanisms governing the changes in aspects of drought in future climate.

Changes in drought are driven by both thermodynamic and dynamic factors (Sillmann *et al.*, 2017; Seneviratne *et al.*, 2021). Thermodynamic processes increase the atmospheric evaporative demand driven by changes in air temperature, radiation, wind speed, and relative humidity. Dynamical processes affect drought through changes in the frequency, duration and intensity of circulation anomalies related to precipitation variability (Seneviratne *et al.*, 2021). Even though changes in circulation are difficult to discern from natural variability, model-predicted changes in seasonal precipitation are expected and are already being experienced in some regions. It will not be uncommon to have non-uniform changes in the global water cycle as a response to twenty-first century warming. Over land, the additional heat to the climate system from climate change generally goes into drying such that natural drought would be initiated much more quickly and become more intense and last much longer. In this view, climate change may not necessarily manufacture droughts, but rather accelerate their occurrence and expand the regions of their occurrence.

Projections of other forms of droughts generally rely on simulations of hydrological models forced with outputs of global or regional climate models (Seneviratne *et al.*, 2021). The application of hydrological models varies from region to region and there is not much evidence to suggest that future hydrological droughts have been extensively investigated in Malawi and the wider southern African region. Moreover, the hydrological processes essential for hydrological drought evaluation take place at river basin scales too small to be generalised at the regional scale.

2.6.2 Model evaluation

Substantial uncertainties have been highlighted for global and regional projections of drought (Trenberth *et al.*, 2014; Liu *et al.*, 2018; Spinoni *et al.*, 2020). Uncertainty in assessments of future drought can be traced back to various sources including the indices used, the sufficiency of the historical reference periods, methods used to compute potential evapotranspiration and observed data discrepancies. A considerable level of uncertainty is implicit in climate model differences, manifested in the uncertainties in projected water balance variables, most importantly precipitation. The limited evidence on model performance in relation to simulation of droughts has limited the comparison of performance between generations of models (Seneviratne *et al.*, 2021).

Notwithstanding global and regional impetus for climate model evaluation, the emphasis on drought has remained relatively lower such that a comprehensive model evaluation for drought has been lacking for many years (Flato *et al.*, 2013). The multiplicity of the drought definition means that the few model evaluation studies focusing on drought are constrained by the context in which the drought is defined. This is compounded by the fact that droughts in models can be produced by different mechanisms. For instance, Mccrary and Randall (2010) found, in the context of droughts in the Great Plains, that climate models produced the same drought patterns with different mechanisms in which case acknowledging consistency on the basis of the drought climatology alone could be misleading. In this view, it is imperative that climate model evaluation of drought emphasises on both aspects of drought including mechanisms that produce them.

Ujeneza and Abiodun (2015) examined drought regimes across southern Africa in CMIP5 models, presenting a first known evaluation study focusing on droughts in the region. Their results indicated that global climate models simulated the SPEI distribution in time and space reasonably well but considerable disparities, more pronounced at longer averaging periods, were identified. Spinoni *et al.* (2020) demonstrated the consistency of model simulation of drought frequency and severity based on both the SPI and SPEI across several CORDEX domains including southern Africa (encompassing the southern part of Malawi) and equatorial Africa (encompassing the northern part of Malawi).

Over southern Africa, model evaluation for climatic variables essential for drought processes has received considerable attention across generations of climate models. In most cases, models are generally consistent in their simulation of temperature such that most of the attention is given to precipitation where considerable discrepancies are apparent. Over southern Africa, CMIP5 models capture the meridional precipitation gradient characteristic of austral summer rainfall but exhibit systematic positive biases in precipitation (Lazenby *et al.*, 2016) as shown in Figure 2.8. Systematic biases in precipitation are generally sustained throughout the year (Munday and Washington, 2018) as shown in Figure 2.9 with respect to CMAP precipitation. Other studies have also identified systematic biases in simulated precipitation over Malawi. For instance, an examination of 17 CMIP5 models by Libanda and Nkolola (2019) identified that the majority of models (14) overestimated mean annual precipitation with respect to station precipitation. Such inconsistencies have created the need for further examination of climate models to identify the sources of such biases and how they can be corrected in future generations of climate models.

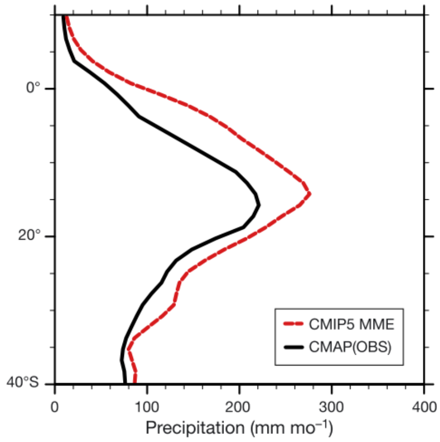

Figure 2.8 | Biases in summer precipitation over southern Africa for precipitation averaged over longitudes 25 to 50° E. The red (dashed) line is a 44-member ensemble mean while the black (solid) line is CMAP average for the same period 1979/80 – 1998/1999 (from Lazenby *et al.*, 2016).

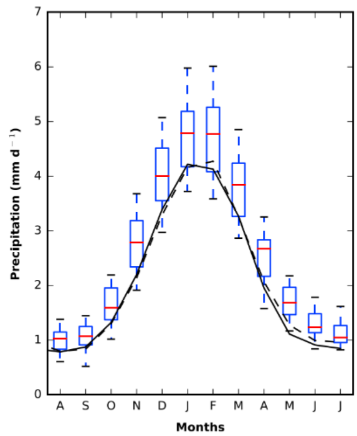

Figure 2.9 | Biases in mean annual precipitation cycle in an ensemble of CMIP5 Models (21) relative to CMAP precipitation. Box plots show the spread in the mean monthly precipitation across the models for the period 1979 – 2005 (from Munday and Washington, 2017).

James *et al.* (2018) provided an in-depth look at climate model evaluation studies over African domains and proposed a move towards more process-based climate model evaluations. In their view, climate model evaluation is classified into two categories: a) analysis of physical processes; b) quantification of performance. The latter involves quantifying model performance against observations and has been the dominant feature of evaluation studies over the domain. It has since proven to be a valuable undertaking with regard to constraining model uncertainty in development applications and impact studies as it creates a basis for selecting models that offer a reasonable representation of the observed climate. Performance evaluation highlights model deficiencies while providing a basis for understanding how models can be improved. Performance evaluation has received relatively little attention, but efforts have gained traction in recent years, leading to incremental and transformational gains as far as physically based understanding of model biases over African domains are concerned.

James *et al.*'s (2018) work presents regional case studies that contextualise the value in process-based evaluation of climate models at the continental and regional scales based on examination of the UK Met Office's HadGEM3-GC2 model. At a continental scale, they highlight the apparent model biases in mid-tropospheric vertical velocities (omega at 500 hPa / $omega_{500}$) that could potentially explain inaccuracies in model location of the ITCZ which, despite emerging views that it (the ITCZ) is not as coherent and uniform as theory might have suggested (Nicholson, 2009), is a prominent pan-African feature responsible for meridional migration of tropical convention which underpins African climate. The study shows that regions where the model has a wet bias are associated with negative biases in vertical velocity ($omega_{500}$) which indicate enhanced ascent, relative to reanalysis products. Anomalous subsidence is apparent in regions where the model has a dry bias as shown by positive biases in $omega_{500}$ relative to reanalysis. For southern Africa, the study examines the simulation of TTTs and associated precipitation contribution to the overall precipitation in CMIP5 models. On average, the model has almost double (90) the number of TTT events relative to satellite observations (48) and produces more TTT associated precipitation events. The misrepresentation of TTTs is also noted in terms of seasonality as illustrated in Figure 2.10. Typically, TTTs are a summer phenomenon yet they occur throughout the year in the model, a misrepresentation in seasonality that could be associated with seasonal precipitation biases in the model.

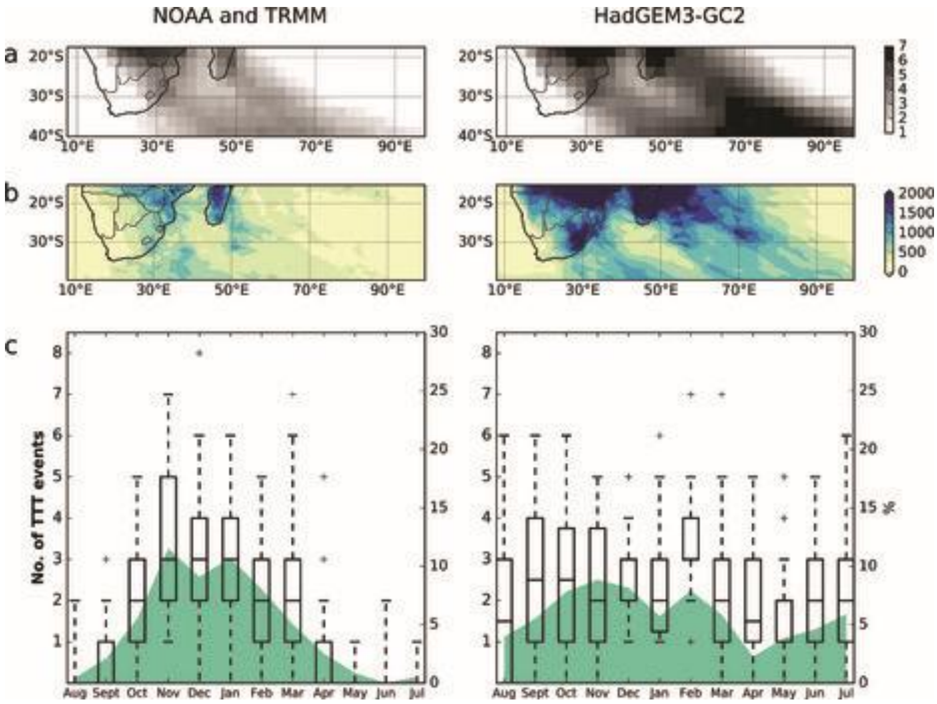

Figure 2.10 | Characteristics of TTT events in satellite dataset and the Met Office HadGEM3-GC2 model. (a) Shows the grid-point frequency of cloud bands for the month of December as number of occurrences on grid point per year. (b) Shows the sum of precipitation (mm) contribution from TTT events for the month of December for the years 1998 – 2013. (c) Shows the annual cycle of TTTs over the continental domain (7.5 ºE – 40 ºE) shown as box plots, and percentage of precipitation contributed by TTTs during continental events shown as green shading. (Source: (James *et al.*, 2018)**).**

Feature-specific studies have focused on the evaluation of features relevant for southern African precipitation including the Angola Low, the Southern Indian Ocean Convergence Zone, the Mozambique Channel Trough, as well as orography (Lazenby *et al.*, 2016; Munday and Washington, 2017, 2018; Barimalala *et al.*, 2020). Munday and Washington (2017) examined model simulation of the Angola Low and noted that 40-60% of inter-model variability in simulated precipitation can be attributed to the differences in the simulated intensity and location of the Angola Low. This resonates with the findings of (Lazenby *et al.*, 2016) who noted that precipitation biases around the Southern Indian Ocean Convergence Zone can be associated with low level moisture flux biases around the Angola Low region noting that such biases are *almost entirely* due to circulation – rather than specific humidity – biases.

Orographic influences have been highlighted in the context of the Madagascar Island's influence on moisture flows associated with the Southern Indian Ocean High Pressure on to the continental land mass (Barimalala *et al.*, 2018) as well as the influences of the high orography in Tanzania and Malawi on the north-easterly flow onto the continent (Munday and Washington, 2018). The latter highlights that inter-model variability is, to an extent, influenced by differences in how GCMs represent the orographic influence on the north-easterly flow. Topographic influences and their representation in global climate models can also influence other features such as the Mozambique Channel Trough. Inter-model differences in the simulation of the Mozambique Channel Trough have been highlighted by Barimalala *et al.* (2022) even though a causal link between biases in the trough and biases in precipitation could not be established. Isolating the influence of biases in the simulation of specific features on precipitation biases is not particularly straightforward given the interactions between several features to influence precipitation across the region.

Whether such biases in processes can be associated with potential biases in model ability to simulate drought characteristics is not yet known. A move towards more process-based evaluation of climate models has highlighted the potential for explaining model biases and projection uncertainties (Lazenby *et al.*, 2018). This bodes well with assertions that drought-based evaluations should emphasise on both characteristics and mechanisms in a way fitting the current trajectory of evaluations over southern Africa and across the rest of the continent. Emphasis is therefore required on climate model evaluation based on functional and operational definition of drought which would aid a more in-depth analysis of drought characteristics and whether climate models produce such characteristics based on mechanisms consistent with observations.

2.7 Implications for irrigation

Impacts of climate change on irrigation can be manifested through changes in irrigation water requirements and the supply of water to meet that demand (Döll, 2002). Gross irrigation demand determines the amount of water which must be abstracted from a water resource to meet the per hectare irrigation demand, taking into account losses (Abdolahipour *et al.*, 2022). The gross irrigation demand encapsulates the full range of factors influencing irrigation demand other than climate and these generally influence agricultural water demand through increase in area under irrigation, dry season production, and growing water intensive crops to respond to increasing in population, rising incomes and changes in dietary preferences (increase in consumption of high value crops) (de Fraiture and Wichelns, 2010). Thus far, population growth and rising demand for food as well as changes in dietary preferences have been highlighted as the main drivers for changes in water demand for agriculture in the past few decades with signs of an increase in net irrigation demand due to climatic changes.

A wide range of studies indicate a likely increase in global irrigation water demand which could translate into an increase in water abstractions to meet the extra demand (de Fraiture and Wichelns, 2010; Wada *et al.*, 2013; Woznicki *et al.*, 2015). While a number of studies and have been undertaken to determine irrigation potential for southern Africa (Faurès *et al.*, 2002; Xie *et al.*, 2014) and Malawi (Pauw and Seventer, 2010; Government of Malawi, 2015b), emphasis has been put on the potential that irrigation has to alleviate drought-related challenges without comprehensively exploring how irrigation systems are, in themselves, susceptible to droughts.

Changes in rainfall patterns and water availability during the growing season (Faramarzi *et al.*, 2013; Conway *et al.*, 2015; Adhikari and Nejadhashemi, 2016), coupled with increase in net losses due to irrigation are likely to increase the net irrigation demand. This occurs in the context of already rising food demand and changes in diets requiring more intensive food production systems with high irrigation intensities. This highlights the need for emphasis on future impacts of climate change on irrigation systems so that systems are designed that are responsive to likely impacts of climate change on irrigation.

Most studies examining the influence of climate change on irrigation water demand have focused on changes in the mean state of the climate with relatively little focus on variability and droughts. This was highlighted by Döll and Siebert (2002) for the global scale with not much evidence suggesting a focus on extreme events and irrigation at the local scale for this region of Africa. Furthermore, the emphasis of most studies has been on irrigation water requirements. That irrigation is often touted as key to developing resilient agricultural sectors in the face of climate change, is often a manifestation of the lack of a complete picture of the climate related risks for the irrigation sector affecting not only irrigation water requirements but supply of water to meet such demands too.

Based on the CERES crop model, Daccache *et. al* (2015) analysed the impacts of climate change on both rain-fed and irrigated rice where they established, based on a 3-GCM under two emissions scenarios (B1 and A2), an increase in yield in the 2050s. Substantial uncertainties are highlighted based on changes in the management practices following farmer adaptation practices among other iterations in the system. However, the analysis does not reflect on the full range of hydrological factors that could present limiting factors to production.

2.7.1 Droughts and irrigation: the role of variability

Most studies on the impacts of climate change on irrigation demand emphasise changes in the multi-year average with relatively meagre emphasis on years with particularly enhanced irrigation demand reflective of the impact of droughts. Fewer studies have highlighted the relationship, albeit not straightforward, between meteorological drought and irrigation demand as well as streamflow significant to meet irrigation demand. For instance, using both statistical and process analyses where they looked at atmospheric processes and associated impacts on water resources, Adler *et al.* (1999) noted that water resource deficits can be attributed to anomalous circulations leading to periods of anomalously low rainfall. Such periods of anomalous deficits can occur at different lengths with some lasting decades, but with intermittent short spans with anomalously wet conditions which are also important for water resources. The role of inertia of basins in responding to anomalously low rainfall is specifically demonstrated in this case where it was noted that groundwater storage plays an important role in influencing basin responses to rainfall reduction. Such level of detail is often not highlighted in global hydrological models with which irrigation demand changes are determined making it imperative that comprehensive basin-scale assessments be taken to substantiate the general picture from coarse resolution models.

2.7.2 Dynamical drought prediction and biophysical modelling of irrigation water demand

From a physical sense, the impacts of drought on agriculture and water resources reflect the propagation of drought from meteorological to agricultural and hydrological categories. The time lag for the propagation of a drought from meteorological to agricultural and hydrological is crucial as it determines the simultaneous or sequential occurrence of drought events across different components of the hydrological cycle (Mishra and Singh, 2010; Van Loon, 2015; Hao *et al.*, 2018; Mukherjee *et al.*, 2018). The relationships that govern the propagation of drought between different components of the hydrological cycle are fundamental for determining the risk of drought from an agricultural and hydrological perspective as much as it is fundamental for evaluating impacts of drought and their mitigation. Figure 2.11 highlights the relationships between the different variables and what it implies for different categories of drought. These interactions are essential for the methodological frameworks that underly the evaluation of different categories of droughts and their associated impacts.

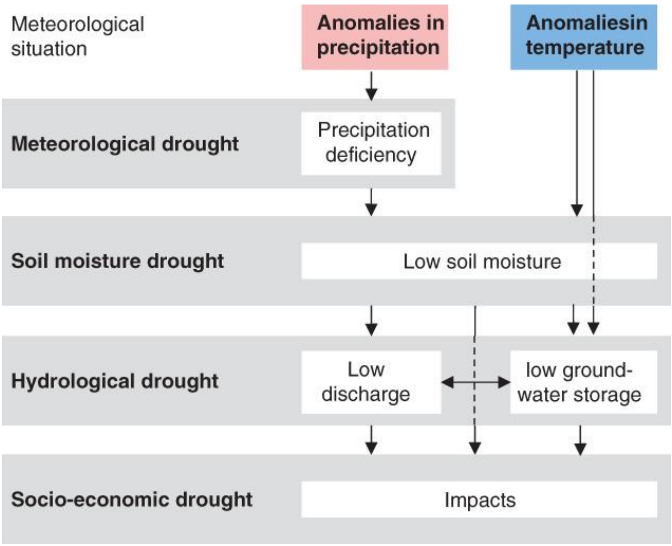

Figure 2.11 | Relationships between different hydrometeorological variables and how they interact to create drought conditions in different components of the hydrological cycle. (Source: (Van Loon, 2015)**).**

Seasonal drought forecasts can be achieved both statistically and dynamically (Hao *et al.*, 2018). Statistical evaluations are based on statistical relations based on predictor-predictand relationships established from historical relationships. Dynamical prediction considers the physical relationships in the hydrological system for which the drought risk is being determined by making use of hydrological models. Several hydrological models are available with various degrees of complexity and resolution which, along with other factors such as computational feasibility, form the basis for choice of model to use in the process.

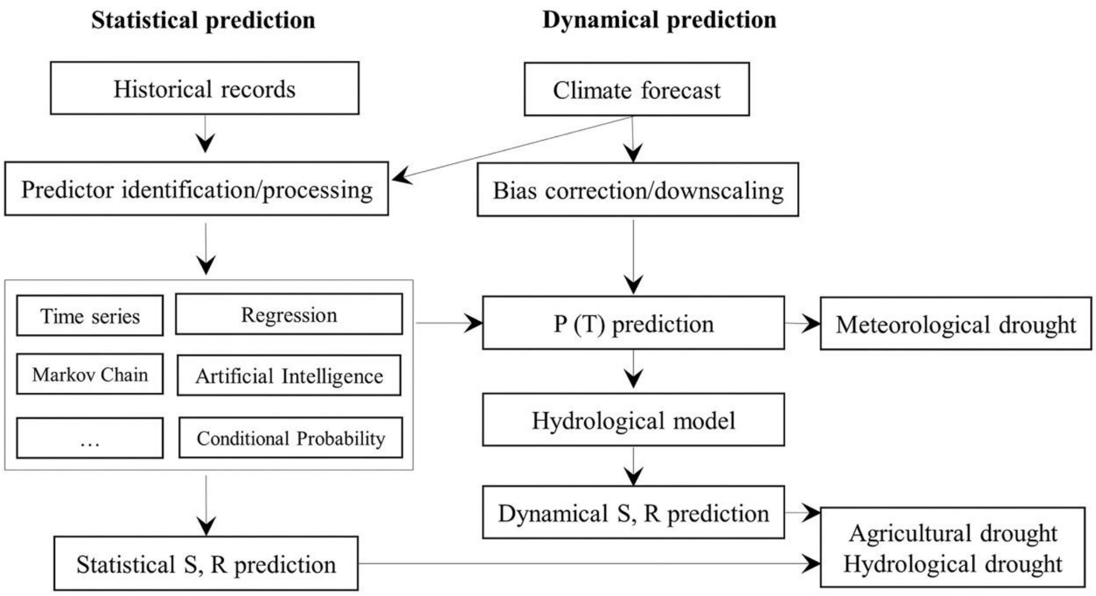

Figure 2.12: Schematic of drought risk prediction and monitoring and how the relationship between different categories of drought governs the forecast and risk evaluation framework. (Source: (Hao *et al.*, 2018)**).**

In Malawi, the dynamical drought prediction tool has only been recently established as part of the open decision support system for predicting and monitoring droughts and floods accessible at http://www.flooddroughtmonitor.com/data?u=Malawi&p=Malawi. While there are studies indicating the impacts of drying on crop water requirements, the emphasis on droughts is notably missing. Statistically based analyses have been done previously by Jayanthi *et al.* (2013) who, while studying in the context of Maize, found that droughts and dry spells have positive correlation with yield reduction. By relating monthly standardised precipitation index (SPI) values with yield, they noted that negative SPI values in the months of February and March have the most significant impact on maize yield reduction as compared to any other months in the austral summer which is key for seasonal crops grown in Malawi. Such a statistical analysis is indicative of the impact of droughts but does not highlight the full picture in terms of what it entails for irrigation demand as the relationship is purely statistical with emphasis limited to rain-fed systems.

The Soil and Water Assessment Tool (Neitsch *et al.*, 2011) (SWAT) is one of the most widely used hydrological models. SWAT is a physically based, semi-distributed hydrological model that delineates a river basin into subbasins based on topography. Subbasins are further discretized into hydrologic response units (HRUs) based homogeneous land use, soil, and slope characteristics. It is a continuous time-model that runs at a sub-daily to daily timestep depending on the input weather data. Simulation of the basin hydrology is separated into two major phases. The first phase – the land phase – controls the amount of water, sediment, nutrient and pesticide loadings to the main channel in each subbasin. The second phase is the is the water routing phase, generally defined as the movement of water, sediments and other loadings through the channel network of the basin to the basin outlet (Neitsch *et al.*, 2011). The simulation of the hydrologic cycle is principally governed by the equation:

$$SW_t = SW_0 + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}\right) \qquad (2.1)$$

where SW_t is the final soil water content (mm H_2O), SW_0 is the initial soil water content (mm H_2O), *t* is the time (days), R_{day} is the amount of precipitation on day *i* (mm H_2O), Q_{surf} is the amount of surface runoff on day I (mm H_2O), E_a is the amount evapotranspiration on day *i* (mm H_2O), w_{seep} is the amount of water entering the vadose zone from the soil profile on day *i* (mm H_2O), and Q_{gw} is the amount of return flow on day *i* (mm H_2O) (Neitsch *et al.*, 2011).

2.8 Policy perspectives

The extent to which different mechanisms of droughts influence the anatomy of the resulting events is not well known. Yet, the local level planning and investment towards drought resilience is inspired by these local scale variations. The emphasis of vulnerability assessments is boiled down to these levels given the need to plan local resources and direct them towards where communities and ecosystems are the most vulnerable to droughts. The Malawi Hazard and Vulnerability Atlas (2016) highlights such details and the implications for policy based on mapping of physical exposure to past droughts. Ranking exposure from very low to very high, the southern and central western parts of the country exhibit highest densities in terms of very high physical exposure ratings (as has been shown in Figure 2.1). Elsewhere across the central and northern regions, exposure is relatively low with notable exceptions for a few areas along the lakeshore and northwards close to the border with Tanzania.

The widespread vulnerability to droughts has been central to government and development partner plans to build resilience in the agriculture sector. Several plans and policies have been developed in line with these aspirations including but not limited to the National Resilience Strategy (NRS), Vision 2063, and Green Belt Initiative (GBI – this has changed over time to be known as the Green Belt Authority). Irrigation, which is thought to have the potential to address some of the food production related challenges while creating an export base, forms a key area of the NRS. Indeed, irrigation has demonstrated the potential to improve yields in dry years that way enhancing the resilience of food production systems in Malawi (Pauw and Seventer, 2010). As of 2016, the area under irrigation was estimated at 104,000 hectares representing 27% of the “net irrigable land” which is estimated to be 385,000 hectares.

Deliberate efforts had long been put in place to accelerate development of sustainable irrigation systems through the GBI but success has been limited due to a number of challenges including, but not limited to, institutional capacity and land tenure issues (Chinsinga, 2017). The resilience plan aims to invest heavily in irrigation and utilise the reformed GBI to alleviate some of the impediments. The resilience plan also aims to develop new irrigation schemes of up to 6,500 hectares. The areas targeted for such schemes are Nthola-Ilola-Ngosi in Karonga district (1000 hectares), Malombe scheme in Mangochi district (500 hectares), Chikwawa Scheme (1,000) hectares, and other sites (5,000) to be identified (Government of Malawi, 2016). More scope for irrigation development beyond the GBI is highlighted in the 2015 Irrigation Master Plan (IMP) and Framework for Investment for 2015-2035. Through the IMP, several areas have been identified as having the potential for irrigation development based on physical suitability as well as the availability of water resources.

Overall, irrigation investments have increased in the past few decades, with the percentage of land under irrigation by smallholder farmers increasing by up to 247% between 2007 and 2014 (Government of Malawi, 2015). Despite the increase, the scope for irrigation in Malawi remains high, given the amount of land under irrigation against total arable land, currently standing at approximately 1%. Comprehensive assessments leading up to the development of the IMP observed that potentially irrigable areas have not been substantially developed to support irrigation. As of 2015 (the base year for the IMP), the estimated land under irrigation stood at 104,000 hectares, which represented 4% of all arable and 26% of potentially irrigable land. Overall, the IMP notes that the maximum potentially irrigable area for Malawi, based on available water resources is 400,000 hectares. Vision 2063 (2021), Malawi’s overarching long-term development framework, aims to achieve 100% irrigation of all potentially irrigable area by 2050 (Government of Malawi, 2020a). The first 10-year medium implementation (MIP-1) for the Vision aims to increase the area under irrigation to 175,843 hectares by 2030. This is within projected targets in the IMP which seeks to increase the land under irrigation to 220,000 hectares (an increase of 116,000 hectares) by 2035. Thus, the trend expansion of landscapes for irrigation is likely to increase.

With irrigation water demand across the region expected to increase – by as much as 66% in some countries by the 2050s (Nkomozepi and Chung, 2012) – it is imperative that plans for irrigation development properly account for associated climatic risks. The IMP provides a detailed technical overview that highlights the link between droughts and irrigation feasibility revealed through evaluation of water resources to meet estimated irrigation water demand across different landscapes. Underlying this relationship is a measure of streamflow reliability, traditionally determined from minimum river flows that would still permit the abstraction of water at volumes enough to sustain the irrigation demand during lowflow periods. However, it is so often the case that such irrigation requirements and river flows are based on historical climate such that future climate change presents a lack of clarity in future irrigation water requirements and streamflow reliability.

Recent studies (e.g., Siderius *et al.*, 2021; Bhave *et al.*, 2022) highlighted the role of future climate change on water resources including stream flow regimes but with less emphasis on irrigation water supply and sustaining irrigation-focused food production systems. A larger scale study focusing on the Zambezi river basin and countries within the basin established some of these relationships, albeit at a larger spatial scale (Fant *et al.*, 2013). In Malawi, Kumambala (2010) showed streamflow responses to climate change in which case it was established that climate change would result in significant streamflow reductions in dry months albeit from a single climate model which may not represent the full range of scenarios. While there is some understanding of the potential impacts of climate change on crop yields and irrigation demand, as well as supply of water to meet such demand, a detailed evaluation of those interactions is still lacking.

Previous studies have highlighted the value that climate information, based on physically comprehensive systematic and systemic analyses, could have on development decision making in the context of climate change (Jones *et al.*, 2015; Vincent *et al.*, 2017). While assessments of the country's irrigation potential account for irrigation requirements in relation to water resources (Government of Malawi, 2015b), the recognition of climate change as a risk to irrigation remains largely qualitative and superficial. The IMP notes that achieving the country's irrigation development targets would see a significant jump in water utilized for irrigation from the baseline value (2012) of 934 million cubic meters (Mm^3) per year to 2,273 Mm^3 per year in 2035 when the 116-hectare expansion is reached. Transforming food production systems via this route therefore hinges on leveraging available water resources and sustaining the potential to achieve optimum irrigation without creating new vulnerabilities. In this view, poorly conceived irrigation plans could fall short of their expected gains and have negative environmental and social impacts hence added value could be realised through place-based comprehensive drought risk analyses.

2.9 Conclusion

The literature review has provided a detailed synthesis of the current state of knowledge of drought processes in Malawi and its vicinity, specifically the subtropical southern Africa and eastern Africa. The reflection is ground in the context of the relevance of droughts to society and ecosystems in Malawi, and increasing drought risk due to climate change evidence of which has been provided from global and regional assessments. A limited number of studies have been done on drought processes in Malawi, however, limiting the extent to which the physical processes associated with droughts are understood. Regional inferences are not straightforward either as the understanding of regional drought processes is elusive. The complexities surrounding regional inferences are compounded by evidence of influence from processes responsible for precipitation variability – and, potentially, droughts – in both subtropical southern Africa and eastern Africa with Malawi's geographical location showing north-south contrasts in precipitation distribution during drought years. This highlights the need to develop a comprehensive picture of drought processes in Malawi, building on an examination of the country's drought climatology and mechanisms associated with droughts.

The climate change context prompts the need for examining the extent to which the drought climatology and underlying mechanisms are reliably simulated in GCMs. The GCMs are the basis for understanding future climate change and associated changes in drought risk. While considerable work has been done in evaluating hydrometeorological variables relevant for drought assessment, there is not much work to build on that has specifically explored droughts, from an operational definition point of view, in models. Such work would offer a basis for a more developed picture of model performance in that regard. Remote evidence suggesting consistent simulation of drought climatology matched with inconsistent simulation mechanisms highlights the need for a complementary climatology and process-based evaluation of drought processes.

An informed view of model performance with regards to drought simulations sets the basis for examining how droughts change in future climate, against changes in the background state for relevant hydrometeorological variables, namely temperature and precipitation. Given the predominantly agrarian context in which such events and changes are experienced, it is almost natural that a key strategy for adapting food systems to these changes is irrigation. Yet, current scientific landscape suggests limited evidence of the implications of such changes in droughts and the mean background state of relevant hydrometeorological variables for irrigation itself. Such implications would be expressed in terms of both irrigation water demand and the supply of water to meet such demand. A balanced assessment of these dynamics, reflecting on the interaction between climate variability and physiographic characteristics for river basins of interest is therefore necessary.

The policy landscape is crucial for ensuring that such information informs decisions and practices at relevant levels. Policies relevant for adaptation in the agricultural sector recognise the threat posed by droughts with irrigation interventions prominently highlighted. A reflection of how such policies have evolved over time is key to identifying opportunities and challenges for integrating evidence of key climate risks for irrigation development as an adaptation to droughts and changing climatic conditions. Such a reflection is lacking for Malawi. The physical science basis picture that would be developed based on the gaps identified in this review would provide a solid foundation for such an assessment. The following chapters build on these gaps to develop a comprehensive picture of drought processes in current and future climate and their implications for irrigation in Malawi. The review also guides the approaches taken in this mixed-methods study that ties together reflections from a range of disciplines. The methodology section under each chapter furthers the methodological insights in relation to this review.

Chapter 3

Austral Summer Droughts and Their Driving Mechanisms in Observations and Present-day Climate Simulations in Malawi

3.1 Overview

This chapter examines drought processes in Malawi based on observations and global climate model simulations. Droughts are an important feature of the southern and eastern African climate. Their recurrence and impacts on agriculture pose a significant threat on predominantly agrarian economies across the region. Impacts on other sectors such as water, energy, and ecosystems amplify their societal relevance and the need for their better understanding for improved risk assessment, prediction, and monitoring. Impacts of drought in Malawi have been well documented, and their role in shaping policy is apparent. Notably, most drought assessments are event-based, with key emphasis placed on impacts, losses, and recovery but less so on the physical processes that govern them. The prospect of a growing risk of drought with anthropogenic climate change makes the need for a better understanding of their anatomy and governing processes far more imperative. This chapter contributes towards the improved understanding of meteorological aspects of droughts. The knowledge generated provides a basis for comprehensive evaluation of climate model simulation of drought processes.

3.2 Introduction

Increasing risk of drought in both long-term observations and 21st century climate projections (Dai, 2013; Trenberth *et al.*, 2014; Maure *et al.*, 2018) underscores the need for their improved understanding given their well-documented impacts. Moreover, relying on global climate models for future drought information will require comprehensive evaluation of climate models to determine the extent to which they reliably simulate drought processes. Notably, droughts have received relatively little attention in climate model evaluation (Flato *et al.*, 2013; Ujeneza and Abiodun, 2015) for a range of reasons among which is the limited understanding of their meteorological aspects at regional and local scales.

Notwithstanding the growing body of knowledge on droughts, and their governing processes across southern Africa (see Chapter 2), key knowledge gaps still exist (Ujeneza and Abiodun, 2015; Blamey *et al.*, 2018). Droughts in southern Africa are relatively short-lived, typically occurring at seasonal timescales (Masih *et al.*, 2014). Accordingly, droughts across the region are largely associated with drivers of interannual rainfall variability, the most dominant of which is the El Niño Southern Oscillation (ENSO) (Mulenga *et al.*, 2003; Ujeneza and Abiodun, 2015; Blamey *et al.*, 2018; Pomposi *et al.*, 2018; Kolusu *et al.*, 2019). The positive ENSO phase (El Niño) is typically associated with dry summers across southern Africa, while wetter conditions are expected during the negative phase (La Niña) (Lazenby *et al.*, 2016; Kolusu *et al.*, 2019). The opposite is typically expected across eastern Africa, creating a regional precipitation dipole that is characteristic of the ENSO-rainfall teleconnection over southern and eastern Africa.

The relationship between ENSO and precipitation for the region is, however, not without complexities. The extensively documented non-linear nature of the ENSO-precipitation teleconnection (Mulenga *et al.*, 2003; Blamey *et al.*, 2018; Gore *et al.*, 2020) makes the association between ENSO and droughts less straightforward. The role of other modes of variability, including the Indian Ocean Dipole (IOD), acting independently or in concert with ENSO has also been previously highlighted (Saji *et al.*, 1999; Black, 2005; Gaughan *et al.*, 2016; Blau and Ha, 2020).

Droughts in Malawi have been largely attributed to El Niňo (Jury and Mwafulirwa, 2002; Mtilatila *et al.*, 2020). As more observations become available, however, spatial patterns over Malawi indicate a dry-south-wet-north pattern during El Niňo and vice versa during La Nina, challenging the unilateral association of drought and El Niňo as applying for the whole country. The transitional nature of Malawi's (as well as neighboring countries such as Zambia and Mozambique) geographical position in relation to the ENSO-precipitation teleconnection over southern and eastern Africa compounds the background complexities associated with drought processes in this location. This prompts the need for a diligent examination of dynamics and salient interactions that govern droughts and underly regional disparities in their occurrence.

Over southern Africa, precipitation variability associated with ENSO, IOD, and other modes of variability is fundamentally driven by variations in atmospheric circulation patterns responsible for moisture transport, convergence, and convection (Todd and Washington, 1999; Mulenga *et al.*, 2003; Vigaud *et al.*, 2009; Blamey *et al.*, 2018). The tropical west Indian Ocean and the subtropical southwest Indian Ocean are the primary sources of oceanic moisture for the region's summer rainfall (Gimeno *et al.*, 2012, 2016).

Anomalous circulation patterns linked to variations in moisture transport relative to these sources are essential for explaining the mechanisms that govern summer precipitation variability associated with droughts over the region.

Improved understanding of drought processes would provide a basis for examining the extent to which climate models reliably produce future drought information. There is considerable work examining the circulation features relevant for droughts, such as the Angola Low, Tropical-Temperate Troughs, and the Southern Indian Ocean Convergence Zone (SIOCZ) (Lazenby *et al.*, 2016; Munday and Washington, 2017; James *et al.*, 2018). However, droughts themselves have received relatively little attention in evaluation studies both at regional and global scales (Flato *et al.*, 2013; Ujeneza and Abiodun, 2015). The need for improved understanding of drought processes and how well they are represented in climate models cannot be overemphasized as information on future drought risk is becoming increasingly important for investment and development decisions, particularly in developing countries such as Malawi (Vincent *et al.*, 2017; Siderius *et al.*, 2021). It is against this backdrop that this chapter aims to examine meteorological drought characteristics and associated atmospheric circulation patterns in observations and present-day CMIP5 simulations. Specifically, this chapter seeks to:

1. Examine drought characteristics and evaluate differences in regional drought attributes across Malawi from 1961 to 2017.
2. Examine circulation patterns associated with droughts and their global drivers during the austral summer – the main rainfall season and the growing season for most crops including the staple cereals.
3. Evaluate present-day global climate model simulations of droughts and associated circulation patterns across Malawi.

3.3 Material and methods

3.3.1 Description of study area

This examination split Malawi (32-36^{o}E, 9-18^{o}S) into two regions[1] – north and south – separated by latitude 13^{o} S (Figure 3.1a), to reflect the two regions with contrasting responses to ENSO. In both subdomains, the wet season runs from November to April, with most of the rainfall received during the austral summer months (DJF) (Figure 3.1b).

[1] Malawi's administrative regions/provinces are known as a Northern Region, Central Region, and Southern Region. The classification of the domains into southern and northern regions is not in line with this.

The drought analysis was limited to the austral summer (DJF) season due to it being critical for drought initiation and termination. In Malawi, the DJF season is also critical for the production of key crops such as maize (Njoloma *et al.*, 2011) which accounts for over 60% of the total food production and forms the basis for a predominantly starchy Malawian diet (Mazunda and Droppelmann, 2012) as well as other cereals and legumes.

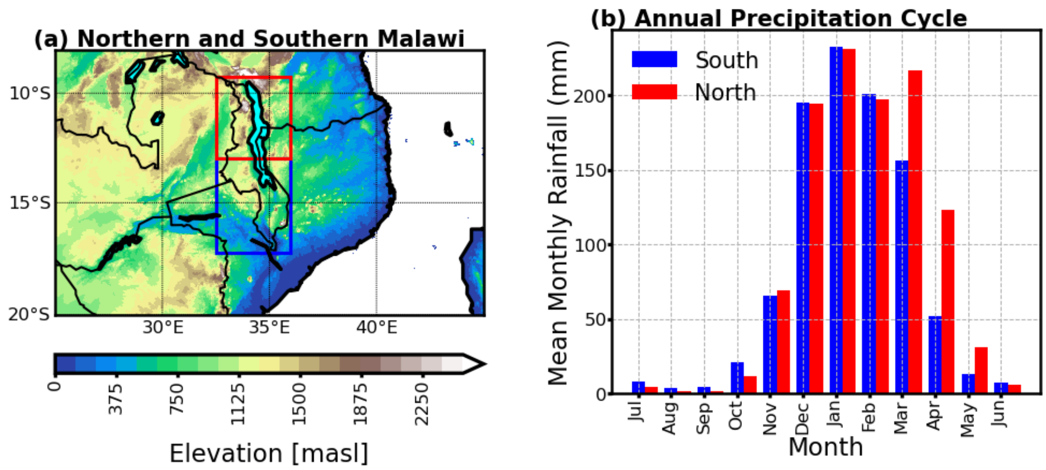

Figure 3.1| (a) Topographic map of Malawi and surrounding areas with red and blue boxes showing the subdomain boundaries for the north and south respectively. (b) annual precipitation cycle for northern and southern Malawi (as defined by the two subdomains) showing temporally averaged cumulative monthly precipitation for the period 1981-2016.

3.3.2 Observations and reanalysis

Gridded precipitation and temperature from the Climate Research Unit (CRU) (Harris *et al.*, 2014) was used to identify and characterize droughts in Malawi over a 55-year period from 1961 to 2017. The CRU TS v4.404 dataset was derived from interpolating monthly climate anomalies from extensive networks of weather station observations. It extends from 1901 to 2019 and covers all global land domains at a 0.5° x 0.5° resolution. Periodic updates of the CRU dataset have been carried out to, among other things, incorporate more stations and, for CRU TS v4, to change the interpolation method to angular distance weighting. The angular distance weighting method improves the traceability of the gridded value and the input observation. While station observations were made available for this examination, the spatial and temporal coverage was less extensive.

ERA5 reanalysis (Hersbach *et al.*, 2020) was used to examine anomalous circulation patterns during droughts that coincide with the DJF season. ERA5 is available at 0.25 x 0.25 resolution from 1979 to present day. Links between austral summer droughts and associated circulation patterns with global drivers were examined using sea surface temperature (SST) anomalies obtained from the NOAA (National Oceanic and Atmospheric Agency) Optimum Interpolation Sea-Surface Temperature product (Reynolds *et al.*, 2002) available from 1981 to present day at 1^o x 1^o horizontal resolution. Since diagnostic variables start from a much later date, the examination of mechanisms causing droughts was a restricted to the 1981 – 2017 period as all the observation and reanalysis datasets overlap over that period. Consequently, the CRU data were regridded to ERA5 resolution for more objective examination of the relationship between respective variables from the two datasets.

3.3.3 Computation of the SPEI and drought attributes

The Standardized Precipitation and Evapotranspiration Index (SPEI) (Vicente-Serrano *et al.*, 2010) was used with the run theory (Yevjevich, 1967) to identify and characterize droughts across Malawi. The SPEI is a multiscalar drought index derived from monthly climatic water balance which makes it essential for studying droughts in agrarian contexts (Labudová *et al.*, 2017). The climatic water balance is derived from equation (3.1), where P and PET are precipitation and potential evapotranspiration for the month i. The CRU dataset contains PET derived from the Penman-Monteith method which is often considered to be a relatively more accurate representation of the processes essential for evapotranspiration. For this examination, PET was estimated from the temperature data using the Thornthwaite method (Thornthwaite, 1948). This was the case as global climate model datasets for related examinations did not contain all the variables necessary for the computation of PET using the Penman-Monteith method. Vicente-Serrano *et al.*, (2010) acknowledge that the inclusion of PET in the drought index is aimed at obtaining a relative temporal estimation in which case the method for calculating PET is not utterly critical.

$$D_i = P_i - PET_i \qquad (3.1)$$

To calculate the SPEI, a probability distribution function is fitted to the climatic water balance timeseries. Thus far, there is no consensus as to which probability distribution function is the most appropriate for the SPEI calculation, with evidence of different probability distribution functions performing differently in different regions. The gamma distribution was used to derive the SPEI for this examination.

Essentially, the SPEI can be calculated for various time scales ranging from 1 to 48 month(s), each potentially reflecting the various categories of drought. For this examination, the SPEI was computed at 3-monthly timescales. To achieve this, the climatic water balance (D) for each month was determined based on equation 3.1. The resulting D timeseries was then aggregated at three-monthly timescales based on the same procedure as with the SPI (McKee *et al.,* 1993) and as described by Vicente-Serrano *et al.* (2010). This creates a new moving dataset since the value corresponding to each month is created from the previous 3 months i.e., information of the previous timesteps in incorporated into the current timestep which allows the SPEI values to adapt to the memory of system under study.

A key downside of the SPEI, as with a few other drought indices, is its susceptibility to the influence of non-stationarity in the timeseries of input variables namely temperature and precipitation. Such non-stationarity – clearly apparent in most observations and simulations owing to the human influence on global temperatures – obscures the physical constancy associated with hydrologic processes (Mukherjee *et al.*, 2018). On the same front, the performance of drought indices may also be influenced by the choice of the calibration period (Um *et al.*, 2017). Both factors were considered given this chapter's emphasis on drought climatology in relation to natural factors of variability. To counter issues with non-stationarity, both precipitation and temperature data were linearly detrended prior to the calculation of the SPEI. A self-calibration was implemented to counter issues associated with the influence of the reference period on the resulting SPEI. By self-calibrating, the probability distribution parameters for the calculation of the SPEI are derived from the whole dataset, rather for an isolated reference period.

The SPEI values were computed for each grid box over the domain. In each grid box, droughts were identified based on the theory of runs. The theory of runs is based on the principle of truncation, where a threshold (0 is this case) is set for the temporal variable (SPEI in this case) from which the drought is determined (Mishra and Singh, 2010). A run is then defined as a portion of the timeseries when the timeseries is below (negative run) or above (positive run) the threshold in which case a negative run corresponds to a drought. Figure 3.2 shows a conceptual framework of the theory of runs and the corresponding definitions of various drought attributes – duration, severity, intensity, as well as initiation and termination times – used to characterize each drought episode.

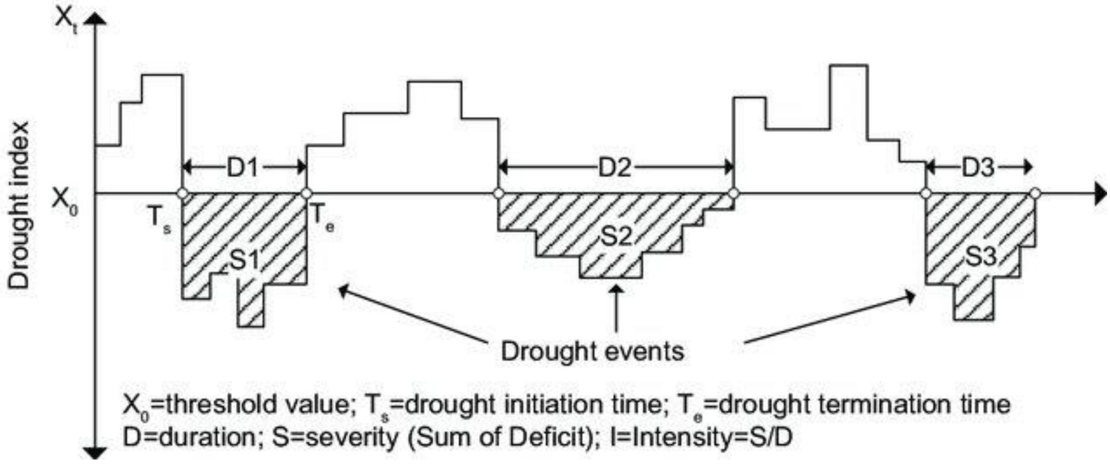

Figure 3.2 | Schematic representation of the theory of runs and the corresponding illustrations of the corresponding drought attributes. Three events are present in the schematic denoted D1, D2, D3 which also essentially denote the durations of the different droughts. The severity of the drought is illustrated as the sum of SPEI value bound by (and including) the SPEI values for the first and last months of the run. The drought intensity is the scaled severity given as the severity divided by the duration.

For purposes of this examination, a run corresponding to a drought was defined as a progressive run of negative SPEI-3 values that reaches -1 before the next non-negative SPEI-3 value. By so doing, runs where the SPEI did not reach negative -1 were not considered as droughts, limiting the analysis to more extreme events. For each run, and thus drought episode, the following drought attributes were determined:

i. Initiation time – the starting point of the water shortage period corresponding to the first negative data point.
ii. Termination time – when the water shortage becomes sufficiently small so that drought conditions no longer persist, corresponding with the first non-negative SPEI value following the negative run.
iii. Duration (months) – the period during which the SPEI is continuously below zero (i.e. the time between initiation and termination).
iv. Severity – the cumulative sum the negative SPEI over the duration.
v. Intensity – the average negative SPEI, computed as drought severity divided by duration.

Drought characteristics were examined only for those drought events that occur over the DJF season (regardless of whether they are initiated prior to the DJF season or they terminate afterward). Despite the emphasis on the DJF season, each event was evaluated in its entirety and not only based on its attributes during the season of interest. For instance, a drought occurring from November to March would be selected based on it spanning the DJF season and, accordingly, be characterized as having a duration on 5 months (November – March) to reflect the attributes in the entirety of the event. On the same principle, multiyear events i.e., events with duration of more than 12 months, were effectively defined as a single event despite the spanning through two DJF seasons.

Comparisons of drought attributes were done at regional level to determine the extent to which the drought climatology of the northern and southern subdomain was similar given likely differences in associated processes. Having done the evaluation at the grid scale, regional droughts were assumed when the area under drought was at least 40% of the region (40% of the total number of grid boxes representing that region). There is no unanimously agreed threshold for regional drought with various studies using different thresholds to define the size of the area undergoing drought conditions for it to be considered a regional drought e.g., 30-50% of total area (Paulo *et al.*, 2003), 75-90% (Hisdal and Tallaksen, 2000) and 5-95% (Jasim and Awchi, 2020). For purposes of this study, a 40% areal threshold was deemed sufficient. Thus, drought episodes that did not reach or exceed an area equal to or greater than 40% of the total area (in either region) were deemed not extensive enough to be considered regional hence they were not considered in the analysis.

3.3.4 Composite analyses and examination of moisture flux pathways

The composite analysis approach was used to evaluate anomalous circulation during drought years. The governing hypothesis for the composite analysis is that circulation in austral summers with droughts is not different from the mean circulation over the entire study period. Relevant diagnostic fields from the ERA5 datasets were examined for summers that coincide with droughts in the two subdomains. Special emphasis was put on the role of advected moisture and its influence on DJF precipitation, as well as its anomalous behavior during the drought summers.

Moisture advection was examined from vertically integrated moisture flux (VIMF) into the domain, following the principles applied by Brubaker *et al.* (1993); Chakraborty *et al.* (2006); Athar and Ammar (2016); and Guo *et al.* (2018) among others. The underlying principle for this examination is that continental precipitation is supplied from two sources; (i) water vapor advected into the region by airmass motion, (ii) water vapor supplied by the evapotranspiration over that land region (Brubaker *et al.*, 1993). VIMF was determined based equation 3.2.

$$Q = \frac{1}{g}\int_{P1}^{P2} q\ V\ dp \qquad (3.2)$$

where q is specific humidity (kg kg^{-1}), V is the horizontal wind vector (m s^{-1}), P_1 and P_2 are the pressure level limits bounding the column for which the integration is done, and *dp* represents the pressure intervals for the column in Pascals. g is the acceleration due to gravity in m s^{-2} hence the units for Q are in kg m^{-1} s^{-1}. For the current study, moisture flux is integrated between 1000 hPa and 100 hPa pressure levels. Moisture transport was considered without the deliberate decomposition into contributions from mean motion and transient eddies.

To determine the moisture flux into and out of the domain, a 1-grid segment was created just outside of the domain boundary by inserting a 1-grid wider boundary to the original domain. The magnitude and direction of VIMF at each grid point was recorded and fluxes corresponding to moisture in and out of the domain were summed to determine the total moisture flux into and out of the domain via a given direction. Typical moisture flux budgets define such directions based on the side of the domain (left, right, top, or bottom) (Brubaker *et al.*, 1994; Guo *et al.*, 2018). However, a slight adjustment was made for this examination to allow the moisture flux directions correspond to circulation patterns around the domain.

To achieve this, moisture flux sources were defined based on the climatological wind directions thus removing the distinction between the zonal and meridional boundaries of the domain and give priority to prevailing circulation patterns. For example, moisture fluxes from the same northeasterly airmass can flow into the domain via both the north and eastern boundary in which case distinguishing the source by domain side could obscure the fact the fluxes are from the same origins. This was also particularly the case for this examination where the easterly flow into the eastern boundary of the domain originates from different sources, the respective behaviors of which were critical to the examination as will be seen in the results.

3.3.5 Climate models

18 CMIP5 models were evaluated to determine how well they simulate drought characteristics and their driving mechanisms over Malawi. Table 3.1 shows the list of

models, and their respective modelling centers. One ensemble member (r1i1p1) for each model was used for this examination. A detailed description of the models and their setup based on the CMIP5 experimental framework is found in Taylor *et al.* (2012). The choice of models was based on the availability of all desired outputs over time periods used in this study. Prior to the evaluation, GCMs were regridded to ERA5 horizontal resolution using bilinear interpolation. This allows a relatively more objective comparison with finely resolved observations and reanalysis outputs.

Table 3.1 | List of CMIP5 models evaluated for their simulation of drought processes and their respective modelling centres and original resolutions.

Modelling Centre/Group	Model	Resolution (Lat x Lon x Lev)
Commonwealth Scientific and Industrial Research Organisation (CSIRO), and Bureau of Meteorology (BOM), Australia	ACCESS1-0	1.25º ×1.875º ×38
	ACCESS1-3	
Beijing Climate Centre, China Meteorological Administration	BCC-CSM-1	1.875º ×1.875º ×16
	BCC-CSM-1-1-M	
College of Global Change and Earth System Science, Beijing Normal University	BNU-ESM	2.81º ×2.81º ×26
Centro-Euro Miditerraneo per I Cambiamenti Climatic	CMCC-CESM	3.443º ×3.75º ×39
Centre Nationale de Recherches Meteorologiques/ Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	CNRM-CM5	1.4º ×1.4º ×31
NOAA Global Fluid Dynamics Lab	GFDL-CM3	2º ×2.5º ×48
	GFDL-ESM2G	2º ×2.5º ×24
	GFDL-ESM2M	2º ×2.5º ×24
Met Office Hadley Centre	HadGEM2-CC	1.25º ×1.875º ×38
	HadGEM2-ES	1.25º ×1.875º ×38
Institute for Numerical Mathematics	INMCM4	1.5º ×2º ×21
Institut Pierre-Simon Laplace	IPSL-CM5A-MR	1.25º ×2.5º ×39
	IPSL-CM5B-LR	1.9º ×3.75º ×39
Max-Planck-Institut fur Meteorologie (Max-Planck Institute for Meteorology)	MPI-ESM-LR	1.8653º ×1.875º ×47
	MPI-ESM-MR	1.8653º ×1.875º ×95
Norwegian Climate Centre	NorESM1-M	1.9º ×2.5º ×26

For each model, the SPEI was computed from linearly detrended monthly precipitation and temperature from 1961 to 2005. Summer droughts were identified based on the theory of runs following the same procedure used for the observations. Biases in model drought attributes, relative to observed drought attributes, were evaluated for the period 1981 to 2005. The evaluation was limited to 1981 – 2005 as the variables of interest across all the datasets, including model outputs (for the historical simulations) overlap during that period. The comparison of drought attributes provided a basis for examining model simulation of the drought climatology. Model simulation of moisture transport and convergence patterns was examined to evaluate the extent to which models consistently simulate mechanisms associated with droughts over Malawi. A key aspect of this evaluation was the comparisons of similarities in the correlation between moisture flux and precipitation in models and observation. To achieve this, Fischer's test for correlation similarity was applied to determine the similarities in the flux-rainfall relationships between each model and reanalysis/observations.

3.4 Results

3.4.1 Climatology of droughts

Figure 3.3 shows timeseries for SPEI-3 values derived from both raw and detrended input data. A clear post-1990 shift in the drought frequency is apparent in the timeseries for the SPEI computed with raw input data. This is apparent in both regions (Figures 3.3 a and b) and consistent with drying trends across southeastern Africa (Dai, 2013) and reflects trends in the SPEI's water balance components across Malawi (Ngongondo *et al.*, 2015). Drought events in the detrended SPEI timeseries are more evenly distributed in both regions (Figures 3.3 c and d). The SPEI timeseries computed from raw input data reveals the critical patterns in the drying trend, potentially driven by anthropogenic climatic changes. However, the non-stationary nature of the raw timeseries obscures the physical constancy characteristic of hydrologic events such as droughts. Detrending, therefore, ensures a relatively more objective approach to identifying and characterizing droughts as well as identifying natural processes that drive them. This is essential for discussing either observed or simulated variability associated with droughts (Joetzjer *et al.*, 2013; Mukherjee *et al.*, 2018). It is for this reason that the rest of this analysis is based on droughts identified from the detrended timeseries.

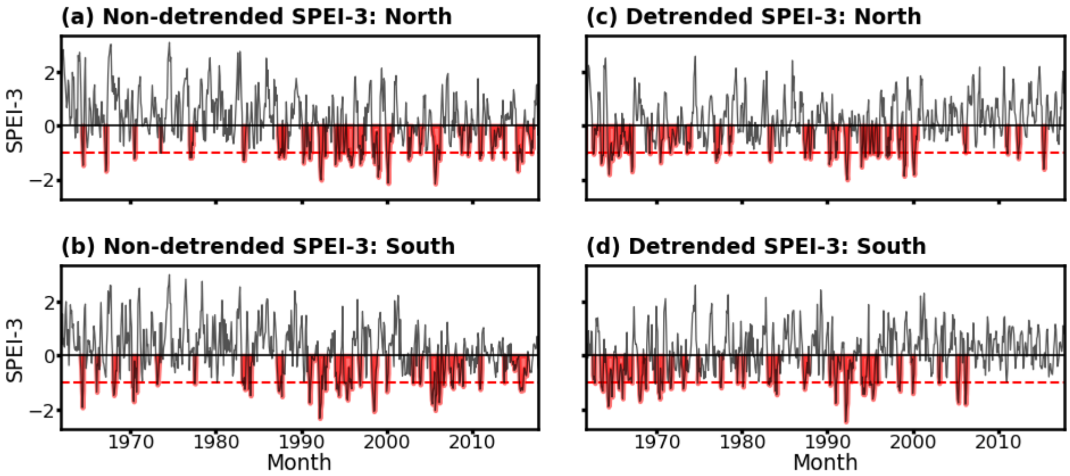

Figure 3.3 | SPEI-3 timeseries for the northern and southern regions. (a) and (b) show SPEI-3 timeseries computed from raw precipitation and temperature observations. (c) and (d) show SPEI-3 timeseries computed from linearly detrended precipitation and temperature observations. The red shaded areas are the periods defined as droughts, i.e., where negative SPEI-3 runs reach at least -1 before the next non-negative SPEI-3 value.

3.4.2 Summer drought characteristics

A total of 12 and 13 summer droughts were identified for the period between 1961 and 2017 in the northern and southern subdomains respectively. Figure 3.4 shows the statistical summaries – median, minimum, maximum, interquartile range – of drought attributes in both regions. Drought duration and severity are statistically indifferentiable across the two regions, with the north having a median of 7.5 months (and mean of 7.6 months) against a median of 7.3 months (and mean of 7.2 months) in the south. The longest meteorological drought was recorded for the southern region, with a duration of 15.4 months between 1991 and 1992. The longest drought in the north occurred in 1987/88 and had a duration of 12.2. Notably, both regions experienced unusually longer droughts in the 1994/1995 with mean durations of 10.8 months and 9.5 months in the north and south respectively. Drought severity is generally similar between the two regions, with median values of 6.8 in the north, and 6.2 in the south (Figure 3.4b). The mean drought severity is 6.9 and 6.8 for the north and south respectively. The intensity of droughts between the two regions is also generally similar, with most events in both regions having mean intensities between 0.7 and 1.1.

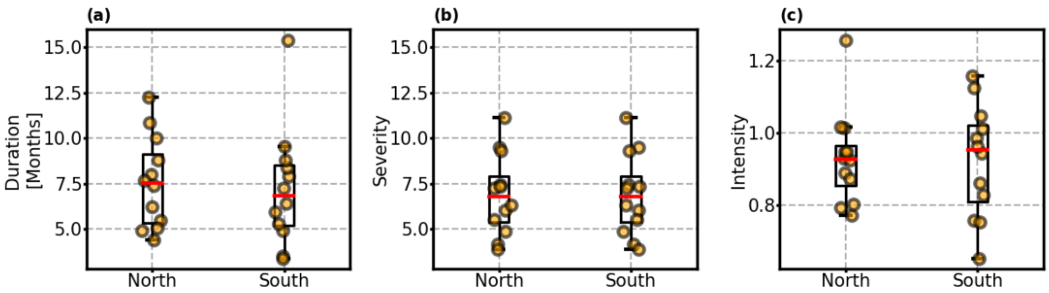

Figure 3.4 | Statistical summaries of regional droughts in the north and south of Malawi. Scatters indicate individual drought events across the two regions. The box and whisker plots indicate the minimum and maximum values, as well as the median (red line), and 1st and 3rd quartiles for each of the three drought attributes namely duration (a), severity (b), and intensity (c).

