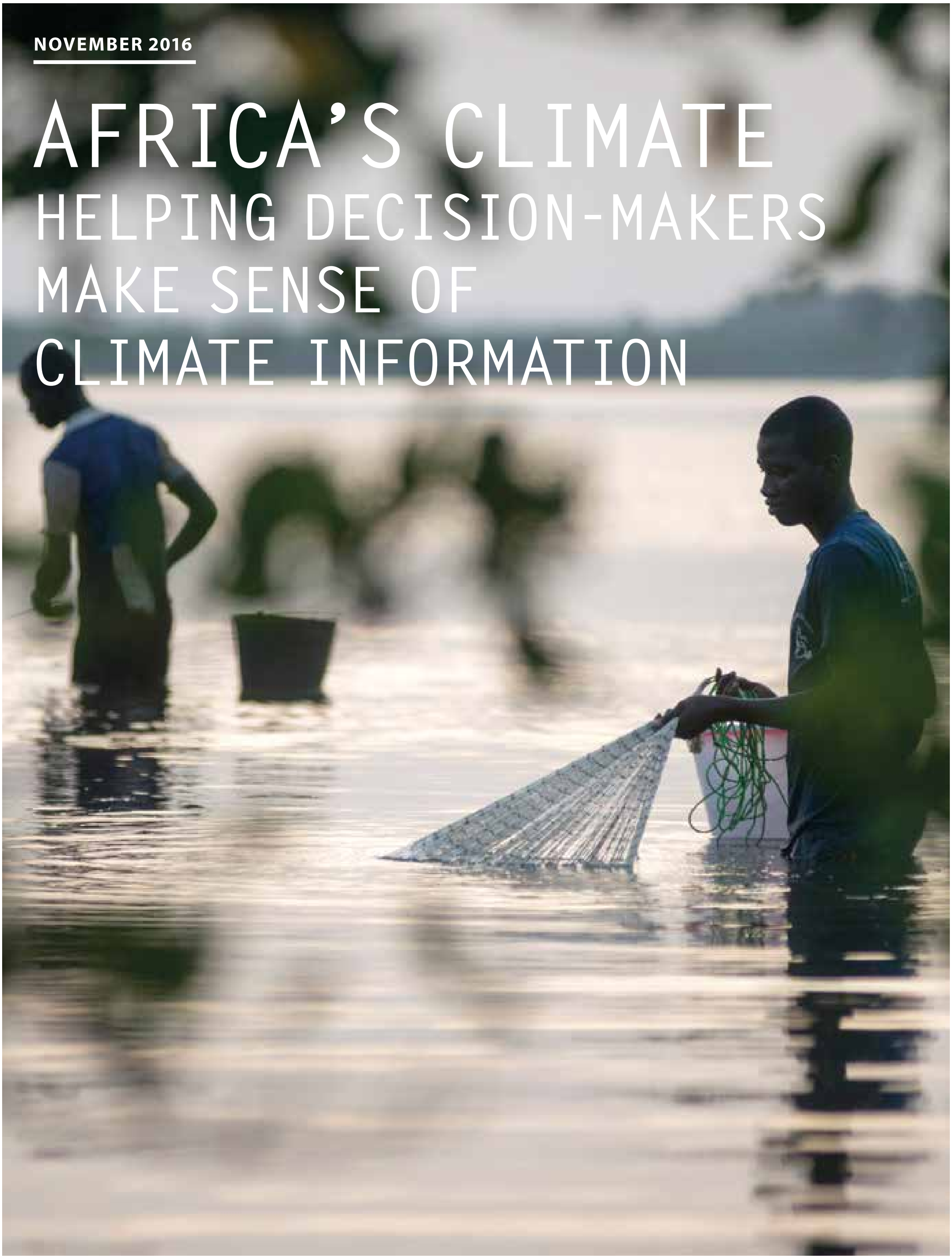
NOVEMBER 2016

AFRICA'S CLIMATE

HELPING DECISION-MAKERS MAKE SENSE OF CLIMATE INFORMATION



FUTURE CLIMATE FOR AFRICA

CONTENT

INTRODUCTION

African decision-makers need reliable, accessible, and trustworthy information about the continent's climate, and how this climate might change in future, if they are to plan appropriately to meet the region's development challenges.

The Future Climate for Africa report, ***Africa's climate: Helping decision-makers make sense of climate information***, is designed as a guide for scientists, policy-makers, and practitioners on the continent.

The research in this report, written by leading experts in their fields, presents an overview of climate trends across central, eastern, western, and southern Africa, and is distilled into a series of factsheets that are tailored for specific sub-regions and countries. Some of these capture the current state of knowledge, while others explore the 'burning scientific questions' that still need to be answered.

Africa's climate is an interim product of the Future Climate for Africa programme, which seeks to identify the gaps in knowledge, and fill those with robust, evidence-based information.

The Future Climate for Africa programme includes leading researchers and institutions from across Africa, in collaboration with peers and peer institutions in Europe and the UK. The work is funded by the UK Department of International Development (DFID) and the Natural Environment Research Council (NERC).

Development professionals will be able to use the report as a touchstone in their everyday work, and as a starting point for considering climate risk. The contents of this report will also be useful for students and researchers seeking an introduction to African climate science, and to intermediaries such as climate knowledge brokers, who can tailor the volume's peer-reviewed analysis to their broader awareness-raising, education and training efforts.

The report consists of 15 factsheets that are grouped into three sections:

- *Regional Overviews* focus on regionally relevant questions for east, west, central and southern Africa.
- *Burning Questions* focus on the key issues relating to the ability of the current science to accurately provide climate change projections and communicate future climate change in Africa.
- *Country Factsheets* provide information on the climate and the possible impacts for Rwanda, Uganda, Senegal, and Zambia. They also consider how climate information is used in Tanzania and Malawi, and how accessible the information is to the communities that need it.

While readers may find the full set of contributions in this collected volume, each factsheet is also designed to be read and used separately in each of the targeted countries and regions (readers may download individual factsheets on our website, www.futureclimateafrica.org).

WHO WILL BENEFIT FROM THIS REPORT?

- Policy-makers: national government officials and advisors who seek to integrate climate information into policy.
- Research-related audiences: undergraduate and interdisciplinary researchers in environment and geographic sciences, or researchers interested in concise summaries of issues to use as a valuable reference tool, as recommended reading, or incorporation into course material.
- Intermediary training and educational institutions: those who train journalists, public officials and others.
- Climate knowledge brokers: National Meteorological and Hydrometeorological Agencies (NMHAs), extension services, consultants and other communicators of climate information.
- Advocacy organisations: non-governmental organisations working in Africa – both domestic and international – with development and/or environmental conservation as their mission.
- News outlets and syndicates: agencies with an interest in African environmental and climate change news, who have the ability to reach millions of community and household level decision-makers as well as to shape political agendas.
- Funding partners: those funding research programmes looking to identify and fill the gaps in knowledge, as well as those seeking to integrate climate information into the broader development agenda.
- The factsheets are labeled as either for 'scientists' where they require a higher level of technical knowledge for use, of for 'general' audiences where they are more broadly accessible. The Future Climate for Africa team welcomes your feedback on the report, so that it may guide our efforts. Please write to us at info@futureclimateafrica.org

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GENERAL READERS

CENTRAL AFRICA
REGIONAL OVERVIEW

CENTRAL AFRICA'S CLIMATE SYSTEM

LEAD AUTHORS

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UMFULA CLIMATE RESEARCH TEAM

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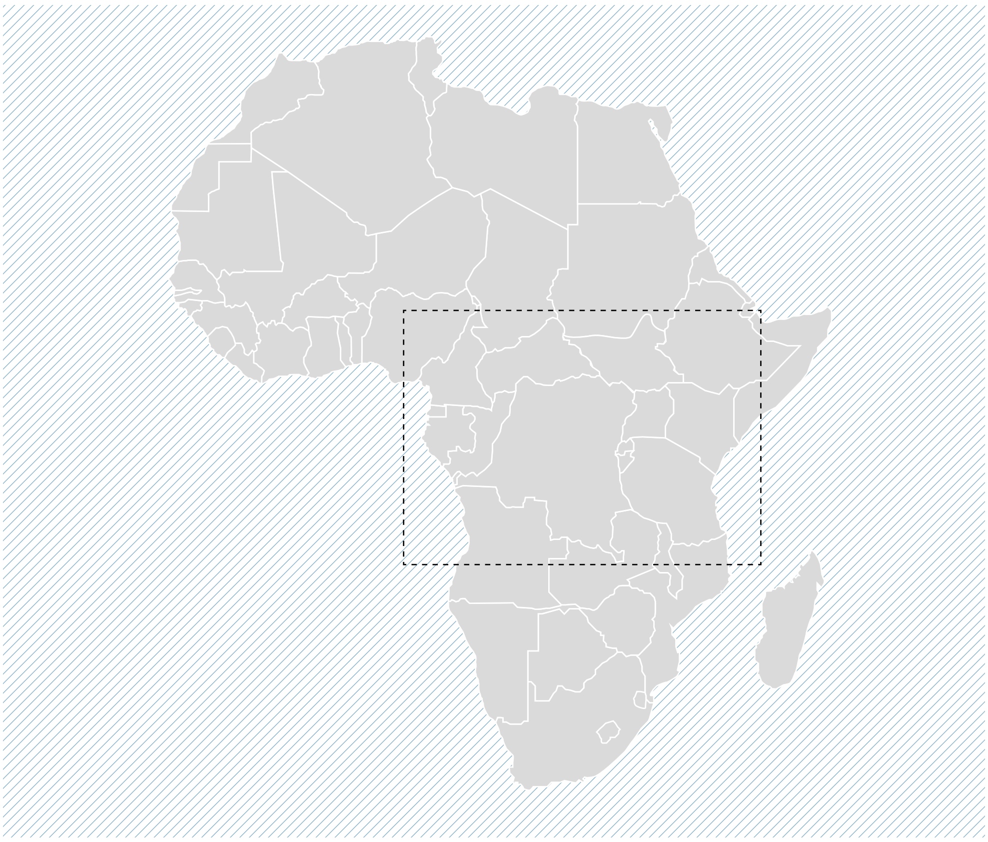


NEED TO KNOW

Central Africa's climate system influences the climate across the globe. Therefore, the decision-making that happens here – in terms of climate change, land use cover, and management of forests and water – has global and regional implications.
As we discuss here:

- the region is severely understudied, because of a lack of scientific observation data, such as that from weather stations
- a thorough study of climate dynamics and regional climate drivers will improve understanding of the regional system
- refining and improving modelling processes will fill important knowledge gaps and give decision-makers useful climate information.

CENTRAL AFRICA: UNDERSTANDING THE REGIONAL CLIMATE SYSTEM

Thunderstorms, also known as convective systems, are a key part of the large-scale air circulation that transfers warm air from the tropics towards the poles

Central Africa is one of the most important climatic regions in the world: the Congo Basin is the biggest water catchment in Africa; and the Congo rainforest is the second largest tropical forest on Earth (see Figure 1). It is one of three major global hotspots of thunderstorm activity. Thunderstorms, also known as convective systems, are a key part of the large-scale air circulation that transfers warm air from the tropics towards the poles. This influences the climate and weather across Africa and the globe.

During the rainy seasons, the Congo is the wettest place on Earth, and adds 3.5mm to global sea level each year.[1] Central Africa also has the world's most intense thunderstorms and the highest frequency of lightning flashes.[2]

The Congo rainforest is a vital store for carbon: the trees draw atmospheric carbon dioxide from the air and store it in their leaves, wood, and roots, and also transfer it into the soil. The amount of carbon stored just in the above-ground vegetation means that the Democratic Republic of Congo's national carbon stock is the second largest in the world. These forests are critical for offsetting climate change. The rainforest is also particularly vulnerable to changes in rainfall, or length of dry seasons. Small changes in rainfall patterns could cause large changes in land cover.[3, 4]

Given the above, and the fact that so much of the population in central Africa relies on rain-fed agriculture, understanding the implications of climate change for this region is vital.

1 Beighley, R. E., R. L. Ray, Y. He, H. Lee, L. Schaffer, M. Durand, K. M. Andreadis, D. E. Alsdorf, and C. K. Shum, 2011. Comparing satellite derived precipitation data sets using the Hillslope River Routing (HRR) model in the Congo River Basin. *Hydrological Processes*, 25(20):3216–3229.

2 Cecil, D. J. 2006. LIS/OTD 0.5 Degree High Resolution Monthly Climatology (HRMC). Dataset available online from the NASA Global Hydrology Resource Center DAAC, Huntsville, Alabama, U.S.A.

3 Zelazowski, P., Y. Malhi, C. Huntingford, S. Sitch, J. B. Fisher, 2011. Changes in the potential distribution of humid tropical forests on a warmer planet. *Philosophical Transactions of the Royal Society A: Mathematical, Physical, and Engineering Sciences.* 369(1934):137–160.

4 Malhi, Y., S. Adu-Bredu, R. A. Asare, S. L. Lewis, and P. Mayaux, 2013. African rainforests: past, present and future. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 368(1625), 20120312.

Shortage of climate information

The central African climate system is one of the most understudied in Africa and the world. This is mainly due to a shortage of weather records. There are far fewer meteorological stations spread out across the region than the World Meteorological Organization recommends. In the past few decades, changes in the management of meteorological services, alongside economic crises and political instability, have led to the breakdown of much of the network of weather stations. There has been a dramatic decrease in the number of rain gauges in the region over the past two decades. The result is a large gap in weather and climate information, particularly for the Congo.

The Congo is therefore disproportionately underrepresented in global climate databases, such as the Climate Research Unit database (CRU). Figure 2 shows the number of CRU weather stations in central Africa, compared with the UK, an area less than one tenth in size. For the remaining weather stations in central Africa, instruments are not well maintained or calibrated, so the quality of the information they gather is not reliable. This, alongside the difficulty of accessing the existing records from these stations, has hindered the ability to study current climate variability, and how this might change in the future.

Because of the overwhelming importance of the region for the planet's climate, this leaves a significant gap in climate science globally.

THE REGIONAL CLIMATE

The movement of the Inter Tropical Convergence Zone (ITCZ) dominates central Africa's climate, the ITCZ is a region in the atmosphere where the low-level trade winds from the north-east and south-east meet. It moves to its most northerly position in the northern hemisphere summer, before migrating south to its most southerly position during the northern hemisphere winter. The ITCZ crosses the equator twice a year, resulting in two rainy seasons (March to May, and September to November) and two dry seasons (June to August, and December to February) in the central part of the region. This, and the complex topography of the region, shapes the regional climate.

Central Africa is bordered to the north and south by subtropical dry areas. The contrast in air temperature and pressure encourages the formation of strong winds around 5km above ground over northern and southern central Africa – the African Easterly Jets – and their strength and interaction with the regional climate changes with the seasons. The jets are both active from September to November, bringing heavier rains than in March to May, when only the northern jet is noticeable. The March to May rainfall season is usually longer, whilst the September to November period is relatively short, with heavier rains.

The Atlantic and Indian oceans play an important role in shaping the regional climate. During the southern hemisphere summer, differences in surface air pressure between the two oceans drive an east-west air circulation cell which makes the rainfall more variable over southern central Africa. The transport of low-level water vapour from the Atlantic Ocean brings clouds and rain to central Africa throughout the year.

Other oceanic factors also influence the regional climate, such as pressure and sea surface temperature variations in the South Atlantic High, Atlantic, and Indian oceans, and as far away as the North Atlantic.[5] These factors make rainfall in central Africa more variable from year to year, which could have implications for future changes in the system. How these interactions among air circulation, land surface, and sea surface temperatures are manifested

5 Todd, M. C., and R. Washington, 2004. Climate variability in central equatorial Africa: Influence from the Atlantic sector, *Geophysical Research Letters*, 31(23):1–4.

in central Africa needs a lot more research. The influence of El Niño on the region, for instance, is more uncertain than for east, west, and southern Africa. Recent work suggests a complex set of global interactions have varying effects across the basin.[6]

BUILDING BETTER CLIMATE MODELS

The credibility of climate model simulations depends on their ability to show the regional climate system, as well as processes of change

Climate models represent complex physical atmospheric processes using mathematical equations. These tools are important for understanding present climate systems, and projecting future changes. The credibility of climate model simulations depends on their ability to show the regional climate system, as well as processes of change. We can test the credibility of models by comparing their simulations of historical climate to observed historic data.

For central Africa, models tend to disagree with one another in their representation of historical climate, leading to large amounts of uncertainty about the current and future climate system.[7] If there are large variations between model simulations of historical climate, the same uncertainty will carry forward when the models are run to simulate the future climate. For instance, in some seasons, rainfall differs by a factor of five between different climate models,[8] meaning the level of uncertainty about future rainfall trends is relatively high.

Models also vary vastly in where they position rainfall over the region, with strong discrepancies in where the maximum rainfall occurs. These differences are partly because of the limited understanding of the region's climate system, along with the shortage of weather station information. This makes it difficult to test which models are the most credible. If we cannot establish how credible models are for simulating the historical climate, it is difficult to decide which projections of future climate are trustworthy. Assessing the climate model simulations for the region is a central part of current research in this field.

CURRENT RESEARCH AND FUTURE PLANS

Owing to the shortage of weather station information, there would be benefits from studying large scale circulation systems more closely in order to improve our understanding of regional climate dynamics. Recent work has studied the drivers of atmospheric circulation for the lower atmosphere, which in turn influence how much moisture is provided by the Atlantic Ocean to central Africa.[9, 10] Further research is also exploring how the atmospheric jets (fast-moving air currents) in the middle and the upper atmosphere over central Africa contribute to the uplift of air in different seasons, and how this relates to rainfall variability over the region. Researchers are now prioritising efforts to overcome these large differences in the model results, to reduce the high levels of uncertainty.

6 Nicholson, S. E. and A. K. Dezfuli, 2013. The relationship of rainfall variability in western equatorial Africa to the tropical oceans and atmospheric circulation. Part I: The boreal spring. *Journal of Climate*, 26(1), 45–65.

7 Washington, R., R. James, W. Pokam, and W. Moufouma-Okia, 2013. Congo Basin rainfall climatology: can we believe the climate models. Philosophical Transactions of the Royal Society B: Biological Sciences, 368:1–7.

8 Creese, A. and R. Washington. (submitted) Using qflux to constrain modelled Congo Basin rainfall in the CMIP5 ensemble.

9 Pokam, W. M., L. A. Tchotchou Djiotang, and F. K. Mkankam, 2012. Atmospheric water vapor transport and recycling in Equatorial central Africa through NCEP/NCAR reanalysis data. *Climate Dynamics,* 38:1715–1729.

10 Pokam, W. et al., 2014. Identification of Processes Driving Low-Level Westerlies in West Equatorial Africa. *Journal of Climate*, 27(11):4245–4262.

Researchers from a range of organisations (see UMFULA, below) are looking at a number of appropriate climate models and the available weather records for the region.[11] The team has studied the circulation factors influencing modelled rainfall,[12] and assessed the range of possible future climate change and its implications for the region's rainforests.[13] This has allowed us to fully appreciate the importance of moisture circulation patterns in models, which is closely related to how they simulate rainfall patterns. If we can measure moisture fluctuations into the Congo Basin, this will allow climate models to simulate rainfall more accurately. New research will also assess regional climate models, particularly those that are good at simulating local thunderstorm activity. We are also studying the relationship between sea surface temperature and rainfall more closely.

FCFA'S UMFULA PROJECT

Project objectives

UMFULA ("river" in Zulu) is a four year research project that aims to improve climate information for decision-making in central and southern Africa, with a particular focus on Tanzania and Malawi. UMFULA is a global consortium of 15 institutions specialising in cutting edge climate science, impact modelling and socio-economic research.

UMFULA aims to support long-term – five to 40 year – planning decisions in central and southern Africa around resource use, infrastructure investment and cross-sectoral growth priorities, by identifying adaptation pathways that are robust and resilient in the face of climate change and other non-climate stressors.

The team is generating new insights and more reliable information about climate processes and extreme weather events and their impacts on water, energy and agriculture. These insights will support the more effective use of climate information in national and local decision-making. See www.futureclimateafrica.org/project/umfula

The institutions involved in UMFULA are:

- Grantham Research Institute on Climate Change and the Environment (London School of Economics and Political Science)
- Kulima Integrated Development Solutions
- University of Oxford
- University of Cape Town
- Sokoine University of Agriculture
- Lilongwe University of Agriculture and Natural Resources
- University of Leeds
- Council for Scientific and Industrial Research
- University of Manchester
- University of KwaZulu-Natal
- University of Sussex
- University of Dar Es Salaam
- University of Yaoundé
- Tanzanian Meteorological Agency
- Mozambique National Institute of Meteorology

11 Washington, R. James, R., Pokam, W., and Moufouma-Okia, W. (2013) Congo Basin rainfall climatology: can we believe the climate models. Philosophical Transactions of the Royal Society B: Biological Sciences, 368:1–7.

12 Creese, A. and Washington, R. (submitted) Using qflux to constrain modelled Congo Basin rainfall in the CMIP5 ensemble.

13 James, R. and Washington, R. (2013) Changes in African temperature and precipitation associated with degrees of global warming. *Climatic Change*, 117:859–872.

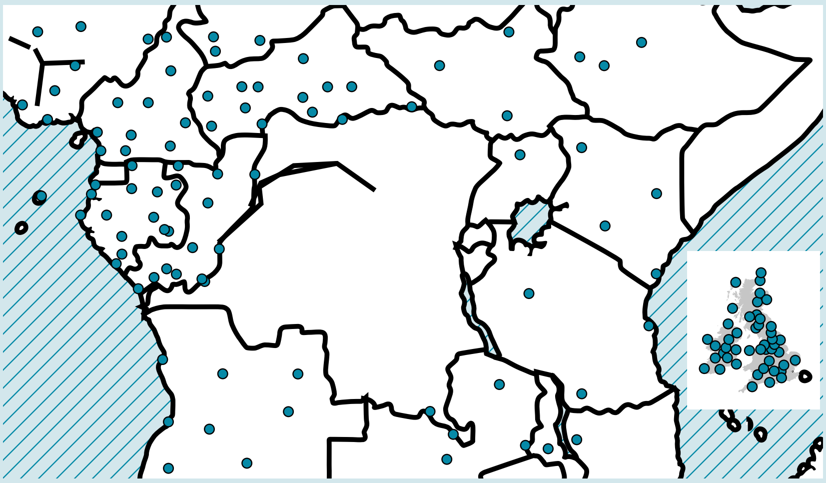
FIGURES

Figure 1

The Congo Basin (dark blue) and the Congo rainforest play an important role in global climate regulation.[14]

Figure 2

This figure shows the sparse distribution of weather stations contributing to global datasets in central Africa (left), compared with the UK (right), an area less than one tenth in size.[15]



14 Map: produced by the authors.

15 Harris, I., P. D. Jones, T. J. Osborn, D. H. Lister, 2013. Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 Dataset. Int J Climatol. 2014;34:623–42.

Figure 3

Land surface height for the African continent. The eastern boundary of the Congo Basin gives way to high mountainous regions, which influences the flow of air and moisture into the region. The north-west of the basin also features high topography, for example, Mount Cameroon.[16]

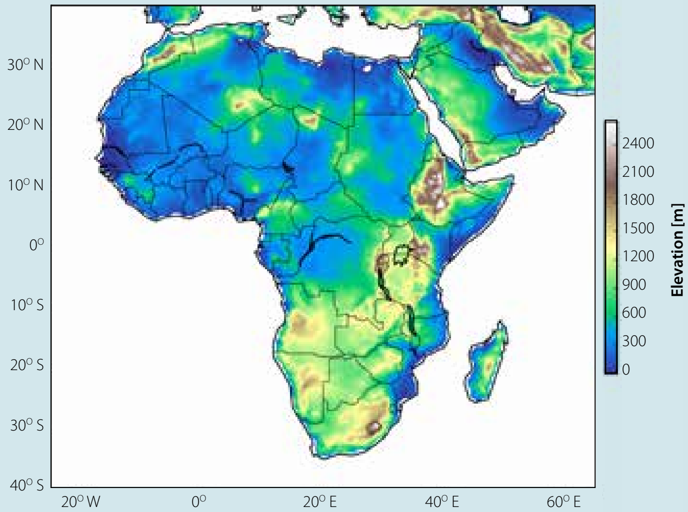
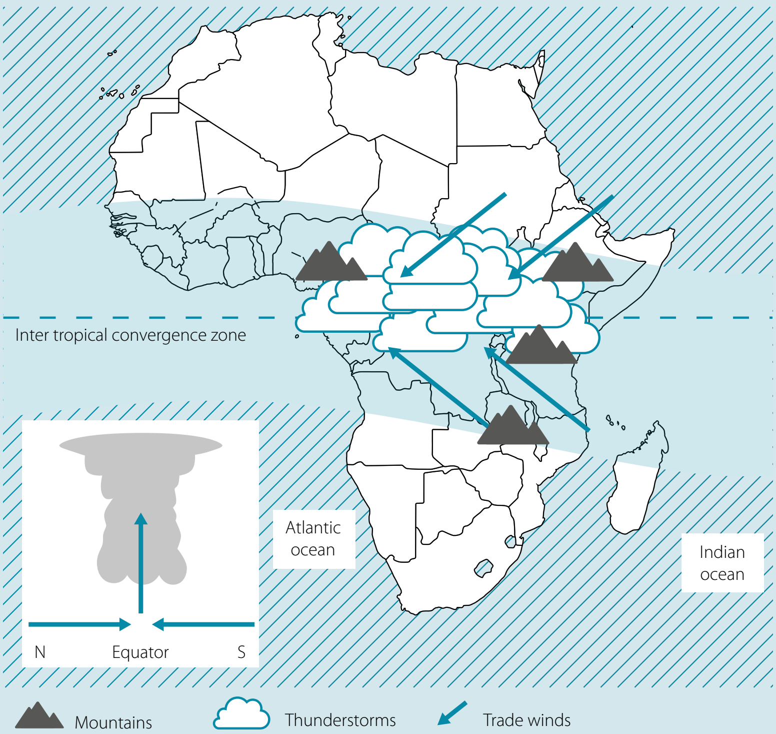


Figure 4[17]

Schematic of the central African climate system. The movement of the Inter Tropical Convergence Zone (ITCZ) throughout the year dominates the climate system in central Africa and surrounding regions. The location of large thunderstorms moves north and south throughout the year. The large scale circulation brings moisture to the region via the trade winds. Moisture is also recycled heavily in the basin.



16 https://lta.cr.usgs.gov/GTOPO30

17 Map: produced by the authors.

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GENERAL READERS

EAST AFRICA
REGIONAL OVERVIEW

EAST AFRICA'S CLIMATE: PLANNING FOR AN UNCERTAIN FUTURE

AUTHORS

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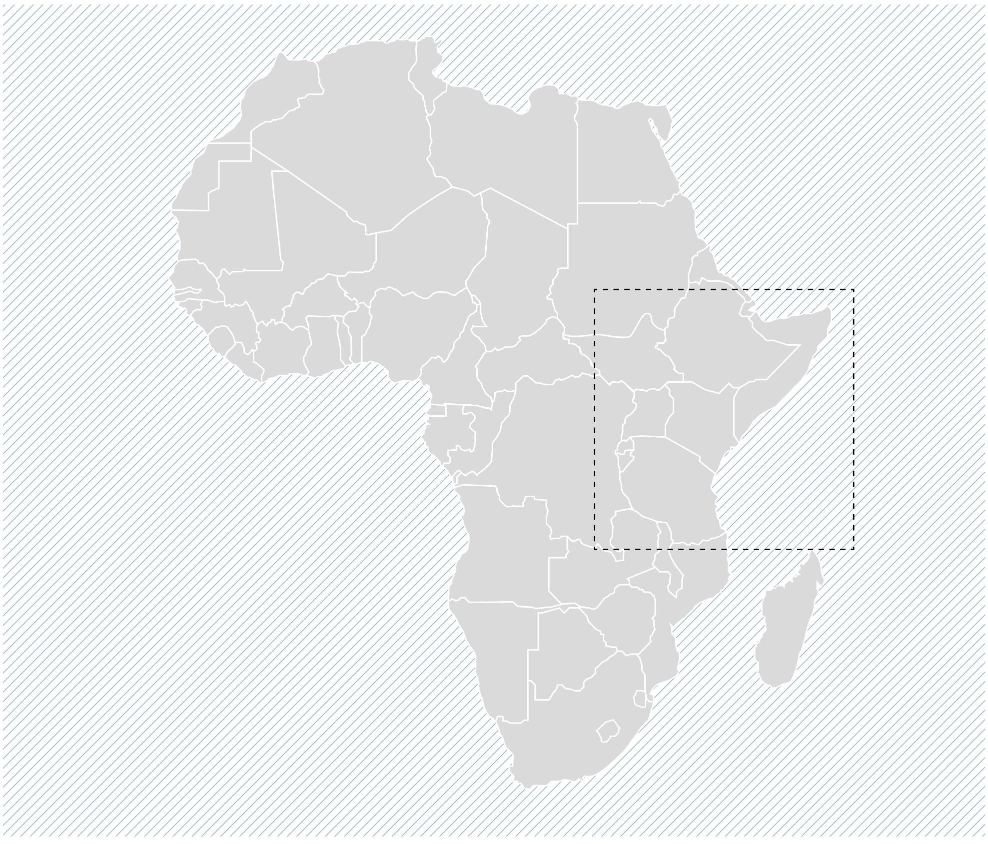


NEED TO KNOW

Rising temperatures and changing rainfall patterns will have significant impacts across east African society. Decision-makers need accessible information on likely climate change if they are to plan appropriately for this uncertain future.

This factsheet considers how the climate is likely to change in east Africa, and the likely implications for:

- water availability
- sanitation
- livelihoods, including agriculture and fresh water fisheries
- hydropower
- the potential for wind energy.

EAST AFRICA'S CLIMATE IS ALREADY CHANGING

The equatorial and southern parts of eastern Africa have experienced a significant increase in temperature since the early 1980s

The equatorial and southern parts of eastern Africa have experienced a significant increase in temperature since the early 1980s. Seasonal average temperatures have risen in many parts of the region over the past 50 years. Rainfall in the region is extremely variable across time and space. Several physical processes, including the El Niño Southern Oscillation, affect rainfall. Countries bordering the western Indian Ocean experienced a trend towards more frequent heatwaves, droughts, and storms between 1961 and 2008.[1]

There is a lack of evidence about observed trends in extreme temperature, extreme rainfall, and drought in east Africa. Changes in the Indo-Pacific oceans appear to have contributed to more frequent drought during the 'long rains' (from March to May) over the past 30 years. It is not clear whether these changes are due to human-caused climate change, or to natural climatic variability.[2]

FUTURE PROJECTIONS

Climate modelling indicates that east Africa is expected to warm in the next five to 40 years, although changes in rainfall are much less certain.

Temperature changes:

- maximum and minimum temperatures over equatorial east Africa will rise, and there will likely be an increase in warm days[3]

1 Climate & Development Knowledge Network. 2014. The IPCC's Fifth Assessment Report: What's in it for Africa?. Accessed on April 5, 2016 from: http://cdkn.org/resource/highlights-africa-ar5/

2 Ibid.

3 Ibid.

- the average annual temperature will likely increase by 1°C to 2.4°C by 2065[4]
- there will be a rise in warm nights in particular (an increase of about eight to 12 days per decade), and warmer days will likely happen more often.[5]

Rainfall changes

Tropical rainfall changes are challenging to project. Scientists must understand how the water content of the atmosphere will change as conditions warm, and also predict how storms form in response to the movement of heat and water in the atmosphere.

For eastern Africa, the 'long rains' season has recently experienced a series of devastating droughts, whilst most of the climate models predict increasing rainfall for the coming decades. This is the so-called 'east African climate change paradox'.

Future change can have serious implications for livelihoods in east Africa as water availability, sanitation, and energy are all influenced by the climate

This may be explained by the difficulty in modelling the change, or that models do not incorporate all factors driving this change. This is an area of active research.[6] Currently, global projections suggest that by the end of the 21st century, the climate in eastern Africa may be wetter or drier, but more likely to be wetter (with rainfall changing by between -6% and 17%).[7] The projections suggest a wetter climate during October to December, and March to May. By mid-century, the 'long rains' season may shorten for Ethiopia, Somalia, Tanzania, and southern Kenya. However, the 'short rains' season in southern Kenya and Tanzania (from October to December) may lengthen.[8]

Extreme rain events over most of the mid-latitude land masses and over wet tropical regions will very likely become more intense and more frequent by the end of this century, as temperatures warm,[9] and dry spells may increase.

While there is often uncertainty in the projections, this should not be a reason for inaction. Instead, these projections mean that adaptation measures should be robust for different scenarios, or be flexible enough to allow responses to change.

Society-wide impacts

Future change can have serious implications for livelihoods in east Africa as water availability, sanitation, and energy are all influenced by the climate.

4 IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

5 Ibid.

6 Rowell, D. P., B. B. Booth, S. E. Nicholson, P. Good, 2015. Reconciling Past and Future Rainfall Trends over Eastern Africa. J. Climate. 28, 9768–9788. DOI: 10.1175/JCLI-D-15-0140.1.

7 IPCC, 2013.

8 Climate & Development Knowledge Network. 2015. The IPCC's Fifth Assessment Report: What's in it for Africa?. Accessed on April 5, 2016 from: http://cdkn.org/resource/highlights-africa-ar5/?loclang=en_gb

9 IPCC, 2013.

The implications of climate change for east Africa will be wide, including landslides in mountainous regions, complex ecosystem changes, and intensification of socio-political pressures. Therefore, climate change information must be integrated into decision-making and governance at all levels, and across traditional sectors and national boundaries.

Water availability

The uncertainty in climate projection makes it difficult to predict the precise impact on water resources. If there are to be more extended dry spells and a higher proportion of rainfall occurring as intense events, this could have a significant detrimental impact on the reliability of surface water stores, environmental flows, and soil water. This could have important implications for water supply, agriculture, and energy policy and development in a region where terrestrial water stores are already highly spatially variable.

Likewise the timing of groundwater recharge, and therefore the seasonal dynamics of groundwater stores, may be altered. This is particularly important in areas with hard rock aquifers which have low storage capacity and which cover much of east Africa.

More intense rainfall is likely to lead to an increase in surface flooding, more extreme river flow dynamics, and less predictable surface water stores. In some regions with relatively low annual average rainfall (less than 1000mm per annum), there is some evidence that this may lead to enhanced recharge of aquifers.

While groundwater resources are modest across the region, they are more buffered from climate variability compared to surface water, and may grow in importance regionally to meet future changes in water resource demands. Monitoring of groundwater resources is essential to ensure that in low storage aquifers, the groundwater resources are not overexploited.

