REPUBULIKA Y'U RWANDA
UBUMWE - UMURIMO - GUKUNDA IGIHUGU

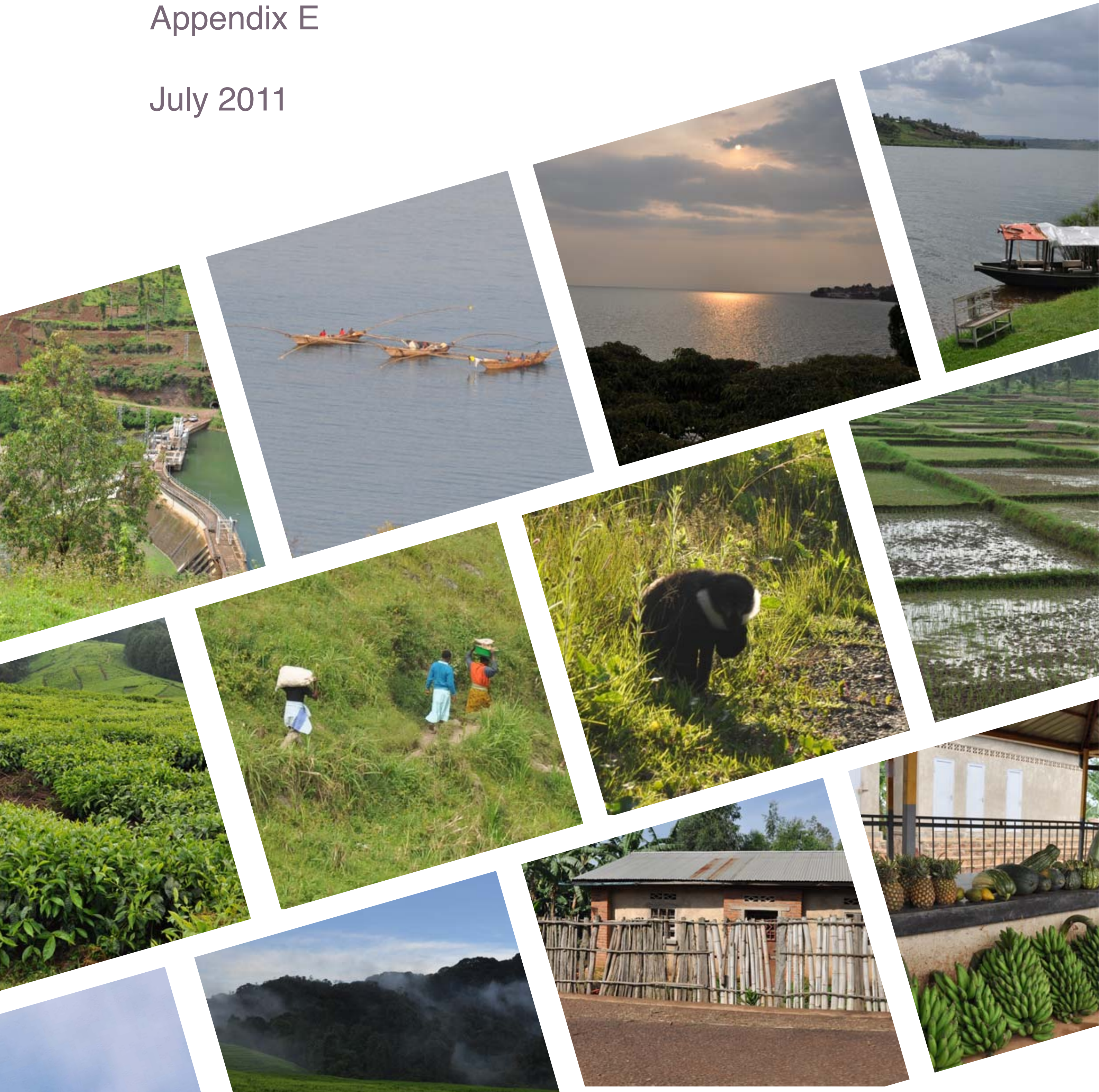
Smith School of Enterprise and the Environment