Despite the generally similar characteristics of droughts between the north and south, the timing of drought events is noticeably different. Table 3.2 shows the summers during which droughts were experienced in each region and highlights years when droughts were experienced in both regions. The differences (and similarities) in the timing of events potentially indicates the influence of different (and shared) drivers of droughts.

Table 3.2 | Summers with droughts in the two region. Years in bold font are summers when drought was experienced across both regions.

Summers With Droughts in The North	Summers with Droughts in the South
1964, **1966**, 1976, 1987, **1990, 1993**, **1994**, 1996, 1998, **1999**, 2005, 2010	1965, **1966**, 1967, 1972, 1983, **1990**, 1991, **1993**, **1994**, **1999**, 2002, 2003, 2015

3.4.3 Circulation anomalies associated with summer droughts

Mean DJF circulation and its anomalies during droughts were examined for the period between 1981 and 2017. Nine events occur in each region over that period as indicated in Table 3.2. Four of these droughts occurred simultaneously between the two regions and can therefore be considered as droughts occurring across the whole country, while the rest were confined to the respective region. On this basis, for subsequent analyses, drought years were classified into three different sets of composites representing drought years in the north only; drought years in the south only; and drought years in both regions which are referend to as synchronous drought years for convenience.

3.4.3.1 Low-level winds and specific humidity

Figure 3.5 shows the climatological mean and composite anomalies of DJF winds, geopotential height, and specific humidity at 850 hPa, a known key level for moisture transport in the region (e.g. Reason and Smart, 2015; Finney *et al.*, 2020). Two dominant semi-permanent high-pressure systems (marked “H’’) are present in the climatology (Figure 3.5a): the South Atlantic High-Pressure system, and the South Indian Ocean High-Pressure (SIHP) system. Two key low-pressure systems (marked “L”) – the Angola Low over Angola and Namibia, and the Mozambiquan Channel Trough – are also prevalent in the climatology. Northeasterly winds associated with the cross-equatorial monsoonal flow prevail to the northeast of Malawi. These converge with southeasterly trades – originating from the subtropical southwestern Indian Ocean around the South Indian Ocean High-Pressure system – to complete the local ITCZ. The Atlantic southeasterly trade winds associated with the South Atlantic High-Pressure system recurve eastwards at the equator, turning into a northwesterly current associated with the Angola Low (Lazenby *et al.*, 2016; Creese and Washington, 2018; Howard and Washington, 2019). This converges with the easterly flows from Indian Ocean to the west of Malawi to form the Congo Air Boundary.

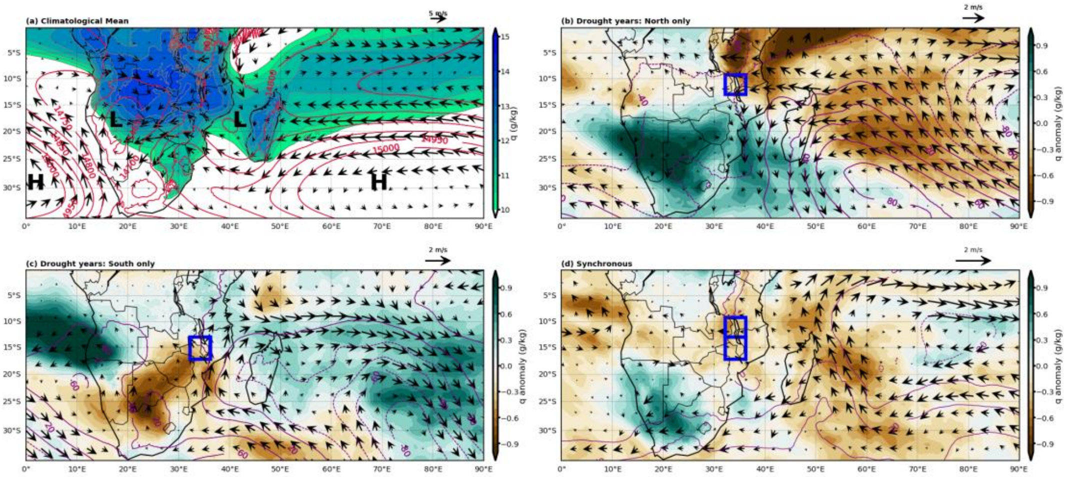

Figure 3.5 | (a) DJF Climatological circulation patterns shown by contours of 850hPa geopotential height, filled contours of specific humidity and vectors of winds. Anomalies of the variables in (a) are shown in (b) and (c) for DJF seasons with droughts in the northern and southern regions of Malawi respectively, as well as (d) for synchronous drought events. Solid contour lines in (b), (c), and (d) indicate positive geopotential height anomalies while dashed lines join fields with negative geopotential height anomalies. The spacing between geopotential height contours in the climatology (a) is 50m and 20m in the anomalies (b -d).

Drought years in the north are associated with a zonal displacement of the SIHP (Figure 3.5b) such that its center is anomalously west of its climatological position. The westward shift of the SHIP increases pressure in the Mozambiquan Channel Trough region. Positive geopotential height anomalies extending into the Mozambiquan Channel signify the weakening of the trough. The meridional component of the southeasterly flow into

Malawi gets weaker as indicated by the corresponding anomalous northerly flow around the Mozambiquan Channel in Figures 3.5b – and zoomed in to for elaborate details in Figure 3.6b. The equatorward ridging over the oceanic region around Madagascar, and the extension of the South Indian Ocean High-Pressure system is also associated with an anomalous easterly wind to the north of Madagascar. This anomalous easterly current flows on to the subcontinent between 5° S and 15° S, recurving southwards over northern Malawi and areas to the northeast across northern Mozambique and Southern Tanzania. Pressure over most of the southern African subcontinent is also reduced.

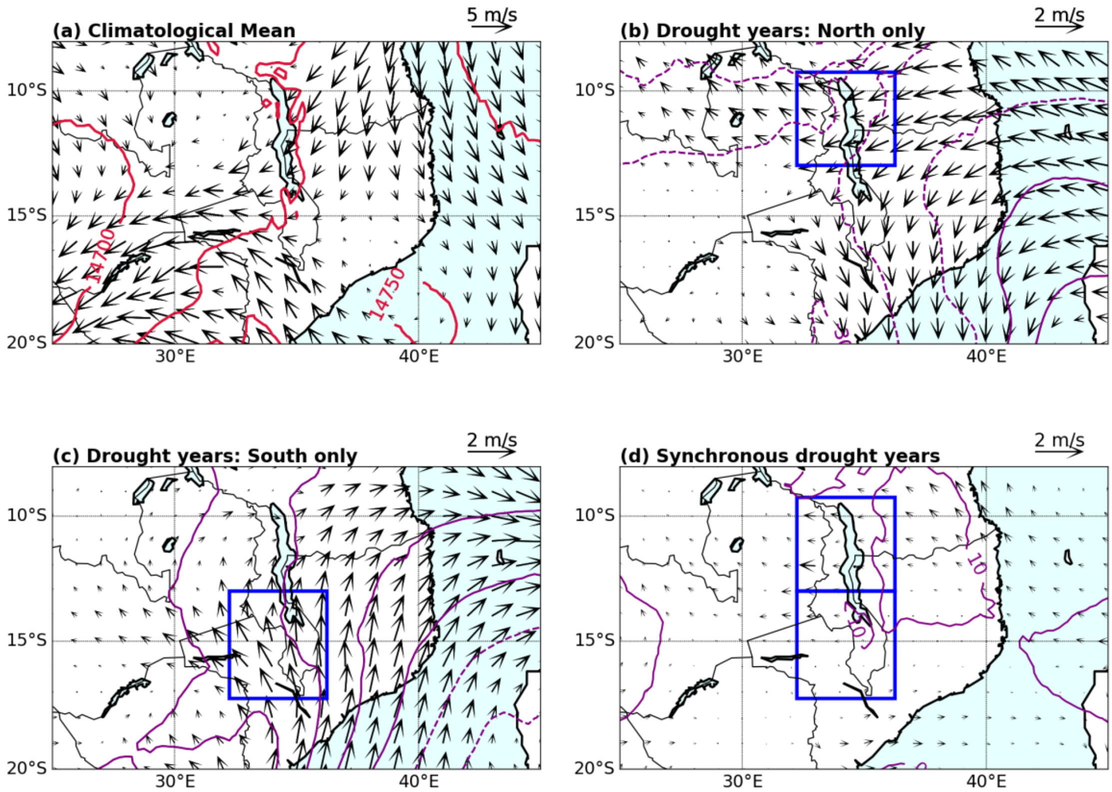

Figure 3.6 | Same as Figure 5 (without specific humidity) but zoomed in to highlight circulation patterns around Malawi. 3.6 (b) shows a weakening of the southerly flow from the southwestern Indian Ocean and the Mozambiquan Channel Trough. 3.6 (c) shows a strengthening of the southerly flow consistent with the strengthening of the Mozambiquan channel trough.

In contrast, droughts in the southern region are associated with a decrease in pressure over the southern Indian Ocean (Figure 3.5c). Negative geopotential height anomalies over the climatological region of the SIHP indicate a weakening of the system. The area of negative geopotential height anomalies extends into the Mozambiquan Channel leading to a strengthening of the trough and the consequent anomalous southeasterly flow into southern Malawi. This coincides with a weakening of the continental low-pressure area as indicated by positive geopotential height anomalies across southern Africa and around the Angola Low region (over Namibia and Botswana). A weakening of the SIHP and the Angola Low translates into diminished moisture advection and convergence across most of the subcontinent including the southern parts of Malawi (Blamey *et al.,* 2018) thus creating conditions that are less favorable for precipitation.

Synchronous droughts are associated with a weaker northwesterly flow from the Congo Basin as shown in Figure 3.5d. An extensive area of high pressure, situated across the southern African subcontinent and extending into the southwestern Indian Ocean is also apparent in synchronous drought years. This coincides with negative geopotential height anomalies and anomalous cyclonic flow over the Indian Ocean northeast of Madagascar. Relatively drier air over Malawi and most of the oceanic region, indicated by negative anomalies of specific humidity, suggests the prevalence of predominantly dry air advection during the DJF seasons with synchronous drought events. Anomalous circulation patterns during some drought years can however be consistent with anomalies associated with droughts in either region as subsequent analyses will show. The tendency to show signs in either direction potentially leads to signals cancelling each other out when these years are composited.

3.4.3.2 Meridional overturning circulation

Meridional overturing circulation over Malawi (32^o – 36^o east) indicates a zone of ascent prevailing between the equator to ~25^o S in DJF, vertically extending from the surface up to 300hPa as shown in Figure 3.7a. This is consistent with the local Hadley circulation associated with the ITCZ. The zone where the meridional winds converge is centered at 16° S, with a tendency to shift during droughty summers. Figures 3.7 b-d show differences in the patterns of meridional overturning circulation for composites associated with the different categories of droughts. Droughts in the north are associated with a southward shift in the convergence zone. This is indicated by a poleward extension of its southern edge and the southward shift in maximum meridional convergence to 18^o S (Figure 3.7 b). Positive omega anomalies in Figure 3.7 e signify suppressed ascent over the north between 14^o S and the equator. On the contrary, droughts in the south are associated with an equatorward shift of the southern edge of the convergence zone. The peak of the northerly and southerly wind convergence and subsequent ascent is anomalously north at 14°S (Figure 3.7 c). Vertical motion is generally suppressed over southern Malawi and across countries to the south of Malawi as shown by positive omega anomalies in Figure 3.7f. Synchronous droughts are generally associated with a reduction in vertical motion across the whole country and a slight northward shift in the zone of maximum ascent.

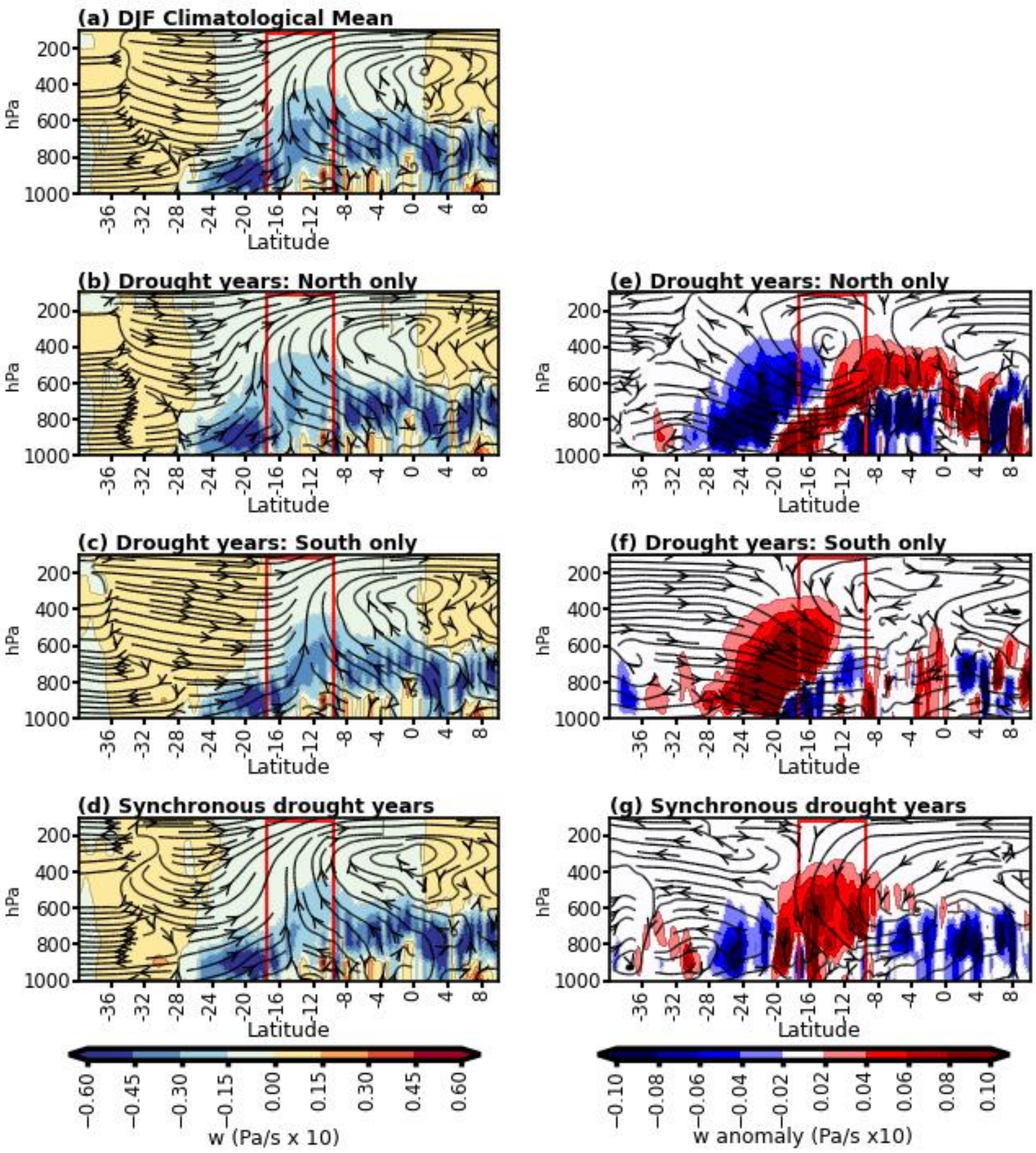

Figure 3.7 | (a) Mean DJF meridional overturning circulation averaged over longitudes 32º E – 36º E. Filled contours are vertical velocity, streamlines are vertical velocity and the meridional wind vector (v). The red box indicates the latitudes bounding Malawi to the north and south. (b), (c), and (d) are composite means of meridional overturning circulation while (e), (f), and (g) are their corresponding anomalies for years with droughts in the north, droughts in the south, and synchronous drought years respectively.

Figure 3.8 illustrates the shifts in the convergence zone during drought years. Shifts in the location of the convergence zone were examined at the 700 hPa level, using the north-most latitudes where the meridional mass flux has a positive vector as a proxy for the location of the convergence zone. The 700 hPa level was chosen as it represents the lowest level free from the influence of boundary layer processes. Figure 3.8a shows the average position of the convergence zone and its standard deviation in DJF for the whole study period, consistent with Figure 3.7a. The apparent south poleward shift in the convergence zone is highlighted in Figure 3.8b for drought years in the north. The contrast in the location of the convergence zone between regional droughts is seen in Figure 3.8c which highlights an equatorward shift in the convergence during drought years in the south. The location of the convergence zone during synchronous drought years indicates only a slight equatorward shift in the convergence zone over the eastern longitudes of the domain but there are similarities with the

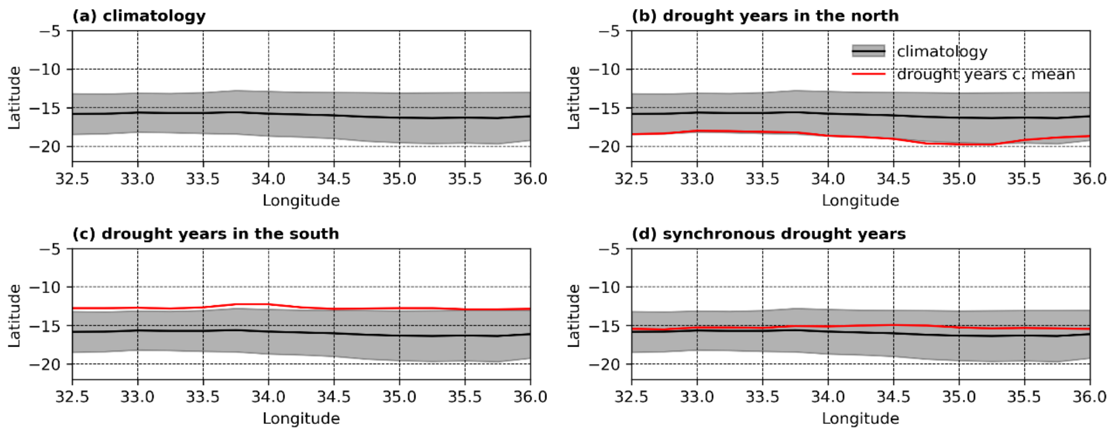

Figure 3.8 | The average position of the northmost latitudes with positive meridional mass flux vectors, presented as the climatological mean and standard deviation (shaded area) (a) and composite means for years with droughts in the north (b) south (c) and whole domain (d). The convergence zone is, in this illustration, summarised with respect to all the longitudes over the domain (rather than the average of longitudes as in the standard meridional overturning circulation plots in Figure 3.7). The average position of the convergence zone is shown as the black covering the longitudinal extent of the domain. Red lines in 3.8 (b) – 3.8(d) show the average position of the of the convergence zone for each category of drought thus indicating its shifts relative to the average position.

3.4.3.1 Low-level moisture flux

Patterns of low-level moisture flux were analyzed to examine the influence of circulation anomalies on moisture transport. Both low-level moisture flux patterns and, in more detail, vertically integrated moisture flux patterns were analyzed. Figure 3.9 shows the low-level moisture flux pattern and fields of vertically integrated moisture divergence (VIMD) for the DJF season as an average of the whole study period (Figure 3.9 a) and as composite anomalies for the different categories of droughts (Figure 3.9b -d). VIMD is indicative of whether atmospheric motions are acting to increase or decrease the vertical integral of moisture over the period of interest. The same illustration is presented in Figure

3.10 to highlight, in more detail, patterns in the vicinity of the domain. Figure 3.9a shows the three origins of moisture flux into Malawi – the equatorial Indian Ocean, the subtropical western Indian Ocean, and the Congo Basin region. The patterns of transport are consistent with prevailing climatological winds in DJF.

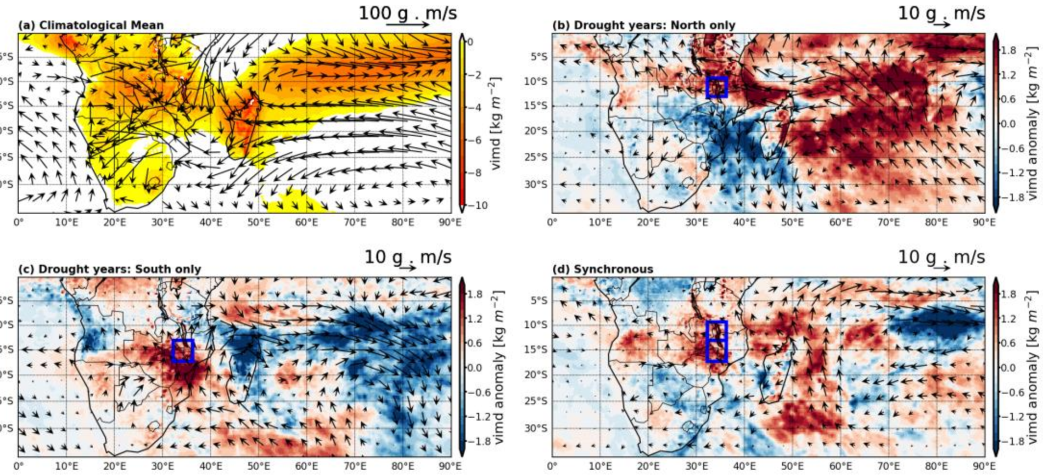

Figure 3.9 | Low-level moisture flux (vectors) and ERA-5 vertically integrated moisture divergence (filled contours) in DJF. Positive values of VIMD indicate divergence while negative values indicate convergence. Divergence fields (positive VIMD) are masked in in 3.9a so that areas of convergence are highlighted. Positive VIMD anomalies in 3.9b – d indicate areas with pronounced divergence (supressed convergence) while negative anomalies of VIMD indicate areas with pronounced convergence.

Droughts in the north are generally associated with reduced moisture flux convergence northwards of 13^{o} S. Given the moisture budget equation $MFC + E - P = \partial W/\partial t$— where *MFC* is the moisture flux convergence, *E* is evaporation, *P* is the precipitation and *W* is the total column water or precipitable water, the change in which is approximately equal to zero for long periods of time (such that *MFC*+*E* ~ *P* or *MFC*+*E*-*P* ~ 0) – positive values of moisture flux convergence indicate net precipitation (positive *P*-*E*) and vice versa for negative values. The region of diminished moisture flux convergence stretches northwards into Tanzania and eastwards into Mozambique. A hint of diminished moisture flux convergence is also apparent to the west in parts of Zambia and Angola.

Negative anomalies of moisture flux convergence are also prevalent in the Indian Ocean, off the Mozambiquan northeast coast, and to the east of Madagascar where a large area of decreased moisture flux convergence sits across the Indian Ocean between 50^{o} E and 80^{o} E. Reduced moisture flux convergence across the north coincides with an area of enhanced convergence over southern Malawi. The region of enhanced convergence has a northwest-southeast orientation, covering parts of Mozambique, Zimbabwe, and South Africa, and stretching seawards into the Mozambiquan Channel and the Agulhas region.

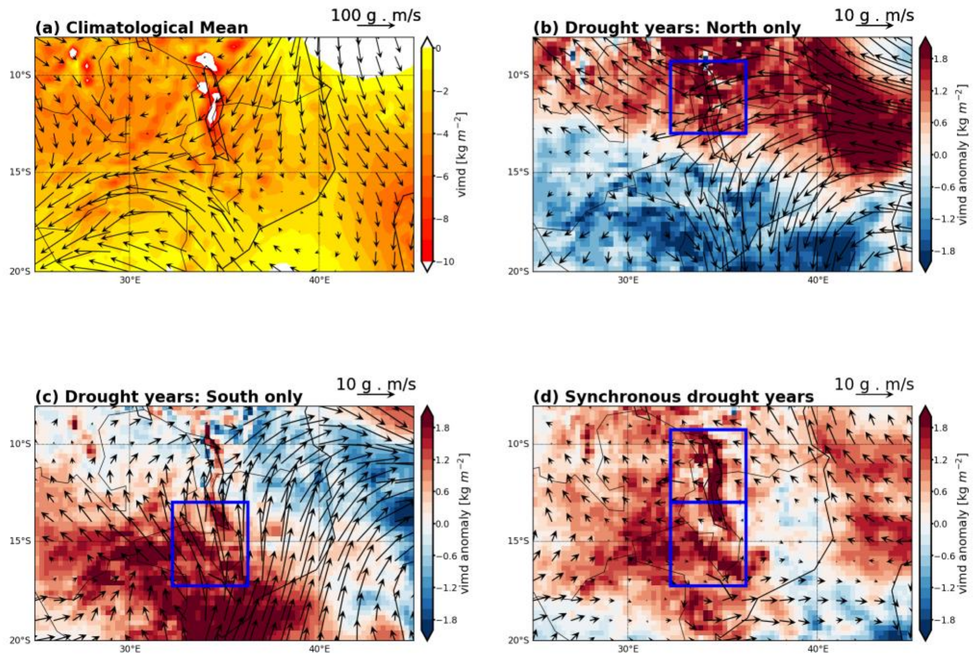

Figure 3.10 | Same as Figure 3.9 but zoomed in to highlight moisture flux and convergence patterns in the vicinity of the region of interest.

In contrast, droughts in the southern region are associated with diminished moisture flux convergence over southern Malawi (Figures 3.9 c and 3.10c). Negative anomalies of moisture flux convergence are organized into a northwest-southeast oriented band covering parts of Zambia, Zimbabwe, and Mozambique. Anomalously higher moisture flux convergence is apparent to the north of the Mozambiquan Channel, stretching eastwards across the Indian Ocean. Synchronous droughts are associated with negative moisture flux convergence anomalies across the whole country (Figures 3.9d and 3.10d). These coincide with negative anomalies in the northwesterly moisture fluxes to the northwest of Malawi and over the Congo Basin. Anticyclonic anomalies around the Angola Low indicate weaker moisture flux around the Angola Low. The region associated with negative anomalies in moisture flux convergence extends westwards close into Angola near the west coast, and eastwards into the Indian Ocean.

3.4.3.2 Vertically integrated moisture transport

Vertically integrated moisture flux was computed from wind vectors and specific humidity between the 1000 hPa and 100 hPa levels for the DJF season. Three main tracks of moisture advection into Malawi were identified, generally consistent with DJF climatological wind patterns and low-level moisture flux patterns. Figure 3.11a highlights the three main tracks of moisture advection into the domain in DJF. Oceanic moisture is essentially advected into Malawi via the northeasterly and southeasterly tracks from the equatorial Indian Ocean and the subtropical southwestern Indian Ocean respectively. A northwesterly track of moisture flux from the Congo basin completes the trio of moisture advection tracks into Malawi in DJF. The interaction of the three tracks forms a northwest-southeast oriented convergence zone situated over Malawi and extending into the neighboring Zambia to the northwest, and the Mozambiquan Channel to the southeast, consistent with patterns identified by McHugh and Rogers (2001) and Lazenby *et al.* (2016) at 850 hPa. The apparent meridional precipitation gradient with a peak over Malawi, Zambia, and Mozambique (Figure 3.11a) signifies the prevalence of the convergence zone. Moisture is advected out via a northwestward track located on the southwestern edge of the domain. This recurves southwestwards and enters neighboring regions to the southwest as a northeasterly flow.

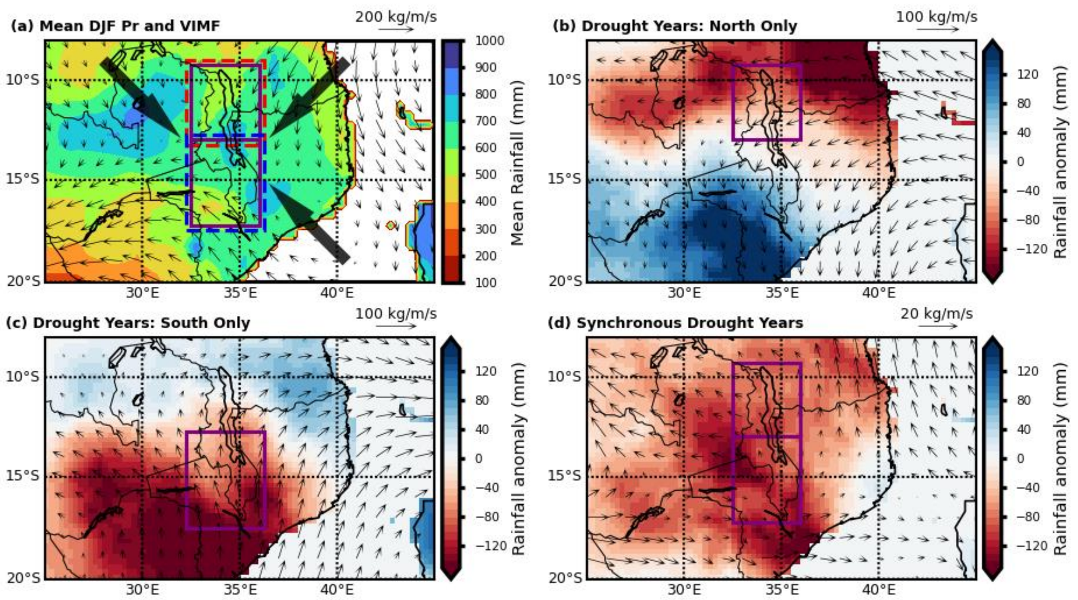

Figure 3.11 | (a) Climatological mean of DJF vertically integrated moisture flux (vectors) and precipitation (filled contours). Three board arrows indicate the three main tracks of moisture advection into Malawi in DJF. The segment between the solid and dashed boxes indicates the grid boxes from which the moisture advected into the domain is calculated. (b), (c), and (d) are the composite anomalies of the vertically integrated moisture flux (vectors) and precipitation (filled contours) for years with droughts in the north, south, and synchronous droughts respectively.

Composite anomalies associated with the three different categories of droughts depict stark contrasts in moisture fluxes and ensuing precipitation distribution for the different categories of droughts. A meridional precipitation dipole is apparent during regional droughts such that dry conditions in one region coincide with wetter conditions in the other (Figures 3.11b and c). The southeasterly flow into southern Malawi is weaker during droughts in the north. This coincides with an anomalous easterly flux into northern Malawi. In contrast, an anomalous southerly flux from the Mozambiquan Channel into southern Malawi is apparent during summers with droughts in the south. Kolusu *et al.* (2019) found similar patterns at 850 hPa over a wider spatial scale where they noted an anomalous southerly flow linked to drier (wetter) conditions in southern (eastern) Africa during the El Niňo of 2015/16. During synchronous drought years, negative anomalies of precipitation are apparent across the whole country, with a peak over the southern region and extending into Mozambique. An anomalous easterly flow during synchronous droughts (Figure 3.11d) indicates a weakened contribution of the northwesterly moisture flux from the Congo basin and, potentially, an effective westward shift of the convergence zone.

The relationship between precipitation and moisture fluxes associated with the different tracks of moisture advection was examined to establish how their respective variability – and ensuing variability in their interaction – influences precipitation variability that underlies drought conditions. The precipitation timeseries for the study period was regressed onto the net total VIMF timeseries for each domain. DJF precipitation (CRU) is strongly correlated (at 95% confidence level) to the net total moisture flux (ERA5) across all the domains ($r = 0.7, p < 0.05$ in the north; $r = 0.6, p < 0.05$ in the south; and $r = 0.6, p < 0.05$ for whole domain) (Figures 3.12a-c). The strength of the correlations is much higher when the ERA5 rainfall is used instead of CRU ($r = 0.83, p < 0.05; r = 0.83, p < 0.05; r = 0.82, p < 0.05$ for north, south, and whole domain respectively) (not shown) accentuating that precipitation variability across Malawi is principally driven by variability in advected moisture.

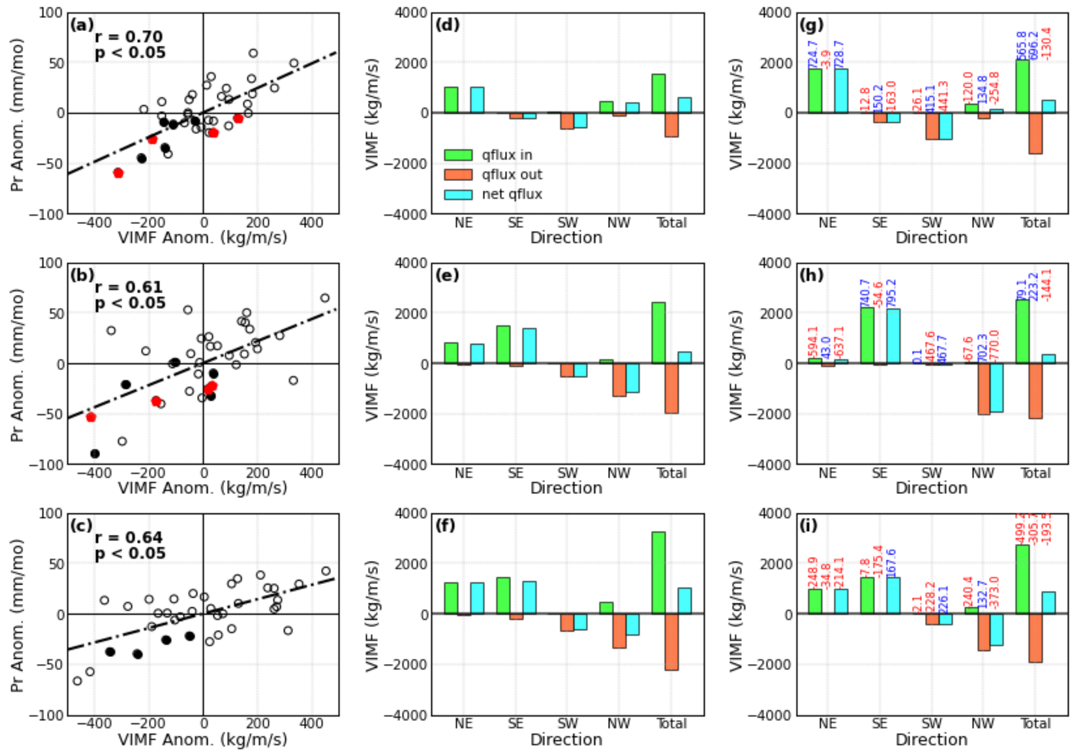

Figure 3.12 | Correlation between net total VIMF and precipitation for (a) the north, (b) the south, and (c) the whole domain. Solid dots in (a), (b), (c) indicate years when there is a drought with the red dots in (a) and (b) indicating when such a drought is synchronous in nature. (d), (e), and (f) show the climatological mean DJF moisture fluxes associated with different directions of flow relative to the domain, and their corresponding totals. (g), (h), and (i) are composite means for when there is a drought in the north (g), south (h), and whole country (i). The labels on the bars in (g), (h) and (i) are the corresponding anomalies with blue and red indicating positive and negative anomalies respectively.

The relative contribution of the three tracks to the total VIMF varies within each region while each track's contribution to the total VIMF also varies between the two regions. Figures 3.12d-f show the mean moisture fluxes (in, out and net) across the three different tracks including the total moisture flux in the two regions and for the whole country. In this view, the direction of moisture flux out of the domain is described based on its destination rather than its origin (as is the tradition for climatological wind direction). Moisture is typically advected into the northern subdomain via the northeasterly and northwesterly moisture advection tracks, and advected out via a southwestwards flow (Figure 3.12d) that enters the southern subdomain as a northeasterly flux.

The northeasterly flow into the southern subdomain, and the southeasterly flow from the Mozambiquan Channel are the main tracks of moisture advection into the southern region (Figure 3.12e). The contribution of the northwesterly track (making its way through the western boundary of the subdomains) is relatively smaller in the southern region. However, we note that the northwesterly flux into the northern subdomain recurves southwards to join the northeasterly track flowing into the southern subdomain. Moisture exits the southern subdomain via a southeast-northwest flow, hence the pronounced northwestward outflow in Figures 3.12e, f. This northwestward outflow recurves southwards to the west of Malawi, flowing into countries to its southwest as a northeasterly moisture flux. The variability of the convergence zone, underlain by its meridional migration and degree of moisture flux convergence, is driven by variability in the moisture flux tracks. Composite means and anomalies of moisture flux associated with the three tracks demonstrate the intricate interactions of the moisture flux tracks to create drought conditions by influencing the location and intensity of the convergence zone.

Figures 3.12g-i confirm the patterns of anomalous VIMF associated with the different categories of drought illustrated in Figures 3.11b-d. The moisture flux from the northeasterly track is anomalously stronger when droughts occur in the north. This is linked to the pronounced northeasterly flow from the cross-equatorial monsoon and the southward shift of the convergence zone as shown in Figure 3.5b and 3.7b. The southeasterly track tends to be weaker as the rain-bearing systems are shifted southwards. This is consistent with the negative anomalies of moisture flux convergence over the northern region coinciding with anomalously high convergence in southern Malawi and areas to its south.

Droughts in the south are associated with an anomalously stronger southeasterly track while the moisture flux from the northeasterly track is weaker as the convergence zone shifts northwards towards the equator (Figure 3.12h). This is also consistent with the meridionally oriented dipole pattern in the moisture flux convergence anomaly, signifying a northward shift in the rain-bearing mechanisms. The meridional shift of the convergence zone in regional drought years produces the precipitation dipole that characterizes regional droughts. In both cases of regional droughts, the northwesterly track’s contribution to total moisture flux is weaker. The anomalous weakening of the northwesterly track is more pronounced during synchronous events (Figure 3.12i) which are also associated with diminished contribution of the other two tracks and suppressed convergence across the whole country.

3.4.4 Potential drivers of moisture flux variability

Sea surface temperature anomalies were examined as candidate drivers of atmospheric circulation variability associated with droughts. Composite SST anomalies for drought years in the north depict patterns reminiscent of La Nina, indicated by anomalous cooling in the central and eastern Pacific Ocean (Figure 3.13a). On the other hand, anomalous warming in the central and eastern Pacific Ocean, consistent with patterns characteristic of El Niňo, is apparent during drought years in the south (Figure 3.13b). Incidentally, three out of the five droughts in the south (1991, 2002, 2015) occurred during El Niňo years while three of the five droughts in the north (1998, 2005, 2010) coincided with La Nina. The El Niňo of 1994 and the La Nina of 1999 were associated with droughts that affected the whole country, rather than being confined to either region as would be expected for a typical case. Typically, regional droughts would be expected in both instances, characterized by drying in the south (north) for the 1994 (1999) episode, with contrasting wetter conditions in the other region.

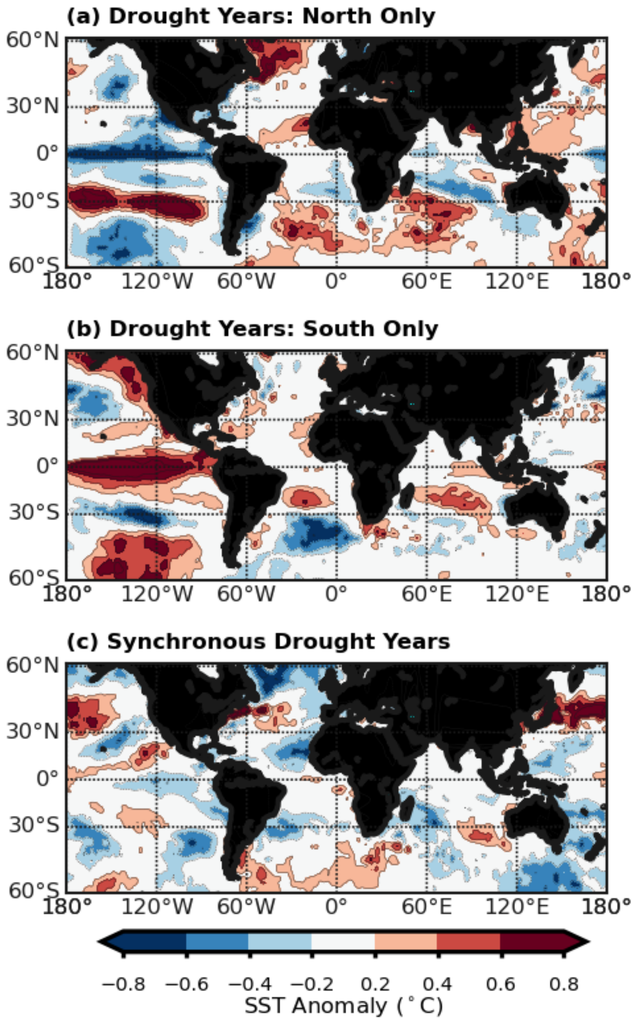

Figure 3.13 | Composite anomalies of sea surface temperature for (a) drought years in the north, (b) drought years in the south, and (c) synchronous drought years.

SST anomalies with a hint of a meridional dipole pattern are also apparent in the Indian Ocean for regional droughts. Positive SST anomalies across the equatorial Indian Ocean coincide with negative anomalies across the subtropical southwestern Indian Ocean during droughts in the north, and vice versa during droughts in the south. The dipole pattern and strength of anomaly is generally more pronounced for drought years in the north. Synchronous drought years depict no real pattern with regards to SST anomalies. The tendency of such years to have anomalies with opposite signs leads to composite anomalies cancelling each other out. This is particularly apparent for years 1994 and 1999, two summers with synchronous droughts that coincided with El Niňo and La Nina respectively. Figure 3.14 shows the SST anomalies for the individual synchronous drought years especially highlighting conditions characteristic of El Niňo and La Nina conditions in Figures 3.14c when such conditions led to synchronous droughts rather than the typically expected regional droughts.

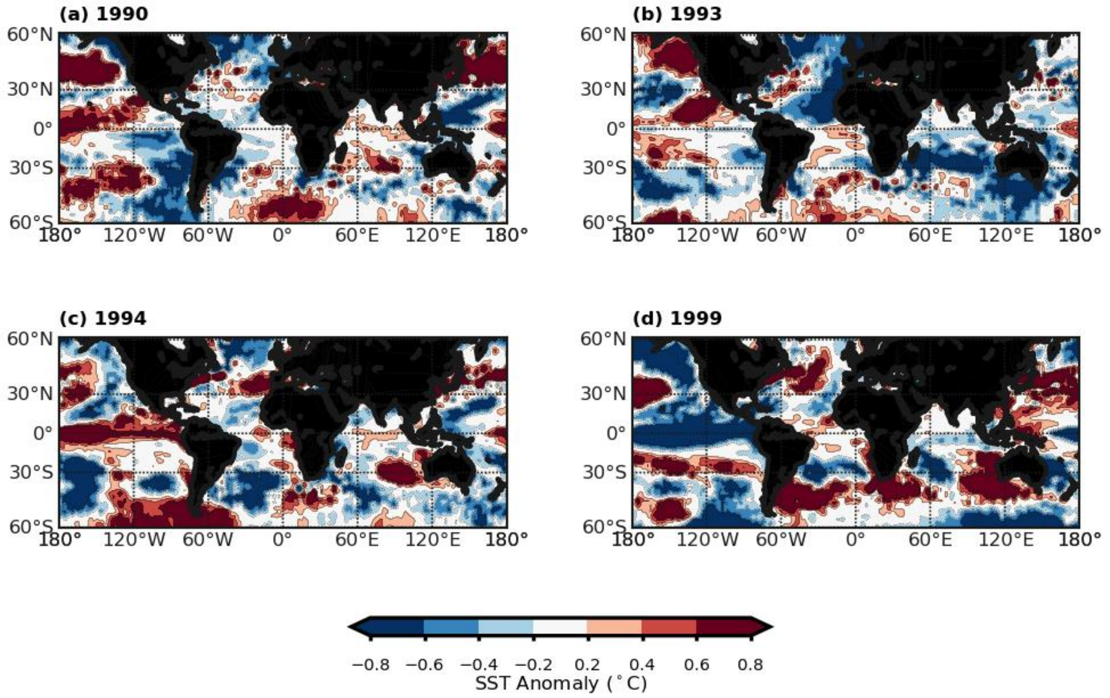

Figure 3.14 | SST anomalies for the individual years with synchronous droughts. Years 1994 and 1999 are El Niňo and La Nina years respectively, but with a drought spatial signature different from other El Niňo/La Nina drought years as the ensuing droughts were synchronous, rather than regional.

Regressing VIMF from the different tracks onto SST anomalies reveals relationships indicative of the influence of synoptic and global drivers of variability and how they are uniquely linked to the different tracks. Figure 3.15a illustrates the positive correlation between the southeasterly VIMF and SSTs in the central and eastern Pacific Ocean. Warmer SSTs, typical of El Niňo, are associated with a stronger southeasterly flow and the subsequent equatorward shift of the convergence zone leading to drier (wetter) conditions in the south (north) as the convergence zone shifts northwards towards the equator. The opposite takes place when colder SSTs – characteristic of La Nina – prevail in the central and eastern Pacific Ocean. The southeasterly moisture flux also shows a basin-wide correlation with SSTs in the Indian Ocean, with a hint of a dipole pattern in the subtropical Indian Ocean.

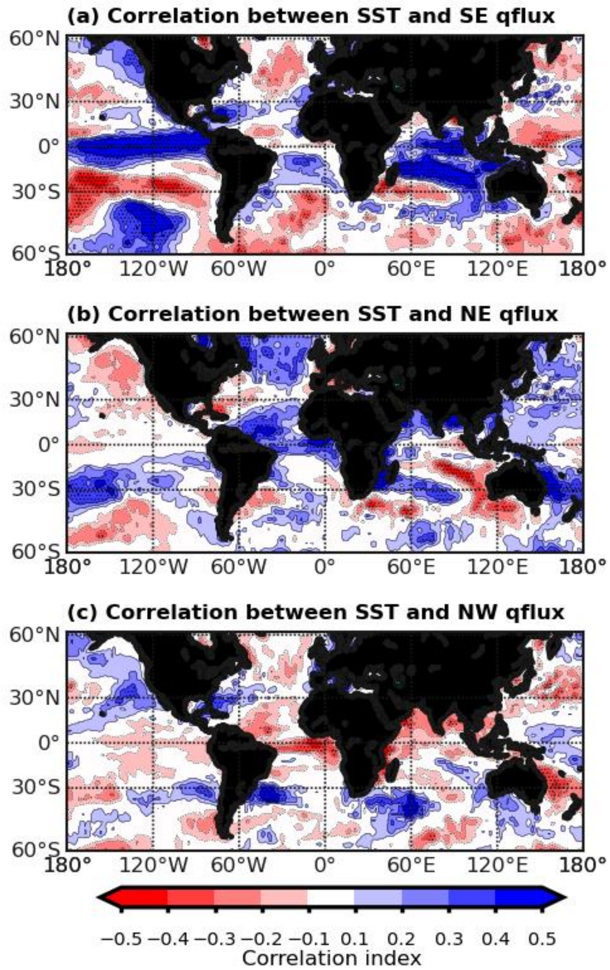

Figure 3.15 | Correlation between DJF SST and VIMF anomalies for each of the three tracks: (a) southeasterly, (b) northeasterly, and (c) northwesterly. Stippling indicates where the correlation is significant at 95% confidence level.

Figure 3.15b indicates that the subtropical Indian Ocean SSTs also show a positive/negative correlation dipole with the northeasterly VIMF. The direction of the associated correlation indices is the opposite of patterns seen for the VIMF from the southeasterly track. This dipole pattern is reminiscent of the Subtropical Indian Ocean Dipole (SIOD) (Behera and Yamagata, 2001; Hoell and Cheng, 2018). The negative phase of the SIOD, characterized by cooler SSTs in the subtropical southwest Indian Ocean, and warmer SSTs off the Australian southwestern coast, is associated with drier conditions over parts of southern Africa. Precipitation variability associated with the SIOD is driven by variations in the SIHP, a key feature in sustaining the southeasterly track and its interaction with the other two tracks.

Relationships between the northeasterly moisture flux variability and SSTs in the Indian Ocean (Figure 3.15b) also reveal patterns bearing resemblance of the Indian Ocean Dipole (IOD) (Saji *et al.*, 1999). The IOD – characterized by an east-west SST dipole – peaks in the austral fall (September – November) with strongest variability in October (Blau and Ha, 2020). It can act independently or in concert with ENSO (Black, 2005) to influence precipitation in eastern and southern Africa. Regressing the northwesterly VIMF onto SSTs shows spatial patterns that closely resemble those noted for the northeasterly VIMF but in the opposite direction (Figure 3.15c). This multiplicity of drivers of variability linked to droughts highlights the complexity of drought processes given the modulation effect that the different drivers may have on each other and on the ensuing drought characteristics. Table 3.3 summarizes the drought events between 1981 and 2017 and the phases of ENSO and IOD that they coincided with.

Table 3.3 | List of events and the phase of ENSO and IOD that was prevailing in that year.

Drought Year x Region			**ENSO phase**	**IOD phase**
North	**South**	**Synchronous**		
	1983		Negative	
1987			Positive	
		1990	Neutral	
	1991		Positive	
		1993	Neutral	
		1994	Positive	Positive
1996			Neutral	Negative
1998			Negative	Negative
		1999	Negative	
	2002		Positive	
	2003		Neutral	
2005			Negative	
2010			Negative	Negative
	2015		Positive	Positive

3.4.5 Representation of droughts in CMIP5 models

3.4.5.1 Drought attributes and precipitation

The simulation of drought attributes in climate models is not without bias. Figure 3.16a-d displays biases in frequency, duration, severity, and intensity across the 18 CIMP5 models that were evaluated. 10 models underestimate drought frequency in the south by at least two events over the period of evaluation, with GFDL-CM3 having the least events – four less than the observation. Most of the models tend to have more droughts in the south than in the north, consistent with regional frequency disparities found in observation. However, the ratio of synchronous droughts to the total number of droughts varies widely across models. Notably, models that overestimate drought frequency tend to produce more synchronous events hence events that would otherwise be counted as occurring in only one region are also counted as occurring in the other. For instance, ACCESS1-3 has 10 events in both regions, nine of which are synchronous while GFDL-CM3, has three synchronous events out of the eight and five it produces for the north and south respectively. This association is also maintained when the evaluation period is extended back to 1961 (not shown). Figures 3.16b and c show that models overestimate drought duration and severity respectively across both regions. A strong correlation between drought severity bias and drought duration bias *($r = 0.9$, $p < 0.05$ in both regions)* (not shown) indicates that biases in severity are influenced by errors in drought duration rather than intensity.

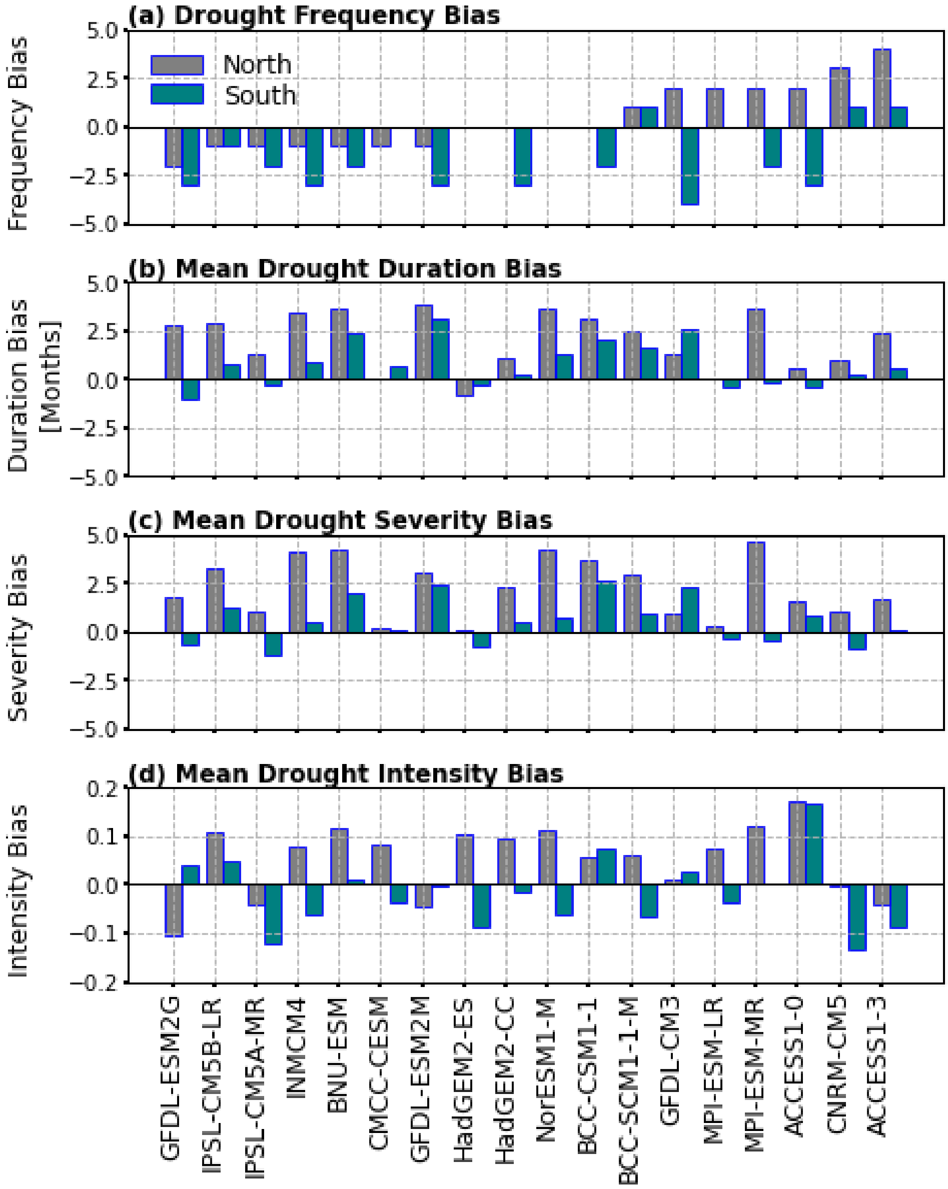

Figure 3.16 | CMIP-5 model biases in drought attributes for north and south of Malawi. Mean values are computed for drought attributes based on events identified in each model for the reference period. The average value for drought attributes based on events identified in observations for the same period is subtracted from the average value in the model to determine the bias direction and magnitude.

Biases in simulated DJF precipitation are a common feature of CMIP5 models in both regions consistent with biases across the wider southern African region (Lazenby *et al.*, 2016; Munday and Washington, 2018). However, there is no sufficient evidence to indicate that model precipitation biases are linked to biases in drought frequency, duration, severity, or intensity. Being a standardized index, the self-calibrated SPEI uses distribution parameters that are configured to the background climatology of the climate for which the drought index is being computed. Thus, each model's wetness or dryness is accounted for in the index, effectively negating the influence of inter-model differences in mean precipitation on inter-model variations in drought attributes. Despite the lack of association between drought attribute biases and model precipitation biases, the relationship between precipitation and moisture flux variability in each model provides a plausible basis for examining drought mechanisms in models as this is the basis for precipitation variability linked to droughts in observation. This helps determine whether model droughts are produced for the right reasons.

3.4.5.2 Biases in simulated moisture fluxes

Net moisture flux and precipitation biases

Biases in net total VIMF are apparent in both regions (Figure 3.17a). Regressing precipitation biases on to net total VIMF biases shows no real association between the two. The correlation between net total VIMF biases and precipitation biases is minute in the north *(r=0.188, p = 0.455)* and, despite a hint of a positive correlation between the net total VIMF biases and precipitation biases in the south *(r = 0.388, p = 0.112)*, the associated correlation index is not significant (at 95% confidence level) (Figures 3.17b and c). Despite the biases in precipitation and VIMF, the correlation between the net total VIMF and precipitation in most models is consistent with observation. This indicates that, like in observation, the interannual variability in CMIP5 models is principally driven by variability in the advected moisture. However, the consistency in the simulation of the moisture fluxes from the different tracks and their respective influence on the precipitation variability varies across the models.

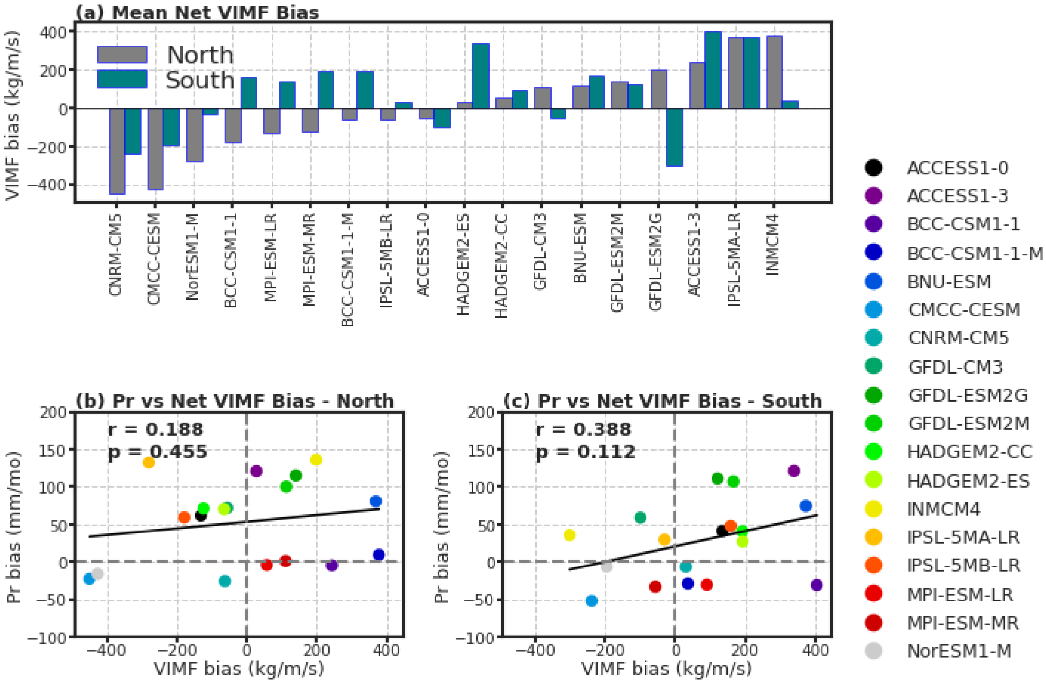

Figure 3.17 | (a) CMIP5 model biases in net total VIMF for the two regional subdomains. (b) and (c) show the relationship (or lack of it) between net total VIMF bias and precipitation bias in DJF in the northern and southern subdomains respectively.

Track moisture flux and precipitation biases

Figures 3.18 illustrates biases in VIMF into Malawi via the three main tracks and how such biases influence biases in precipitation in each region. Most of the models have a positive bias in the northwesterly VIMF and a negative bias in the southeasterly VIMF, while biases in the northeasterly VIMF are generally symmetrical. In both regions, precipitation biases are significantly positively correlated to biases in the northwesterly moisture flux *($r = 0.75$, $p < 0.05$* for the north, and *$r = 0.79$, $p < 0.05$* for the south) as illustrated in Figures 3.18a, b. Thus wetter (drier) models are likely to have a positive (negative) bias in the northwesterly VIMF. On the other hand, negative(positive) biases in the southeasterly moisture flux are associated with positive(negative) biases in precipitation across both regions (Figures 3.18e and f), more so in the south where the associated correlation index is relatively stronger, and statistically significant at 95% confidence level *($r = -0.386$, $p = 0.113$* for the north, and *$r = -0.68$, $p < 0.05$* for the south).

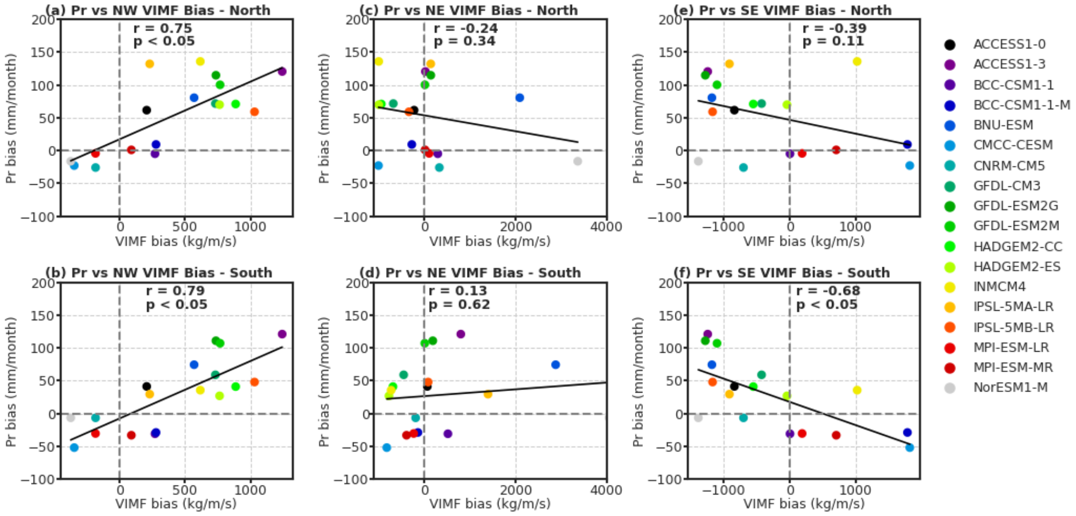

Figure 3.18 | Relationships between biases in precipitation and biases in VIMF from the different tracks. (a) and (b) show the relationship between northwesterly VIMF biases and precipitation in the two regions. (c) and (d) show the relationship (or lack of it given the insignificant correlations) between northeasterly VIMF biases and precipitation biases in the two regions. (e) and (f) show the relationship between southeasterly VIMF biases and regional precipitation biases.