Water supply and sanitation

The main climate-linked challenge relating to urban sanitation is flooding, which is expected to increase in frequency and intensity.

The main climate-linked challenge relating to urban sanitation is flooding, which is expected to increase in frequency and intensity. Direct impacts of this include: wash out of pits and tanks, causing contamination at the local level; overflow of sewers (where combined sewers are used), resulting in by-passing or wash out of treatment facilities (local or centralised); and wash out and destruction of sewers and treatment plants.

In addition, flooding may result in the isolation of areas with on-site sanitation, which then cannot be emptied, as well as an increase in transport costs for trucking excreta due to flooded roads and access points.

Where changes in climate result in increased waterlogging, this is likely to cause pits, tanks and sewers to be inundated with groundwater, which will impact on treatment processes.

The combined result of all of these factors will be an increase in the outbreak of water-borne diseases.

The consequences of the increases in average and extreme temperatures that are projected by climate models are likely to be: changes in the incidence of several critical excreta-related diseases; an increase in water consumption (this is also impacted by the availability and quality of urban water supply which in turn is influenced by the climate); and the extent and rate of algal growth in nutrient-enriched surface waters.

All of these considerations need to be integrated into decisions on urbanisation, water supply, and sanitation and drainage.

Rural livelihoods

The implications for productivity of food and cash crops, and lake fisheries will be profound, likely negatively impacting livelihood patterns and household incomes for farmers and fishing communities within the Lake Victoria Basin (LVB).

Many factors make long-term predictions problematic, including uncertainty about future climate, population dynamics, productivity, prices, employment, and other factors influencing such highly variable and complex livelihood systems.

Support for rural livelihoods and adaption to climate change will need better information on income and livelihood patterns, both within and between different populations across the region. Crops and fisheries will need to be monitored, along with their sensitivity to changes in climate, surface and ground water availability, government policies and active year-to-year management of impacts. Such information is key to developing sound strategies for land and water resource management.

Smallholder farmers with limited capital for investment in alternative income sources face multiple challenges: climate change; issues of market confidence; and lack of short-term security, which overrides longer-term investment decisions. Strategies aimed at improving access to and functioning of market systems could help increase the demand for, and supply of, affordable goods and services. Meanwhile, this will enable the rural poor to participate in markets and benefit from economic opportunities. Irrigation plans and strategies for diversification of food and income sources will be key.

Changing rainfall variability will impact on water levels in rivers and lakes, highlighting the importance of adapting the water 'release rules' followed by the hydropower sector

Hydroelectric energy industry

Hydroelectric energy is important for many states in east Africa. For example, hydroelectric schemes provide most of Uganda's industrial energy, and some is exported to Kenya. Climate change may increase or decrease water availability for hydropower. Energy planning must take this into consideration.

Changing rainfall variability will impact on water levels in rivers and lakes, highlighting the importance of adapting the water 'release rules' followed by the hydropower sector. For example, the current release rule at the source of the Nile means that the release from the Nalubaale Dam should follow the natural flow from Lake Victoria that would have existed prior to the existence of the dams.

Alternative release rules have been proposed that would save water during high rainfall years, to use in times when there is less rainfall. This may become more important with climate change. The research community has already used climate model projections to rank the release rules proposed by the Ugandan Ministry of Energy to minimise load shedding in future decades. Certain climate models can help refine this prioritisation of the proposed release rules, and assist government with developing new regulatory strategies and decisions in planning for the optimal mix of energy sources for the future.

Wind power over Lake Victoria

The need to slow climate change provides a strong incentive to develop renewable power sources, such as wind energy. Exploration and exploitation of wind power should help east African nations to meet their green energy targets for climate mitigation.

Studies have successfully determined the potential for wind power throughout most of east Africa. This has led to investment in large wind power plants over the northeast region of Kenya, with similar plans for central Tanzania. Paradoxically, these studies haven't enabled wind power investment over the LVB, which is one of the most powerful atmospheric circulation systems in the world. Climate scientists are working on advancing climate models that incorporate the interactions of land, lake, and atmospheric forces in order to better understand how climate change could affect the availability of wind energy across east Africa.

FCFA'S HyCRISTAL PROJECT

Project objectives

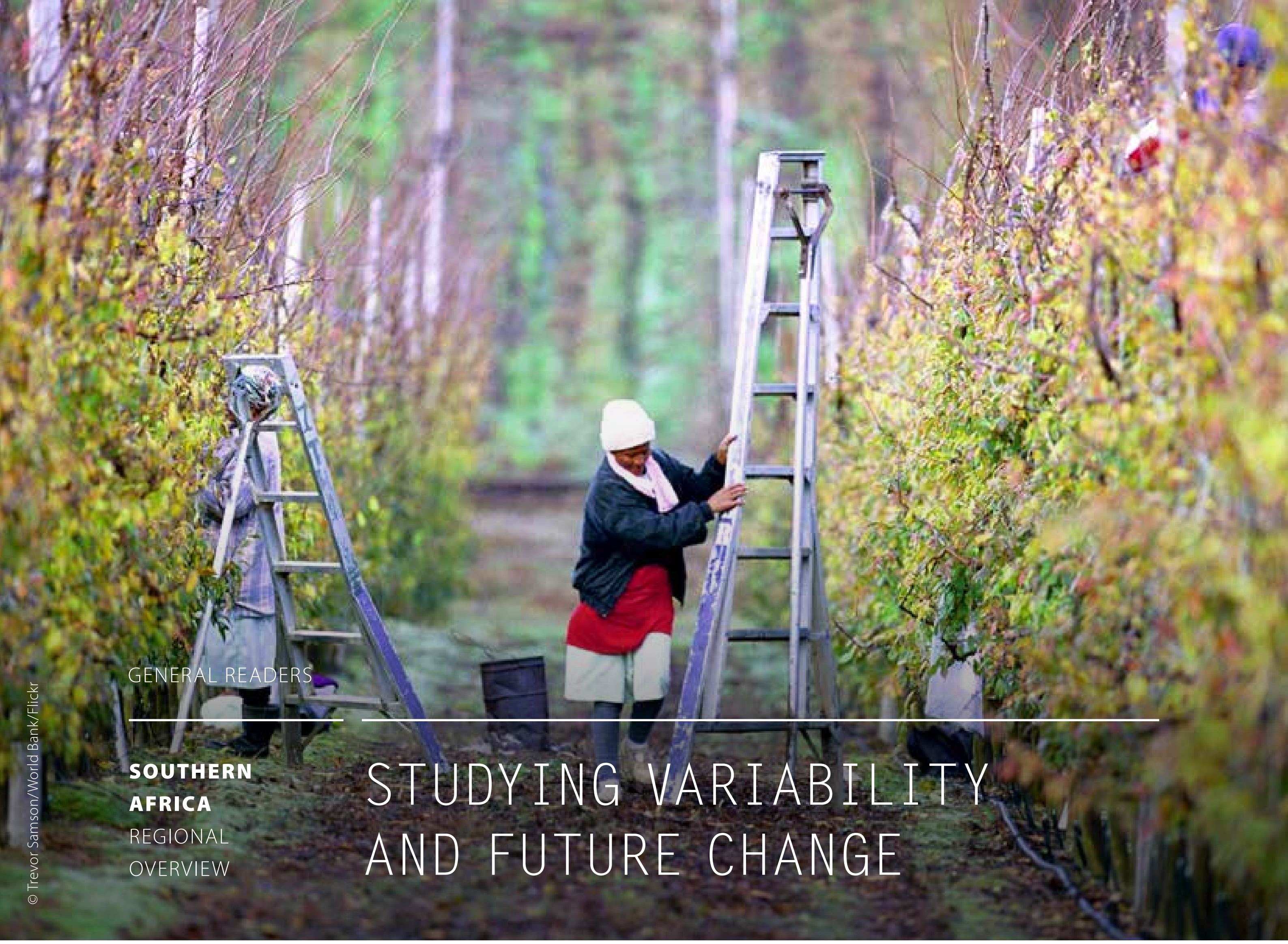
The availability of water is fundamental for development in east Africa. However, this vital resource is already under stress from land degradation, pollution and overfishing. Climate change adds to these problems, greatly increasing the vulnerability of the poorest people in the region.

Climate projections show a warming trend in east Africa in the decades ahead, but changes in rainfall and weather extremes are currently uncertain. HyCRISTAL will tackle current uncertainties which exist around climate change projections for the region, concentrating in particular on what they mean for the availability and management of water.

HyCRISTAL will develop new understanding of climate change and its impacts in east Africa, working with the region's decision-makers to manage water for a more climate-resilient future. See www.futureclimateafrica.org/project/hycristal/

The institutions involved in HyCRISTAL are:

- University of Leeds
- African Centre for Technology Studies
- British Geological Survey
- Centre for Ecology and Hydrology (UK)
- Evidence for Development
- Jomo Kenyatta University
- Loughborough University
- Met Office (UK)
- National Centre for Atmospheric Science (UK)
- National Fisheries Resources Research Institute (Uganda)
- North Carolina State University
- Practical Action
- Stony Brook University
- Tanzanian Meteorological Agency
- Ugandan National Meteorological Authority
- Ugandan Ministry of Water Resources
- University of Connecticut
- Makerere University
- Maseno University
- Walker Institute
- University of Reading (Africa Climate Exchange)



GENERAL READERS

SOUTHERN AFRICA REGIONAL OVERVIEW

STUDYING VARIABILITY AND FUTURE CHANGE

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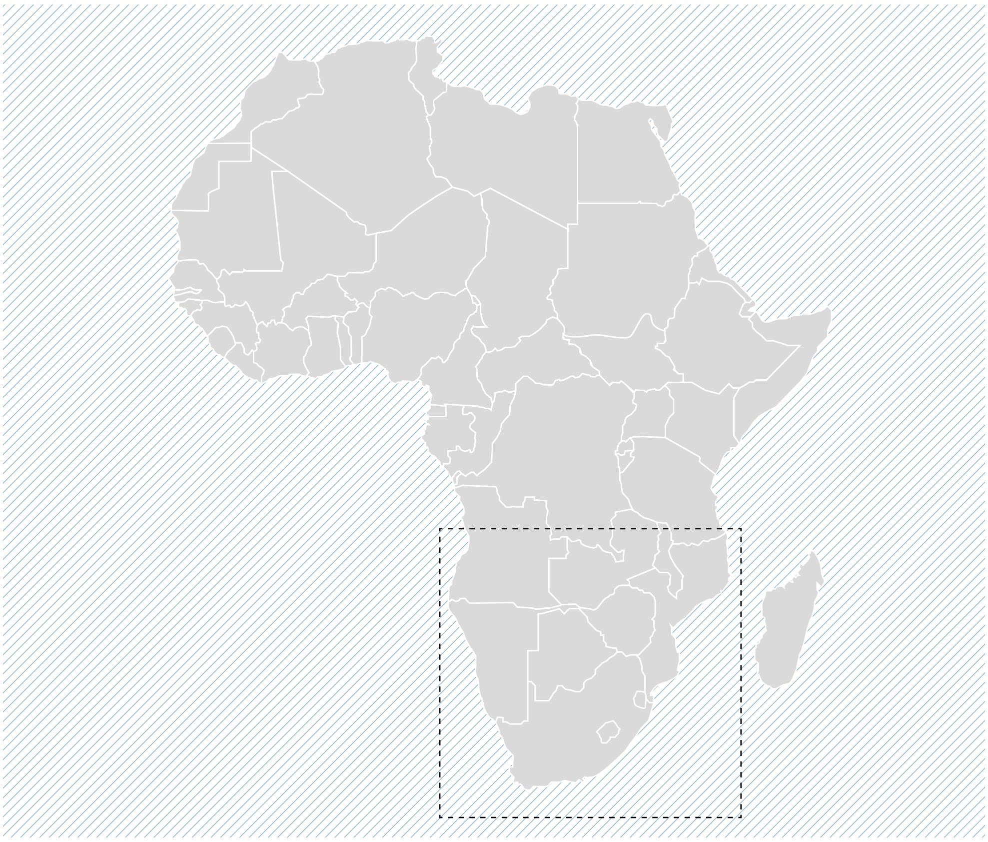


NEED TO KNOW

Southern African countries need reliable, robust climate information to be able to buffer their economies and communities against the impacts of climate change. Scientists working on climate modelling for the region are concerned with:

- understanding the complex physical forces that drive the 'natural' variability of the climate across the region
- refining and improving the climate models, in order to give more reliable forecasts for how the climate might shift in the future
- calibrating how reliable the current climate simulations are.

UNDERSTANDING SOUTHERN AFRICA'S CLIMATE SYSTEM

Southern African communities need to adapt urgently to the region's changing climate, and informed decision-making is key to acting pre-emptively.

Southern African economies are exposed to weather and climate vulnerabilities, particularly through sectors such as agriculture, energy, and water management. It follows that the supply of essential resources are all extremely at risk as the climate becomes more changeable and extreme. Communities and countries need to begin planning, adapting and investing now so they can be more resilient.

Having reliable and useful climate information at their fingertips is therefore critical. 'Climate information services' are developing and spreading this information more effectively through the region. But there is still a great deal of uncertainty about what climate change will mean for the region, and decision-makers struggle to know which sources of information to trust and use.

Through improving our understanding of how the climate system works in southern Africa, and improving the mathematical models that simulate the future climate, climate scientists working in the region hope to provide reliable climate information to those who need it.

GETTING THE SCIENCE RIGHT

There are two main challenges to producing suitable, reliable climate information.

1) How the atmosphere and oceans create 'uncertainty' in projections

The interplay between the atmosphere and oceans, which drive our climate, is extremely complex. These interactions can produce large variations in weather or climate, spanning seasons, years, and even decades. El Niño events, for instance, can bring severe droughts in sub-tropical Africa and floods to east Africa, relative to 'normal' years.

Projecting how the climate will change in future, as greenhouse gases increase in the atmosphere, needs mathematical modelling tools that can capture and simulate these complicated and region-specific ocean-atmosphere interactions.

2) Large timeframes, great distances: why climate modelling is difficult

Modelling weather and climate is difficult, not least because of the variations through time and across distance. Models divide distance into a grid with one grid typically covering tens of kilometres. As a result, information at the local scale, for example a typical farm or village, is difficult to produce in a reliable way. A key challenge is to develop models and understanding that allow us to provide climate information at the appropriate space and time scale for specific planning decisions. This could be irrigation management in a large river catchment, or deciding which crops to grow in a particular agricultural region in the future.

Much of the climate science being undertaken in the southern African region aims to improve our understanding of the physical forces that shape southern African's climate. There is strong emphasis on seeing what climate models can tell us about the near-term climate changes, and the risks for specific regions within countries here. Researchers have access to an archive containing over 40 climate models that have simulated the next five to 50 years of climate change under increasing greenhouse gas concentrations. Many models have even run up to 100 years into the future.

However, these produce a wide range of results. In order to understand which models are credible, we need to better understand the fundamentals of how the seasons change over the region, and how the oceans influence or modify these seasonal changes in rainfall, wind, and temperature.

WHAT WE KNOW (AND DON'T KNOW) ABOUT THIS CLIMATE SYSTEM

During winter, the skies above southern Africa are generally clear, and there is little rainfall. As the summer approaches, the sun moves south across the subcontinent, heating the land surface rapidly and drawing in moisture from surrounding oceans. Southern Africa has a complex array of mountain ranges (see grey shading in Figure 1) with a high plateau covering much of the subcontinent, and several mountain ranges that are higher than 2,500m. The sun's heating effect is amplified over the higher terrain, and the sharp gradients in the terrain interrupt and redirect the low-level, moisture bearing winds across the region, leading to a complex flow of air (Figure 1). The mountainous terrain is also efficient at triggering the development of thunderstorms. However, we do not fully understand the workings of these systems, such as clusters of thunderstorms called mesoscale convective complexes, and the regional air movement that helped create them.

Further south, in the sub-tropics, waves of high-altitude westerly air, about 10km above the ground, also shape the climate. These waves either encourage or suppress how warm air rises here, and can bring widespread rainfall over southern Africa. Further bands of clouds – known as tropical temporal troughs – bring rainfall and thunderstorms across the region. An important gap in our knowledge is how these waves and cloud bands impact thunderstorms further north over the continent.

The oceans on either side of the subcontinent play a significant role in the region's climate. For example, warm ocean temperatures in the tropical oceans and the Agulhas current create warm, humid air, and changes in the strength of the high air pressure systems over oceans, all influencing the flow of moisture over the subcontinent, and therefore the amount of rainfall across the region.

Ocean temperatures also play a key role in the likelihood of extreme weather events such as cut-off lows, tropical cyclones and tropical temporal troughs' cloud bands, which bring strong winds and flooding across the region (Figure 1).

Nevertheless, more research is needed to better understand the links among ocean temperatures, the high pressure systems, and extreme events over southern Africa.

The El Niño weather phenomenon can also disrupt air flow and impact on extreme events. Some of the worst droughts in sub-tropical Africa, and the worst floods for east Africa, have occurred during El Niño events. And yet, scientists still don't have a clear understanding of how El Niño influences the wet season over sub-tropical southern Africa.

HOW CREDIBLE ARE OUR CLIMATE SIMULATIONS?

Climate models are mathematical tools that try to simulate how the climate will behave in the future, based on the physical forces that are known to shape the climate system. To test the accuracy of these models, they are first used to replicate the past climate, and this is compared to historical records. Then, they are run forward to project the future climate as greenhouse gas levels increase and cause regional temperatures to rise.

The difficulty is that the various models can give different results. In order to test which simulations are the most credible, and therefore which will generate the most useful climate information, we need to understand three things:

- How do these forces balance and produce the weather and climate over seasons and years that we have already observed over southern Africa?
- What are the differences between models that are responsible for the different climate simulations over southern Africa, and how does this inform our trust in the models?
- What do the future simulations say about likely changes in the behaviour of regional air circulation patterns?

The climate scientists tackling these questions are trying to understand the link between the various physical forces that shape air movement and cloud, thunderstorm, and rainfall formation. Current climate models tend to overestimate southern African wet season rainfall, so there is a need to analyse the processes that are causing this.

Much of the climate risk for southern Africa is associated with year-to-year variability in the regional weather. For climate models to offer useful information, they will need to be able to simulate this variability realistically, and a great deal of work is being done to assess whether the models are capable of doing so.

For southern Africa, it is particularly important to simulate changes in the local (e.g. south-west Indian Ocean) and remote (tropical Pacific) ocean temperatures. These models also need to reproduce the shifts in the high pressure systems over the oceans which, together with ocean temperatures, are important for how much moisture moves inland into southern Africa.

For southern Africa, tropical cyclones and cut-off lows can produce severe flooding and damaging winds. Severe droughts are typically associated with substantial changes of the average seasonal cycle, such as the 2015/16 El Niño event. Scientists are currently working to assess whether climate models simulate these seasons and then see how they may change in the future.

FCFA'S UMFULA PROJECT

Project objectives

UMFULA ("river" in Zulu) is a four year research project that aims to improve climate information for decision-making in central and southern Africa, with a particular focus on Tanzania and Malawi. UMFULA is a global consortium of 15 institutions specialising in cutting edge climate science, impact modelling and socio-economic research.

UMFULA aims to support long-term – five to 40 year – planning decisions in central and southern Africa around resource use, infrastructure investment and cross-sectoral growth priorities, by identifying adaptation pathways that are robust and resilient in the face of climate change and other non-climate stressors.

The team is generating new insights and more reliable information about climate processes and extreme weather events and their impacts on water, energy and agriculture. These insights will support the more effective use of climate information in national and local decision-making. See www.futureclimateafrica.org/project/umfula/

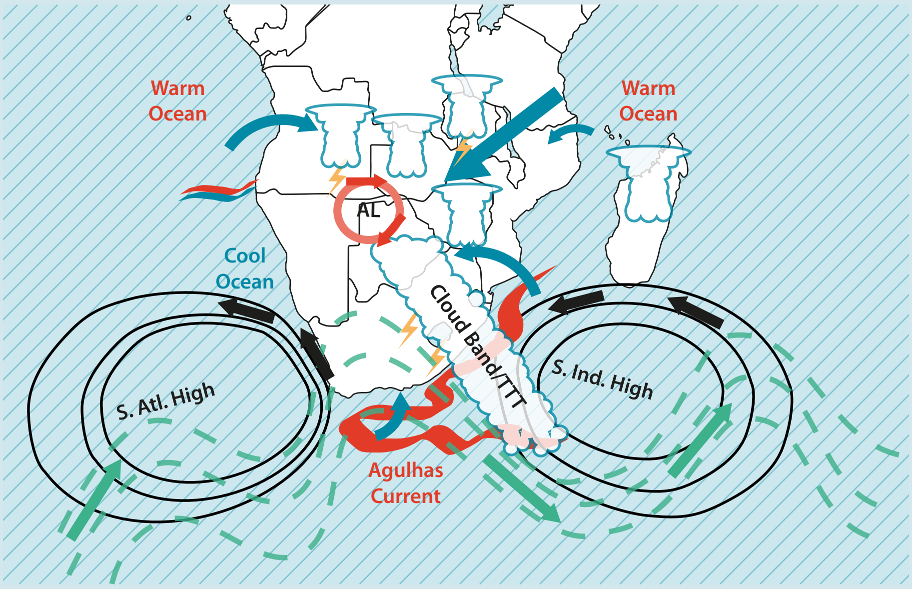
The institutions involved in UMFULA are:

- Grantham Research Institute on Climate Change and the Environment (London School of Economics and Political Science)
- Kulima Integrated Development Solutions
- University of Oxford
- University of Cape Town
- Sokoine University of Agriculture
- Lilongwe University of Agriculture and Natural Resources
- University of Leeds
- Council for Scientific and Industrial Research
- University of Manchester
- University of KwaZulu-Natal
- University of Sussex
- University of Dar Es Salaam
- University of Yaoundé
- Tanzanian Meteorological Agency
- Mozambique National Institute of Meteorology

FIGURES

Figure 1[1]

Schematic detailing key features of the southern African climate system



AL Angola Low

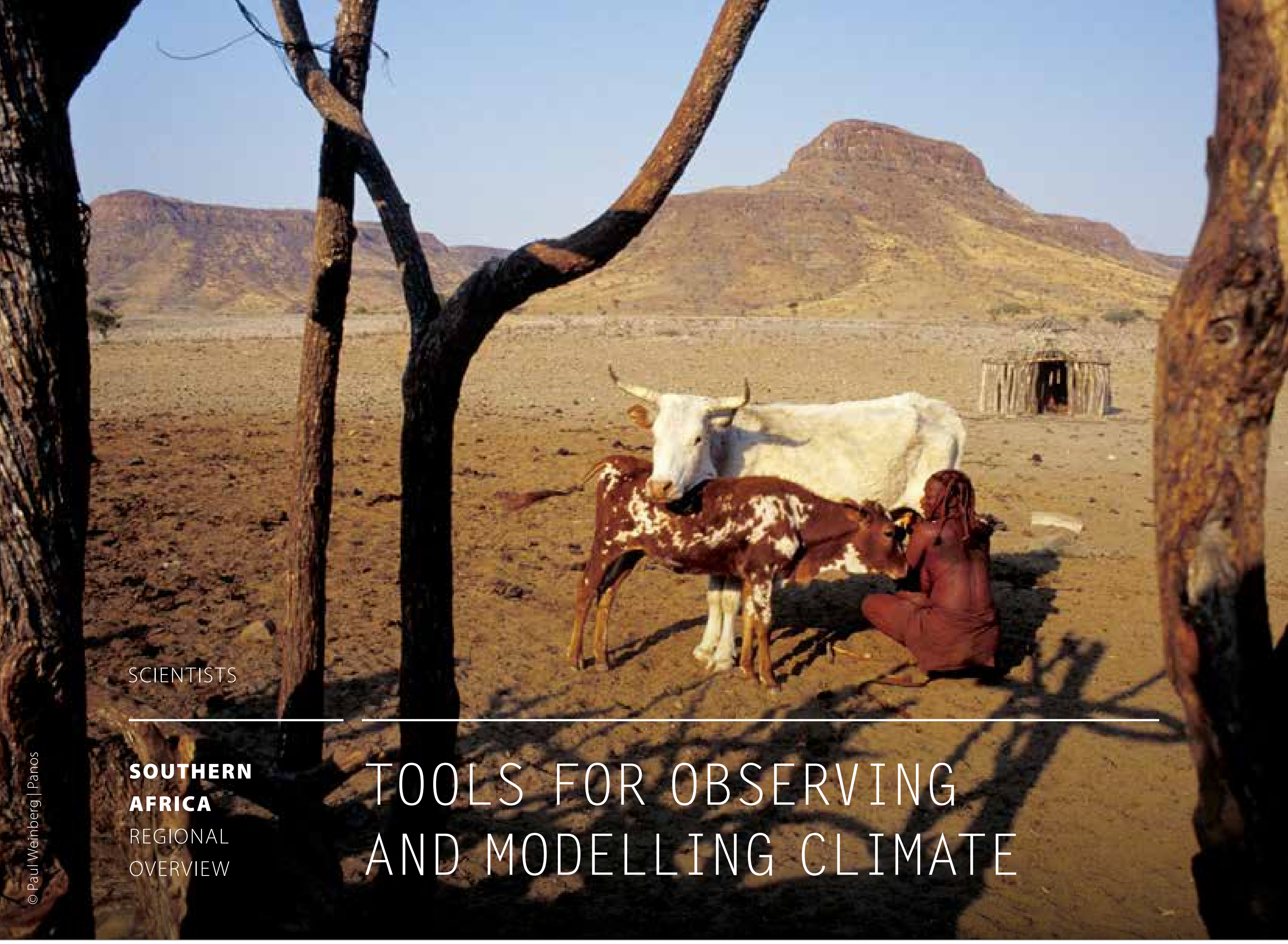
Thunderstorms

Low-level Moisture Transport

Upper-level Flow

TTT tropical temporal troughs

1 Map: produced by the authors.



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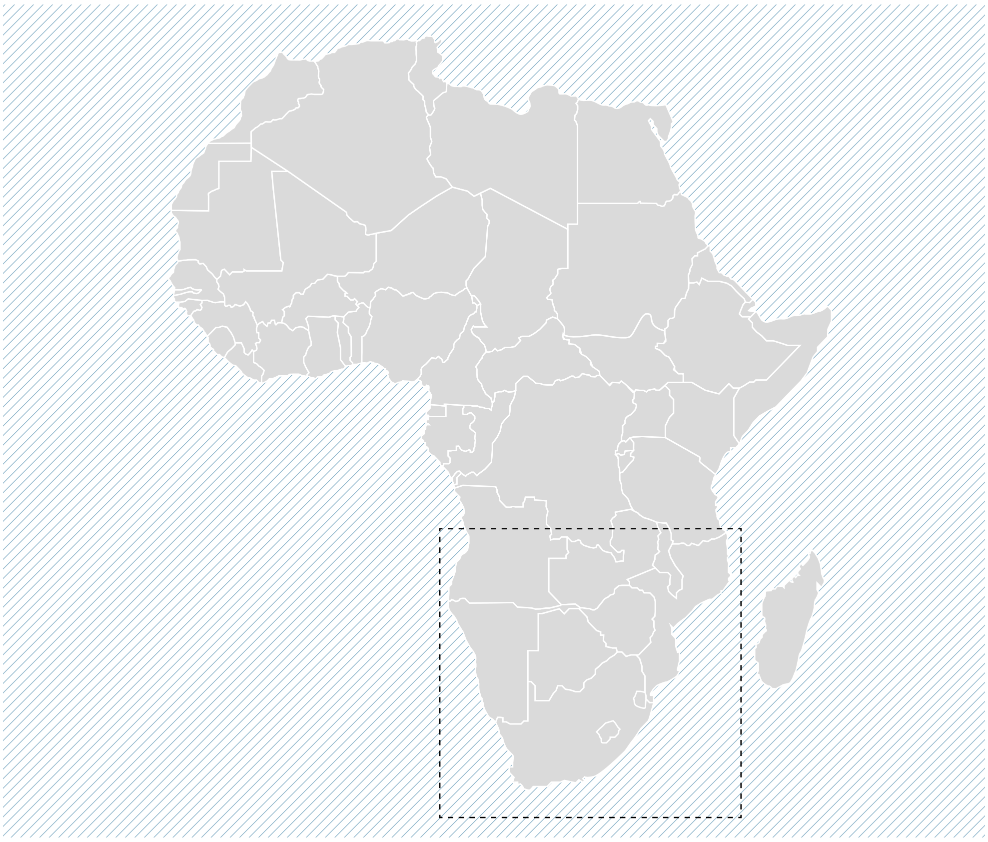
SCIENTISTS

SOUTHERN AFRICA REGIONAL OVERVIEW

TOOLS FOR OBSERVING AND MODELLING CLIMATE

AUTHORS

Chris Jack, Piotr Wolski, Izidine Pinto, Victor Indasi



NEED TO KNOW

Much of the climate information that feeds through to African decision-makers comes from a process of gathering observed atmospheric conditions, such as temperature, rainfall and wind speed, and merging it with sophisticated climate models. The objective is to build reliable projections of what the region's future climate might look like, so that decision-makers can plan accordingly.
This factsheet describes:

- Some of the 'observational' tools that scientists use when they study climate;
- How they merge that information with an analysis process; and
- How the results may agree with, or contradict each other, and what this means for scientists and decision-makers.

INTRODUCTION

We need observations in order to continue advancing our understanding of the climate system

Atmospheric observations form the bedrock of climate science. We need observations in order to continue advancing our understanding of the climate system. This involves an analysis of the variability at inter-annual and longer time scales, as well as analysis of trends, and the relationships between variables. We also use observations to validate the increasingly complex and sophisticated climate simulation models. Without this, we are unable to continue improving models and increasing the accuracy of climate projections.

However, observing the climate system is incredibly challenging. Spatial scale is a challenge, particularly since two thirds of the atmosphere is over ocean, where we cannot easily place weather stations. Conditions here are continually changing, minute by minute, and hour by hour. We increasingly need to measure temperature, wind speed, and humidity at high altitudes as we search for a better understanding of important features, such as the polar jet streams. Measuring wind speeds at 5km altitude above the southern oceans, for example, creates some unique challenges.

There are two broad types of observations of climate systems. Earth-based ('in situ') measurements include data from weather stations, radiosondes, buoys, and similar platforms. Space-based ('remotely-sensed') observations include data from satellite platforms.

There are obvious and significant differences between these two types of observations. The in situ observations provide a direct, precise, and relatively continuous measurement of a particular variable, for instance, wind. Those measurements are, however, representative of a very small area. The space-based observations are obtained indirectly, and may not be precise. For instance, measurements of wind over the ocean rely on wind causing ripples on the ocean surface; these are measured by a backscatter of the microwave 'radar' signal, which is sent and received by a satellite.

Space-based platforms represent a larger area (typically tens of metres to several kilometres); they may have large spatial coverage, sometimes even global; and they have relatively uniform temporal coverage (e.g. every three hours, or daily).

It is critical to note that space-based observations are also reliant on Earth-based observations to calibrate and check their estimates. Backscatter-based ocean wind estimates, as described above, are only possible because of accurate Earth – or ship-based wind speed observations against which algorithms can be tested and calibrated.

OBSERVATIONAL PRODUCTS

Both Earth-based and space-based observations are available through an ever increasing array of observational products, from a range of sources. Observational products are typically *post-processed* versions of the original raw observations. Post-processing is used to convert raw measurements to useful variables, to adjust for known errors or biases in the raw data, as well as to produce types of data that are easier for others to use.
Observational products generally fall into three categories:

- Direct Earth-based observed products (weather stations, ship observations, radiosonde, aircraft, etc.).
- Pure space-based and blended space and Earth data products.
- Re-analysis (or blended model/direct observations) products.

Earth-based products

These products include quality control original station observations, as well as products derived from these such as the CRU 3.23 rainfall dataset that use[1] station-based rainfall observations. In the case of the CRU dataset, quality-controlled data from individual stations were added into the process to produce a uniform grid of data points spanning the entire Earth, and covering over 100 years. Such a product can be easily used at any place on Earth in a variety of applications such as trend analyses or hydrological modelling, with an advantage of relative consistency in space and time.

However, datasets such as CRU are still very dependent and vulnerable to raw weather station observations, and the spatial density of those observations. Similar to many parts of the world, the density of land-based station observations is on the decline. Figure 1 shows the average density of observing stations for the southern African region, spanning a century. The latest CRU monthly rainfall dataset clearly shows a rapid decline in the number of stations contributing to the dataset during the last two decades of observations.

Satellite-derived rainfall datasets are particularly interesting because they can be used in numerous applications outside of climate science, for instance in hydrology, water resources, or agriculture

Satellite-based products

The second category covers a plethora of products ranging from sea surface temperature readings, to wind and rainfall. Satellite-derived rainfall datasets are particularly interesting because they can be used in numerous applications outside of climate science, for instance in hydrology, water resources, or agriculture. The Tropical Rainfall Measuring Mission (TRMM) rainfall dataset (now discontinued) and its successor, the Global Precipitation Mission (GPM), include three-hourly data with a resolution of a grid that is about 25km by 25km for the area spanning between -60º South and 60º North.

Satellite-based products can include satellite measurements only, or be a blend of satellite and in situ observations. For example, the recently developed Climate Hazards Group InfraRed Precipitation (CHIRP) rainfall dataset is based on processing of data from a number of satellite platforms. A version that uses station observations to adjust the satellite-derived values is called CHIRPS.

1 This is a relatively well-known dataset that was created in the Climatic Research Unit (CRU) of the University of East Anglia in the UK. Since the dataset is periodically updated, various updates differ in code. CRU 3.23 is the most recent update at the time of writing this factsheet.

Re-analysis

A third category is the 're-analysis' products, which are able to merge observed data with climate simulations. Re-analyses use climate models to simulate long periods of historical climate (e.g. 1979–2015) just like a normal climate simulation, except the simulation is continuously being 'corrected' by historical observations of temperatures, pressures, and moisture. The process can be seen as a sophisticated interpolation scheme. Different re-analyses use different historical observations and use slightly different approaches to correcting the simulation. Some long climate reconstructions have been done that extend from 1850 through to 2014,[2] and are corrected using long records of historical sea level pressure and sea surface temperatures.

However, there are strong differences between how these re-analyses represent the historical climate conditions, particularly in the tropics where there are few observations and the climate processes involved large exchanges of moisture and energy/heat in extensive rainfall systems. Figure 2 shows the correlation between two of the most common re-analyses, showing strong differences.

The NCAR Climate Data Guide is a valuable resource for searching through the range of observed climate data products available.