UNIVERSITY OF OXFORD

Rwanda's Climate: Observations and Projections

Appendix E

July 2011



Editor
Megan Cole
megan.cole@smithschool.ox.ac.uk

Author
Robert McSweeney
robert.mcsweeney@atkinsglobal.com

Government Counterpart
John Ntanganda Semafara
johnntaganda@yahoo.com

Expert Advisor
Dr Richard Washington

Photography by Megan Cole

This document is an output from a project funded by the UK Department for International Development (DFID) for the benefit of developing countries. However, the views expressed and information contained in it are not necessarily those of or endorsed by DFID or the members of the Climate and Development Knowledge Network, which can accept no responsibility or liability for such views, completeness or accuracy of the information or for any reliance placed on them.*

**The Climate and Development Knowledge Network ("CDKN") is funded by the Department for International Development and the Dutch Ministry of Foreign Affairs and is led and administered by PricewaterhouseCoopers LLP. PricewaterhouseCoopers LLP is assisted in the management of CDKN by an alliance of organisations comprising the Overseas Development Institute, Fundacion Futuro Latinoamericano, South-South-North, LEAD International, and INTRAC.*

Smith School of Enterprise and the Environment
University of Oxford
Hayes House
75 George Street
Oxford OX1 2BQ
United Kingdom
www.smithschool.ox.ac.uk

Executive Summary

This report presents an analysis of observed meteorological data and an assessment of climate change projections for Rwanda. The purpose of this document is to provide a summary of Rwanda's climate during the 20th century and its projected climate for the 21st. This will provide the context for the actions presented in this Strategy.

The quantity and quality of observed data for Rwanda limits the capacity to draw firm conclusions about its climate in the 20th century. Complete and reliable records are lacking for all variables, including mean temperature and precipitation. There are few temperature records extending back earlier than 1970, while precipitation data are lacking since the genocide. This highlights the importance of developing the station network in Rwanda and strengthening the data collection and verification processes.

The data available indicate that mean temperatures have increased in Rwanda over the past 40 years (0.35°C per decade), with similar increases in minimum and maximum temperatures. Rainfall records, by comparison, show no significant trend between 1931-90 (there are not sufficient data to assess the most recent past).

Projections of future climate for Rwanda indicate a trend towards a warmer, wetter climate. Increases in mean temperature are projected under all models and all emissions scenarios, while the majority of models also indicate increases in annual rainfall totals, though a few show small reductions. Rainfall totals for the two rainy seasons are projected to increase, though as with annual changes, the increases in rainfall are generally small relative to the interannual variability currently experienced in Rwanda.

Analysis of daily data for Butare specifically suggests an increase in the frequency of days that would be characterised as 'Hot' in the current climate. The projected changes to heavy rainfall events are less conclusive, with daily data for Butare showing little change for the 2050s or 2090s, whereas other published research using CMIP3 data has found increases in heavy rainfall for Rwanda. This reflects the uncertainty in projections for heavy rainfall in climate models.

Contents

Climate Data

Acronyms and Abbreviations

CMIP3	Coupled Model Intercomparison Project 3
CSAG	Climate System Analysis Group
DTR	Diurnal Temperature Range
ENSO	El Niño-Southern Oscillation
GCM	General Circulation Model
GHG	Greenhouse Gas
GtC	Gigatonnes of Carbon
IOD	Indian Ocean Dipole
ITCZ	Inter-Tropical Convergence Zone
IPCC	Intergovernmental Panel on Climate Change
JF	January-February
JJAS	June-July-August-September
MAM	March-April-May ('long rains')
OND	October-November-December ('short rains')
RCM	Regional Climate Model
RMS	Rwanda Meteorological Service
SOM	Self-Organising Maps
SRES	Special Report on Emissions Scenarios
SST	Sea Surface Temperature
WCRP	World Climate Research Programme

Introduction

This report presents the analysis of observed meteorological data held by the Rwanda Meteorological Service (RMS) and a set of climate change projections available through the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project 3 (CMIP3). The purpose of this document is to provide a summary of Rwanda's climate during the 20th century and its projected climate for the 21st. This will provide the context for the actions presented in this Strategy.