Subjecting the correlations between the precipitation and moisture flux from each of the three tracks reveals varying degrees of similarity between GCMs and observation. Table 3.4 provides a summary of the correlation between moisture fluxes and precipitation in the respective models. Apart from NORESM1-M (in both regions) and HadGEM2-ES (in north), the rest of the models exhibit positive correlations between DJF precipitation and the northwesterly moisture flux consistent with patterns in observation. Notably the NORESM1-M model only has a northeasterly flow all over Malawi such that moisture fluxes from the rest of the tracks are non-existent. Except for CMCC-CESM, the negative correlation between precipitation and the northeasterly moisture flux in the north is maintained, albeit at varying magnitudes. The correlation between the northeasterly moisture flux and precipitation in the south is insignificant in observation hence there is no basis for evaluating the similarity with models in that regard. 12 of the 18 models exhibit a positive correlation between the southeasterly moisture flux and precipitation in the north, consistent with observations.

Table 3.4 | Summary of CMIP5 model performance in relation to the simulation of the relationship between vertically integrated moisture flux and precipitation. *NA* indicates where the correlation between VIMF and precipitation in ERA5 for that particular region is insignificant hence there is no basis for comparison with CMIP5.

	Correlations							
	Net total moisture flux and precipitation in CMIP5		*Northwesterly moisture flux and precipitation in CMIP5*		*Northeasterly moisture flux and precipitation in DJF*		*Southeasterly moisture flux and precipitation in DJF*	
	North	*South*	*North*	*South*	*North*	*South*	*North*	*South*
Mean r	*0.73*	*0.73*	*0.50*	*0.54*	*-0.54*	*-0.20*	*0.38*	*-0.13*
Stand. dev. Of r	*0.22*	*0.27*	*0.27*	*0.19*	*0.27*	*0.32*	*0.24*	*0.27*
Proportion of models with r in the opposite direction or not significant	*6%*	*11%*	*NA*	*17%*	*17%*	*NA*	*22%*	*78%*
Proportion of models with r in the same direction as ERA5 but magnitude is either too small or too big	*11%*	*11%*	*NA*	*6%*	*17%*	*NA*	*17%*	*6%*

The influence of the southeasterly VIMF on the meridional shift of the convergence zone and its links with ENSO has been demonstrated for observations/reanalysis. Crucially, most models do not exhibit the negative correlation between the southeasterly moisture flux and precipitation observed in the south to complete the precipitation dipole associated with the southeasterly moisture flux variability as shown in Table 3.4. This could be attributed to models not accurately locating the peak of the convergence zone, given the finely balanced circulation and interactions of the moisture tracks over what is a transitional zone. At a wider regional scale, for instance, Lazenby *et al.* (2016) established that CMIP5 models simulate the Southern Indian Ocean Convergence Zone albeit with an uncharacteristically pronounced zonal orientation. Beyond that, models could also be struggling to simulate the ocean-atmosphere interactions fundamental to the regional synoptic features and processes that supply and sustain the moisture advection tracks, particularly the southeasterly track.

To evaluate model simulation of the convergence zone over Malawi, the mean DJF meridional overturning circulation in models was examined with respect to ERA5. Figure 3.19 shows the average meridional overturning circulation for the longitudes bounding the domain in CMIP5 models. Differences in the size, location and intensity of the convergence zone are apparent and biases with respect to ERA5 are shown in Figure 3.20.

Most models have the tendency to underestimate omega – an established measure of large-scale vertical motion (James *et al.*, 2018) – in the lower levels of the atmosphere. Drier models overestimate omega fields for levels higher than 700 hPa which may signify suppressed ascent (or too much descent) in those models. The location of the convergence zone is key to identifying regions of preferred convergence and convection and how they shift during droughts. The inconsistent simulation of such locations could potentially undermine the regional distribution of droughts and the simulation of the precipitation dipole observed during regional droughts.

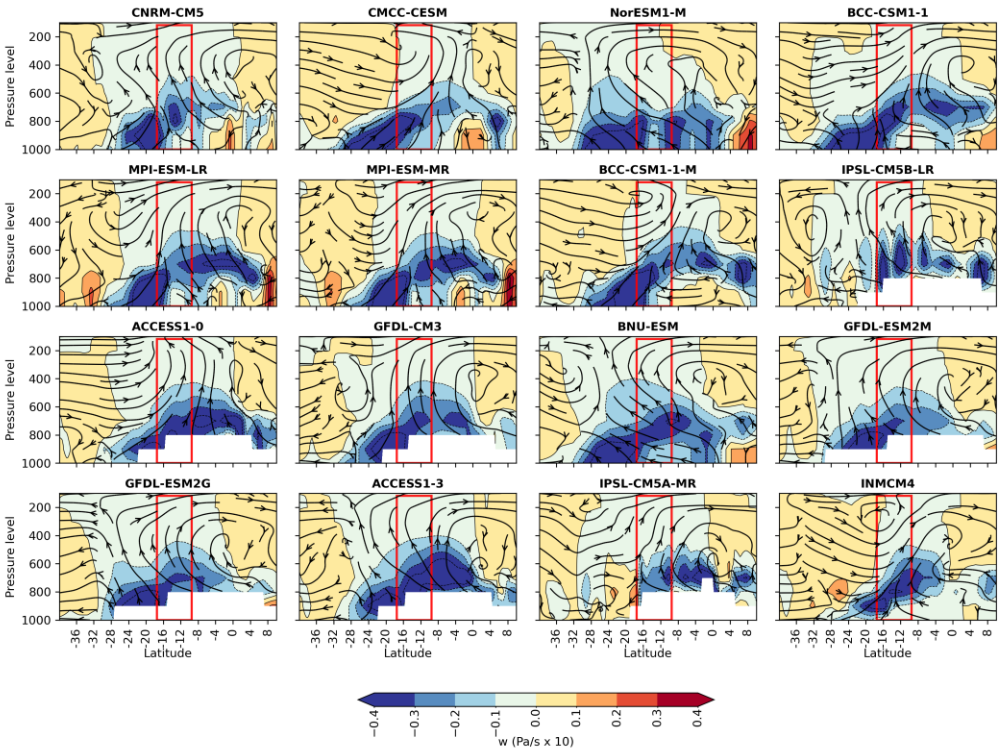

Figure 3.19 | Average meridional overturning circulation across CMIP5 models over the austral summer (DJF) season. Mean meridional overturning circulation is computed from simulated specific humidity and vertical velocities across different pressure heights (between 1000 hPa and 100 hPa) for the period and averaged over the longitudinal cross section (32.5 – 36 degrees east) and covering a latitudinal transect extending from 10 degrees north to 40 degrees south. The red box indicates the latitudes over which Malawi is located.

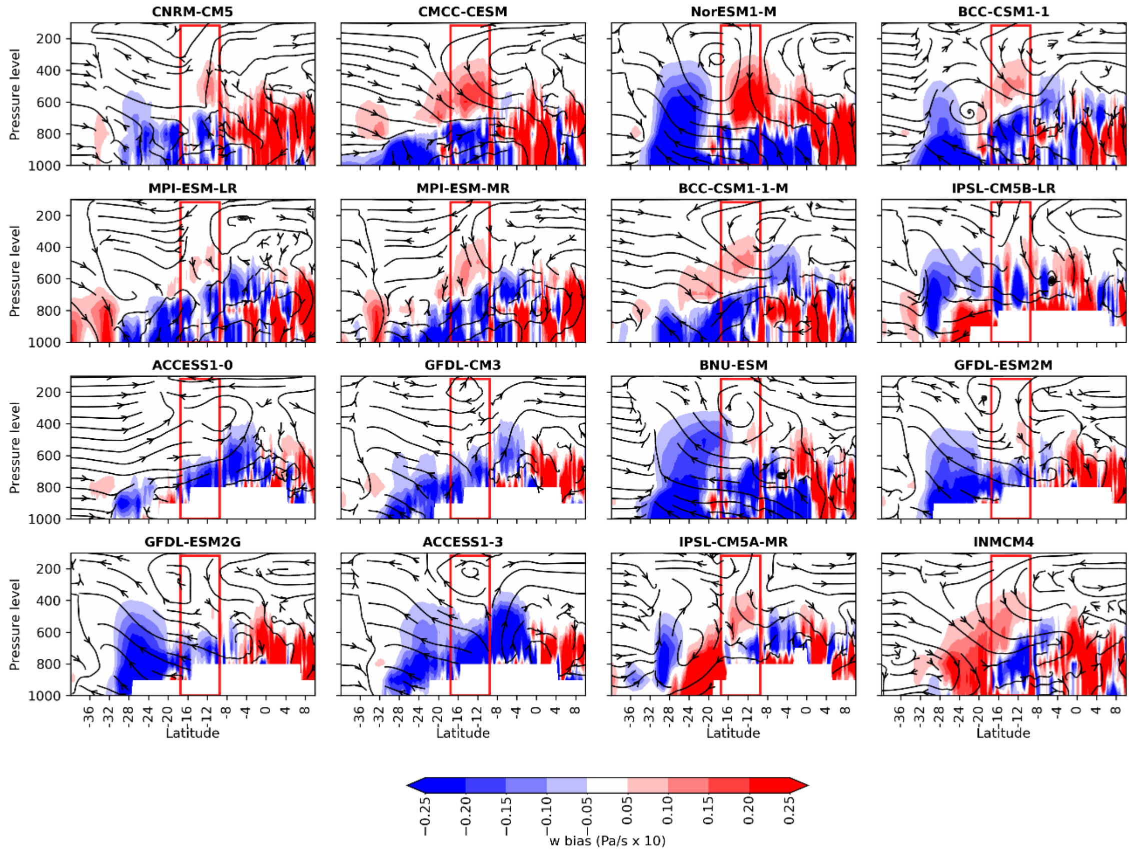

Figure 3.20 | Biases in the components of meridional overturning circulation. Contours are biases of vertical velocity (omega) while streamlines are anomalies of moisture fluxes in the vertical column (computed from the product of meridional wind vector and vertical velocity). Biases are computed from the difference between DJF meridional overturning circulation components (omega and the product of omega and specific humidity across pressure coordinated) in respective CMIP5 models and ERA5 for the period 1979 – 2005 (Following the setup in 3.19). As negative (positive) vertical velocity indicates ascent (descent), negative biases (portraying pronounced omega values in the negative direction) indicate pronounced ascent and vice versa for positive anomalies.

3.5 Discussion and conclusion

Malawi's unique, transitional geographical location underpins the need for comprehensive examination of droughts and other key weather phenomena whose understanding across regions either side of the country remains elusive. This examination has demonstrated the means to objectively examine attributes of meteorological drought and elicit their associated dynamics in observations/reanalysis products and present-day climate simulations. Summer drought attributes are generally similar across Malawi. However, the timing of drought events with respect to the two regions with contrasting ENSO responses demonstrated the need for detailed scrutiny of associated dynamics and underlying mechanisms. This examination attempted to address these questions and highlighted key processes and interactions between features that drive precipitation variability over Malawi and govern the occurrence of droughts between the north and south of the country. Figure 3.21 is a schematic illustration of these interaction from a climatological perspective and for years when there are droughts.

The location of summer droughts with respect to the two regions is largely driven by variation in the interaction of three tracks of moisture flux that interact to form a convergence zone over Malawi. Meridional shifts in the convergence zone and the associated precipitation dipole between the north and south of Malawi – characteristic of typical drought conditions – highlights the influence of drought processes in subtropical southern Africa and eastern Africa on drought processes in Malawi. Cross-regional influences on Malawi's precipitation climatology have been previously highlighted by Nicholson *et al.* (2014) while latter studies e.g., Kolusu *et al.* (2019) and Siderius *et al.* (2021) provide a further basis for contextualizing these regional-local relationships. This examination has highlighted the different (to a considerable extent opposing) circulation patterns associated with droughts in the north and south of Malawi that reinforce this position from a dynamical point of view. In so doing, the study has further developed the understanding of drought processes from previous big picture studies that may not have elucidated these key circulation patterns and subtle interactions.

Meridional shifts in the convergence zone is to an extent consistent with the northeast-southwest movement of the SIOCZ, and the ensuing precipitation variability which is characterized by a dipole pattern (Lazenby *et al.*, 2016). Over Malawi, rainfall deficits associated with droughts in the north (south) of the country tend to occur simultaneously with above normal rainfall occurrence in the south (north). Similar patterns can be seen across Zambia and Mozambique, the scale of which is essential for identifying the extent of the convergence zone beyond Malawi and its behavior to produce drought conditions. Key to the poleward (equatorward) shift of the convergence zone is the weakening and withdrawn (intensified) influence of the MCT in sustaining the southeasterly track of moisture advection. The MCT influences precipitation variability across southeast Africa through modulation of moisture that is transported from the southeasterly trades and northeasterly monsoon (Barimalala *et al.*, 2020). The study has also highlighted the link between the MCT and the SIHP's location and intensity variations in which influence droughts in Malawi. This concurs with the findings of Barimalala *et al.* (2020). Kolusu *et al.* (2019) highlight this process in the context of the 2015/16 drought in southern Africa, including parts of southern Malawi, which coincided with wetter conditions over eastern Africa including parts of northern Malawi.

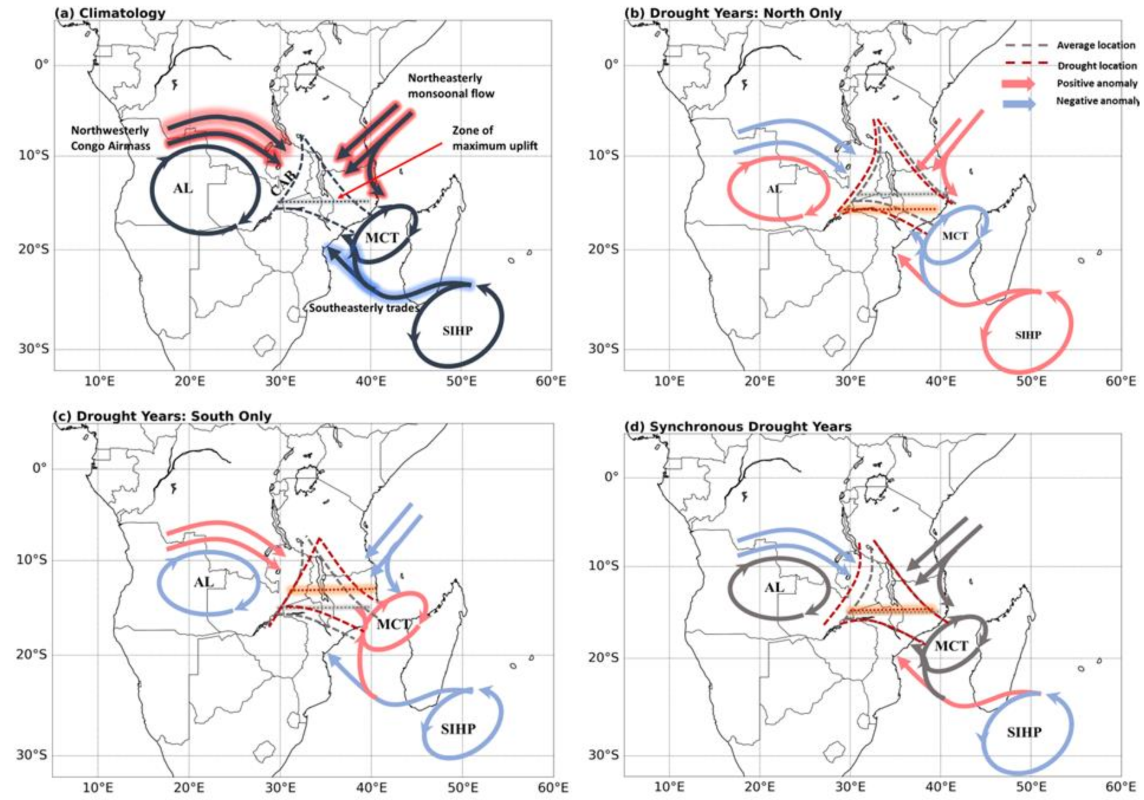

Figure 3.21 | Schematic of the interaction between the moisture advection tracks to form the convergence zone over Malawi, and regional circulation features that sustain it, (a) being during normal conditions. The regional circulation features include the Angola Low (AL), Mozambiquan Channel Trough (MCT) and the Southern Indian Ocean High Pressure System (SIHP). Red glows on tracks indicate moisture being transported from relatively warmer regions while blue glows on tracks indicate moisture being transported from relatively colder regions. (b) and (c) Illustrate the same systems in the context of a southward and northward shift of the convergence zone (as indicated by the red dashed lines which indicates the assumed positions of the air boundaries in drought years relative to their climatological locations – grey dashed lines) during droughts in the north and south respectively. (d) Illustrates the westward shift of the convergence zone in synchronous drought years (as indicated by red dashed line). Red and blue arrows in b-c indicate positive and negative anomalies respectively. Shapes are not drawn to scale.

Links between moisture flux variability and SST anomalies indicate the influence of various synoptic drivers of variability on circulation patterns associated with droughts. The examination has specifically highlighted the influence of ENSO on the southeasterly moisture flux and its role in sustaining the convergence zone over Malawi. A stronger southeasterly flow during El Niňo is linked to the northward shift of the convergence zone, and the subsequent droughts in the south. In La Nina years, the southeasterly track is weaker and withdrawn, leading to a southward shift of the convergence zone and the ensuing drier conditions in the north which coincide with wetter conditions in the south. This is a key dynamical link for the teleconnection between precipitation and ENSO, and possibly the SIOD (Hoell *et al.*, 2017; Hoell and Cheng, 2018), and the ensuing precipitation dipole between the north and south in La Nina and El Niňo years.

The extent of the shifts in the convergence zone may be extreme in some cases such that drought conditions may be experienced across the whole country during La Nina or El Niňo conditions as was the case with the El Niňo of 1994 and La Nina of 1999. This reflects the interaction of multiple factors and drivers to produce drought conditions. Among such processes is the IOD, whose influence on eastern African precipitation has been widely acknowledged (Black, 2005; Gaughan *et al.*, 2016; Blau and Ha, 2020) including its covariability with ENSO to influence intra-seasonal variability in the short rains across eastern Africa. The influence of the IOD is particularly pronounced over northern Malawi, where the ENSO signal in consistent with patterns over eastern Africa.

Synchronous droughts identified during neutral ENSO years indicate the influence of drivers other than ENSO. A withdrawn northwesterly track from the Congo underlies such events, potentially indicating a westward shift of the Congo Air Boundary and the subsequent creation of conditions less favorable for rainfall over Malawi. Westerlies associated with the northwesterly moisture track have been known to bring well-distributed rainfall across Malawi (Kumbuyo *et al.*, 2014) thus making plausible the relationship between negative northwesterly anomalies and widespread drying. McHugh and Rogers (2001) highlighted the influence of variability in the westerlies and linked it to the North Atlantic Oscillation with the indication that dry summers in southeastern Africa are associated with an anomalously high level (300 hPa) flow. Enhanced rainfall linked to intensified westerly influx from the Congo has also been highlighted by Finney *et al.* (2020) but for a much wider region and, more specifically, by Howard and Washington (2019) in relation to the CAB. Both studies indicate that precipitation around southeastern Africa is linked to variability in low-level westerlies which and, in the context of the CAB, could be considered an essential component of the teleconnection processes delivering remote signals at synoptic timescales.

Remarkably, findings from this examination indicate that there have been no synchronous droughts since 1999. The lack of such events does not necessarily imply the lack of activity in the circulation patterns that drive them. The finely balanced circulation patterns and interactions responsible for droughts in Malawi may mean that a change in one circulation aspect, when compensated for by another aspect, may not lead to the typically expected outcome, hence the relationship is not perfectly linear. The interaction of the northwesterly moisture flux track and the two easterly tracks and their links with SSTs furthers this view. The extent to which these drivers modulate each other may be key to understanding the variability in the ensuing drought events not only in terms of region of occurrence but with regards to drought attributes including duration, severity, and intensity.

The objectively determined drought climatology for Malawi sets a basis for evaluating climate model simulation of droughts. Diagnostic metrics to examine drought mechanisms also help create a further basis for evaluating mechanisms through which droughts are simulated in GCMs. Emphasis on mechanisms is essential for establishing whether droughts in models are produced for the right reasons. This is in line with the view that climate models may reliably simulate the drought climatology, albeit for the wrong reasons (Flato *et al.*, 2013). Biases in drought attributes are apparent across the models that were evaluated but there is no association with the precipitation biases inherent in these models. This can be attributed to the fact that the SPEI's parameters are configured to each model's climatology such that droughts are produced with the background aridity in each model accounted for. Calculating model SPEI with parameters from the observed timeseries could potentially produce different results. This would mimic the *relative index* approaches (e.g. Dubrovsky *et al.* (2009) – *where drought indices for one location are estimated using parameters derived from another* – but there is no basis for this in the scope of the current analysis. The association between drought frequency bias and the ratio of synchronous to regional droughts suggests that biases in drought attributes could be linked to mechanisms responsible for producing them.

Despite biases in both DJF precipitation and VIMF, the relationship between DJF precipitation variability and net total VIMF is consistently simulated in most models. Thus, like in observations, precipitation variability in GCMs is governed by variability in advected moisture. The correlation between precipitation and moisture fluxes in models is generally consistent for the northwesterly and northeasterly moisture flux tracks. Crucially, though, the correlation between the southeasterly moisture flux and precipitation is not consistent, particularly over the southern region. Variability in the southeasterly track is a plausible dynamical link of the influence of ENSO and the meridional shift of the convergence zone as the underlying mechanism for drought, particularly those that are regional. Erroneous simulation of this relationship therefore highlights a potential area of model misrepresentation of drought mechanisms which could undermine the confidence in model simulation of drought processes over Malawi.

This study has presented a detailed examination of drought process, highlighting the similarities in the drought climatology between the north and south of Malawi. However, the SPEI is area-specific and accounts for the background climatology of the area for which it is being calculated. In this view, it would be misleading to conclude that similarities in drought attributes between the two regions imply similarities in associated impacts too. Impact modelling studies reflecting on, among other things, hydrological responses and the complex social interactions that determine the place-based impacts of droughts would provide more detailed information in that regard. The examination of drivers of precipitation variability associated with drought largely focused on advected moisture. It should be acknowledged that local sources of moisture through evapotranspiration and precipitation recycling have the potential to influence variability considerably. The multiplicity of drought definitions also means that some of the conclusions may not be applicable for other forms of drought, particularly those associated with relatively longer timescales. Findings from this study set a plausible meteorological basis for diligent examination of drought processes in both observation and climate model simulations.

Chapter 4

Future Drought and Implications for Irrigation in Malawi

4.1 Overview

This chapter evaluates projected future changes in temperature and rainfall, and the associated change in drought climatology for Malawi. It further examines hydrological responses to climate variability and change across five catchments in the Lake Malawi Shire River Basin (LMSRB). It uses climate scenarios from AMMA2050, a bias-corrected archive of CMIP5 models to evaluate the impacts of climate change on hydrometeorological processes essential for irrigation water demand and supply across the five catchments. Hydrological simulations were performed in the Soil and Water Assessment Tool (SWAT), calibrated, and validated with observed streamflow across all five basins. Upon successful setup, the model for each basin was run with bias corrected climate projections at a daily timestep to simulate hydrological responses to future climate scenarios. Aspects of streamflow were examined along with other aspects of water balance that influence streamflow and water utilization by field crops, taking maize as the representative. Irrigation water demand was determined from the balance between crop water requirements and effective precipitation.

Results from this chapter indicate that, overall, climate models consistently project a significant increase in temperature over the course of the twenty-first century while there is considerable uncertainty in projected changes in precipitation across the country. Significant drying in the south is simulated with relatively pronounced clarity, creating a north-south contrast owing to the hint of wetting – albeit less pronounced – in the north of the country close to Tanzania. Drought frequency, severity, and intensity are all projected to increase across the country. Streamflow across all five river basins is highly sensitive to these changes.

Irrigation water demand generally increases due to increasing crop water requirements and decreasing effective precipitation. Even for wetter models, the hint of projected wetness is not sufficient to offset the projected increase in climatic and hydrological aspects that influence increasing irrigation water demand. The rate of change in irrigation water demand is variable, nonetheless, reflecting variability in projected changes in precipitation across the river basins, coupled with basin characteristic, particularly those responsible for soil moisture retention. Episodic spikes in irrigation water demand tend to coincide with droughts – *meteorological and hydrological* – underscoring the need for careful planning of irrigation in a changing climate.

4.2 Introduction

It is widely anticipated that the risk of drought under global warming will increase across many regions of the world (Dai, 2013; Liu *et al.*, 2018; Spinoni *et al.*, 2020; Vicente-Serrano *et al.*, 2020). Evidence from observations indicates increasing background aridity in many land areas since 1950 (Dai, 2013), and increasing frequency and severity of droughts across southern and eastern Africa (Dai, 2013; Masih *et al.*, 2014; Spinoni *et al.*, 2014). However, examining drought processes in a changing climate is not without challenges, with conceptual and practical limitations undermining the confidence in information on future drought risk.

The complexity of droughts is magnified by interactions between different components of the hydrological cycle where water deficits may occur simultaneously or sequentially and, in some instance, deficits in one component e.g., precipitation, may coincide with surpluses in another, e.g., soil moisture. These interactions underpin the multiplicity of drought definitions and are principal to the methodological approaches for forecasting droughts across different hydrological components (Van Loon, 2015; Hao *et al.*, 2018). The impacts of droughts on different sectors reflect the category of drought while the pattern of distribution of water deficits is key for the adaptation to droughts.

Consequently, examining the impacts of droughts and the relevant interventions to address them requires a solid understanding of how the risk of drought propagates across the different components of the hydrological cycle. As meteorological droughts are the primary drought signal carrier, drought studies have disproportionately focused on meteorological droughts over other categories of drought. Methodological challenges associated with complex models that aid examination of agricultural and hydrological droughts impede efforts for development of a complete picture of drought risk focusing on initiation all through to impacts. Continued development in computational capabilities to conduct dynamical drought predictions presents an opportunity for complete understanding of physical processes that influence drought propagation at scales relevant for water resources planning. Moreover, continued development of climate models presents an opportunity for examining agricultural and hydrological droughts at various timescales. Despite these gains, knowledge of agricultural and hydrological drought risk remains incomplete despite such information being key to the climate resilience agenda.

In Malawi, historical drought impacts, and the prospect of increasing drought risk, have been central to the resilience agenda in the agriculture sector. Of the many interventions, irrigation is widely perceived as a way out of climate-related food production challenges. Locally, a 200% increase in land under irrigation between 2005 and 2015 (Government of Malawi, 2015b) highlights the widely shared appetite for irrigation development through government and donor-led interventions. Farmer-led interventions through small technologies applied at relatively at smaller scales have also grown in recent years (Kamwamba-Mtethiwa *et al.*, 2021). The trend in irrigation development is expected to increase, propelled by continued emphasis on irrigation in agricultural policies and economic development plans including the Vision 2063, Malawi government's blueprint for achieving long-term development. To this effect, the government of Malawi developed the Irrigation Masterplan and Investment Framework the aim of which is to guide the development of land under irrigation from 104,000 hectares in 2015 to 220,000 hectares in 2035. This is in line with what is provided for in the National Water Resources Master Plan jointly developed by the Malawi government and the Japanese International Cooperation Agency (JICA) in 2014. Irrigation development priorities also feature prominently in most sectoral policies.

Emphasis in most of the investments and policies aligned to irrigation development is put on using irrigation to counter impacts of drought on agriculture with the view that water resources would be sufficient to achieve this goal. However, the adequacy with which climate risks for irrigation development are considered is questionable. Climate change impacts on irrigation have been investigated at global and regional scales (Döll, 2002; Wada *et al.*, 2013; Nhemachena *et al.*, 2020). Recent studies have highlighted climate risks in relation to water resources with implications for development providing high-level evaluation of climate risks for water and irrigation development which could be complemented with detailed understanding of the physical processes that underpin these risks.

From global and regional studies, impacts of climate change on irrigation development are two dimensional: (1) impacts on irrigation water demand; (2) impacts on water resources to meet the demand for irrigation. The emphasis in most studies has been on the changes in the mean state, with a limited focus on variability and episodic spikes in irrigation water demand or low water supply linked to droughts. Earlier attempts to examine irrigation water requirements and the corresponding runoff to meet such requirements in typical dry years had demonstrated the value of understanding implications of drought on irrigation at the global level (Döll *et al.*, 1999). Understanding such processes and interactions is essential for water and irrigation planning in relation to the risk of drought.

The complexity of hydrological processes demands a good understanding of the locally relevant processes that could affect irrigation water demand and supply at the basin scale in a changing climate. It is against this backdrop that the aim of this Chapter is to evaluate future drought characteristics and perform hydrological simulations to examine implications of different future climate scenarios and associated hydrological responses for irrigation across different river basins in Malawi. This was achieved through the following specific objectives:

1. Examine changes in meteorological and hydrological droughts under different future climate scenarios.
2. Examine the impact of climate model-based future climate projections on irrigation water demand in the Lake Malawi-Shire River Basin.
3. Examine streamflow reliability to meet irrigation water demand in typical dry years in the Lake Malawi-Shire River Basin under different future climate projections.

4.3 Materials and methods

4.3.1 Description of study area

The study was conducted in the Lake Malawi Shire River Basin (LMSRB), a subbasin of the Zambezi River Basin in southeast Africa. The LMSRB is located at the southern tip of the Great Rift Valley and predominantly located in Malawi with significant flows from Tanzania in the north (Kumambala and Ervine, 2010). Specific focus was placed on five sub-catchments of the LMSRB (Figure 4.1) on the Malawian side, namely Songwe, North Rukuru, Lufira, Bua and Upper Shire. The five sub-catchments were purposely selected to capture variable patterns in climate and other physiographic characteristics. Key to this criterion is the location of the subbasins with respect to regions of varying precipitation responses to ENSO which, for Malawi, is characterized by a north-south precipitation dipole that gives Malawi its unique drought climatology (Likoya *et al.*, 2023) as shown in Chapter 3.

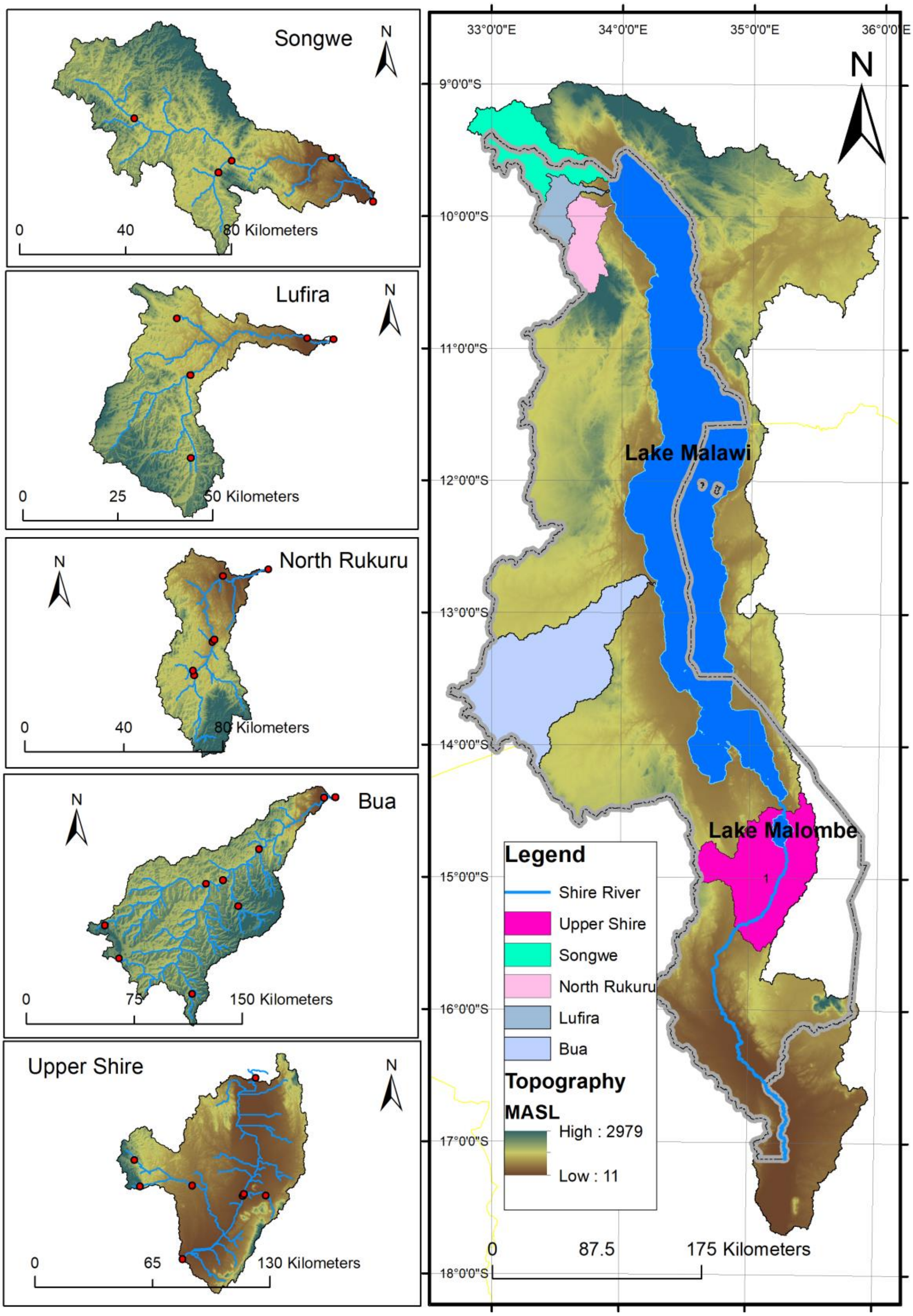

Figure 4.1 | Map of the Lake Malawi-Shire River Basin showing the five subbasins of primary interest to the analysis namely Songwe, Lufira, North Rukuru, Bua, and Upper Shire. Points in basin specific maps indicate monitoring points set in the SWAT model for each basin.

Table 4.1 shows a summary of the basin characteristics for the five river basins and the degree of similarity/variation between various physiographic characteristics including topography, land use (based on SWAT land use classes), and soil characteristics (based on SWAT soil classes). Detailed maps for each of the basins are presented in Annex 1. Land use and soil classes are derived from spatial datasets for land use and soil characteristics described in subsequent sections. Of the fiver river basins under focus Bua (10,651 Km2) river basin is the largest by area, followed by the Upper Shire (7,327). It should be noted that the Shire River Basin is, overall, the largest but the focus in this study is limited to the upper part of the basin. Lufira river basin is the smallest of the five. Dominant land use classes include agriculture and natural vegetation classified as either Savana type of ecosystems or forests of variable densities. Forested areas are mostly present in the northern river basins, likely due to the mountainous landscapes to the west of the three basins.

Table 4.1 | River basin characteristics for the five river basins under study.

	Songwe	Lufira	North Rukuru	Bua	Upper Shire
Area (km2)	4139	1453	2,075	10,643	7,327
Alt. range (masl)	476-2434	481-2338	482-2612	472-1755	454-2077
Mean Temp (C) (1981 - 2010)	19.83	21.57	21.38	21.95	22.96
Mean Precipitation (mm/yr) (1981 – 2010)	912.24	943.34	993.33	959.73	950.44
Dominant Land Use (Type: %)	AGRL:38 SAVA:42 FOEB: 12	AGRL:41 FODB:38 SAVA:17	AGRL:39 SAVA:17 FODB:33	AGRL:31 SAVA:62	AGRL:37 SAVA:53

[Key – AGRL: Agricultural land; SAVA: Savana grasslands; FODB: Deciduous broadleaf forests; FOEB: Evergreen broadleaf forest].

4.3.1.1 Agricultural activity and irrigation

A wide range of crops are grown across the five different basins. Seasonal crops such as maize, rice, and legumes are the most dominant. Data on areas under irrigation are scanty but the extent to which irrigation is practiced varies across the five basins as does the potentially irrigable area. Table 4.2 shows the estimated potentially irrigable area for each basin as reported in the National Irrigation Master Plan (Government of Malawi, 2015b) indicate the scope for irrigation development. Irrigation farming is principally done in the dry season as the wet season typically receives enough rainfall to satisfy the crop water requirements of the various crops without requiring supplementary additions. In recent years, however, irrigation systems have been modified to allow for supplemental irrigation in the summer during instances of dry spells. Various crops are grown under irrigation, with rice and maize being the most dominant cereals as they form the Malawian staple.

Table 4.2 | Potentially irrigable area for the five river basins and the proportion of the potentially irrigable area to the size of the basin as reported in the National Irrigation Masterplan (2015). Songwe and Lufira River Basins are considered as one Water Resource Area (WRA) for administrative purposes as such data on irrigation are not differentiated between the two basins. Values for the Shire River basin are for the whole basin rather than the Upper Shire River basin which was the focus of the current study.

Basin	Potentially Irrigable Area (km^2)	% of basin area
Songwe & Lufira	1073	29%
North Rukuru	208	10%
Bua	7,529	71%
Shire	7,611	40%

4.3.2 Data

A range of datasets were used including (a) bias-corrected GCM outputs for analysis of projected changes in temperature, precipitation, and drought climatology; (b) a wide range biophysical data to aid the hydrological model setup after which the hydrological models were run with the bias-corrected GCM outputs in (a). A detailed description of the various datasets – and pre-processing procedures where applicable – is given below.

4.3.2.1 Climate model data

Examination of changes in drought and relevant climatic variables were performed based on the African Monsoon Multidisciplinary Analysis (AMMA) bias corrected dataset (Famien *et al.*, 2018). The AMMA2050 is a dataset of bias corrected CMIP5 model outputs for precipitation, mean air temperature, minimum and maximum air temperature, solar radiation, and wind speed. The dataset covers the domain 20^o W – 55^o E/40^o S – 40^o N and is available at a daily timestep, at 0.5^o x 0.5^o horizontal grid resolution. Famien *et al.* (2018) produced the AMMA2050 bias-corrected dataset by applying the cumulative distribution function transform (CFD-t) onto CMIP5 data using WFDEI (Watch Reference Data applied to Era Interim) reference data (Weedon *et al.*, 2014) which is an improved version of the Watch Forcing Data (WFD) (Weedon *et al.*, 2011). WFDEI improves on the 3D-var data assimilation systems in ERA-40 by using the 4D-var data assimilation system with 6-hour windows in ERA-Interim. The suite of satellites, atmospheric soundings, network of surface observations is also relatively more extensive in the new framework.

For this evaluation, the SPEI is computed from precipitation and temperature from 18 bias-corrected models (Table 4.3) for RCP8.5 and RCP4.5. Historical simulations (raw outputs) from the 18 GCMs were the basis of the evaluation in Chapter 3.

Table 4.3 | List of AMMA2050 models used in the analysis of projected changes in climate and outputs of which were used to drive the SWAT models. Also included are the models' respective modelling centres and original resolutions.

Modelling Centre/Group	Model	Resolution (Lat x Lon x Lev)
Commonwealth Scientific and Industrial Research Organization (CSIRO), and Bureau of Meteorology (BOM), Australia	ACCESS1-0	1.25º ×1.875º ×38
	ACCESS1-3	
Beijing Climate Centre, China Meteorological Administration	BCC-CSM-1	1.875º ×1.875º ×16
	BCC-CSM-1-1-M	
College of Global Change and Earth System Science, Beijing Normal University	BNU-ESM	2.81º ×2.81º ×26
Centro-Euro Miditerraneo per I Cambiamenti Climatic	CMCC-CESM	3.443º ×3.75º ×39
Centre Nationale de Recherches Meteorologiques/ Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	CNRM-CM5	1.4º ×1.4º ×31
NOAA Global Fluid Dynamics Lab	GFDL-CM3	2º ×2.5º ×48
	GFDL-ESM2G	2º ×2.5º ×24
	GFDL-ESM2M	2º ×2.5º ×24
Met Office Hadley Centre	HadGEM2-CC	1.25º ×1.875º ×38
	HadGEM2-ES	1.25º ×1.875º ×38
Institute for Numerical Mathematics	INMCM4	1.5º ×2º ×21
Institut Pierre-Simon Laplace	IPSL-CM5A-MR	1.25º ×2.5º ×39
	IPSL-CM5B-LR	1.9º ×3.75º ×39
Max-Planck-Institut fur Meteorologie (Max-Planck Institute for Meteorology)	MPI-ESM-LR	1.8653º ×1.875º ×47
	MPI-ESM-MR	1.8653º ×1.875º ×95
Norwegian Climate Centre	NorESM1-M	1.9º ×2.5º ×26

Prior to the computation of the SPEI, AMMA2050 and raw CMIP5 outputs were evaluated against CRU to determine the value added from the bias-correction. Figure 4.2 shows the biases in simulated rainfall for the raw CMIP5 outputs and the AMMA2050 bias-corrected versions of the same model outputs. Precipitation was used as the basis given the pronounced inconsistencies in model simulation of precipitation across Malawi (Likoya *et al.*, 2023) (as shown in Chapter 3) and the southern and eastern African regions in general (Lazenby *et al.*, 2016). It is apparent that bias correction eradicates negative biases across drier models but there are significant differences in the resulting rate of bias for AMMA2050 between the north and south of Malawi.

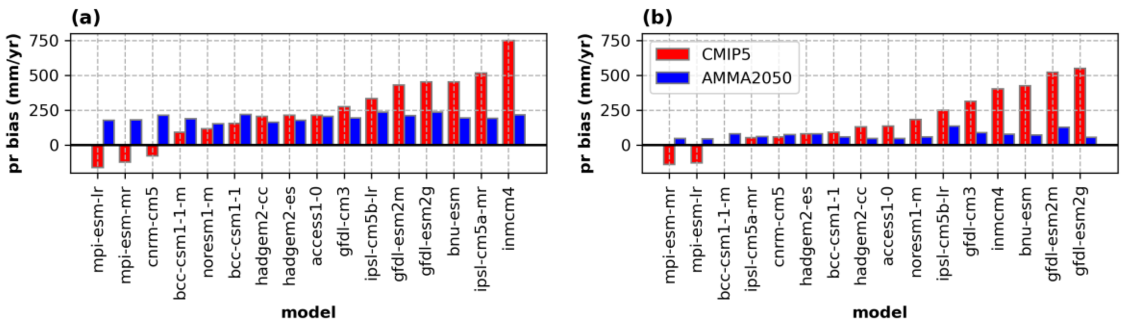

Figure 4.2 | Mean annual precipitation biases in CMIP5 models and their corresponding AMMA2050 bias corrected outputs for the north (a) and south (b) of Malawi for the period 1976 -2005. Biases are evaluated with reference to CRU precipitation over the same period.

The magnitude of bias is significantly reduced across all models in the south but considerable biases remain in the north (Figure 4.2a). Such inconsistencies show that bias-correction is by no means error-free. The extent of the value of bias corrections is limited by a wide range of factors including the method used for the bias correction, as well as the reference data used (Famien *et al.*, 2018). In this context, though, the AMMA2050 archive presented a more reliable dataset for impacts assessments.

4.3.2.1 Input data for hydrological model setup

Multiple spatial datasets are required to set-up and parameterize the hydrological models for each basin in the SWAT modelling system. The datasets used for this evaluation are listed and described below, in levels corresponding to different stages for which they were applied in the model set up process.

Topography

Elevation data was acquired from NASA's Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM), supplied by the United State Geological Survey (USGS). The void filled SRTM NASA Version 3, also known as SRTM Plus, was used in this study. In SRTM Plus, most voids are filled with elevation data from ASTER Global Digital Elevation Model Version 2 (GDEM 2) using interpolation algorithms. Additional void-filling of small areas is done using the GMTED2010 elevation model compiled by the USGS. For this version, data are sampled at 1 arc-second, which is approximately 30 meters, thus providing data at the full resolution of the original measurements.

Land use data

Basin hydrological processes are significantly influenced by land use and land cover. Essentially, the SWAT modelling system accounts for differences in land use and lover cover within the basin and its subdivisions such that land use forms the basic level of discretization of the subbasins into the different HRUs. Land use/cover was characterized based on the USGS Global Land Cover Characterization (GLCC) Africa version 2.0 dataset. The Africa database is one portion of a Global Land Cover Characteristics database that was developed on a continent-by-continent basis. All the continents in the global database have a nominal resolution of 1 km and are based on 1-km Advanced Very High-Resolution Radiometer (AVHRR) data covering the period April 1992 to March 1993. Each continental database has unique features based on the key geographical aspects of the specific continent.

Derived thematic maps produced through the aggregation of seasonal land cover regions are included in each continental database making the preparation of maps and associated lookup tables usable with SWAT relatively straightforward. The GLCC dataset has been prepared for use with the SWAT modelling system such that the land use classes are organized to match the land use classes interpretable by SWAT. In this view, the GLCC is used without modification or reclassification, a key requirement when using other datasets requiring reclassification and organization of the lookup table to match the classes specified in SWAT.

Soil data

The soil data used by SWAT can be divided into two groups, physical characteristics and chemical characteristics (Neitsch *et al.,* 2011). The physical properties of the soil are required as they govern the movement of water and air through the profile and have a major impact on the water exchanges within the modelling unit. Physical characteristics of the soil across the five basins were defined based on the Digital Soil Map of the World (DSMW) by the Food and Agriculture Organization of the United Nations (Sanchez *et al.*, 2009). The DSMW has a total of 4931 mapping units that consist of different soil associations. The soil associations are mixtures of different soil classifications based on the FAO-UNESCO (1974) legend. Each legend entry is a soil unit or an association of soil units occurring within the limits of a mappable physiographic entity. When more than one soil unit occurs within a map unit, the map unit is composed of the dominant soil and of associated soils with the latter covering at least 20 percent of the area within the map unit; important soils covering less than 20 percent of the area are added as inclusions. A total of 106 soils, broadly categorized into 26 soil groups, are used in the DSMW.

A detailed description of the soil types is given in the legend note for the very first versions of the soil map (FAO-UNESCO, 1974) and summarized in the readme file accompanying the DSMW. For each association written out in the map unit, the textural class (*coarse textured, medium textured, fine textured*) of the dominant soil and its slope class (*level to gently undulating, rolling to hilly, steeply dissected to mountainous*) are given. Where indurated layers or hard rock occur at shallow depth, phases are used to indicate stoniness, salinity, or alkalinity. The phases that are recognized on the soil map include: *stony, lithic, petric, petrocalcic, petrogypsic, petroferric, phreatic, fragipan, duripan, saline, soldic,* and *cerrado*.

Weather data

The SWAT model requires six weather variables namely precipitation, minimum and maximum temperature, solar radiation, relative humidity, and wind speed. Solar radiation, relative humidity, and wind speed are required only when the Penman-Monteith method is being used to compute potential evapotranspiration. For this study, a combination of satellite (for rainfall) and reanalysis (for the rest of the variables) were used as quasi observations with which to perform the initial and control runs. Daily precipitation was acquired from Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) dataset (Funk *et al.*, 2015). CHIRPS is a quasi-global rainfall dataset covering latitudes 50° S - 50° N (and all longitudes) and ranging from 1981 to near-present. It incorporates 0.05^{o} resolution satellite imagery, and in-situ station data to create gridded rainfall time series.

The rest of the variables were acquired from the Climate System Forecast Reanalysis (CFSR) (Saha *et al.*, 2010) by the National Centre for Environmental Prediction (NCEP). CFSR data have been widely used for SWAT simulations as they have been made readily available for all global land areas in formats prepared specifically for SWAT. Variables include precipitation as well as relative humidity, solar radiation, wind speed, and minimum and maximum temperature for the calculation of potential evapotranspiration. Examining the data at the model setup stage however indicated that NCEP precipitation has a considerably high positive bias leading to unrealistically high runoff and streamflow which prompted the choice for CHIRPS as the basis for precipitation.

Management data

Management data were acquired from field visits to the basins of interest, and from Ministry of Agriculture through the department of Irrigation in Malawi. The field visits would be conducted mainly in line with specific objective 3 of the overall study, results of which are presented in Chapter 5. The field visits would also provide the opportunity to get insights into the husbandry practices associated with irrigation farming. Management data include the aspects of the tillage practices, crops grown under rainfed and irrigated systems as well as operations including tillage time, planting time, fertilization time, harvest time. Management aspects of irrigation include the start of the irrigation season, and aspects of the irrigation system including scheduling, irrigation technology (both field water application technology and source-to-field water transfer technologies), and water abstraction levels. These data were however not readily available in which case the examination of irrigation was restricted to the evaluation of irrigation water demand.

Hydrological Data

Observed streamflow was acquired from Malawi Government’s Department of Water Resources which maintains HyDATA – a national hydrological database containing streamflow data for all gauging stations. Streamflow data are often scanty and typically characterized by gaps and a lack of continuity, more so for this region of Africa (Mwale *et al.*, 2012). Table 4.4 provides a summary of the data for the stations that were used for this evaluation. It highlights the starting and ending date of observations for each station, as well as the completeness of the records over that period. Notably, the observations have different starting and ending points over the period of interest and this informed the choice of period for which to perform the model calibration and validation as will be explained shortly.

Table 4.4 | Summary of hydrometric stations. The coverage is determined as a percentage of number of available data points against the total length of observations for that station. For basins that have multiple gauging stations, calibration was done for the outlet station marked with (*).

Basin	Station name	Station code	Drainage area (km^2)	Start Date	End Date	Coverage
Bua	Bua at S53 Bridge *	5C1	10514.9	Jan-80	May-02	50.54
	Bua at Bua Drift	5D1	9034.0	Dec-85	Nov-98	33.24
	Bua at Mchinji	5E6	155.8	Jan-81	Oct-98	54.32
	Rusa at Kasela	5F1	2540.5	Jan-80	Oct-94	40.0
Lufira	Lufira at Ngerenge *	9A2	1436.4	Nov-80	Sep-09	86.76
	Lufira at Chilanga	9A4	783.3	Nov-80	Oct-94	44.05
	Kalenje at Chipwera	9A5	92.0	Jan-80	Oct-96	54.05
North Rukuru	North Rukuru at Mwakimeme	8A5	1860.1	Jan-80	Oct-97	55.41
Songwe	Songwe at Mwandenga*	9B7	3892.1	Sep-85	Jun-03	49.73
	Songwe at Ipenza	9B6	764.1	Nov-84	Oct-96	37.30
Upper Shire	Shire at Liwonde*	1B1	130200.0	Jan-80	Apr-10	95.14
	Shire at Matope	1P2	133700.0	Jan-80	Oct-05	50.0
	Rivirivi at Balaka	1R3	743.3	Feb-80	Aug-04	68.65

4.3.3 Evaluation of drought attributes in future climate

Chapter 3 highlighted the episodic nature of droughts in Malawi and the basis for defining a drought climatology based on the collection of events and their underlying attributes. To examine changes in drought in future climate, droughts were identified over two future 30-year time slices – mid-21st century (2041 – 2070) and end of century (2071 – 2100) – based on SPEI timeseries computed for each on the 18 bias-corrected GCMs. The computation was performed on a continuous time series of precipitation and PET extending from the historical period (1951) to the end of the 21st century (2100) for two emission scenarios – RCP4.5 and RCP8.5. PET was computed using the Thornthwaite method (Thornthwaite, 1948) given available variables.

Different methods for computing PET may lead to differences in subsequent drought identifications (Mukherjee *et al.*, 2018) but comparisons between historical SPEI timeseries based on PET computed with the Thornthwaite methods and a Penman-Monteith pre-calculated PET dataset (Harris *et al.*, 2020) indicated no notable differences between the two timeseries thus rendering the Thornthwaite method applicable in this context. Prior to the computation of the SPEI, precipitation and temperature timeseries were detrended using the Box and Jenkins method which transforms a data point (x) at time (t) into $y(t) = x(t) - x(t-1)$ (Box & Jenkins, 1970). This would help remove the trends that would lead to spurious droughts under conditions of global warming. A temporally sensible evaluation was achieved by calibrating the SPEI with the historical portion of each model's timeseries (1951 – 2005) to create a reference climate.

From each historical-future SPEI timeseries, droughts were identified and characterized based on the run theory (Yevjevich, 1967) following the same approach in Chapter 3. The frequency, duration, severity, and intensity of droughts for each time slice were determined based on the approach outlined in Chapter 3 (See Section 3.3.3). Changes in droughts and drought attributes were then examined relative to drought characteristics for droughts identified over a 30-year historical reference period, 1976-2005 (i.e., the final 30-year window of historical simulations in CMIP5). Relationships between meteorological and hydrological droughts were determined based on the association between meteorological drought variables and hydrological drought variables derived from hydrological simulations described in subsequent sections.

4.3.4 Hydrological simulations to examine the implications of drought for irrigation.

Hydrological simulations were performed in Soil and Water Assessment Tool (SWAT) to examine basin responses to observed climate variability and projected changes in the climate, using the AMMA2050 bias-corrected model outputs as the basis for future climate scenarios. Simulations were performed for each of the five river basins (subbasins of the LMSRB) described in 4.3.1 to examine the extent to which physiographic characteristics and climate variability and change interact to influence processes essential for irrigation water demand and supply of water from streamflow. The interaction between meteorological and hydrological drought was also examined with the view of investigating climate risks for irrigation, putting emphasis on changes in mean state and the episodes of pronounced irrigation water demand during incidences of droughts. The approach to performing the simulations and hydrological analyses is described in more detail below.

4.3.4.1 SWAT model setup

Details of the SWAT model are provided in Chapter 2. For this examination, SWAT was set up separately for each of the five basins. That is, despite the interconnectedness of the system, each of the five subbasins of the LMSRB that are considered for this evaluation is modelled separately and independent of processes in another basin. From the DEM, basins are delineated based on a specified outlet and the topographic characteristics with respect to the outlet. The basin is further subdivided into sub-catchments which are discretized into Hydrologic Response Units (HRU), the smallest unit representing homogeneous land use, soil, and slope characteristics. The HRU is the basic unit of computation, but outputs are integrated appropriately to reflect processes representative of the whole basin or portion of the basin that are characterized by a particular common feature such as land use classes corresponding to agriculture activities.

Two unique features of the Upper Shire River basin, namely Lake Malawi and Kamuzu Barrage (Figure A1.13 in Annex 1) – a barrage located downstream of the lake system which is used to regulate downstream flows – demand careful consideration and assumptions for setting up the model for this basin. The connectedness of the basin and Lake Malawi means that the lake provides a regular supply of flows into the basin ultimately leading to pronounced discharge observations even during the dry season. For this setup, the Lake Malawi was defined as a draining watershed with daily streamflow observations upstream of the Upper Shire River basin used to define the draining watershed contributions over the historical period.

Complementing this setup is the assumption governing the influence of the barrage which acts as a dam to create a reservoir stretching from the lake outlet to the barrage. Bhave *et al.* (2020) identified the complexity posed by the barrage and provided a model setup framework which was used as a basis for setting up the SWAT model for the Upper Shire River basin in the current study. Key to this set up is the definition of the water body between the Lake exit and Kamuzu barrage, in the ‘middle’ of which is Lake Malombe (Msiska *et al.*, 2021), as a reservoir with the barrage as the dam. Historical and future barrage operational rules used in Bhave *et al.* (2020) are also applied here and summarized in Table 4.5. These values are used as the basis for the reservoir outflow ranges used to define the reservoir in SWAT.

Table 4.5 | Kamuzu Barrage operational characteristics over different periods (Bhave *et al.*, 2020) **specifically showing three periods when flow was not restricted (1960 – 1993), when flow was restricted to 200 cumecs (1994 – 2003), and when flow was/is restricted to 300 cumecs (2003 – 2050). For this assessment, the 300 cumecs threshold is maintained to the end of twenty-first century. Reservoir outflow limits in SWAT are set based on these values.**

Period	**Maximum hydraulic flow characteristics**
1960 - 1993	Monthly maximum hydraulic flow ranges from 575 – 535 cumecs
1994 -2003	Flow is restricted to 200 cumecs
2003 – 2050	Flow is restricted to 300 cumecs

Discharge observations from a gauging station just downstream of the barrage, and a secondary station for one of the sub-catchments were used for calibration and validation of SWAT in the Upper Shire River basin, the general procedure for which is explained in subsequent sections. Upon successful calibration, the model was set up again, this time based on parameters from the calibrated model but with contributions from the draining watershed set to 0 and with no reservoir defined. This was done to eliminate the Lake Malawi inflows (values for which would not be available for the future scenarios) as well as the human controls as a result of the barrage operations. In so doing, the analysis is based on the assumption that the simulated streamflow is a reflection of locally generated flows.

4.3.4.2 Experimental design

Figure 4.3 illustrates the conceptual framework for the experimental setup and how the SWAT model connects with the observed datasets and climate model simulations to generate future scenarios for irrigation water demand and other hydrological characteristics. For each basin, the SWAT model was set up and forced with observed and reanalysis meteorological variables namely precipitation, temperature, wind, and solar radiation. Streamflow outputs from initial runs were compared with observed streamflow after which relevant model parameters were adjusted to improve the simulation. Upon satisfactory simulation of observed streamflow – the basic hydrological variable for evaluating model performance – the model was then forced with bias-corrected outputs of global climate models for the period 1950 – 2100 where the first 20 years were used as spin-up period. Outputs from each simulation were used to examine irrigation water demand and irrigation water supply associated with each climate scenario. Outputs of hydrological simulations with observed climate date were used as synthetic data (or quasi-observations) which permitted characterization of hydrological processes for the present-day period in the absence of observations.

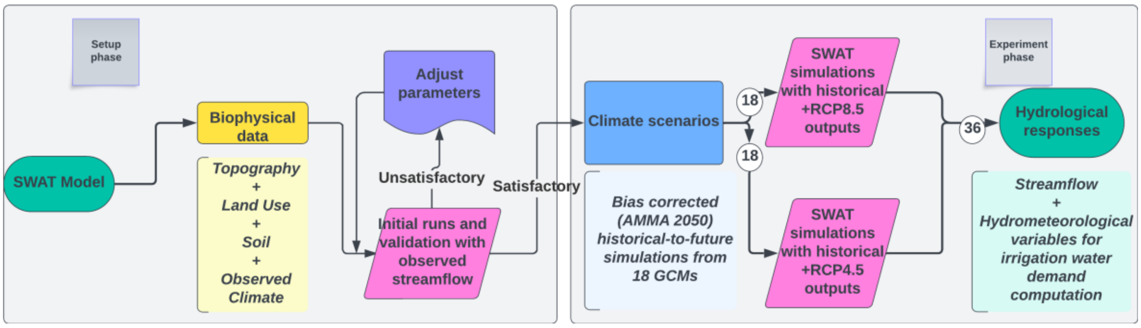

Figure 4.3 | Experimental framework depicting the connection between the SWAT model and outputs of bias corrected GCMs as well as the variables underlying relationships between drought, irrigation water demand, and supply of water to meet the same.

4.3.5 Calibration and validation

The initial simulation provides an overview of the model performance and, based on the differences between the simulated and observed variable of interest – typically streamflow – provides a basis for configuring specific parameters to produce satisfactory simulation results. For this evaluation, calibration was done manually by adjusting each relevant parameter to a level yielding a satisfactory simulation. Parameter adjustment was done while ensuring that the parameter values are within the plausible range (as stipulated in the SWAT user manual) and to levels that make physical sense. A selected range of parameters for the model setup in each of the five river basins is given in Annex 2.

The split-sample approach (Biondi *et al.*, 2012) was used to calibrate and validate the SWAT model in each basin. This involved running the initial simulation over a period of time for which relatively more continuous data were available such that the first half of the period was used for calibration, and the other half for validation. Locating such periods implies that the calibration and validation was done for different periods for different basins given the differences in the data availability for any given period as has been previously highlighted in Table 4.4. However, emphasis was put on ensuring that the calibration years for all the basins were not too far apart.