Climate scientists specialising in this area of observation and climate modelling, with a special focus on southern Africa (see FRACTAL, below), are compiling a catalogue of observed data products of relevance to the region.

AGREEMENTS AND CONTRADICTIONS IN TRENDS

It is clear that there is a large array of observed climate data products available to scientists. The question that commonly arises is which data product is 'the best', or which product should we use. This is a difficult question to answer, and the kind of product we choose is strongly dependent on the case and context in which each is used (where, over what period, and for what purpose).

There are three common types of uses:

- **Climate normals.** When the question revolves around how much it rains in a particular location, or what the average summertime temperature is, then we are interested in climate normals or averages. In this case we are looking for a dataset that has low *bias* or, in other words, has accurate average values for a particular location or area.
- **Climate trends.** A very common usage is figuring out if the climate in a location or region has changed over time. Again, surface observations are important here, for two reasons. Satellite observations are typically limited to the post-1980s or even later as there are very few satellite data products prior to that. For trend analysis, particularly rainfall trend analysis, statistics require that we look at at least 30 years of data.
- **Climate variability.** Lastly, a very common use is trying to understand the variability or changes in weather from year to year, and from decade to decade. Similar to trend analysis, this requires a dataset with a fairly long set of records, but also requires a dataset that represents natural variability well.

Researchers are putting effort into advancing our understanding of the suite of observed data products available. Some initial results are shown in Figure 3, which illustrates the differences in calculated long term trends across a subset of the available data products

2 The NOAA 20th century re-analysis:
https://climatedataguide.ucar.edu/climate-data/noaa-20th-century-reanalysis-version-2-and-2c

that includes station-based products (Climatic Research Unit (CRU), Global Precipitation Climatology Project (GPCP), Global Precipitation Climatology Centre (GPCC), University of Delaware (UDEL)), satellite-based products (TRMM, CHIRP, Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS), Climate Prediction Center Merged Analysis of Precipitation (CMAP)), and re-analysis products (WATCH-Forcing-Data-ERA-Interim (WFDEI)). It clearly shows that there is significant disagreement between the trends calculated using different datasets, which should raise a red flag for anyone trying to understand historical climate trends using this data. What can also be seen is that some data products show similar trends. This is often because they draw on similar underlying source data such as station observations, or the same satellite sensor data. The end goal of this work is to be able to provide a framework to assist researchers in identifying the suitable single or set of data products to use in a particular use case.

The end goal of this work is to be able to provide a framework to assist researchers in identifying the suitable single or set of data products to use in a particular use case

CONSEQUENCES FOR CLIMATE SCIENCE AND DECISION-MAKING

Figure 3 highlights the potentially large differences in results that we can obtain by using different datasets. For example, if we were interested in the historical trend in rainfall over western Zambia, in the important Kafue Flats region, and we selected the CMAP dataset because it has good spatial coverage, we might conclude that the region has been experiencing a steady reduction in rainfall over the past decades. However, selecting the commonly used GPCC dataset we might conclude the opposite.

This could have important consequences for research as we attempt to understand local responses in river flows with changing rainfall, or it could have large implications in policy and strategic development if the conclusions inform strategic planning for the region. It is therefore critical that observed data products are well understood before the conclusions we draw from them are used for further research or decision-making. A team of climate scientists and practitioners from South Africa and Europe are collaborating in order to contribute substantively to this process through the observed data selection framework.

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FCFA'S FRACTAL PROJECT

Project objectives

One of the chief scientific challenges for understanding southern Africa's climate is that different models give contradictory scenarios for climate trends in the next five to 40 years. FRACTAL's team will advance scientific knowledge about regional climate responses to human activities and work with decision-makers to integrate this scientific knowledge into climate-sensitive decisions at the city-regional scale (particularly decisions relating to water, energy and food with a lifetime of five to 40 years).

Through scientific research, FRACTAL will contribute to improved understanding of climate processes that drive the African climate system's natural variability and response to global change. By bringing together scientists and people who use climate information for decision-making, the project will enhance understanding of the role of such information. FRACTAL will distil relevant climate information that is informed by and tailored to urban decision-making and risk management. The team's activities will understanding of how scientists from different disciplines can work effectively together. See www.futureclimateafrica.org/project/fractal/

The institutions involved in FRACTAL are:

- University of Cape Town
- Met Office (UK)
- Stockholm Environment Institute
- START
- ICLEI–Local Governments for Sustainability
- Swedish Meteorological and Hydrological Institute/ Sveriges Meteorologiska och Hydrologiska Institut
- Red Cross Red Crescent Climate Centre
- University of Oxford
- Aurecon
- Council for Scientific and Industrial Research
- US National Atmospheric and Space Administration
- Lawrence Berkeley National Laboratory
- European Commission Joint Research Centre
- City of Cape Town
- City of eThekwini

FIGURES

Figure 1

Plot of average station density – stations per 0.5deg x 0.5 deg (~50km by 50km) grid cell, for the southern African region (south of 10°S) from 1900 to 2014 for the CRU TS 3.23 rainfall dataset. Value of 0.3 corresponds to approximately 3 stations per 25,000km².

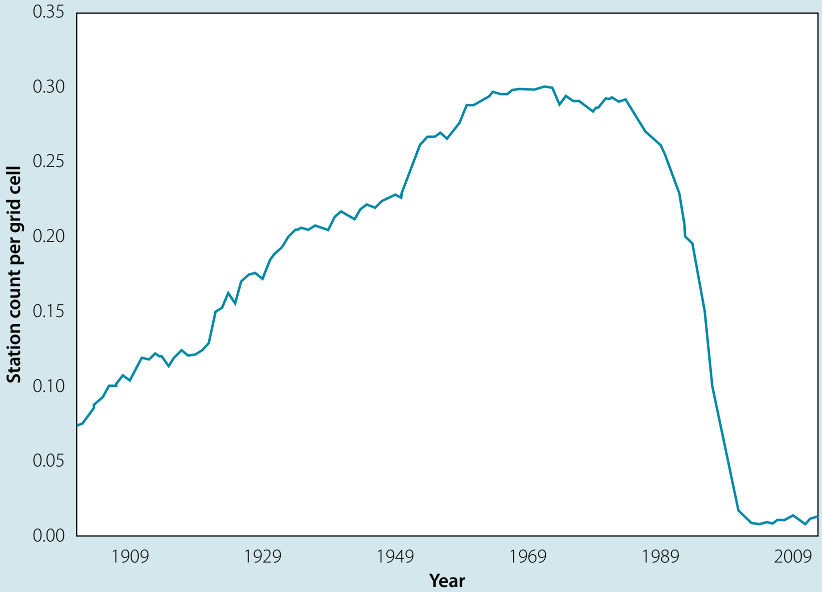
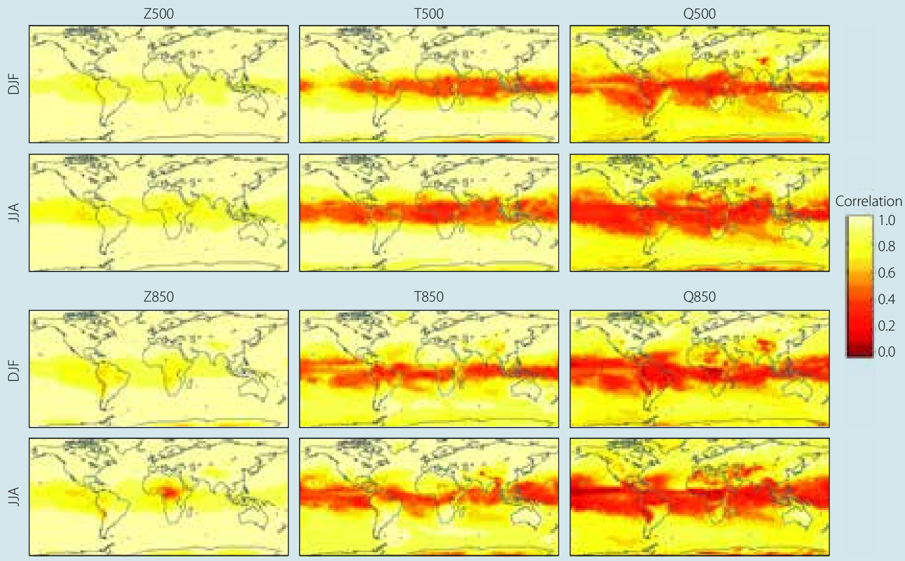


Figure 2

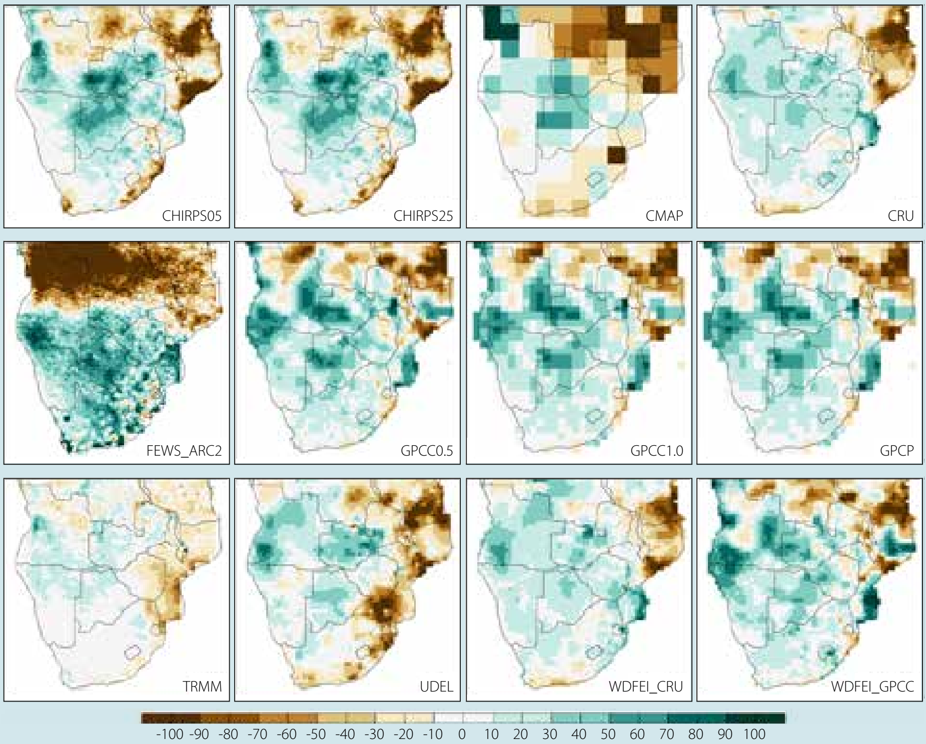
Maps of consistency for the day to day sequence of the daily time series of ERA-40 and NCEP–NCAR , two common datasets, showing the geopotential height (Z), temperature (T), and specific humidity (Q) in the upper and lower parts of the atmosphere respectively (top – 500 hPa; and bottom – 850 hPa), as revealed by the Pearson correlation coefficient. Colour darkening from yellow to black indicates increasing dissimilarity between the two datasets.[3]



3 Brands S, J. Gutiérrez, S. Herrera, A. Cofiño, 2012. On the use of reanalysis data for downscaling. *J Clim* 25:2517–2526. DOI: http://dx.doi.org/10.1175/JCLI-D-11-00251.1

Figure 3[4]

Assessment of climate trends in various observational products. The panels illustrate rainfall trend (expressed in mm/decade) over the period 1979–2010 except for CHIRPS 0.05deg, CHIRPS 0.25deg & FEWS_ARC (1984) and TRMM (1998). Areas where the trend is positive (i.e. there is an increase in rainfall over that period) are shown in green, and areas where the trend is negative are shown in brown. Note that various products have different spatial resolution (finer or coarser 'pixels'). Where trends are similar (e.g. panels 2, 3 and 4 in the middle row, and the one in the bottom-right corner), products are based on the same or similar raw dataset.



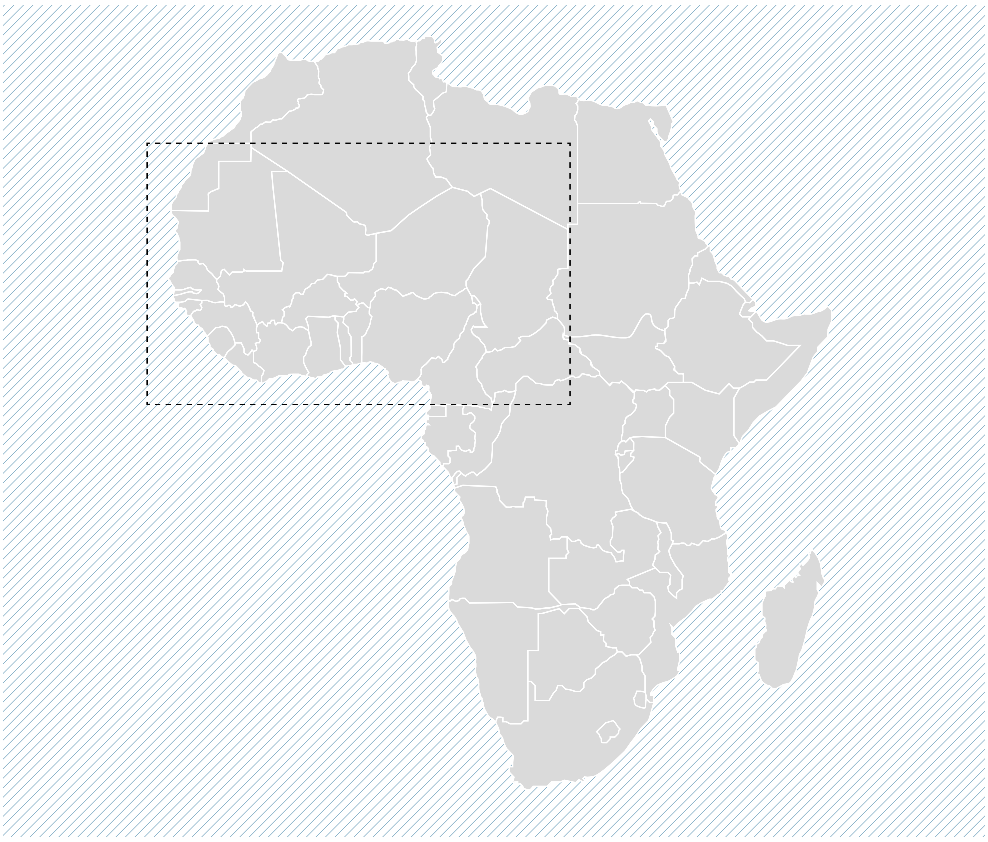
4 Maps: produced by the authors.

GENERAL READERS

WEST AFRICA
REGIONAL
OVERVIEW

A CENTURY OF CLIMATE CHANGE: 1950–2050

AUTHORS
Andrew Hartley, Dave Rowell, Serge Janicot, Françoise Guichard, Ian Macadam, Chris Taylor, Douglas J Parker



NEED TO KNOW

In west Africa, people's lives and livelihoods are significantly impacted by season to season, and year to year variability in climate. Climate change will worsen these impacts.

- Decision-makers need reliable climate projections in order to plan effectively for warmer temperatures, altered rainfall patterns, and changing frequency of droughts and heatwaves.
- Scientists have greater confidence in projections of future temperature change from existing climate models, than for future rainfall change.
- Scientists are working on both improving understanding of existing models, and on improving the next generation of climate models, to produce more reliable projections.
- Scientists are also working to better understand the role of human-caused greenhouse gas emissions and sea surface temperatures in driving the west African climate, especially rainfall.

SETTING THE SCENE

Some of the world's poorest people live in west Africa. Since the 1950s, this region has experienced extreme variations in climate, relative to anywhere else on Earth. Extremes of drought, flooding and temperature have had severe impacts on populations that are highly exposed to these sorts of hazards. This is, in part, due to a strong dependence on rain-fed agriculture, poor sanitation and limited access to clean water. This is particularly true for the Sahel region.

Historical climate records have documented the severity of the recent drought during the 1970s–1990s, and subsequent recovery in the 2000s. More work, however, needs to be done to understand the natural and human causes that drive these trends.

Average temperatures in west Africa are already rising. Since 1950, weather stations have measured an increase of around 1°C across the region

Another area of research is to understand how the regional climate responds to large-scale changes in climate forcings, such as the temperature of surface water in nearby oceans, and land use change.

The models that simulate west Africa's future climate often disagree with one another, particularly in terms of how rainfall patterns may change. This makes it difficult for regional stakeholders to make effective adaptation plans.

CLIMATE IS ALREADY CHANGING IN WEST AFRICA

Average temperatures in west Africa are already rising. Since 1950, weather stations have measured an increase of around 1°C across the region.[1] However, in the Sahel, the change is

1 Morice, C. P., J. J. Kennedy, N. A. Rayner, and P. D. Jones, 2012: Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 data set. J. Geophys. Res., 117, D08101, doi:10.1029/2011JD017187. http://doi.wiley.com/10.1029/2011JD017187 (Accessed September 25, 2015).

higher: 1.5 to 2°C. Monthly temperature records show that the warmest months of the year – April, May, and June – have experienced even greater increases in temperature of up to 3°C,[2] mainly due to warmer night time temperatures.

Rainfall trends across the Sahel from 1950 to 2010 fall into three distinct periods:

- 1950s and 1960s: above average monsoon rains.
- 1970s, 1980s and 1990s: a period of extended drought, where the monthly rainfall was lower than the average, by about 30mm per month.
- 2000s and 2010s: weather records show a recovery in rainfall, albeit with increased variability in year to year rainfall. Looking at the figures taken from rain gauges across the Sahel,[3] it looks as though this 'recovery' is actually accompanied by greater volumes of rain falling during extreme storm events, and by a general decrease in the number of rainy days. The contribution of extreme rainy days to the annual total, during this time, was higher than at any point during the 1950–2010 period.

What is driving these historical changes?

Many studies have linked Sahel rainfall variability to change in sea surface temperatures, increases in atmospheric carbon dioxide, and air pollution in the northern hemisphere

Understanding whether these changes are due to normal decade to decade variability, or whether they are a response to human-induced or natural drivers of global change, can help improve projections of future change. For example, many studies have linked Sahel rainfall variability to change in sea surface temperatures, increases in atmospheric carbon dioxide, and air pollution in the northern hemisphere.

When sea surface temperatures (SSTs) cool in the northern tropical Atlantic, and warm slightly in the South Atlantic, the Sahel tends to become drier.[4, 5, 6] Warmer SSTs in the Indian Ocean also seem to correlate with drought over the Sahel, as well as when there is a large difference in the gradient of surface water temperatures across the eastern Pacific.[7]

Decadal variations in the temperature of surface water in the Mediterranean also influences rainfall trends in the Sahel.[8, 9] However, there is still debate about whether this is due to natural fluctuations, human activity, or a combination of both. There is some evidence

2 Guichard, F., L. Kergoat, F. Hourdin, C. Léauthaud, J. Barbier, E. Mougin and B. Diarra, 2015. Le réchauffement climatique observé depuis 1950 au Sahel. in Les sociétés rurales face aux changements climatiques et environnementaux en Afrique de l'Ouest (Sultan B, Lalou R, Amadou Sanni M, Oumarou A et Soumaré M A eds.), IRD Editions, 23–42.

3 Panthou, G., T. Vischel, and T. Lebel, 2014. Recent trends in the regime of extreme rainfall in the Central Sahel. Int. J. Climatol., n/a–n/a, doi:10.1002/joc.3984. http://doi.wiley.com/10.1002/joc.3984 (Accessed March 26, 2014).

4 Giannini, A., R. Saravanan, and P. Chang, 2003. Oceanic forcing of Sahel rainfall on interannual to interdecadal time scales. *Science*, 302, 1027–1030, doi:10.1126/science.1089357. www.ncbi.nlm.nih.gov/pubmed/14551320 (Accessed July 13, 2016).

5 Biasutti, M., I. M. Held, A. H. Sobel, A. Giannini, 2008. SST Forcings and Sahel Rainfall Variability in Simulations of the Twentieth and Twenty-First Centuries. J. Climate, 21, 3471–3486, doi:10.1175/2007JCLI1896.1. http://journals.ametsoc.org/doi/abs/10.1175/2007JCLI1896.1 (Accessed August 25, 2014).

6 Folland, C. K., T. N. Palmer, and D. E. Parker, 1986. Sahel rainfall and worldwide sea temperatures, 1901–85. Nature, 320, 602–607.

7 Janicot, S., A. Harzallah, B. Fontaine, and V. Moron, 1998. West African Monsoon Dynamics and Eastern Equatorial Atlantic and Pacific SST Anomalies (1970–88). J. Clim., 11, 1874–1882. http://journals.ametsoc.org/doi/full/10.1175/1520-0442-11.8.1874 (Accessed June 3, 2016).

8 D. P. Rowell, C. A. Senior, M. Vellinga, and R. J. Graham, 2016. Can climate projection uncertainty be constrained over Africa using metrics of contemporary performance? Clim. Change, 134, 621–633, doi:10.1007/s10584-015-1554-4. http://link.springer.com/10.1007/s10584-015-1554-4 (Accessed July 21, 2016).

9 Gaetani, M., B. Fontaine, P. Roucou, and M. Baldi, 2010. Influence of the Mediterranean Sea on the West African monsoon: Intraseasonal variability in numerical simulations. J. Geophys. Res., 115, D24115, doi:10.1029/2010JD014436. http://doi.wiley.com/10.1029/2010JD014436 (Accessed July 25, 2016).

to suggest that air pollution related to human activity, especially in the northern hemisphere during the latter part of the 20th century, may also be partially responsible for drought in the Sahel.[10, 11] Interestingly, current levels of carbon dioxide in the atmosphere tend to push up rainfall in west Africa, yet this is countered by present-day sulphur dioxide concentrations related to air pollution, which tend to lead to reduced rainfall across the region.

While sea surface temperatures were undoubtedly the main driver of drought in the Sahel from the 1970s to the 1990s, vegetation cover has also been shown to potentially feed back into rainfall variability in west Africa. The time-lagged response of vegetation on a year to year timescale has for example been shown to have exacerbated the Sahelian drought via reduced evaporation and transpiration. The link between the land surface condition and rainfall is also evident at shorter time scales, where the presence of woodlands in savannah regions, and wet or dry patches of soil in the Sahel, have been shown to enhance localised rainfall, particularly during the monsoon.

FUTURE CLIMATE: WEST AFRICA BY 2050

Temperature increases

Average temperatures over west Africa are projected to increase by between 1.5°C and 4°C by mid-century, relative to 1986–2005

Average temperatures over west Africa are projected to increase by between 1.5°C and 4°C by mid-century, relative to 1986–2005.[12] Larger increases are expected in the Sahel and the Sahara Desert compared to the Guinea coast, especially under a high end climate change scenario. Extremes of temperature are expected to change, with night time (minimum daily) temperatures expected to increase at a faster rate than day time (maximum daily) temperatures. The number of heatwave days each year is also projected to increase significantly by mid-century, especially in the western Sahel.[13] Despite uncertainty on the range of future temperature change, this is still a confident projection due to our understanding of the processes that drive this change.

Rainfall and drought

The projected changes in rainfall trends by the 2050s are less certain than for temperature. For large parts of west Africa, climate models do not agree on whether rainfall will increase or decrease, and in many cases, models show significant trends in both directions.[14] Relative to 1986–2005, the rainfall projections for July to September in the 2050s range between -40% and +20% in the western Sahel, and between -20% and +40% in the central and

10 Ackerley, D., B. B. B. Booth, S. H. E. Knight, E. J. Highwood, D. J. Frame, M. R. Allen, and D. P. Rowell, 2011. Sensitivity of Twentieth-century Sahel Rainfall to Sulfate Aerosol and CO2 Forcing. J. Clim., 24, 4999–5014, doi:10.1175/JCLI-D-11-00019.1. http://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-11-00019.1 (Accessed November 27, 2015).

11 Booth, B. B. B., N. J. Dunstone, P. R. Halloran, T. Andrews, and N. Bellouin, 2012. Aerosols implicated as a prime driver of twentieth-century North Atlantic climate variability. Nature, 484, 228–232, doi:10.1038/nature10946. http://dx.doi.org/10.1038/nature10946 (Accessed March 1, 2013).

12 Niang, I., O. C. Ruppel, M. A. Abdrabo, A. Essel, C. Lennard, J. Padgham, and P. Urquhart, 2014. Africa. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1199–1265.

13 Vizy, E. K., and K. H. Cook, 2012. Mid-Twenty-First-century Changes in Extreme Events over Northern and Tropical Africa. J. Clim., 25, 5748–5767, doi:10.1175/JCLI-D-11-00693.1. http://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-11-00693.1 (Accessed December 3, 2015).

14 Niang, I. et al, 2014.

eastern Sahel.[15, 16] Additionally, rainfall projections generally show delayed onset of early season rainfall (June and July), particularly in the western Sahel, and an increase in late season rainfall (September and October), particularly in the central and eastern Sahel.

It is important to be clear that while the majority of models project a general drying trend in the west and a wetting trend in the central and eastern Sahel, equally credible models do not project this spatial pattern of change. This therefore brings into question the mechanisms by which models project rainfall changes, and emphasises the importance of understanding these processes in order to improve the reliability of model projections.

Weather impacts on people are most commonly experienced via high impact events, such as very intense rainfall or long dry spells. Under a warming climate, we might expect that the intensity of rainfall events will increase, because a warmer atmosphere can hold more water.[17] Regional climate modelling studies[18, 19] confirm this by projecting trends of more intense, but less frequent, rainfall events in the 21st century. These projections appear to indicate a continuation of the trends found in rain gauge observations since 2000, where high year to year rainfall variability was accompanied by increases in intense rainfall and decreases in the number of wet days.

FUTURE CHALLENGES

Normal variation in the climate – season to season, year to year, and decade to decade – already have a significant impact on people's lives and livelihoods in west Africa. More work still needs to be done to reliably project how climate change will alter these normal variations, particularly for precipitation in the region. It is therefore imperative that climate scientists develop new approaches to understand why projections from climate models differ, and provide expert judgement on which models are the most trustworthy for use by stakeholders.

In order to do this, there are two key challenges facing climate scientists.

First, there is a need to better understand the historical drivers of observed climate trends, such as the links between sea surface temperatures and air pollution, and to use this knowledge to identify models that have performed well for reconstructing the historical climate of the region.

Second, there is also the need to understand the mechanisms of future change in models, and to use this knowledge to identify models that produce a trustworthy projection of future change. With more robust and reliable projections of future change, stakeholders in the region will be able to make more confident adaptation plans that improve the lives and livelihoods of the people of west Africa.

15 Rowell et al, 2016.

16 Niang, I., et al., 2014. 1199–1265.

17 Giorgi, F., E. -S. Im, E. Coppola, N. S. Diffenbaugh, X. J. Gao, L. Mariotti, and Y. Shi, 2011. Higher Hydroclimatic Intensity with Global Warming. J. Clim., 24, 5309–5324, doi:10.1175/2011JCLI3979.1.

18 Sylla, M. B., F. Giorgi, J. S. Pal, P. Gibba, I. Kebe, and M. Nikiema, 2015. Projected Changes in the Annual Cycle of High Intensity Precipitation Events over West Africa for the Late 21st century. J. Clim., 28, 6475–6488, doi:10.1175/JCLI-D-14-00854.1. http://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-14-00854.1 (Accessed June 13, 2015).

19 Vizy and Cook, 2012.

FCFA'S AMMA-2050 PROJECT

Project objectives

AMMA-2050 will improve understanding of how the west African monsoon will be affected by climate change in the coming decades – and help west African societies prepare and adapt. The AMMA-2050 team will investigate how physical processes interact to cause 'high impact weather events' such as storms and heawaves that affect lives and livelihoods. Not only will they look at how the total amount of rainfall is likely to change – but also at how rainfall is likely to be distributed throughout the wet season. For example, heavy rainfall concentrated in just a few hours places great stress on human settlements, infrastructure and agriculture. By applying expert judgement, they will identify adaptation options in water resources and agriculture. See www.futureclimateafrica.org/project/amma-2050/

The organisations involved in AMMA-2050 are:

- Centre for Ecology and Hydrology (UK)
- National Agency for Civil Aviation and Meteorology (Senegal)
- Félix Houphouët – Boigny University
- University of Cape Coast
- Senegalese Institute for Agricultural Research
- VNG Consulting Limited
- University of Leeds
- Met Office (UK)
- University of Sussex
- Institute for Development Research – Hydrology and Environment (France);
- Pierre Simon Laplace Institute – Oceanic and Climate Laboratory
- French Agricultural Research Centre for International Development
- National Centre for Meteorological Research – the Meteorological Atmosphere Study Group (France)

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SCIENTISTS

ALL OF AFRICA
BURNING QUESTIONS

IMPROVING CLIMATE MODELLING FOR AFRICA

AUTHORS

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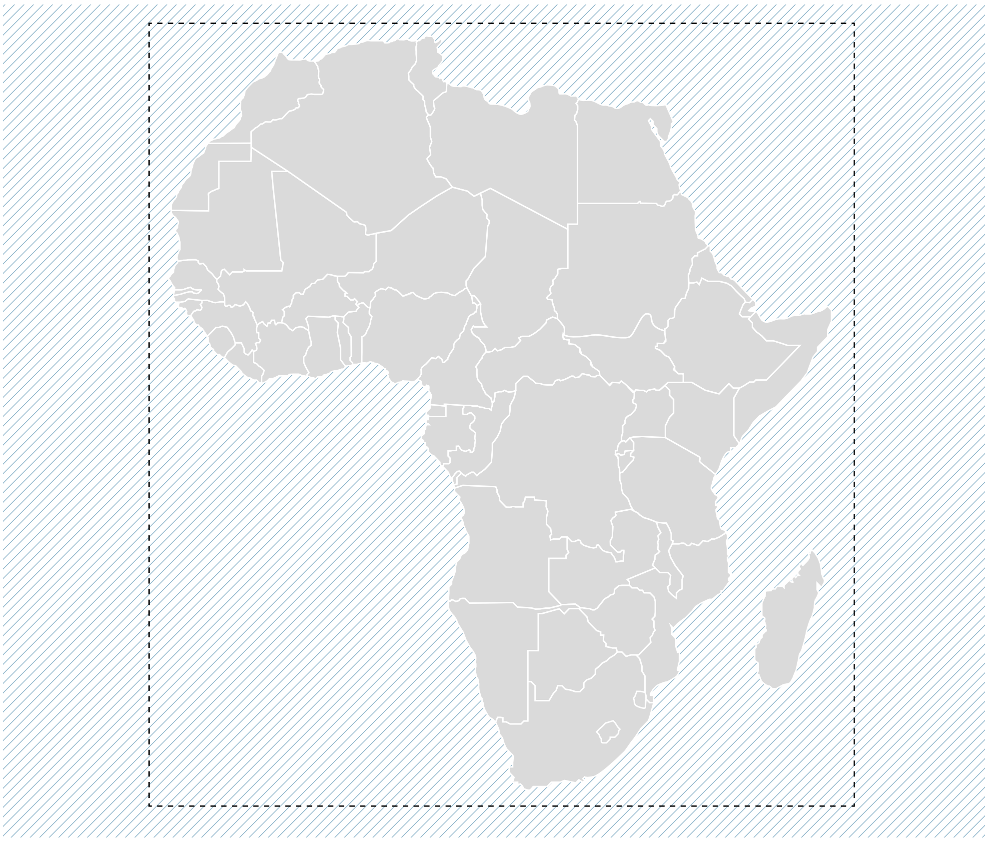

NEED TO KNOW

The climate models used to project Africa's likely future climate only have a modest ability to capture the physical processes driving the climate on the continent. But work is now being done to improve them in order to produce information that can better assist African decision-makers. Researchers are endeavouring to:

- better understand the physical drivers of climate on the continent, especially how local processes interact with more distant influences
- gain better observations of the processes driving African climate variability and change
- improve modelling techniques including refining model grids to represent individual cloud systems
- target regional evaluation of how these physical processes work in the models by applying an 'Africa lens' to the problem.

INTRODUCTION

There is an urgent need to deliver actionable climate information for sub-Saharan Africa, to support planning for climate resilience and adaptation, in order to better inform sustainable poverty alleviation strategies.

A key building block for adaptation is reliable, robust projections of future climate over the coming decades

A key building block for adaptation is reliable, robust projections of the future climate over the coming decades, as well as across regional, national, and smaller space scales. However, current climate models have a modest ability to capture the processes driving the African climate. There has been slow progress in improving their performance over the past six years.[1] This limits confidence in the climate projections, and thus how useful they are for supporting decision-makers in Africa.

This factsheet discusses the key questions relating to the capability of climate models used to study Africa's climate, and aims to describe some of the reasons for the lack of progress in improving these models. It considers why there are now real opportunities to speed up the rate of improvement, and how this can deliver both advice and data to impact scientists and decision-makers on the continent.

LIMITATIONS OF MODELS FOR AFRICA'S CLIMATE

Interacting time and space scales

The distribution of sub-Saharan rainfall is largely determined by atmospheric deep convection that develops as a result of the interaction of regional circulations with local gradients in surface heating and moisture. These regional circulations are driven by local radiative heating and land surface conditions, as well as by more distant tropics-wide

1 Flato, G., J. Marotzke, B. Abiodun, P. Braconnot, S. C. Chou, W. Collins, P. Cox, F. Dri-ouech, S. Emori, V. Eyring, C. Forest, P. Gleckler, E. Guilyardi, C. Jakob, V. Kattsov, C. Reason, and M. Rummukainen, 2013. Evaluation of climate models: IPCC WGI Fifth Assessment Report, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, chapter 9.

circulation patterns. Africa's climate is therefore highly susceptible to fluctuations of patterns of the global climate and their links (or 'teleconnection pathways') to the continent. Consequently, to predict future trends in African rainfall variability, global climate models (GCMs) must be able to capture the multi-scale nature of the problem. This includes the interaction of locally occurring small-scale processes with wider weather patterns across Africa and how warming sea surface temperatures far from the continent can influence these.

The challenge of convection

Contemporary climate models have typical grid-spacing of around 100km. Processes and feedbacks such as convection, atmosphere-land interactions, or aerosols that work on a smaller scale than this 100km x 100km grid thus have to be simplified when they are included in these models. This involves relating these complex processes to the large-scale properties of the atmosphere, such as wind, temperature and humidity. The different choices made in this process of simplification are often a result of our limited knowledge of how the local climate system works, or a lack of good scientific observations. These are a major reason for the uncertainty in future projections of climate from GCMs, and for a lack of confidence in the representation, particularly for convective processes.