The report discusses the data used and the methods involved in the analysis, which includes a series of quality control tests that were undertaken to determine which observed records were suitable to be used. The results for observed and projected data are then presented and discussed in turn. As the most complete observed records are available for Kigali Airport, these data are examined in a specific section. The discussion of temperature and rainfall records for other stations then follows. Projections are presented for annual, seasonal and daily timescales, for three future timeslices in the 21st century.

Context

Despite being located in the tropical belt, Rwanda experiences a temperate climate as a result of its high elevation. The Albertine branch of the Rift Valley runs along the western side of Rwanda and much of the border with the Democratic Republic of Congo (DRC) is mountainous (and volcanic) with elevations over 2000m. Elevations reduce towards the central plateau (1500-2000m) of Rwanda and then again in the eastern plateau towards the border with Tanzania (<1500m). The average temperature for Rwanda is around 20°C and varies with the topography described. The warmest annual average temperatures are found in the eastern

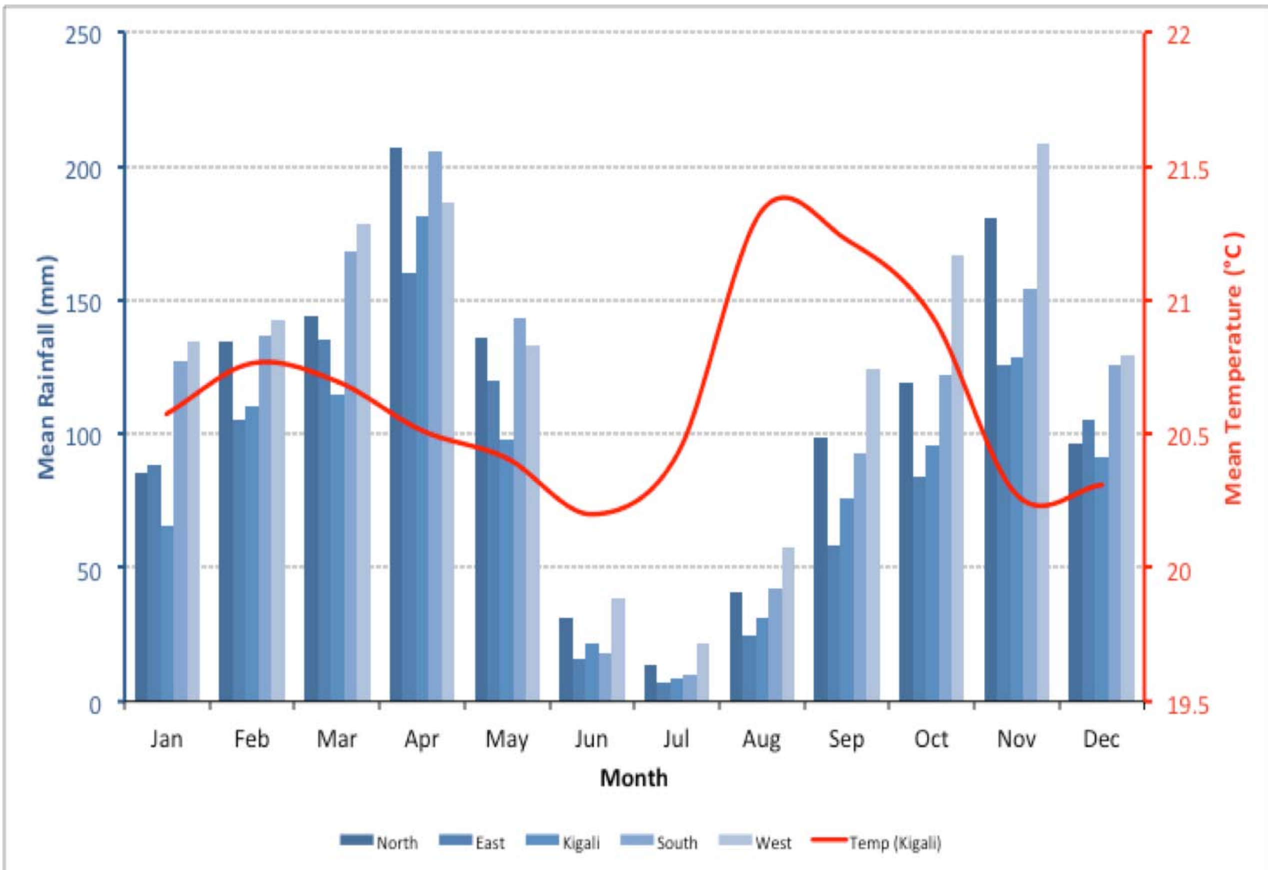


Figure 1: Monthly average rainfall for each region in Rwanda and monthly average temperature for Kigali Aero (1961-90). Stations used: Rulindo (North), Kibungo (East), Kigali Aero (Kigali), Kibeho (South) and Mugonero (West).