The satisfactory simulation was examined through visual inspection of the hydrograph and distribution of precipitation through the different components of the water balance as per equation 2.1, as well as through evaluation of a range of performance metrics. The visual inspection of the timeseries provides a sound qualitative evaluation approach, and a basic step in model validation of temporal dynamics through the graphic comparison of simulated and observed timeseries (Moriasi *et al.*, 2007). Figure 4.4 shows the simulated and observed streamflow for each of the five basins. Overall, the model reasonably simulates streamflow with a satisfactory level of consistency with observed streamflow. The impact of controls imposed on the Upper Shire River basin (as highlighted in section) to mimic real world regulations by Lake Malombe and the barrage is also captured with consistency (Figure 4.4e).

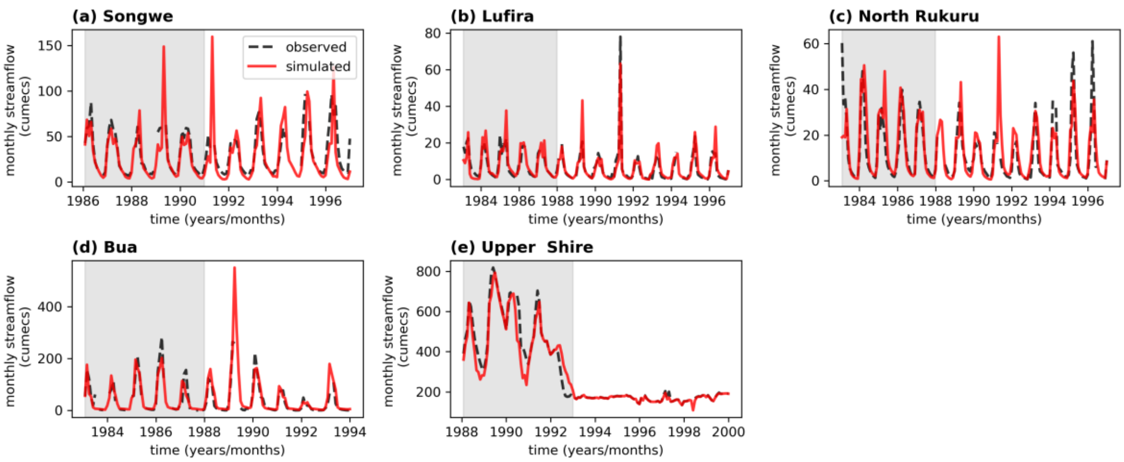

Figure 4.4 | Simulated and observed streamflow at the most down-stream station for each of the five basins as follows: (a) Songwe at Mwandenga (9B7); (b) Lufira at Ngerenge (9A2); (c) North Rukuru at Mwakimeme (8A5); (d) Bua at S53 Bridge (5C1); (e) Shire River @ Liwonde (1B1). For each plot, the shaded area indicates the calibration period for the corresponding river basin.

SWAT model is able to simulate all the peaks and low flows, consistent with observations across all the basins. While this is the case, apparent observational gaps during periods with very high simulated flows make the comparison less straightforward. The majority of such peaks are characterised by missing observations, making the comparison between observed and simulated streamflow relatively difficult. Pronounced observed peaks may entail that the corresponding rivers may have experienced floods in such years, leading to overtopping or damage of observation equipment. Anomalously high rainfall during such years reinforces the validity of this assumption.

4.3.5.1 Model evaluation with performance metrics

Performance metrics are generally grounded on objective functions based on the simulation errors identified by mathematical associations between the simulated and observed variables (Biondi *et al.*, 2012). A wide range of performance indices exists, each with a different diagnostic power. Some metrics, such as the Akaike Information Criterion and Bayesian Information Criterion among others, are governed by a statistical foundation while others are based on principles for evaluating the model fit (Moriasi *et al.*, 2007; Biondi *et al.*, 2012). A few goodness-of-fit metrics are based on the regression operations between simulated and observed data. These include the coefficient of determination (R^2), the index of agreement, and the Nash-Sutcliffe coefficient of efficiency (NSE).

The NSE is by far the most utilized index in evaluating hydrological model performance. For this evaluation, three performance metrics were used on top of the graphical approach based on the visual inspection of simulated and observed streamflow hydrographs. The three metrics include the Root Mean Square Error (RMSE), the Nash-Sutcliffe coefficient test (NSE), and the Kling-Gupta Efficiency (KGE) index as shown in equations 4.1, 4.2, and 4.3 respectively.

$$RMSE = \left[\frac{1}{N}\sum_{t=1}^{N} |y_{s,t} - y_{o,t}|^2\right]^{1/2} \ldots\ldots\ldots\ldots\ldots\ldots \textit{(equation 4.1)}$$

$$NSE = 1 - \frac{\sum_{t=1}^{N}(y_{s,t} - y_{o,t})^2}{\sum_{t=1}^{N}(y_{o,t} - \overline{y_o})^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots. \textit{(Equation 4.2)}$$

The Kling-Gupta Efficiency is a relatively new metric whose use in hydrological applications has grown in recent years. It was proposed as a modification of the NSE. Essentially, the NSE tests the model's capability to 'reproduce' the mean and variance of the discharge and the coefficient of the correlation between the simulated and observed discharge (Gupta *et al.*, 2009; Biondi *et al.*, 2012). In a detailed examination of the NSE leading up to development of the KGE, Gupta et al (2009) note that the extent of the weight associated with each of the three statistics is based on the magnitude of the observed data, but generally concentrated around the correlation. Thus, to improve on this, the KGE is expressed as an explicit function of the three statistics. The KGE is given by the equation 4.3 below.

$$KGE = 1 - \sqrt{(r-1)^2 + (\alpha - 1)^2 + (\beta - 1)^2} \ldots\ldots\ldots\ldots\ldots\ldots \textit{(Equation 4.3)}$$

Table 4.6 shows the values corresponding to each evaluation metric for the five river basins. All three metrics of model evaluation indicate satisfactory or better model performance across all five river basins (Moriasi *et al.*, 2007). Best performance ratings are noted for basins with better coverage of streamflow observations (i.e., Bua and Upper Shire River basins). Issues with missing streamflow observations apparent in most of the basins were resolved by removing days with missing data in the records prior to the computation of the evaluation metric. While interpolation provides another statistically plausible technique for handling missing data, long stretches of missing data distorted observations and compromised the confidence of the comparison between observed and simulated streamflow.

Table 4.6 | Model performance for each of the five basins based on three performance metrics (NSE, RMSE, and KGE) for the timeseries covering both the calibration and validation periods.

Basin	NSE	RMSE	KGE
Songwe	0.56 (Satisfactory)	19.19	0.64
Lufira	0.78 (Very Good)	3.93	0.89
North Rukuru	0.56 (Satisfactory)	8.52	0.77
Bua	0.6 (Satisfactory)	39.15	0.73
Upper Shire	0.93 (Very Good)	46.14	0.92

4.3.6 Water balance components and streamflow characteristics

River basin scale processes were examined to gain an insight into the water balance components and hydrometeorological characteristics and interactions of each basin. An evaluation of key processes was done based on model outputs from simulations performed with observed and reanalysis meteorological data. Such runs provided synthetic data that were essential for examining essential processes in the absence of actual observations for all water balance variables. Processes examined include soil moisture storage, surface runoff, groundwater recharges, evapotranspiration, lateral flow, and return flow. This also aided the examination of water yield and resulting streamflow contributions from surface runoff and baseflow. SWAT treats baseflow as the combination lateral flow and groundwater (shallow aquifer) return flow. For each variable, daily outputs were integrated to monthly values to examine seasonal and annual patterns and long-term patterns for some variables.

Streamflow characteristics were examined to identify seasonality of streamflow and associated relationships with other hydrometeorological variables. Low flow assessments were a key part of the analysis of streamflow responses to climate variability and change. Low flow thresholds may vary from one authority to the other but so often flows that are exceeded 347 days of the year (or with an exceedance probability of 95%) is taken as the reference (Hingray *et al.*, 2014). The National Irrigation Masterplan of 2015 – 2035 defines thresholds for the streamflow reliability referring to 80% (Q80) and 90% (Q90), with the former used as the basis for defining reliable streamflow for irrigation development given current climatic conditions. 80% and 90% reliable streamflow imply discharge that is reached or exceeded 292 and 329 days a year. Representative Q90 flows were identified for each of the five basins after which frequency analyses were performed to examine the extent to which streamflow corresponding to Q90 flows in the historical and future climates differed in each basin. This would determine the extent to which streamflow reliability would change under different climate scenarios.

4.3.7 Computation of irrigation water demand

With the right amount of data, the SWAT model can simulate irrigation processes for various crops through routines that automatically trigger irrigation computation when water stress is detected (Neitsch *et al.*, 2011). However, data constraints limited the extent to which this could be reliably achieved as there was no reliable basis for evaluating the performance of the SWAT model in simulating irrigation across the five basins. An alternative approach was to use the simulated hydrometeorological components to compute irrigation water demand based on the FAO method (Brouwer and Heibloem, 1986) for computing irrigation water demand based on principles of crop water requirements and effective rainfall which will be described shortly. Noting similar circumstances, Akoko *et al.* (2020) implemented a similar integrated approach in the context of Kenya where they linked SWAT with the FAO-Cropwat model to examine impacts of climate change on irrigation in a data-scarce catchment.

The computation of irrigation water demand is principally governed by the concept of crop water requirements and effective rainfall. The crop water requirement is the depth of water required to meet the water consumed through evapotranspiration. The crop water requirement of a given crop is determined with the underlying assumptions that the crop is growing disease-free, growing in a large field with no restricting soil conditions including soil water and fertility, and achieving full production potential under the given growing conditions. The crop water requirement of any given crop varies with the growing stage hence the total crop water requirement per season is determined as the sum of daily crop water requirements for that crop over its growing period. The crop water requirement of a given plant is given by equation 4.4 below.

$$ET_{crop} = K_c - ET_o \quad \text{……………………………………………………(4.4)}$$

Where ET_{crop} is the crop evaporation or crop water need in millimeters per unit time, ET_o is the reference crop evapotranspiration in millimeters per unit time and K_c is the crop coefficient (unitless). The reference crop evapotranspiration is used as the basis for calculating the evapotranspiration of the actual crop. It is typically based on grass, in which case it is defined as the rate of evapotranspiration from a large area, covered by green grass, 8 to 15 cm tall, which grows actively, completely shades the ground and which is not short of water. The crop coefficient determines the relationship between the reference crop and the actual crop. It is dependent on the crop type, stage of growth and type of climate. The crop coefficients for each stage of the growing season and the duration corresponding to that particular stage are summarized in Figure 4.5 for a maize crop with a growing season of 125 days.

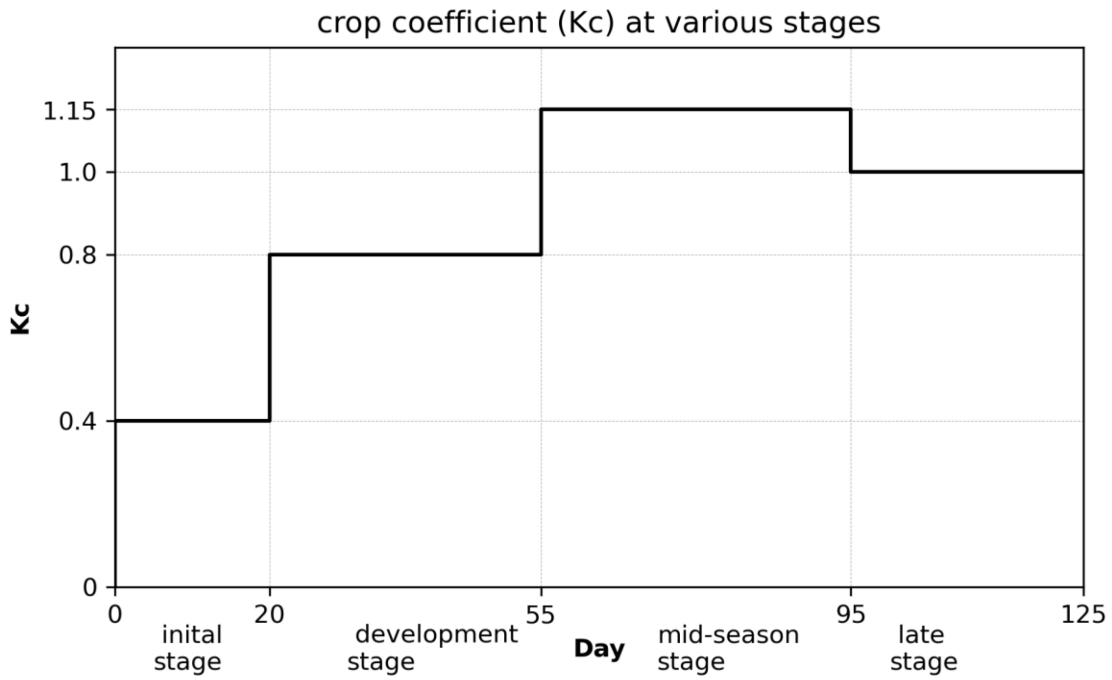

Figure 4.5 | Crop coefficient (Kc) values for maize at various crop stages from the initial stage to the late stage. This is based on the assumption that the crop has a cycle of 125 days.

Crop water requirements can naturally be satisfied – independently or in concert – by rainfall, soil-water storage, and groundwater contribution. The irrigation water requirement is the net depth of water that is required to be artificially applied to the crop to satisfy its crop water requirement in the instance where the natural sources of water are insufficient. Irrigation water demand is then computed as the difference between the crop water requirement and effective rainfall. To compute effective rainfall, runoff, evaporation, and deep percolation are subtracted from the total precipitation which gives the fraction of the rainfall that is retained in the soil root zone and remains available to plants. Mathematically,

$$P_{eff} = P_{tot} - R - E - Perc \qquad (4.5)$$

Where P_{eff} is the effective rainfall (mm), P_{tot} is the total precipitation (mm), R is the surface runoff (mm), E is the evapotranspiration (mm) and $Perc$ is deep percolation (mm). Thus, irrigation water demand for field crops (in this case, maize), was systematically determined based on the following steps:

Step1: Determine the reference crop evapotranspiration: ET_o

Step2: Determine the crop factors: Kc

Step3: Calculate the crop water need: $ET_{crop} = ET_o \times Kc$

Step4: Determine the effective rainfall: P_{eff}

Step 5: Calculate the irrigation water need: $IN = ET_{crop} - P_{eff}$

The link between the method applied for the computation of irrigation water demand and hydrological simulation in SWAT is thus underlain by the integration of simulated hydrological processes essential for defining crop water requirements and effective rainfall. Additionally, the definition of management operations relating to the field crop for which the irrigation water demand is being computed was key to this process. Figure 4.6 shows the definition of the management options for a field crop grown in two seasons – the wet season which coincides with the austral summer and the dry season which coincides with the austral winter. Each season is assumed to have 125 days, consistent with the average length of the maize life cycle for most parts of Malawi as summarized in the FAO crop calendar (https://cropcalendar.apps.fao.org/#/home).

Current Management Operations

	Year	Month	Day	Operation	Crop
>		4	30	Harvest and kill operation	
		5	1	Tillage operation	
		6	1	Plant/beginning of growing season	AGRL
		6	30	Auto fertilization initialization	
		10	31	Harvest and kill operation	
		11	1	Tillage operation	
		12	1	Plant/beginning of growing season	AGRL
		12	31	Auto fertilization initialization	
*					

Figure 4.6 | Set up of crop management operations in SWAT. The same operations are applied across all agricultural HRUs in all the five river basins. A new season starts with tillage operation and ends with harvest and kill operation. Two seasons are defined to reflect wet (predominantly rainfed) and dry (predominantly irrigated) seasons.

The planting date is critical as it defines the start of the cropping season while the harvesting date defines the season duration. This timing is critical given the interaction between crop characteristics and climate to determine crop water requirements and the effective rainfall to meet them. In the context of this setup, management operations start with tillage operations while they end with the harvest and kill operation, paving way for the start of management operations associated with another crop or season. Irrigation water demand was computed at a daily timestep *(and integrated to longer timescales – month or year – where necessary)* for HRUs with agriculture related land cover classes. The time series of monthly cumulative irrigation water demand (the determination of which is described below) was examined to identify periods when irrigation water demand was pronounced for whatever reason. These episodic spikes in irrigation water demand were compared with incidental declines in rainfall and streamflow to determine the frequency and extent of coincidence between water scarcity and irrigation water demand.

4.3.7.1 Computing episodic spikes in irrigation water demand

For easy comparison with other drought indices, the examination proposed the use of a standardised monthly anomaly of cumulative irrigation needs. In this context, cumulative irrigation need is defined as the total net amount of water that would have been required to irrigate a unit area by any given point in time during the growing season. Thus, the cumulative irrigation needs *i* on day *x* during the growing season is the irrigation need on day $x_{(i)}$ plus the sum of daily irrigation needs from day *1* to day *x-1*. In the context of this analysis and setup, the 125th of the growing season corresponds to the day with the maximum cumulative irrigation needs.

From the timeseries of monthly cumulative irrigation water demand, the mean monthly cumulative irrigation need was computed over a reference period (1981 - 2010) to examine the mean state and variability in irrigation needs for each of the two seasons. The standardised anomaly of monthly cumulative irrigation needs (the difference between the observed monthly cumulative irrigation and the mean monthly cumulative irrigation for the corresponding month divided by the corresponding standard deviation) is then used to identify episodic spikes in irrigation water demand comparable to droughts determined from timeseries of drought indices for meteorological and hydrological droughts through the SPEI and SDI respectively.

4.4 Results

The results are presented in two sections. The first section provides an overview of projected changes in temperature and precipitation across Malawi, paying attention to mean state and extremes relevant for drought processes. Projected changes in droughts and drought attributes are also presented, highlighting projected changes in attributes – including duration, severity, intensity, and spatial extent across – across the twenty-first century. The second section dwells on the hydrological responses to climate variability and change. This provides a basis for examining irrigation water demand as a function of crop water requirements and effective rainfall to satisfy them. Hydrological processes are examined based on current climatic conditions and future climate scenarios derived from bias corrected outputs of CMIP5 GCMs.

4.4.1 Projected changes in temperature and precipitation

Emphasis is placed on three regions, identified as north (Region 1), central (Region 2) and south (Region 3). While Malawi's administrative regions are identified as Northern Region, Central Region, and Southern Region, the disaggregation in this study is based on the location of the five river basins of interest and their geographical position with respect to the ENSO-rainfall teleconnection and does not necessarily follow the administrative boundaries. Due to their proximity and climatological similarity, Songwe, Lufira, and North Rukuru Regions are clustered into one region (i.e., Region 1 – or the north). Bua and Upper Shire River basins locations correspond to Region 2 (central) and Region 3 (south) respectively.

4.4.1.1 Projected changes in temperature

The multi-model ensemble (MME) mean for projected changes in temperature indicates a sustained increase in temperature across Malawi over the course of the twenty first century (Figure 4.7). The projected temperature increase is statistically significant across the mid-century and end-of-century time slices for both the RCP4.5 and RCP8.5 scenarios, with the most prominent increase projected for the low-mitigation (RCP8.5) scenario. The increase is consistent with, but more pronounced than, the projected increase in mean annual temperature globally, and within the regional average projected increase for southern Africa where the projected increase in temperature is in the range of 4 – 6 degrees Celsius by the end of the twenty-first century (Niang *et al.*, 2014; Engelbrecht *et al.*, 2015). While being statistically significant, projected changes in mean annual temperature over Malawi are also generally robust. Robustness is assumed where at least two thirds *(66%)* of the models consistently project significant changes towards a given direction (Almazroui *et al.*, 2020).

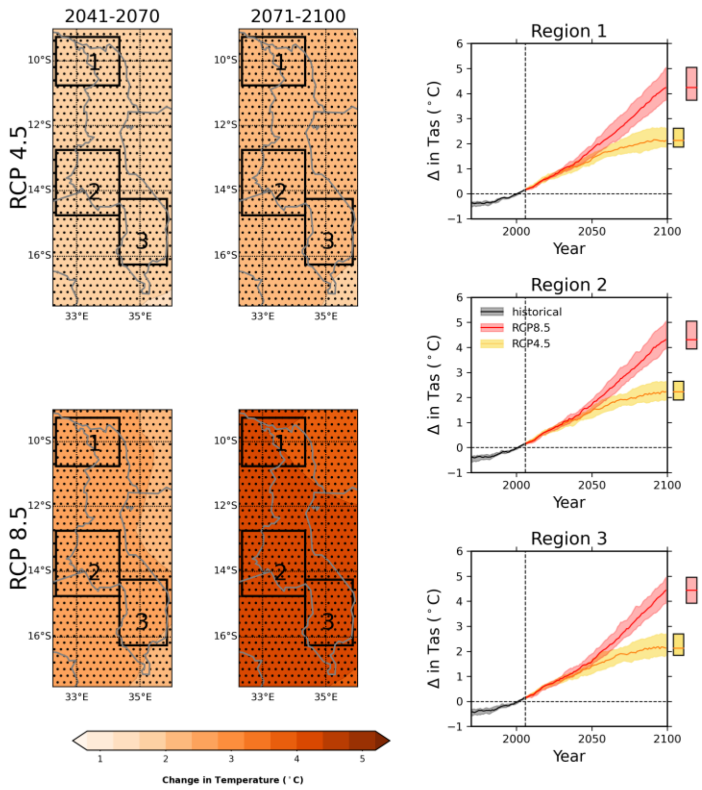

Figure 4.7 | MME mean of projected changes in mean annual temperature across the mid-century and end of century time slices for the two emissions scenarios (RCP4.5, RCP8.5). Stippling indicates where projected changes are statistically significant at 95% confidence interval. For spatially averaged, mean annual temperature is presented as annual anomalies (relative to 1976 – 2005), smoothed by computing the 20-year cumulative mean.

Similarly, trends in projected changes in mean annual temperature exhibit similar patterns across the three regions. Overall, mean annual temperature is projected to increase by 2 degrees Celsius by the 2060s for both RCP4.5 and RCP8.5, relative to the 1976 – 2005 mean. There is a clear separation in the projected changes between the two emission scenarios beyond 2060, with mean annual temperature projected to increase by up to 4 degrees Celsius in all three regions by the end of the century for the RCP8.5 emission scenario. The separation in the projected changes reflects the scenario uncertainty shown through the spread in projections arising from differences in responses to different greenhouse gas emission and concentration scenarios (Kirtman *et al.*, 2013) and indicative of the implications of continued global greenhouse gas emissions and concentration on local temperatures in this region.

4.4.1.2 Projected changes in precipitation

Unlike temperature, projected changes in precipitation are characterized by a considerable degree of uncertainty with regards to both direction and magnitude of change. Overall, mean annual precipitation is projected to decrease across most parts of the country (Figure 4.8) with the most pronounced, and statistically significant (at 95% confidence level) drying occurring in the southern part of the country (Region 3). A hint of wetting is apparent in the north, to an extent creating a north-south dipole of the projected change in mean annual precipitation across Malawi, specifically notable in RCP8.5. Regional projections of changes in precipitation are overly characterized by pronounced uncertainty, but there is a notable sign of contrasting changes between subtropical southern Africa and eastern Africa, reminiscent of the north-south dipole observed over Malawi for the end of century time slice in RCP8.5.

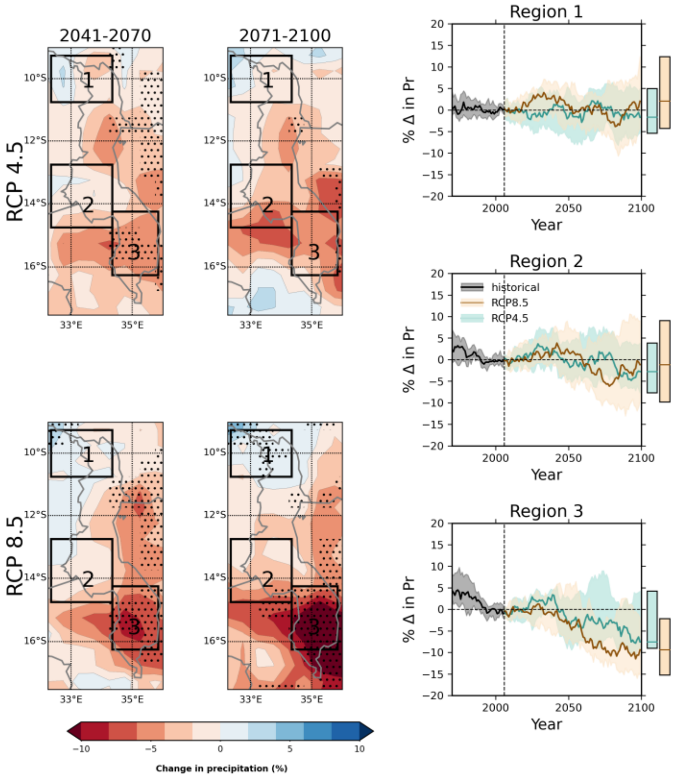

Figure 4.8 | MME mean of projected changes in mean annual precipitation across the mid-century and end-of century time slice for RCP4.5 and RCP8.5, and spatially averaged trends in projected change in precipitation for three regions (1, 2, and 3). Projected changes in precipitation are precipitation are presented as the percentage of the difference between the projected mean and the mean over the historical reference period (1976 – 2005). The projected timeseries is presented as percentage change of projected rainfall relative to the historical reference period and smoothed by computing the 20-year cumulative mean.

The regional contrast in the MME mean of the projected change in mean annual precipitation is clearly reflected in the spatially averaged projected timeseries of precipitation change over the course of the twenty-first century. The direction of change in the north is not generally definitive, while there is a hint of drying in the central region (region 2) around the Bua River basin. A drying trend is more pronounced for the southern region around the Shire River basin. Irrespective of the projected direction of change, precipitation projections are characterized by a considerable degree of uncertainty which may cascade down the impact assessment and decision-making value chain.

Projected changes in precipitation depict seasonal patterns characterized by widespread drying from September to November while a hint of wetting, albeit statistically insignificant, is apparent across most parts of the country during the DJF season (Figure 4.9). Widespread drying in the austral spring (SON) is an indication of delayed onset of the rainy season in future climate for which the confidence is high. Drying in the austral winter (JJA) is statistically significant for the northern and southern parts of the country but it should be noted that the actual absolute volumes both for the historical and future periods are minute. The JJA season is, in fact, the driest season in Malawi (Nicholson *et al.*, 2014) but drying could indicate reduction in wintery showers and creation of conditions that promote moisture losses through evapotranspiration.

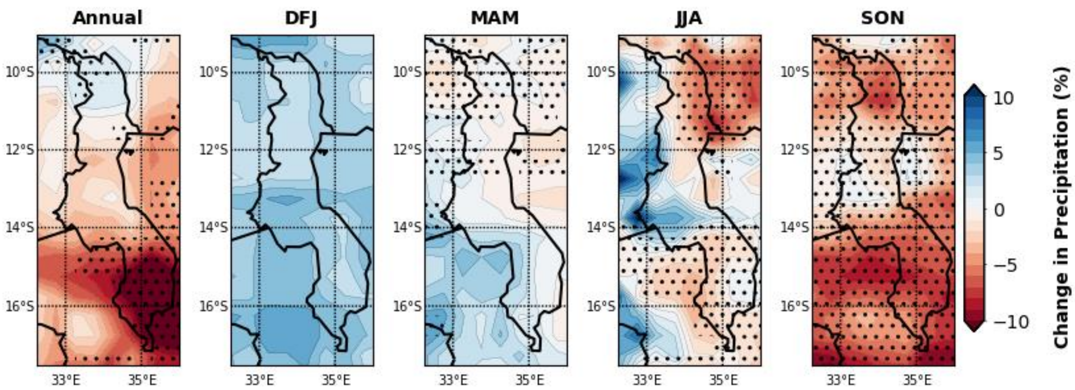

Figure 4.9 | MME mean of projected changes in annual and seasonal precipitation over the end of century time slice for RCP4.5 and RCP8.5 emission scenarios, presented as the percentage of the difference between projected precipitation and precipitation averaged over the historical reference period. Stippling indicates where projected changes are significant at 95% confidence interval.

Inter-model comparison of projected changes in mean annual precipitation highlights the extent of model consistency, or lack thereof, in the projected changes in precipitation. Figure 4.10 shows the projected change in mean annual precipitation across the 18 models for the end of century time slice for RCP8.5. Except for four models, the majority depict spatially uniform (country-wide) changes. The other four (MPI-ESM-LR, MPI-ESM-MR, BCC-CSM1-1-M, GFDL-CM3), depict a north-south dipole characterized by a wetter north and a drier south, consistent with the MME mean for RCP8.5. Malawi's transitional geographical location means that slight misrepresentations of feature locations, and the intensity of processes responsible for moisture transport and convergence around the convergence zone which moves meridionally to influence the north-south precipitation gradient (Chapter 3), can potentially lead to differences in locating where specific projected changes in precipitation occur.

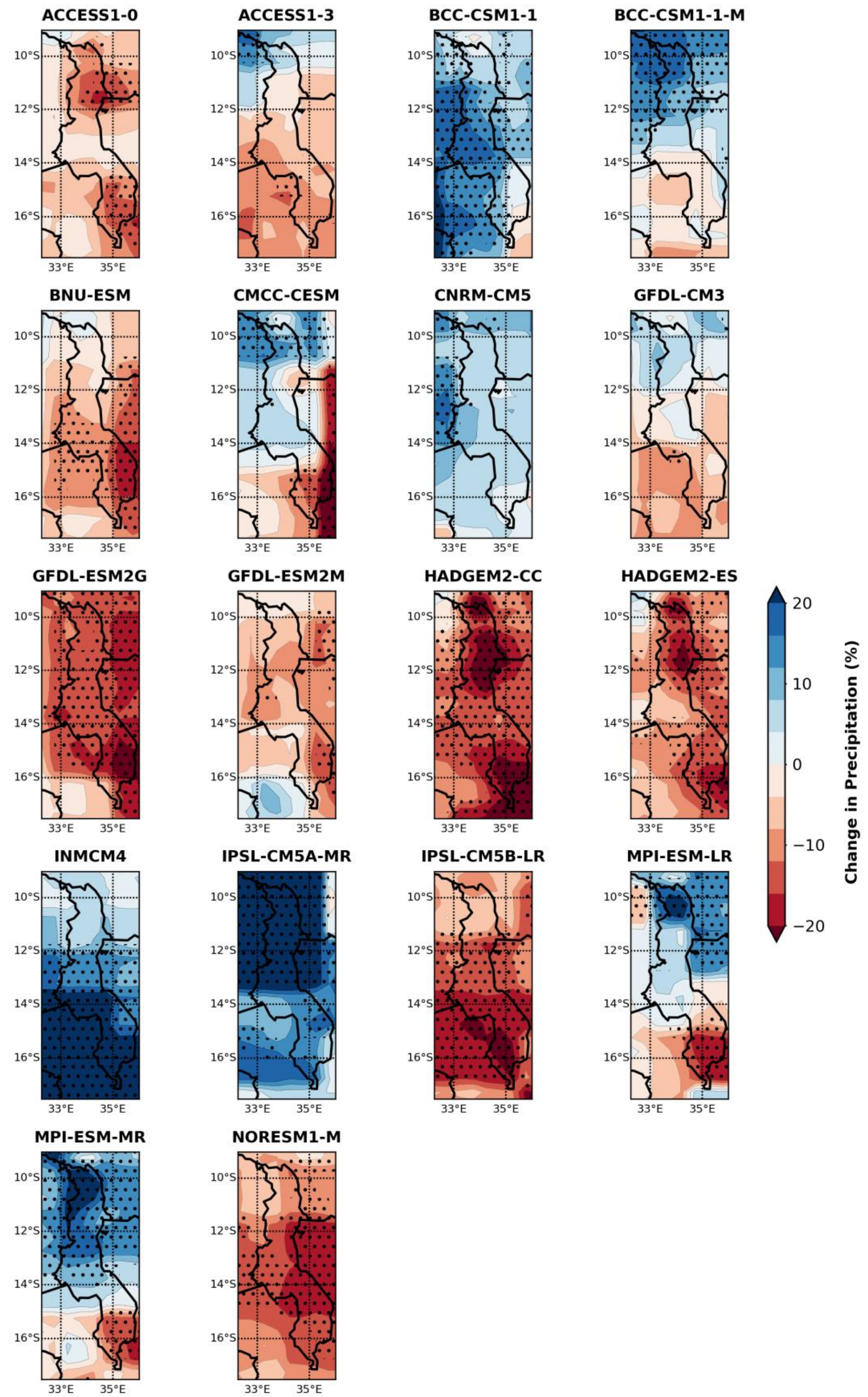

Figure 4.10 | Projected changes in mean annual precipitation for RCP8.5 across bias-corrected CMIP5 models over Malawi for the end of century time slice (2071 - 2100) relative to the historical reference period (1976 – 2005). Stippling indicates where the projected change is statistically significant at 95% confidence level.

The examination of changes in mean state – focusing on both temperature and precipitation – provided basic insights into projected changes in the climate over Malawi, and how changes vary temporally and spatially across different emission and climate scenarios. While this provides a basis for further examination of the impacts of changes under average conditions, it is imperative that changes in extremes be examined. This helps contextualize the subsequent emphasis on droughts and anomalously dry conditions, the patterns of which may vary in ways that affect adaptation decisions associated with irrigation and its presumed role in offsetting climate impacts on rainfed production.

4.4.1.3 Extremes relevant for drought processes

Two precipitation extreme indices were examined to further insights into projected changes in precipitation and provide context for the examination of drought conditions. The Expert Team on Climate Change Detection and Indices (ETCCDI) defined several temperature and precipitation related indices (Sillmann *et al.*, 2013) two of which are consecutive dry days (CDD) and wet day frequency (WDF) and form the basis for this analysis. The two indices were deliberately chosen given their applicability for examining conditions associated with drought and anomalously dry conditions.

Consecutive dry days

ETCDI defines consecutive dry days (CDD), as the largest number of consecutive days where precipitation is below a given threshold (typically 1 mm) (Sillmann *et al.*, 2013). Figure 4.11 shows the projected change in consecutive dry days across Malawi. Irrespective of the spatial differences in the projected change in precipitation, there is considerable spatial consistency in a projected increase in CDD across Malawi, with the longest consecutive dry days becoming 20 or more days longer in the low-mitigation scenario over the end of century time slice. Projected changes in CDD across Malawi are consistent with Maure *et al.* (2018) for southern Africa, with an increase in the number of consecutive dry days indicating an increase in the risk of drought in future climate.

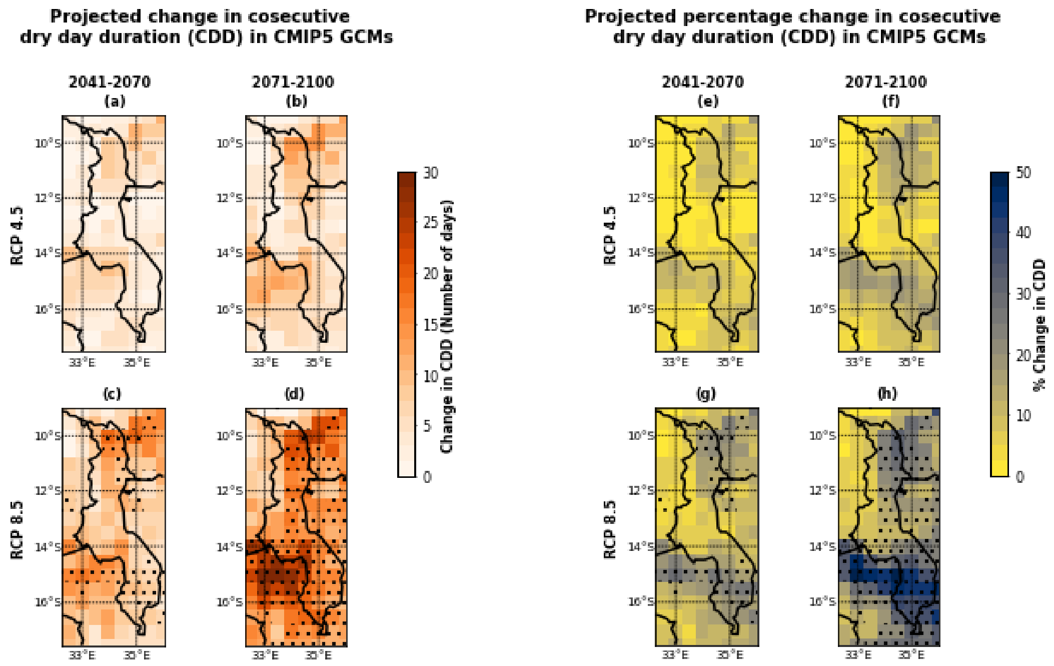

Figure 4.11 | MME mean of projected changes in consecutive dry days across two time slices for RCP4.5 and RCP8.5. CDD is computed from daily precipitation and projected changes are presented as the difference in absolute values between future mean CDD and the mean over the historical reference period (1976 – 2005). Projected changes are shown as both absolute values and percentage changes to highlight the extent of the change relative to the background state for each location (grid box).

Wet day frequency

The wet day frequency, here defined as the number of days when precipitation is greater than or equal to 5 mm, is projected to decrease in future climate. As noted by Sillmann *et al.* (2013), the definition of a wet day can be subjective and vary from one location to another. Lower thresholds could be particularly problematic for climates with higher rates of evapotranspiration. In view of this, a wet day is, in this case, defined as any day with precipitation equal to or greater than 5 mm (R5mm). Figure 4.12 shows changes in R5mm for the two future time slices for each of the two emission scenarios. The extent of reduction of wet day frequency in the southern part of the country reinforces the relatively higher risk of drying in future climate over the region. While entailing an increase in the background aridity, the combination of increasing temperatures and reduced rainfall may potentially indicate an increase in the risk of drought too.

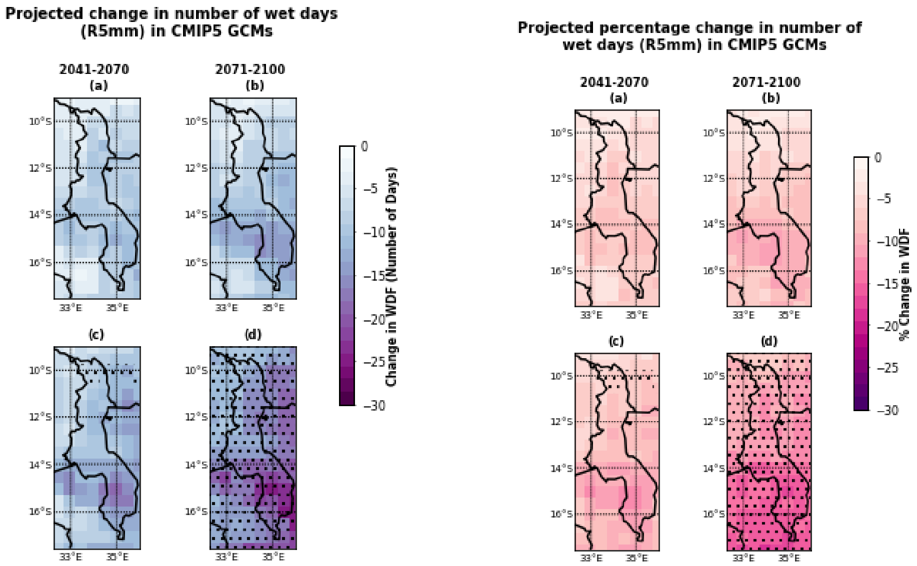

Figure 4.12 | MME mean of projected changes in wet day frequency for two future time slices relative to the historical reference period for two emission scenarios – RCP 8.5 and RCP 4.5. Projected changes are shown as both absolute values and percentage changes to highlight the extent of the change relative to the background state for each location (grid box).

Projected changes in mean temperature and precipitation and associated indices have highlighted and contextualised projected changes in the climate in Malawi. Long term changes in the mean state are critical for development decisions including adaptation and change of practices to align with the changes in mean state. Changes in extremes associated with droughts are indicative of changes, in this context an increase, in drought risk. An index-based analysis furthers this insight, providing an objective assessment of drought conditions in the context of altered climatic conditions. The following section provides a summarised picture of changes in drought attributes in Malawi, paying attention to key drought attributes including frequency, duration, severity, and intensity.

4.4.1.4 Projected changes in drought attributes

The frequency of drought in future time slices is significantly higher than the number of droughts identified over the historical reference period (Figure 4.13). The average number of droughts in the historical period is somewhat similar across all three regions but changes in future drought frequency are more pronounced in the southern part (Region 3). On average, approximately 7 drought events were identified across all three regions for simulations over the historical reference period (1976 - 2005), with the number of events doubling (14) in the end of century time slice over the southern part (Region 3) and an average of 11 and 13 drought events projected for the same time slice in the north

(Region 1) and central (Region 2) regions respectively. The increase in drought frequency is consistent, irrespective of the direction or magnitude of change in precipitation, highlighting the interactive influence of thermodynamic and dynamic factors that underly the occurrence of droughts and other extreme events (Seneviratne *et al.*, 2021), and impact other attributes of drought such as duration, severity and intensity.

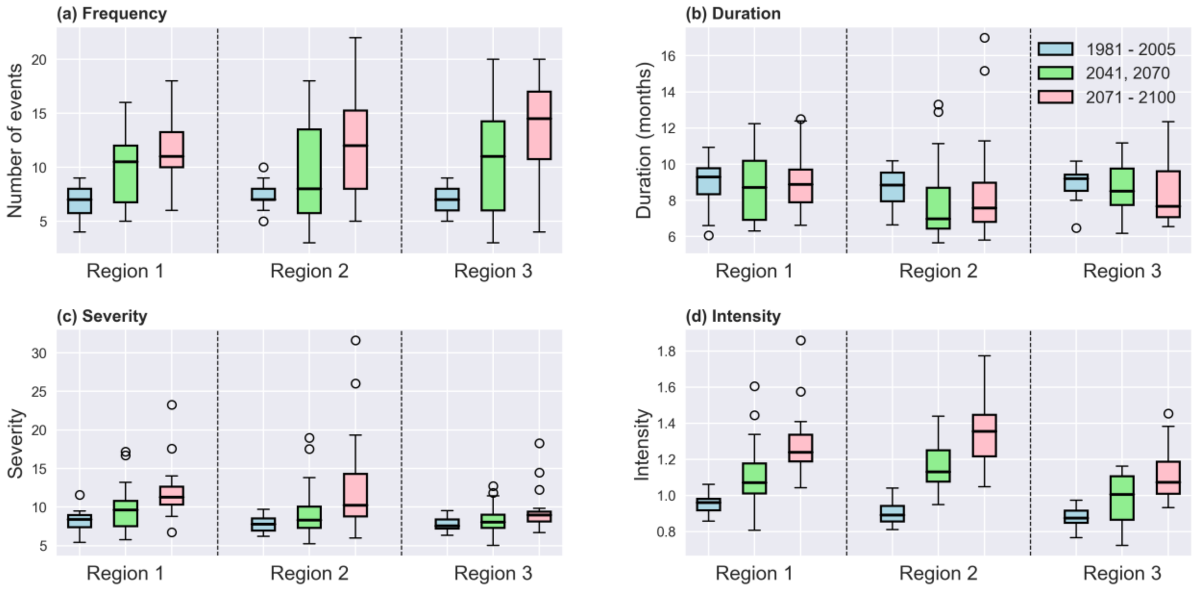

Figure 4.13 | Drought attributes across the historical, mid-century and end of century time slices for RCP8.5 (for the future time slices) indicating drought frequency (a), drought duration (b), drought severity (c) and drought intensity (d) for regions 1, 2 and 3 based on the MME mean for the 18 bias-corrected GCMs.

Variability in drought duration increases in future climate with no apparent changes in the mean drought duration in region 1, and a hint of a decrease in drought duration in regions 2 and 3. The overall decrease in mean drought duration is however not a result of droughts becoming shorter in duration but rather a result of the addition of more short-lived high-frequency events, effectively reducing the mean drought duration from 9 months (historical reference period) to 7 months (end of century time slice) in the central (Region 2) and southern (Region 3) regions respectively. Drought severity increases in future climate. As described in Chapter 3, drought severity integrates drought duration and the corresponding SPEI value to determine the cumulative SPEI over the period of the drought hence the relatively less pronounced drought severity increase in Region 3. However, drought intensity, which determines the extent of dryness at any point during a drought is consistently projected to increase, indicating that droughts in future climate will be characterized by a level of dryness higher than is the case of the historical reference period. Similar patterns are noted for the RCP4.5 scenarios but with relatively lower magnitudes (Figure 4.14).

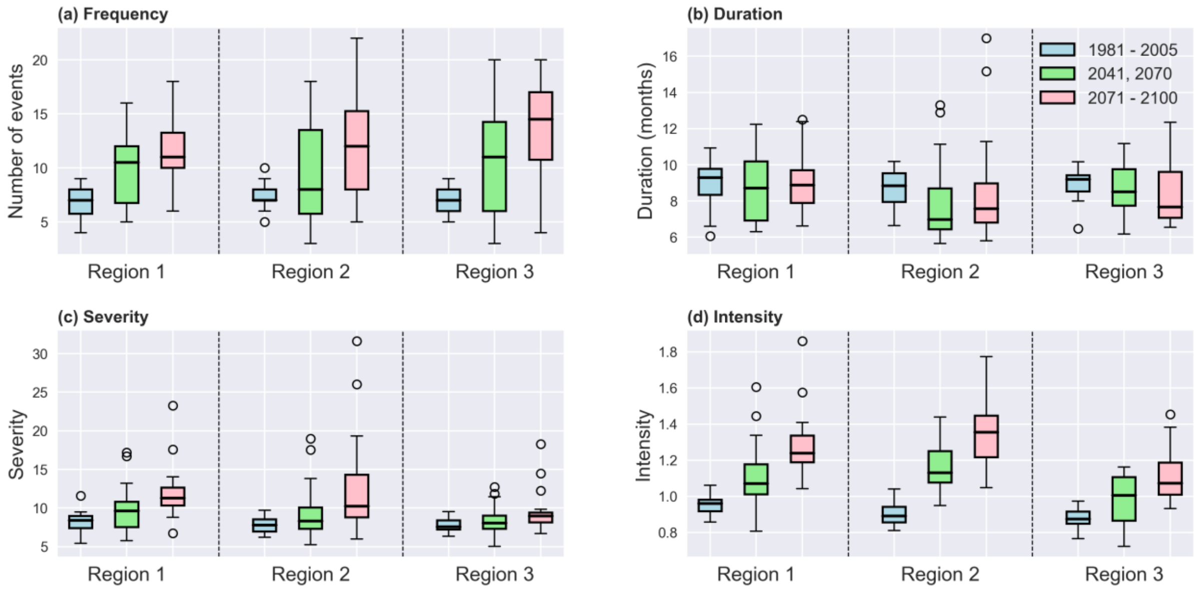

Figure 4.14| Same as Figure 13 but for RCP4.5.

The impacts of projected changes on various systems including water resources and irrigation are a function of several factors. Such factors act in concert to determine the nature of systems responses to the stress imposed by changes in climatic conditions. The response of river basin dynamics to changes in weather conditions can be influenced by its physiographic characteristics including topography, land use and soil characteristics. Human influences such as infrastructure (including dams and built-up areas that can alter natural hydrological regimes) also play an important role in basin responses to stresses from climate variability and change. The following sections present results of hydrological simulations that offer insights into hydrological responses in hydrometeorological variables essential for irrigation.

4.4.2 Hydrological responses to climate variability and change, and implications on irrigation in the Lake Malawi-Shire River Basin

The second part of the results focuses on the hydrological impacts of projected changes in temperature, precipitation, and meteorological drought climatology, emphasising their implications for irrigation across five river basins in the Lake Malawi Shire River Basin. Outputs of the SWAT simulations form the basis of the analyses in this section, which firstly looks at the basin hydrology as depicted by control simulations, and projected changes as well as sensitivity of various hydrological processes to projected changes in temperature and precipitation based on running the SWAT models with bias corrected outputs of the global climate models extracted from the AMMA2050 archive.

4.4.2.1 Basin hydrology: insights from control simulations

Figure 4.15 shows the monthly averaged water balance components derived from running the calibrated SWAT model across the five river basins with observed precipitation and temperature. The distribution of the different water balance components depicts a strong seasonality in basin scale processes, primarily influenced by seasonal changes in precipitation and temperature. Precipitation in Malawi is strongly seasonal, with the austral summer months (December – February) being the wettest for most parts of the country (Nicholson *et al.*, 2014). The onset and cessation of precipitation spells the onset and cessation of several other processes including soil moisture storage, surface runoff and groundwater recharge.

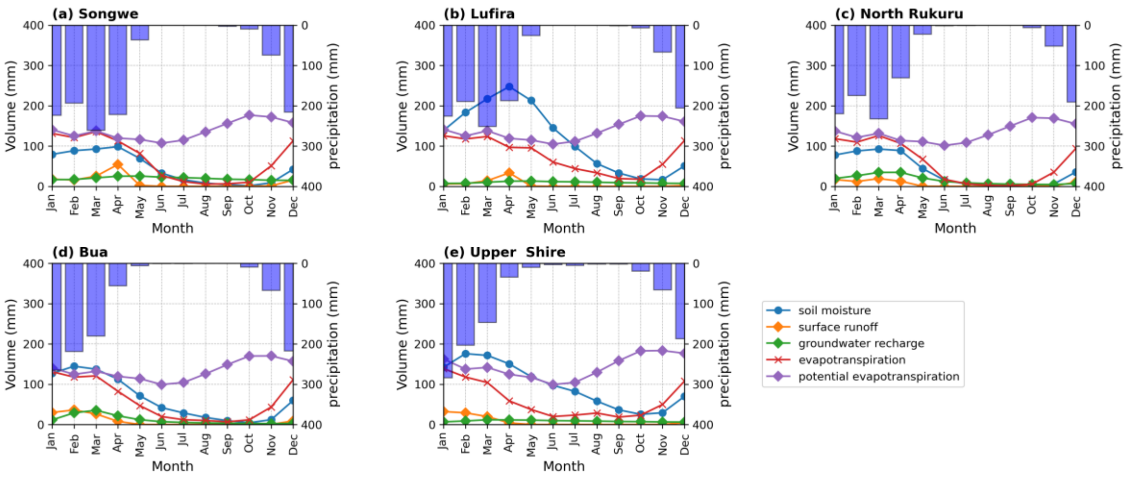

Figure 4.15 | Monthly water balance components showing, for each of the five basins, mean monthly values for soil moisture, surface runoff, groundwater recharge, evapotranspiration, and potential evapotranspiration and the corresponding observed precipitation (bars on secondary y-axis) from CHIRPS computed as monthly average for the period 1981 – 2010. The rest of the variables are outputs of SWAT simulation (calibrated) using observed weather variables over the same period.

Potential evapotranspiration is mostly pronounced in October and November, typically the hottest months over most parts in Malawi. Actual evapotranspiration is however fundamentally determined by the available moisture hence it peaks during the rainy season, when actual evapotranspiration approaches potential evapotranspiration. Except for the Lufira basin, soil moisture follows the same pattern as precipitation. A huge proportion of the Lufira basin is flat, and a flood plain sandwiched between the western highlands and the Lake Malawi to the east thus permitting considerable moisture retention which has been known to support winter cropping in the basin using residual moisture.

All five basins are underlain by generally low yielding aquifers (Scheidegger *et al.*, 2014) such that ground water yield is generally insufficient to sustain a considerable degree of baseflow in the dry season. The strong seasonality in precipitation and the low-yielding nature of the underlying base rocks gives most river basins in Malawi a sharp contrast between wet season and dry season flows, the pattern of which mimics precipitation seasonality. Across most rivers, streamflow in the dry season can fall to as low as 5% of overall discharge with the Shire River taking exception owing to the role of Lake Malawi in acting as a balancing pond which effectively reduces seasonal variations (Government of Malawi, 2011b). Flows in the Shire River can only fall to as low as 60% of average annual discharge due to contributions from Lake Malawi (Government of Malawi, 2011b).

4.4.2.2 Meteorological and hydrological droughts under current conditions

Across all five basins, hydrological droughts show a tendency to be rarer but long lived, consistent with what is generally expected of hydrological droughts (Van Loon, 2015). This would entail that a hydrological drought, once triggered by a meteorological drought would require consecutive wetter-than-normal seasons to be terminated. Except for the Upper Shire River basin, the rest of the river basins exhibit low basin inertia, usually typified by short response times. Streamflow variability across the four river basins in the northern and central Malawi are strongly dependent on precipitation variability and low-yielding aquifers that sustain low-flows during the dry season. The low basin inertia leads to short lags and considerably quick propagation of the drought signal. A lag is, in this context, defined as the time between the onset of a meteorological drought and the onset of the subsequent hydrological drought.

Figure 4.16 shows the timeseries for hydrological and meteorological droughts for the five basins. There is a strong tendency for the two categories of drought to coincide owing to the short lag time between the meteorological and hydrological droughts. This is consistent with the patterns exhibiting the interaction between precipitation and streamflow variability at inter-seasonal timescales which are characterised by sharp contrasts in streamflow between the rainy and dry seasons. Underlying this feature and relationship are the low-yielding aquifers beneath most river basins across Malawi and the consequent slow recharge of groundwater which would act as a buffer for streamflow during the dry season and when there is anomalously low rainfall indicative of a meteorological drought.

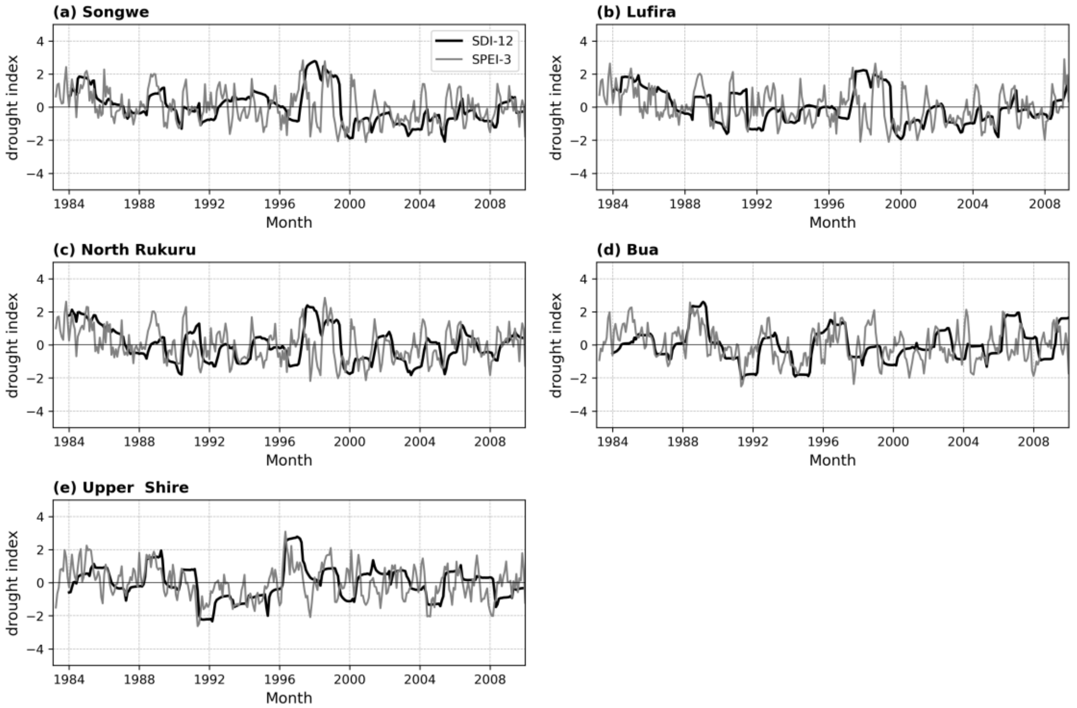

Figure 4.16 | Timeseries of the SPEI-3 and SDI-12 (thicker line) for the five river basins for the period 1981 – 2010. Runs below the threshold (i.e., index value = 0) indicate the occurrence of anomalously dry conditions (and wetter conditions for runs above index value = 0). A 3-month and 12-month window is used for meteorological and hydrological droughts to reflect the relevant temporal scales associated with the two categories of drought.

4.4.2.3 Irrigation water demand under current conditions

Figure 4.17 shows the monthly irrigation water demand for each month starting from the date of planting to the date of harvesting. It accounts for the differences in crop water requirements associated with each stage the length of which is aggregated accordingly when deriving the monthly values. For instance, given a planting date of 1st December, the monthly irrigation water demand for December accounts for the total irrigation water demand over the crop's initial stage (which is 20 days long) and the total irrigation water demand for the 11 days of the 35 days corresponding to the crop development stage. Computing the irrigation water demand for monthly timescales allows for easy comparison with other hydrometeorological variables.

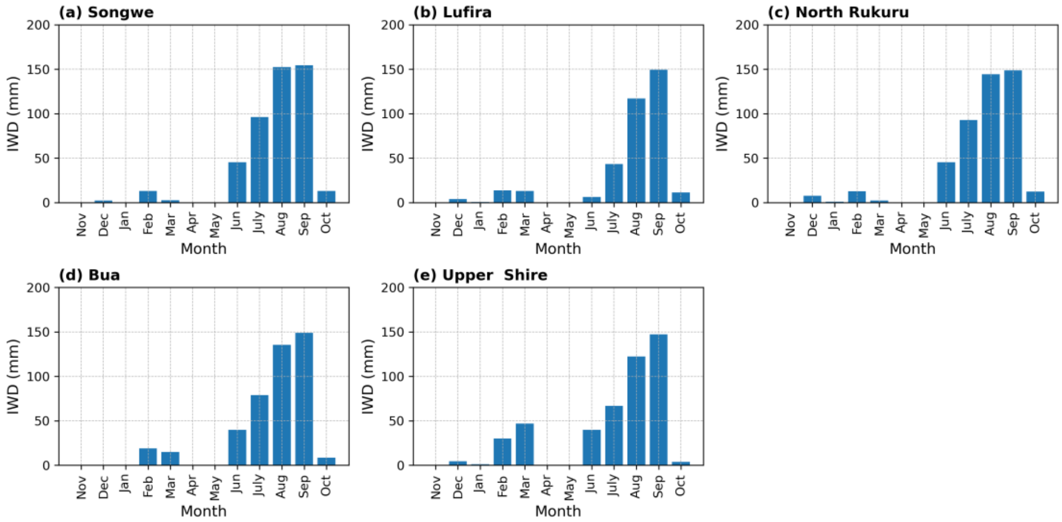

Figure 4.17 | Average irrigation water demand for wet-season (December – April) and dry-season (June – October) for field crops. Irrigation demand is determined for maize as the reference crop. Mean irrigation water demand is computed from irrigation water demand for each month for the period 1981 – 2010. The months of May and November have no associated irrigation water demand as there are no crops in the field (in the model) over those months.

Expectedly, irrigation water demand is higher during the dry season due to the lack of effective precipitation as opposed to the wet season. Irrigation water demand increases linearly from the date of planting towards the penultimate month before a sharp decline in the last month when the crop has reached maturity and is ready for harvesting. While the irrigation water demand in the penultimate month of the dry season (when irrigation water demand is the highest) and the last month is comparable across all the river basins, the irrigation water demand in the first three months is considerably lower in the Lufira River basin. The peaking of irrigation water demand in the Lufira river basin is notably slower compared to the other basins due to wetter soils that supply a considerable amount of residual moisture to meet the crop water requirements in the early stages of the irrigation season.

It is important to note that the gradual increase of irrigation water demand means that irrigation water demand is the highest when soil moisture is significantly diminished and when streamflow is typically the lowest across most river basins. The mismatch in the irrigation water demand and the supply of water to meet the same is key to irrigation system designs. In Malawi, for example, irrigation schemes are planned around streamflow reliability, where streamflow reliability is defined around 80% (Q_{80}) of reliable streamflow (Government of Malawi, 2015b). It is assumed that streamflow below this threshold is not sufficient to sustain irrigation if other uses and environmental flow requirements are to be met (Government of Malawi, 2015b). Temporal variations in irrigation water demand are therefore an essential factor to consider when planning irrigation development bearing in mind variations in streamflow.

Figure 4.18 shows the standardized anomalies of cumulative irrigation water demand for field crops in each river basin. Cumulative irrigation water demand is derived for each season by computing the moving sum of irrigation water demand for each season. The moving sums are broken up in the transition month when there are no crops growing as the essence is to determine the total irrigation water demand at any point during the season when there are crops growing. The mean cumulative irrigation water demand associated with each month is then determined as well as its associated standard deviation both of which are used to compute the unitless standardized irrigation water demand anomaly. This makes it convenient for easy comparisons across basins and for examination of relationships with drought indices.