Historical lack of 'Africa lens' in model development

The cycle of model evaluation and development has often been most focused on regions of prime interest to research funders

The cycle of model evaluation and development has often been most focused on regions of prime interest to research funders, whose priority has typically been the developed countries of the northern hemisphere. Hence more rapid progress has been made in the modelling of drivers of the climate in these regions. The current generation of GCMs show a range of biases in their simulation of Africa's climate and the key driving processes. They can capture some important modes of climate variability,[2] but often the teleconnections with African rainfall on inter-annual and decadal timescales are weaker than observed.[3, 4, 5, 6] Most models show similar biases in the timing, organisation and propagation of convective storms.[7, 8, 9, 10] These are at least partly as a result of inadequate coupling in the models

2 Rowell D. P., 2013. Simulating SST teleconnections to Africa: what is the state of the Art? J Climate 26:5397–5418. doi:10.1175/JCLI-D-12-00761.1.

3 Ault, T. R., J. E. Cole and S. St. George, 2012. The amplitude of decadal to multi-decadal variability in precipitation simulated by state-of-the-art climate models, *Geophysical Re-search Letters* 39, L21705, doi:10.1029/2012GL053424.

4 Biasutti, M., I. M. Held, A. H. Sobel, A. Giannini, 2008. SST forcings and Sahel rainfall variability in simulations of the twentieth and twenty-first centuries. *J. Clim.*, 21, 3471–3486.

5 Vellinga, M., A. Arribas, and R. Graham, 2013. Seasonal forecasts for regional onset of the West African monsoon, *Climate Dynamics*., 40, 3047–3070, doi:10.1007/s00382-012-1520-z.

6 Philippon N, Doblas-Reyes FJ, Ruti PM., 2010. Skill, reproducibility and potential pre-dictability of the West African monsoon in coupled GCMs. *Climate Dynamics* 35: 53–74. DOI: 10.1007/s00382-010-0856-5.

7 Birch, C. E., D. J. Parker, J. H. Marsham, D. Copsey, and L. Garcia-Carreras, 2014a. A seamless assessment of the role of convection in the water cycle of the West African monsoon, J. *Geophys. Res. Atmos*., 119, 2890–2912, doi:10.1002/2013JD020887.

8 Taylor, C. M., C. E. Birch, D. J. Parker, N. Dixon, F. Guichard, G. Nikulin, and G. M. S. Lister, 2013. Modelling soil moisture-precipitation feedback in the Sahel: Importance of spatial scale versus convective parameterization, *Geophys. Res. Lett*., 40, 6213–6218, doi:10.1002/2013GL058511.

9 Birch, C. E., J. H. Marsham, D. J. Parker, and C. M. Taylor, 2014b. The scale depend-ence and structure of convergence fields preceding the initiation of deep convection. *Geophys. Res. Lett*., 41 (13), 4769–4776, doi:10.1002/2014GL060493.

10 Pearson K.J., G. M. S. Lister, C. E. Birch, R. P. Allan, R. J. Hogan, S. J. Woolnough, 2014. Modelling the Diurnal Cycle of Tropical Convection Across the 'Grey Zone', *QJRMS*, 140, 491–499, doi: 10.1002/qj.2145.

between local convection and the larger-scale monsoon circulation.[11] Furthermore, synoptic weather systems, such as African Easterly Waves (the passage of which are typically associated with enhanced rainfall), are also often too weak and infrequent in models, and only weakly connected to en-hanced rainfall.[12] The shortage of scientific observations over the African continent has also resulted in land surface processes not being well represented in models, hence key processes such as evaporation from bare soil or fluxes in a drying landscape are not well captured.

A ROADMAP FOR MODEL IMPROVEMENT

The ability of models to simulate important features of the African climate, such as rainfall, heatwaves, and dust storms, depends critically on the representation of key processes and feedbacks

As outlined above, the ability of models to simulate important features of the African climate, such as rainfall, heatwaves, and dust storms, depends critically on the representation of key processes and feedbacks. The most notable of these involve convection, land surface, and aerosols.

These processes include:

- convective processes, and convective organisation, which take place across time as well as spatial scales
- the impact of clouds and aerosol on radiative heating
- the influence of convective dynamics on aerosol transport
- important stores of moisture in the soil and heat in the oceans that influence surface fluxes.

Uncertainties in all these aspects are the result of imperfect knowledge of the relevant physical and dynamical processes, compounded by lack of scientific observations over the African continent. However, in the past decade, the knowledge gained from detailed field experiments and increased use of remote sensing, combined with the ability to run numerical models at a resolution that can incorporate convective processes (100m–1km), make this an ideal time to advance our understanding of these key processes and improve their representation in the GCMs.

A better understanding and representation of global climate variability and its teleconnection pathways to Africa is also starting to emerge, at least in part, from the use of higher resolution global models. These use improved horizontal grid spacing, so that we are now starting to capture weather systems. They also use increased numbers of vertical levels, capturing better the exchanges between the troposphere and stratosphere, which can play an important role in teleconnection pathways.

Recent work[13] has highlighted the importance of large-scale energetic constraints on drivers of African rainfall through influencing the location of the Inter Tropical Convergence Zone (ITCZ) and locally the location of the West African Monsoon (WAM). This opens up the potential for the application of such 'emergent constraints' from newly available global observations.

11 Marsham, J. H., N. S. Dixon, L. Garcia-Carreras, G. Lister, D. J. Parker, P. Knippertz, and C. E. Birch, 2013a. The role of moist convection in the West African monsoon sys-tem: Insights from continental-scale convection-permitting simulations. *Geophys. Res. Lett.*, 40 (9), 1843–1849, doi:10.1002/grl.50347.

12 Bain, C. L., K. D. Williams, S. F. Milton, J. T. Heming, 2013. Objective tracking of African Easter-ly Waves in Met Office models. Q. J. R. *Meteorol. Soc.* 140: 47–57, doi: 10.1002/qj.2110.

13 Haywood, J. M., Jones, A., Bellouin, N. & Stephenson, D., 2013. Asymmetric forcing from stratospheric aerosols impacts Sahelian rainfall. *Nature Clim. Change* 3, 660–665.

PROGRESS IN TACKLING THESE CHALLENGES

The reasons for poor climate model simulations are complex and therefore this research may not deliver 'quick wins', but it is fundamental for longer-term improvements in GCM performance

Climate scientists working in this area of research are building on previous African-focused model development projects through collaborations between the Met Office, UK universities, and African researchers from across the continent. A key part of this work is to build the link between improved modelling of local processes, and the drivers of five to 40 year African climate variability and teleconnections.

The reasons for poor climate model simulations are complex and therefore this research may not deliver 'quick wins', but it is fundamental for longer-term improvements in GCM performance. In parallel, researchers will focus on the fundamentals of the representation of smaller-scale convective processes in GCMs. Crucially, this challenge can, for the first time, be addressed through the use of high resolution simulations representing individual convective cloud systems across the whole of Africa.

Additionally, researchers will use newly extended scientific observations to tackle long-standing issues of how to model the daily to seasonal variations in surface fluxes of heat and moisture. Refined modelling of the impact of African mineral dust, and ash and smoke from burning biomass have the potential to deliver 'quick wins'.

BETTER MODELS MEAN BETTER CLIMATE PROJECTIONS

The aim of this work is to deliver a step-change in climate modelling capability for Africa. It will come through an improved, physically credible representation of key driving processes. It will deliver more robust, less uncertain, future projections, and new understanding of the remaining limitations of climate models as the basis for actionable advice.

High-resolution regional information will more accurately simulate the key processes and local-scale weather phenomena, including extreme events. This will provide a new source of regional and local scale data for impact studies across a range of important sectors, such as agriculture, health, urban water resources and infrastructure. These can be used in combination with multi-model projections of regional or extreme signals of climate change to identify robust signals and highlight extreme risks.

Nowhere are model developments more urgently needed than over tropical Africa. These will provide greater confidence in future climate projections of key measures, such as timing of the onset of the monsoon, or active and break cycles. More confident, targeted projections will increase their utility for planning and development across many critical sectors including health, agriculture, water management and renewable energy.

FCFA'S IMPALA PROJECT

Project objectives

The project aims to tackle a major scientific hurdle that limits decision-makers from using climate information: current climate models have only a modest ability to capture African climate systems. Because of this, there is large uncertainty and low scientific confidence in important aspects of the projections for Africa's climate in the next five to 40 years.

This project will focus on a single climate model, the Met Office Unified Model, to improve its simulation of African climate through a better understanding and representation of weather and climate processes. This will result in reduced uncertainty in future projections of the African climate and provide valuable information to climate scientists and modellers within Africa and worldwide, and empower decision-makers with information that can be used to reduce risks and help protect the livelihoods of the most vulnerable.

The initiative aims to deliver a step change in global climate model capability that will reduce uncertainty and enable better informed evaluation of the robustness of future projections. See www.futureclimateafrica.org/project/impala/

The institutions involved in IMPALA are:

- Met Office (UK)
- African Centre of Meteorological Applications for Development
- Centre for Ecology and Hydrology (UK)
- University of Cape Town
- University of Exeter
- University of Leeds
- University of Nairobi
- University of Oxford
- University of Reading
- University of Yaoundé

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SCIENTISTS

CENTRAL AND SOUTHERN AFRICA
BURNING QUESTIONS

BURNING QUESTIONS FOR CLIMATE SCIENCE

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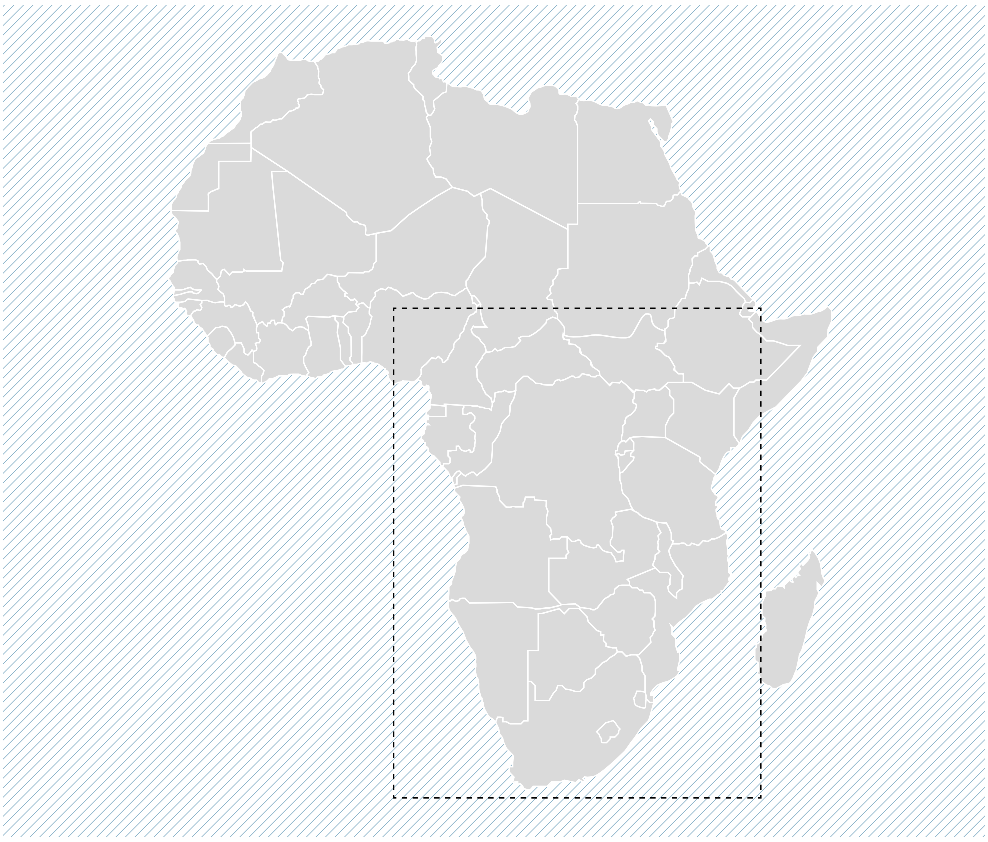


NEED TO KNOW

Societies and economies in central and southern Africa are extremely vulnerable to climate change and extreme weather events. Policy-makers need credible climate information if they are to plan for and address regional development challenges. New research into the climate of this area will investigate:

- Why the region is so vulnerable to climate change.
- The gaps in our understanding of the current climate system and how it might change in response to human-induced warming.
- How climate researchers are addressing some of these gaps, with the aim of improving climate change modelling.

THE STATE OF CLIMATE SCIENCE IN CENTRAL AND SOUTHERN AFRICA

The gaps in our knowledge of the central and southern African climate system have contributed to dramatic differences in future climate projections produced by climate models, both in the size of the change, and the direction

Our understanding of the climate system in central and southern Africa is at a relatively early stage compared to many other world regions. Several factors are responsible for this situation, including: a poor weather station network; relatively low investment in climate services (such as national meteorological services); and a lack of dedicated international science campaigns. As a consequence, there are fundamental gaps in our scientific understanding of the central-southern African climate system.

This is a problem because effective adaptation to climate change relies on credible information about how climate and extreme events might change in the next five to 40 years. Climate models can provide this information for adaptation planners. But without tackling gaps in the basic climate science, it is difficult to judge the quality of models' projections of future climate change. Scientists working in this area of research, as part of the Future Climate for Africa initiative, hope to be able to improve our understanding of the regional climate system, and how well it is captured by climate models.

WHY WE NEED TO UNDERSTAND THE CENTRAL-SOUTHERN AFRICAN CLIMATE SYSTEM

Economies are sensitive to the impacts of climate change and extreme events

Agriculture contributes a large proportion to the regional economy: 20% in Zambia, 30% in Tanzania, Madagascar and Mozambique, and over 40% in the Democratic Republic of Congo (DRC) and Malawi. Yet it is highly dependent on rainfall, with only 5% of cropland equipped for irrigation. The proportion of electricity produced by rainfall-sensitive hydroelectric sources is high: over 30% in Tanzania, Madagascar, Swaziland and Zimbabwe, and almost 100% in DRC, Lesotho, Malawi and Zambia.[1] To address regional development needs, especially in the agricultural and energy sectors, we need to understand the nature of regional climate change.

1 World Bank, 2014. World Development Indicators 2014. World Development Indicators. Washington, DC. https://openknowledge.worldbank.org/handle/10986/18237 (Accessed July 2016).

The gaps in our knowledge of the central and southern African climate system have contributed to dramatic differences in future climate projections produced by climate models, both in the size of the change, and the direction. For instance, while many models agree that temperature will increase in southern Africa (Figure 1), they do not agree on the amount of warming.

In the two models in Figure 1, the difference is as much as 2°C in some places. A 2°C difference in the average climate could change the frequencies of extreme events, such as drought, as well as affecting day to day weather patterns. The patterns of rainfall change are also vastly different: over the Congo Basin, for example, one model shows the area will get wetter by the end of the century, while another model shows that it will get drier.

Divergence between future climate projections is a well-known issue with climate models, and adaptation planners are often faced with a choice of more than 30 modelled future climates, each with different outcomes. It is very difficult to establish which, if any, of these is more credible, particularly as the models also simulate large differences in the present day climate.

In the present day extreme weather and climate events, in particular floods and droughts, have a lasting impact on the regional economy and society

In the present day, extreme weather and climate events, in particular floods and droughts, have a lasting impact on the regional economy and society. Flooding in January 2013, caused by a cloud band extending south from the tropics to the mid-latitudes, resulted in over 100 deaths and 200,000 people being displaced in southern Africa (Figure 2). More recently, a drought from November 2015 to January 2016 left nearly 17 million people in conditions of acute food insecurity.[2]

Future changes in the average climate will be accompanied by changes in the frequency and size of extreme events. The severe impacts detailed in the examples above illustrate why it is so important to understand the climate drivers behind such extreme events, and how they might change in the future.

GAPS IN UNDERSTANDING OF THE CENTRAL-SOUTHERN AFRICAN CLIMATE SYSTEM

The impact of global and regional ocean conditions

Global and regional ocean dynamics affect southern African rainfall. El Niño events, which originate in the Pacific Ocean, are often associated with drought over southern Africa. The regional climate system is also influenced by changes in the pattern of surface temperatures in the Indian Ocean and in the Benguela region in the south-east Atlantic. Despite much work into understanding these interactions, the ways in which the oceans affect the central and southern African climate system are still unclear.

Climate models have difficulties representing the links between ocean dynamics and the regional climate system. For example, most climate models overestimate average sea surface temperature (SST) by up to 2°C in the south-east Atlantic Ocean,[3] and are generally poor at simulating the known links between El Niño events and African rainfall.[4] These model errors probably affect the model simulation of the present day climate, but this influence is unclear. It is important to understand these problems in the present climate if we are to assess model reliability in projecting the future climate.

2 www.fews.net/southern-africa

3 Wang, C., L. Zhang, S. Lee, L. Wu, and C. R. Mechoso, 2014. "A global perspective on CMIP5 climate model biases", *Nature Climate Change*, vol. 4, no. 3, 201–205.

4 Dieppois, B., M. Rouault, and M. New, 2015. "The impact of ENSO on southern African rainfall in CMIP5 ocean atmosphere coupled climate models", *Climate Dynamics*, vol. 45, no. 9–10, 2425–2442.

Despite the importance of the interaction between weather systems inside and outside the tropics, we have not paid enough attention to their dynamics

Connectivity between the central and southern African climates remains an area of much uncertainty. Tropical rainfall and thunderstorms are key drivers of the tropical circulation. They influence local and regional climate dynamics through changing the location and amount of heating in the atmosphere. In the southern African summer the main band of tropical rainfall, the Inter Tropical Convergence Zone (ITCZ), shifts south from the equator to Angola, southern DRC and Zambia. The direct effect of tropical rainfall on regional circulation in southern Africa has received almost no attention.

Thunderstorms also interact with weather systems outside the tropics that pass south of South Africa in the path of the mid-latitude westerly winds. This interaction produces large, north-west to south-east oriented cloud bands. These cloud bands contribute a large proportion of annual regional rainfall,[5] and can be the source of extreme flood events.[6] Despite the importance of the interaction between weather systems inside and outside the tropics, we have not paid enough attention to their dynamics. In part, this is due to climate scientists studying the two regions separately.

ADDRESSING THE KEY KNOWLEDGE GAPS

A focus on the whole region

By focusing on the central-southern Africa climate system as a whole, we hope to give new insights into how the regional climate system works. This can be achieved by investigating phenomena, such as tropical-extratropical cloud bands, which rely on the interaction between the two regions. In addition, we will use high resolution models, which can better represent tropical rainfall processes, such as thunderstorms. We hope that these models will provide an insight into how rainfall in central Africa affects region-wide air circulation and rainfall patterns.

Researchers working in this area (see UMFULA below) will also have a particular *focus on understudied regional circulation features*, such as the Botswana High and the Angola Low. These circulation features, which are important for regional rainfall, interact with remote climate influences, such as El Niño events. However, the origin of these features and their precise role in maintaining the average state of the climate and influencing year to year changes is unclear. Understanding these features is very important, particularly as recent work has suggested that the simulation of these features in climate models affects their simulation of rainfall across the region.[7]

Finally, climate scientists will try to understand why models differ in their simulation of present day climate and future change. To do this, the scientists will look closely at how well models simulate interactions between different parts of the climate system: the oceans, regional circulation features, and rainfall. This will help us understand not only how, but why models are different from each other and from weather station records. This will help to guide improvements in the modelling of the regional climate system. We will also identify models that simulate present climate and year to year variability in a plausible way, based on the analysis related to the points above, and then use these models to assess future change.

5 Todd, M., and R. Washington, 1998. Extreme daily rainfall in southern African and Southwest Indian Ocean tropical-temperate links, *S. Afr. J. Sci.,* 94(2), 64–70.

6 Hart, N. C. G., C. J. C. Reason, and N. Fauchereau, 2012. "Building a tropical-extratropical cloud band metbot", *Monthly Weather Review,* vol. 140, no. 12, pp. 4005–4016; Manhique, A. J., Reason, C. J. C., Silinto, B., Zucula, J., Raiva, I., Congolo, F. & Mavume, A. F. (2015) "Extreme rainfall and floods in southern Africa in January 2013 and associated circulation patterns", *Natural Hazards,* vol. 77, no. 2, pp. 679–691.

7 Munday and Washington (submitted) Circulation controls on southern African precipitation in coupled models: the role of the Angola Low.

FCFA'S UMFULA PROJECT

Project objectives

UMFULA ("river" in Zulu) is a four year research project that aims to improve climate information for decision-making in central and southern Africa, with a particular focus on Tanzania and Malawi. UMFULA is a global consortium of 15 institutions specialising in cutting edge climate science, impact modelling and socio-economic research.

UMFULA aims to support long-term – five to 40 year – planning decisions in central and southern Africa around resource use, infrastructure investment and cross-sectoral growth priorities, by identifying adaptation pathways that are robust and resilient in the face of climate change and other non-climate stressors.

The team is generating new insights and more reliable information about climate processes and extreme weather events and their impacts on water, energy and agriculture. These insights will support the more effective use of climate information in national and local decision-making. See www.futureclimateafrica.org/project/umfula/

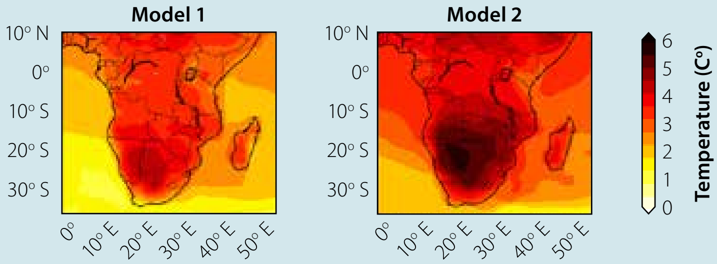
The institutions involved in UMFULA are:

- Grantham Research Institute on Climate Change and the Environment (London School of Economics and Political Science)
- Kulima Integrated Development Solutions
- University of Oxford
- University of Cape Town
- Sokoine University of Agriculture
- Lilongwe University of Agriculture and Natural Resources
- University of Leeds
- Council for Scientific and Industrial Research
- University of Manchester
- University of KwaZulu-Natal
- University of Sussex
- University of Dar Es Salaam
- University of Yaoundé
- Tanzanian Meteorological Agency
- Mozambique National Institute of Meteorology

FIGURES

Figure 1

(a) Future annual temperature change. The whole of central and southern Africa is projected to warm by the end of the century compared to the recent past (1979–2005). Darker shades indicate stronger projected increases in temperature.[8]



(b) Future annual rainfall change: blue colours are where the amount of rainfall is projected to be greater at the end of the century compared to 1979–2005, orange colours indicate projected decreases in rainfall.

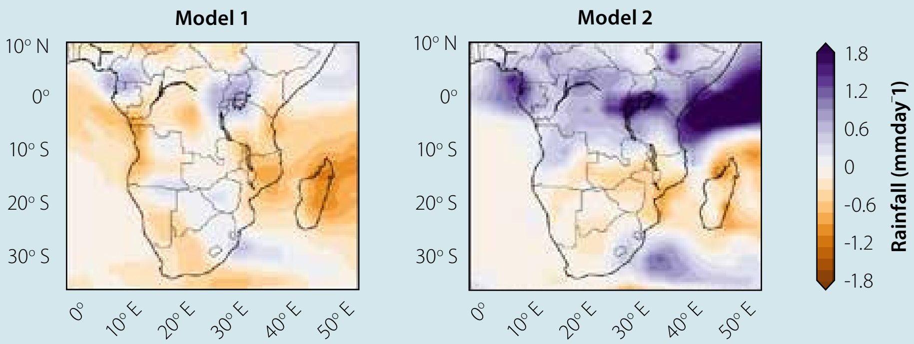
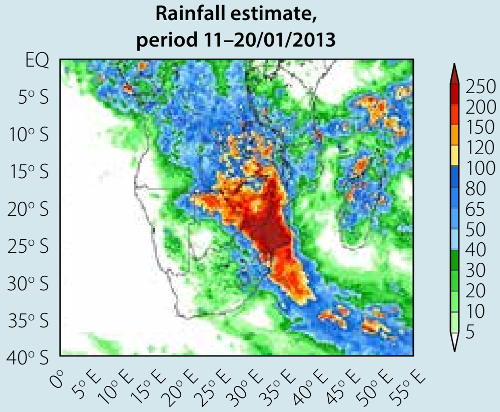


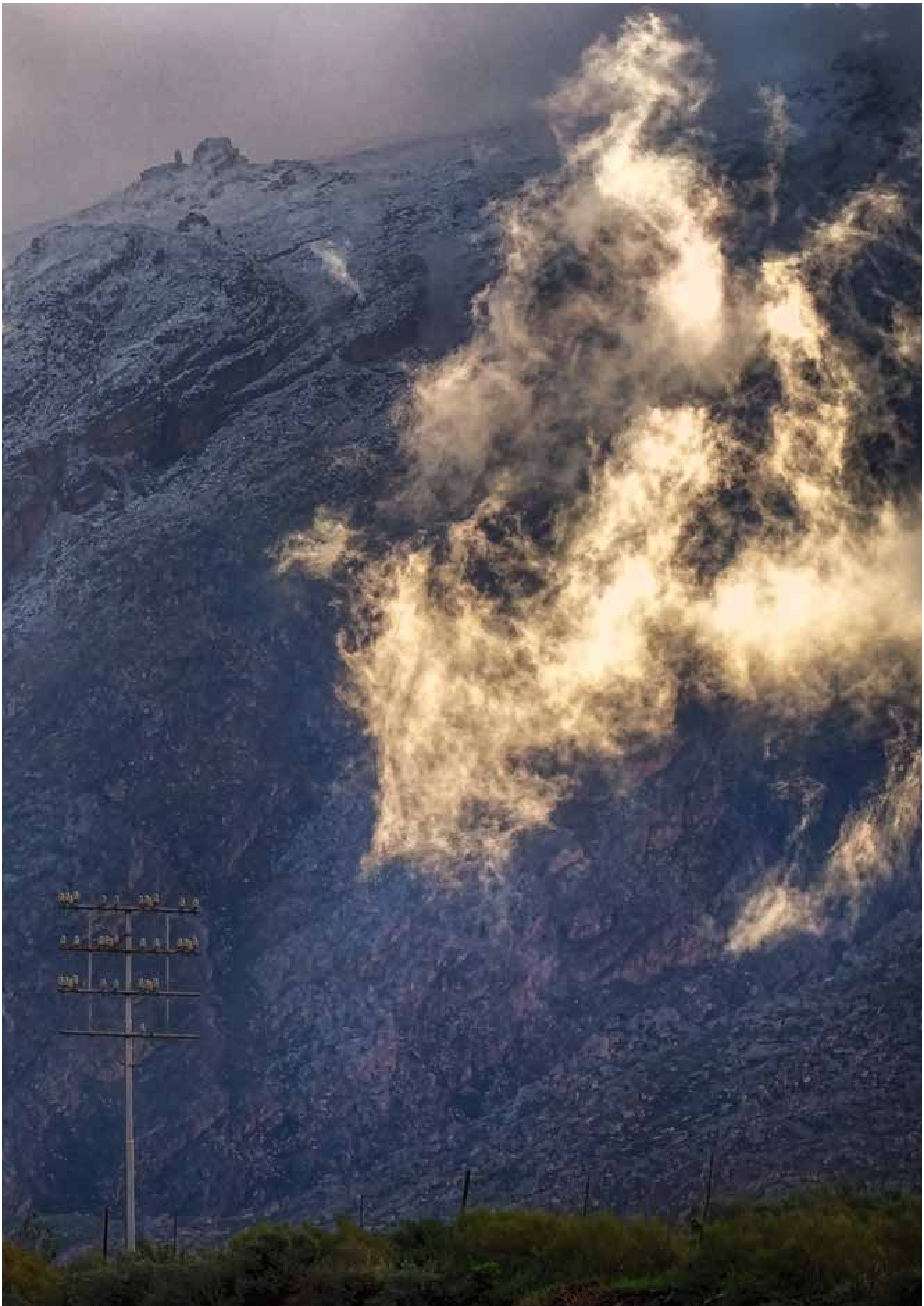
Figure 2

Flooding in January 2013 caused by interactions between thunderstorms and weather systems to the south of the continent. These floods resulted in over 100 deaths, and 200,000 people displaced from their home.[9]



8 Maps: produced by the authors.

9 Adapted from Manhique, A. J., C. J. C. Reason, B. Silinto, et al. Nat Hazards, 2015. 77: 679. doi:10.1007/s11069-015-1616-y.



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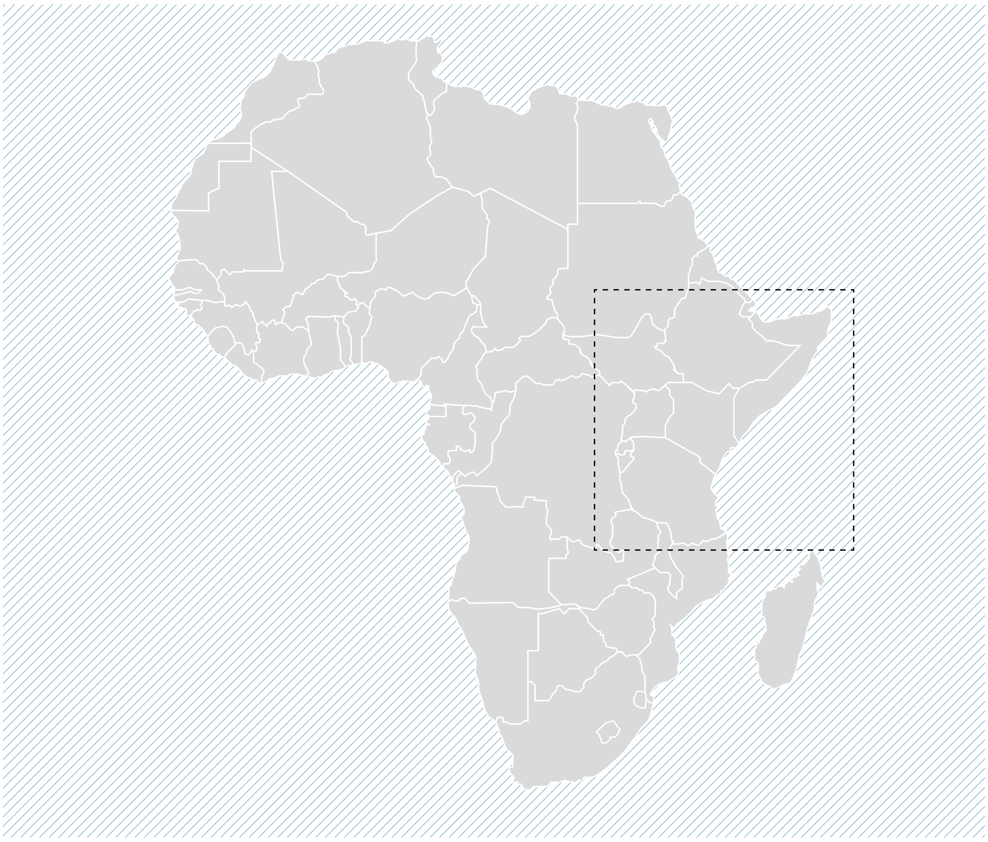
SCIENTISTS

EAST AFRICA
BURNING QUESTIONS

EAST AFRICAN CLIMATE VARIABILITY AND CHANGE

AUTHORS

Julio Araujo, John Marsham, Dave Rowell, Nkulumo Zinyengere, Andrew Ainslie, Andrew Clenaghan, Rosalind Cornforth, Giovanna De Giusti, Barbara Evans, Declan Finney, Dan Lapworth, David Macdonald, Celia Petty, John Seaman, Fredrick Semazzi, Celia Way



NEED TO KNOW

Scientists focusing on climate change in east Africa are interrogating climate models to provide more reliable information for decision-makers. Their burning questions include:

- How will aspects of climate that are relevant to decision-makers change? Will heavy rain and droughts increase? Will the region get wetter or drier in future?
- How will climate change impact on above- and below-ground water flow, the water levels of Lake Victoria, and underground water storage?
- What are the implications for rural livelihoods, including those dependent on rain-fed agriculture and fishing? And what are the policy and governance considerations within these sectors?
- How can cities design the most resilient water, sanitation and hygiene systems, in light of future climate change predictions?

INTRODUCTION

Climate change is expected to impact east Africa in the coming decades, with an overall warming trend, but much is still uncertain. Climate researchers working in this field aim to quantify, understand and reduce this uncertainty.

On a five to 40 year timescale, climate projections are uncertain because the models used to predict the expected response from greenhouse gas emissions cannot capture all the relevant processes sufficiently well. In addition, many of the standard climate models do not fully consider all regional factors causing local climate change. There are therefore several 'burning questions' that scientists hope to address.

WHAT DO DECISION-MAKERS NEED TO KNOW? HOW WILL EXTREME WEATHER CHANGE?

Climate research often considers factors such as average annual temperatures, or annual rainfall totals in its analysis. There are good scientific reasons for studying and understanding how and why these change. However, decision-makers often need more specific information, such as expected changes in sub-daily rainfall extremes, seasonal changes in night-time minimum temperatures, or changes in lengths of dry spells during the growing season. Although the overall change in rainfall is uncertain (see below) there is good evidence that both heavy rain and droughts will increase. Climate scientists aim to investigate such changes in the east African region and quantify decision-relevant metrics of climate change and their uncertainties from a range of climate models.

QUESTION 1: THE EAST AFRICAN 'CLIMATE PARADOX': WETTER OR DRIER?

While global warming is unequivocal, predicting changes in regional rainfall patterns over the coming decades is much more challenging. Over much of east Africa, the 'long rains' in March, April and May have been observed to be decreasing, whilst global climate models tend to predict a wetting.

Researchers will investigate the causes for the observed changes, as well as the modelled trends, to understand this so-called paradox. Currently, the different controls on the 'long rains' and 'short rains' are not well understood for an unperturbed climate. A better understanding of this will be a key step for climate scientists in their work to better understand climate change for east Africa throughout its seasonal cycle.

New understanding of how the east African climate responds to natural variations in Earth's climate in remote regions ('teleconnections', such as the El Niño Southern Oscillation and the Madden Julian Oscillation) will allow researchers to produce novel ways to test the reliability of different climate models.

As the Earth warms globally, rainfall increases, but some regions will get wetter and others drier

As the Earth warms globally, rainfall increases, but some regions will get wetter and others drier. Predicting changes in atmospheric circulation is critical to predicting changes in rainfall for any particular region. This requires sufficiently accurate modelling of both the drivers of change, and the atmospheric response.