plateau (20-21°C) and Imbo and Bugarama Valleys (23-24°C), and cooler temperatures in higher elevations of the central plateau (17.5-19°C) and highlands (<17°C) (Malesu et al., 2010). Temperatures vary little through the year (see Figure 1).

Rwanda experiences a bimodal pattern of rainfall, which is driven primarily by the progression of the Inter-Tropical Convergence Zone (ITCZ). The ITCZ is point where the northern and southern trade winds converge; it is characterised by a belt of low pressure and rainfall (Godwin, 2005). The ITCZ migrates from southern to northern Tropics and back through the course of the calendar year; the 'long rains' occur over March, April and May (MAM) as the ITCZ moves north and the 'short rains' of October, November and December (OND) occur on its return south. Approximately a third of annual rainfall falls in each of these seasons (see Figure 1). The OND rainy season is generally associated with a greater interannual variability as the migration of the ITCZ tends to be more swift on its return south (Camberlin & Philippon, 2002; McGregor & Nieuwolt, 1998).

Figure 2 shows how annual rainfall varies across the country, with the highest totals in western Rwanda (>1200mm) and then diminishing towards the East (<900mm).

The ITCZ is primarily an oceanic system and will lie over the warmest areas of surface water, whereas over land its position is affected by topography of the land mass and by large water bodies such as Lake Victoria (Marchant et al., 2006). Rainfall anomalies in eastern Africa have been linked to the influence of ocean-atmosphere climate phenomena ENSO (El Niño-Southern Oscillation) and the IOD (Indian Ocean Dipole). Warm ENSO events ('El Niño') are characterised by a build up of warm sea surface temperatures (SSTs) in the eastern Pacific Ocean, which brings associated increases in rainfall to the western coast of South America. These events have been linked with impacts beyond those countries around the Pacific Ocean, including high rainfall anomalies in East Africa – particularly for the short rains (Mutai & Ward, 2000; Nicholson & Kim, 1997). The IOD is a relatively recent discovery (it was identified in Saji et al., 1999) and a positive event is characterised by

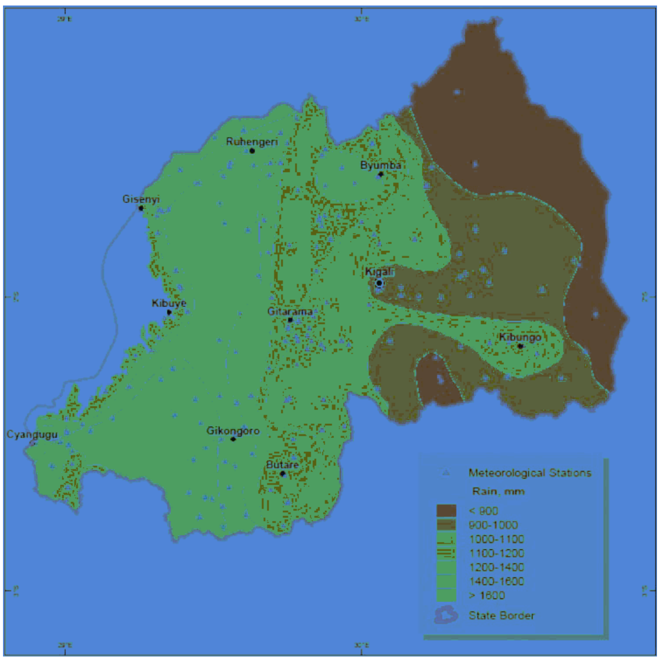


Figure 2: Distribution of rainfall across Rwanda, with annual average total figure
Source: Malesu et al., 2010