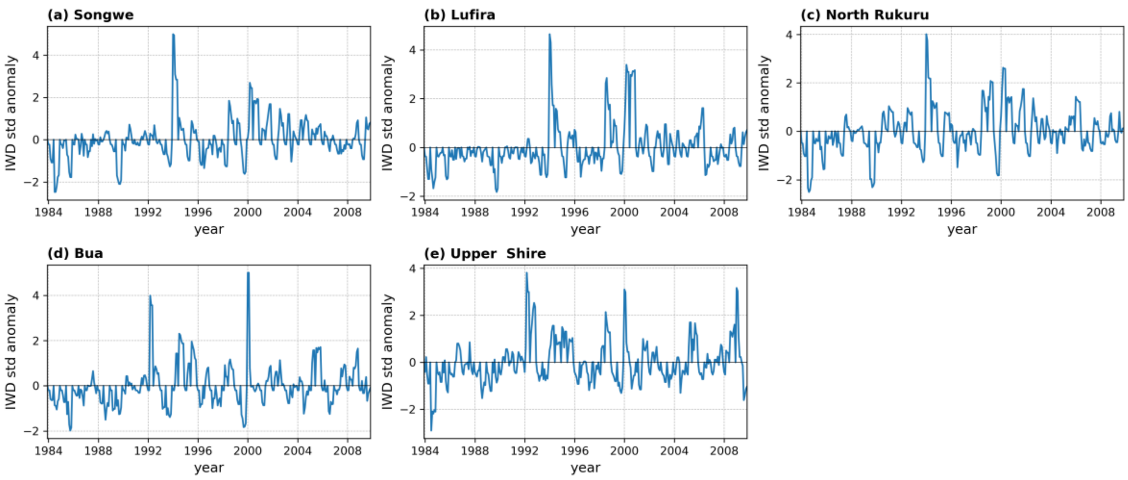

Figure 4.18 | Standardised anomalies of cumulative irrigation water demand in the five basins. Positive IWD standardised anomaly indicates periods when irrigation water demand is anomalously higher than the mean cumulative irrigation water demand for the corresponding month.

Average cumulative irrigation water demand is evenly distributed in seasons prior to 1990 across all river basins but frequent episodes of pronounced irrigation water demand are apparent in years after 1991. The emergence of frequent episodic spikes in irrigation water demand is evident across all five river basins but the pattern of the timing for such episodes is variable for basins in the north (i.e., Songwe, Lufira, and North Rukuru) and the south (i.e., Upper Shire River basin).

4.4.2.4 Droughts and episodic spikes in irrigation water demand

Figure 4.19 shows the long-term fluctuations in cumulative irrigation water demand – based on the standardized anomalies of cumulative irrigation water demand – and their coincidence with hydrological droughts. Episodic spikes in irrigation water demand (positive IWD) show a tendency to coincide with pronounced water deficits (negative SDI) thus creating challenges for irrigation the demand for which is the highest amidst water scarcity. Isolated or rare cases with pronounced irrigation water demand (positive IWD) coinciding with periods of pronounced streamflow (positive SDI) are also apparent across all five river basins. This is the case for Bua River basin for the period between 2007 and 2009, as well as 1998 in Lufira, North Rukuru, and Songwe River basins. The timing of episodic spikes in irrigation demand and extended, diminished streamflow is key for planning irrigation, especially when conceived as an adaptation strategy to droughty conditions, more so in a changing climate.

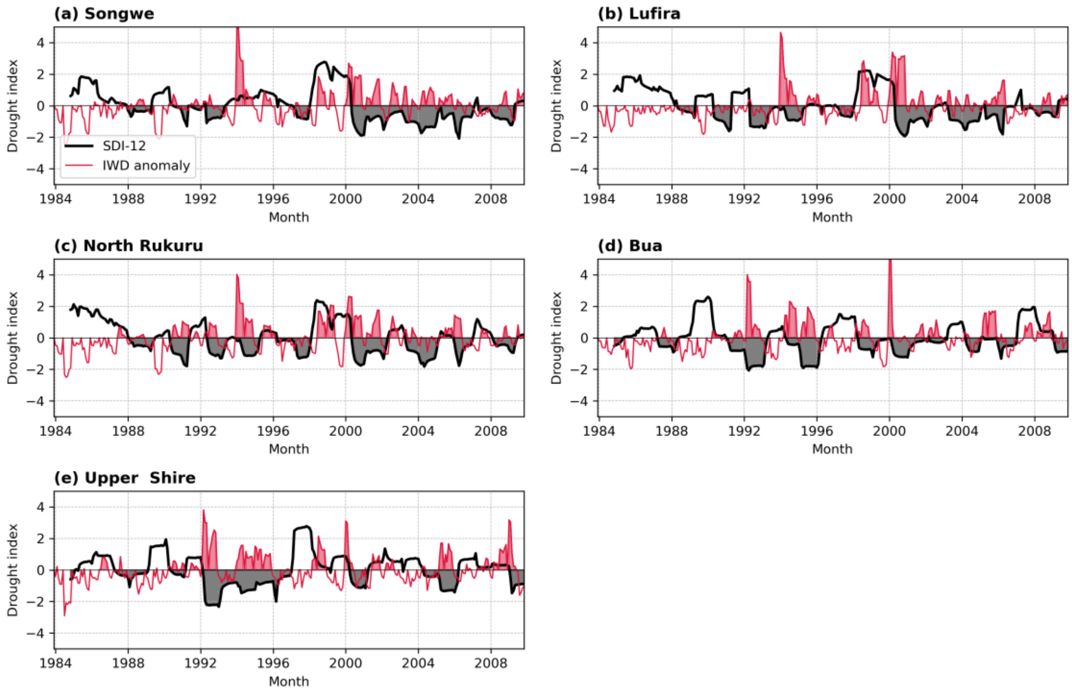

Figure 4.19 | Standardised monthly cumulative anomalies of irrigation water demand and SDI-12 (thicker line) for each of the five river basins. Both the cumulative irrigation water demand anomalies and streamflow drought index are computed from water balance and streamflow variables realised from running SWAT with observed weather variables. The drought index and standardised cumulative IWD anomalies on the y-axis are unitless but comparable as standardised variables. Shaded areas for irrigation water demand highlight periods when irrigation water demand is anomalously high while shaded areas for streamflow drought index highlight periods when streamflow is too low (i.e., hydrological drought).

4.4.2.5 Projected changes in irrigation water demand

Figure 4.20 shows the projected changes in irrigation water demand across the five river basins. Irrigation water demand is consistently projected to increase across all the five river basins. The most pronounced changes are indicated for Lufira and Upper Shire River basins where mean annual irrigation water demand increases by up to 40% and 50% by the end of the twenty-first century (RCP8.5) respectively. The rate of change shows regional disparities with basins in the north and central exhibiting a relatively lesser increase than the Upper Shire River basin in the south. The regional difference in the rate of change is attributed to the differences in the projected changes in precipitation which may act to offset the increase in irrigation water demand triggered by pronounced crop water requirements as the temperature increases. Such a dampening effect is dependent on the projected direction and magnitude of the change in precipitation. Drying in the south amplifies the irrigation water demand as effective precipitation becomes diminished hence a more pronounced increase in irrigation water demand in the Upper Shire River basin.

Basin characteristics also play a key role in influencing the rate of change in irrigation water demand. This is particularly apparent in the north where the Lufira River basin exhibits a relatively higher increase in irrigation water demand than the other two basins in the same climatologically homogenous region. This is attributed to the Lufira River basin's characteristics that allow considerable soil moisture storage leading to the basin having the lowest irrigation water demand over the historical period. The pronounced influence of an increase in temperature leads to considerable soil moisture losses and the disproportionate increase in irrigation water demand in comparison to the other two basins in the same region.

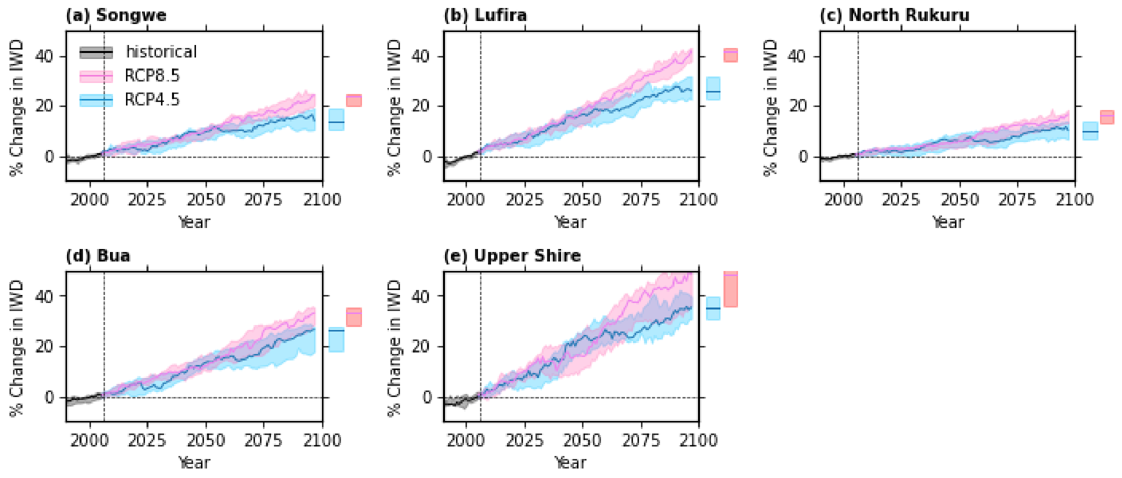

Figure 4.20 | Projected changes in irrigation water demand across the five river basins over the course of the twenty-first century for the RCP4.5 and RCP8.5 emission scenarios, relative to the 1976 – 2005 historical period. The projected change in irrigation water demand is computed as a percentage deviation from the average annual irrigation water demand (per unit area) for agricultural HRUs in SWAT.

Projected changes in irrigation water demand show an increase in IWD across both the rainy season and the dry season but the associated rates of change vary with season. Figure 4.21 shows the projected change in IWD for the wet season. Irrigation water demand changes by approximately 100% or more for the low-mitigation scenario by the end of the twenty-first century. The actual average irrigation water demand for the wet season is typically smaller therefore the projected change in absolute terms is not particularly dramatic but significant, nonetheless. The increase in temperature and subsequent evapotranspiration essentially triggers an increase in crop water requirements leading to heightened irrigation water demand magnified by a reduction in precipitation or seasonal shifts in rainfall distribution.

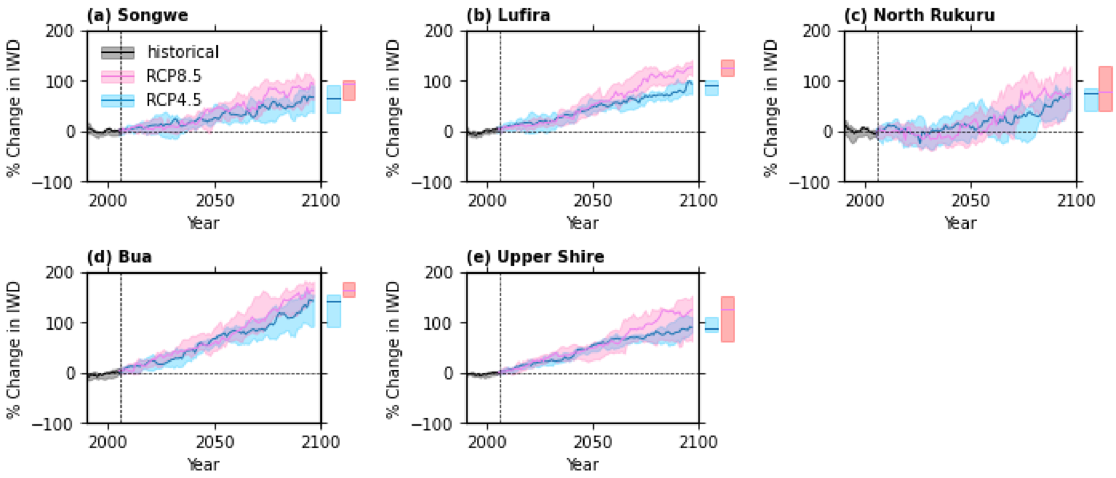

Figure 4.21 | Same as figure 4.20 but for the wet season (beginning 1 December as the planting date).

The projected increase in irrigation water demand during the winter (dry) season (Figure 4.22) – when irrigation is typically the primary source of water – is relatively smaller than the summer season. It should be noted, however, that the absolute values are larger. Except for the Lufira and Upper Shire River basins, the increase in irrigation water demand is between 15 and 20% by the end of the twenty-first century for RCP8.5. Pronounced changes in the Lufira and Upper Shire River basins have been highlighted and attributed to climatic and basin physiographic factors associated with soil moisture retention.

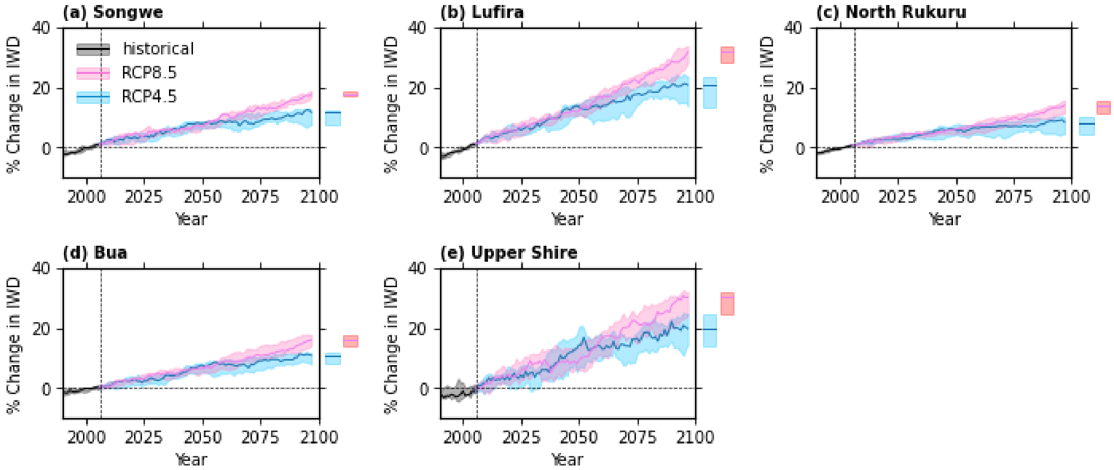

Figure 4.22 | Same as Figures 4.20 and 4.21 but for the dry season (1 June – End of October) when irrigation is the primary source of water.

Seasonal projections are computed with no assumption that there may be adaptive alterations to agronomic practices that may have an influence on the cumulative irrigation water demand. Such changes in practices may include the change in planting dates as well as shifts towards crops and varieties that are early maturing and have physiological characteristics that reduce their overall crop water requirements. The pronounced projected decrease in precipitation associated with the dry season is key to the projected increase in irrigation water demand, which is primarily driven by the increase in temperature and associated crop water requirements.

Irrigation water demand changes may be offset by changes in water supply to meet the increasing demand for irrigation. To further insights into climate risks for irrigation – reflecting both irrigation water demand and the supply of water to meet the same – the analysis is concluded by an examination of how streamflow changes under future climatic conditions. The next section examines streamflow responses to projected changes in climate, focusing on climate sensitivity of mean annual streamflow, projected changes in streamflow seasonality, as well as projected changes in reliable streamflow, with Q80 and Q90 discharge volumes as the basis. This provides a basis for further examining linkages between agricultural water demand and supply and projected climate risk, emphasizing both mean state and variability associated with droughts.

4.4.2.6 Sensitivity of streamflow to projected changes in precipitation

Examination of streamflow sensitivity to projected changes in precipitation furthers the insight into the implications of climate risks for irrigation in the LMSRB. Figure 4.23 shows the percentage change in simulated mean annual streamflow against the percentage change in mean annual precipitation in the five river basins for the period from 2006 to 2099 across all the 18 GCMs. Overall climate sensitivity of streamflow to projected changes in precipitation is derived from the fitted local regression (black regression line). A similar approach was used by Aich *et al.* (2014) in their examination of four major river basins across Africa.

Sensitivity of streamflow to projected changes in precipitation varies from one basin to another but there are considerable similarities. The largest increase in simulated mean annual streamflow resulting from a 25% increase in mean annual precipitation is noted in the Upper Shire River basin where, because of that level of increase in precipitation, mean annual streamflow increases by ~70%. The least increase is apparent in Songwe where, for a similar increase in mean annual precipitation, simulated mean annual streamflow increases by 43%. Increases in simulated mean annual streamflow in Lufira, North Rukuru, and Bua are ~60%, 54%, and 60%, respectively. Reducing precipitation by 25%

leads to simulated mean annual streamflow reductions ranging from 38% (North Rukuru) to 51% (Bua).

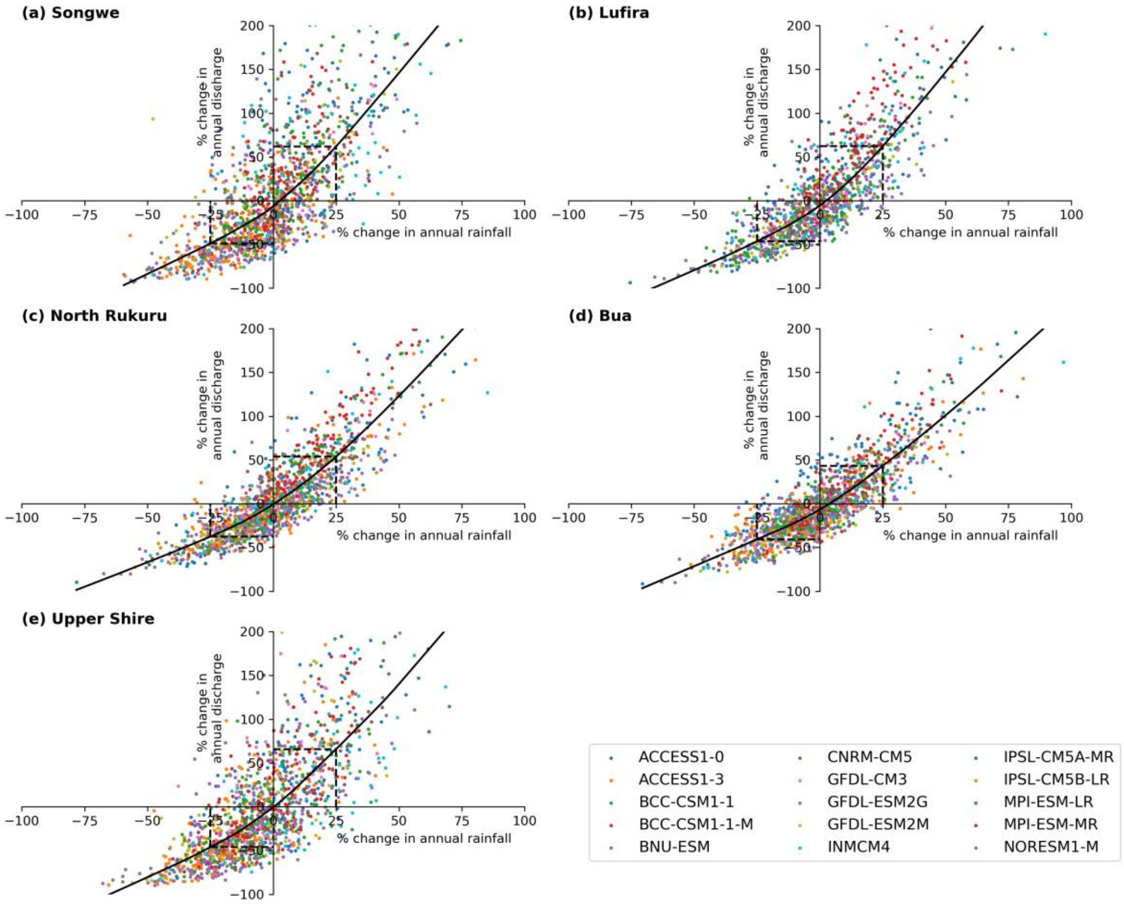

Figure 4.23 | Sensitivity of annual streamflow to projected changes in annual precipitation. Values are compared for change in modelled annual streamflow against change in modelled precipitation for the period 2006 – 2099, relative to the historical reference period 1976-2005. Curves show fitted local regression over all values for each basin. All figures present only the values in the range of -100% to 100% for % change in annual precipitation and 100% to 200% for % change in annual discharge. While values outside of this range are not shown, they were still included in the computation of the LOWESS curve.

4.4.2.7 Projected Streamflow Seasonality

Figure 4.24 (a-e) shows the observed and simulated streamflow seasonality for the five river basins. The observed streamflow is based on outputs of SWAT simulations with observed weather inputs rather than streamflow observed at gauging stations for easy comparisons with the Upper Shire River basin where only locally generated streamflow is considered. There is considerable consistency between observation based and climate model-based streamflow seasonality across all the five river basins. The intra-seasonal variability is consistently captured in the MME mean but there are notable outliers particularly inclined towards a positive bias, with the most pronounced biases noted for the Songwe River basin.

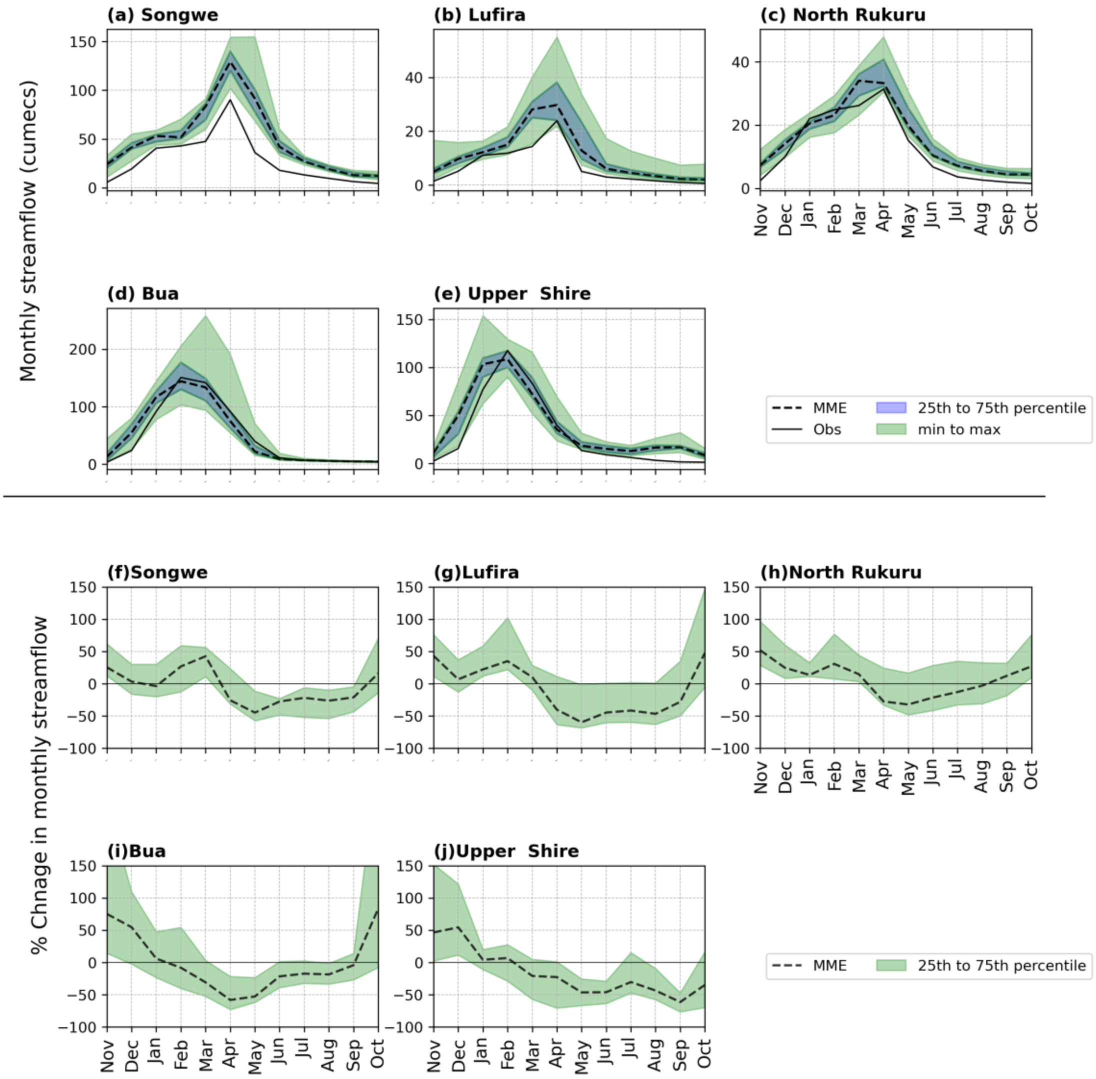

Figure 4.24 | (a) – (e) seasonality of streamflow across the five river basins over the historical period presented as the MME mean, the 25th and 75th percentiles and minimum and maximum, shown relative to observed streamflow (based on synthetic datasets generated from running SWAT with observed weather inputs). (f) – (j) projected changes in monthly streamflow for the end of century time slice (RCP8.5) relative to the historical reference period. Note that analyses and illustrations for the Shire River basin are based on locally generated streamflow.

Considerable changes in monthly streamflow are projected across all the five river basins albeit with considerable uncertainties in the magnitude of change towards each direction (Figures 4.24 f - j). A projected increase in streamflow is apparent for the majority of the wet season in river basins located in the north. Dry season streamflow is projected to decrease across all the river basins, with the most pronounced decrease noted for the Upper Shire River basin. Despite an increase in parts of the wet season (especially around

December) in the Upper Shire River and Bua River basins, a projected decrease in monthly streamflow is noted much earlier (as early as February) and sustained for the rest of the year whereas a small recovery is noted for the basins in the north in the latter months of the rainy season. Reduced streamflow during the dry season is particularly important for decision making around irrigation as it may influence low flows and streamflow reliability.

4.4.2.1 Low flow thresholds for meeting irrigation water demand

As one way of managing climate risk, irrigation system designs are developed with consideration of periods of low flow. Figure 4.25 shows the historical (from simulations) and projected changes in Q90 flows associated with different return periods. Projected changes in low flow generally show an increase in the frequency of low flows across four of the five basins, with the North Rukuru being the only exception. The increase in the frequency of low flows is pronounced and statistically significant in the Upper Shire River basin, consistent with the projected drying trend in the southern part of Malawi. The implication of the increase is that low flow volumes associated with specific return periods are much lower in the future climate scenarios, relative to the historical period thus affecting the criteria for defining irrigation potential based on streamflow reliability.

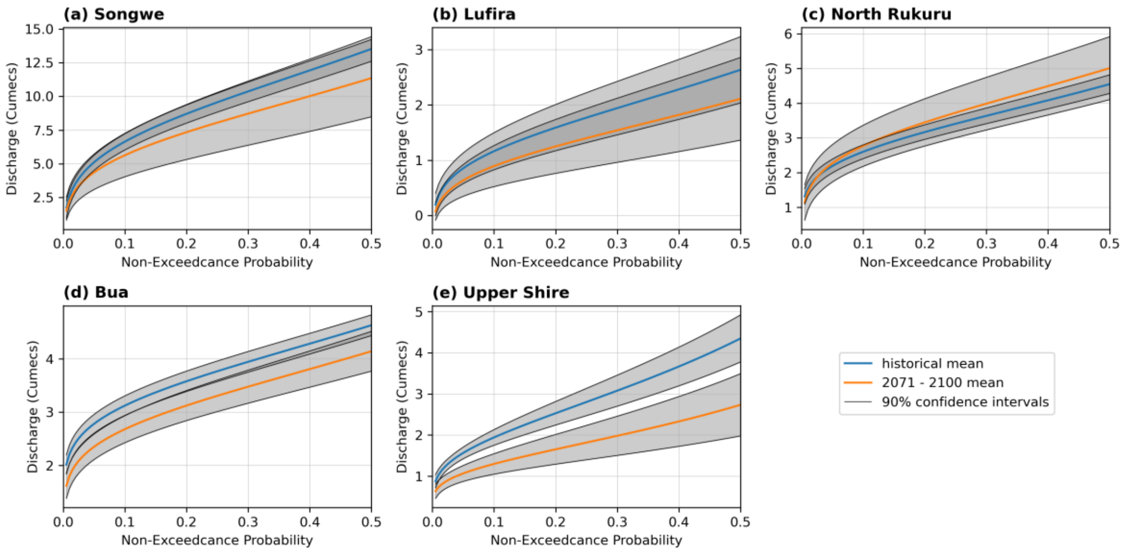

Figure 4.25 | Historical (1976 – 2005) and projected (RCP8.5: 2071 - 2100) low flow (Q90) discharges and their associated non-exceedance probabilities. Historical and projected Q90 flows are based on theoretical distributions (generalised extreme value) fit on simulated historical and projected flows for the respective 30-year periods. Shaded areas show 90% confidence intervals. Where confidence intervals do not overlap (4.35 e), differences in low flows associated with the corresponding exceedance/non-exceedance probabilities are statistically significant at 90% confidence level.

4.5 Discussion and Conclusion

This chapter explored the interaction between climate risk and irrigation development across five river basins in the Lake Malawi Shire River Basin. Hydrometeorological processes underlying the interaction between meteorological and hydrological drought were examined based on simulations with the Soil and Water Assessment Tool. Five models, set for each of the five river basins, provided a basis for linking climate scenarios and hydrological processes, providing insights into how the interaction between climate and physiographic variability influences irrigation water demand in observations, present-day simulations, and climate projections under two emission scenarios. Projected changes in irrigation water demand and sensitivity of streamflow to projected changes in precipitation provided the basis for understanding climate risks for irrigation in the context of changes in both mean state, and variability linked to droughts.

All climate models within the ensemble project a significant increase in temperature across all five river basins throughout the course of the twenty-first century. The projected local increase in temperature is consistent with, but more pronounced than, global trends. Projected changes are consistent with regional patterns for both eastern and subtropical southern Africa (Niang *et al.*, 2014; Engelbrecht *et al.*, 2015) where mean annual temperature is projected to increase in the range of 4 to 6 degrees Celsius by the end of the century for RCP8.5. Such changes in temperature are critical to droughts, owing to the thermodynamic influences associated with, among other things, atmospheric evaporative demand which increases with increasing temperature (Seneviratne *et al.*, 2021). Confidence in the projected increase in temperature is high, as is its influence on the occurrence of drought, a view that these findings reinforce for Malawi given the spatial and inter-model consistencies in the projected increase. Changes in temperature and the subsequent influence on atmospheric evaporative demand are critical to irrigation, especially when considered in the context of changes in precipitation.

While there is consistency in the projected changes in mean annual temperature, projected changes in precipitation depict considerable uncertainty in terms of the direction and magnitude of change. The projected change in mean annual precipitation exhibits a north-south dipole characterized by a drier south and wetter north, albeit with less clarity and confidence for the latter. The drying in the south is relatively more pronounced, with >66% of the model projecting dryness, consistent with the projected signal for subtropical southern Africa (Lazenby *et al.*, 2018). The north-south dipole is to an extent reflective of the transitional nature of the country's geographical position with respect to rainfall bearing mechanisms that are associated with convergence of moisture fluxes from the Indian Ocean and Congo River Basin (Likoya *et al.*, 2023) (See Chapter 3). Regional patterns identified by Lazenby *et al.* (2018) depict this dipole for eastern Africa and subtropical Africa (either side of Malawi's meridional axis), attributing it to the northward shift of the ITCZ. The shift in the ITCZ deprives areas to the south of the rainfall maxima of considerable precipitation while confining rainfall favoring processes to the north of Malawi.

It was noted in Chapter 3 that not all models are able to simulate the interaction between the three moisture fluxes that converge over Malawi (Likoya *et al.*, 2023) , leading to inconsistencies in the simulation of processes associated with the north-south contrast apparent during drought events, particularly those associated with ENSO. Inter-model comparisons indicate that the north-south contrast in the projections of rainfall changes over Malawi in also not universally produced across all models in which case inconsistencies may be attributed to the misrepresentation of circulation feature intensity and location. Evidence of misrepresentation of key features in southern Africa exists (Lazenby *et al.*, 2016; Munday and Washington, 2017; Barimalala *et al.*, 2018; James *et al.*, 2018) supporting the picture presented in Chapter 3 and possibly governing uncertainties in projected precipitation over Malawi as identified in this chapter.

Drought frequency is projected to increase over Malawi. This is somewhat consistent with the anticipated increase in drought risk over southern Africa owing to thermodynamic drivers (Spinoni *et al.*, 2020), the confidence for which is relatively higher (Seneviratne *et al.*, 2021). Changes in other drought attributes highlight the interaction of thermodynamic and dynamic factors to influence other drought attributes including duration, severity, and intensity. Projected mean drought duration is less than the historical period, but this is attributed to the increase in high-frequency short-lived events rather than droughts themselves becoming shorter in duration. The severity of drought is projected to increase, owing to the increased extent of drying which also increases the intensity. This implies that the extent of drying at any given point during a drought will be comparatively higher in future climate conditions. The combination of projected changes in the mean state and frequent droughts with more pronounced attributes may present critical risks for irrigation in future climate.

Irrigation water demand was examined for each of the five river basins and results have been presented at basin, rather than regional scale. Irrigation water demand was computed as unit demand, i.e., per unit area, and not as a gross value given other factors that require realistic representation of conveyance technologies among others. Irrigation water demand exhibits strong seasonality owing to the intra-annual rainfall pattern which creates two distinct wet and dry seasons. The irrigation water demand in the wet season is minute as all the crop water requirements are typically met by effective precipitation under normal conditions. However, interannual variability and incidental droughts and dry spells create deficits that have historically affected yields in Malawi (Pauw and Seventer, 2010; McCarthy *et al.*, 2021). Dry season farming is characterized by higher irrigation water demand, the cumulative magnitude of which varies with basin characteristics associated with soil moisture retention. Where moisture retention is high, a considerable proportion of crop water requirements is met with residual moisture, but the lack of precipitation ultimately drives the demand for irrigation in the latter parts of the season.

Climate risks for irrigation have been examined in this chapter. A reflection of irrigation water demand spikes and how they interact with drought processes across the five river basins formed the basis for this examination, insights of which were furthered by the examination of how irrigation changes under different future climate conditions across the five river basins. Except for the Shire River basin, the rest of the basins generally have a low inertia, characterized by quick streamflow response times to changes in precipitation. This relationship underlies the quick propagation of the drought signal, or the short lag in transitioning from one drought category to another. More importantly, this chapter has established that episodic spikes in irrigation water demand, triggered by meteorological droughts, often coincide with diminished streamflow, creating an imbalance in irrigation water demand and the supply of water to meet the same. Understanding this relationship is critical to development and management of irrigation landscapes, more so when such landscapes are developed to counter the effects of droughts and dry spells.

Mean annual irrigation water demand is projected to steadily increase over the course of the twenty-first century. This is the case across all five river basins for both RCP4.5 and RCP8.5 scenarios. The rate of change however varies across the basins, and this is attributed to the interaction between projected changes in precipitation and temperature.

The increase in temperature has a positive impact on irrigation water demand through the increase in crop water requirements as evapotranspiration increases with increasing temperature. The projected change in irrigation water demand is the highest in the Upper Shire River basin due to the combined effects of increasing temperature (leading to increase in crop water requirements), and reduction in rainfall (leading to the decrease in effective rainfall). Elsewhere, the increase in irrigation water demand is partially offset by the small increase in precipitation but precipitation increases are not high enough to completely negate the increase in irrigation water demand due to increasing temperatures. The increase in irrigation water demand in the Lufira River basin is remarkably higher than the rest of the basins in the same region. This is because a significant part of crop water requirements in the Lufira River basin is met by residual moisture over the historical period. Such soil moisture is lost under future climate conditions which compounds the change in irrigation water demand relative to the Songwe and North Rukuru River basins.

Irrigation water demand projections were performed with the assumption that there is no change in practices to adapt irrigation to projected climatic changes. Such practices may include choices of varieties with differences in time to maturity, as well as the alteration of planting dates. A further key assumption is that irrigation water demand is met with river abstractions. The examination of streamflow sensitivity further reveals key climate risks for irrigation. Analyses performed for the five river basins indicate considerable streamflow sensitivity to changes in precipitation. Across all five river basins, a 25% reduction in mean annual rainfall leads to approximately 50% or higher reduction in streamflow. While there is no definitive direction of change in rainfall for the most part, and therefore no definitive direction in the projected change in streamflow, understanding the sensitivity of streamflow provides a basis for understanding system limits. Moreover, the examination of droughts in future climate indicated an increase in drought frequency and subsequent dips in streamflow. The interaction of these dips and episodic spikes in irrigation water demand, coupled with the overly projected increase in irrigation water demand highlights the need for climate aware irrigation landscape development and management.

This chapter built on a comprehensive examination of global climate model outputs to examine future changes in precipitation, temperature, and droughts in Malawi. Hydrological simulations with satisfactorily performing SWAT models provided a basis for linking these changes to irrigation through a fundamental understanding of hydrological processes linked to irrigation water demand and streamflow sensitivity to projected changes in the climate. With irrigation being central to the agricultural innovation and food systems transformation agenda in Malawi, the relevance of findings from this chapter transcends scientific insights and understanding of physical processes related to climate risks for irrigation.

From a developmental perspective, these findings provide a basis for informed decision making in ensuring development of resilient irrigation landscapes while safeguarding potential to irrigate in a changing climate. This is critical not only for Malawi, but for the majority of sub-Saharan Africa where the demand for food and the need for agriculture commercialization hinges on developing production systems that withstand the impacts of climate change. Future studies may explore similar questions with a focus on specific crops and integration of adaptation decisions for improved understanding of system dynamics. Newer generations of climate models may also provide a basis for understanding added value of model improvements in uncertainty reduction and improved confidence in simulations.

Chapter 5

Climate Risk Perceptions and Multi-Level Governance of Irrigation in Changing Climate Policy Landscape in Malawi

5.1 Overview

Climate resilience in Malawi's agriculture sector is dominated by efforts to transform predominantly rainfed agricultural landscapes towards more irrigation. Efforts to develop irrigation are grounded on the perception that underperformance and vulnerabilities in the agriculture sector can be traced to overreliance on rainfed agricultural systems. The rationale that irrigation would alleviate climate related challenges is usually supported by reference to previous drought events and irrigation opportunities that may have been missed. While the current state of water resources may support this view, climate risks for irrigation revealed in Chapter 4 make this rationale for irrigation development questionable.

This chapter seeks to develop an account of shifting perspectives in policy instruments with a focus on how climate change has been integrated in policies related to agriculture development on one hand, and how issues of irrigation have been reflected in climate policies on the other. It further explores how climate risk is perceived across various levels of decision-making in the irrigation management and development space, particularly focusing on the local government and grassroots levels. It finds that the integration of climate information in irrigation related policies has increased with time as more evidence of climate change becomes available and influences policy narratives. However, the dominant narrative is that irrigation is key to adapting the agricultural sector to climate change. Climate risks for irrigation are not adequately addressed but there is some level of recognition to make irrigation sustainable and resilient to climatic shocks. At the grassroots levels, irrigating farmers recognize the risks that climate change presents for irrigation, learning from their encounters with low water availability to fully sustain irrigation activities. These challenges are compounded by other factors such as poor irrigation infrastructure, lack of investment and limited access to profitable markets all of which are key to farmer decisions around climate risk management for irrigation.

5.2 Introduction

Irrigation has been identified as one of the key enablers of growth in Malawi's agrarian economy. The emphasis on irrigation in the country's long-term development blueprint, the Vision 2063, underscores its envisioned role in expanding production and improving food production and greater shifts to commercial crops (Government of Malawi, 2020a). Presumed gains in agricultural commercialization and economy-wide implications add significant weight to the emphasis on irrigation in developing the agricultural sector as stressed in the Vision 2063 and related sectoral policies. Furthermore, irrigation is widely viewed as a key intervention in adapting agriculture to climate change thus presenting the prospect of addressing 'twin' challenges of climate change adaptation and agricultural transformation (Gwiyani-Nkhoma, 2011; Mdee and Harrison, 2019; Kamwamba-Mtethiwa *et al.*, 2021). Climate change has implications for policies relevant for irrigation development and often provides considerable justification for rigorous investment in the sector.

The rationale to invest in irrigation development Is supported by views anchored on the shortcomings of rainfed agricultural systems and Malawi's highly variable rainfall climatology (Chidanti-Malunga, 2011; Fiwa, 2015; Mdee and Harrison, 2019). The susceptibility of rainfed systems to climatic shocks such as droughts reinforces narratives that slow growth of the agricultural sector can be attributed to low levels of irrigation. This view has formed the basis for public irrigation development policy, enhanced by the narrative that Malawi has *abundant* water resources that have not been fully exploited for agricultural gains through irrigation (Government of Malawi, 2007, 2011a, 2015b). However, the interface between climate risk and irrigation as revealed in Chapter 4 for example, and any potential opportunities that may arise from changing climatic patterns, demands the need to critically interrogate this narrative.

The multi-level governance nature of irrigation management presents considerable challenges to decision makers and grassroots communities alike (Mdee and Harrison, 2019; Kamwamba-Mtethiwa *et al.*, 2021), especially in the context of climate change and the quest to create more efficient irrigation systems (de Bont *et al.*, 2019). Avenues for effective collaboration in managing irrigation resources can be cultivated to facilitate meaningful transformation and climate change adaptation (Mdee and Harrison, 2019). Such aspects of governance are key to development of sustainable and resilient irrigation systems.

The integration of climate change in irrigation development plans and policies is gradually being realized even though policy integration across the wider climate smart agriculture landscape remains generally weak (Dougill *et al.*, 2021). A growing body of evidence of climate change and associated impacts across relevant sectors continue to cultivate narratives that will shape policy perspectives in irrigation development. For instance, Chinsinga and Chasukwa (2018) show how different climate change narratives have shaped agriculturally relevant policy perspectives in Malawi, in which they highlight how different narratives govern policy discussions and interventions implemented in ways that reflect both competition and complementarity. The range of issues governing irrigation development present a unique set of factors to facilitate convergence and/or divergence of policy narratives essential to achieving sustainable and resilient irrigation amid climate change and competing demands for water resources.

The limited policy coherence in relation to climate change adaptation in Malawi has been previously highlighted (England *et al.*, 2018) with crucial gaps noted for long-term development targets and the adequacy with which they address the threat of climate change. Moreover, Bhave *et al.* (2022) highlight key issues relating to irrigation development within plausible limits given competing interests in water resource development and limits imposed by future climate change. To ensure that irrigation developments do not fall short of their expected gains, it is imperative that threats associated with climate change are adequately addresses across the irrigation management decision-making value chain. It is against this backdrop that this study aims to examine how perspectives around climate change variability shape actions in irrigation management and development across different levels in Malawi. Specifically, the study is undertaken to:

1. Develop an account of how perspectives around climate change and irrigation have evolved in relevant policies over the past two decades (2000 – 2020) in Malawi.
2. Develop an account of multilevel governance of irrigation in Malawi and how players at different levels perceive climate risk in relation to irrigation management and development.

5.3 Materials and methods

This assessment combines policy analysis and stakeholder (district and local) workshops to examine current irrigation development and management issues in relation to climate change at the national, district, and community levels. The multi-level nature of irrigation governance in Malawi prompted this vertical layering of the analysis for systematic identification of trends and issues in climate change integration in development planning and irrigation management.

5.3.1 Policy analysis

A range of national policies (Table 5.1) relevant for irrigation development and climate change management were analyzed to examine how they address issues of irrigation development and management in relation to climate change. Sectoral policies for agriculture, water, and irrigation were examined in relation to their integration and portrayal of climate change in relation to irrigation development and management on one hand. On the other hand, climate change related policies and frameworks were analyzed in relation to how they address issues of irrigation management and development. Policy analyses also extend the focus to overarching development frameworks, investigating how they address issues of irrigation development and management in relation to climate change and vice versa. This provides a basis for examining how policies from different sectors and adopted at various points in time over the past two decades have perceived and integrated issues of climate change.

Table 5.1 | List of policies analysed and their respective designated national authorities or government departments within which they are administered.

Category	Policy	Designated national authority
Sectoral	National Irrigation Policy (Government of Malawi, 2016c)	Department of Irrigation
	National Irrigation Act (Government of Malawi, 2001)	Department of Irrigation
	National Water Policy (Government of Malawi, 2007)	Department of Water Resources
	National Water Resources Act (Government of Malawi, 2013)	Department of Water Resources
	National Agriculture Policy (Government of Malawi, 2016a)	Department of Agriculture
	National Irrigation Masterplan (Government of Malawi, 2015b)	Department of Irrigation
	Water Resources Investment Strategy (Government of Malawi, 2011b)	Department of water resource
Climate change management	National Climate Change Management Policy (Government of Malawi, 2016b)	Environment Affairs Department
	National Climate Change Response Strategy (white paper) (Government of Malawi, 2012)	Environmental Affairs Department
	National Adaptation Programmes of Action (NAPA) (Government of Malawi, 2006)	Environmental Affairs Department
	Intended Nationally Determined Contribution (NDC) (Government of Malawi, 2020b)	Environmental Affairs Department
	National Communication to the United Nations Framework Convergence on Climate Change (Government of Malawi, 2002, 2021)	Environmental Affairs Department
	Disaster Risk Management Policy (Government of Malawi, 2015a)	Department of Disaster Management Affairs
	National Environmental Policy (Government of Malawi, 2004) Environmental Management Act (Government of Malawi, 1996)	Environmental Affairs Department
Cross-cutting	Malawi Vision 2063 (Government of Malawi, 2020a)	National Planning Commission
	Malawi Growth and Development Strategy III	Economic Planning and Development
	National Resilience Strategy	Department of Disaster Management

The selection of policies for the analysis was purposeful. For sectoral policies, the selection was constrained to policies that have direct implications for irrigation development in relation to water resources. The relevance of other policy instruments such as those related to land tenure and administration cannot be overemphasized, with a breadth of studies that underline their relevance for the sector (e.g. Chinsinga and Chasukwa, 2012; Chinsinga, 2017; Mdee and Harrison, 2019) but these were not included to limit the analysis to interactions between climate, water resources, and associated socio-political interactions.

Climate change related policies and frameworks were selected to ensure that key milestone policies and frameworks were included in the analysis. The Malawi Vision 2063 and the Malawi Growth and Development Strategy III (MGDS III) are Malawi's blueprint development frameworks for the long and medium terms respectively – at least for the period under consideration – hence both were included in the analysis. The National Resilience Strategy (NRS), developed to guide cross-sectoral development in line with enhancing resilience to climatic shocks was also included as part of the overarching development frameworks. The policy coverage across the three categories (sectoral, climate-specific, and overarching) provided a comprehensive sample of relevant policies and frameworks in the irrigation development and management space in general and, specifically, in relation to climate risk management. In instances where newer versions of policies have replaced old ones, reference to previous versions/editions of such policies or frameworks was made as much as possible. This would also provide a basis for examining how narratives have changed over time as more information on climate risk and climate change became available.

5.3.1.1 Approach to conducting the policy analysis.

There are a number of approaches for conducting policy analyses, some of which are described by Browne *et al*. (2018), the nature of whose analytical orientation is broadly categorized as traditional, mainstream, and interpretive. Emphasis was placed on the interpretive approaches to policy analysis (Browne *et al.*, 2018). This approach is governed by ideas that reality is socially constructed, and that language and discourse have an important role in shaping the way in which social reality is created. Interpretive approaches can take several forms. One such approach is the argumentative discourse analysis following the work of Fischer and Forester (1993) which was later revisited in 2012 (Fisher and Gottweis, 2012) following decades of research based on the approaches from the first instance. The basis for the analysis is *to examine how the definition of the political problems relates to the particular narrative in which it is discussed* (Browne *et al.*, 2018). Underlying research questions for the analysis include:

- What are the different ways that the policy problem and responses have been articulated and argued for?
- What traditions, power relations and knowledge structures do these discourses align with?

A search-and-find procedure was undertaken to identify narratives that govern climate change consideration in irrigation related policies (and vice versa). Using both NVIVO and Mendeley, keywords in relation to climate change and variability were searched across all sectoral policies to locate the statements in which they appeared. Each keyword and the whole statement in which it appeared is referred to as a reference henceforth. Each reference was examined to understand the context in which it was presented by looking at pointers such as the section of the policy in which it was presented, passage headings, and neighboring statements. The intended meaning for each reference was established in relation to the aforementioned aspects and the literal meaning of that reference. Keywords in relation to irrigation were searched across climate policies and frameworks to identify irrigation related references in such policies. Both searches were done for overarching policies. Dominant narratives associated with climate change and irrigation were identified and themes assigned.

5.3.2 District stakeholder workshops

Three district stakeholder workshops were conducted in Balaka, Karonga and Nkhotakota districts between September and October 2021. Participants comprised officials from various government departments whose work is related in one way or the other to irrigation management and development. The main aim of the workshops was to examine how district officials perceive climate risk in relation to irrigation and the extent to which they interact with water user associations (WUAs) to manage climate risks for irrigation. A key part of the former focused on identifying self-determined constraints for irrigation development and the extent to which the stakeholders deemed climate change and variability to be a key constraint. The latter focused on examining the role of district stakeholders in influencing access to irrigation by individuals in and around irrigation schemes; the role of district stakeholders in influencing the choice of crops grown under irrigation; and water management issues including enforcement of regulations. This furthered the assessment of climate change considerations by decision makers at the national level and created a basis for examining how perspectives at the district level align with perspectives that are central to national level policy provisions for irrigation management and development in line with climate risk.

5.3.2.1 Description of study area

The three districts were purposely selected as they fall in the three regions that formed the basis for the examination of impacts of droughts in future climate on irrigation in Chapter 4, i.e., Karonga District aligning with Songwe, Lufira, and North Rukuru River basins; Nkhotakota District aligning with Bua River basin; and Balaka District aligning with Upper Shire River basin. Figure 5.1 shows the three different districts. The choice of district was also guided by the predetermined view that each of the three districts has a set of factors – both climatic and non-climatic – that have potentially influenced irrigation development in the past and could be key to future irrigation development.

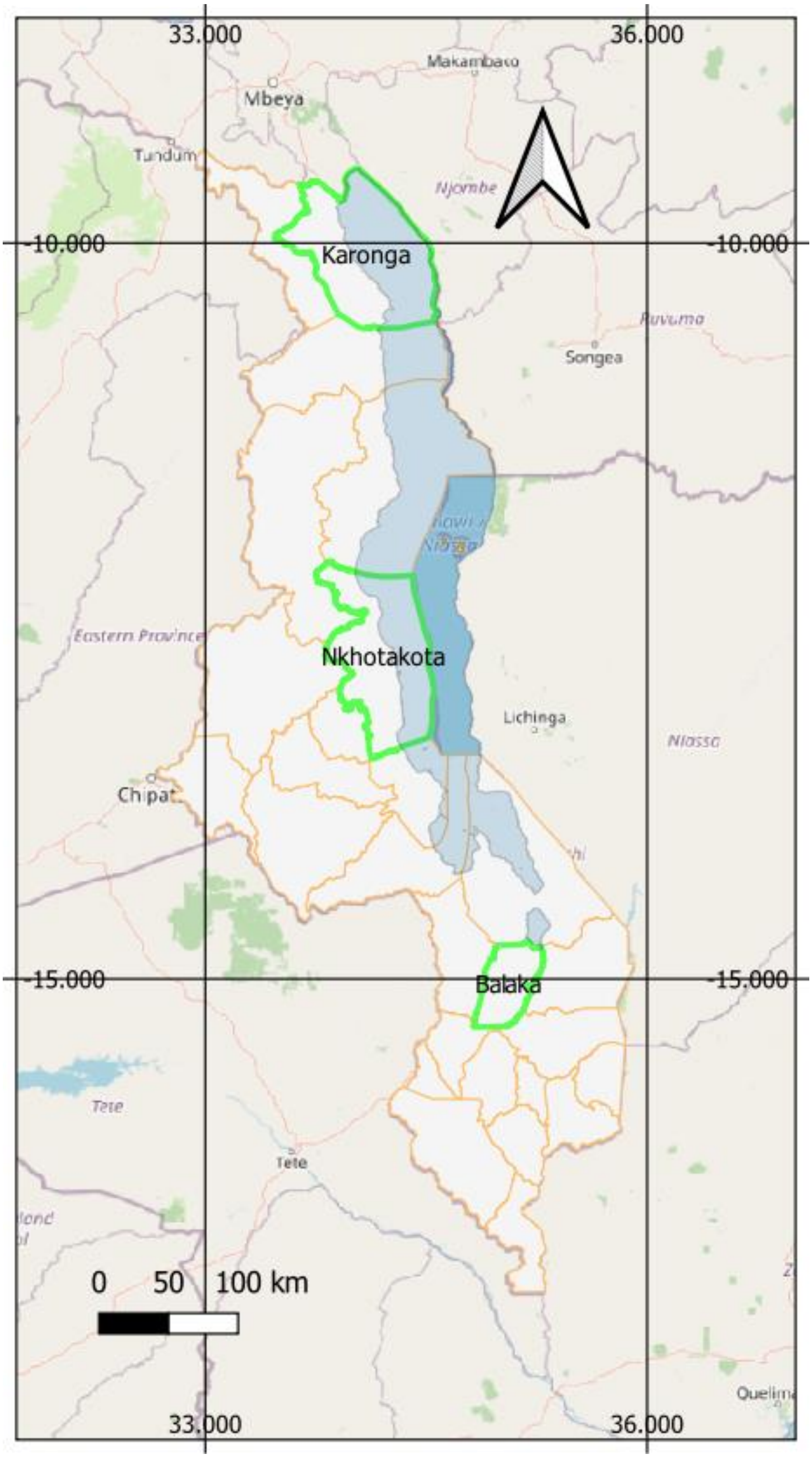

Figure 5.1 | The three districts in Malawi where the stakeholder workshops and focus group discussions were conducted with local government stakeholders and grassroots communities respectively.

Karonga is one of the smallholder irrigation hotspots in Malawi with irrigation schemes that have been developed over different periods of time during which irrigation development was governed by different policies. More future irrigation development sites have been identified in line with the Green Belt Initiative, Songwe Basin Management and the Programme for Rural Irrigation Development (PRIDE) among other irrigation development strategies for Malawi. Irrigation is also widely practiced in Nkhotakota where both smallholder and estate-managed irrigation schemes are operational. The latter is largely through the Dwangwa sugar estate operated by Illovo Sugar Limited and managing approximately 8000 hectares of irrigated land. In contrast, the extent of irrigation is relatively lower in Balaka. The district has a historically dry climate with persistent water scarcity issues. Nonetheless, key irrigation developments have been earmarked for the district with some schemes already under development.

5.3.2.2 Approach to identifying workshop participants.

Workshop participants were identified in liaison with officials from the Department of Irrigation – the primary department of interest in the consultations. Initial approval was sought from the Department of Irrigation headquarters through the Deputy Director of Irrigation responsible for research who also approved the choice of districts. For each district, a tentative list of departments of interest was presented to the head of Irrigation Services Department. Emphasis was made to include participants from different departments to ensure representation of stakeholders with different interests in the agriculture, irrigation, and water governance space. A final list of participants was developed depending on the activity of respective departments in irrigation management and development. Table 5.2 shows the list of departments that participated in the workshops across the three districts. Logistical limitations meant that some departments could not be represented in the workshop *(considering schedules and presence at the office as the government was implementing a decongested office space policy at the time in line with Covid-19 control measures).*

Table 5.2 | List of participants for the district stakeholder workshops identified by the departments in which they are stationed.

District	Department	Number of Participants
Balaka	Agriculture – crops	1
	Forestry	1
	Irrigation	2
	Land resources conservation	1
	Water resources	1
	Environmental affairs	1
	Total	7
Karonga	Irrigation	2
	Environmental affairs	1
	Agriculture – crops	1
	Water resources	1
	Climate change and meteorological services	1
	Planning and development	1
	Disaster management affairs	1
	Forestry	1
	Total	9
Nkhotakota	Irrigation	2
	Agriculture – crops	1
	Land resources conservation	1
	Environmental affairs	1
	Water resources	1
	Lands	1
	Community development	1
	Forestry	1
	Fisheries	1
	Environmental affairs	1
	Social welfare	1
	Total	12
Total		28

5.3.2.3 Approach to conducting the workshops

The workshops were guided by a checklist of pre-determined themes. Annex 3 is the checklist for the stakeholder workshops. Specific open-ended questions were developed for each theme to permit more engaging discussions and for participants to elaborate on their points. Specific details for each theme are described below. The workshops started with a brief presentation of the aims of the study and some initial findings (climate projections from Chapter 4) that informed the basis of this component of the research. The presentation also included a note on the ethical considerations and consent issues as will be highlighted later in detail.

Theme 1: Water resource accounting and institutional alignment with water user associations.

Discussions around this theme involved participants mapping the water resources in their respective districts, as well as identifying key water uses associated with major water resources. This helped build a picture of water resource availability and usability in each of the three districts, outlining how much water is used for irrigation against other uses. The interactions between various stakeholders and water user associations were also identified at this stage.

Theme 2: Irrigation water use in the context of climate change and other water use categories.

Discussions under this theme were centered on water utilization for irrigation and how the participants ensure that there is a balance between irrigation and other water demands. Specific questions for this theme were guided by the view that irrigation development is principally influenced by availability of water resources with the recognition that water resources serve varying interests. Putting stakeholders in the same place to discuss such issues was essential in the attempt to understand the different roles of the respective sectors in decision-making along the irrigation development value chain. This theme was designed to build an expert-based base of information on irrigation practices including challenges that are both climatic and non-climatic in nature and how they are addressed at the local government level.

Theme 3: Constraints to future irrigation development and role of climate change

This theme focused on scenario development where participants identified the main challenges and opportunities for irrigation development in their respective districts. Participants identified the main constraints for irrigation development in the foreseeable future. The constraints were deliberately categorized as climatic or non-climatic in nature. In so doing, participants would identify whether climate change presents any potential threats or opportunities to irrigation development in the next 10 – 30 years. Participants would then discuss the intersection of the climatic and non-climatic constraints to conceptualize a future where each of the two types of constraints progressed in a trajectory that permitted or limited irrigation development. The ultimate outcome of the scenario building exercise was a 2-axis matrix combining the identified climatic factor in a projected direction of change that would suit (positive) or impede (negative) irrigation development on the x-axis and the same for a non-climatic factor on the y-axis as illustrated in Figure 5.2. The matrices for the respective workshops would then be aggregated into one matrix to identify common and unique scenarios.

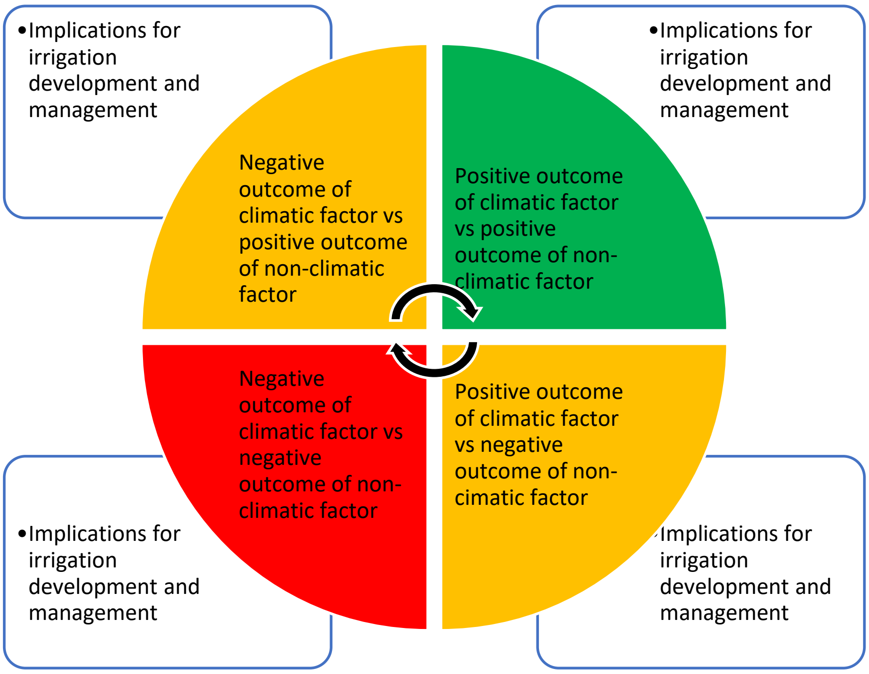

Figure 5.2 | Schematic of scenario matrix combining the most important non-climatic factor (agreed by participants in any given workshop or focus group discussion) and a climatic factor relevant for irrigation development. A traffic light colouring system indicates the nature of scenario where green indicates a desired trajectory in both climatic and non-climatic factors, orange indicates a positive (desirable) trajectory in one aspect and negative in the other, red indicates a negative trajectory in both factors.