Researchers will address drivers of change that are often not considered in standard climate models, such as:

- land use change
- changes in aerosol emissions in remote regions such as Asia, as a result of increased fossil fuel burning
- changes in lake temperatures; for example Lake Victoria is the largest tropical lake in the world, and its temperature affects circulations on scales of hundreds of kilometres
- how to represent small-scale storms in the models, which produce most rainfall in east Africa and are a key component of the atmospheric circulation.

Researchers will capitalise on unprecedented high-resolution modelling to understand how changes in moist convection may affect changes in rainfall and the regional circulation over east Africa. This work is expected to produce an expert judgement on the reliability of various aspects of climate projections for east Africa.

QUESTION 2: WATER FLOWS, LAKE LEVELS AND GROUND WATER RECHARGE

The impact of future climate change on surface and groundwater stores is highly uncertain. However, there are some emerging future climate narratives for east Africa around the duration of dry spells and rainfall intensity that help focus hydrology research questions. Current climate extremes cause significant impacts, including flooding and drought; these signals may be intensified under future climate scenarios.

While changes in climate are very important, it is worth noting that other impacts will also have larger implications for water resources across parts of east Africa on a five to 40 year time scale, namely population growth and land use change. The current uncertainty regarding the future climate, the complex interaction of climate and non-climate factors, as well as the limited data availability for long-term rainfall, river flow and groundwater levels in this region, all combine to make the estimation of future changes in terrestrial water storage hugely challenging.

Future extremes and long-term water resources

Key questions include the extent to which surface water flow variability will change, whether there will be a significant difference in the amount of surface water flow, and what this means for lake levels. Behind these questions is the need to understand if future water flows and lake levels will be adequate to sustain environmental needs, water supply and energy requirements, and how these will impact on the future frequency and scale of flooding.

The lack of rainfall and river flow observations at a high temporal and spatial resolution currently limits flood impact modelling. Climate scientists are starting to address this deficit.

Another important research question is how changes in climate will alter the relative importance of recharge processes and groundwater storage in the long term. This will be particularly critical in more arid regions that are underlain by hard-rock aquifers with lower storage capacity, so are therefore more susceptible to over-exploitation.

Future water resources and meeting the demand

Irrigation is likely to be an important sector for investment and development, if food production is to increase to meet future demand, and if rainfall becomes more variable, or reduces. The region will need to seek alternatives to rain-fed agricultural practices, alongside exploring new climate-tolerant crops.

In addition, while there may be adequate water resources, how will socio-economic constraints limit future exploitation? Hotspots of higher water demand, such as urban centres and irrigation schemes, will grow. This is particularly true around the shores of Lake Victoria.

There may well be a future spatial mismatch between local water demand on the one hand, and the availability of water resources on the other. This needs to be assessed and quantified. Groundwater can help meet some of this demand, even in low storage hard-rock aquifer settings, provided there is effective water resource management. The increased use of water resources for irrigation will require agricultural extension, as well as more readily available financing, particularly for small-scale farming.

If groundwater becomes a more important source of water supply, which is highly likely, natural water quality considerations and constraints, such as fluoride, arsenic and iron may become more important. Overall, as is now the case in parts of Asia, water quality constraints may emerge as a bigger issue in the region than water resource availability, given population growth and urbanisation, as well as salinisation associated with agricultural intensification.

Environmental water flows

Groundwater sustains baseflow in rivers during low rainfall periods, and shallow groundwater levels maintain groundwater-dependent wetlands. Baseflow typically provides an underlying good quality source of water that is key for maintaining the natural ecology in these habitats. These wetlands have local and international significance, as well as being important for tourism.

The necessity of this baseflow contribution may grow under future climate change if dry spells are longer on average, particularly in already marginal areas. Observations are required to underpin the assessment of habitat impact and modelling to predict future status. Environmental flows and water quality may emerge as a crucial issue around Lake Victoria, given the future impact from urbanisation in this region. Locally, the priority to maintain environmental flows may be considered low, with competing demands that override environmental considerations. Therefore, it is necessary to make impartial predictions

Environmental flows and water quality may emerge as a crucial issue around Lake Victoria, given the future impact from urbanisation in this region

about the consequences of decisions. This is likely to be a growing issue across the whole of east Africa in the next 40 years, particularly in regions experiencing large increases in population growth.

QUESTION 3: RURAL LIVELIHOODS

- People (farmers, fishers, micro-entrepreneurs etc), households and businesses in the Lake Victoria Basin (LVB) are making daily decisions to adjust and hopefully enhance their diverse suite of short-term and longer-term livelihood strategies to household-level and wider changes. What are the key signals that currently drive decision-making across these domains?
- If the wider region takes successive hits from changes in rainfall and temperature and from increasingly unpredictable weather events, then what additional population movements could this give rise to, and how would that affect governance in the LVB, particularly regarding access to land, labour, livelihoods and crucially, the rule of law?
- In a scenario where fish stocks have contracted permanently over time, and the livelihoods and incomes for all those active in the fishing value chain are adversely affected, what other livelihood options do the affected people in the LVB realistically have to make a viable living?
- How effectively are the current actors and structures of governance serving local communities and administrations in the delivery of climate services and information?
- What kinds of bottlenecks (e.g. coordination, accessibility of data, financial, technological, human resources, and regulatory constraints) are present within and across these governance structures, and what is currently being done to overcome them?
- Given the specificities of the LVB context, which strategies that are effective in other regional contexts can be adapted for the generation and sharing of critical, scaled information about climate risk and livelihood adaptation with and for institutions and households?
- To what extent are climate change impacts currently integrated into decisions related to development projects, programmes and policies related to infrastructure, agriculture, fisheries, and resource management?
- Given the probabilistic nature of climatic events, the complex evaluation of costs and benefits, and the contextual bias towards the present, what innovations, including insurance schemes of various types, can be developed and/or repurposed to increase system resilience?

Decisions need to be made about investment in water, sanitation and hygiene systems, in the context of a range of possible future climate scenarios

QUESTION 4: WATER, SANITATION, AND HEALTH IN TOMORROW'S CITIES

Which types of infrastructure and services should cities prioritise to ensure that the benefits of water supply and sanitation are sustained under a range of probable climate futures?

Decisions need to be made about investment in water, sanitation and hygiene systems, in the context of a range of possible future climate scenarios. To ensure that cities can plan for and design resilient systems, climate scientists will seek to identify solutions that perform well under as many of these different scenarios as possible.

For example, changes in rainfall intensity under climate change are likely to affect requirements for drainage systems. Existing and best-available alternatives will be modelled in selected areas of the study cities, to explore how relative costs and benefits are likely to change in light of future climate trends. This will help develop a better understanding of long-term economically viable and sustainable approaches to water, sanitation and hygiene issues in east Africa.

FCFA'S HyCRISTAL PROJECT

Project objectives

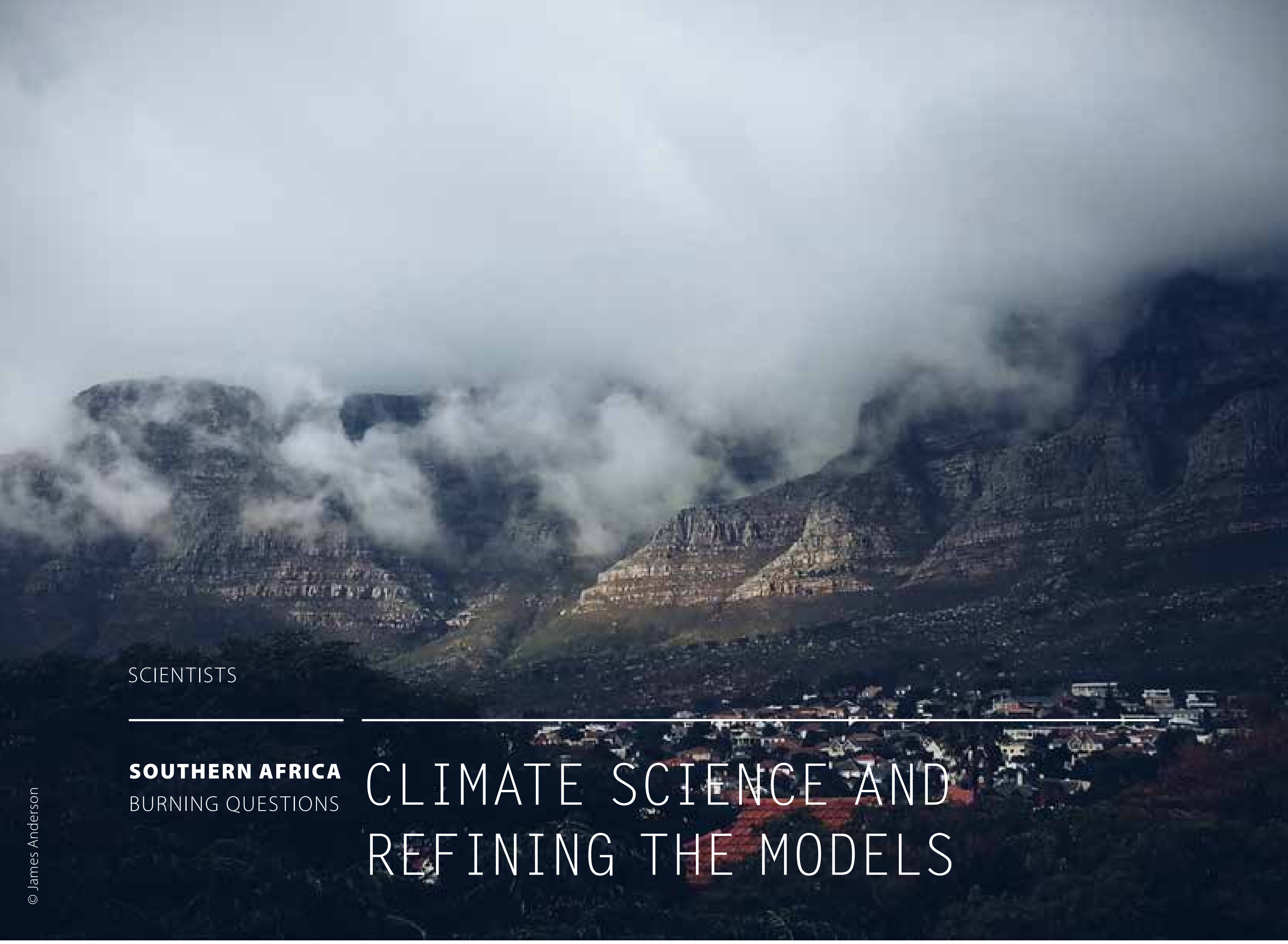
Availability of water is fundamental for development in east Africa. However, this vital resource is already under stress from land degradation, pollution and overfishing. Climate change adds to these problems, greatly increasing the vulnerability of the poorest people in the region.

Climate projections show a warming trend in east Africa in the decades ahead, but changes in rainfall and weather extremes are currently uncertain. HyCRISTAL will tackle current uncertainties which exist around climate change projections for the region, concentrating in particular on what they mean for the availability and management of water.

HyCRISTAL will develop new understanding of climate change and its impacts in east Africa, working with the region's decision-makers to manage water for a more climate-resilient future. See www.futureclimateafrica.org/project/hycristal/

The institutions involved in HyCRISTAL are:

- University of Leeds
- African Centre for Technology Studies
- British Geological Survey
- Centre for Ecology and Hydrology (UK)
- Evidence for Development
- Jomo Kenyatta University
- Loughborough University
- Met Office (UK)
- National Centre for Atmospheric Science (UK)
- National Fisheries Resources Research Institute (Uganda)
- North Carolina State University
- Practical Action
- Stony Brook University
- Tanzanian Meteorological Agency
- Ugandan National Meteorological Authority
- Ugandan Ministry of Water Resources
- University of Connecticut
- Makerere University
- Maseno University
- Walker Institute
- University of Reading (Africa Climate Exchange)



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SCIENTISTS

SOUTHERN AFRICA
BURNING QUESTIONS

CLIMATE SCIENCE AND REFINING THE MODELS

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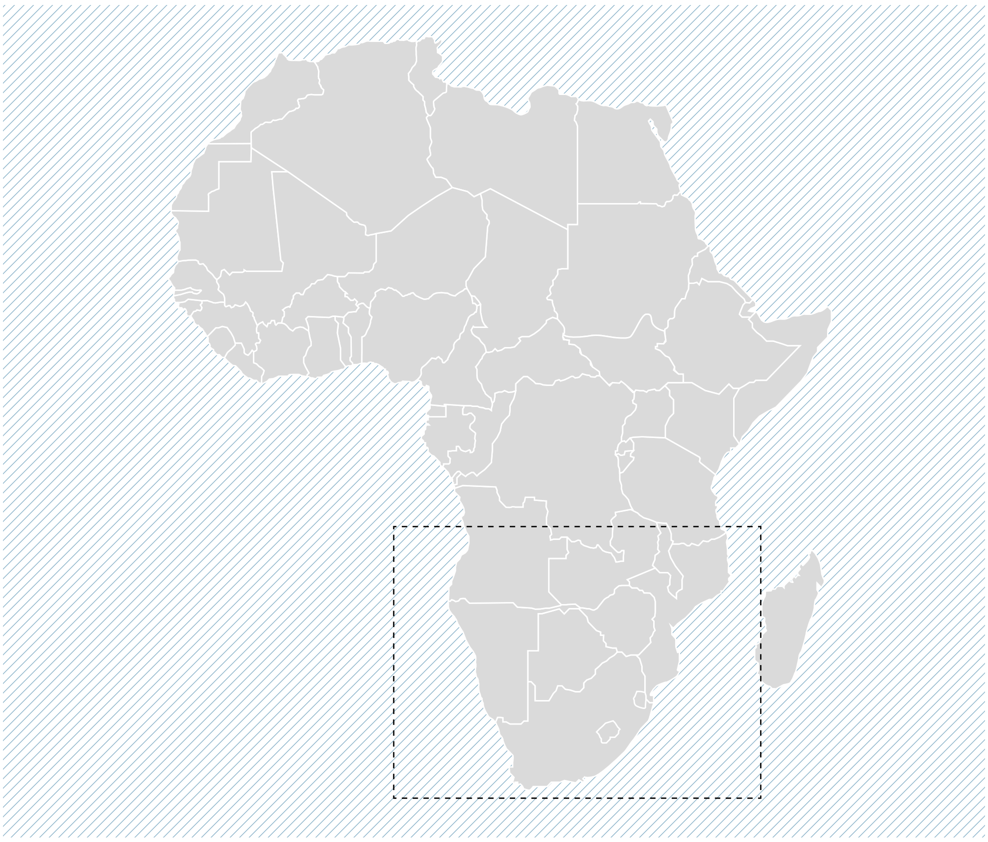


NEED TO KNOW

Climate scientists are refining their models so that they can give decision-makers in southern Africa credible, evidence-based projections for the region's future climate.

This factsheet:

- discusses the three main tiers of modelling ('global', 'downscaled', and 'impacts' models)
- compares a global and a downscaled modelling project, to illustrate how well they work and where the gaps are
- considers the implications for those who generate, and those who use, climate information.

INTRODUCTION

The combination of rapid urbanisation and climate change will produce a potential crisis of urban development in the region in the coming decades

There are two strong forces shaping society in southern Africa today: urbanisation and climate change. While most urbanisation in the 20th century was concentrated in the global north, the highest rates of urbanisation over the next 40 years are expected to be concentrated in Asia and Africa.[1]

At the same time, some regions of Africa, including areas of southern Africa, are likely to experience climate change more rapidly and intensely than the global average.[2] The combination of rapid urbanisation and climate change will produce a potential crisis of urban development in the region in the coming decades.

The ability to avert this crisis, and eventually capitalising on emerging opportunities, rests on good decision-making across regional, national, and urban scales, and requires robust evidence to support these decisions.

THREE TYPES OF MODELS

Climate projections are the starting point for one important line of such evidence. These are produced primarily through a cascading process of modelling, using three main approaches:

1. Modelling starts with Global Climate Models (GCM) producing projections of large scale changes.
2. Downscaling (empirical or dynamical) then attempts to resolve finer-scale features, for instance, how climate across the region influences thunderstorm activity that happens at a smaller-than-100km scale.
3. Impacts models relate changes in climate to changes in phenomena such as water availability, crop yields, and even economic systems.

1 United Nations, Department of Economic and Social Affairs, Population Division, 2014.

2 IPCC, 2013: Annex I: Atlas of Global and Regional Climate Projections [van Oldenborgh, G. J., M. Collins, J. Arblaster, J. H. Christensen, J. Marotzke, S. B. Power, M. Rummukainen and T. Zhou (eds.)]. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

While disagreements between models are typically conflated under the label of 'uncertainty', much of the apparent contradiction is actually the result of natural variability of the climate system

Each model in this chain is built on a set of assumptions, limitations and constraints. The resultant messages of change delivered to decision-makers therefore rests on complex layers of assumptions and limitations that are currently poorly described and understood.

Added to this is the necessity of using multiple models in order to capture specific elements of uncertainty. The apparently contradictory messages that result can cause confusion and lack of trust amongst decision-makers. While disagreements between models are typically conflated under the label of 'uncertainty', much of the apparent contradiction is actually the result of natural variability of the climate system, and not model disagreement. The same climate model, initialised differently, can produce different projected future climates as it represents natural climate variability. These are apparent contradictions rather than real contradictions. The conflation of real and apparent contradictions is seldom, if ever, described or unpacked in the process of producing climate change evidence.

A key focus for the climate science team working in this area is to understand, describe, and unpack contradictions, and their consequences, in this process of producing evidence.

AVAILABLE PROJECTIONS AND DOWNSCALED PRODUCTS

There is at present an unprecedented volume of climate simulation data available to researchers. This is largely captured by initiatives such as the Coupled Model Intercomparison Project (CMIP) and the COordinated Regional Downscaling EXperiment (CORDEX) projects – described in some detail below – although other more specialised data is also available. For example, the Climate Prediction.net[3] project produces very large sets of simulations for the purposes of attributing extreme events to climate change.

A GLOBAL MODELLING PROJECT: CMIP5

At present the CMIP provides the most definitive suite of Global Climate Model simulations for researchers. The most recent iteration is the CMIP5 project, which includes simulations produced by around 40 models to which 17 research institutions contribute.

CMIP has evolved through several generations of model development, culminating in the most recent one, CMIP5. While it represents some significant changes in the ability to simulate Earth's climate, compared with previous iterations, the reality is that the climate projections produced by CMIP5 do not differ strongly from the previous CMIP3 project.

In the paper by Knutti and Sedláček[4] (Figure 1 below), for example we see that projected changes in rainfall do not differ strongly between CMIP3 and CMIP5. This does not mean that the models are not improving. Whereas many of them are representing far more detail and have improved significantly, the resultant projections are not substantively different.

CMIP5's projected changes for southern Africa show a high degree of disagreement. Figure 2 below shows projected changes in rainfall across the southern African region produced by a subset of 11 of the CMIP5 GCMs. The figure illustrates the level of disagreement between the different GCMs.

3 www.climateprediction.net

4 Knutti, Reto, and Jan Sedláček. 'Robustness and uncertainties in the new CMIP5 climate model projections.' *Nature Climate Change* 3.4., 2013. 369–373.

A 'DOWNSCALED' MODEL PROJECT: CORDEX

CORDEX is similar to CMIP in that it attempts to coordinate a set of simulations run by multiple research institutions. CORDEX, however, focuses on regional climate simulations. CORDEX currently contains data from six different Regional Climate Models (RCMs) that have been used to downscale 12 GCMs from the CMIP5. In this downscaling process, GCM data is used to drive (or force) the RCM model that represents a smaller area of the globe, but at higher resolution than the 'parent' or driving global model. Each RCM is unique, and has a different way of representing features such as land surface, vegetation types, and clouds. There is no data yet for every combination of RCM and GCM in CORDEX. This data is currently available at Earth System Grid Federation (ESGF).

The CORDEX Africa project has focussed on simulation of the African climate system. Figure 3 below compares CORDEX model simulations of past climate with different observed datasets, and shows that different regional models perform differently when attempting to simulate historical climate over Africa, particularly in the case of rainfall. All models show errors in some regions, though some models are clearly better at simulating past climate than others. The figure also highlights the differences between different observed climatologies for Africa, as discussed in detail in our regional overview factsheet, 'Tools for observing and modelling climate'.

Climate scientists who focus on southern Africa, are trying to better understand why models disagree with each other. More specifically, they focus on why regional models driven by global models can produce different future projected changes compared to their driving global models.

In Figure 4 below, for instance, we can see a set of global models in the top row, and their projected rainfall changes for the 2069 to 2098 period. In the second row, we can see the COSMO Climate Limited-area Model (CCLM) forced by the GCM from the row above, and its projected change in rainfall. And in the third row, a different regional model forced by the same GCM and its projected change in rainfall. Some initial work is currently being written up in an academic paper but it seems to indicate that regional climate simulations are fairly 'free' to simulate quite different climate compared to their driving global models.

A PROCESS-BASED VIEW

The processes that are relevant depend on the region, and deciding what the key processes are, is a parallel area of ongoing research

Understanding model-based projections, and apparent versus real contradictions, is made more difficult by focussing on surface responses, such as rainfall and temperature. We know that dynamical models, particular GCMs, are often unable to represent local surface responses well. It is likely that many apparent contradictions between model projections are only present in the surface responses (such as local rainfall), rather than the fundamental physical process changes (such as atmospheric circulation). It is noted, for example that every model in the CMIP5 archive projects a shift in the mid-latitude jet system towards the south, even though the closely related projected changes in rainfall in South Africa show disagreements across the models.

This is the primary driver behind a process-based view on climate modelling and projections. In a process-based view, models are evaluated based on how they represent key regional climate process. The processes that are relevant depend on the region, and deciding what the key processes are is a parallel area of ongoing research. An example in the southern African context is some key processes and features, which include Tropical

Temperate Troughs, the Angola low pressure system, cloud bands, and the Inter Tropical Convergence Zone (ITCZ). However, other processes may also be important, such as land surface and vegetation interactions with the atmosphere, and key regional ocean process such as the Agulhas current dynamics.

While prior work has attempted to use process-based model evaluation,[5] climate researchers have undertaken a comprehensive process-based analysis of the southern African regional climate, and both global and regional model representations of processes. The process-based approach will also allow them to understand the contradictions between model projections described above. Science's contribution to southern African climate modelling will therefore provide a rigorous framework and example implementations of a process-based regional climate analysis and model performance analysis.

CONSEQUENCES FOR CLIMATE SCIENCE AND DECISION-MAKING

There are many documented cases where poor selection or understanding of climate data products, whether historical or future projections, has led to poor information being made available to decision-makers

With ever increasing pressure to provide detailed information about future changes in climate, researchers and climate services practitioners are digging deep into the available climate data.

However, with many disagreements between products producing contradicting messages of past and future change, it is more important than ever that climate data products are well studied, understood, and described. Climate researchers and practitioners should be fully aware of the underlying assumptions, caveats, and limitations of the data products they are using.

There are many documented cases where poor selection or understanding of climate data products, whether historical or future projections, has led to poor information being made available to decision-makers. This poor information can take many forms, including misrepresentation of uncertainties, misrepresentation of the real information content, or misunderstanding of the limitations in accuracy of the information.

Climate researchers see that contributing to both the understanding of the products, as well as informing downstream users of the products about best practice, is a key contribution to the science and practice of climate change projections.

5 McSweeney, et al. Selecting CMIP5 GCMs for downscaling over multiple regions, *Climate Dynamics*, 44.11, 2015. 3237–3260.

FCFA'S FRACTAL PROJECT

Project objectives

One of the chief scientific challenges for understanding southern Africa's climate is that different models give contradictory scenarios for climate trends in the next five to 40 years. FRACTAL's team will advance scientific knowledge about regional climate responses to human activities and work with decision-makers to integrate this scientific knowledge into climate-sensitive decisions at the city-regional scale (particularly decisions relating to water, energy and food with a lifetime of five to 40 years).

Through scientific research, FRACTAL will contribute to improved understanding of climate processes that drive the African climate system's natural variability and response to global change. By bringing together scientists and people who use climate information for decision-making, the project will enhance understanding of the role of such information. FRACTAL will distil relevant climate information that is informed by and tailored to urban decision-making and risk management. The team's activities will understanding of how scientists from different disciplines can work effectively together.

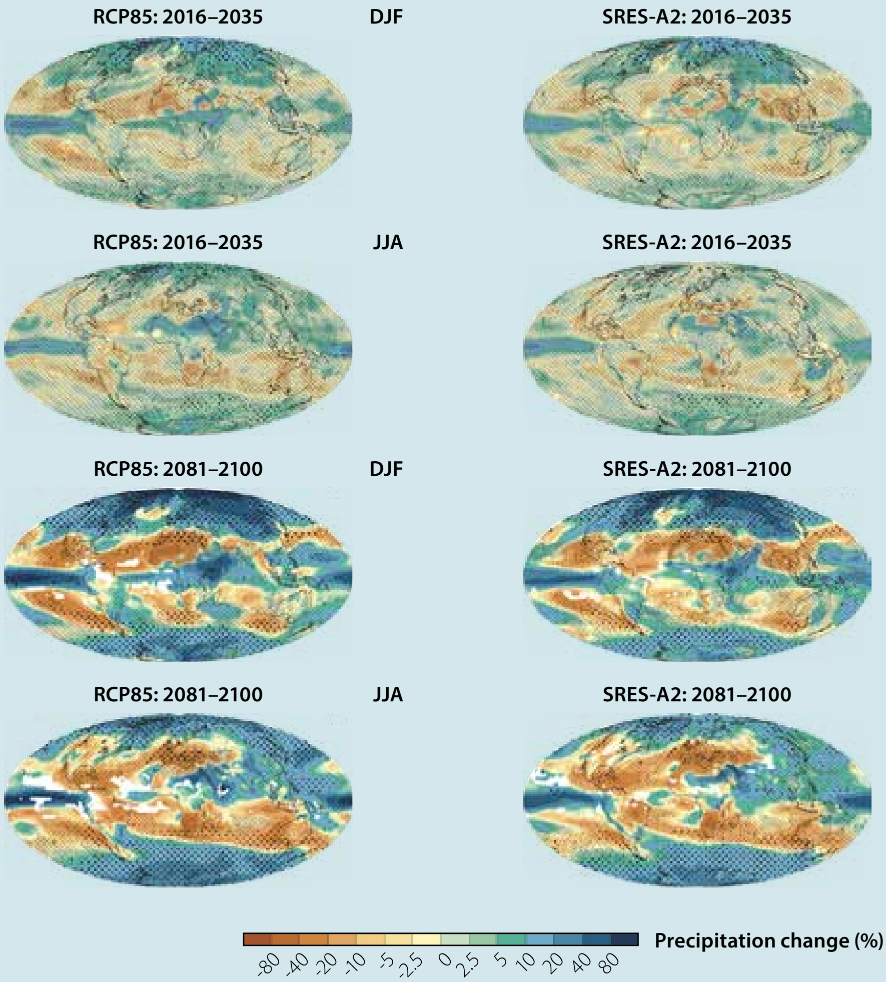
See www.futureclimateafrica.org/project/fractal/

The institutions involved in FRACTAL are:

- University of Cape Town
- Met Office (UK)
- Stockholm Environment Institute
- START
- ICLEI–Local Governments for Sustainability
- Swedish Meteorological and Hydrological Institute/ Sveriges Meteorologiska och Hydrologiska Institut
- Red Cross Red Crescent Climate Centre
- University of Oxford
- Aurecon
- Council for Scientific and Industrial Research
- US National Atmospheric and Space Administration
- Lawrence Berkeley National Laboratory
- European Commission Joint Research Centre
- City of Cape Town
- City of eThekwini

FIGURES

Figure 1
Multi-model mean relative precipitation change for two seasons (December–February, DJF, and June–August, JJA) and two 20-year time periods centred around 2025 and 2090, relative to 1986–2005, for CMIP5 (left) and CMIP3 (right). Stippling marks high robustness, hatching marks no significant change, and white areas mark inconsistent model responses.[6]



6 Knutti, Reto, and Jan Sedláček. "Robustness and uncertainties in the new CMIP5 climate model projections." *Nature Climate Change* 3.4, 2013. 369–373.

Figure 2[7]

Projected changes in December–February rainfall produced by 11 different CMIP5 GCMs for southern Africa for the period 2046–2065 (relative to the 1986 to 2005 period).

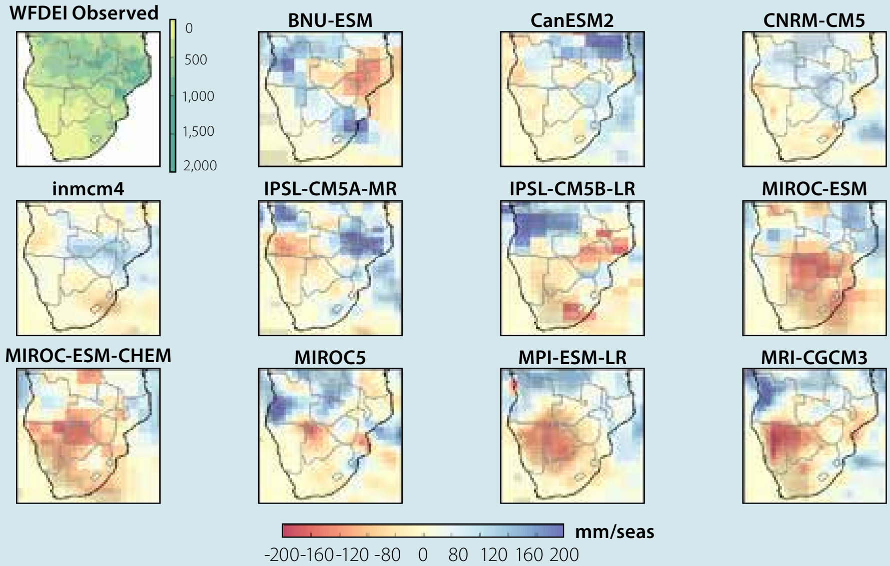
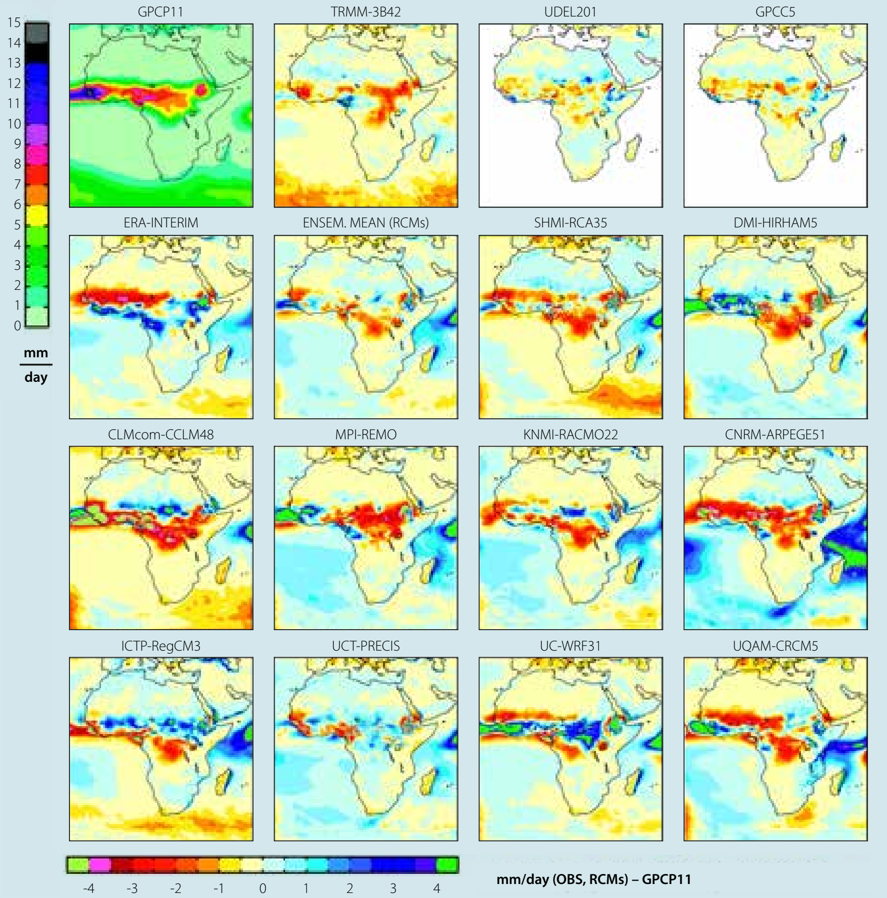


Figure 3[8]

GPCP mean July–September (JAS) precipitation for 1998–2008 and differences compared to GPCP in the other gridded observations (top row), the individual RCMs (rows 2 to 4), and their ensemble average (row 2 column 2).

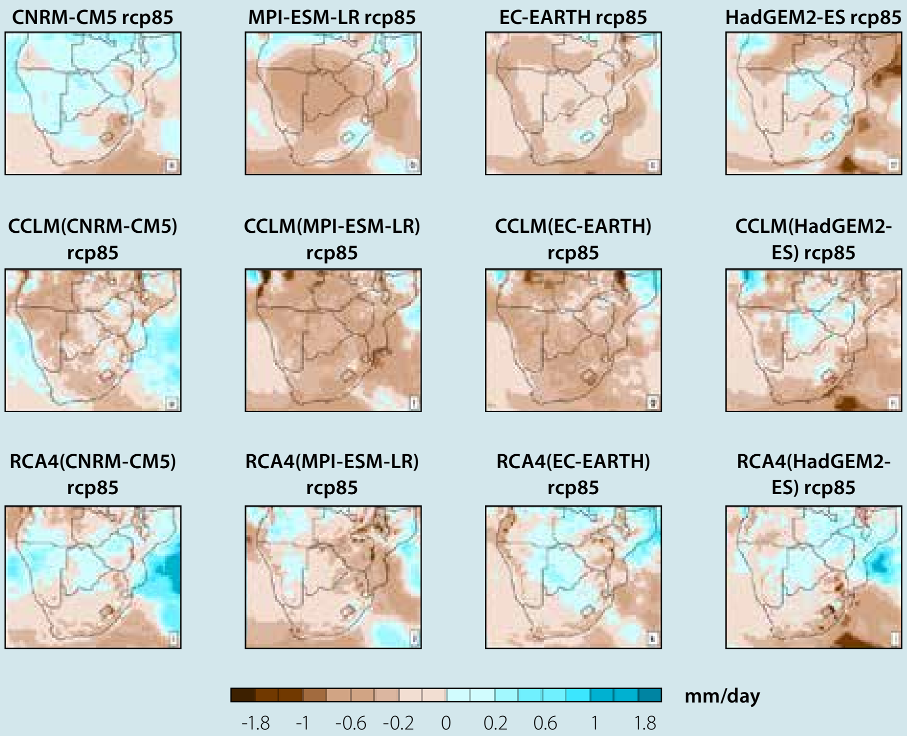


7 Maps: produced by the authors.

8 Nikulin, Grigory, et al. "Precipitation climatology in an ensemble of CORDEX-Africa regional climate simulations." *Journal of Climate* 25.18, 2012. 6057–6078.

Figure 4[9]

Temporally averaged changes in mean daily precipitation by 2069–2098 under RCP8.5 relative to the reference period 1976–2005. a-d shows the GCMs, e-h shows the CCLM forced by GCMs and i-l shows RCA forced by GCMs.



9 Maps: produced by the authors.

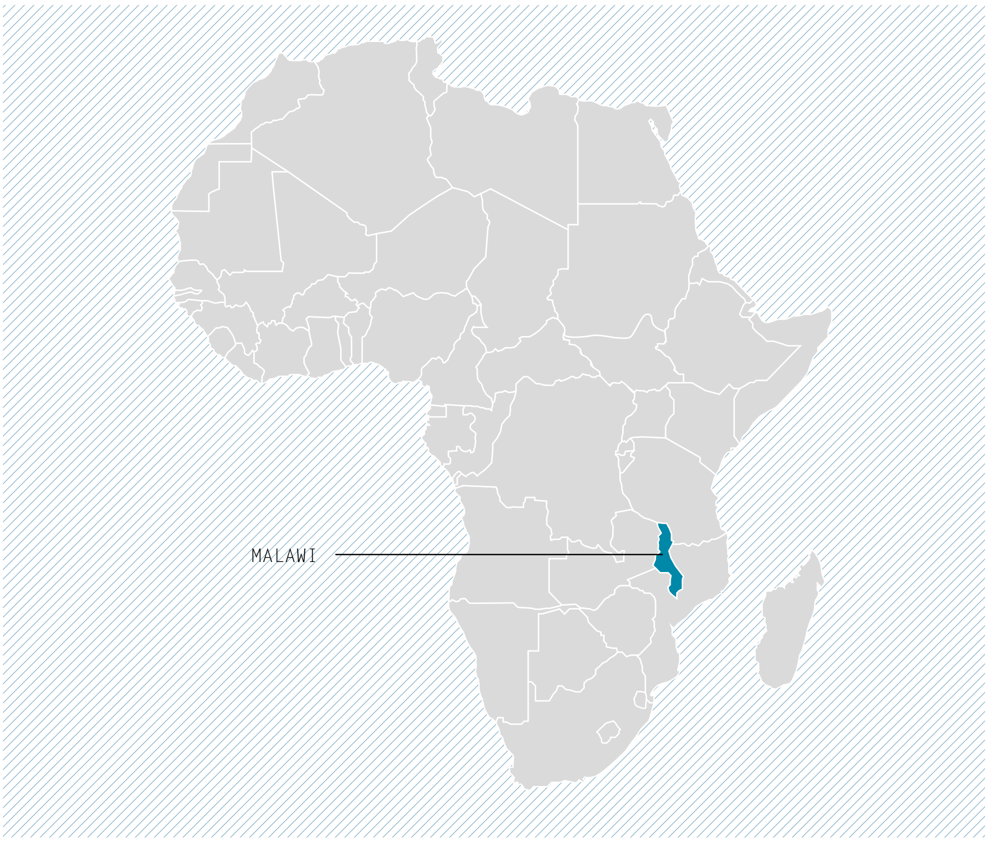
GENERAL READERS

MALAWI
COUNTRY
FACTSHEET

WEATHER AND CLIMATE INFORMATION FOR DECISION-MAKING

AUTHORS

This factsheet was written by the UMFULA research team, with inputs from Malawi's Department of Climate Change and Meteorological Services.



NEED TO KNOW

Malawian decision-makers need robust information on short-term weather forecasts, as well as longer-term climate trends, so they can plan for near-term variability and distant changes to the climate system. This fact sheet outlines:

- the kind of weather and climate information available in the region
- who is using it, and how
- how climate information can be more useful to inform decisions.

CURRENT WEATHER AND CLIMATE INFORMATION IN MALAWI

In Malawi, weather information is already distributed and used fairly widely. But recent extreme weather events have highlighted the potential for climate change to disrupt efforts to address development in the region. Malawian decision-makers have the following kinds of weather and climate information available to them.

Short-term weather forecasts

Daily and five-day weather forecasts

These give predictions of temperature, rainfall, and wind for the forecast period. These are distributed through television and newspaper media, as well as on the Department of Climate Change and Meteorological Services (DCCMS) website (www.metmalawi.com).

10-day forecasts

These come out every Monday, and are sent via email to a variety of national and local government departments, as well as development partners and non-governmental organisations (NGOs).

These highlight ongoing trends (for example, the weather consequences of an El Niño event), and help users interpret the information. They also give advanced warnings, such as the potential for flooding if heavy rainfall is expected on already-saturated ground.

10-day weather and farming bulletins

During the growing season, from October to April, the DCCMS issues 10-day weather and farming-specific meteorological bulletins.

These are based on comparing the observed conditions at local weather stations over the preceding 10-day period (rainfall, temperature, wind speed, humidity, and sunshine hours), with the conditions that would be expected over the same time period, based on a 10-year average. There is a particular focus on rainfall. The bulletin also gives the cumulative total through the season, compared with historical records.

To sign up for the 10-day forecast and/or 10-day weather and farming bulletins, email Adams Chavula, Principal Meteorologist (Agrometeorology and Customer Services) (adamschavula@metmalawi.com).

This seasonal forecast is different from a short-term weather forecast, in that it outlines whether the expected rainfall totals for the season will be normal, above normal, or below normal

Seasonal forecasts

A seasonal rainfall forecast for the entire southern African region is issued each year by the Southern African Climate Outlook Forum (SARCOF), a function of the Southern African Development Community diplomatic and economic bloc.

This gives a forecast of the expected rainfall over the coming rainy season for the region, and is localised for Malawi by the DCCMS for the months of October to March.

This seasonal forecast is different from a short-term weather forecast, in that it outlines whether the expected rainfall totals for the season will be normal, above normal, or below normal. SARCOF updates its seasonal forecast mid-way through the rainy season, with a second issued for the period January–February–March.

There are additional seasonal forecasts covering Malawi, produced by other regional and international bodies, and are available online (see box). These tend to be updated more regularly (including every month for the immediate three month period), and give projections for temperature, wind, and rainfall.

Climate change projections

Projections for climate trends look at longer time windows, from now to 2065, 2080, and further.

These are drawn from the results of various global climate modelling (GCM) simulations, and are published in the Intergovernmental Panel on Climate Change's (IPCC) periodic assessments of the most current science. The most recent was the IPCC Fifth Assessment Report, published in three volumes from 2013 to 2014.

The most recent climate projections to focus on Malawi were done by the University of Cape Town's Climate Systems Analysis Group (CSAG), and South Africa's Centre for Scientific and Industrial Research (CSIR). Their modelling projects the amount of deviation from the long-term average with respect to a number of temperature and rainfall variables.

Some key sources of weather and climate information for Malawi

- Malawi Department of Climate Change and Meteorological Services (DCCMS) – daily, five-day, 10-day agro-meteorological forecasts during the rainy season, and seasonal forecasts.
- SADC Climate Services Centre, seasonal, monthly agro-meteorological bulletins during the rainy season.
- Climate Systems Analysis Group at the University of Cape Town in South Africa, for seasonal and localised projections.
- Council for Scientific and Industrial Research (CSIR) in South Africa, for seasonal and El Niño Southern Oscillation forecasts.
- International Research Institute for Climate and Society, at Columbia University in the United States, for seasonal and El Niño Southern Oscillation forecasts, and climate change projections for coming decades.
- Intergovernmental Panel on Climate Change Fifth Assessment Report, the United Nations' body of experts, which approximately each five to seven years publishes a comprehensive overview of all the current climate projections for regions across the globe.

WHO IS USING THIS INFORMATION, AND HOW?

Short-term weather forecasts

This is the most widely used form of information in Malawi, including by government departments such as the Ministry of Local Government and Rural Development, and the Department of Disaster Management Affairs within the Office of the President and Cabinet. These forecasts are typically used as a warning of extreme weather events.

The variety of short-term forecasts (the one to 10 day, and the farming bulletins) are also used by the Ministry of Agriculture, Irrigation and Water Development (including the Departments of Agricultural Extension Services and Land Resources and Conservation) and non-governmental organisations supporting livelihood interventions. They use them to inform planting times, extension services, and so forth.

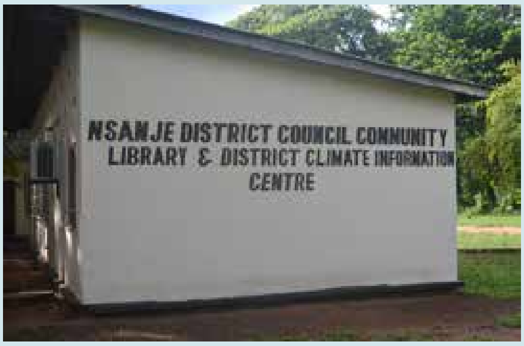
There is a bottleneck in the distribution of information to the grassroots level, which a few international organisations and NGOs are trying to resolve

But there is a bottleneck in the distribution of information to the grassroots level, which a few international organisations and NGOs are trying to resolve.[1] For instance, they are using local radio and mobile phone text services.[2] Climate Information Centres have also been established in a number of districts, from where residents can access the forecasts on the DCCMS website.

Seasonal forecasts

Seasonal forecasts are used by the Ministry of Agriculture, Irrigation and Water Development for annual planning. The Department of Land Resources and Conservation coordinates the process of interpreting the information for agricultural purposes, and the Department of Agricultural Extension Services leads on cascading the information through their institutional structures to the local level. The Department of Disaster Management Affairs also uses seasonal forecasts to inform the development of the annual National Contingency Plan.

Climate Information Centre in Nsanje District, in southern Malawi.



1 Chapota, R., J. Emmanuel, A. Tall, S. Huggins-Rao, M., Leclair, K. Perkins, H. Kaur, and J. Hansen, 2014. Delivering climate services for farmers and pastoralists through interactive radio: scoping report for the GFCS Adaptation Programme in Africa. CCAFS Working Paper no. 111. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). Copenhagen, Denmark. Available online at: www.ccafs.cgiar.org

2 The Farm Radio Trust, Zodiak radio and National Association of Smallholder Farmers of Malawi broadcast forecasts, and the Farm Radio Trust also complements this with mobile phone text message distribution. The National Agricultural Development Content Committee provides the agricultural interpretation. In addition a number of NGOs and programmes are also supporting communication of weather information, for example the Red Cross, Global Framework for Climate Services and Enhancing Community Resilience Programme.

Climate change projections

Climate change projections are rarely used in planning activities in Malawi. However, there is increasing interest to do so, partly prompted by the 2015 floods, and the 2015–16 El Niño event and drought. These exposed the significant vulnerabilities of the region to current extreme weather events, and the increased likelihood of them owing to future changes in climate.

IMPROVING WEATHER AND CLIMATE INFORMATION USE

There is often a misunderstanding of what climate projections are – that they are not crystal ball predictions – which undermines usability in the modelled results

Even though the short-term and seasonal weather forecasts are used widely here, particularly for helping the agriculture sector, climate information is not used much in planning. There is often a misunderstanding of what climate projections are – that they are not crystal ball predictions – which undermines usability in the modelled results, and has acted as a barrier to using this climate information.

Getting models that produce useful information

The agriculture sector needs reliable projections of anticipated trends in rainfall, temperature, humidity and potential evapotranspiration rates, for example, so they can plan and design future investments, such as irrigation projects, and their implementation. However, there is a shortage of modelled projections. This forces people to rely on the use of past observed data. Applying past data to the future, which is also used by other ministries, is potentially problematic as it assumes that the future climate will mirror the past, which may not be the case for projected climate change.

Getting the timescales right

Most government departments are planning according to a three- to five-year time horizon, while the climate projections are based on decades-longer timeframes, such as looking to 2050 and beyond.

Too technical for the average user

The climate model results and scenarios are too technical for most users, which affects how the information is understood, used and spread. This is particularly evident in how it prevents the use of such information in sector-specific decision-making. For instance, the DCCMS and others interpret this climate information for the farming sector. But other sectors don't have institutions offering them the same kind of analysis of trends.

WHERE TO FROM HERE?

After the major 2015 floods in Malawi, a new National Disaster Risk Management Policy was proposed. This makes provision for an Early Warning System that will give the Department of Disaster Management Affairs the scope to use weather and climate information beyond the one-to-ten day forecasts for immediate warning of extreme events.

Similarly the National Adaptation Plan process, currently underway, intends to develop scenarios of climate change that will address the problem of choosing what information to use from among multiple projections.

DCCMS is developing climate services, partly through the Global Framework for Climate Services project (2014–16) (www.wmo.int/gfcs/Norway_2). The agency is assessing information needs and appropriate ways to target the thematic needs of the food security, disaster risk reduction, and health communities. Scientists working in the field aim to support this process by providing climate information suitable for medium-term planning in Malawi (see below).

FCFA'S UMFULA PROJECT

Project objectives

UMFULA ("river" in Zulu) is a four year research project that aims to improve climate information for decision-making in central and southern Africa, with a particular focus on Tanzania and Malawi. UMFULA is a global consortium of 15 institutions specialising in cutting edge climate science, impact modelling and socio-economic research.

UMFULA aims to support long-term – five to 40 year – planning decisions in central and southern Africa around resource use, infrastructure investment and cross-sectoral growth priorities, by identifying adaptation pathways which are robust and resilient in the face of climate change and other non-climate stressors.

The team is generating for the region new insights and more reliable information about climate processes and extreme weather events and their impacts on water, energy and agriculture. These insights will support the more effective use of climate information in national and local decision-making. See www.futureclimateafrica.org/project/umfula/

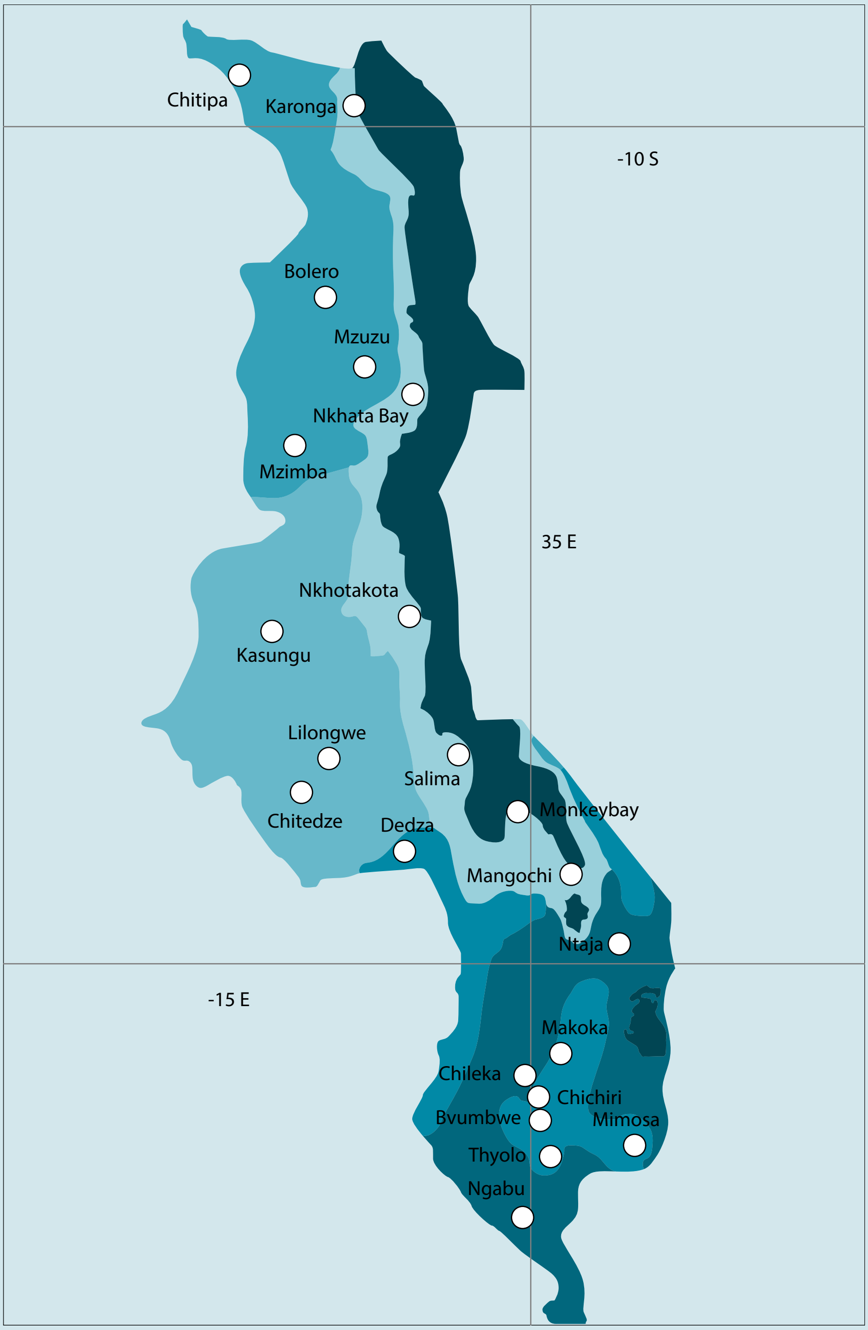
The institutions involved in UMFULA are:

- Grantham Research Institute on Climate Change and the Environment (London School of Economics and Political Science)
- Kulima Integrated Development Solutions
- University of Oxford
- University of Cape Town
- Sokoine University of Agriculture
- Lilongwe University of Agriculture and Natural Resources
- University of Leeds
- Council for Scientific and Industrial Research
- University of Manchester
- University of KwaZulu-Natal
- University of Sussex
- University of Dar Es Salaam
- University of Yaoundé
- Tanzanian Meteorological Agency
- Mozambique National Institute of Meteorology

FIGURES

Figure 1

The spread of Malawi's weather stations (source: www.metmalawi.com)



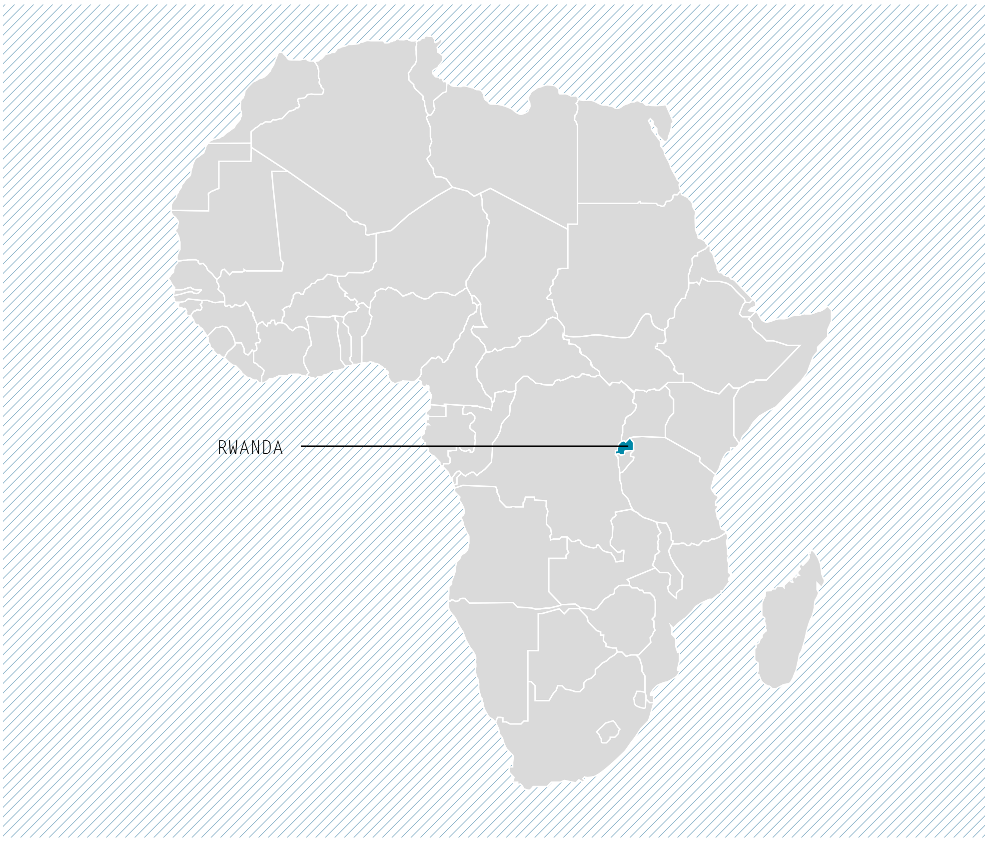
GENERAL READERS

RWANDA
COUNTRY
FACTSHEET

CLIMATE INFORMATION FOR AN UNCERTAIN FUTURE

AUTHORS

Julio Araujo, Nkulumo Zinyengere, John Marsham, Dave Rowell



NEED TO KNOW

There are already noticeable changes in Rwanda's average temperature. Climate change is expected to further alter temperature and rainfall, and likely amplify the kinds of extreme events, such as flooding and drought, that the region already experiences.

This factsheet considers:

- Rwanda's current climate, and how it might change
- the likely impacts for the country and economy
- the type of climate information available to decision-makers, and how widely and effectively this is used.

RWANDA'S VARIABLE AND EXTREME CLIMATE

Rwanda's 'natural' climate is already variable, and prone to extremes. The rainfall varies throughout the year, and across the country, resulting in floods and landslides in the western and northern regions, but droughts in the east. Flooding has caused loss of human lives, and damaged crops and infrastructure. Similarly, historical drought events have caused famines.[1] The impacts of these hazards are exacerbated due to Rwanda's high population density. Addressing these current risks is a priority for early adaptation efforts.

Rwanda's climate

Rwanda has a temperate climate, with considerable differences across the country owing to the varying topography: mountains, valleys, and low-lying areas influence the temperature and rainfall. It is typically cooler and wetter in the west, mainly because of the high mountains, and warmer and drier in the east, where the elevation is lower.

The warmest annual average temperatures are found in the eastern plateau (20°C to 21°C) and Bugarama Valley (23°C to 24°C), and cooler temperatures in the central plateau (17.5°C to 19°C) and highlands (less than 17°C).[2] Rwanda has two rainy seasons, the 'long' rains from March to May, and the 'short' rains from September to December. However, there are large variations in rainfall between years, driven by global and regional weather systems.

1 [MIDIMAR] Ministry of Disaster Management and Refugee Affairs. 2015. The National Risk Atlas of Rwanda. Accessed on August 10, 2016 from: http://midimar.gov.rw/uploads/tx_download/National_Risk_Atlas_of_Rwanda_electronic_version.pdf

2 McSweeney R. 2011. Rwanda's climate: observations and projections Appendix E. United Kingdom: www.smithschool.ox.ac.uk/library/reports/Rwanda_Climate-data- final_proofed.pdf

HISTORIC TRENDS IN RWANDA'S CLIMATE

Weather records show that Rwanda is becoming hotter: the annual average temperature has increased 0.35°C per decade between 1971 and 2010.[3] Minimum and maximum temperatures have increased over the past few decades, with the minimum temperature having a greater increase and thus implying a reduction in the diurnal temperature range. There are no clear trends for rainfall change, although there are some signs that the variation between years is becoming greater.

RWANDA'S FUTURE CLIMATE

Future climate change is likely to lead to new risks: the negative impacts seen from today's climate variability are likely to become worse. We expect that temperatures in Rwanda will continue to rise, with an increase in the number of hot days.[4] This may reflect at different scales across the region, from the broader east African, to a local point in Rwanda.[5] Global Climate Models (GCMs) indicate that Rwanda's temperature may increase by 0.9°C to 2.2°C by the mid-21st century, relative to the period 1970 to 1999.[6]

Predicting regional rainfall changes in the tropics is a major challenge for climate science, and so rainfall projections are more uncertain. Whilst on average, models project a slight increase in annual mean rainfall; some project of both an increase and decrease, and therefore no robust indication of direction and magnitude of change rainfall by the 2060s (22% increase, and a 10% decrease, Table 1[7]). The same message can be said for the main rainy seasons occurring in the March to May and October to December months.

It is likely that climate change will increase the intensity of heavy rainfall events, owing to the likely increase in temperature by the mid-21st century. Other changes are less certain, i.e. whether average and seasonal rainfall will change, and whether the frequency and length of dry spells or droughts will increase. It is clear, at least, that the periodic droughts that happen today are likely to continue.

Trends in future temperature show clear changes in weather extremes that, along with current climate trends, will lead to impacts

While there is often uncertainty in the projections, this should not be a reason for inaction. Instead, these projections mean that adaptation measures should be robust for these different scenarios, or be flexible enough to allow responses to change. Trends in future temperature show clear changes in weather extremes that, along with current climate trends, will lead to impacts, i.e. from current climate variability. Addressing these options will provide benefits today and build resilience to future climate change. Early planning to better understand and prepare for this is also an important and early priority.

3 McSweeney R. 2011.

4 Hot days are the daily maximum temperature that is exceeded on the highest 10% of days in that season for the baseline period 1961 to 2000 (McSweeney, 2015).

5 [CDKN] Climate & Development Knowledge Network. 2015. The IPCC's Fifth Assessment Report: What's in it for Africa?. Accessed on April 5, 2016 from: http://cdkn.org/resource/highlights-africa-ar5/?loclang=en_gb [CSAG] Climate Systems Analysis Group. 2016. Climate Information Portal. Accessed February 3, 2016 from: http://cip.csag.uct.ac.za/webclient2/datasets/africa-merged-cmip5/

6 McSweeney R. 2011.

7 Ibid.

Table 1: The changes in rainfall, temperature, and number of hot days for Rwanda, by the 2050s, represented by season. Dashed lines indicate where no data is available, pale blue colour indicates an increase, while dark blue colour indicates a decrease. Min, Med and Max represent the minimum, maximum and median values of the data range.[8]

		Annual			January to February			March to May			June to September			October to December		
		Min	Med	Max	Min	Med	Max	Min	Med	Max	Min	Med	Max	Min	Med	Max
Temperature (°C)	High	1.3	1.8	2.2	–	–	–	–	–	–	–	–	–	–	–	–
	low	0.9	1.4	1.9	–	–	–	–	–	–	–	–	–	–	–	–
Hot days % Frequency	High	–	–	–	48	66	72	54	75	85	63	76	85	51	66	71
	low	–	–	–	46	55	60	47	59	71	57	63	77	44	51	57
Rainfall (%)	High	-6	3	17	–	–	–	-10	9	19	–	–	–	-7	3	19
	low	-4	5	15	–	–	–	-9	5	22	–	–	–	-4	4	12

IMPACTS OF CLIMATE CHANGE FOR RWANDA

Cost to the economy

Although there is uncertainty associated with the future climate projections, climate change will have significant economic impacts in Rwanda. Given the high levels of uncertainty, it is difficult to accurately determine the economic cost of climate change. However, model estimations indicate that the additional net economic costs (on top of existing climate variability) could be equivalent to a loss of almost 1% of GDP each year by 2030, though this excludes the future effects of floods and other extremes.[9] This estimate is therefore conservative. There are indications that heavy precipitation – such as the number of heavy rainfall days, or intensity of rainfall – may increase, raising the potential risks of floods, landslides, and soil erosion. This could mean that current flooding and landslides that occur in the western areas will likely continue and could increase in future. Major flood events that occurred in 1997, 2006, 2007, 2008, and 2009 have caused fatalities, as well as infrastructure and crop damage.[10] The impacts of these events are economically significant, with the 2007 flood causing an estimated direct economic cost of $4 to $22 million (equivalent to around 0.6% of GDP) for two districts alone.[11]

8 Adapted from McSweeney, 2011.

9 [SEI] Stockholm Environmental Institute. 2009. The economics of climate change in Rwanda. Accessed from www.weadapt.org/sites/weadapt.org/files/legacy-new/knowledge- base/files/4e2572b33fe5bPresentation_summary.pdf

10 Ibid.

11 Ibid.

Future climate change could also significantly increase the health burden of malaria in Rwanda. Since malaria is restricted by temperature, rural populations living at higher altitudes have previously been at lower risk of contraction. Since future projections will result in warming of areas at higher altitudes, the risk of contraction may increase by 150% by 2050s. The increase in the disease burden is significant, and could lead to full economic costs that are over $50 million/year.

Table 2: Extreme weather, climate events, and associated impacts[12]

Extreme	Area affected	Impacts
Droughts	Affects livestock, wildlife, agriculture, water resources	Deaths of people and animals, lack of food, amongst others
Dry spells	Damage to crops	Crops diseases, lack of food
Floods	Damage to crops, shelter, infrastructure	Loss of lives, water resources, water quality, soil erosion, landslides
Hailstones	Damage to crops, damage to property	Loss of crops, stock, and human live
Lightning	Damage to shelter and infrastructure	Loss of life and aircraft
Strong winds	Damage to property, water transport	Loss of life
Extreme temperatures	Damage to crops and health	Lack of comfort, human and crops diseases
High humidity	Effect on human health	Lack of comfort, diseases
Fog	Affects road and air transport safety	Loss of life and property

CLIMATE INFORMATION USE IN RWANDA

Current climate models do not capture all the fine features of Rwanda's varied climate and terrain, but despite this limitation, provide valuable information. There is also a lack of information and observational data on current climate and risks across the country, which limits decision-makers' ability to contextualise future projections.

There are, however, efforts to make climate information more available, and use it appropriately in strategic planning.[13]

12 Mutabazi A. 2004. Generation and Application of Climate Information, Products and Services for Disaster Preparedness and Sustainable Development in Rwanda. Chapter 1: Weather and Climate.

13 [FCFA] Future Climate For Africa. 2015. Final Report: Rwanda Pilot. Accessed on August 10, 2016 from: www.futureclimateafrica.org/resource/rwanda-technical-report

Climate risks have generally been given a low priority when compared to other issues, such as socio-economic drivers

The gaps in climate information

Currently, most policy-makers are not using quantitative future climate projections for adaptation decisions, and instead rely on qualitative narratives of future change. The complex issue of understanding and communicating uncertainty is still limiting climate information usage in Rwanda. In many cases, decision-makers omit uncertainty messages, even when this is included in the primary studies and portals that they cite. Thus, sometimes the needs of the end user are not adequately met by the information generated from the climate science producers.

Decision-makers are interested in information on climate extremes and agro-meteorological and hydro-meteorological outputs, as well as average future trends. They are also much more interested in the next five to 15 years, than longer time periods. In some cases, a lack of time, resources, and capacity to include detailed climate information, has prevented decision-makers from using future projections.

Important socio-institutional issues also enhance or hinder the use of information in decisions. For example, often the decision window for addressing adaptation is short; it is therefore important to provide timely information during these windows of opportunity. In many cases, existing adaptation activities have not yet considered medium- or long-term climate information. Similarly, climate risks have generally been given a low priority when compared to other issues, such as socio-economic drivers.

Where climate information is used well

There are cases where Rwandan decision-makers plan to use climate information; which is evident in the energy sector. A policy objective has been developed to integrate climate and hydrological information into the planning, design, construction, and operations of Rwanda's hydroelectric power facilities. Climate information is currently informing the design of the Rusumo Falls hydroelectric plant. Interestingly, the use of climate information can differ between the public and private sectors. This is evident in Rwanda's hydropower projects, where it is far more difficult to encourage the use of climate information – and resilience – by the private sector for long-term decisions.

Rwanda's climate change and environment fund, FONERWA, is at the forefront of climate information usage in the country. The key decision context is on the appraisal process for adaptation projects, and the inclusion of climate change information into project fund applications, as well as the cost-benefit analysis that they are evaluated against.

FCFA'S HYCRISTAL PROJECT

Project objectives

Availability of water is fundamental for development in east Africa. However, this vital resource is already under stress from land degradation, pollution and overfishing. Climate change adds to these problems, greatly increasing the vulnerability of the poorest people in the region.

Climate projections show a warming trend in east Africa in the decades ahead, but changes in rainfall and weather extremes are currently uncertain. HyCRISTAL will tackle current uncertainties which exist around climate change projections for the region, concentrating in particular on what they mean for the availability and management of water.