5.3.3 Focus group discussions

A total of 22 focus group discussions were conducted with farmers around irrigation schemes across 12 sites in Balaka, Karonga and Nkhotakota districts around the same time as the stakeholder workshops (i.e., September – October 2021). The intention was to engage farmers with access to irrigation through an irrigation scheme and, for each site, another cohort of farmers that farm on the peripherals of the irrigation schemes but have no access to irrigation. The two cohorts of farmers will be referred to as irrigating and non-irrigating farmers henceforth. Health restrictions relating the Covid-19 pandemic meant non-irrigating farmers could not be engaged for two sites, namely Khwisa irrigation scheme (Balaka District) and Mphinga irrigation scheme (Karonga District) hence the total number of focus group discussions would be 22 rather than 24. The results were aggregated at district level such that missing out on one cohort of farmers at the two sites would not have a significant impact on the results.

5.3.3.1 Identification of participants for the focus group discussions

The list of irrigation schemes targeted for the focus group discussions was developed in liaison with officials from the Irrigation Services Department at the district level. Ideally, these would be referred to as water user associations (WUA) but not all the irrigation schemes are formally registered as WUAs in some areas. A tentative list of irrigation schemes was first developed with irrigation schemes selected based on size, number of beneficiaries, irrigation technology (diversion being the preferred for direct reference to findings in Chapter 4) and source of water (prioritizing those abstracting water from within the basins of interest in Chapter 4). Notably, ground water (shallow wells) is a key source of water for irrigation schemes in Balaka district in which case the emphasis on diversion technology was less strict to allow for more irrigation schemes to be considered. Table 5.3 shows the number of schemes that were sampled in each district as well as the number of irrigating and non-irrigating farmers that participated in the focus group discussions.

Table 5.3 | Details of focus group discussion participants for each site and district, and the overall sample size.

District	Scheme/Area	Technology	PIA	Area currently under irrigation	Number of beneficiaries (Number of Female Beneficiaries)	Irrigating farmers sampled (n)	Non-irrigating farmers sampled (n)
Balaka	Khwisa	Diversion	150	100	385 (140)	8	Na
	Lifumba	Shallow Well (Pumping)	100	23	265 (100)	8	6
	Mtengachako	Shallow well	15	5.5	52 (24)	11	8
	Nakatale	Treadle pumps	20	15	98 (46)	5	6
	Total					**32**	**20**
Karonga	Hara	Diversion	238	238	631 (90)	4	11
	Lufilya	Diversion	800	400	1145 (378)	4	6
	Mphinga	Diversion	405	300	647 (164)	13	Na
	Timoti	Diversion	75	27	128 (56)	12	10
	Wovwe	Diversion	450	365	1110 (363)	10	8
	Total					**43**	**35**
Nkhotakota	Bua 1	Diversion	380	45	711 (250)	8	19
	Bua 2					6	9
	Bua 3					9	9
	Total					**23**	**37**
Total						**98**	**92**

5.3.3.2 Focus group discussion design.

The focus group discussion was designed following the same themes as the district stakeholder workshops with slight modifications to the specific questions to reflect circumstances and social interactions at the scheme level. For instance, the mapping of water resources in 'theme 1' for the district stakeholder workshop put emphasis on water resources at the district level while the spatial extent in the vicinity of the irrigation scheme was the focus of the water resource mapping in the focus group discussions. The relationships between WUAs and district authorities were also viewed from the position of the WUA rather than that of the district authorities as is the case with the district stakeholder workshops. The emphasis of some guiding questions was also differentiated based on focus group – i.e., whether irrigating or non-irrigating farmers. Annex 4 is the checklist for the focus group discussions.

5.3.4 Analysis of stakeholder workshops and farmer focus group discussions

Notes and audio recordings of the stakeholder workshops and focus group discussions were transcribed and analyzed in NVIVO. Patterns and thematic areas for analysis were generated and presented the basis for comparison and generalization of patterns at one level (i.e., comparison between stakeholder workshops or focus group discussions), and the route for comparison across the different levels (i.e., comparison between stakeholder workshops and focus group discussions). Nodes and classification codes in NVIVO were informed by the themes of the workshops and focus group discussions. Each theme forms the broader category (parent node) within which sub-themes and categories (as sub nodes in NVIVO) were developed to identify the patterns and interactions within and across scales.

Cross-scale relationships were examined based on how similar themes and sub-themes relate horizontally across different irrigation schemes or districts, and vertically between scheme and district levels of decision making. The grassroots level of analysis in this case was the irrigation scheme rather than the river basin given variations in the sizes of the river basins within which the different schemes are situated. For example, Bua irrigation scheme is in Nkhotakota district but the Bua River basin itself flows through four districts. Themes and patterns at the district and scheme levels were further compared to themes and patterns governing the constraints for irrigation development targets at the national level as identified from the policy analysis. Emphasis was also placed on understanding how the relationship between different themes at one level relate to relationships between similar themes on another level. Deliberate emphasis focused on identifying the existence of negotiation spaces and platforms for deliberate engagement by players at the different levels of decision-making and implementation.

The level of analysis for the climatic and non-climatic constraints for future irrigation development was the district. For the stakeholder workshops, the factors would have been identified right in the workshop given that one stakeholder workshop was conducted per district. The focus groups were aggregated at district level in which case the scenario matrix is based on the union set of factors identified in each focus group discussion. Scenario matrices are disaggregated by farmer cohorts to identify relationships and gaps between the two cohorts of farmers and how each relates to priorities and concerns at the district level.

5.4 Ethical considerations for stakeholder workshops and focus group discussions

Prior to undertaking the exercise, ethical clearance was sought and granted by the ESSL, Environment and LUBS (AREA) Faculty Research Ethics Committee at the University of Leeds in 2019. The ethics approval is attached as Annex 5. A key ethical consideration was the informed consent of the participants, as well as the security of their biodata and information provided during the discussions. Consent forms and information sheets were provided to study participants and, in instances where these needed to be read out to them, the researcher took on the responsibility to do so. The consent form, which was submitted along with the ethics application form to the University Research Ethics Committee, is also attached as Annex 6.

Responses provided by workshop and FGD participants were anonymized to ensure data protection. References to responses in the synthesis and discussion of the results do not make mention of specific people or identifiers that would reveal their identities. Permission to take photographs and record (audio) during the workshops and focus group discussions was sought prior to the meetings in which case it was made clear to the participants that such media files would only be used for purposes of the study.

The Covid-19 pandemic meant that there would be a long break between the ethics approval and the actual fieldwork as travel and fieldwork activities had been suspended between 2020 and 2021. Infrastructural constraints meant that conducting the workshops and focus group discussions would be very challenging and impossible in some instances. As a result, data collection was delayed to such a time when international travel between the United Kingdom and Malawi was permitted. The delay also considered the regulations around gatherings in Malawi. When it was safe to proceed, measures were taken to ensure that participants were kept safe. Such measures included provision of face masks, hand sanitizers, as well as daily Covid-19 tests for the researcher and research assistants all of which were done voluntarily and with the consent of the participants and research assistants. The number of participants and meeting venues also considered arrangements for physical distancing.

5.5 Results

5.5.1 Timeline of national policies and milestone frameworks in agriculture, water, irrigation, climate change and development

The reflection on the integration of climate change in sectoral policies relevant to irrigation draws from the view that perspectives around climate change and their representation in public policy in Malawi and neighboring countries have changed over time (Pardoe *et al.*, 2018). As such, the analysis begins with a look at the timeline of policy development in the climate change, agriculture, water, and irrigation development space. Figure 5.3 shows the timeline for policy development at the national level in Malawi, highlighting milestone years when key policies and frameworks were adopted.

Sector

	Irrigation	**Agriculture**	**Water**	**Climate**	**Cross-cutting**
2000	Irrigation policy and development strategy				Vision 2020
2001	Irrigation act				
2002				Initial national communication	
2003					
2004				Environmental policy	
2005			Water policy		
2006				NAPA 1	MGDS 1
2007					
2008					
2009					
2010					
2011	Greenbelt initiative		Water resources investment strategy	Second national communication	MGDS II
2012				Climate change response strategy	
2013			Water resources act		
2014					
2015	Irrigation masterplan and framework for investment			-NAPA edition II -DRM policy	
2016	Irrigation policy	Agriculture policy		Climate change management policy	
2017					-MGDS III, -National Resilience strategy
2018					
2019					
2020					Vision 2063
2021				Third national communication	

Figure 5.3 | Timeline of policies and frameworks in irrigation management and development, and climate change management in Malawi.

The first National Irrigation Policy was adopted in the year 2000, coinciding with the adoption of Malawi's long-term development plan – the Vision 2020. 2001 saw the adoption of the National Irrigation Act, the legally binding statute to regulate irrigation management and development in the country. Importantly, these policy milestones came into effect before the National Environmental Policy and the National Water Policy were adopted in 2004 and 2005 respectively. This order of policy adoption has potential implications on how policies relate with each other with regards to water resources management and utilization as well as the extent to which they emphasize the threat of climate change.

Local policy emphasis on climate change starts to become evident with Malawi's first NAPA which was completed in 2006, building on the country's Initial National Communication to the UNFCCC in 2002. These very first climate change management frameworks provided a comprehensive assessment of the climate change threat and the necessary action to address impacts of climate change. Evidence of a step-change in climate integration into sectoral policies following the development of the NAPA in other African countries is available as shown by Pardoe *et al.* (2018) in the case of Tanzania, for example, where the first NAPA was developed around the same time as Malawi. The 2006 NAPA, coincided with the adoption of MGDS I, Malawi's overarching short-term development plan which acknowledged the impacts of climate change on water and sanitation in Malawi.

The MGDS II was adopted in 2011 and, included 'climate change, natural resources and environmental management' as one of its nine key priority areas. The specific goal for this priority area was to enhance resilience to climate change risks and impacts. In the absence of a climate change management policy, a Climate Change Response Strategy in the form of a white paper that would be developed into a policy was adopted in the year 2012. Other key milestones included the adoption of the National Climate Change Investment Plan as well as a range of projects in response to climate change. Key to irrigation development was the establishment of the Green Belt Initiative (GBI) in 2011 (now called the Green Belt Authority). The GBI was premised on the rationale that increasing drought frequency in a changing climate presents significant challenges that ought to be overcome by increased investment in irrigation.

> *"...Over-dependence on rain fed agriculture has led to low agricultural production and productivity due to weather shocks and natural disasters (unreliable rainfall patterns, erratic rains, dry spells, pest and diseases, droughts, floods etc..). This has led to low socio-economic growth and development in the country."* (Pp 8).

The completion of the Water Resources Investment Strategy in 2011 provided a technical basis for water resources development in which irrigation development and issues of climate change featured prominently. This was followed by the adoption of the 2013 Water Resources Act, replacing the 1969 Water Resources Act. 2016 saw the adoption of three key policies – the National Agriculture Policy, the new and revised National Irrigation Policy, and the National Climate Change Management Policy. This was preceded by the adoption of the 2015 Disaster Risk Management Policy and the National Irrigation Master Plan and Investment Framework (IMP).

The IMP offers a comprehensive evidence base, and pathways for action in development of new irrigation schemes and landscapes vis-à-vis sound management of existing schemes. Threats and constraints for irrigation development – including climate change – are substantively explored in the IMP, a substantial part of which maps the potentially irrigable areas in Malawi, considering physical factors necessary for irrigation development as well as water allocation for other needs. The irrigation masterplan is in line with the National Water Resources Masterplan which was jointly developed by the Malawi government and Japanese International Cooperation Agency (JICA). While being a long-term framework, the IMP is phased such that its implementation is organized in three phases (2015-2020), (2021-2025), (2026-2035) which is key to short- to medium-term plans and integration of new and emerging knowledge.

While the timeline indicates dates associated with policy adoption, one must note that the period between a policy's initiation and its adoption may vary from one policy to another. One policy may be initiated and adopted while another, which was initiated much earlier, is still being deliberated. This can be attributed to several factors including the complexity of the policy contents – which may affect the deliberation process – the political will, as well as the occurrence of unprecedented events which can lead to the acceleration of adoption of certain policies. The latter was a key factor in the adoption of the Disaster Risk Management Policy, for instance. This followed a major flooding event in the aftermath of cyclone Bansi and tropical storm Chedza in January 2015, which led to hundreds of deaths and destruction of several billions worth of property. In the aftermath of the event, the adoption of the Disaster Risk Management Policy, in draft then, was expedited to provide guidance to stakeholders in disaster risk management.

The timeline of policy development in Malawi highlights that narratives in such policies are a product of their times, and somewhat guided by narratives in related policies that precede them. Policy initiation and adoption lags, including expedited policy adoptions for various reasons may challenge this view, however. Previous studies such as that of Chinsinga and Chasukwa (2018) note such apparent lags in the context of the climate change management in Malawi. While such lags and disparities are not highlighted in Figure 5.3, their potential influence on policy coherence with regards to perspectives around irrigation management and development is explored in the sections below.

5.5.2 Climate change perspectives in sectoral policies

Policy analyses focused on identifying and examining the narratives related to policy thematic areas associated with climate change and variability, water resources management, and irrigation development. The context and implied meaning of key individual climate references is determined, and main themes identified to establish the dominant narratives around climate change and variability in relation to irrigation management and development. These narratives are explored for three different classes of policies. The first class consists of sectoral policies – focusing on agriculture, irrigation, and water resources – and the manner and extent to which they account for climate risk. The second class of policies consists of climate policies in which the emphasis of the review is the manner and extent to which irrigation development and management is accounted for. Finally, the review explores irrigation development and management narratives in relation to climate risk across selected overarching (cross-sectoral) development policies.

5.5.2.1 Dominant narratives around climate change and variability in sectoral policies

Climate change and variability have been reflected upon to varying degrees within the three sectoral policies namely National Agriculture Policy (2016), National Irrigation Policy (2016) and National Water Policy (2005). Two main points of view are generally apparent. The first point of view identifies challenges related to climate change and the need to adapt through deliberate interventions targeting agriculture, irrigation, and water sectors. In this view, climate change is posited as a basis for the rationale behind irrigation and water development in the country. The second point of view acknowledges the threat of future climate change, and the constraints it imposes to future developments, specifically around water and irrigation development. This view identifies climate change as a risk factor imposing limits on the intended developments in the agriculture, water, and irrigation sectors. Table 5.4 illustrates the climate references across all three sectoral policies and the extent to which each policy contains the references associated with the two respective viewpoints.

Table 5.4 | Climate change and variability references in sectoral policies and their alignment with the two central narratives for climate risk and irrigation.

Sectoral Policy	References to climate change		
	Reference to climate as rationale for irrigation development	Reference to climate risk as a constraint for irrigation development	Total
National Agriculture Policy	14	3	17
National Irrigation Policy	4	2	6
National Water Policy	5	8	13
Total	23	13	36

The National Agriculture Policy identifies climate change and weather variability as one of the underlying causes of fluctuations in agricultural production to the extent that climate change forms the basis for some of the interventions advocated for in the policy. Climate change is not considered in isolation but rather as one of the many factors that interact to compound the challenges limiting the growth of the sector. The reference to climate change and variability is made 17 times, 14 of which qualify as belonging to the view point that climate change and variability is a problem that needs addressing through actions proposed in the policy, most of which are focused on irrigation. Reference to climate change and variability is extended to include reference to words such as droughts and floods both of which are collectively highlighted in the policy's implementation and monitoring plan, calling for the need to promote and adopt drought resistant or 'drought and flood tolerant' crops. One reference is noted as fitting both points of view:

'Climate change has enhanced biotic and abiotic constraints that demand continued development of improved crops that are tolerant of climate changes, while maintaining farmer and market preferred traits. In consequence, a resilience perspective that enables the country to prudently manage risk in the agriculture sector is necessary to avert calamities.' (Pp. 17)

Most of the references acknowledge the threat of climate change, but there is a lack of specificity in the nature of the changes and their associated impacts on the sector. While this is the case, planned annual policy reviews and five-year comprehensive reviews provide an opportunity for continuous integration of evidence of climate change and its impacts as well as plausible pathways for long-term adaptation. The lack of evidence in terms of national and grassroots impacts of climate change on agriculture may have been key to previous policies not giving thorough consideration of climatic risks for agricultural development in relation to irrigation development. Massive opportunities for integrating climate information in the agriculture policy are arising with improved understanding of climate risks in the agriculture and water sectors.

In most instances the basis for inclusion of aspects of climate risk in the policy is predicated on past climatic shocks. The prospect that such shocks increase in frequency underlies the agriculture policy's motivation to consider irrigation as central to adaptation goals for the sector. A major drought in 2004 is particularly singled out, with policy implications in its wake acknowledged while seasons with erratic rainfall in 1992, 1994, 2002, 2004, and 2015 are also highlighted as the underlying precursor for food crises that ensued then. It is viewed that irrigated farming would increase crop production and make it less variable in the face of increased weather variability. This view is collaborated in the national irrigation policy which is presented as *"one of the tools for adapting to climate change which allows crop production during droughts and dry spells" (Pp. 2).*

There is more weight towards the narrative that irrigation provides solutions to climate related challenges for agricultural production as opposed to the narrative that irrigation is, in itself, susceptible to climatic shocks. Some references reflect on both aspects in which case it may be difficult to assign the narrative with which they align based on a relaxed framework such as this. For instance, part of the National Irrigation Policy reads:

"*The NIP attempts to provide solutions to these challenges by addressing three priority areas of sustainable irrigation development, management, and capacity development. The policy acknowledges several opportunities that exist for accelerated irrigation development, namely; effects of climate change, public private partnerships, improved governance reforms in water and land management, and increasing interest by stakeholders." (Pp ix)*

Reference to issues of climate change and variability is vividly distinct between the 2016 National Irrigation Policy and its predecessor – the 2000 National Irrigation Policy and Development Strategy. The latter hardly touched on issues around climate change and neither did the 2001 Irrigation Act – the legally binding act of parliament that defines the legal issues around irrigation management and development in Malawi (a draft Irrigation Act was being developed at the time of the study). The previous irrigation policy had acknowledged the impact of droughts on agricultural production and the role of irrigation in alleviating them. However, there is no part suggesting that this thought guided the rationale, or any interventions advocated for in the policy. It is also clear that the 2000 National Irrigation Policy and Development Strategy hardly acknowledged the threat of climate change on future irrigation systems.

Current policies and plans are critical in the design of systems and investments that are future proof with respect to emerging threats from climate change among other risks. Notably, the review of the 2000 National Irrigation Policy and Development Strategy, leading up to the development of the 2016 National Irrigation Policy, was propelled by the need to consider *emerging* issues and developments in the irrigation sector among which was climate change. The use of the term 'emerging' highlights a temporal issue, key to explaining non-existent references to issues around climate change in the 2000 National Irrigation Policy and Development Strategy and their subsequent inclusion in the recent policy.

By the year 2000, no policy frameworks had been developed in response to the threat of climate change owing to, among other things, the limited evidence of changes in climate in Malawi and their associated impacts on relevant sectors. The Environmental Management Act (EMA) of 1996 and the National Environmental Action Plan (NEAP) of 1994 were the standard environmental policy frameworks at the time. Issues of climate change were not substantively discussed in the EMA while, despite the acknowledgement of climate change in the NEAP, the framing of climate change references indicates a potentially prevailing view that the evidence around climate change and associated impacts was only rudimentary at the time.

Further proof of the limited evidence at the time can be found in the Vision 2020, Malawi's long-term development plan adopted in the year 2000. The Vision 2020 acknowledged the threat of climate change but viewed it as a global issue that required the contribution of nations to be managed, clearly downplaying threats at the national level. One statement acknowledges that *"air pollution and climate change issues are currently relatively small environmental concerns"* nevertheless calling for the need for efforts to manage them before they become serious problems. No strategic sector-specific interventions in managing climate change and responding to variability were proposed in the Vision 2020, with specific climate action points being along the lines of awareness campaigns and education. Despite this limited view on climate change, the need to develop irrigation to 'stabilize' crop production in times of drought is acknowledged, with irrigation development being one of the strategic priority areas. Threats to irrigation development emanating from climate change were effectively disregarded in this view.

The turn of the 21st century saw a further development of issues around climate change including the development of the NAPA in 2006 and more in-depth discussions of the threat that climate change poses on human systems, including more strategic – and sometimes sector-specific – interventions to address it in sectoral policies such as the 2005 National Water Policy. By then, Malawi had also submitted its Initial National Communication to the UNFCCC in 2002 and undertaken efforts to establish climate policies.

The acknowledgement of the threat of climate change becomes more evident in the 2005 National Water Policy which notes climate change and variability as one of the challenges the water and sanitation sector is faced with. The National Water Policy followed the development of ground-breaking work in the climate change policy space – particularly the development of Malawi's Initial National Communication to the UNFCCC while the first NAPA was also being developed at the time. With growing evidence and resources in relation to assessment of the threat of climate change, a platform was created that would permit more meaningful integration of climate change and variability in sectoral policies. Of the 13 climate references in the National Water Policy, the majority align with the viewpoint that climate change and variability impose threats that should be navigated by the provisions in the policy. One of the key guiding principles of the policy is that:

> *'There shall be no agricultural and infrastructure construction activities below the 477-meter above mean sea level contour line along Lake Malawi and below the 100-year flood water level along rivers, except where written communication from the responsible minister is granted.'* (Pp 7)

The implications of such a principle with regards to water and irrigation development in a changing climate cannot be overemphasized. Changes in the climate may be such that water levels corresponding to such 100-year return periods may change over time. Implications of developments guided by such a threshold may be different in different climates. The use of climate information is thus paramount if such decisions are to be objectively guided. The role of meteorological data was emphasized in the 2005 National Water Policy with four references specifically highlighting the need for making necessary climate information – including early warnings as well as weather and climate *'forecasts'* – available for water resources management.

Climate specific provisions in the 2005 National Water Policy are also echoed in the 2013 Water Resources Act. The reference to climate in relation to water resources is prominent, forming a core part of the Act and its various provisions. While the Act does not necessarily address changes in climate over time, its contents have temporal implications that could influence both action and directives in relation to water resources management in a changing climate. For instance, specific reference to drought features conspicuously in the Water Resources Act. Reference is specifically made in Section 65 of the Act which prescribes emergency powers to the relevant minister in case of serious water shortages preceded by a drought – therein defined as an exceptional shortage of rainfall – or an accident or other unforeseen circumstances. A ministerial declaration is a requisite for any area to qualify as – by the definition of the Act and its implications – being under drought. Actions pertaining to the distribution of water under such conditions are outlined, with legal implications succinctly elaborated. Further implications in relation to droughts are also outlined in the Section 86 under Part VII. Under this section, the Act outlines provisions in relation to protected areas and controlled activities which, among other things, indicates that an area under drought may be temporarily assigned the status of a protected area.

5.5.3 Irrigation perspectives in climate change policies and frameworks

References to irrigation development were examined in climate change management frameworks. Such frameworks include the 2021 Third National Communication to the UNFCCC; the 2016 National Climate Change Management Policy; the 2015 National Disaster Risk Management Policy; the 2015 Nationally Adopted Programmes of Action (NAPA - second edition); the 2012 National Climate Change Response Strategy; the 2004 National Environmental Policy. These frameworks were deliberately excluded from the examination of climate change references given that this would be their primary topic thus making the comparison less objective. The underlying assumption for the disaggregation of policies was that the examination of climate references in sectoral policies and the examination of irrigation references in climate change frameworks would help identify points of convergence and/or diversion between the two classes of policies.

Table 5.5 highlights the extent of references to irrigation in the various policies and the narratives against which such references are made. The extent to which issues of water and irrigation development are highlighted in climate change policies and frameworks is variable. References to irrigation in the context of climate change are generally characterized by two dominant viewpoints. The first viewpoint acknowledges the impacts of climate change on agricultural production and suggests irrigation as a solution to alleviating climate-related production challenges. This is supported by the view that, failings in the agriculture sector can be attributed to an overreliance on a somewhat poorly developed and underperforming rainfed agricultural system while noting the opportunities that exist for irrigation development given available water resources. The second viewpoint acknowledges the impact of climate change on irrigation itself, and the need to adapt irrigation systems to climate change. The two viewpoints are not contradictory but have the potential to create conflicting or unbalanced and incomplete solutions with regards to irrigation development in a changing climate.

Table 5.5 | Irrigation references in climate change policies and management frameworks. Policies with zero references are included for context. It should be noted that references are limited to those references in relation to irrigation with respect to the two central narratives. References to irrigation may be found in such policies but they were discarded if they were not presented with respected to the two narratives of interest.

Climate Change Policy	References to irrigation		
	Irrigation as an adaptation strategy	Susceptibility of irrigation to climate change	Total
INC	4	6	10
Environmental policy	0	3	3
NAPA 1	1	2	3
NAPA 2	10	4	14
NDC	10	1	11
TNC	23	7	30
Climate Change Response Strategy	0	0	0
Disaster Risk Management Policy	0	0	0
Climate Change Management Policy	0	0	0
Total	48	23	71

5.5.4 Climate change and irrigation perspectives in overarching policies

Finally, the examination looks at how overarching or cross-cutting development frameworks frame the relationships between climate change and irrigation. Given the emphasis on the range of issues and their interaction in the policy and development space, the underlying assumption is that there is reasonable representation of issues of interest in cross-cutting policies as opposed to sectoral policies where the theme is typically unilateral. The view is that examining how both climate change and irrigation are referenced in one document would not present challenges where one theme is predominant and makes the comparison less objective.

Three cross-cutting policies were examined. These include the Malawi Vision 2063, adopted in 2021; the 2016 National Resilience Strategy; and the Malawi Growth and Development Strategy III (2017) (and to some extent its predecessors – MGDS II (2010) and MGDS I (2006)). Table 5.6 illustrates the references to irrigation and climate change across the three overarching frameworks. The dominant narrative surrounding irrigation development in the context of climate change is governed by the view that irrigation offers the solution to managing impacts of climate change on agriculture and food production. This is the case across all three frameworks with references to irrigation being susceptible to the impacts of climate change being relatively fewer.

Table 5.6 | References to irrigation development and climate change in cross-cutting development frameworks and the frequency with which they reflect the two central narratives.

Climate change policy	References to irrigation		
	Irrigation as an adaptation to climate change	Susceptibility of irrigation to climate change	Total
MGDS III	41	20	61
NRS	37	6	43
Vision 2063	7	0	7
Total	85	26	111

The level of detail in terms of the reference to irrigation varies from one policy to the other with more references identified in the Malawi Growth and Development Strategy. Being a relatively short-term plan, the MGDS outlines specific actions to achieving irrigation development including projects and programmes proposed in line with the same. As with all other development targets, irrigation development references in the Malawi Vision 2063 are at a much higher level and therefore do not extend to elucidate details to similar lengths as observed in the short-terms plans. It is, however, anticipated that the short-to-medium-term implementation plans for the Vision 2063 will cover such topics in greater detail in which case opportunities for identifying gaps and scope for climate integration could be identified.

In its current status, and in the context of climate change, the Vision 2063 largely refers to irrigation as being key to developing resilient agricultural systems, yet again setting off from the point of view that attributes limited growth of the sector to shortcomings in rainfed agricultural systems. The Vision, however, makes references to climate smart agriculture and, somewhat synonymous with the 2016 National Irrigation Policy, repeatedly calls for the development of ‘sustainable’ irrigation systems. It is not clear, however, as to what constitutes a sustainable irrigation system in this view. Part of the Vision recognizes irrigation as a climate smart agriculture strategy in the process emphasizing the need to foster ‘approaches’ to avert adverse climatic variability.

> *"We recognize that increasingly variable and adverse climatic conditions continue to affect our rain-fed agriculture system. Broad investment in sustainable irrigation systems and technologies as well as approaches to averting adverse climatic variability will be prioritized"* (Pp 15).

5.5.5 Specific governance provisions with respect to multi-level governance of water and irrigation development

Narratives and perspectives around irrigation management have the potential to influence governance provisions with regards to managing climate risks for irrigation development. The nature of irrigation and water resources governance is, in itself, layered, with potentially different views underlying climate risk perception and irrigation governance at each level. In the policy landscape, governance structures and provisions are reflective of the multi-level governance nature of the water and irrigation management and development space. For instance, the 2013 Water Resources Act provides for the establishment of the National Water Authority which is supposed to work in liaison with the ministry on issues of water governance at the national level while making provisions for grassroots management structures such as catchment management committees and water user associations. In this regard, multi-level provisions of the trickling down of authority from the national to the community level provides an indication of the will to decentralize authority in water resource management.

Paramount authority rests at the national level with the responsible ministry who, in liaison with the National Water Resources Authority, has the powers to disestablish the water user association if that course of action is deemed necessary. The duties of the WUAs are outlined in the Water Resources Act. They are largely underpinned by the need for equitable distribution of water resources among all water users. Central to the establishment of the water user association is the resource, and not necessarily its intended use such that an association may comprise members that relate differently to the water resource. This provision is particularly essential with regards to understanding the composition of water user associations in irrigation schemes.

While providing general directions in relation to authority established to oversee management of water resources, the 2013 Water Resources Act does not provide specific guidance with regards to such authority in relation to irrigation management beyond giving the minister the authority to appoint the secretary responsible for irrigation. Irrigation management authority is rather outlined in the 2001 National Irrigation Act which also makes provisions for cross-scale establishment of authorities to oversee irrigation management and development. The 2016 National Irrigation Policy stipulates that the ministry is at the ‘center’ of irrigated agriculture development, highlighting shared responsibilities among the various departments within the ministry other than the department of irrigation. These provisions indicate that the irrigation scheme, and the authority responsible for its governance is an entity different from the water user association.

The National Irrigation Board is a key institution at the national level whose main role is to monitor the progress of irrigation development and management at the national level in compliance with irrigation standards and guidelines. Provisions guiding the establishment of the board are outlined in the 2001 Irrigation Act, while its role in irrigation development and management is clarified in the 2000 National Irrigation Policy and Development Strategy. A key mandate of the National Irrigation Board is to ensure that proposals for development are not contradictory or overlapping but are mutually supporting and forming a coherent policy framework.

5.5.6 District level perspectives

District stakeholder workshops provided insights into irrigation management and development at the district level. District officials are an essential player in irrigation management and development owing to their engagement with national policies on the one hand, and irrigating communities on the other. The extent to which each of such roles is played varies from one department to another as district officials under specific line ministries engage with policies developed under the mandate of their ministry. Policy provisions relating to irrigation development vary from one policy to another thus providing the scope for each sector’s involvement in irrigation activities at the district level. The interactive nature of the irrigation space means that a wide range of district stakeholders engage with irrigating communities, albeit for various aspects of irrigation management (e.g., crop management, water resources management, land resources management).Thus, other than the Department of Irrigation, district officials from other departments including the Department of Agricultural Extension Services, Department of Water Resources, Department of Land Resources Conservation, and Department of Crops also interact with irrigation schemes or WUAs from time to time. Government ministries tend to be restructured from time to time but, in most cases, all these departments tend to be under the Ministry of Agriculture.

The extent of interaction between different departments and irrigation schemes varies from one department to the other. It was apparent from the workshops that the Department of Irrigation engages the most with irrigation schemes. Except for Balaka district, participants generally indicated that WUAs are formed, and typically operate, around irrigation schemes. Grassroots focus group discussions would confirm the existence of functional WUAs or lack thereof across the irrigation schemes that participated in the study. The organization of irrigation and water governance structures at the grassroots levels is critical for the trickling down of climate risk management responsibility and the perceptions on which it is centered.

5.5.6.1 Irrigation management

Assertions from all three district stakeholder workshops indicated that irrigation was done throughout the year. In the rainy season, where such infrastructure is available, irrigation is done to supplement rainfall deficits, but the emphasis was on total irrigation during the dry season. In each case, participants noted a range of water resources within their district, each with a different degree of utilization for a particular use. Such water resources included rivers (mostly perennial) and boreholes as well as lakes for Karonga and Nkhotakota districts, and shallow wells for Balaka district. Most of the irrigation – the biggest reported user across all three districts – is developed from river diversions but the shallow wells are also a key source of water for irrigation schemes in Balaka.

The seasonality of irrigation water use is apparent given the varying irrigation water needs in the rainy and dry seasons, as highlighted in Chapter 4, and confirmed by the workshop participants. Rice is the main crop grown under irrigation in Karonga and Nkhotakota districts. This is the case for both the rainy season when irrigation is supplementary, and the dry season when irrigation is the primary source of water. Participants in Balaka indicated that there are variations in the choice of crops grown during the rainy season and under irrigation with participants highlighting that *"high value"* crops are preferred for the irrigation season. Despite this view by authorities, it was reported that they have no influence on the choice of crops that are grown under irrigation. One participant noted:

> *"Our role as district office bearers is not to dictate what farmer grow. We only offer guidance and advise farmers on what are the most*

profitable crops that would suit the growing conditions and their capital."

The indication that farmers themselves have the autonomy to decide which crops to grow is essential for policy implications given the power dynamics that are characteristic of the irrigation management space, often reflected through such issues like which crops are grown in which areas. Similarly, all three district workshops indicated that the district authorities have no influence on individual farmer access to irrigation schemes. Arrangements with regards to who accesses irrigation are made at the local level with the role of the district levels reserved to ensuring that support is available to ensure wider access. Such support may be in form of operation and maintenance interventions and the establishment of new irrigation schemes.

5.5.6.2 Climate hazards and risk management for irrigation management

Participants identified climate hazards that impact irrigation activities in their respective districts. Such climate hazards also prompt specific actions with respect to management of water resources and allocation regulations but the extent to which this is carried out is not thoroughly organized. Special regulations in line with climatic shocks have been outlined in the Water Resources Act, giving the responsible minister the authority to declare restrictions in the event of a drought for example. Incidentally, droughts – and dry spells – were identified as a major climate hazard across all three districts, along with floods and erratic rainfall. The impact of floods in Balaka is however localized, generally affecting areas close to the Shire River towards Mangochi district. Early cessation of rainfall was specifically highlighted for Balaka district while pests and diseases – which participants felt have climatic associations – were specifically noted for Karonga district.

Table 5.4 shows the various coping strategies that are promoted or coordinated by the district stakeholders across the three districts. Coping mechanisms are hazard-specific but can be broadly classified as proactive/anticipatory or reactive. The scale of interventions is variable and not limited to the irrigation scheme as some strategies target the whole catchment area and are, to an extent, designed to address wider livelihood issues rather than being limited to issues specific to irrigation management. In this view, different government departments play different roles in addressing specific challenges associated with climate variability some of which converge towards addressing irrigation management in one way or the other. Other measures such as diversification with livestock are aimed at sustaining livelihoods in instances where agriculture sector-wide impacts are severely pronounced to the extent that irrigation – viewed as a coping strategy – is not sufficient.

Table 5.7 | Coping measures identified by workshop participants across the districts.

District	Coping mechanisms for climate hazards promoted or facilitated by the district stakeholders
Balaka	Flood early warning systems in flood-prone areas Groundwater monitoring systems Flood control infrastructure Gully reclamation Practices to minimize soil water losses
Karonga	Upland catchment management (including promotion of conservation structure) Reducing the area under irrigation during low water supply instances Planting disease-resistant varieties Integrated pest management Construction of dams for water storage and flood control
Nkhotakota	Planting drought-resistant and early maturing varieties Afforestation Rainwater harvesting Conservation agriculture Diversifying with livestock Manure application

Specific interventions for the irrigation sector include both water management practices as well crop management practices aimed at reducing irrigation water demand. For instance, rainwater harvesting was identified across the three districts which, especially for Karonga district, is also integrated with flood control measures. Participants from Karonga districts also highlighted the deliberate reduction of the area under irrigation during instances when there is low water supply (owing to climatic shocks rather than seasonality). Crop management practices generally draw from soil and water conservation principles of conservation agriculture. Such measures were specifically identified for Karonga and Nkhotakota districts. Conservation agriculture has been widely promoted as a key measure for moisture conservation and managing the impacts of droughts and dry spells, albeit with underwhelming levels of adoption (Chinseu *et al.*, 2019; Hermans *et al.*, 2021) and no evidence of its extensive use in irrigated fields.

5.5.6.3 Self-determined constrains for irrigation development

Constraints for irrigation development were identified and accordingly classified as climatic and non-climatic in nature. For each constraint, implications were suggested for access to irrigation, other water needs, and the general state of water resources for the next 10 – 30 years. Table 5.8 provides a summary of the list of constraints that were identified across all three workshops and their implications for access to irrigation, general state of water resources, and other water demands. Access to irrigation was in this case based on availability of land for irrigation development as well as water resources to permit development of new schemes and sustaining existing ones. Implications for other water needs were determined based on what a given constraint would entail for water needs beyond irrigation assuming that irrigation was prioritized. The general state of water resources was determined based on perceived implications for both quantity and quality of water to sustain human life and support ecosystems.

The implications are color coded using a traffic light system to indicate the perceived impact associated with a given constraint on access to irrigation, state of water resources and other water needs. Green indicates the most desirable outcome while red indicates the least desirable outcome for that aspect due to the trajectory for that constraint and its perceived impacts. Orange indicates no definitive direction in terms of the outcome being overly negative or positive in its influence on irrigation development and associated implications for water resources. As constraints were self-determined, participants were not asked beforehand how they thought any climatic constraints would constrain irrigation development. This was only teased out as a follow-up question in cases where no climatic constraints were mentioned in the first instance.

Three main constraints were identified for Balaka where participants noted population growth and levels of investment towards irrigation development as the key non-climatic constraints for irrigation development in the next 10 – 30 years. Climate change was also highlighted as a key constraint, citing changes in precipitation patterns and frequency of droughts and dry spells as key climatic aspects the direction of whose change would either facilitate or impede irrigation development. Climatic constraints in the districts have been pronounced historically and these have been compounded by other natural factors. One participant noted that land suitable for irrigation in Balaka was a pre-existing issue given the limited proximity to reliable water bodies and predominantly saline soils that are not suitable for irrigation. Uncontrolled population growth would magnify challenges associated with land on top of heightening the demand in a historically water scarce district.

Table 5.8 | Self-determined constraints for irrigation management and development at the district level and the implications of different constraints trajectories for access to irrigation, state of water resources and other water needs. Colour codes indicate what each scenario would entail for access to irrigation, state of water resources and other water needs with green being ideal, gold being manageable, and red highlighting a significant impediment for growth.

District	Constraint	Change in positive direction			Change in negative direction		
		Access to irrigation	State of water resources	Other water needs	Access to irrigation	State of water resources	Other water needs
Balaka	Population growth						
	Investment						
	Climate change						
Karonga	Water availability						
	Land availability						
	Development cost						
	Climate change						
Nkhotakota	Soil and water resources						
	Population growth						
	Forestry resources						
	Dry spells and erratic rains						

Common themes with regards to constraints for irrigation development are clear across the three districts albeit with differences in the way in which such constraints are viewed and expressed. For instance, land and development costs for irrigation were identified as the main non-climatic constraints for irrigation development in Karonga while climate change and water availability were the main climatic constraints. Participants noted that population growth would play a vital role but that its influence would be reflected through specific aspects of irrigation, especially land and water, hence making explicit reference to such. Population growth was also specifically highlighted for Nkhotakota district where issues of water – viewed collectively with soil – were also highlighted. Unique to Nkhotakota, forestry resources were also identified as a key constraint for irrigation development where participants cited impacts of deforestation on soil erosion and siltation. Soil erosion and siltation of rivers were identified as some of the main challenges associated with irrigation management due to their impacts on riverbed conditions and soil deposition into irrigation canals.

5.5.7 Farmer perspectives

Focus group discussions provided the basis for examining grassroots perspectives and governance issues including self-determined (by farmers) constraints for irrigation management and development in the face of climate change. Farmers' perceptions of climate risk and the relative importance of climatic constraints against a range of other non-climatic limitations are guided by several factors. Perceptions about the nature of change in different aspects of the climate have been found to influence on-farm choices in Malawi, including decisions around maize varieties to grow in relation to changes in season length for instance (Sutcliffe *et al.*, 2016). The role of climate information in supporting farmer decisions is key to adaptation decisions but providing the right information is key to coupling such information, perceptions, and experiences to identify the best actions to address the relevant risks.

It is key to note that farmer perspectives were examined at the irrigation scheme level such that the interpretation of risk and constraints for irrigation development is principally from a collective point of view. Smallholder irrigation in Malawi is generally a collective venture with an irrigation scheme being the primary level of organization to promote the sharing or resources, mainly technologies for water access. The organization around water resources and sharing of the same often means that irrigation schemes operate as one and the same thing as – or hand in hand with – WUAs. For most cases, the water user associations were reported as the standard governing structure for irrigation management at the grassroots level. As noted in the grassroots focus group discussions, not all sites were managed by a well-defined water user association – at least that which is legally defined in the water governance statutes in Malawi, reflecting admissions from the district stakeholder workshops.

Procedures regarding the establishment of WUAs in relation to irrigation schemes can be traced through historical narratives surrounding irrigation development and associated policy reforms in the sector. Most large-scale irrigation schemes were constructed soon after independence in the late 1960s and early 1970s. This was the case for Bua Irrigation Scheme in Nkhotakota district as well as Wovwe Irrigation Scheme, Hara Irrigation Scheme, and Lufira Irrigation Scheme in Karonga District. Management of such schemes was overseen by the Taiwanese Government through the Taiwanese Agricultural Technical Mission (Gwiyani-Nkhoma, 2011) with locals working at the irrigation schemes – operating as mini factories – as tenants.

Changes in the Chinese/Taiwanese foreign policy, which included withdrawal of funding support for the irrigation schemes, coupled with local economic challenges saw the gradual shift in irrigation scheme ownership, management, and resource provision. Most of irrigation schemes would be handed over to the communities between 1980s and 1990s, creating a basis for the need to create water user associations through which water abstraction licenses are provided. WUAs can be established wherever there is water infrastructure that is not necessarily meant for irrigation as was indicated by participants in the stakeholder workshop in Balaka district. It is apparent that the establishment of WUAs is not a prerequisite for the establishment of farmer-led irrigation schemes that are not characterized by significant infrastructural developments or significant abstraction activities that require licenses.

The general roles for water user associations are enshrined in the 2013 Water Resources Act. The operation of the WUAs established in relation to the irrigation schemes is unique, however, in the sense that it is primarily made up of farmers practicing irrigation in the irrigation scheme. The WUA is the primary group to which water rights for the sake of the irrigation scheme are awarded by the government. They are the custodian of abstraction licenses. Where irrigation schemes exist without WUAs, laws in relation to water use are not strict but there is an indication that government is committed to facilitate formal processes for the establishment of water user associations to safeguard the interests of all water users and ensure that access to water by irrigation schemes is not compromised.

Water user associations are legal entities which operate as small water boards, responsible for overseeing operation and maintenance of rural piped schemes. The primary functions of the WUA are succinctly outlined in the 2013 Water Resources Act and their formation and operations are legally defined as transcending the frontiers of an irrigation scheme. Mdee and Harrison (2019) highlight the rationale behind WUAs as a collective form of solving the competing interests of water users. Specific to irrigation management, irrigation management authorities are the community level committees mandated by the 2001 Irrigation Act to oversee irrigation management at the local level. Such committees can include an irrigation scheme, club, cooperative or association. Interactions with district stakeholders did not provide indications that the role of the WUAs was defined as such, with no further indications by the irrigating farmers that there was a level of separation between the WUA and any other committee that would identify as an irrigation management committee.

As the primary custodian of water rights and abstraction licenses, the water user associations essentially operate as the local irrigation management authorities in this case. Access to the irrigation scheme by individual farmers is through the WUAs and – where WUAs were more formally established – access was through payment of access fees which comprise a membership fee, plot fee, and water fee. The actual process of one becoming a member of the scheme varied from scheme to scheme with other schemes, especially those with less formally established associations, providing membership through customary ownership of a plot within the scheme. This arrangement was also found to be the case in Mphinga irrigation scheme where a formally established WUA is operational but notably established at the same time as the irrigation scheme in 2008. The institutional arrangement with respect to irrigation management is essential for both risk perception and conception of solutions to manage climate risks particularly in contexts where climate risk and adaptation decisions affect different users in different ways.

Beyond the institutional arrangements, the perception of climate risk is generally influenced by the medium of production which, for irrigation, constitutes both land and water. Participants identified and mapped water resources in their vicinity, in each case identifying the water use associated with each resource. Agriculture was universally identified as the main water user in terms of volumetric consumption, but domestic utilization was more critical in terms of the frequency of utilization and the purposes for which water is used. Uses such as tourism, fishing and navigation were more important in areas close to Lake Malawi and Shire River. Despite authorities from the respective districts identifying Lake Malawi and Shire River as being critical water resources for their districts, their relevance to the grassroots communities varied from one area to the other depending on the extent of their interaction with the resource. Figure 5.4 is an example of the map produced by irrigating farmers at Bua irrigation scheme, showing the location of various water resources with respect to the location of the irrigation scheme.

Figure 5.4 | An example of a community water resource drawn by participants in one of the FGDs.

Farmer perception of climate risks for irrigation and the potential to develop or expand irrigation systems stemmed from their understanding of water resources in their vicinity and their interaction with the water resources to provide necessary services on top of irrigation. Irrigation schemes are generally developed around more reliable water resources where, in this case, reliability was generally viewed as the ability of the resource to provide water all-year round. In general, this would mean a perennial stream that has reliable flows even during the dry season when irrigation demand peaks. The potential for irrigation development at different scales is overlay underlain by the availability of water resources to support and sustain irrigation activities. The implications for climate change are rooted in this aspect of irrigation development.

Secondary factors for irrigation development are key for providing the context in which climate risk is perceived and solutions for which are conceived. Such secondary factors include aspects of irrigation management and development beyond land and water resources. Key to this is the 'technology' used to transfer water from the source to the field and the ability of such technologies to transport enough water to sustain irrigation activities during periods of seasonal low flows and diminished supply due to episodic scarcity. Agronomical practices at the irrigation scheme are also essential for farmer encounters with climate risk and how decisions to address such risks are made. Except for Timoti irrigation scheme, rice was the crop of choice across irrigation schemes in Karonga and Nkhotakota district while only farmers at Khwisa irrigation scheme acknowledged to prioritize rice with the rest growing a variety of crops including maize, legumes, and leafy vegetables. The choice of crop, resting with farmers in this case, is guided by the suitability of the crop to the conditions of the area, as well as water availability. In turn, it affects the amount of water that is required to meet its crop water requirements as well as agronomic practices that can be employed to offset climate related challenges, some of which may be particular to a crop.

Climate hazard is a primary constituent of climate risk and therefore primary to the discussion of farmer perception of climate risk and the interpretation of how it translates to implications for irrigation development. Farmers identified a range of climate hazards that have had an impact on irrigation management in recent years. Hazards were generally associated with rainfall and included late onset and early cessation of rains, erratic rainfall, and extremes at both ends i.e., droughts and dry spells and flood causing heavy rains. Tours of irrigation schemes confirmed damages caused by recent flood events while farmers indicated that impacts of droughts and dry spells are reflected in reduced water levels during the dry season. In fact, the reservoir at Khwisa irrigation had very low water levels at the time of the study (Figure 5.5) with fears that it would not be enough to support irrigation activities for the rest of the season if irrigation potential was to be fully met. Farmers attributed the low water levels to low yield associated with below normal rainfall in the previous rainy season.

Figure 5.5 | Water levels in the reservoir at Khwisa irrigation scheme in Balaka district just before the end of September 2021.

Farmers identified both anticipatory and reactive coping mechanisms and adaptation strategies to sustain irrigation in the face of climate hazards. In most cases, the water user associations indicated that they help facilitate catchment protection activities including reforestation of upland areas and they viewed this as one way of limiting the impacts of climatic shocks. Reforestation efforts are also undertaken to address wider catchment degradation issues the impacts of which can be reflected in siltation of rivers as well as silt and sediment accumulation in irrigation systems (heads and canals). The latter is a recurring issue that most of the irrigation schemes face and one that bloats operation and maintenance costs from time to time.

When faced with low water supply, irrigation schemes are forced to cultivate only a part of the irrigation scheme. Over time, however, this has become a permanent, rather than episodic issue, due to low water supply resulting both from diminished river flows and deteriorating infrastructure. The glaring impacts of low water supply and failure to get water to the remotest parts of an irrigation scheme were more apparent in Lufilya irrigation scheme where 200 of the 400 hectares of the scheme are left uncultivated in the dry season when crops are grown under total irrigation. Similar issues were noted in Bua irrigation scheme. In Wovwe irrigation scheme, water shortages prompted farmers to grow maize and legumes in the remote parts of the scheme, instead of rice which is the priority crop. Consequently, diminishing water supply and the declining capacity of irrigation infrastructure was identified as one of the most pressing challenges for irrigation management and development.

Farmers identified other challenges that transcend the typical frontiers of the irrigation scheme. These included access to capital and better markets for their produce. Farmers indicated substantial variability in terms of arrangements for selling off their produce. Most schemes primarily grow rice, but the mode of sale varied from one scheme to the other as some farmers usually sell it individually while some sell as a collective, often operating as a cooperative. In some instances, a cooperative was operational within the scheme, but farmers did not have the obligation to join the cooperative simply by virtue of them being members of the scheme, a rather different arrangement from the WUA membership where all farmers are members by virtue of farming in the scheme. Cooperatives operate as a separate entity, concerned with marketing and, in some cases, value addition.

Questions around marketing were not explored in more detail to avoid straying off the scope of the study but there was an indication that selling rice through the cooperative provided an opportunity for better markets (where better market is essentially defined by the price at which the produce is sold). In most cases, however, cooperatives sell the produce much later, which may not align with the immediate financial needs of the farmers that eventually opt to sell their commodities independently. For irrigation schemes that grow freshly harvested crops (e.g., leafy vegetables at Mtengachako irrigation scheme in Balaka and freshly harvested maize at Timoti irrigation scheme in Karonga), crops are sold right on the garden to roaming middlemen due to the lack of storage facilities that could allow farmers to store their produce and sell at a later stage. Such aspects of production were highlighted with overwhelming frequency to an extent indicating the holistic view of farmers in terms of what constitutes a successful irrigation venture. Remarkably, issues of marketing were also highlighted as being a key constraint for irrigation development in the next 10-30 years.

5.5.7.1 Constraints for irrigation development at the grassroots level

Constraints for irrigation development emanate from the challenges encountered by farmers in carrying out their irrigation activities. Irrigating farmers identified a range of constraints that are both climatic and non-climatic in nature. Where climatic constraints were not identified in the first instance, the discussion probed further to deliberately ask farmers' perceptions of climate risk and how irrigation development in the next 10 to 30 years could be constrained by changes in climate. Except for irrigating farmers at Mphinga irrigation scheme in Karonga district, all participants indicated that changes in climate have some sort of implications for irrigation development.

Climatic constraints generally bordered around rainfall aspects including onset and cessation, cumulative rainfall over the year, and extremes in form of droughts or dry spells and flood-causing heavy precipitation. Prospective changes in temperature were not widely identified as having the potential to influence irrigation management and development. In general, farmers are more *intimately* connected to rainfall and water resources than they are to temperature, even though its influence on crop water requirements and effective precipitation is essential for irrigation – more so in a warmer climate as shown in Chapter 4. Only one group was on hand to point out impacts of temperature on rice growth and development but the rest of the groups that acknowledged climate risks for irrigation did so in connection with rainfall.

Non-climatic constraints are rooted in a range of factors including government policy, limited capital or propensity to invest, environmental degradation, non-climatic natural hazards, as well as commercial aspects such as access to better markets. Constraints were not generally distinct for farmers across the different districts but there are notable differences in the perception of risk between irrigating and non-irrigating farmers owing to differences in their encounter with the challenges from which constraints for future irrigation are drawn.

For non-irrigating farmers, constraints for irrigation development are viewed in the context of factors that currently stop them from accessing irrigation services. In all cases, all non-irrigating farmers expressed interest towards participating in irrigation activities but noted a range of challenges that exclude them from such. In fact, some farmers expressed frustration to the fact that canals moving water from the source to the irrigation fields (at the scheme) pass right in their fields when they cannot access irrigation services. This is particularly the case for Bua irrigation scheme where the irrigated fields are a considerable distance away from the intake.

5.5.8 Cross-scale linkages

Cross-scale relationships across the three levels of irrigation governance –national, districts, and grassroots – were examined largely based on alignment of governance structures and perception of risk and constraints for irrigation management and development in the next 10-30 years. Through practice, irrigating farmers have accumulated both negative and positive experiences that are central to the epistemic values that influence their perception of climate risk and what constitutes constraints for irrigation development in a changing climate. This distinguishes their views and underlying perceptions of risk from the mostly technocratic views that guide the same processes at the district and national levels of irrigation planning.

Such disparities were apparent in some cases where farmers were bypassed in the process of identifying and implementing solutions for challenges that required engineering solutions and may be critical for climate risk planning and management in government and farmer-led irrigation landscape development. For instance, irrigating farmers in one of the irrigation schemes in Karonga district noted how an engineering consultant once ignored their suggestions during the construction of a new intake point for the irrigation scheme only for the structure to be washed away two years after construction.

5.6 Discussion and conclusions

The study has explored perceptions of climate risk and irrigation management and development at various levels of decision-making and action. Perceptions at the national level were examined through a longitudinal assessment of policies relevant to climate change and irrigation development, specifically focusing on the extent to, and the way in which climate change is integrated in such policies. District and grassroot community levels were examined through stakeholder workshops and focus group discussions, based on tools that sought to solicit information on how decision makers at the district level and farmer communities perceive the interaction between climate risk and irrigation development. Through these approaches, the assessment has identified divergent and convergent perspectives around climate change and irrigation development across different levels and contexts, governed largely by the developing evidence of climate risk and the nature of interactions between various groups of people and irrigation landscapes.

At the policy development (national) level, there is a clear impetus to develop irrigation as one way of sustaining agricultural production in the face of climate change. Policy priorities are intent on expanding areas under irrigation and ensuring productivity of irrigation schemes. Evidence of growing land under irrigation highlights the potential for growing the sector with the background land under irrigation providing overwhelming scope in terms of the land that could potentially be developed into irrigation schemes. Technical evaluations through the 2015 Irrigation Master Plan and other assessments such as the 2012 Water Resources Investment Plan provide the context – both socio-economic and biophysical – and the foundations in terms of the feasibility of developing irrigation systems and the direction to achieving such goals.

Information from such technical evaluations has been woven into the guiding sectoral policies which also extend to address other issues including governance. Overarching policies are generally guided by sectoral policies effectively creating a landscape where one policy is influenced by provisions in another. Except for the National Resilience Strategy, the extent to which the overarching policies reflect on the biophysical aspects elucidated in the masterplans and investment plans is generally superficial. The scope of such overarching policies however covers a wide range of developments such that only key aspects of some of the developments are highlighted. Moreover, institutional arrangements and implementation frameworks often refer to the key sectoral policies in which case a trace of information and evidence can be generated through links between the different policy and technical documents. In this view, it cannot be concluded that such overarching policies simply disregard the evidence provided by technical evaluations, even though establishing whether such information is indeed used to guide overarching policies cannot be easily ascertained.

A notable feature in terms of climate change is the increasing reference to climate risk with time. Time and evidence of changes in climate, observed and projected, has inspired the integration of climate change in sectoral policies. Climate considerations are generally influenced by experience and the perceived gains that irrigation would have provided during years when climate hazards such as droughts and dry spells exposed the shortcomings of rainfed agricultural systems. This is notable from the reference to years when anomalously low rainfall was experienced – often referred to as ‘bad’ years – from an agricultural point view and an overriding view that has eventually influenced scholarly paradigms in that regard. The changing regional and global climate policy landscape may have potentially influenced the change in policy narratives at the local level too. This is seen from the coincidence of effective climate change integration with the development of NAPAs and UNFCCC national communications among other local commitments to global climate policy actions.

Reference to ‘bad years’ in the context of agriculture does, in this context, paint the picture that climate risk for agricultural production is generally – and almost disproportionately - perceived in the context of rainfed agriculture with the view that irrigation has the potential to address the shortcomings of rainfed agricultural systems and their vulnerability to climate change. Up to this point the view has been that irrigation is critical to the management of climate change impacts on agriculture. The susceptibility of irrigation to the impacts of climate change is not adequately discussed but the growing evidence of climate impacts on irrigation, as exposed in Chapter 4 - demands the need for a shift in the narrative. This is no way a deterrence of efforts to develop irrigation, but to safeguard the potential to irrigate in the context of climate change and competing interests of water users and the environment.

Chapter 4 has highlighted the potential for irrigation to be constrained by climatic risk, reaffirming the view that, if poorly conceived, irrigation may fall short of its expected gains and create new vulnerabilities (Molden, 2007). The potentially paradoxical nature of irrigation development in a changing climate is an issue that has received relatively little attention. Long-term changes in water levels, compounded by failing infrastructure and growing pressure on water resources from other sectors place a burden on water resources to the extent that some irrigation schemes have reduced the cultivated area during the irrigation season when irrigation demand peaks.

District level stakeholders are an essential conduit for irrigation development as they sit at the interface of the grassroots communities (the medium where policy actions are effected) and the central government (where policies are developed). Their role in interpreting climate risk and opportunities for irrigation development is thus guided by both knowledge systems that underpin their technical know-how and experiences through negative and positive encounters with local aspects of irrigation development. Their role in planning and implementing developments of this nature is limited, as most of such developments are conceived at the national level. In some cases, irrigation development plans at the district level are outlined in district development plans but these are often aligned to plans at the national level and guided by overarching frameworks such as the National Irrigation Masterplan (2015) and other prevailing policies. For example, one of the participants in Nkhotakota district hinted that the district authority was intending to establish mega farms – a theme that speaks to the current administration's agricultural development aspirations.

Other irrigation developments relevant at the district level are also led by NGOs and other development partners. These are often governed by disaster recovery and resilience agenda, with the view that winter cultivation would offset bad encounters from the previous summer season and provide a basis for diversified production systems. However, these are often on ad-hoc basis and the extent to which they reflect climate risk is not well defined. The involvement of the district authorities through district executive committees ensures the alignment of such projects with district development agenda in which case considerations for climate can be negotiated through such avenues.

The resource constraints associated with irrigation system development and the farmer landscape in Malawi often imply that most farmers cannot individually invest in irrigation to scales that would break-even, given the resources that would be required against the size of land that would be irrigated. Moreover, the access to land in proximity of water resources that would permit cheaper alternatives to moving water from the source to the farm is limited in most cases. Where such land is available – often in form of small, shallow wetlands locally known as *dambos* – irrigation is practiced using watering cans or low-cost technologies such as treadle pumps (Kamwamba-Mtethiwa *et al.*, 2021). In such cases, winter cropping of freshly harvested crops is prioritized. Informal irrigation along riverbanks is also evident along most perennial rivers, a tendency that authorities have identified as one of the main drivers of siltation, along with deforestation in upland areas.

Access to landscapes suitable for irrigation development is a key, perhaps the most important, constraint for individual farmer investments towards irrigation. The irrigation scheme arrangement therefore offers an opportunity for farmers to pool resources while providing a platform for government support via the responsible ministry through the department of irrigation services. Being a scheme, however, entails that access and membership is limited to a few – often those that had customary rights to the land within which the scheme is developed, or those with the resources to access and sustain membership.

Farmer recognition of climate risks for irrigation and the multi-risk contexts in which they occur highlights the potential role that farmers could play to advance farmer-led irrigation. Government and donor-led initiatives have historically provided the basis through which irrigation developments are advanced (Gwiyani-Nkhoma, 2011). Yet, failures and inadequacies have created problems for the very communities that are meant to benefit from irrigation initiatives (Veldwisch *et al.*, 2009b; Gwiyani-Nkhoma, 2011). Narratives governing perceptions of climate risk and irrigation provide loopholes for poor governance and advancement of irrigation development goals and targets that may fail to stand the test of climate change. Chinsinga and Chasukwa (2018) reflect on such ambiguous narratives in the wider context of agriculture and climate change in Malawi, noting how different interests and circumstances necessitate competing policy targets among stakeholders.

Being a multi-sector issue, irrigation development is not immune to such competing perspectives the result of which of has been, among other things, slow investment towards sustainable irrigation and failure of large scale irrigation investments to meet their intended goals (Higginbottom *et al.*, 2021). Issues underlying poor performance of irrigation schemes identified by Higginbottom *et al.* (2021) have also been noted in this context some of which are localized and become magnified in the context of climate change.