HyCRISTAL will develop new understanding of climate change and its impacts in east Africa, working with the region's decision-makers to manage water for a more climate-resilient future. See www.futureclimateafrica.org/project/hycristal

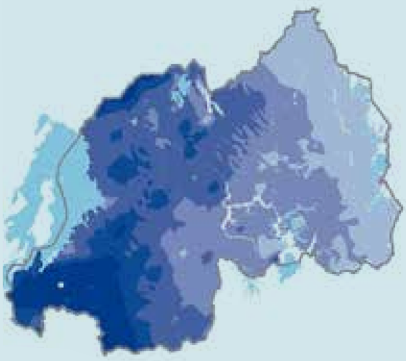
The institutions involved in HyCRISTAL are:

- University of Leeds
- African Centre for Technology Studies
- British Geological Survey
- Centre for Ecology and Hydrology (UK)
- Evidence for Development
- Jomo Kenyatta University
- Loughborough University
- Met Office (UK)
- National Centre for Atmospheric Science (UK)
- National Fisheries Resources Research Institute (Uganda)
- North Carolina State University
- Practical Action
- Stony Brook University
- Tanzanian Meteorological Agency
- Ugandan National Meteorological Authority
- Ugandan Ministry of Water Resources
- University of Connecticut
- Makerere University
- Maseno University
- Walker Institute
- University of Reading (Africa Climate Exchange)

FIGURES

Figure 1

Rainfall classification map for Rwanda[14]



Legend

Country boundary

Lakes

Scale

0 10 20 30 40

Date 16 December 2014

Source
Rwanda Natural
Resource Authority

Rainfall (mm/year)

<1,000

1,000–1,200

1,200–1,400

1,400–1,600

>1,600

Coordinate system: WG584 TM Rwanda
Projection: Transverse Mercator
Datum: WGS 1964

False Easting: 500,000.0000
False Northing: 5,000,000.0000
Central Meridian: 30.0000
Scale Factor: 0,9999

Latitude of Origin: 0.0000
Units: Metre

14 [MIDIMAR] Ministry of Disaster Management and Refugee Affairs. 2015. The National Risk Atlas of Rwanda. Accessed on August 10, 2016 from: http://midimar.gov.rw/uploads/tx_download/National_Risk_Atlas_of_Rwanda_electronic_version.pdf

GENERAL READERS

SENEGAL
COUNTRY
FACTSHEET

CLIMATE INFORMATION AND AGRICULTURAL PLANNING

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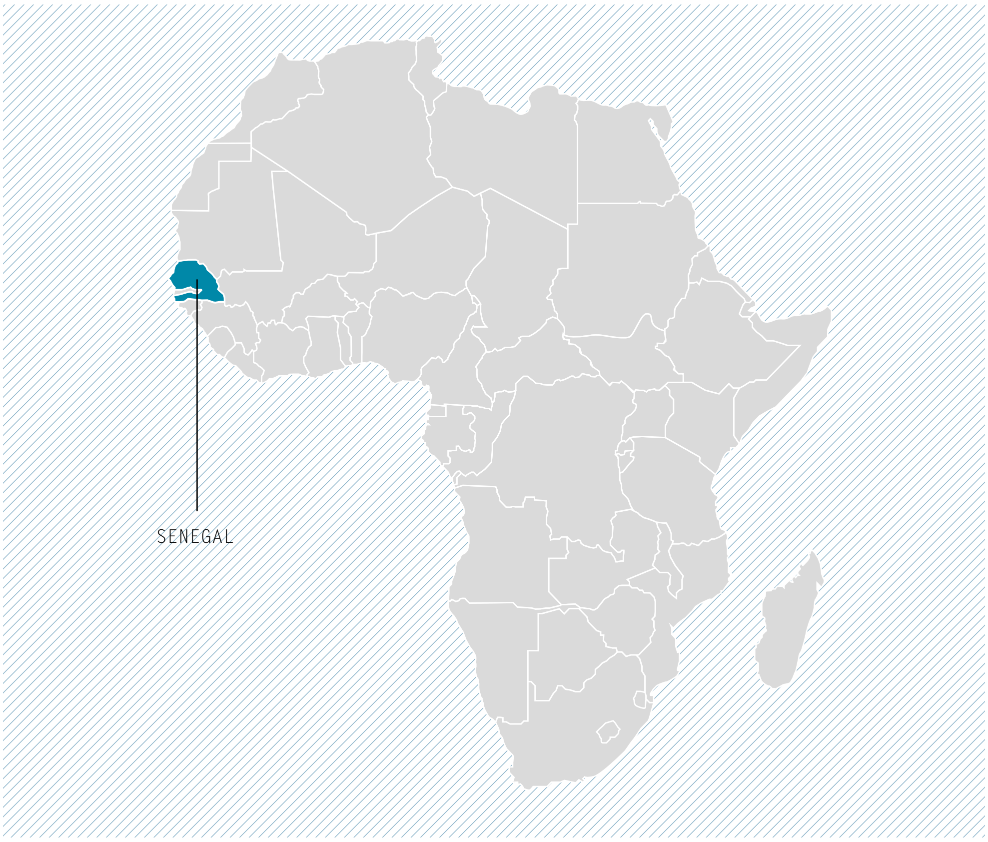

NEED TO KNOW

Climate information needs to be packaged in a way that is widely and easily accessible to those who need it most. This factsheet considers:

- the need for climate information for agricultural planning to be appropriate to the timescales (for instance, seasonal planting, as well as longer-term infrastructure planning), and zoomed in to the right local scale
- the need for it to be accessible and understandable, while being frank about the uncertainties inherent in the science of modelling the future climate
- how policy-makers craft national and regional policies that account for extreme events, as well as the uncertainties in forecasting.

AGRICULTURE, CLIMATE, AND PLANNING FOR CHANGE

To better tackle the effects of climate variability, national and regional policies should take into account extreme events and uncertainty in forecasts

West Africa has experienced some of the most extreme rainfall variability anywhere in the world in recent decades. This has impacted on food security in Senegal, owing to the fact that extreme weather events (particularly droughts and heavy rainfall) have impacted on agricultural yields. Climate change and rapid population growth can make this even worse. Better access to reliable climate information underpins effective planning towards mitigation and adaptation within the agriculture sector.

However, agriculture planners in Senegal do not always trust or use climate information in their decision-making and planning. This is because:

- climate information doesn't meet stakeholders' needs, in terms of the time and geographical scales of the information
- there is uncertainty in climate projections, and climate impacts
- the information isn't accessible, because it is not well distributed (rural people, in particular, don't know where to find climate information).

To better tackle the effects of climate variability, national and regional policies should take into account extreme events and uncertainty in forecasts.

The government of Senegal invests more than 10% of its Gross Domestic Product (GDP) in agriculture each year. The sector employs more than 70% of the population and supplies the main source of livelihood and income in rural areas at risk of food insecurity. The country has therefore identified agriculture in its long-term vision, the Emerging Senegal Plan, as the primary driver for food security and socio-economic growth by 2035.

Senegal's agriculture is based both on cash crops (groundnuts, cotton, horticultural products), and food crops (mainly cereals). The country has vast arable lands, important water resources, and capacity to switch from being a net importer of food products, to an exporter.

SENEGAL'S CLIMATE: PAST, PRESENT, AND FUTURE

Climate change is already happening here

Historically, west Africa has recorded decades of severe drought, interspersed with cycles of above average rainfall. This has reduced agricultural production significantly. Climate changes in Senegal are communicated through precipitation and temperature data.

The analysis of rainfall from 1921 to 2014 showed a clear downward trend, albeit with improved annual totals from 1999. The decrease in annual quantities is thus accompanied by some irregularity that is manifested by a succession of years of deficit and surplus phases.

Extreme weather events across the west African region in recent years appear greater than can be explained by the natural climate variability: land surface temperature has increased by 0.5°C or more, on average, during the past 50 to 100 years; there is also a significant increase in the temperatures recorded on the hottest days and coolest days, in some parts, according to the 2013 United Nations Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report.

In terms of rainfall, the latest trends show the most significant change has happened in the semi-arid regions. Projections indicate a 20% reduction of the length of the growing period in 2050, and early end-dates of rainfall that are now negatively impacting locally on agriculture.

In summary, these climate variations observed in Senegal and across west Africa agree with the IPCC scenarios and indicate that climate forecasts could be used with 'moderate confidence' for agricultural planning.

More climate change to come

Climate modelling projections suggest that the average temperature here will increase by between 3ºC and 4ºC by 2050, that there will be an increase in the number of hot days. There is likely to be a decrease in rainfall over the Sahel region.

These changes will contribute to a likely shortening of the agricultural growing season by about 20% by 2050. The rainy season will end earlier than normal, which will have negative consequences for agriculture.

The observed changes in climate in Senegal and across west Africa are in step with the IPCC's scenarios for future climate change here. This confirmation of the robustness of the information suggests that policy-makers can use them in agricultural planning with a good degree of confidence.

Climate variability, and costs of extremes events

Climate variability will worsen existing stresses on West African agriculture: higher temperatures and increased potential evapotranspiration will make farming systems less productive and more vulnerable

Climate variability will worsen existing stresses on west African agriculture: higher temperatures and increased potential evapotranspiration will make farming systems less productive and more vulnerable.

Integrated assessment studies suggest that damages from climate change, relative to population and GDP, will be far more significant in Africa than in any other region in the world. For example, a mean temperatures rises of 2°C by 2060 will cost the equivalent of 3.4% of Africa's GDP. Adaptation costs in Africa are estimated at US$ 20–30 billion per annum over the next 10 to 20 years. Simulations made to support Senegal's national climate commitment, the Intended Nationally Determined Contribution (INDC) to the United Nations, estimate at US$ 14.6 million the total cost of adaptation options to climate change by 2035, of which US$ 1.6 million are in the agriculture sector.

TOWARD A FITTING POLICY

Policy-makers and other stakeholders are acutely aware of the implications of climate change for the region's agriculture. Without appropriate adaptation measures, climate change could affect food production in Senegal negatively. Policy-makers therefore need access to reliable climate information, including better assessments of the likely impacts of climate change. With this, they can create the necessary policies, and prioritise interventions to support the most vulnerable.

In 2006, Senegal initiated an adaptation and mitigation policy in line with intentional trends, including a National Adaptation Programme of Action (NAPA).

A National Committee on Climate Change (COMNACC) was appointed by presidential decree in order to create a central platform for co-operation on climate change, and to integrate climate information to support decisions and national strategies. As a result, climate change is linked to the promotion of sustainable development as defined in the Emergent Senegal Plan.

Analysing the African climate to empower policies and decision-making

Researchers who are focusing on the implications of climate change for the west African monsoon (see below), aim to:

- build a dialogue with the stakeholders' community
- develop methodologies for using climate and impacts models
- use pilot sites in Senegal and Burkina Faso to demonstrate the benefits of climate risk management.

Since west African countries share similar climate challenges, the approach is to take these local-level solutions, and apply them more broadly across the region and in other sectors, such as health, energy, and water resources.

Using more refined and accurate climate information, researchers will work with decision-makers, stakeholders, and technologies that can support policies in the mid- to long-term.

A pilot study in Senegal will experiment with ways of adapting the agriculture within the context of the African monsoon, to enhance productivity and resilience across the region.

Researchers hope to provide decision-makers with science-based climate information that addresses:

- the potential of biodiversity to adapt to climate extremes
- intensified and agro-ecological agricultural practices and planning adapted to climate projections
- ways to mitigate dry spells, and developing heat-resistant varieties.

These will help build climate-resilient frameworks for agricultural planning.

FCFA'S AMMA-2050 PROJECT

Project objectives

AMMA-2050 will improve understanding of how the west African monsoon will be affected by climate change in the coming decades – and help west African societies prepare and adapt. The AMMA-2050 team will investigate how physical processes interact to cause 'high impact weather events' such as storms and heawaves that affect lives and livelihoods. Not only will they look at how the total amount of rainfall is likely to change – but also at how rainfall is likely to be distributed throughout the wet season. For example, heavy rainfall concentrated in just a few hours places great stress on human settlements, infrastructure and agriculture. By applying expert judgement, they will identify adaptation options in water resources and agriculture. See www.futureclimateafrica.org/project/amma-2050

The organisations involved in AMMA–2050 are:

- Centre for Ecology and Hydrology (UK)
- National Agency for Civil Aviation and Meteorology (Senegal)
- Félix Houphouët – Boigny University
- University of Cape Coast
- Senegalese Institute for Agricultural Research
- VNG Consulting Limited
- University of Leeds
- Met Office (UK)
- University of Sussex
- Institute for Development Research – Hydrology and Environment (France);
- Pierre Simon Laplace Institute – Oceanic and Climate Laboratory
- French Agricultural Research Centre for International Development
- National Centre for Meteorological Research – the Meteorological Atmosphere Study Group (France)

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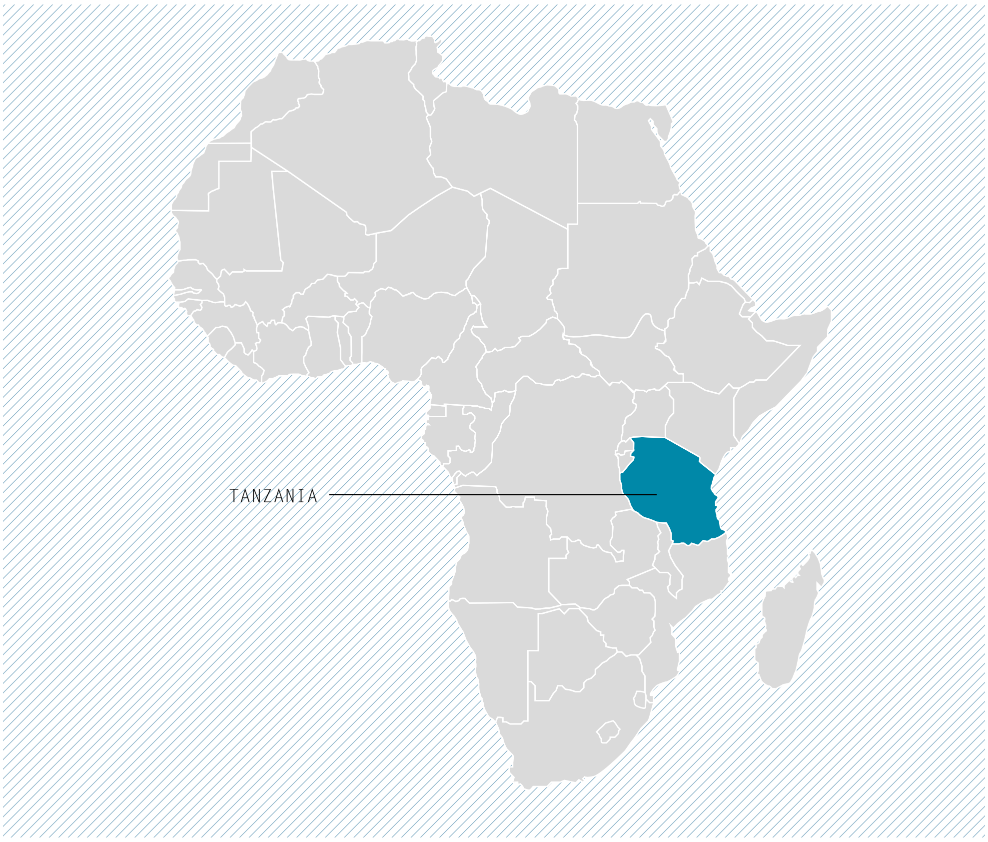
GENERAL READERS

TANZANIA
COUNTRY FACTSHEET

WEATHER AND CLIMATE INFORMATION FOR DECISION-MAKING[1]

AUTHORS

This factsheet was written by Tanzania's UMFULA research team.



1 This report is based on interviews conducted with staff from government departments and ministries, non-governmental organisations and civil society organisations during April and May 2016. It also incorporates insights from a conference to launch the El Niño emergency projects (TCP/URT/3506) (April 2016). Other sources have been recognised throughout.

NEED TO KNOW

Decision-makers in Tanzania are eager to get more useable climate information in order to make short- and long-term plans.

This factsheet outlines:

- the kind of weather and climate information available in the region
- who is using it, and how
- how climate information can be more useful, in order to inform decision-making and planning.

CURRENT WEATHER AND CLIMATE INFORMATION IN TANZANIA

Tanzanian decision-makers have the following kinds of weather and climate information available to them:

Short-term weather forecasts

Immediate weather advisories

The Tanzania Meteorological Agency (TMA) issues extreme weather warnings and advisories. These alerts are issued for the attention of both the general public and/or other key sectors such as aviation, agriculture, water resource management, disaster management, health and the construction industry.

Next 24 hours to next 10 days

TMA issues short range weather forecasts covering the next 24 to 48 hours, and medium range forecasts that extend up to 10 days ahead. They contain information on temperature, precipitation and wind speeds. These are broadcast through television, radio, the TMA website (www.meteo.go.tz/) and via mobile phone alerts. Users are most familiar with these short- and medium-range forecasts.

Targeted 10-day forecasts

TMA also issues bulletins targeted at the agricultural sector. These bulletins are similar to the standard 10-day forecasts. However, they have some additional interpretation. They review the temperature and rainfall conditions, and the resulting agro-meteorological and hydrological conditions that were observed over the previous 10 days. They also predict temperature, rainfall and hydrology, and provide an agro-meteorological advisory (the Agromet Bulletins), for the coming 10 days.

Monthly forecasts

TMA produces monthly forecasts. They review the climate and weather systems that have affected the country over the previous month, and the rainfall observations, as well as predicting what rainfall will look like in different parts of the country over the coming month.

Seasonal forecasts

Seasonal forecasts

The seasonal forecasts tend to be produced for three key periods: the two rainy seasons, (the Vuli season: October to December; and the Masika season: March to May), and the January/February period in between.[2]

These seasonal forecasts provide a review of rainfall performance, and an outlook for the next season. They also capture phenomena that are likely to affect conditions over the whole season, such as the development of El Niño conditions, and the implications of sea surface temperatures for rainfall amounts. This information is targeted at specific advisories for agriculture and food security, pastures and water for livestock and wildlife, natural resources and tourism, energy and water, local authorities, the health sector, disaster management and the media.

Climate change projections

Projections for climate trends look at longer time windows, from now to 2065, 2080, and further

Projections for climate trends look at longer time windows, from now to 2065, 2080, and further. These are drawn from the results of various Global Climate Modelling (GCM) simulations, and are published in the Intergovernmental Panel on Climate Change's (IPCC) periodic assessments of the most current science. The most recent was the IPCC Fifth Assessment Report, published in three volumes from 2013 to 2014.

Much of the information about the potential risks and impacts of climate change for Tanzania comes from targeted research carried out by universities, in particular Sokoine University of Agriculture, and the University of Dar es Salaam.

Some key sources of weather and climate information for Tanzania

- Tanzania Meteorological Agency (TMA) – daily, 10-day and seasonal forecasts in addition to extreme weather alerts.
- World AgroMeteorological Information Service (Tanzania) – archive of previous 10-day and seasonal climate bulletins issued by TMA.
- SADC Climate Services Centre – seasonal, monthly agro-meteorological during the rainy season.
- Climate Systems Analysis Group at the University of Cape Town in South Africa – seasonal and localised projections.
- Council for Scientific and Industrial Research (CSIR) in South Africa – seasonal, El Niño forecasts.
- International Research Institute for Climate and Society at Columbia University in the United States, for seasonal, El Niño forecasts, and climate change projections for coming decades.
- Intergovernmental Panel on Climate Change Fifth Assessment Report, the United Nations' body of experts, which periodically publishes comprehensive overviews of all the current climate projections for regions across the globe.

2 TMA (online) www.wamis.org/countries/tanzania.php

WHO IS USING THIS INFORMATION, AND HOW?

Short-term weather forecasts

Government departments, non-governmental organisations (NGOs), and private sector actors use the short-term weather forecasts widely. These are also available to the general public, which means that small-scale farmers can access them, usually through radio or television. Short-term weather forecasts are particularly useful for the agriculture sector during the early rainy season to help farmers determine when they should plant their crops and apply fertilisers.

Weather information is also distributed through official channels: TMA prepares the information, and shares it with the Prime Minister's office, which in turn disseminates it to the regional and district levels. Different sectors have specific uses for this information, such as the energy sector, which requires the forecasts to manage dam releases for optimal hydropower generation.

Seasonal forecasts

The district governments that receive seasonal forecasts try to build them into their plans for the coming season. However, a major challenge has been the timing of the forecasts, which tend to arrive after they have finalised their plans. A key challenge to improving how these forecasts are incorporated into planning is ensuring that they are distributed more rapidly following their release.

Seasonal forecasts are particularly valuable to the agriculture sector, and form the foundation of the advice that extension officers provide to farmers

Seasonal forecasts are particularly valuable to the agriculture sector, and form the foundation of the advice that extension officers provide to farmers. This is particularly true at the start of the rainy season, when farmers need to decide what crops and seed varieties to plant, and when. Knowing that an El Niño event is approaching, for example, can inform farmers' choices. However, forecasts are often not reliable, which affects trust.

Besides the districts, seasonal forecasts are not spread as widely as the daily and 10-day forecasts. Among government and NGO staff there is a sense that such the longer-range forecasts are less easily available and often require a request to TMA.

Climate change projections

There is a great deal of uncertainty in the climate change projections for Tanzania, because they tend not to reflect differences between the country's diverse climate and ecological zones. Although TMA recognises the increasing importance of climate change for Tanzania, their focus is more on providing daily, 10-day and seasonal forecasts than longer-term climate projections. Efforts to raise awareness of the projections and climate change impacts tend to rest more with the research institutions. Climate change projections are therefore not routinely integrated into planning and decision-making in Tanzania.

IMPROVING WEATHER AND CLIMATE INFORMATION USE

Better weather data from around the country

The country is large, with highly remote areas that are difficult to access for a weather service that has logistical and resource challenges. Tanzania is trying to install more automatic stations that send the information to a central point, but transporting these into the field and then making them operational is expensive. Producing reliable forecasts without such observations is a challenge as it is therefore difficult to predict the effects of different weather systems on the diverse climate and ecological zones.

Making sure information arrives at the right time

Seasonal forecast information often arrives too late for it to be used in planning. District governments, for example, noted that whilst they regard this information as useful, they struggle to include it because they have already prepared their plans and activities for the season.

While seasonal forecasts and climate change projections are produced by TMA, they are not distributed automatically – instead they must be requested.

Tanzania comprises eight distinct climate zones, and their differences are currently not well represented in climate models

Having more robust climate projections

Tanzania comprises eight distinct climate zones, and their differences are currently not well represented in climate models. This introduces a great deal of uncertainty in the results. Since the country does not have many weather stations, the lack of data makes it hard to refine these models.

Understanding climate change

Another challenge is interpreting information and knowing what it means for planning in the different sectors. Those involved in planning and decision-making in different departments are not used to including long-term climate information in their planning. They often feel that climate change, as a relatively new topic on the national agenda, is not well understood and the implications can be difficult to determine from the sparse availability of technical information and data.

WHERE TO FROM HERE?

Tanzania has limited resources to address the key challenges of developing climate information, and is therefore focussing efforts on the seasonal forecasts. TMA already analyses the performance of the seasonal forecasts, in order to refine and improve them.

Some new automated monitoring stations are also being installed across the country to improve weather data collection. Projects and research being carried by the key national universities (Sokoine University of Agriculture, and the University of Dar es Salaam) and other partners, continue to support the development of enhanced climate information and insights into what this means for long-term planning.

FCFA'S UMFULA PROJECT

Project objectives

UMFULA ("river" in Zulu) is a four year research project that aims to improve climate information for decision-making in central and southern Africa, with a particular focus on Tanzania and Malawi. UMFULA is a global consortium of 15 institutions specialising in cutting edge climate science, impact modelling and socio-economic research.

UMFULA aims to support long-term – five to 40 year – planning decisions in central and southern Africa around resource use, infrastructure investment and cross-sectoral growth priorities, by identifying adaptation pathways which are robust and resilient in the face of climate change and other non-climate stressors.

The team is generating new insights and more reliable information about climate processes and extreme weather events and their impacts on water, energy and agriculture. These insights will support the more effective use of climate information in national and local decision-making. See www.futureclimateafrica.org/project/umfula

The institutions involved in UMFULA are:

- Grantham Research Institute on Climate Change and the Environment (London School of Economics and Political Science)
- Kulima Integrated Development Solutions
- University of Oxford
- University of Cape Town
- Sokoine University of Agriculture
- Lilongwe University of Agriculture and Natural Resources
- University of Leeds
- Council for Scientific and Industrial Research
- University of Manchester
- University of KwaZulu-Natal
- University of Sussex
- University of Dar Es Salaam
- University of Yaoundé
- Tanzanian Meteorological Agency
- Mozambique National Institute of Meteorology

GENERAL READERS

UGANDA
COUNTRY FACTSHEET

CURRENT AND PROJECTED FUTURE CLIMATE

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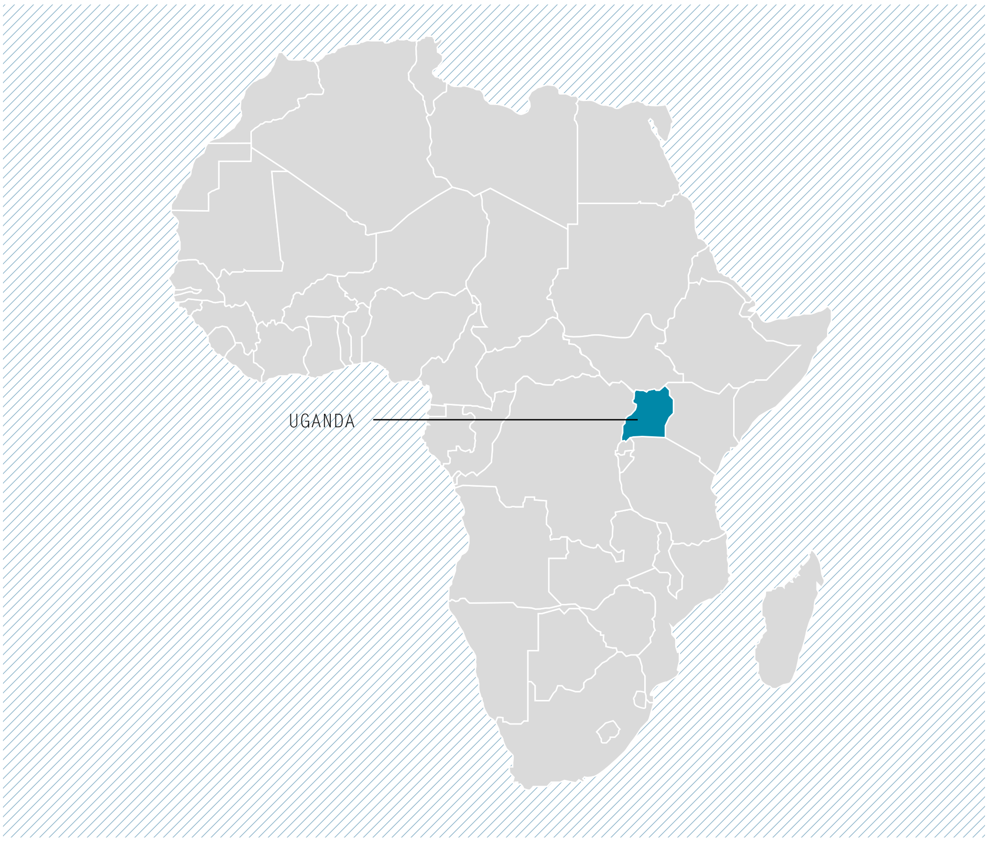


NEED TO KNOW

Stakeholders in climate-sensitive sectors in Uganda have varying levels of understanding about climate change and related issues. They therefore need climate information that is produced, packaged, and delivered in a way that meets their various needs, so that they can make decisions on appropriate responses to climate change. This is particularly important when it comes to plans, investments, policies and actions. This factsheet outlines:

- The country's 'natural' climate, and how this appears to be changing.
- How the climate is anticipated to change, outlining the likely increases in temperature, but noting the uncertainty with regards to changes in future rainfall patterns.
- The likely impacts for climate-sensitive sectors, including water, energy, agriculture, fisheries and health.

UGANDA AT A GLANCE

Uganda is a landlocked country located on the east African plateau and lying within the Nile Basin. The country has a unique and wide ranging topography that includes large bodies of water and mountain ranges. Elevation ranges from 620m above sea level in the Nile Valley, to 5,110m at the peak of Mount Rwenzori.

THE CURRENT CLIMATE OF UGANDA

Topography, prevailing winds and lakes cause large differences in rainfall patterns across the country

Uganda lies within a relatively humid equatorial climate zone. Topography, prevailing winds and lakes cause large differences in rainfall patterns across the country (Figure 1). Changes in sea surface temperatures in the distant tropical Pacific, Indian and, to a lesser extent, Atlantic Oceans strongly influence annual rainfall amounts and timing. Rainfall occurs in a significantly varied manner across the country, over two main seasons (March to May, and October to December) in three quarters of the country, and over one season (March to October) towards the north and north-east.

The south-western and north-eastern parts of the country are generally drier. Annual mean rainfall ranges from 400 to 2200mm and averages 1,180mm per year. Annual mean temperature ranges between 16°C and 31°C, with mean daily temperature averages of 28°C. Temperature can be below 0°C in the mountain ranges.[1]

HISTORIC TRENDS IN UGANDA'S CLIMATE

Historic trends show that the climate is changing in Uganda. Average annual temperatures increased noticeably by 1.3°C between 1960 and 2010, with the largest increase occurring

1 Ministry of Water and Environment, 2014. Uganda Second National Communication to the United Nations Framework Convention on Climate Change.

during January and February. The frequency of hot days[2] in the country increased significantly (by 20%) between 1960 and 2003, while the frequency of cold days decreased across all months, except December, January and February.[3]

There do not appear to be any clear changes in annual rainfall trends across the whole country over the past 60 years. A modest decline has however been detected in some northern districts e.g. Gulu, Kitgum, and Kotido.[4] A significant decreasing trend, at the rate of 6mm per month per decade, occurred during March to May.[5, 6] Trends in extreme rainfall conditions are mixed, and complicated by a lack of data. There is, however, a significant discernible trend in the changes in heavy rainfall events.[7] Droughts are on the rise in Uganda. The western, northern and north-eastern regions have, over the past 20 years, been experiencing more frequent and longer-lasting droughts than have been seen historically. For example, between 1991 and 2000, there were seven meteorological droughts in the Karamoja region. Droughts also occurred in 2001, 2002, 2005, 2008 and 2011.[8, 9]

FUTURE PROJECTIONS OF CLIMATE CHANGE FOR UGANDA

Temperature: a clear signal for increase

Some projections suggest an increase of up to 1.5°C as early as 2030

The evolution of future climates in Uganda will depend on the global growth path, i.e. whether the world follows a high or low emissions pathway. The warming trend is projected to continue in Uganda, with some projections suggesting an increase of up to 1.5°C as early as 2030. Similarly, temperatures could rise between 0.9°C and 3.3°C by the 2060s (Table 1).

Rainfall: much less certainty

Predicting regional rainfall changes in the tropics is a major challenge for climate scientists, and rainfall projections are therefore more uncertain. On average, the projections for Uganda show a slight increase in mean rainfall. However, some models project an increase (of as much as 43%), and others a decrease (16%, according to one model), and therefore there is no robust indication of direction and magnitude of change in rainfall by the 2060s (see Table 1).

There is significant variability across months (some months indicate increases in rainfall, and others indicate decreases). However, rainfall is consistently projected to increase in December, January and February, a commonly dry season across the country. Most of the increase in rainfall is projected for the western shores of Lake Victoria and the Mount Elgon region in the central west, and to the zone extending from Mount Rwenzori to the southern parts of Lake Kioga.[10] However, such projections should not simply be taken at face value as

2 The daily maximum temperature (TX) which is exceeded on the 10% warmest of days in the standard climate period (1970–99).

3 McSweeney, C., M. New, and G. Lizcano, 2010. UNDP Country Climate Profiles: Uganda. UNDP. Available from: http://countryprofiles.geog.ox.ac.uk/UNDP_reports/Uganda/Uganda.hires.report.pdf

4 Netherlands Commission for Environmental Assessment, 2015.

5 McSweeney et al., 2010.

6 USAID, 2015. Climate Change Information Fact Sheet: UGANDA. USAID, Washington D.C.

7 McSweeney et al., 2010.

8 Ministry of Water and Environment, 2007.

9 UNDP, 2013. Climate Risk Management for Sustainable Crop Production in Uganda: Rakai and Kapchorwa Districts. United Nations Development Programme (UNDP), Bureau for Crisis Prevention and Recovery (BCPR). New York.

10 Ministry of Water and Environment, 2014. Uganda Second National Communication to the United Nations Framework Convention on Climate Change.

predicting regional changes in rainfall is very challenging and models may not incorporate all relevant natural forces shaping the climate here.

Extreme events

Extreme events (floods, droughts, heatwaves, and so on) are expected to change and in most cases increase into the future. Annually, the 'hot' days are projected to occur in 15% to 43% of the days by 2060s. Although projections are uncertain, there are suggestions from some models of a 14% increase in heavy rain events by the 2060s (Table 1). Owing to increasing heavy rain events, runoff is projected to increase; the Upper Nile Basin region of Uganda could possibly see an increase in runoff as early as the 2030s.[11, 12]

Table 1: Future climate change projections for Uganda (2060s), across the different seasons.[13] The light blue blocks indicate increases, the dark blue indicate decreases. Min, Med and Max represent the minimum, median, and maximum values of the data range.

		Annual			January to February			March to May			June to September			October to December		
		Min	Med	Max	Min	Med	Max	Min	Med	Max	Min	Med	Max	Min	Med	Max
Temperature (°C)	High	1.9	2.5	3.1	1.5	2.3	3.3	1.8	2.5	2.9	2.0	2.6	3.2	1.8	2.2	3.1
	low	1.0	1.8	2.2	1.0	1.5	2.3	1.1	1.7	2.2	0.9	1.9	2.4	0.9	1.6	2.1
Hot days % Frequency	High	19	29	43	23	32	62	19	35	50	31	45	58	17	29	52
	low	16	22	30	17	29	32	15	27	34	20	33	43	16	23	38
Rainfall (%)	High	-2	6	21	-16	5	42	-10	7	19	-8	0	43	-4	7	21
	low	-5	4	13	-12	4	34	-9	3	21	-12	1	21	-8	5	11
Heavy rain events (%)	High	1	4	8	-6	4	12	0	3	8	-1	2	14	0	5	9
	low	0	3	5	-1	2	9	0	3	6	-5	1	8	0	2	6

11 Niang, I., O. C. Ruppel, M.A. Abdrabo, A. Essel, C. Lennard, J. Padgham, and P. Urquhart, 2014. Africa. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working GroupII to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V. R., C. B. Field,D. J. Dokken, M.D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma.

12 USAID, 2015. Climate Change Information Fact Sheet: UGANDA. USAID, Washington D.C.

13 McSweeney, C., M. New, and G. Lizcano, 2010. UNDP Country Climate Profiles: Uganda. UNDP. Available from: http://countryprofiles.geog.ox.ac.uk/UNDP_reports/Uganda/Uganda.hires.report.pdf

IMPACTS OF CLIMATE CHANGE IN UGANDA

Climate is a strong determinant of the state and sustainability of natural resources from which the basis of socio-economic development in Uganda is formed. Vital sectors where natural resources are strongly linked include agriculture, fisheries, water, and energy. Other sectors, such as health, are significantly climate-sensitive despite not being linked to natural resources. Table 2 shows the impacts and mechanisms by which climate change will affect these sectors.

Table 2: Impacts of climate change on various sectors in Uganda

Sector	Projected Impact	Mechanism
Water	Flooding	Increased intense rainfall events and possibly higher rainfall will increase risk of flooding, loss of life, property and infrastructure
	Water scarcity	Higher temperatures, with more variability in rainfall may lead to drought stress, higher demands for water, conflict, and biodiversity loss
Agriculture	Change in crop yields	More intense rainfall, soil erosion, high temperatures, and droughts could cause loss in yields; changes in average rainfall may increase or decrease yields
	Livestock changes	Increased droughts could cause losses in livestock; increased rainfall could expand areas suitable for livestock
	Fisheries	High temperatures and changes in water levels can cause reduced spawning
Health	Water borne diseases	Diseases such as diarrhea and cholera are likely to increase with increased rainfall intensity and flooding, largely affecting areas with poor sanitation
	Malnutrition	Reduced food options from low rainfall, high temperatures, and extreme events associated food crop losses will result in malnutrition and famine
	Malaria	Higher temperatures may result in an extension of malaria into higher altitude regions
Energy	Biomass loss	Increased temperatures will increase the risk of forest fires; reduced livelihood options will exert more pressure on forest products
	Hydro capacity	Reduced rainfall would lead to changes in lake levels and river flows

WATER

Conservative estimates suggest that the cost of unmet water demand by 2050 could be in the magnitude of $5.5 billion, with the largest losses expected in the Lake Victoria, Albert Nile, and Lake Kyoga watersheds. In the past, annual economic losses from droughts have been up to $237 million.[14] Similarly, future droughts will likely have significant negative effects on water supply in Uganda.

ENERGY

The majority of energy supply in Uganda comes from traditional biomass sources. It is expected that climate change will have negative impacts on biomass, estimated at a reduction of up to 10% in wood biomass between 2020 and 2050, thereby placing additional stress on traditional energy sources. A huge deficit between energy supply and demand is expected by the 2050s. Additional energy sources, such as liquified petroleum gas (LPG) will need to be explored, and these may require additional capital investments of $5 to $11 billion to meet demand.[15] Hydropower contributes the largest source of installed electricity capacity (84%), and could be affected by declining lake levels and river flows.

AGRICULTURE

Agriculture in Uganda employed about 66% of the working population in 2009/10, and contributed about 22% to total GDP in 2012

Agriculture in Uganda employed about 66% of the working population in 2009/10, and contributed about 22% to total GDP in 2012.[16] Climate change will have significant effects on this sector. It could see a reduction in the national production of food crops such as cassava, maize, millet and groundnuts by 2050.

Overall losses of food crops by the 2050s could reach up to US$1.5 billion. Major export crops like coffee and tea could also see a reduction in yields leading to combined economic losses of about US$1.4 billion in the 2050s.[17] Fishing provides a source of livelihood for up to 1.2 million people, and employs about 8% of the total labour force.[18] Climate change is likely to stress fisheries, resulting in disrupted livelihoods and significant economic losses.

HEALTH

Uganda is prone to climate-sensitive diseases such as malaria, cholera, and dysentery. Malaria continues to be the most fatal disease, and accounts for up to 50% of outpatient visits. Future climate change could cause the incidence of malaria to rise in high altitude areas where prevalence is presently lower.[19, 20, 21] Extreme weather events have historically had significant

14 Taylor T., A. Markandya, P. Droogers, and A. Rugumayo, 2014. Economic Assessment of the Impacts of Climate Change in Uganda Data Water Sector Report. Water Sector Report. CDKN.

15 Markandya, C. Cabot-Venton, and O. Beucher, 2015. Economic assessment of the impacts of climate change in Uganda: Key results. Climate Change Department, Ministry of Water and Environment, Uganda.

16 Uganda Bureau of Statistics, 2013.

17 Markandya, A. et al., 2015.

18 Uganda Bureau of Statistics Statistics , 2013. Statistical Abstract. Uganda Bureau of Statistics. Kampala.

19 Ministry of Water and Environment, 2010. Climate Change: A current and future threat to the socio–economic development of Uganda. Policy Brief No.1/2010. Climate Change Unit.

20 Ministry of Water and Environment, 2014. Uganda Second National Communication to the United Nations Framework Convention on Climate Change.

21 M. J. Bouma, and M. Pascual, 2011. Epidemic malaria and warmer temperatures in recent decades in an east African highland. Proceedings of the Royal Society B: Biological Sciences, 278(1712), 1661–1669.

effects on the health sector, through injuries, deaths, food insecurities, and malnutrition. Increases in such extreme events will therefore increase the burden on the health sector.

CLIMATE INFORMATION USE

Stakeholders in climate sensitive sectors have varying levels of understanding about climate change and related information. Yet, they need to make decisions on appropriate responses (actions, plans, investments, polices, and so on) to climate change. As such, there is a need to ensure that climate information is produced, packaged and delivered to meet the varying needs of stakeholders in climate sensitive sectors in Uganda. This is especially true for the water, energy, agriculture, fisheries, and health sectors.

There are barriers to the use of climate information in Uganda. These include a lack of technologies and the capacity to utilise them appropriately, lack of weather and climate monitoring infrastructure, limited technical capacities in climate modelling and forecasting, inconsistent messaging from various organisations in the climate and development space, and a lack of data, amongst others. As such, Uganda's 'national adaptation programmes of action' (NAPA) identifies the need to develop systems for climate change-related information to inform practice and decision-making processes in the country as a vital component of the country's climate change response.[22]

Efforts have already been underway to improve information use in various sectors. The Climate Change Adaptation and ICT (CHAI) project, for example, improved climate information delivery and use through the use of information and communication technologies (ICT), such as mobile phones, to provide adaptation information to users in the agricultural sector here.

The ICT-based system used information from 46 local market outlets, daily weather data from 22 weather stations in target districts, interactive radio, mobile phones, and community meetings for information dissemination. The system provided localised seasonal weather forecasts and agricultural information, weekly livestock and crop market information, guidance on low cost rainwater harvesting techniques, and timely information on drought and flood coping mechanisms. This information reached over 100,000 people in three languages and three districts, enabling farmers to take appropriate response actions.[23]

22 Ministry of Water and Environment, 2007. Climate Change: Uganda National Adaptation Programme of Actions, Department of Meteorology, Government of Uganda.

23 Gebru B., and E. Mworozi, 2015. Improved access to climate information reduces crop loss and damage in Uganda. IDRC, Canada.

FCFA'S HYCRISTAL PROJECT

Project objectives

Availability of water is fundamental for development in east Africa. However, this vital resource is already under stress from land degradation, pollution and overfishing. Climate change adds to these problems, greatly increasing the vulnerability of the poorest people in the region.

Climate projections show a warming trend in east Africa in the decades ahead, but changes in rainfall and weather extremes are currently uncertain. HyCRISTAL will tackle current uncertainties which exist around climate change projections for the region, concentrating in particular on what they mean for the availability and management of water.

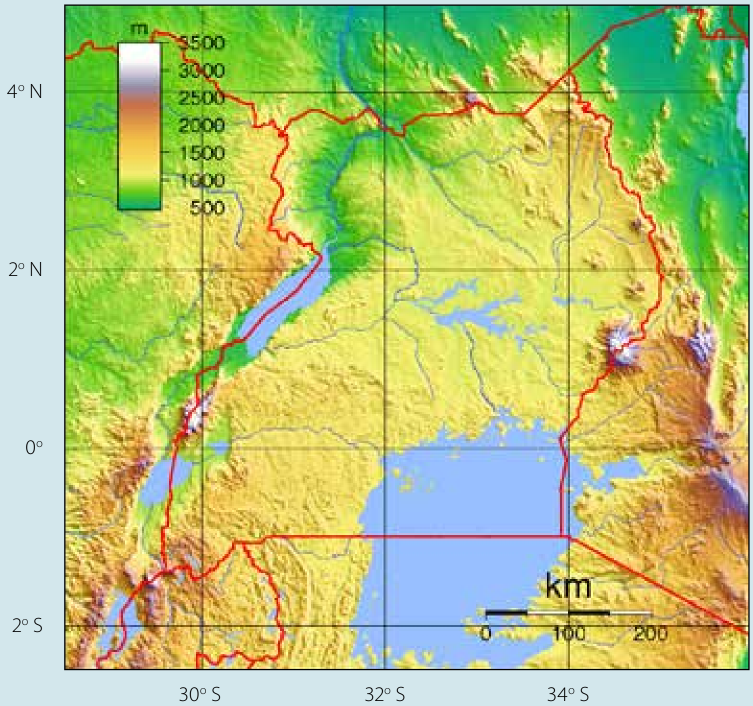
HyCRISTAL will develop new understanding of climate change and its impacts in east Africa, working with the region's decision-makers to manage water for a more climate-resilient future. See www.futureclimateafrica.org/project/hycristal/

The institutions involved in HyCRISTAL are:

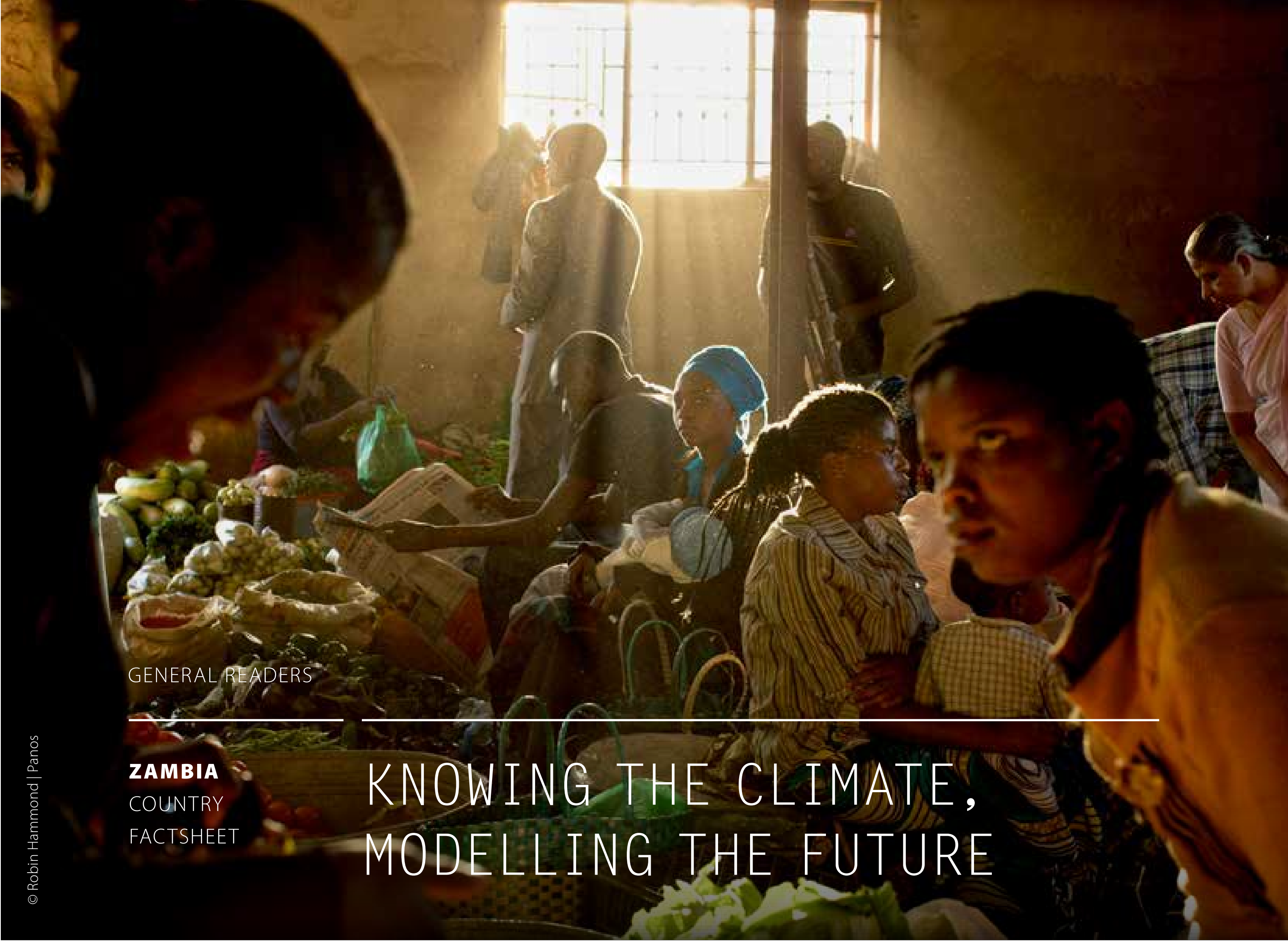
- University of Leeds
- African Centre for Technology Studies
- British Geological Survey
- Centre for Ecology and Hydrology (UK)
- Evidence for Development
- Jomo Kenyatta University
- Loughborough University
- Met Office (UK)
- National Centre for Atmospheric Science (UK)
- National Fisheries Resources Research Institute (Uganda)
- North Carolina State University
- Practical Action
- Stony Brook University
- Tanzanian Meteorological Agency
- Ugandan National Meteorological Authority
- Ugandan Ministry of Water Resources
- University of Connecticut
- Makerere University
- Maseno University
- Walker Institute
- University of Reading (Africa Climate Exchange)

FIGURES

Figure 1[24]
Topography of Uganda



24 https://commons.wikimedia.org/wiki/File:Uganda_Topography.png

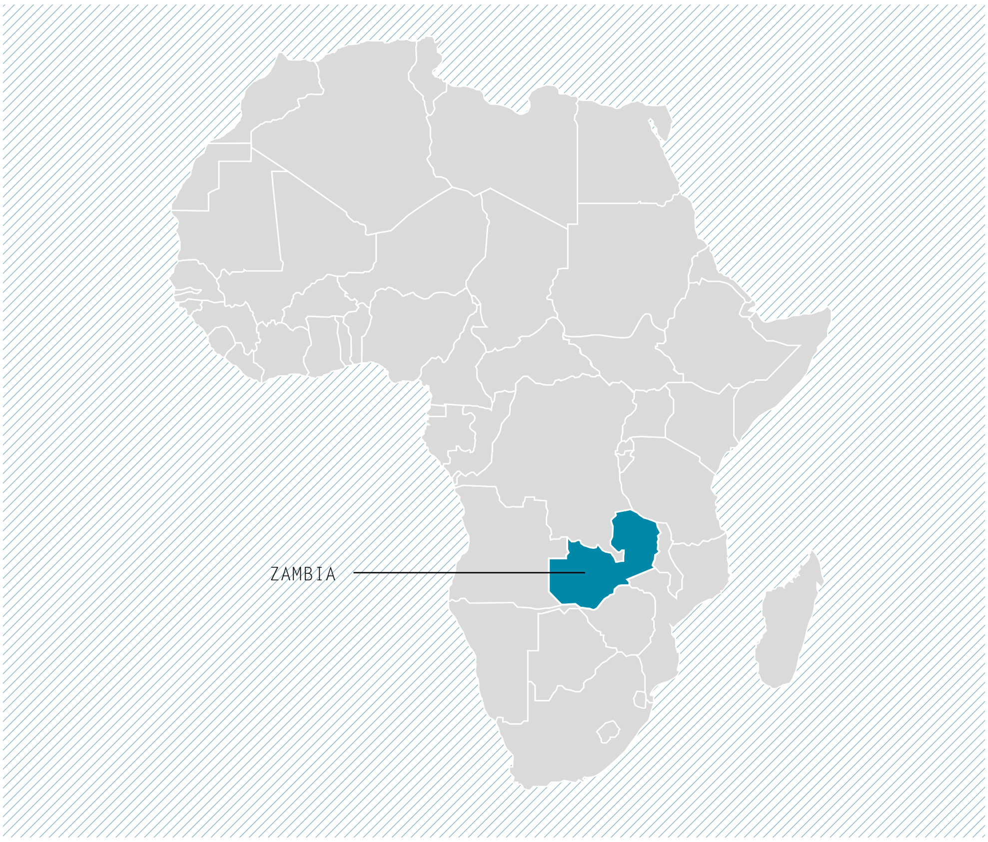


GENERAL READERS

ZAMBIA
COUNTRY
FACTSHEET

KNOWING THE CLIMATE, MODELLING THE FUTURE

AUTHORS
Chris Jack, Piotr Wolski, Izidine Pinto, Victor Indasi



NEED TO KNOW

Climate change will impact significantly on Zambia's water supplies, which will cascade through the energy and agricultural sectors, and impact the entire economy. Climate scientists hope to provide Zambian decision-makers with information that can help them plan appropriately for this uncertain future. This research considers:

- how sensitive Zambia's water system is to disruption by rising temperatures and changing rainfall patterns
- how the climate system across the region works
- the strengths and weaknesses of the current climate models, in terms of projecting future changes to the system.

OVERVIEW

Zambia is critically dependent on water and sound water management practices

Zambia is a country of rivers, wetlands, rich wildlife, and mineral reserves. The map below illustrates how the country is dominated by the Zambezi River and its catchments. Almost 100% of its electricity is produced by hydroelectric sources[1], most notably the Kariba hydroelectric scheme. Similarly, local food production is dependent on the river for irrigation. Zambia is critically dependent on water and sound water management practices.

WATER: KEY TO THE ECONOMY

One of the most pressing climate-related issues for Zambia is water supply to the nation's capital city, Lusaka. Lusaka currently sources around 50% of its water through pumps and a pipeline from the Kafue River, 60km south of the city. The remaining 50% is sourced from an array of around 90 well points across the broader city. Both the Kafue pipeline pumps and the borehole pumps require large amounts of electrical power to operate. As a result there is a strong relationship between power supply stability and water supply for the city.

The recent drought conditions combined with other factors have resulted in the Kariba hydropower scheme's reducing its output significantly, with subsequent regular power cuts across Zambia, including Lusaka. This has, in turn, limited pumping capacity, resulting in water shortages across the city.

While the current drought will pass, growing urban population and water demand will increasingly stress existing water supply capacity, even without amplification of these stresses due to climate change. Current plans and infrastructure development are focused largely on upgrading the Kafue-Lusaka water supply through new pipelines and upgraded pumping. However, these plans may need to be influenced by constraints imposed by future needs of multiple water users including farming, energy generation, and environment.

Expanding the groundwater well-fields remains another option if water quality concerns resulting from industrial contamination of the groundwater can be managed. In fact, recent shortages in municipal water supply have already caused expansion of the system of private boreholes tapping groundwater under the city. As it is largely uncontrolled, it creates the

1 www.iea.org/countries/non-membercountries/zambia

potential for resource over-exploitation, pollution, and problems of a social nature related to equity of access.

However, regardless of water sources, energy supply to support pumping and treatment is a key issue. This expands our focus beyond Lusaka and the Kafue to the Kariba Dam, but also to the region as a whole and the southern African Power Pool (SAPP). Will the Grand Inga project in the Congo significantly alter the regional power landscape? How will climate impact on other regional power supplies such as ESKOM in South Africa, and Cahora Bassa in Mozambique?

CLIMATE DATA OVERVIEW

For many stations, publicly available records end in the late 1990s or early 2000s, which limits analysis of recent variability and trends

The Zambian Meteorological Department (ZMD) is the primary weather observing institution in Zambia. ZMD manages a network of 37 weather stations across the country, which is supplemented by other networks operated by institutions such as the Zambian Electricity Supply Corporation (ZESCO), and new initiatives such as the southern African Science Service Centre for Climate Change and Adaptive Land Use (SASSCAL). Some of this data is available to researchers through global station data archives such as the Global Historical Climatology Network. However, for many stations, publicly available records end in the late 1990s or early 2000s, which limits analysis of recent variability and trends. Figure 2 below shows the number of observing stations contributing to one of the blended satellite-station rainfall datasets for Zambia, and shows a rapid decline over the past 40 years. Considering the fairly wide ranging climate across Zambia, a sample of less than 20 stations is far from adequate to accurately describe its climate.

The ZMD does continue to archive more complete data, and these data can be made available as a service offered by ZMD.

As a result of the lack of primary observed data for Zambia, much of the work on historical climate trends and variability analysis is dependent on merged satellite and re-analysis data products (please see *Southern Africa: tools for observing and modelling climate* fact sheet). The analyses of these datasets indicate the lack of strong rainfall trends, but increases in air temperature. These are set against a relatively high level of natural variability at inter-annual to multi-decadal time scales.

CLIMATE PROCESSES

Most of Zambia receives rain during November to April. The highest summer rainfall occurs in the north-east parts of the country, and gradually decreases towards the south-west. This pattern is determined by the seasonal migration of the boundaries between three distinct air streams that form within the tropical and sub-tropical circulation systems:

- the north-easterly monsoon bringing in warm and moist air from the tropical western Indian Ocean,
- the south Indian Ocean anticyclone creating a flux of cooler and less saturated air from the mid-latitude Indian Ocean,
- the inflow of cooler and less moist air from south Atlantic redirected within the equatorial westerlies.

In this complex system, rainfall over Zambia is influenced by how far southwards the air masses meet (or converge), and how much moisture is brought in from over the oceans.

These, in turn, depend on the sea surface temperatures, and the configuration of high pressure systems over the oceans to the east and west of the subcontinent. They are also affected by global drivers of climate variability, such as El Niño Southern Oscillation (ENSO), and by human-caused climate change.

CLIMATE PROJECTIONS

There are two sources of climate projections for Zambia. A set of Global Climate Models (GCM), available through the CMIP5 archive, gives projections that the United Nations Intergovernmental Panel on Climate Change (IPCC) includes in its Fifth Assessment Report (AR5). The other key source is a series of 'downscaled' climate projections, which zoom in more closely on the region. The CMIP5 projections, simulations of future climate from 17 centres throughout the world, differ from each other for a number of reasons, expressing an aspect of uncertainty in projecting future climate. It is impossible to select a single 'best' model or simulation, and the ensemble simulations have to be looked at concurrently, considering the spread of the results as an expression of this uncertainty in projections and variability in climate.

Figure 3, from the IPCC AR5, gives information at a broad spatial scale. It shows that overall, the GCMs project mostly no change to drying across the broader Zambian region for the wet season (October to March). However, it is only the drier subset of models (left column) which show drying that is more than naturally observed in the past. The middle and 'wetter' subset of models (middle and right column) show almost no real change, and no changes greater than natural observed variability.

Figures such as those in Figure 4 are traditionally used to present climate projections, but do not easily convey the distinction between the robust and the uncertain aspects of these projections. Scientists are thus developing alternative approaches that provide a better overview of future conditions. For example, Figure 4 illustrates rainfall projections for the region of Lusaka from a number of models, where the projected rainfall is tracked through time, and the strong departures from the natural (recent) levels are highlighted. The majority of projections stay within conditions similar to these observed in the past, and only a few indicate consistently drier conditions, with rainfall reduced by 15% to 20%.

Figure 5 shows how air temperatures for Lusaka might change over time. Here we can see that temperatures are consistently projected to rise in the future, strongly exceeding the levels of natural variability, and, towards the end of 21st century, reaching 1.8°C to 3.2°C above the recent levels.

GCM projections, as presented above, provide a broad overview of future climate, and do not allow for differentiating various local influences that may be relevant from water resources and development planning perspective. Such information can be obtained from downscaled projections, however.

Dynamically downscaled projections are being generated through the Coordinated Regional Climate Downscaling Experiment (CORDEX). Unfortunately, at this stage, few simulations are available, which do not allow for scientists to paint a defensible picture about the future climate emerging from this set of models. The results, however, concur broadly with the GCM-based projections for the region. The work continues, and it is expected that in near future, CORDEX data will lead to an improvement of our understanding of future climate in southern Africa and in Zambia.

Statistically downscaled projections are available through the University of Cape Town (UCT) Climate Information Platform (CIP: http://cip.csag.uct.ac.za). The plots in Figure 6 and Figure 7 below show statistically downscaled projected changes per month for the 2040 to 2060 period for Lusaka. These results paint a similar picture to that created by GCM projections, in terms of rainfall totals, i.e. that some drying or no change in the future is expected. However, they also indicate that these rainfall totals will be delivered in less frequent events resulting in longer dry spells, mostly during the already dry season but also extending into the early and late rainfall season.

ZAMBIA'S FUTURE CLIMATE

It is clear from all the various projections that temperature increases are expected. These will have significant impacts on a wide range of sectors

It is clear from all the various projections that temperature increases are expected. These will have significant impacts on a wide range of sectors including the water sector, where increased evaporation is likely to reduce runoff and infiltration, increase losses from dams and wetlands, and increase water demand for irrigation and domestic uses.

As a consequence, the moderate uncertainty around projected changes in rainfall is less important. Regardless of changes in rainfall, there will be consequences for water resources across the country.

FCFA'S FRACTAL PROJECT

Project objectives

One of the chief scientific challenges for understanding southern Africa's climate is that different models give contradictory scenarios for climate trends in the next five to 40 years. FRACTAL's team will advance scientific knowledge about regional climate responses to human activities and work with decision-makers to integrate this scientific knowledge into climate-sensitive decisions at the city-regional scale (particularly decisions relating to water, energy and food with a lifetime of five to 40 years).

The institutions involved in FRACTAL are:

- University of Cape Town
- Met Office (UK)
- Stockholm Environment Institute
- START
- ICLEI–Local Governments for Sustainability
- Swedish Meteorological and Hydrological Institute/ Sveriges Meteorologiska och Hydrologiska Institut
- Red Cross Red Crescent Climate Centre
- University of Oxford
- Aurecon
- Council for Scientific and Industrial Research
- US National Atmospheric and Space Administration
- Lawrence Berkeley National Laboratory
- European Commission Joint Research Centre
- City of Cape Town
- City of eThekwini

FIGURES

Figure 1[2]
Zambia's water resources are key to its economy and food security. This map also shows the country's climate observation network.

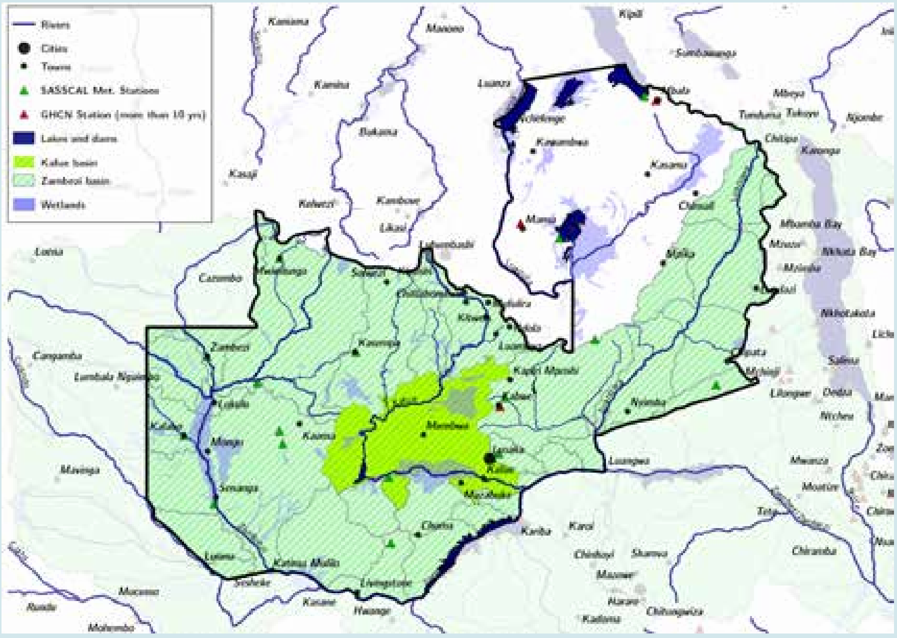


Figure 2[3]
Number of rainfall stations from Zambia, contributing in the last 35 years to global data archives used in derivation of blended satellite-station rainfall datasets.

2 Generated by the authors.
3 Generated by the authors.

Figure 3[4]
Projections of future rainfall for Africa under RCP4.5[5] emission scenarios.

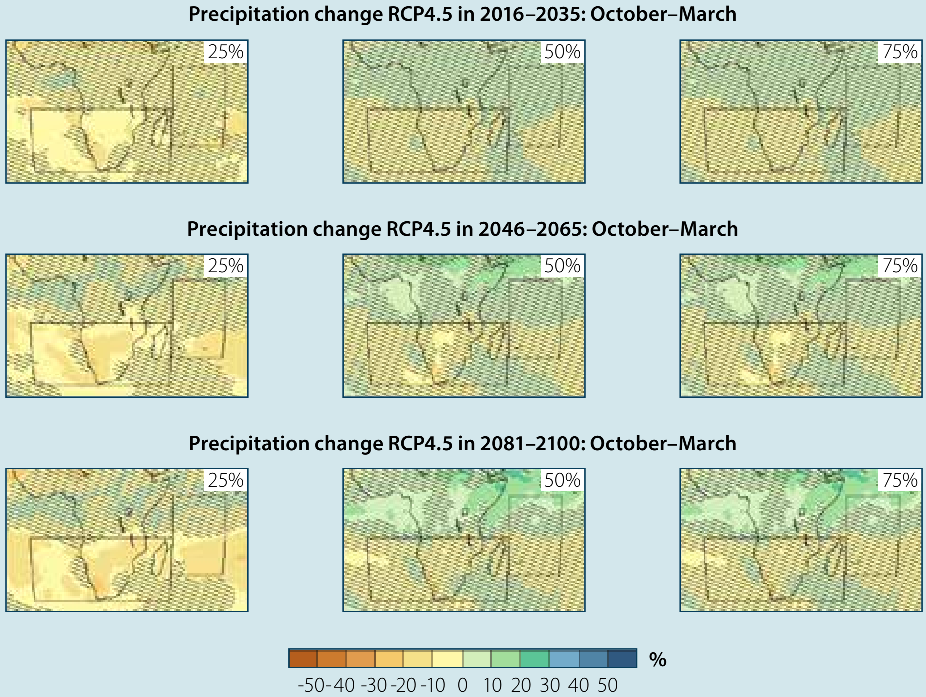
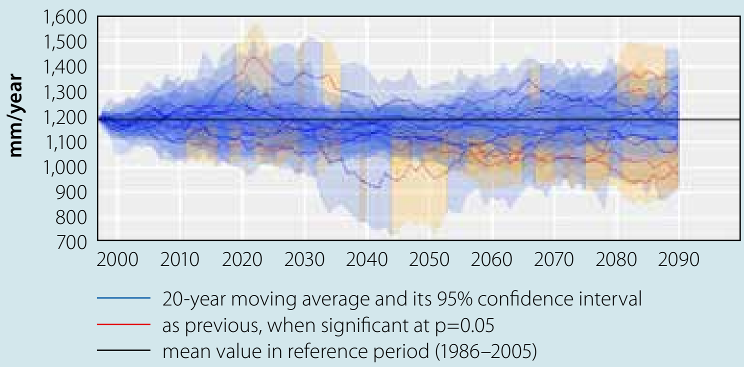


Figure 4[6]
Trajectories of total annual rainfall over Lusaka, simulated and projected by an ensemble of GCMs under RCP4.5 emission scenario.



4 IPCC, 2013: Annex I: Atlas of Global and Regional Climate Projections [van Oldenborgh, G. J., M. Collins, J. Arblaster, J. H. Christensen, J. Marotzke, S. B. Power, M. Rummukainen and T. Zhou (eds.)]. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T. F., D. Qin, G. -K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

5 Climate projections are conditional on the future level of emissions of greenhouse gases. These are reflected by a number of emission scenarios. Scenario coded RCP4.5 considers a moderate reduction of emissions in the future compared to current levels, and is perhaps a realistic mid-way between 'business as usual', and the commitments arising from the 2015 Paris Agreement achieved at the UN Conference of the Parties, COP21.

6 Generated by the authors.

Figure 5[7]

Trajectories of mean annual air temperature over Lusaka, simulated and projected by an ensemble of GCMs under RCP4.5 emission scenario. Legend as in Figure 4.

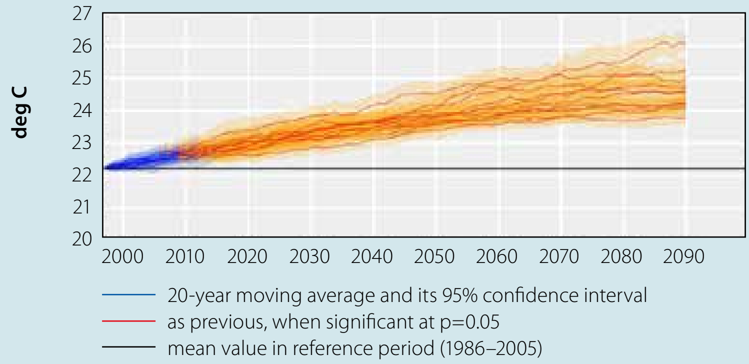


Figure 6[8]

Downscaled projections of total monthly rainfall for Lusaka.

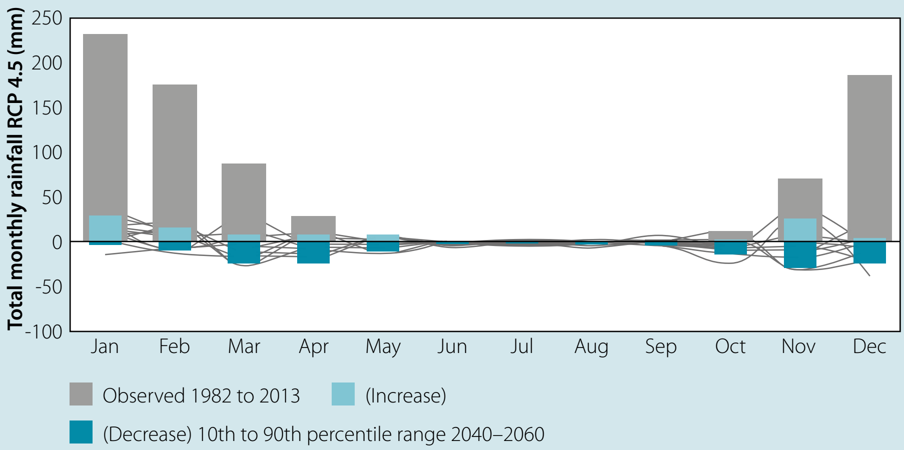
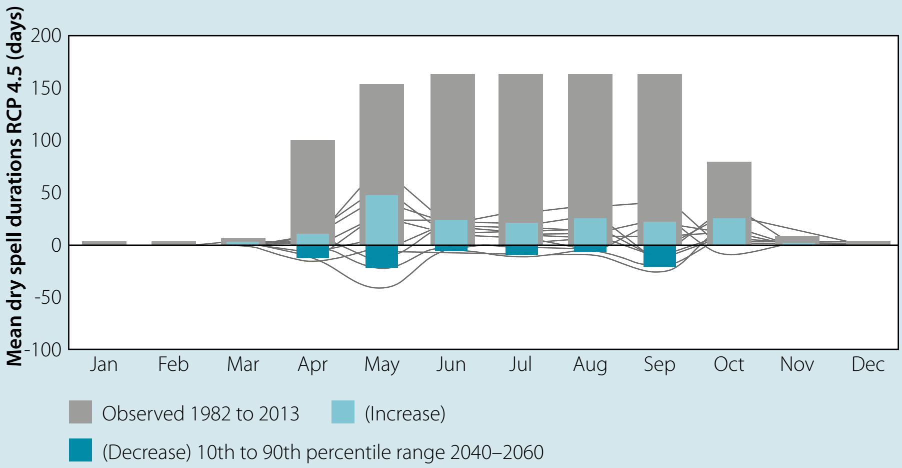


Figure 7[9]

Downscaled projections of dry spell duration for Lusaka.



7 Generated by the authors.

8 Climate information Platform, http://cip.csag.uct.ac.za/webclient2/app/

9 Climate information Platform, http://cip.csag.uct.ac.za/webclient2/app/

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