Overcoming competing targets and priorities would help create an environment where sustainable irrigation can be easily pursued. Farmer-centric initiatives would ideally bolster efforts amongst farmers themselves to sustainably use water resources, bearing in mind demands for the next day and for downstream users. WUAs would play a vital role in advancing sustainable irrigation but the effective inclusion of farmer voices in policies is essential to breaking stereotypes and advancing farmer-led irrigation initiatives vis-à-vis government-led initiatives (Woodhouse *et al.*, 2017; de Bont *et al.*, 2019). The current study has highlighted the epistemic values and ways of knowing on which perceptions of risk are grounded. While valid, the views of farmers are rarely upheld in irrigation policies yet their encounters with climate risks for irrigation in the context of a myriad of other factors could provide a basis for government-farmer collaborations that foster productivity in the context of climate change.

A paradigm shift towards sustainable and climate-smart irrigation could lead to gains in irrigation farming pursued via means that recognize climate risks for irrigation while lessening the risk of negative outcomes of irrigation on competing water users. Risks imposed by climate variability and change demand the need for collaborative efforts between stakeholders confronted by such risks at the policy and practice levels if changes in policy perspectives and farmer practices are to be meaningful.

Chapter 6

Synthesis, Key Findings, and Directions for Future Research

6.1 Introduction

The relevance of droughts to society and ecosystems demands a better understanding of their physical characteristics for improved forecasting, monitoring, assessment, and evaluation of future risk. A regional and local perspective of drought processes is thus essential for decision making around adaptation and climate resilience. The overall aim of this study was to develop a comprehensive picture of drought processes in the current and future climate and evaluate the implications of projected changes in climate and droughts for irrigation in Malawi. Using a multidisciplinary lens, this study sought to explore pertinent questions that underpin physical drought processes, the risk of their occurrence in a changing climate and associated implications for irrigation in diverse river basins, as well as policy and decision-making contexts that guide irrigation development in a changing climate.

A better understanding of the drought climatology and mechanisms associated with droughts could potentially improve forecasting and monitoring of droughts as well as assessment and evaluation of drought risk for sectors such as agriculture and water resources. It also offers a basis for comprehensive and objective evaluation of GCMs and their ability to reliably simulate drought climatology and associated mechanisms. Among other things, this would offer a basis for understanding the mechanisms through which droughts are simulated in climate models and their associated changes. The former is particularly important for confidence in model projections and for model improvements in latter generations of GCMs.

Climate projections and associated hydrological responses put into context the manner in, and extent to, which changes in drought processes and background climatology would impact irrigation across different river basins in Malawi. Basin scale insights into changes in irrigation water demand and water supply to meet the same would provide a basis for local scale analysis of how specific changes interact with different physiographic contexts to impose constraints on irrigation development in the context of climate change. Such information is essential for decision making contexts that the study analyzed for different levels of decision making for the irrigation sector.

6.2 Key findings

The study has developed a comprehensive picture of drought processes through multidisciplinary lens, effectively generating information that fills critical scientific and development gaps. Especially in the context of Malawi, and to a certain degree subtropical southern Africa and eastern Africa, the study has revealed the mechanisms associated with meteorological droughts occurring in regions with closely related and interlinked climatic processes. It has further highlighted the extent to which CMIP5 GCMs simulate drought patterns and their associated mechanisms. A physical understanding of climate processes associated with droughts in Malawi provided a basis for understanding the nature and extent of changes in mean climate and droughts in the future. Model simulations with SWAT highlight the interaction between climate variability and change and basin characteristics to influence irrigation water demand and streamflow reliability, a critical aspect for meeting irrigation water needs.

Similar drought climatology between northern and southern Malawi despite differences in timing and precipitation dipoles that highlight unique drivers.

Chapter 3 sought to develop a comprehensive picture of meteorological drought characteristics and associated atmospheric circulation patterns in observations, reanalysis and present-day CMIP5 simulations. The analysis was done in the context of Malawi, geographically located in a transitional region influenced by weather processes that drive weather and climate variability in subtropical southern Africa and eastern Africa. The analysis specifically focused on the austral summer season (DJF) which is when most of the rainfall is received across the country.

The SPEI was effective in accurately identifying years when droughts were experienced in the north, south, and across the whole country. The north-south divide was purposely identified to examine the influence of the geographical transition in regional drought climatology disparities and their underlying mechanisms. Overall, the drought climatology is similar between the north and south of Malawi as shown by similarities in mean drought duration, severity, and intensity. Despite such similarities, there are considerable differences in the timing of drought events between the two regions although isolated cases of synchronous or countrywide droughts were also identified. This reflects the unique processes associated with regional droughts in both regions highlighted through links to drivers responsible for precipitation variability in southern (eastern)

Africa and their role on the occurrence of droughts in the southern (northern) part of Malawi.

<u>Finely balanced atmospheric circulation patterns create conditions that favor droughts and simultaneous wetter conditions in the north and south of Malawi</u>.

Circulation patterns during austral summer were examined for years when there are different categories of drought (i.e., north, south, and synchronous) relative to average conditions (1981 - 2010). DJF precipitation variability is strongly correlated with vertically integrated moisture flux. This moisture originates from oceanic and continental sources and flows into Malawi via three tracks – northwesterly, southeasterly, and northeasterly – and interact in a convergence zone centered around 16^{o} S. Circulation patterns during droughts often create conditions that favor precipitation in one region while depriving another of conditions favorable for more rainfall. The north-south contrast in precipitation is a regional feature of droughts and wet spells associated with El Niňo and La Nina (Kolusu *et al.*, 2019) and somewhat reflects the broad spatiotemporal precipitation variability in the Southern Indian Ocean Convergence Zone (Lazenby *et al.*, 2016) and the extent to which the country is influenced by tropical and extratropical drivers of precipitation variability relevant for subtropical southern Africa and eastern Africa.

Examination of meridional overturning circulation for a transect situated over Malawi indicates north-south contrasts in vertical motion such that years with droughts in the south tend to experience anomalous subsidence over the region while, simultaneously, the northern part experiences anomalous ascent. A reversal is apparent during years when droughts are observed in the north. Synchronous droughts are characterized by anomalous subsidence over the whole country. Circulation anomalies and subsequent variations in moisture advection in the three tracks of moisture flux into Malawi cause meridional shifts in the convergence zone. The shifts are such that the convergence zone is situated anomalously north (south) towards the equator (south pole) during years when there are droughts in the south (north), thus causing the apparent north-south contrast in rainfall during such years.

Variations in the intensity of the moisture flux tracks and the subsequent shifts in the convergence zone demonstrate links with synoptic and global drivers of variability. The clearest of the links is demonstrated in the relationships between the southeasterly moisture flux track and ENSO, providing a plausible explanation for the dynamical pathway through which ENSO influences rainfall variability and the north-south contrast in precipitation variations over Malawi associated with El Niňo and La Nina. The relationship is such that the southeasterly moisture flux is more pronounced during El Niňo years leading to the anomalous equatorward shift in the convergence zone thus creating conditions that favor reduced (enhanced) rainfall in the south (north). Kolusu *et al.* (2019) noted this to be the case for the 20215/16 El Niňo event which led to widespread drying across southern Africa including southern parts of Malawi and simultaneous wetter conditions in eastern Africa and parts of northern Malawi. Atmospheric conditions during such years are consistent with anomalous circulation patterns that lead to less moisture uplift, convergence, and instability (Giannini *et al.*, 2008; Blamey *et al.*, 2018), creating conditions less favourable for rainfall across southern Africa. During La Nina years, the southeasterly moisture flux track is weaker, effectively leading to an anomalous southward shift in the convergence zone which creates conditions that favor reduced rainfall in the north and enhanced rainfall in the southern parts of the country.

Hints of links with other modes of variability and general relationships with SST anomalies in the Indian and Atlantic Oceans are also apparent, to an extent reinforcing insights by Kumbuyo *et al.* (2015) on precipitation variability in Malawi and links with global sea surface temperature. Links with other modes of variability highlight processes and interactions that may modulate the relationship between rainfall variability and established modes of variability such as ENSO. Such modes of variability include the Indian Ocean Dipole whose influence creates a regional precipitation anomaly contrast reminiscent of the teleconnection apparent for ENSO (Gaughan *et al.*, 2016) and the Southern Indian Ocean Dipole. The interactions between such processes may work to amplify and dampen the independent influence of given processes on precipitation variability over the country. The finely balanced circulation patterns and interactions and the multiple influences that may act in concert or independently to alter circulation patterns highlight the complexity atmospheric dynamics responsible for precipitation variability and droughts in Malawi. Approaches to examining such processes ought to be innovative in this sense, as the non-linear nature of the interactions and associated outcomes may present considerable challenges for conclusive assessments of such processes in observations/reanalysis, let alone in climate model evaluations.

***Biases in simulated drought attributes and errors in key circulation patterns governing precipitation variability underline CMIP5 model inadequacies in simulating drought processes*.**

CMIP5 models demonstrate considerable biases and inconsistencies in simulated drought climatology over Malawi, reflected in inter-model differences in drought frequency and mean drought duration, severity, and intensity. The majority of models overestimate the number of drought events for the historical period. Although the ratio between droughts in the north and droughts in the south is consistent with the regional ratio of events in observations, GCMs produce more synchronous droughts than in observations. A clear example of such an instance is in the ACCESS1-3 model which produces 10 droughts in both regions, 9 of which are synchronous highlighting the inability of the model to capture the spatial variability that underlies drought processes over Malawi.

Overall, GCMs show a wet bias relative to CRU precipitation for the historical period. Despite such inconsistencies, precipitation variability is closely linked to variability in VIMF, consistent with the relationship between precipitation and VIMF in observation/reanalysis. The intensity of the moisture fluxes associated with the three moisture flux tracks shows considerable biases with a likely impact on the precipitation biases. Previous studies had also found moisture flux biases to be linked to precipitation biases over parts of southern Africa (Lazenby *et al.*, 2016; Munday and Washington, 2017, 2018), noting that such biases in moisture fluxes were largely due to circulation biases rather than biases in specific humidity (Lazenby *et al.*, 2016). The current study has established that the clearest relationship is apparent in the northwesterly moisture flux which is overestimated in most models and has a strong and statistically significant positive correlation with precipitation bias in both the southern and northern parts of the country. In contrast, there is a significant negative relationship between precipitation bias in the south and the intensity of the southeasterly moisture flux track. Models with a wet bias over the southern part of the country have a more intense southeasterly moisture flux track and vice versa for models with a drier bias.

The relationship between precipitation and the southeasterly moisture flux track in GCMs mimics the relationship that was identified in observation and reanalysis. In this view, the dynamical pattern associated with reduced precipitation in the southern part of the country, following an enhanced southeasterly moisture flux track, presents a plausible explanation for the dynamic link between the intensity of the southeasterly moisture flux track and precipitation bias over that region. In the same way that the intensification of the southeasterly moisture flux track during El Niňo years pushes the convergence zone anomalously north towards the equator, models with an anomalously intense southeasterly moisture flux track also have the center of the convergence zone anomalously north towards the equator, creating conditions that would be less favorable for rainfall over the southern part of the country. Interactions among the three moisture flux tracks, however, makes this relationship not as straightforward given that the other moisture flux tracks are simulated with varying degrees of intensity, relative to the southeasterly and reanalysis.

Consistently projected increase in temperature and a drier southern region but considerable uncertainty in projected changes in precipitation.

Chapter 4 built on the physical science basis established in Chapter 3 to examine projected changes in mean climate and drought conditions, and simulate the implications of such changes on irrigation, focusing on aspects of irrigation water demand and the supply of water to meet such demand across five river basins in the lake Malawi Shire River Basin. Overall, models consistently project an increase in near surface temperatures for Malawi and across three regions in which the five river basins are located. There is considerable uncertainty – both in terms of the nature and extent of change – in projected changes in mean annual precipitation in the central and northern parts but there is a strong indication that the south will become drier under both RCP8.5 and RCP4.5 scenarios. The north-south contrast in the projected change in mean annual precipitation is to an extent consistent with wider regional patterns (drying across subtropical southern Africa and wetting in east Africa) (Lazenby *et al.*, 2018) the mechanisms for which are governed by a northward shift in the ITCZ in future climate.

Confidence is highest for the projected change in precipitation for the austral spring (SON) season during which widespread drying indicates a potential delay in the onset of the rainy season. Projected changes in precipitation for the DJF season are with less clarity but there is a hint of drying in the north during the MAM season. The MAM (or long rains) season is projected to become wetter in future climate across east Africa in the multi model mean. The drying pattern – albeit less pronounced – in the northern part of Malawi is counterintuitive given the view that the region draws climatic signals from eastern Africa. The geographical location for Malawi and the finely balanced interactions of circulation features to influence climatic variability over the region is a grand challenge for models whose resolution and parameterization may present key limitations for reliably simulating patterns in locations around such transitional regions. Inter-model differences in terms of locating where the drying and wetting signals stop (i.e., only 3 models captured the north-south contrast in the drying/wetting signal while the rest showed the whole country as either being drier or wetter) reinforce this view.

Despite the uncertainties in 21st century projections of precipitation, CMIP5 GCMs consistently project an increase in meteorological drought frequency. Changes in other drought attributes, including duration, severity, and intensity are also projected to increase the nature and extent of whose change reflects the interaction between dynamic and thermodynamic factors to influence drought characteristics in a changing climate. The frequency of droughts with at least the same duration as the historical drought duration increases but additional short-lived, high-frequency droughts reduce the overall mean drought duration in most climate projections under both emission scenarios. The extent of dryness associated with droughts is projected to increase, signified by an increase in the mean drought severity and intensity. The increase in drought intensity specifically signals an increase in the extent of dryness during drought in future climate such that it would be relatively drier at any point during a drought in future climate relative to the historical period.

The changes in drought climatology are consistent with changes in some indicative extremes including wet day frequency and mean consecutive dry days whose projected increase across Malawi is consistent with projections for the wider subtropical southern African region. Such changes in drought characteristics and changes in precipitation attributes collude with changes in temperature and subsequent evapotranspiration to influence irrigation through both irrigation water demand and supply of water to meet the same demand.

Strong seasonality in water balance variables strongly linked to high sensitivity of river basins to temporal climatic variability.

The second part of chapter 4 examined hydrological responses to climate variability and climate change across five river basins in the Lake Malawi Shire River basin. The combination of climatic and other physiographic characteristics including topography, land use and soil characteristics presented the opportunity to explore the interaction of such factors to influence changes in mean state and variability of hydrometeorological variables essential for irrigation development. The SWAT model performed satisfactorily across all the five river basins, but observation data gaps could challenge the extent to which confidence in the simulations is upheld. In the context of this study, simulation outputs provided synthetic data useful in place of observations in instances where records of certain hydrometeorological variables were not available. Model performance and ensuing analyses would be bound by model capabilities and key assumptions that governed model setup across the five subbasins as summarized in Box 6.1.

Box 6.1: Key Assumptions

The modelling process was grounded on key assumptions that may have affected results or the extent to which they can be interpreted with absolute certainty. Some of the assumptions were highlighted in the corresponding methods section but a reflection on some important considerations is valuable, nonetheless.

Static Land Use, Land Cover Characteristics

The model setup does not allow for dynamic land use and land cover over time. While management scenarios to reflect agronomic practices in line with two-season cropping would highlight an element of changing patterns, such changes only occur at inter-seasonal timescales. The models themselves were based on historical land use and land cover characteristics. Changes in such characteristics are equally important for hydrological processes and regimes that may influence irrigation processes. Moreover, there is enough evidence of massive land use transformations in Malawi due to a wide range of factors. Development aspirations towards irrigation may also mean that changes in land use and land cover, as a result of irrigation expansions, do create important feedbacks that may modulate the impacts of climate change.

Monoculture vs Dominant Mixed-Cropping Practices

Modelling capabilities and the analytical framework used in this study employ a monoculture-based method which only allows irrigation water demand assessments for a single crop. While maize may have been a plausible representative, farmer choices, particularly in irrigation contexts, are guided by factors far beyond crop popularity and tradition. Moreover, farmers may want to adapt to changing weather patterns by shifting away from maize, in which case other crops ought to be considered for analysis. The picture provided in this study is still applicable in the context of other crops as it is found on physical processes and contexts in which other crops and practices may occur.

Conceptual irrigation water demand vs actual irrigation demand

A key assumption for the computation of irrigation water demand was that the irrigation would take place in all areas (HRUs) associated with agricultural land use types. The examination of irrigation water demand is thus guided by concept rather than practice. In the case of the latter, irrigation water demand computations would have to be limited to areas where irrigation is either taking place or would actually take place given physical characteristics such as topography and available water resources. An approach based on stress-testing has been suggested in line with evaluating the extent to which such systems or landscapes could withstand specific disruptive climatic conditions. Nonetheless, the conceptual basis provides critical, useful information in line with understanding physical processes governing climate risks for irrigation. Such information is essential for decision-making around irrigation and water resources management, as well as risk-based research.

Water balance variables show strong seasonality across all the five river basins, with streamflow variability showing strong responses to seasonal changes in precipitation. Quick streamflow responses to seasonal changes in precipitation are underlain by basin hydrogeological characteristics which permit less groundwater recharge for dry season baseflow contributions to the total flow. The Shire River is an exception in this case due to sustained outflows from Lake Malawi that make dry season streamflow only fall to 60% of mean annual flow while the majority of the basins in the Lake Malawi Shire River basin fall to as little as 5% of mean annual flow. Such relationships have key implications for irrigation given the view that irrigation offers a route towards navigating production challenges associated with droughts. Other relevant hydrometeorological variables such as potential evapotranspiration, actual evapotranspiration and soil moisture storage also exhibit strong seasonality linked to seasonal changes in precipitation and temperature, the combination of which is critical for irrigation and agricultural water management.

Irrigation water demand highly sensitive to precipitation fluctuations with episodic spikes in irrigation water demand typically coinciding with hydrological droughts.

Irrigation water demand was examined in terms of both variability and trends. The emphasis of the former was on the timing and coincidence of periods when irrigation water demand is anomalously higher with periods when streamflow is reduced to the extent that a hydrological drought occurs. Across all five river basins, episodic spikes in irrigation water demand have the tendency to coincide with periods when streamflow is substantially reduced. Streamflow is highly responsive to seasonal changes in precipitation as well as interannual fluctuations in cumulative rainfall due to hydrogeological characteristics that do not favor groundwater recharges for latter season baseflow contributions to streamflow. Consequently, the propagation of drought signals from meteorological to agricultural (in this case episodic spikes in irrigation water demand) to hydrological drought is much quicker such that meteorological droughts leading to episodic spikes in irrigation water demand are also likely to cause hydrological droughts.

Consistently projected increase in irrigation water demand over the course of the twenty-first century.

Irrigation water demand is projected to increase over the course of the twenty-first century, generally following patterns associated with increasing temperature and the subsequent increase in evapotranspiration and associated changes in crop water requirements for field crops. The basis for computing irrigation water demand in this study was crop water requirements and effective rainfall in which case future changes in irrigation water demand is a function of changes in the two variables. Thus, the nature and extent of the change in temperature and/or precipitation may determine the nature and extent of the change in irrigation water demand. While increasing temperature increases irrigation water demand across all the five river basins, projected changes in rainfall may act to modulate changes in irrigation water demand by imposing either an amplifying or dampening effect.

Consequently, the increase in irrigation water demand in the multi-model mean is highest in the Upper Shire River basin given the pronounced drying in southern Malawi. The increase in irrigation water demand in river basins located in the north is relatively smaller as the slight increase in rainfall partially offsets the increase in irrigation water demand. The pattern of change in irrigation water demand in river basins across the north reflects the influence of non-climatic basin physiographic characteristics too. A clear relationship is apparent in the Lufira river basin which has the most pronounced increase in irrigation water demand of the three river basins in the north. The basin's soil characteristics permit higher soil moisture storage and the contribution of residual moisture towards meeting crop water requirements. That contribution is however negated in future climate projections due to the increase in temperature and subsequent potential evapotranspiration that sufficiently reduces soil moisture storage.

Pronounced climate sensitivity of streamflow across the Lake Malawi Shire River Basin.

The water supply component of the implications of changes in the climate and associated hydrological responses on irrigation was examined based on streamflow responses to climatic forcing. A definitive pattern in the projected change in streamflow is difficult to discern from the change in mean annual streamflow given the markedly high dependence of streamflow on precipitation the uncertainty of whose change cascades to streamflow projections. Despite there being no definitive direction of change, the sensitivity of changes in streamflow to changes in precipitation is clear across all the five river basins. Streamflow sensitivity to changes in precipitation is the highest in the Upper Shire River basin where a 25% increase (decrease) in precipitation leads to a 70% (~48%) increase (decrease) in mean annual streamflow. Elsewhere, a 25% increase in precipitation leads to an increase in mean annual streamflow of 43% to 60% whereas a reduction in mean annual precipitation by the same percentage would lead to a decrease in streamflow in the range of 38% (North Rukuru) to 51% (Bua River basin).

A clear increase in the frequency of low flows undermining streamflow reliability for irrigation in southern Malawi.

Key to the examination of water supply for irrigation is streamflow reliability, a concept which has been utilized for the identification of potentially irrigable areas in Malawi's Irrigation Masterplan and Framework of Investment. The basis of the concept is found on low-flows and the frequency of low-flows of a given threshold. The Masterplan uses Q80 as the low-flow threshold to define streamflow reliability, accounting for other factors such as environmental flow requirements. A Q90 low-flow threshold was used in this analysis as it offers a more standard and comparable basis for low-flow analyses. Frequency curves generated for the future and historical periods indicate that Q90 flows associated with specific return intervals are lower in the future in all but one basin (Lufira where a slight increase is identified). This indicates that episodes when low flows are below the desirable level for irrigation to be sustained become more frequent in future climate projections. The decrease relative to historical low flows is more pronounced and statistically significant in the upper Shire River basin where, coincidentally, the increase in irrigation water demand is the most pronounced under future climate conditions.

***Changing climate policy landscape with increased recognition of climate risks for agriculture governed by narratives that pay less attention to climate risks for irrigation*.**

Given the evidence generated of the interaction between climate risk and irrigation development, it is imperative that policies, systems, and practices are reflective of such evidence to ensure that irrigation development does not fall short of its perceived and expected gains or create new vulnerabilities altogether. In view of this, Chapter 5 developed an account of perspectives in policy instruments and diverse climate risk perceptions across multilevel governance structures for irrigation management and development in Malawi. The approach taken elicited narratives and perspectives at the national level through analysis of government policies, as well as local government and grassroots levels through interactive multistakeholder workshops and focus group discussions. Evidence of climate change has provided an impetus for integration of climate risk information in various policies over time, but dominant narratives are governed by perceptions that may influence decisions, action, and practices for effective climate adaptation in irrigation.

The examination of policies focused on the period 2000 – 2020 over which time the landscape remarkably changed in terms of climate change management policies and the integration of climate change in sectoral policies. Evidence of climate change due to anthropogenic activity was only finding its way into policies in the early 2000s such that reference to climate change is non-existent or limited in policies such as the Vision 2020 (2000) and the National Irrigation Policy and Development Strategy (2000). The development of the country's Initial National Communication to the UNFCCC as well as other instruments such as the NAPA (2004) paved the way for more climate change consideration in sectoral and overarching development policies. The narrative with respect to irrigation is however deeply rooted in the view that irrigation is a solution to climate related challenges in agricultural production with less emphasis on the potential threats from climate change on irrigation itself.

The narrative that irrigation is an adaptation strategy is consistently maintained in sectoral policies (including the National Agriculture Policy (2016), National Irrigation Policy (2016) and the National Water Resources Policy (2007)), climate change management policies, and in overarching development frameworks including the Vision 2063. In some instances, irrigation is referred to as a climate smart agriculture strategy, but the view is more often with in reference to conventional irrigation. Some policies, more so those that are more recent (with respect to the 2000 – 2020 window), refer to *sustainable irrigation* but there is no further insight as to what constitutes sustainable irrigation in the context of the targeted landscapes and in view of the different pressures to which irrigation is exposed, or any new ones that it may create. This view promotes irrigation as an adaptation strategy, which is by no means incorrect, without advancing the need to adapt irrigation to climate change.

Convergent risk perceptions guided by different circumstances between local government and grassroots communities present challenges and opportunities for integrating climate risk information in irrigation and agricultural water management.

Despite largely viewing irrigation as an adaptation to climate change, local government and grassroots stakeholders acknowledged climate risks for irrigation but hardly indicated any measures that are taken to adapt irrigation to climate change or make it resilient to climatic and other environmental shocks. Diminishing water resources had been reported as an intermittent or continuous long-term issue linked to climate change and environmental degradation. Strategies to dealing with such water shortages are mostly responsive, and usually around prudent usage of water resources or reduction of the size of land that is put under irrigation. Leaving portions of the irrigation scheme – especially the remotest areas with respect to the water source – idle is a common feature across most irrigation schemes during the dry season.

While some soil and water management practices have been promoted and adopted in rainfed farms, the adoption of the same in irrigated areas has been limited. Most of such practices have been known to conserve soil moisture which, for irrigated farms, would be key to reducing irrigation water demand and provide solutions for periods when water is in limited supply. Farmer aspirations with regards to issues of water resources and managing periods with shortage were rooted in rainwater harvesting through reservoirs and irrigation water source diversification. In line with the latter, some farmers viewed drilling of wells as an alternative for supplementary water supply during periods of diminished streamflow but there were no reflections with regards to recharging the groundwater reservoirs to sustain the supply of water through such mechanisms. This is particularly important given the hydrogeological characteristics for most river basins in Malawi which permit less groundwater recharge as highlighted in Chapter 4.

Dissecting the problem while paying attention to the layered nature of irrigation governance revealed the complexities of irrigation management in relation to how players at different levels of irrigation governance perceive climate risk and how, in turn, this would influence the role they play in climate smartening of irrigation systems. Climate risk interpretation is reflective of epistemic values that guide decision making at the different levels. Technocracy is key to planning at the national levels while experiential learning is dominant at the local level. Despite signs of reflections on experience of encounters with climate hazards in national and district level plans, experiences are less direct. The differences in risk perceptions are particularly apparent for references to potential future changes in the climate.

Grassroots communities are largely dependent on their past experiences and reserve a level of doubt entrenched in beliefs and traditions among other things. The views and perceptions of decision makers at the local government and national levels are further complemented by interactions with climate information from climate change assessments. The interpretation of climate risk for irrigation is reflective of these differences in knowledge systems which, for comprehensive interpretation of climate risk across the irrigation decision-making value chain, are complementary rather than conflicting. Grassroots communities include farmers and farmer organisations – both irrigating and non-irrigating – in the vicinity of irrigation schemes, water user associations (WUAs), downstream water users and community leaders. These players are critical for governance of irrigation in the context of climate risks as they operate at the level where policies are enacted. They are the primary basis for determining whether actions are having an impact, and an important source of feedback for improvement through their interactions with frontline staff and local government stakeholders operating across various ministries, departments, and agencies.

Frontline staff include extension workers – both government and non-governmental – who work closely with the farmers and other members of the community to implement policy actions. They are vital for passing information and feedback thus providing a crucial link between spaces where policies are developed and where they are enacted. Frontline staff in the agriculture sector have more of overarching roles, especially in relation to agriculture, water, and natural resources. Overall, their role is not limited to offering extension services regarding cropping systems. They are also involved in tasks that speak to catchment management, water resources, and agriculture commodity markets. Their interaction with different knowledge systems which show evidence of converging towards appreciation of climate risks rooted in droughts could provide foundations for progressive action towards sustainable irrigation.

Farmers and decision makers recognize climate risk for irrigation in the context of a wide range of other factors that constitute non-climatic risks. Non-climatic risks vary between grassroots levels and district and national levels. At the grassroots level, non-climatic risk factors include day-to-day resources for smooth implementation of irrigation and agronomic activities. Aspects of agribusiness, including access to loans and capital as well as profitable markets are also essential. At the national and district levels, non-climatic risk factors generally border around economic factors that enable irrigation service provision as well as any other factors that put pressure on resources, e.g., rapid population growth.

Opportunities for climate integration at the different levels exist but avenues for integrating climate information must be developed in recognition of other non-climatic factors that are essential for sustainable irrigation development just as irrigation development in view of other factors has to recognize the risk climate change poses for sustainable irrigation. Cross-cutting policies are forward-looking and present an opportunity for making information on future climate integral to the planning process. Specifically, the Vision 2063 chats plans whose timeframes could make it less challenging for decision makers to incorporate climate projections whose timeframes may seem less applicable for short-term policy processes.

6.3 Directions for future research

This study provided leads to various frontiers for future work that will continue to fill scientific and development gaps in relation to drought processes and irrigation development. The directions for future work are identified across the three disciplines on which the study was grounded. Thus, they highlight specific issues in relation to drought concepts and associated physical process including atmospheric dynamics and underlying mechanisms from an observations and modelling perspective; future climate projections and hydrological responses to climatic variability and change in relation to irrigation development; policy and practice implications of the interactions between climate risk and irrigation development in the quest to develop resilient food systems in a changing climate.

Given the availability of various drought indices, and despite the SPEI showing remarkable and objective performance, future work should focus on the examination of the performance of different drought indices in Malawi and across southern and eastern Africa. The PDSI is relatively more mechanistic index and combines various variables that may provide a more detailed picture of droughts from a forecasting, monitoring, and assessment point of view in the context of various components of the hydrological cycle. That it is mechanistic may not necessarily mean that it would outperform the SPEI as that could also mean drawing uncertainties from a wide range of variables. The SPI is a relatively simpler index but its ability to accurately identify and characterize droughts without incorporating the influence of temperature. Apart from evaluating such abilities, comparisons between the SPI and SPEI would also help determine the relative contributions of temperature (potential evapotranspiration) and precipitation on drought attributes, a particularly important undertaking in the context of global warming and climate change. The comparison of drought indices would set the basis for multi-index drought evaluations in both observations and climate model simulations.

While the study focused largely on atmospheric circulation moisture patterns and the role of moisture fluxes into Malawi on precipitation variability and droughts, the role of evapotranspiration cannot simply be overlooked. This is particularly important in the context of Malawi, given the presence of Lake Malawi, a vast water body potentially acting as a significant source of local moisture and precipitation recycling. Proximity to the lake is known to have some influence on spatial precipitation variability, but the extent to which land-lake processes and moisture from the lake may modulate precipitation characteristics and drought conditions is an area that requires research.

From a modelling perspective, this research has demonstrated considerable biases in simulation of droughts in CMIP5 models. CMIP5 models demonstrated varying degrees of consistency with observations/reanalysis with regards to mechanisms associated with droughts in Malawi. Hypothetically, newer generations of climate models are supposed to offer an improvement on previous generations of models. Research to validate this hypothesis in relation to model simulation of droughts could potentially provide useful insights for continuous model improvement, and a basis for improved assessment of reliability and confidence in newer generations of climate models. The CMIP6 (Eyring *et al.*, 2016) ensemble is a useful opportunity in this sense while newer (than CMIP5) regional climate models including CP4 (Stratton *et al.*, 2018), a convection-permitting RCM for Africa by the UK Met Office provide a basis for improved assessment of process (including convection) simulation deficiencies and their correction. Climatological and process-based evaluation would provide a basis for examining the extent to which newer generations of models may have improved the simulation of drought processes in Malawi and across the region.

An evaluation of newer generations of climate models would provide a basis for comparisons of projections in mean climate and extremes between CMIP5 and CMIP6 models given the uncertainties identified in CMIP5. The availability of CMIP6 does not undermine the usefulness of CMIP5 but rather provides a basis for furthering insights into projected changes in the climate. Evaluation of projections based on CMIP6 is essential in this view but situating such evaluations in the context of comparisons with CMIP5 could help offer insights not only into improved understanding of projected changes, but also highlight improvements in model simulations of the regional climate. This would be particularly useful to contexts in transitional geographical locations such as Malawi and surround countries where the accurate representation of feature locations and associated processes has implications for spatial distribution of projected changes.

Hydrological responses to such projected changes have been examined in the context of CMIP5 models using the SWAT model, through which areas for future research have also been highlighted. Coupling climate and hydrological models following the framework that was adopted in this study provides a basis for this examination which can be complemented with innovative analytical approaches to answer pertinent questions in relation to climate change, water resources, and food systems resilience. Analyses performed in this study can be replicated using CMIP6 and future generations of climate models to further develop the picture of climate risks for irrigation development as newer evidence of climate change becomes available. Current modelling approaches offer the basis for such analyses but there are limitations that can be navigated by complementing such approaches with study designs that permit exploring complex hydroclimatic and socioecological interactions in different physical and social contexts.

The current study has used an offline approach to determining irrigation water demand. Where reliable irrigation and management data are available, approaches based on live simulation of irrigation within the model could offer insights that may further reveal risks to irrigation development reflective of actual practices. The scale at which irrigation is practiced in relation to the spatial scales associated with the SWAT model or other equally distributed models could provide methodological challenges and opportunities as some models may not be able to reliably simulate key processes down to the farm level. Developing irrigation-specific HRUs could provide a practical basis in such instances, but the extent to which such HRUs can be incorporated into the wider basin context and generate plausible information could be a research frontier worth exploring.

Scenario-based approaches could also offer scope for navigating some of the limitations due to modelling capabilities while providing a basis for examining the role of various adaptation decisions for irrigation. The approach used in this study was essentially scenario-based but that was largely limited to climatic projections. Other scenarios could be developed to examine how the system performs in response to various contexts representing other non-climatic scenarios. Jennings *et al.* (2022) highlight the usefulness of such an approach in Malawi reflecting on, among other issues, the combination of different climate and irrigation scenarios on yield projections. Other scenarios may reflect on adaptation decisions which were not considered in the current study including alterations to planting dates as well as adoption of varieties with different durations to maturity stage.

Moreover, modelling capabilities and the analytical framework used to evaluate irrigation water demand in current the study only allow for single-crop computations per iteration. Scenario-based studies would offer insights based on different crop combinations to reflect more realistic agronomic practices. Not only is this essential for improved systems understanding, but it is also important for adaptation decisions as it would help guide decision making around adaptation decisions for irrigation optimization in the context of climatic risks that confront the system.

Stress-testing offers an alternative and complementary approach to scenario-based studies. Bhave *et al.* (2022) applied a stress-testing analysis together with scenario-based approaches in the context of Malawi, in the process demonstrating climate risks for competing sectors including irrigation, hydropower generation and ecosystems management. Stress-tests are essentially used to evaluate the impact of disruptive climatic conditions and are distinguished from climate impact assessments in that a climate stress-test involves a narrower and targeted focus on a discrete event or set of extreme conditions under which a system of interest breaks or fails (Albano *et al.*, 2021). The approach used in the current study is more in line with climate impact assessments which, in contrast with climate stress-testing, assess a diverse range of potential futures expected to be broadly relevant for a particular resource (Albano *et al.*, 2021). The assessment provides a high-level picture of climate risks for irrigation in this context, but stress-test based approaches would provide detailed quantitative assessments particular to specific irrigation schemes and developments.

An example of climate stress-testing in the context of irrigation would thus focus on specific irrigation investments or targets to determine the extent to which they would be able to withstand certain climatic conditions. Irrigation targets have been highlighted in the National Irrigation Masterplan and Investment Framework (2015), which details the maximum potentially irrigable area in Malawi based on specific criteria that consider the physical characteristics, including water availability, in the areas where irrigation can be developed. Overall, the IMP notes that the maximum potentially irrigable area for Malawi, based on available water resources is 400,000 hectares. Vision 2063 (2021) aims to achieve 100% irrigation of all potentially irrigable area by 2050 (Government of Malawi, 2020a). The first 10-year medium implementation (MIP-1) for the Vision aims to increase the area under irrigation to 175,843 hectares by 2030. This is within projected targets in the IMP which seeks to increase the land under irrigation to 220,000 hectares (an increase of 116,000 hectares) by 2035. Stress-testing would, among other things, assess the extent to which such targets could be achieved or sustained against specific changes that have implications for irrigation water demand or supply for instance.

The examination of physical risks for irrigation development has dwelled on climate but there is a plethora of other factors and issues that may present equally important constraints for irrigation development. Such factors may work to modulate the implications of climate variability and change in which case studying their influence would provide valuable insights into physical interactions that determine system-wide risks for irrigation. This would further highlight the extent of the influence or limitations imposed by climate change in the context of environmental change in general. Sectoral policy interdependencies noted from this study underline the need for a better understanding of the various system components and how they interact to create opportunities or challenges for sustainable irrigation development in a changing climate. Such knowledge would create an evidence base on which future policies are grounded to inspire resilient agrifood systems transformations.

6.4 Recommendations

The science generated in this research goes beyond filling scientific gaps and contributing to the research discourse. It addresses critical development gaps in relation to building resilient agrifood systems through irrigation development and sustainable water utilization in light of climate change. The interface between climate risk and irrigation development demands the need to not only look at irrigation as an adaptation strategy but to put in place measures to safeguard irrigation against climatic risk to ensure that irrigation targets are met, irrigation potential is sustained, and the very water resources on which irrigation depends are properly managed. This would require perceiving and conceiving irrigation beyond the conventional sense and shifting the paradigm towards making irrigation climate-smart and sustainable in the face of climate change.

Water source augmentation is one approach that could be undertaken to create resilient irrigation landscapes in the face of climate change. Water augmentation refers to the amalgamation of water resources to secure additional water resources for current and future water users. The idea behind water augmentation techniques is to increase capture and storage of surface runoff to allow storage for later use and recharge of aquifers. The current study paid less emphasis to groundwater as a source of water for irrigation but the threat of over pumping to meet rural water supply and make water available for irrigation is apparent. Climate change and the pressure to irrigate more magnify this threat which, for Malawi, is underlain by the low rate of groundwater recharge. Water augmentation would therefore potentially help address water scarcity issues and make more water available for irrigation and other uses.

Complementary soil and water conservation practices could help reduce irrigation water demand and put less pressure on water resources while allowing farmers to irrigate larger areas during periods of scarcity. Climate-smart and conservation agriculture practices have proven benefits with regards to offsetting challenges associated with crop water stress. While such approaches have been widely tried and tested in the rainfed systems, there is not much to prove their application in irrigated systems. To an extent, farmers in irrigation schemes, particularly those growing fruits and vegetables, use mulching as one way to conserve soil moisture and reduce irrigation water demand although this is usually limited to the sowing and nursery stages. Promoting such practices as well as research to examine the extent to which they are valuable for irrigation systems could provide a basis for a shift in agronomic as well as soil and water management techniques that reduce irrigation water demand and associated pressures on water resources.

Catchment management through afforestation and other environmental conservation efforts may help safeguard irrigation catchments against climatic and non-climatic shocks. Evidence of impacts of upstream catchment degradation on the sustainability of irrigation schemes was presented by workshop and FGD participants highlighting the need to address issues of environmental degradation which collude with climatic shocks to magnify the impacts of such shocks on irrigation. Conceiving irrigation developments in the context of wider catchment management would, therefore, help safeguard irrigation schemes against the impacts of upstream catchment degradation and minimize downstream impacts of such irrigation schemes.

Irrigation technologies vary in their water use efficiency in which case more efficient technologies ought to be sought if irrigation targets are to be met without compromising water resources for other users. Irrigation water losses can be either through losses in the process of transferring water from the source to the field (conveyance) or in the field before it is made available to plants. Conveyance losses can be through seepage, transmission, or evapotranspiration. Canals or other media through which water is transported are characterized by different rates of water loss during conveyance, effectively defining the amount of water that ought to be abstracted from the source. While irrigation has the potential to offset climate related challenges, conventional technologies may fail to stand the test of time in the context of climate change and water scarcity. Thus, the goal for irrigation development ought to be maximizing water-use efficiency rather than simply facilitating the transfer of water from the source to the field.

The role of inter-basin transfers to support irrigation development in a changing climate remains an area of growing research interest. Spatial contrasts in water resources distribution and confrontations with projected changes in the climate could mean that developed water resources in one basin could help offset scarcity related challenges in other basins. Inter-basin transfer is the conveyance of water from one river basin to another using non-natural means such as pipelines, aqueducts, and canals. Inter-basin transfers may provide prominent solutions for basins with chronic water scarcity issues, but they may potentially cause problems in the donor basins and those downstream. Data for inter-basin transfers and their use remains scanty worldwide. Locally, the Salima-Lilongwe water project[2] provides a learning opportunity with regards to sustainable practices and constraints for large scale inter-basin transfer interventions. Experiences and lessons learnt from the project will highlight opportunities and challenges that exist from inter-basin transfers at the local level and the extent to which such interventions may provide opportunities for resilient water use and management in irrigation and other sectors.

The water-energy-food-environment (WEFE) nexus provides an opportunity for an ecocentric system-based approach for sustainable utilization of water resources to support irrigation development in the face of climate change and other competing demands. The WEFE nexus approach departs from the point of view that water, energy, food, and ecosystems are inextricably linked and attempts to highlight the interconnectedness of these system components. The approach identifies mutually beneficial responses that are based on understanding the synergies of water, energy, and agricultural policies. For example, responses may include developing water infrastructure to support irrigation needs and use the same resource for water supply and energy. The nexus approach also informs choices on trade-offs and synergies that maintain the health of ecosystems. This approach allows the development of collective solutions to challenges posed by climate change in ways where solutions for one sector do not create or exacerbate vulnerabilities for others. Implementing WEFE oriented approaches is not a straightforward undertaking given the compartmentalized nature of concerned stakeholders.

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[2] The Salima-Lilongwe water project seeks to construct a 120 kilometers long pipeline to convey water from Lake Malawi in Salima District to the city of Lilongwe. This presents an example, albeit contentious, of inter-basin transfers in action in Malawi.

A functional policy environment is an essential enabler for achieving sustainable irrigation in the face of climate change. The compartmentalized nature of the policy landscape in relation to agriculture, water resources, and irrigation creates considerable difficulties for effective integration of climate information in irrigation management. Different departments mandated to oversee the implementation of the various sectoral policies are guided and constrained by their own sectoral priorities and circumstances. Governance structures and approaches to cross-sectoral management could help provide a platform for more cross-sectoral collaborations which would promote development targets and approaches based on understanding system-wide risks and opportunities. Linkages between sectoral and overarching policies provide an opportunity for such cross-sectoral linkages while allowing integration of climate information relevant for different temporal scales given the differences in the temporal horizons associated with such policies. Producers of climate information and decisionmakers ought to collaborate in these efforts and create co-production spaces where useful and usable climate information is demanded and avenues for its incorporation into policies are chatted.

Other than policies, forecast and monitoring tools would be essential for ensuring effective preparedness and response to droughts and dry spells. Drought prediction is a complex undertaking, but continuous development of knowledge creates a basis for improved understanding of physical processes that would improve predictability and monitoring. A functional operational and decision support tool would help responsible authorities such as the Department of Climate Change and Meteorological Services (DCCMS) to provide more reliable information with regards to drought forecasts. Monitoring ongoing droughts would also help provide information on the extent of various attributes of ongoing events and what their implications could be in relation to agriculture, water resources, and irrigation.

The Operation and Decision Support System (ODSS) (https://www.flooddroughtmonitor.com/home) developed in partnership with the Danish Hydraulic Institute (DHI) offers an important resource for drought monitoring in Malawi but the extent to which it is effective is not known. Developing an effective monitoring framework would involve investing towards monitoring infrastructure including meteorological and hydrometric stations for which there is evidence of poor performance given prolonged periods of missing data. Pseudo observation data sources provide a useful resource for data scarce regions whose value can be maximized while effective data amalgamation is pursued to improve drought early warning, monitoring, and assessment.

Annexes

Annex 1: Detailed Maps of the Five River Basins

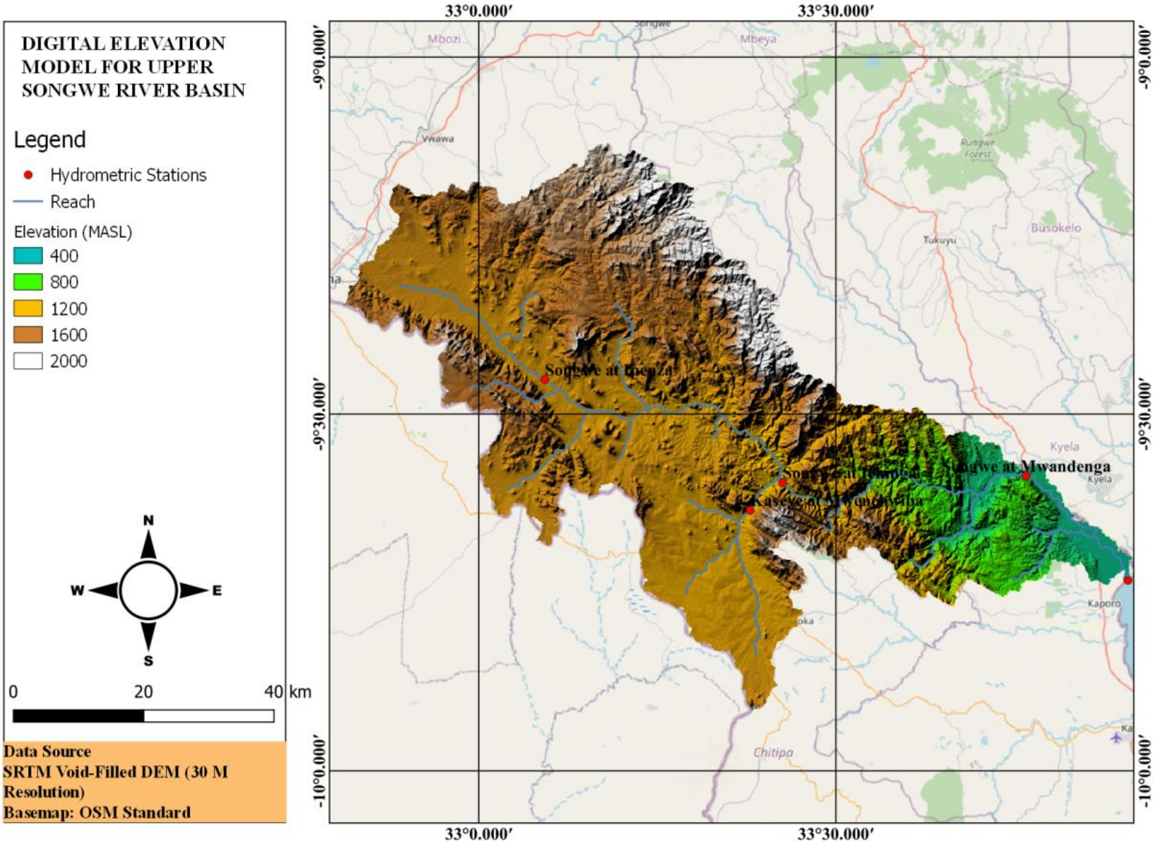

Figure A1.1 | Digital Elevation Model for Songwe River basin. Points indicate subbasin outlet and those corresponding to hydrometric stations are marked with the name of the station.

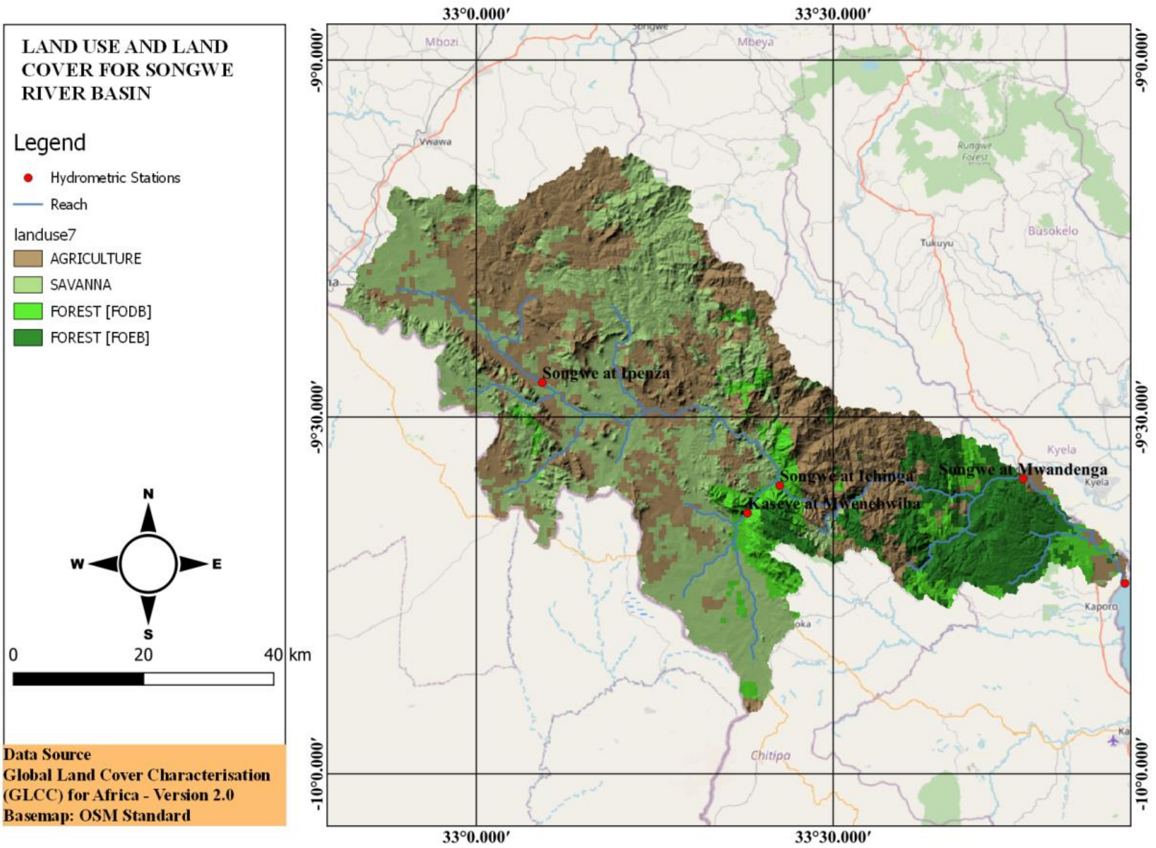

Figure A1.2 | Land use and land cover for Songwe River basin.

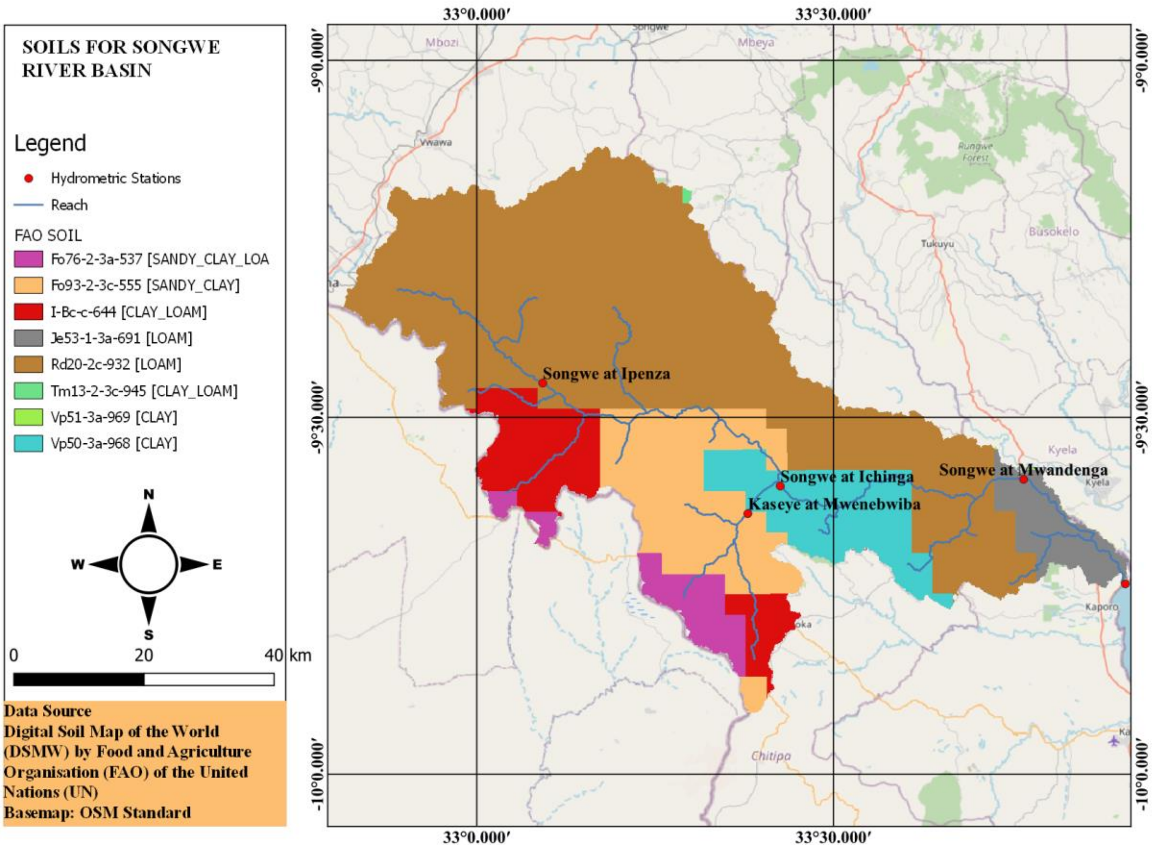

Figure A1.3 | Soils for Songwe River basin.

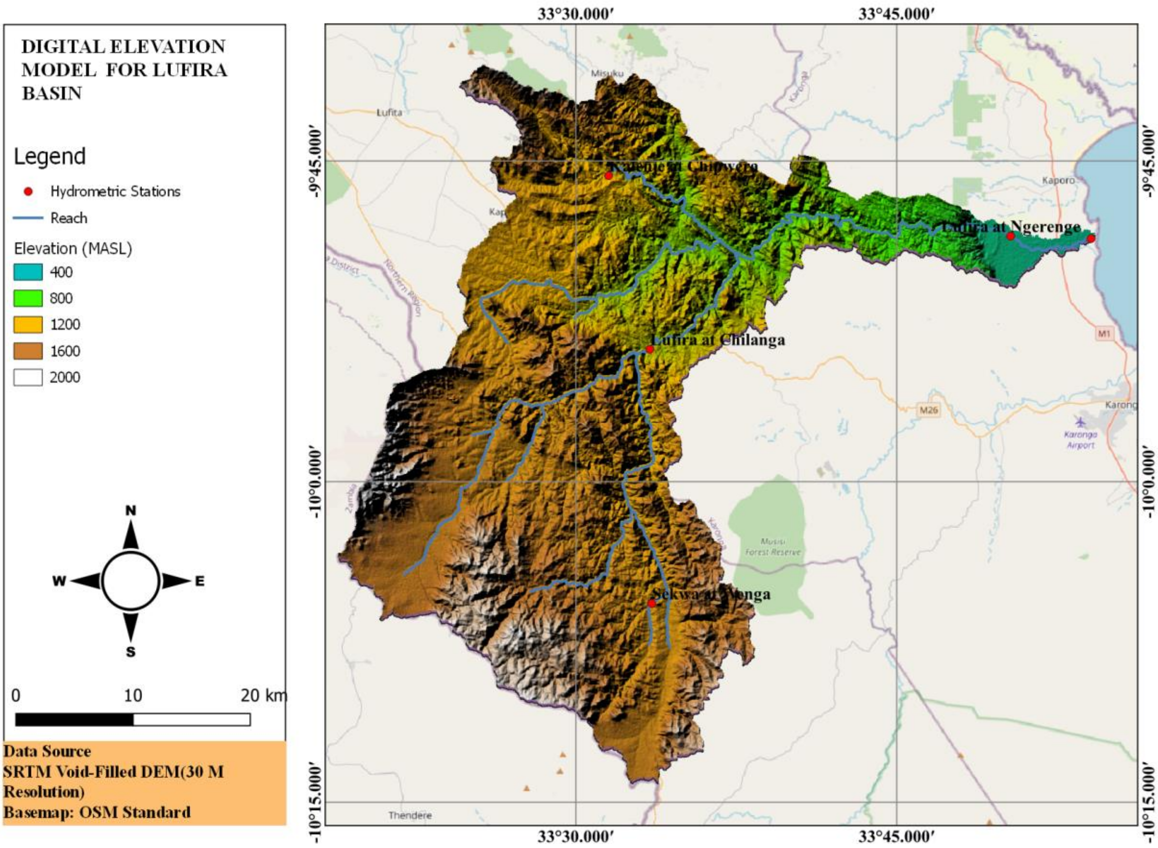

Figure A1.4 | Digital Elevation Model for Lufira River basin. Points indicate subbasin outlet and those corresponding to hydrometric stations are marked with the name of the station.

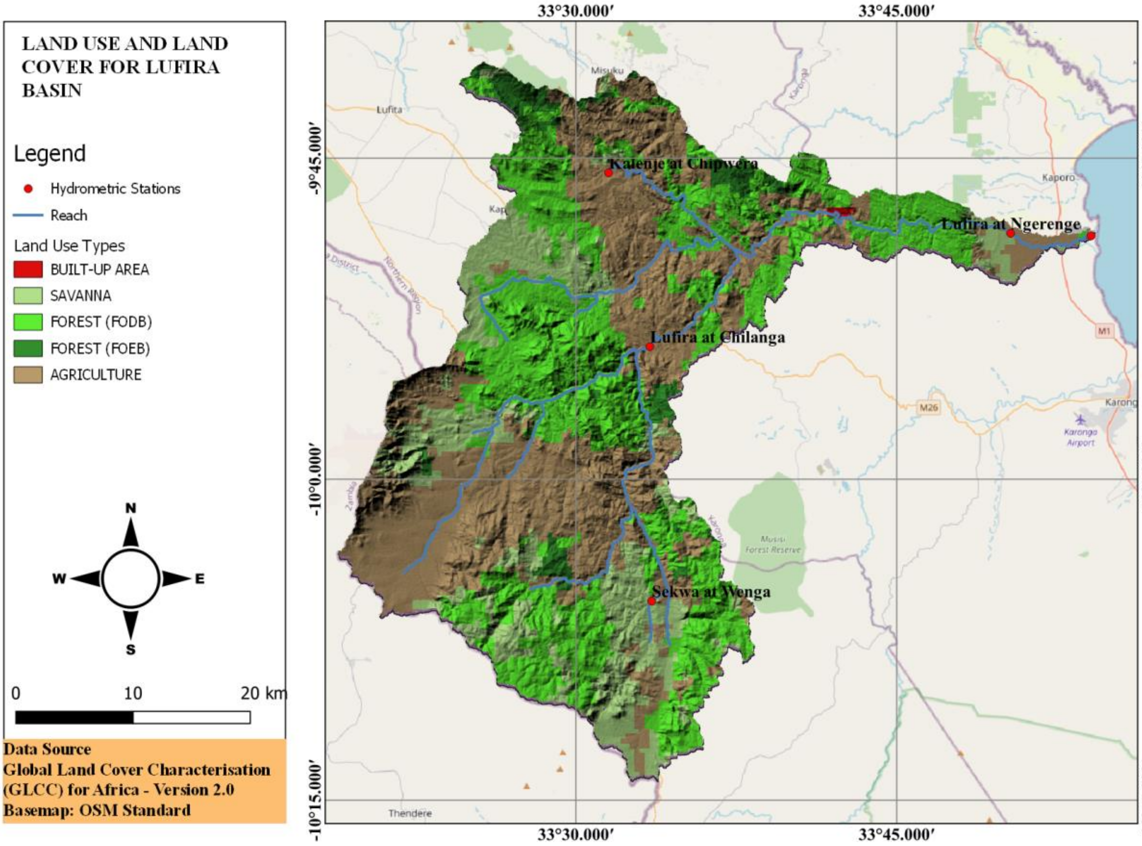

Figure A1.5 | Land use and land cover for Lufira River basin.

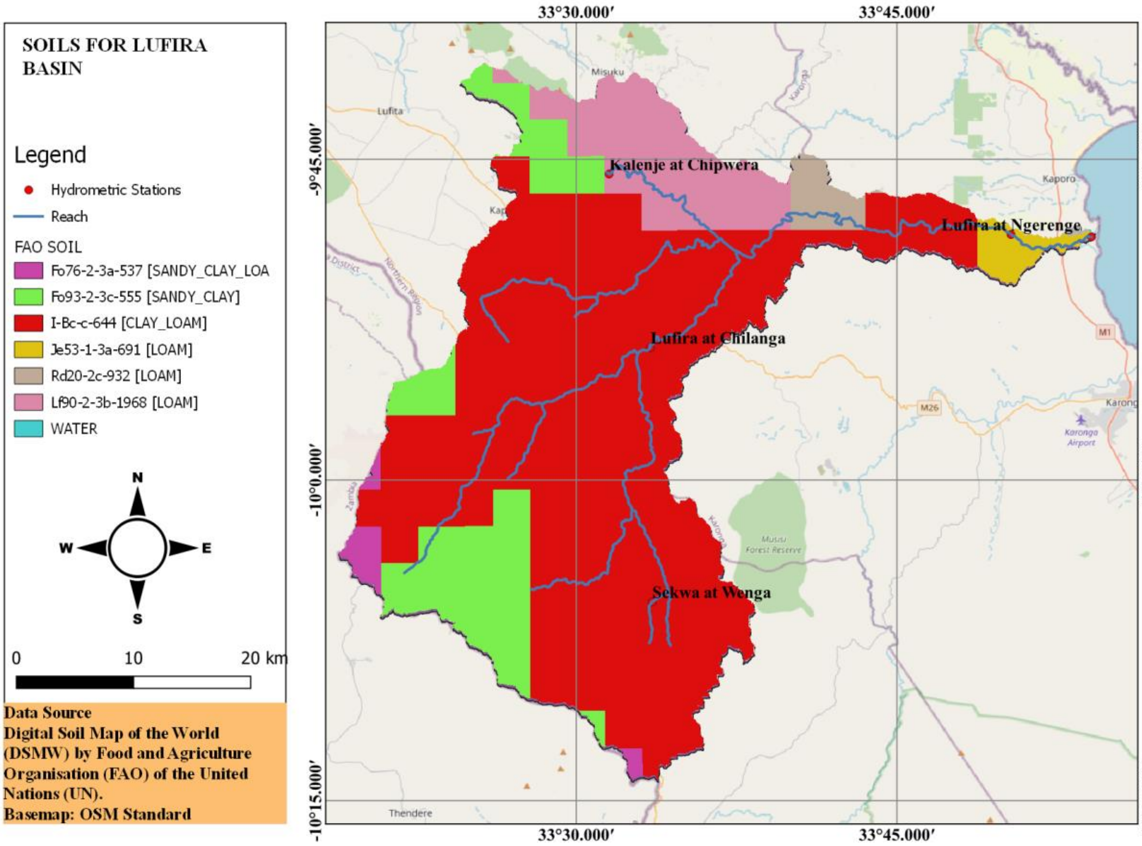

Figure A1.6 | Soils for Lufira River basin.

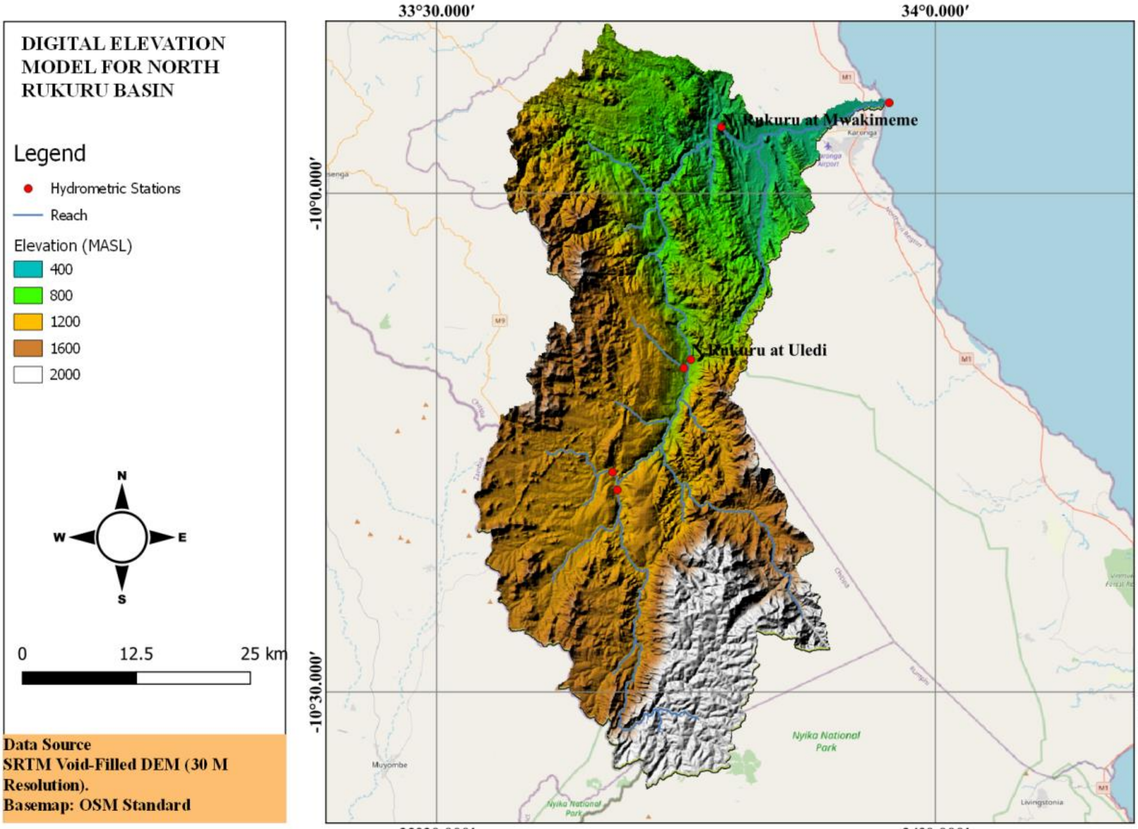

Figure A1.7 | Digital Elevation Model for North Rukuru River basin. Points indicate subbasin outlet and those corresponding to hydrometric stations are marked with the name of the station.

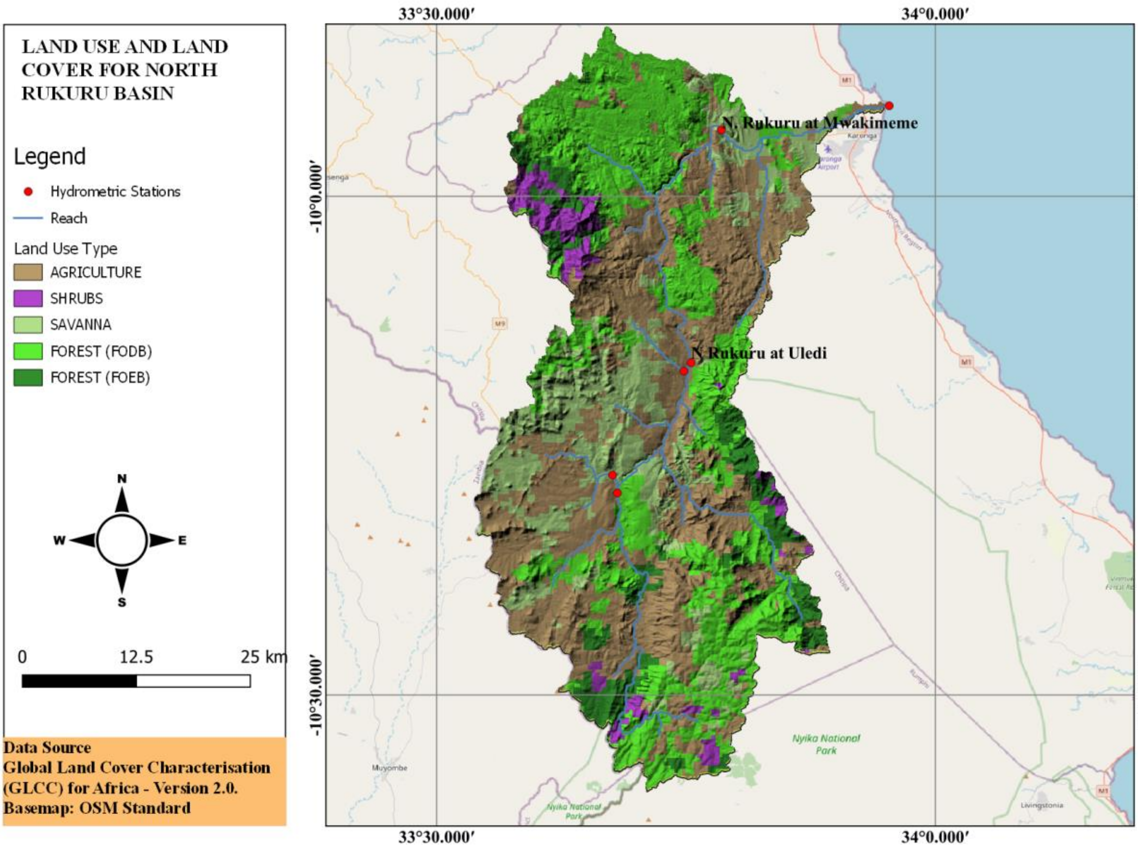

Figure A1.8 | Land use and land cover for North Rukuru River basin.

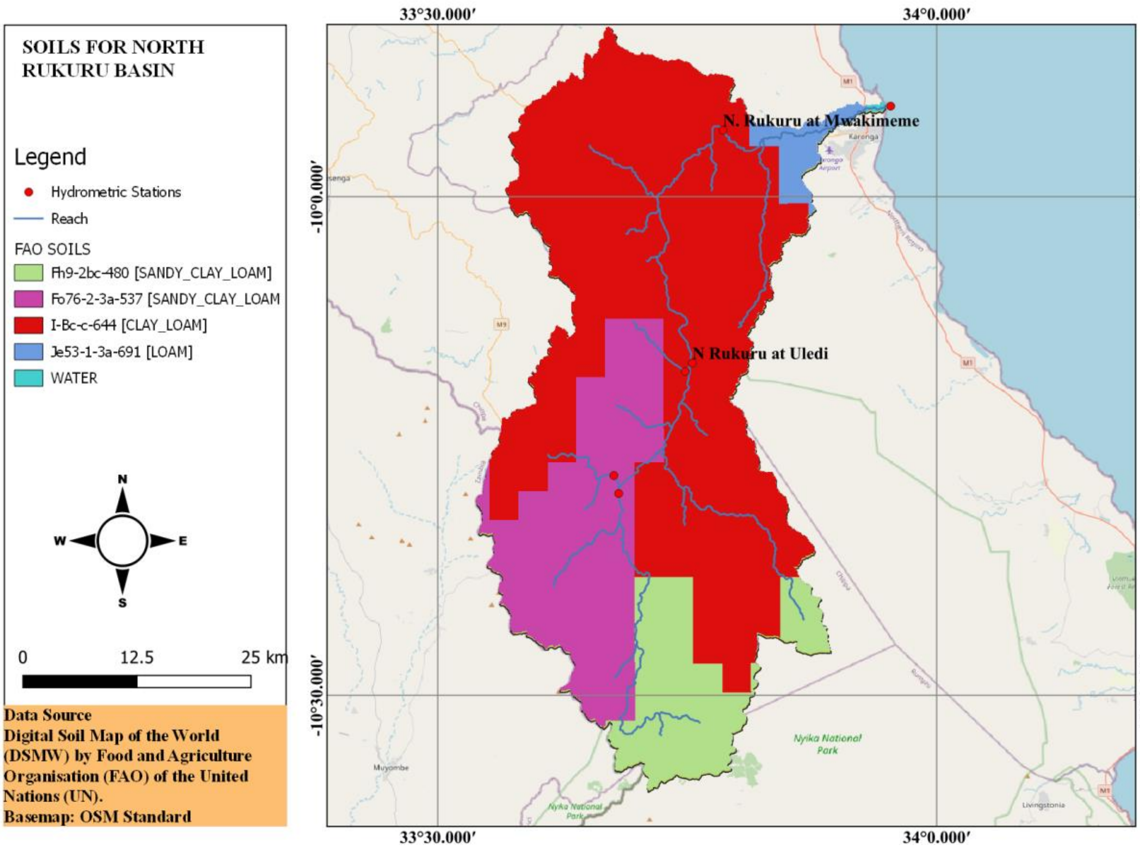

Figure A1.9 | Soils for North Rukuru River basin.

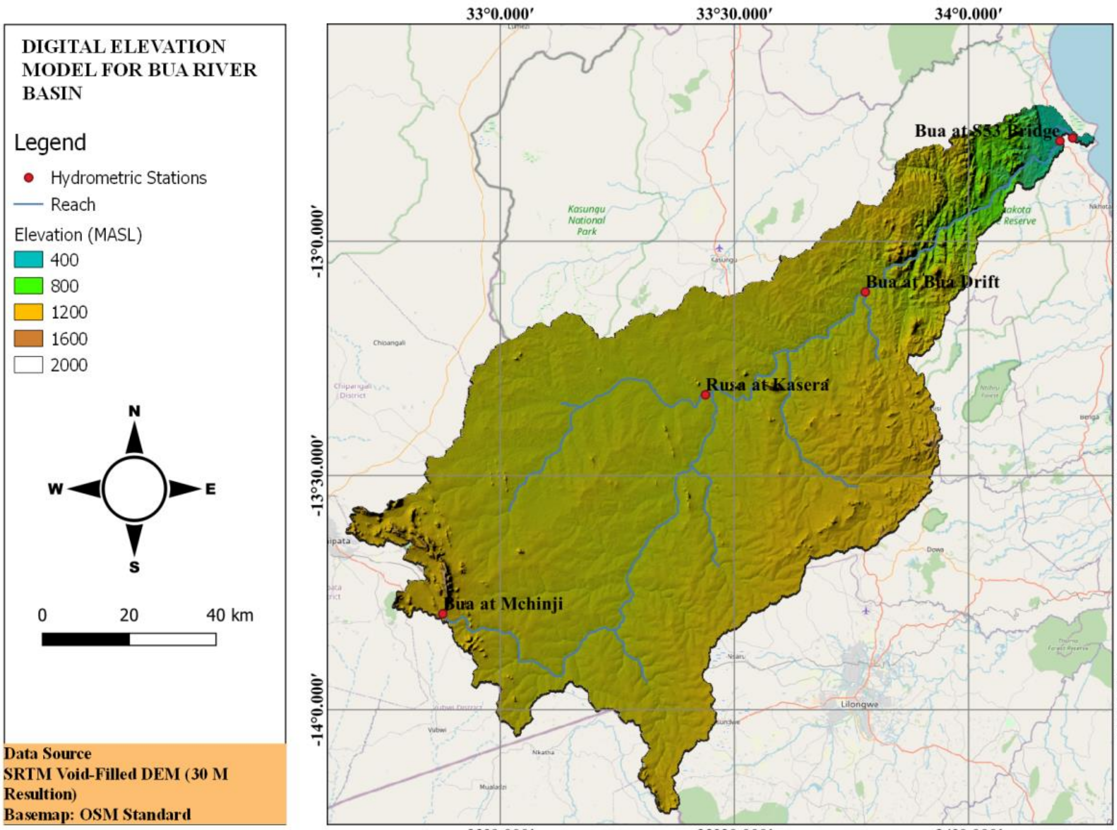

Figure A1.10 | Digital Elevation Model for Bua River basin. Points indicate subbasin outlet and those corresponding to hydrometric stations are marked with the name of the station.

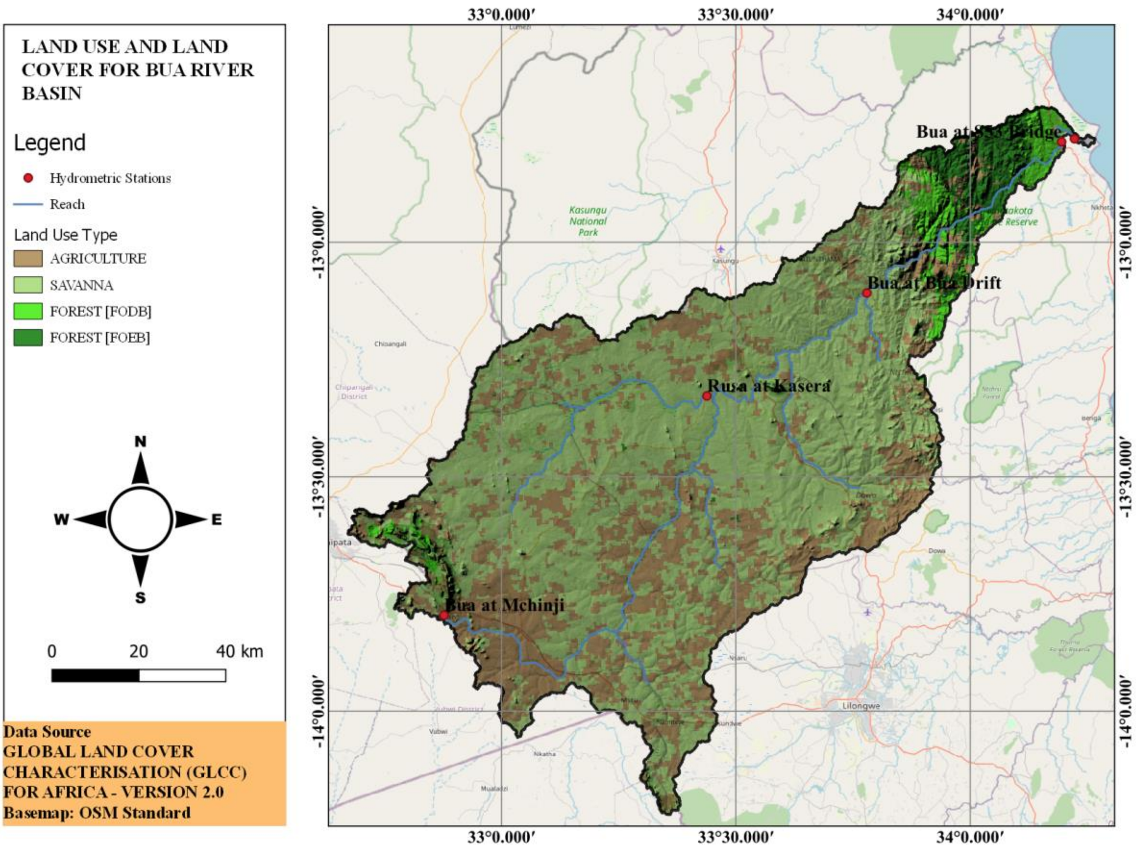

Figure A1.11 | Land use and land cover for Bua River basin.

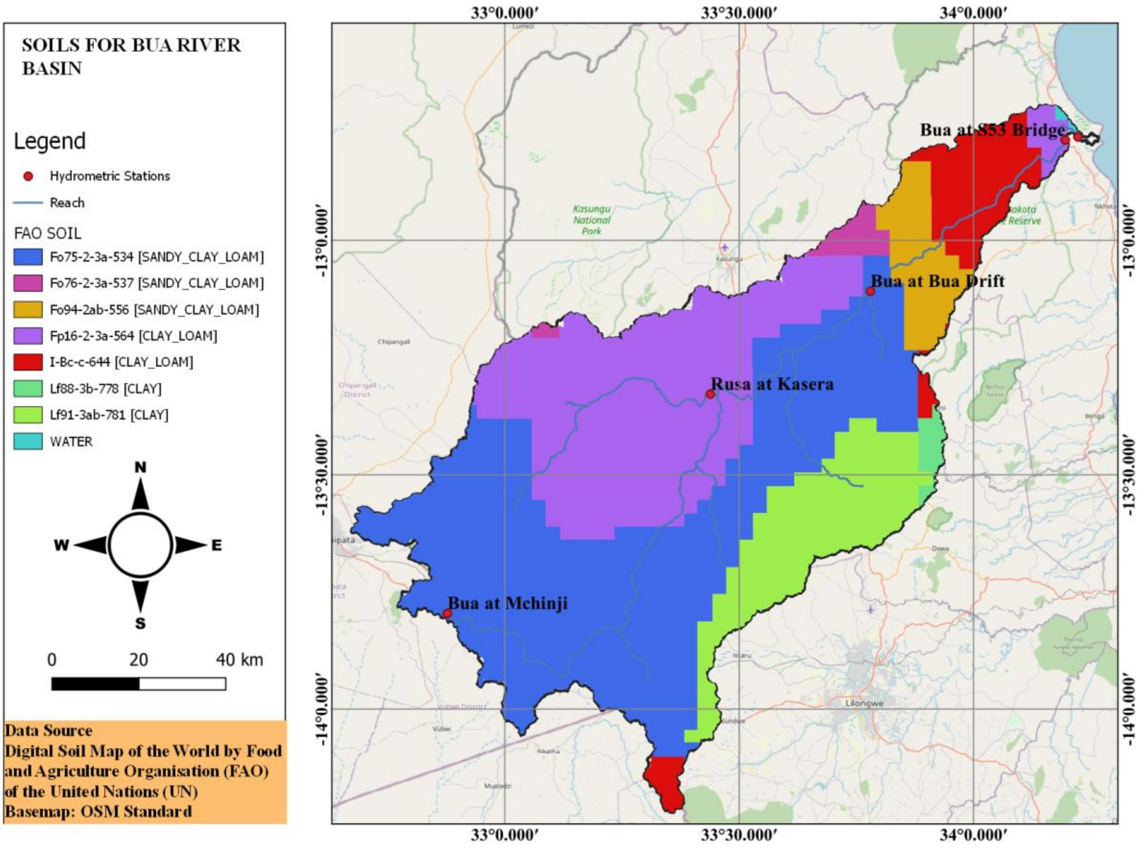

Figure A1.12 | Soils for Bua River basin.

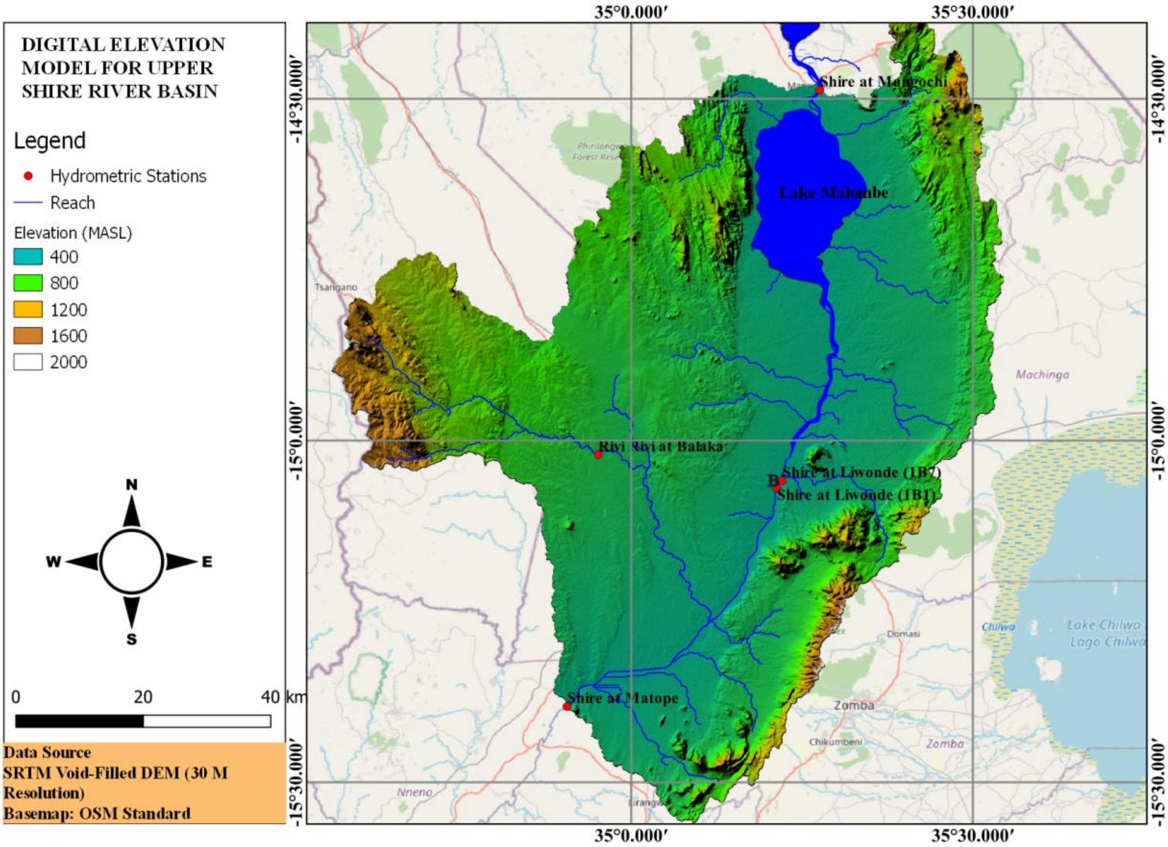

Figure A1.13 | Digital Elevation Model for Upper Shire River basin. Points indicate subbasin outlet and those corresponding to hydrometric stations are marked with the name of the station.

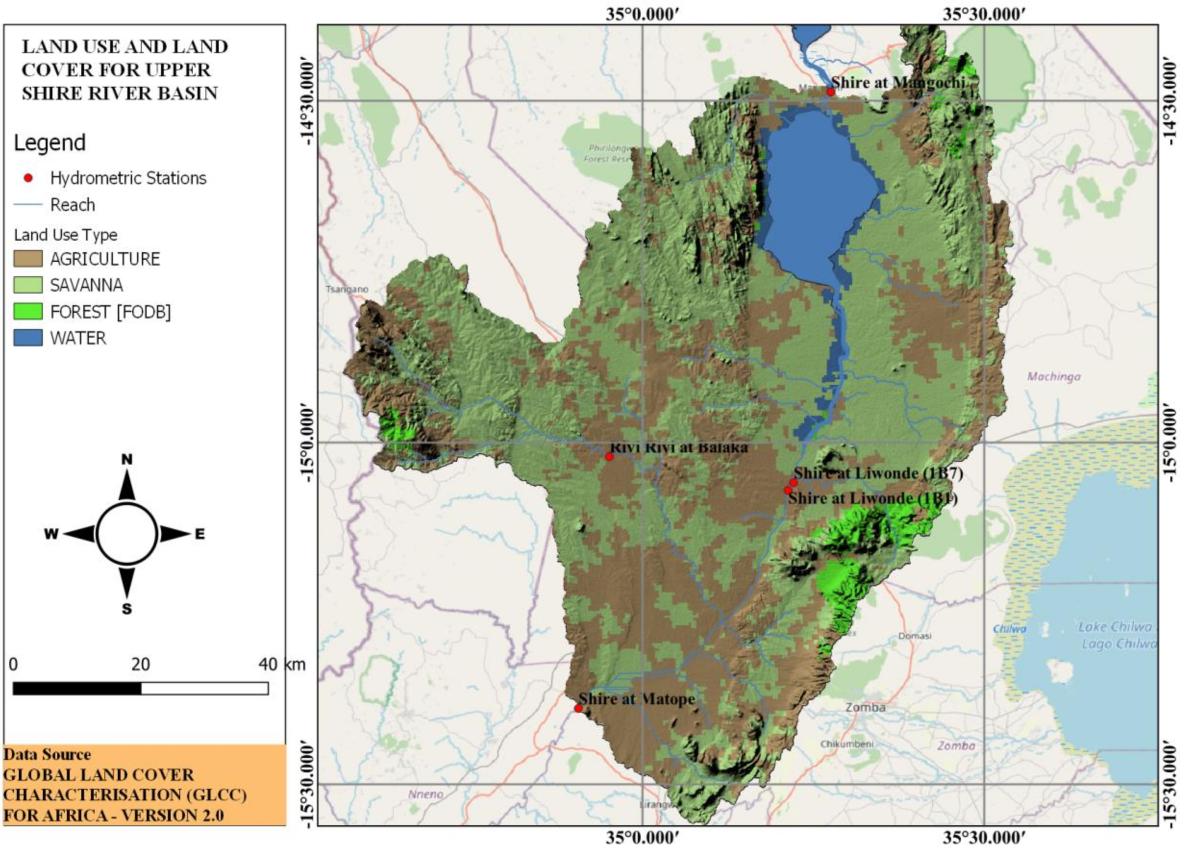

Figure A1.14 | Land use and land cover for Upper Shire River basin.

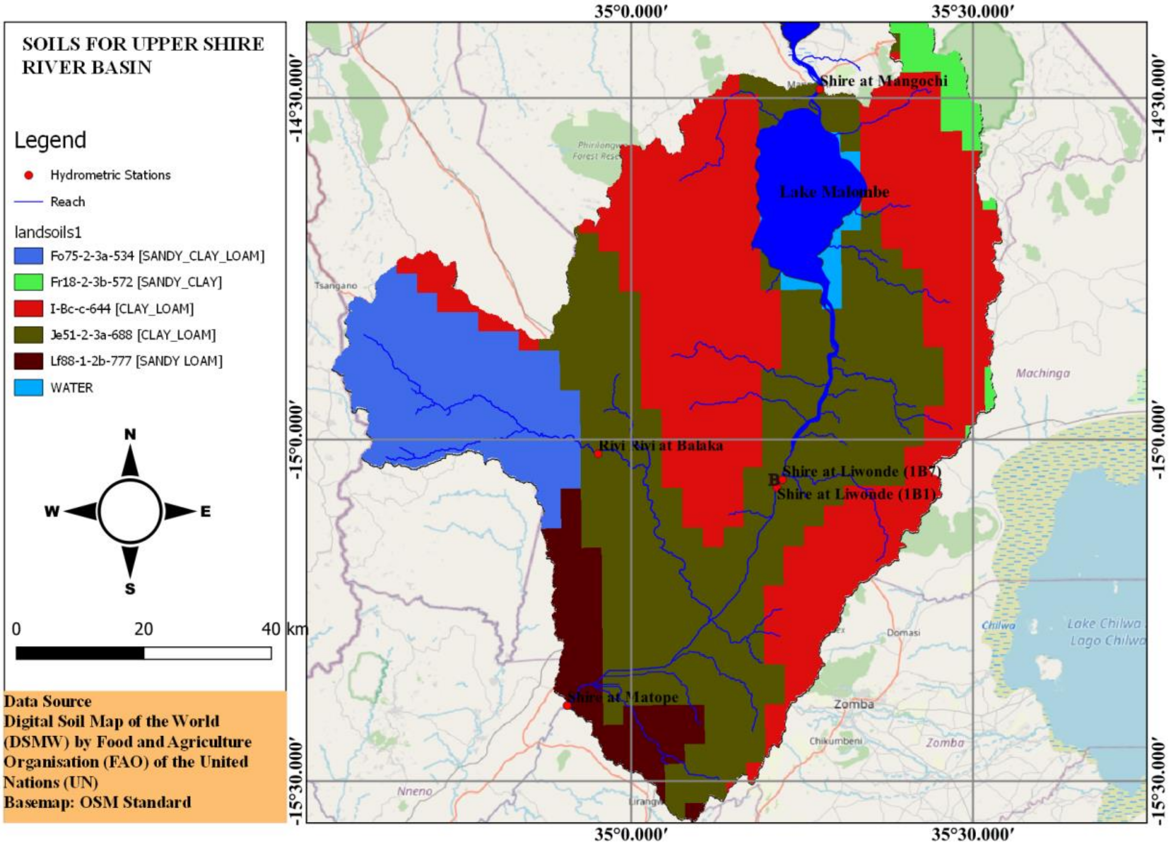

Figure A1.15 | Soils for Upper Shire River basin.

Annex 2: Summary of Model Parameters

Tables A2.1 – A2.5 provide details for the model parameters for each of the five basins. In most instances, parameters are adjusted for each subbasin. As this would be quite laborious to report, the model parameters are reported at basin level. In each case, the minimum and maximum values for each parameter is reported. Where one parameter value is used for the whole basin, the Min and Max values are reported as NA and the corresponding parameter value is reported under the Mean. The number of subbasins and HRUs for each basin is also given.

Table A2.1 | Songwe River basin. Number of Subbasins: 5. Number of HRUs: 39.

Routine	**Parameter**	**Recommended range**	**Parameter Range**		
			Min	Max	Mean
Soil	SOL_AWC	Available water capacity of the soil layer. (mm H_2O/mm soil)	0.072	0.175	0.11
	SOL_K	Saturated hydraulic conductivity. (mm/hr)	6.12	38.1	14.36
HRU	EPCO	Plant uptake compensation factor	1	1	1
	ESCO	Soil evaporation compensation factor	0.3	0.3	0.3
	OV_N	Manning's 'n' value for overland flow	0.14	14	6.18
Groundwater	Alpha_BF	Baseflow alpha factor. (1/days)	0.8	0.8	0.8
	Gw_delay	Groundwater delay time. (days)	365	365	365
	GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur. (mm H_2O)	50	100	78.21
	GW_Revap	Groundwater re-evaporation coefficient.	0.1	0.2	0.16
	Revapmn	Threshold depth of water in shallow aquifer for re-evaporation or percolation to deep aquifer to occur. (mm H_2O)	0	0	0
Routing	CH_N2	Manning 'n' value for the main channel	14	14	14
	CH_K	Effective hydraulic conductivity in main channel alluvium. (mm/hr)	5	5	5
Management	CN2	Initial SCS runoff curve number for soil moisture condition II.	60	87	74.09

Table A2.2 | Lufira River basin. Number of Subbasins: 5. Number of HRUs: 38.

Routine	Parameter	Recommended range	Parameter Range		
			Min	Max	Mean
Soil	SOL_AWC	Available water capacity of the soil layer. (mm H_2O/mm soil)	0.098	0.175	0.14
	SOL_K	Saturated hydraulic conductivity. (mm/hr)	10.77	38.1	25.88
HRU	EPCO	Plant uptake compensation factor	1.0	1.0	1.0
	ESCO	Soil evaporation compensation factor	0.1	0.1	0.1
	OV_N	Manning's 'n' value for overland flow	0.1	0.15	0.12
Groundwater	Alpha_BF	Baseflow alpha factor. (1/days)	0.048	0.048	0.048
	Gw_delay	Groundwater delay time. (days)	365	365	365
	GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur. (mm H_2O)	100	100	100
	GW_Revap	Groundwater re-evaporation coefficient.			
	Revapmn	Threshold depth of water in shallow aquifer for re-evaporation or percolation to deep aquifer to occur. (mm H_2O)	0.1	0.2	0.15
Routing	CH_N2	Manning 'n' value for the main channel	0.014	0.014	0.014
	CH_K	Effective hydraulic conductivity in main channel alluvium. (mm/hr)	0	0	0
Management	CN2	Initial SCS runoff curve number for soil moisture condition II.	68.85	82.7	75.04

Table A2.3 | North Rukuru River basin. Number of Subbasins: 6. Number of HRUs: 49.

Routine	Parameter	Recommended range	Parameter Range		
			Min	Max	Mean
Soil	SOL_AWC	Available water capacity of the soil layer. (mm H_2O/mm soil)	0.098	0.175	0.12
	SOL_K	Saturated hydraulic conductivity. (mm/hr)	64.9	190.5	143.79
HRU	EPCO	Plant uptake compensation factor	1	1	1
	ESCO	Soil evaporation compensation factor	0.15	0.15	0.15
	OV_N	Manning's 'n' value for overland flow	0.1	0.15	0.135
Groundwater	Alpha_BF	Baseflow alpha factor. (1/days)	0.04	0.04	0.04
	Gw_delay	Groundwater delay time. (days)	36	360	234
	GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur. (mm H_2O)	100	100	100
	GW_Revap	Groundwater re-evaporation coefficient.	0.1	0.1	0.1
	Revapmn	Threshold depth of water in shallow aquifer for re-evaporation or percolation to deep aquifer to occur. (mm H_2O)	0	75	38.78
Routing	CH_N2	Manning 'n' value for the main channel	0.1	0.14	0.2
	CH_K	Effective hydraulic conductivity in main channel alluvium. (mm/hr)	0	0	0
Management	CN2	Initial SCS runoff curve number for soil moisture condition II.	51.06	103	71.67

Table A2.4 | Bua River basin. Number of Subbasins: 9. Number of HRUs: 59.

Routine	Parameter	Recommended range	Parameter Range		
			Min	Max	Mean
Soil	SOL_AWC	Available water capacity of the soil layer. (mm H_2O/mm soil)	0	0.175	0.16
	SOL_K	Saturated hydraulic conductivity. (mm/hr)	7.08	99	18.70
HRU	EPCO	Plant uptake compensation factor	1	1	1
	ESCO	Soil evaporation compensation factor	0.5	0.5	0.5
	OV_N	Manning's 'n' value for overland flow	0.1	0.15	0.14
Groundwater	Alpha_BF	Baseflow alpha factor. (1/days)	0.013	0.048	0.039
	Gw_delay	Groundwater delay time. (days)	31	180	68.88
	GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur. (mm H_2O)	100	100	100
	GW_Revap	Groundwater re-evaporation coefficient.	0.05	0.1	0.06
	Revapmn	Threshold depth of water in shallow aquifer for re-evaporation or percolation to deep aquifer to occur. (mm H_2O)	0	0	0
Routing	CH_N2	Manning 'n' value for the main channel	0.014	0.014	0.014
	CH_K	Effective hydraulic conductivity in main channel alluvium. (mm/hr)	0	0	0
Management	CN2	Initial SCS runoff curve number for soil moisture condition II.	70	87	79.89

Table A2.5 | Upper Shire River basin. Number of Subbasins: 5. Number of HRUs: 40.

Routine	Parameter	Recommended range	Parameter Range		
			Min	Max	Mean
Soil	SOL_AWC	Available water capacity of the soil layer. (mm H_2O/mm soil)	0.098	0.175	0.126
	SOL_K	Saturated hydraulic conductivity. (mm/hr)	12.97	38.1	24.04
HRU	EPCO	Plant uptake compensation factor	1	1	1
	ESCO	Soil evaporation compensation factor	0.75	0.75	0.75
	OV_N	Manning's 'n' value for overland flow	0.14	0.15	0.146
Groundwater	Alpha_BF	Baseflow alpha factor. (1/days)	0.48	0.48	0.48
	Gw_delay	Groundwater delay time. (days)	365	365	365
	GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur. (mm H_2O)	100	100	100
	GW_Revap	Groundwater re-evaporation coefficient.	0.1	0.1	0.1
	Revapmn	Threshold depth of water in shallow aquifer for re-evaporation or percolation to deep aquifer to occur. (mm H_2O)	100	100	100
Routing	CH_N2	Manning 'n' value for the main channel	76.5	83	78.78
	CH_K	Effective hydraulic conductivity in main channel alluvium. (mm/hr)			
Management	CN2	Initial SCS runoff curve number for soil moisture condition II.			

Annex 3: Checklist for Stakeholder Workshops

Drought Processes in Current and Future Climate and Implications for Irrigation and Resilient Food Systems in Malawi

PhD Research by Emmanuel Likoya
Supervisors: Andrew J Dougill, Cathryn Birch, Lindsay Stringer

Background

Being predominantly rainfed, Malawi's agricultural production is highly influenced by climatic variability. Irrigation development is often viewed as key to navigating these challenges, more so in a changing climate. Views that irrigation would necessitate commercialization of the agricultural industry provide extra incentives towards irrigation development by both government and its development partners. This is often facilitated by narratives that the country has water resources abundant enough to meet agricultural production in a changing climate. However, evidence of poorly conceived irrigation plans falling short of expected gains exists, while recent studies also indicate potential impacts of climate change on water resources in Malawi. This is against the background of almost-certain pressure on water resources from population growth and economic development.

The PhD Research

This PhD research seeks to improve understanding of drought processes across Malawi and how climate change could influence future drought climatology and aridity, impacting water resources and irrigation farming across the country. To date, the research has explored drought processes across Malawi, and mechanisms that drive them. It has further looked at how well these are represented in climate models which are key to our understanding of future climate behavior. Using the same models, the research has examined the outlook of future drought climatology and hydrological responses to climatic changes that could influence irrigation water demand and water supply to meet that demand. Hydrological simulations have been specifically conducted across five different sub-catchments of the Lake Malawi-Shire River Basin.

The Current Task

The main goal of the current exercise is to examine irrigation and water resource development decision making processes across the irrigation development value chain (catchment, district, and national). This will help draw perspectives and decision-making contexts that would help situate the rest of the research in a people context from which the rationale is drawn. At the catchment scale, the exercise will be completed through focus group discussions with water user groups and associations with access to irrigation schemes and groups of farmers/community members that do not practice irrigation farming or have no access to irrigation schemes. The aim of the stakeholder workshop is to facilitate discussions at the end of which participants will chat the implications of various climate and irrigation development scenarios on water use and water use changes under conditions of climate change.

Date: |___________________________________| (dd/mm/yyyy)

Participants: (1)|_______________________________________|;
(2)|______________________________|;
(3)|__________________________________|;

(4)|______________________________|;
(5)|__________________________________|;

(6)|______________________________|;
(7)|__________________________________|;

(8)|______________________________|.

Gender distribution of participants: (a)|__________(male)|; (b) |_______________(female)|

District:
|____|

Introduce the research and motivation behind the current task and its expected outcomes.

A. Interaction with Water User Associations
(This section only applies for FGDs with WUAs/Water User Groups, otherwise begin from B)

1. To what extent does your department interact with water user associations? – of the departments available, which one interacts with water user associations the most and which ones interact with them the least

B. Mapping water resources
*(Questions with ** apply for FGDs with WUAs/WUGs)*

1. Identify the 5 main water resources in your district? – these include rivers (name them), lakes, groundwater, and rainwater harvesting structures.
2. What is water mostly used for in your district? – think of any infrastructure related to water use?
3. Can you match these uses (in 2) with the different water resources (listed in 1)?
4. Which water resources are mostly used for irrigation?
5. Are there seasonal variations in water use for irrigation?

C. Irrigation Water Use

1. What crops are mostly grown under irrigation in your area? – are there deliberate differences between crops grown under rainfed systems and those grown under irrigation?
    a. Is there any government influence on the choice of crops grown in irrigation schemes?
2. What is irrigation mostly meant for? *Tick applicable response(s)*
    a. Supplementing rainfall deficits
    b. Permanent water supply
    c. Both A and B
    d. Other (specify) |____|
3. When is irrigation mostly done? (months/seasons) i.e. determine whether there are differences in the irrigation water use by season?
   |____|

4. What determines access to irrigation by individuals in irrigation schemes?

|____|

a. Is there any government intervention to influence access to irrigation schemes?

|____|

5. What climate hazards affect irrigation practices in your area?

|____

____|

6. What measures are put in place to cope with these climate hazards (in C7)?

|____

____|

7. How does irrigation water use balance with the other needs? Particularly for those downstream in the case of where irrigation is based on diversion of water from streams/rivers?

Hint– *think around water rationing, water rights etc*

|____

____

____|

8. What measures are put in place to ensure that this balance is maintained?
    a. What measures are put in place in instances of climate hazards that influence access to water for irrigation and other water use categories? i.e think of what gets prioritized during water stress moments?

Hint-*Highlight if there are deliberate measures such as those in 7 but specifically applied as coping measures to climate hazards*.

|____

____

____|

D. Scenario Building

1. Identify 3 key factors that you think could affect irrigation development in the next 10 – 30 years?

|____

_

____

_

____

2. For each factor identified in D1, highlight implications for what changes in either direction (better/worse) could imply for;
    a. Access to irrigation (can be determined from number of farmers accessing irrigation)
    b. State of water resources for irrigation (reflecting on water resources in B1)
    c. Other water needs (reflecting on water use in B2)

	(factor 1)	
	Change for worse	Change for Better
Access to irrigation		
State of water resources		
Other water needs		

	(factor 2)	
	Change for worse	Change for Better
Access to irrigation		
State of water resources		
Other water needs		

	(factor 3)	
	Change for worse	Change for Better
Access to irrigation		
State of water resources		
Other water needs		

3. If not mentioned in D1, reflect on climate hazards in C7 and think of how changes in future climate could affect irrigation, shedding light on implications for aspects in D2.

	Climate	
	Change for worse	Change for Better
Access to irrigation		
State of water resources		
Other water needs		

1. From the factors identified in D1, identify (agree) the one most important non-climate related factor and, for change in either direction, overlay with changes in either direction of the climate factor to create four scenarios (example of the matrix below);

   For each scenario, collate the implications that were indicated for each given factor and reach a consensus on implications associated with each given scenario.

Implications	Scenario 1	Scenario 2
Access to Irrigation		
State of water resources		
Other water needs		
	Scenario 3	Scenario 4
Access to Irrigation		
State of water resources		
Other water needs		

2. What role do you play in decision making around irrigation and water resources development in relation to future climate change?

Annex 4: Checklist for Focus Group Discussions

Drought Processes in Current and Future Climate and Implications for Irrigation and Resilient Food Systems in Malawi

PhD Research by Emmanuel Likoya
Supervisors: Andrew J Dougill, Cathryn Birch, Lindsay Stringer

Background

Being predominantly rainfed, Malawi's agricultural production is highly influenced by climatic variability. Irrigation development is often viewed as key to navigating these challenges, more so in a changing climate. Views that irrigation would necessitate commercialization of the agricultural industry provide extra incentives towards irrigation development by both government and its development partners. This is often facilitated by narratives that the country has water resources abundant enough to meet agricultural production in a changing climate. However, evidence of poorly conceived irrigation plans falling short of expected gains exists, while recent studies also indicate potential impacts of climate change on water resources in Malawi. This is against the background of almost-certain pressure on water resources from population growth and economic development.

This PhD research seeks to improve understanding of drought processes across Malawi and how climate change would influence the drought climatology and impact water resources and irrigation farming. To date the research has explored drought processes across Malawi and mechanisms that drive them. It has further looked at how well these are represented in climate models which are key to our understanding of future climate behavior and, using such models, the research has further examined the outlook of future drought climatology and

The main goal of the current exercise is to examine irrigation and water resource development decision making processes at different levels of decision making and implementation across the irrigation development value chain (catchment, district, and national). This will help draw perspectives and decision-making contexts that would help situate the rest of the research in a people context.

The main aim of the focus group discussions is to facilitate discussions at the end of which participants will chat the implications of various climate and irrigation development scenarios on water use and water use changes under conditions of climate change.

Date: |_________________________________| (dd/mm/yyyy)

Participants: (1)|____|;
(2)|_________________________________|;
(3)|_____________________________________|;

(4)|_________________________________|;
(5)|_____________________________________|;

(6)|__________________________________|;
(7)|______________________________________|;

(8)|__________________________________|.

Gender distribution of participants: (a) |____________(male)|; (b) |_________________(female)|

Name of water user association: |____|

Water resource area: |____|

Water resource unit: |____|

EPA: |____|

Traditional Authority: |____|

District: |____|

E. Water User Association Details

2. How long has the water use association been in operation?
   [Scheme kapena Association yakhala ikugwira ntchito nthawi yaitali bwanji?]

3. What was the motivation behind its formation?
   [Chinakulimbikisani ndi chani kuti mupange gulu limeneli?]

4. What are the main functions of the WUA and how are they derived?
   [Kodi bungwe/gululi limagwira ntchito zanji? Mumapanga bwanji ntchitozi?]

5. How far do these functions extend? Are they primarily based on a specific asset or water body or extend to the wider water resource unit?
   [Nanga ntchitozi zimathera pati? Pa scheme pompa kapena mdera lonseli?]

F. Mapping water resources

6. Identify the 5 main water resources in your area? – These include rivers, lakes, groundwater (bore hole/shallow wells), and rainwater harvesting structures (dams, fish ponds).
   [Madzi mumawapeza bwanji mu mdera lanu lino?]

7. What is water mostly used for in your area?
   [Mdera lino timagwilitsa ntchito kwambiri chani?]

8. Can you match these uses (in 4) with the different water resources (listed in 1)?
   [Talumikizani zogwiritsa ntchito (mu 4) ndi zomwe tinatchula (mu 1) zija?]

9. Are there seasonal variations in the use of water for each of these sources? – note, if any, the role of ephemeral/seasonal rivers and wells?
   [Kodi pamakhala kusiyana kulikonse pakagwiritsidwe ntchito a madziwa kuchokera malo mosiyanasiyanamu?]

10. Which water resource is mostly used for irrigation?
    [Ndichiti chomwe timagwilitsa kwambiri ku nthilira?]

11. Are there seasonal variations in water use for irrigation?
    [Pamakhala kusiyana kulikonse tikamagwiritsa ntchito madziwa ku nthilira?]

G. Irrigation Water Use

9. What crops are mostly grown under irrigation in your area?
   [Ndi mbeu ziti zomwe mumalima ku nthilira mu Mdera lanu?]

10. What is irrigation mostly meant for? (options include permanent water supply, supplementing deficits from rainfall)
    [Nthilira kunoko mumadalira chani?]

11. When is irrigation mostly done?
    [Nthilira timapanga nthawi itiyo?]

12. What determines access to irrigation?
    [Chimapangitsa ndi chani kuti anthu apange ulimi wa nthilira?]

13. What functions does the WUA have in relation to irrigation water use?
    [Ndi ntchito yanji yomwe committee ya scheme/WUA imagwira malingana ndi Madzi opangira ulimi wa nthilira?]

14. What climate hazards affect irrigation practices in your area?
    [Ndi zoopsyezo ziti za kusintha Kwa nyengo zomwe zimasokoneza ulimi wa nthilira mdera lanu lino?]

15. What measures are put in place to cope with these climate hazards?
    [Ndi njira ziti zomwe timapanga kuti tithane kapena kuchepetsa ululu wa ziopsyezozi?]

16. Do you note differences in the farm management between irrigated fields and solely rain-fed fields?
    [Mumaonapo kusiyana Kwa kalimidwe kapena kachitidwe ka ulimi mu minda ya nthilira ndi minda yaku mtunda (yodalira mvula)?]

    a. If yes, what differences are these and why do they arise?

[Ngati Pali kusiyana kwake ndikotani? Ndipo chimapangitsa ndi chani?]

17. How does irrigation water use balance with the other needs? Particularly for those downstream in the case of where irrigation is based on diversion of water from streams/rivers?

[Mumaonesetsa bwanji kuti Madzi a Ulimi wa nthilira wa sakosokoneza kagwiritsidwe ntchito kwa anthu ena omwe ali kumusi kwa nsinje (makamaka pamene tikugwiritsa ntchito njira yopatutsa Madzi)?]

18. What measures are put in place to ensure that this balance is maintained?
[Ndi njira ziti zomwe zinaikidwa zoti tizionesetsa kuti pasakhale kusokonera kulikonse kwa anthu ogwiritsa ntchito madziwa?]

H. Scenario Building

3. Identify factors that you think could affect irrigation development in the next 10 – 30 years?
[Mungatchuleko zinthu zomwe zingapangitse kuti ulimi wa nthilira upite pasogolo kapena ubwelere m'buyo mu zaka 10 kapena 30 zikubwerazi?]

4. For each factor identified in D1, highlight implications for what changes in either direction (better/worse) could imply for;
[Pazimene mwatchula mu D1, Mungalongosoleko kuti zosatira zake (zabwino/zoipa) zingapange pa]
    a. Access to irrigation (can be determined from number of farmers accessing irrigation)
    [Kukwanitsa Kwa alimi kupanga nthilira]

    b. State of water resources for irrigation (reflecting on water resources in B1)
    [Pa komwe timatenga Madzi a ulimi wa nthilira]

    c. Other water needs (reflecting on water use in B2)
    [Nanga ku zinthu zina zomwe timagwiritsira ntchito Madzi?]

5. If not mentioned in D1, reflect on climate hazards in C7 and think of how changes in future climate could affect irrigation, shedding light on implications for aspects in D2.
[Kodi ziopsyezozi za kusintha Kwa nyengozi zingasokoneze bwanji ulimi wanthilira?]

6. From the factors identified in D1, identify (agree) the three most important non-climate related factors and, for change in either direction, overlay with changes in either direction of the climate factor to create four scenarios (example of the matrix below);
[Pa zija tagwirizana mu D1 (mwambamu), kodi zitatu zimene zisakugwirizana kwambiri ndi kusintha Kwa nyengo ndi ziti?]

Better land x drier climate	Poor land x drier climate
Better land x wetter climate	Poor land x wetter climate

For each scenario, collate the implications that were indicated for each given factor and reach a consensus on implications for implications associated with each given scenario.

7. Given current practices (irrigation technology vs management practices mentioned in D8), what would have to change to cope with changes associated with each given scenario?

[Kodi pazinthu zomwe talemba apazi, tingapange chani kuti tichepese ululu wa chilichonse talemba apache?]

8. What role do you play in decision making around irrigation development and
[Ndiye ifeyo timapanga chani popanga ziganizo za chitukuko cha ulimi wanthilira?]

Annex 5: Ethics Approval

The Secretariat
University of Leeds
Leeds, LS2 9JT
Tel: 0113 343 4873
Email: ResearchEthics@leeds.ac.uk

UNIVERSITY OF LEEDS

Emmanuel Likoya
School of Earth and Environment
University of Leeds
Leeds, LS2 9JT

Business, Environment and Social Sciences joint Faculty Research Ethics Committee (AREA FREC)

31 May 2025

Dear Emmanuel

Title of study: **Drought Processes in Current and Future Climate and Implications for Irrigation and Resilient Food Production Systems in Malawi**
Ethics reference: **AREA 19-008**
Grant reference: **201289206**

I am pleased to inform you that the above research application has been reviewed by the Social Sciences, Environment and LUBS (AREA) Faculty Research Ethics Committee and following receipt of your response to the Committee's initial comments, I can confirm a favourable ethical opinion as of the date of this letter. The following documentation was considered:

Document	Version	Date
AREA 19-008 Ethical_Review_Form_V3_Emmanuel Likoya.pdf	1	09/08/2019
AREA 19-008 Irrigation scheme profile_Likoya.docx	1	09/08/2019
AREA 19-008 Participant_Information_Sheet_FGD_Likoya.doc	1	09/08/2019
AREA 19-008 Participant_Information_Sheet_Scoping and KII_Likoya.doc	1	09/08/2019
AREA 19-008 Revised Consent form_Emmanuel Likoya.docx	2	19/09/2019
AREA 19-008 Unified Metrics Questionnaire_Likoya.docx	1	09/08/2019

Please notify the committee if you intend to make any amendments to the information in your ethics application as submitted at date of this approval as all changes must receive ethical approval prior to implementation. The amendment form is available at http://ris.leeds.ac.uk/EthicsAmendment.

Please note: You are expected to keep a record of all your approved documentation and other documents relating to the study, including any risk assessments. This should be kept in your study file, which should be readily available for audit purposes. You will be given a two week notice period if your project is to be audited. There is a checklist listing examples of documents to be kept which is available at http://ris.leeds.ac.uk/EthicsAudits.

We welcome feedback on your experience of the ethical review process and suggestions for improvement. Please email any comments to ResearchEthics@leeds.ac.uk.

Yours sincerely

Jennifer Blaikie
Senior Research Ethics Administrator, the Secretariat
On behalf of Dr Matthew Davis, Chair, AREA Faculty Research Ethics Committee

CC: Student's supervisor(s)

Annex 6: Consent Form

Consent to take part in the research project on "Drought Processes in Current and Future Climate and Implications for Irrigation and Resilient Food Production Systems in Malawi."

I confirm that I have read and understand the information sheet explaining the above research project and I have had the opportunity to ask questions about the project. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason and without there being any negative consequences. In addition, should I not wish to answer any particular question or questions, I am free to decline. I understand that I can request to withdraw the data I have provided till the moment the research team will leave the community. Lead researcher: Emmanuel Likoya Contact number: (+44)7731793387, (+265)993328515
I give permission for members of the research team to have access to my anonymised responses and audio recordings of these responses. I understand that my responses will be kept strictly confidential and will be safely stored and used in relevant future research in an anonymised form. I understand that other genuine researchers will have access to this data only if they agree to preserve the confidentiality of the information as requested in this form.
I understand that other researchers may use my words in publications, reports, web pages, and other research outputs, only if they agree to preserve the confidentiality of the information as requested in this form.
I agree to take part in the above research project and will inform the lead researcher should my contact details change during the project and, if necessary, afterwards.

Name of participant	
Participant's signature	
Date	
Name of lead researcher	
Signature	
Date	

Annex 7: Information Sheet

Participant Information Sheet for Key Informant Interviews

For the Project

Drought Processes in Current and Future Climate and Implications for Irrigation and Resilient Food Production Systems in Malawi

Introduction

You are being invited to take part in a research project. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us/ me if there is anything that is not clear or if you would like more information.

What is the purpose of the project?

This project is about improving understanding of drought processes in current and future climate across different hydrological domains to create a basis for appraising sustainable irrigation systems aimed at enhancing resilience in Malawian food production systems. It is anticipated that the project will improve the understanding of atmospheric drought processes in the current climate and how these will likely change in a future warmer climate and their impact on irrigation systems. The impact on irrigation systems is investigated in two ways first by looking at changes in irrigation demand due to soil moisture balance changes and secondly in terms of availability water resources to meet irrigation demand (as a supplementary moisture source during the rainy season and as the primary source during the dry season) in the context other uses. It is envisaged that being aware of plausible future scenarios in these relationships could be important for decision making in irrigation plans and investments for enhancing resilience in food systems.

Who is organising/ funding the research?

This research is part of a PhD conducted through the University of Leeds with funding from GCRF_AFRICAP Project being implemented in Malawi and three other southern African countries.

Why have I been asked to participate?

You have been identified as an official in a ministry/department/organisation that produces, manages or uses climate (agrometeorological and hydrological) information to inform planning and investment towards irrigation systems aimed at enhancing resilience in Malawian food production systems. Your expertise and experience will help me/us achieve the aims of the study and hopefully generate information that is locally relevant, useful and usable.

Do I have to take part?

You can freely decide whether you would like to participate or not. Taking part in this research is completely voluntary and you can withdraw from the exercise and focus group discussion at any time. If you decide to take part, you will be given this information sheet to keep and be asked to sign a consent form a copy of which you will also keep.

What do I have to do?

Should you decide to participate, you will be given a copy of the information sheet, as well as a consent form to sign, and one to keep and you will be asked to take part in two rounds of key informant interviews. The first round is in September 2019 and for this round you will be asked questions regarding production/utilisation of climate information (depending on whether you are a producer or user of climate information) in relation to resilience planning in general, and irrigation and food system resilience in particular. The aim of this round of interviews is to help me scope and align the focus of my analyses to variables that are consistent with what is locally relevant for different players in the sector. The second round of interviews is to use understand policy processes (from planning to implementation) around resilience and irrigation systems planning in relation to future climate information, particularly on the risk of drought and availability of water resources to meet future irrigation water demand. During the interviews, you will be asked a series of questions, most of which are open-ended for the sake of facilitating a discussion rather than crossing out predetermined responses. Should there be changes to the format of the second round of interviews, you will be notified in time to allow you some time to decide if you would still like to participate.

Who will know if I take part?

The booking will be sent through the secretariat of your department/ministry/organisation as such some people within your line of authority will know that you are taking part in the research. However, the research does not focus on any sensitive issues but rather seeks to understand from your perspectives, expertise, and experience;

1. The relevance of different metrics so as to help the researcher come up with or focus on metrics relevant for your line of other work and other departments that you work in tandem with
2. Understand policy processes and how best knowledge generated from the climate and hydrological analyses in this work can be used to add value to such processes to ensure that irrigation systems are resilient and sustainable in the context of climate change

What are the possible benefits of taking part?

There are no immediate benefits of taking part in the research in terms of any gifts or handouts as any form of payment or token for taking part. However, the expected outcomes of the research may potentially inform planning and management of the irrigation systems and water resources so that irrigation projects are conceived in such a way that they do not fall short of their expected gains or lead to new liabilities in the context of climate change.

Are there risks involved in taking part in this project?

There are no known risks to you or any participants taking part in this research. Data will be anonymised, and your names or identities will not be used in any publications (should there be need to do, your permission will be sought). Should you feel that you would like to withdraw at any point during the discussion, you will be allowed to do so, and any information provided will be discarded.

Will I be recorded, and how will the recorded media be used?

Data will be recorded in note books and using audio recording devices. However, these will be only used as data capturing methods and once the data has been transcribed, such files will be destroyed. The audio files will be stored in encrypted format and password protected devices until they are destroyed. The same applies for the notebooks. The data stored in the transcribed format will be stored in anonymised format.

What will happen with the information I share for this research project?

The information that you share will be analysed and published in the process of completing this PhD project. The information may also potentially be published in other outlets/channels such as scientific papers in academic journals, policy briefs, conference presentations and blogs. As a way of reporting back and disseminating results may also be shared with you and your department.

Withdrawing

Your participation in this research is voluntary and you maintain the right to withdraw at any point or seek clarity in instances where you are not sure about the relevance of some of the questions being asked during the exercise. If you would like to withdraw during the exercise, please notify the me. If you would like to withdraw after the discussions, please contact me through the contact details below and in the consent form.

Thank you,

We thank you for reading the information provided in this information sheet and we encourage you to freely decide if you would like to take part in this research. Your participation beyond this point will be very much appreciated and we hope that it will positively contribute to development planning and climate risk management in Malawi. For further information please feel free to contact the lead researcher through the contact details below.

Contact for further information

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