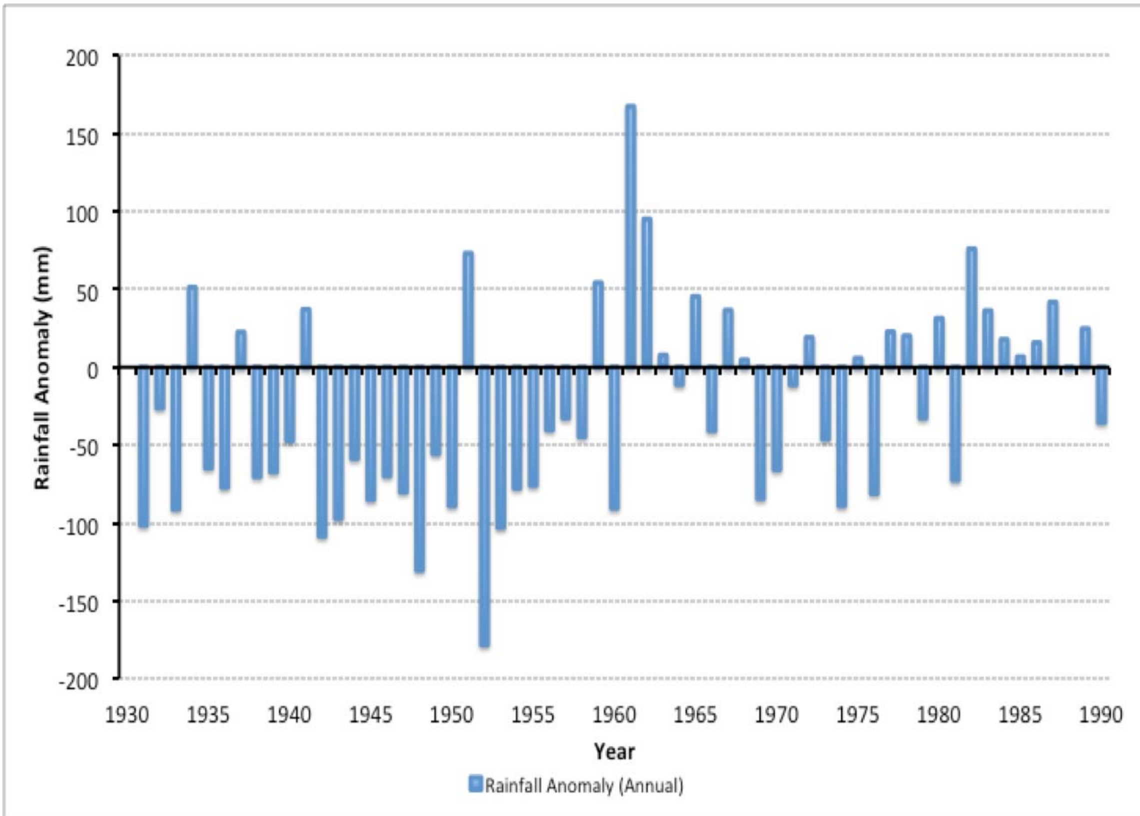


Figure 3: OND rainfall anomaly for Rwanda average (1931-90 against a baseline of 1961-90); from 26 stations. Note high rainfall of 1961, coinciding with positive IOD event.

warmer SSTs in the western equatorial Indian Ocean off the coast of East Africa, and a corresponding drop in SSTs in the southeastern Indian Ocean. Like warm ENSO events, positive IOD events are thought to cause anomalously high rainfall in East Africa (Black, 2005; Saji & Yamagata, 2003). Whether the IOD is an independent phenomenon or is linked to ENSO is still debated (see Marchant et al. (2006) for a full discussion). Many of the El Niño events that have corresponded with high rainfall in East Africa have coincided with positive IOD events (e.g. 1963, 1972, 1982 and 1997), while high rainfall anomalies in East Africa have been recorded when positive IOD events have occurred independently of ENSO (Black, 2005). Most notably, this includes the second strongest positive IOD event of the 20th century, which occurred in 1961; the very high Rwandan rainfall in the short rains of this year can be seen in Figure 3.

It should be noted that climate models struggle to recreate the conditions of these climate phenomena; as a result, understanding of how they will be affected by climate change is limited. An assessment of the IOD under climate change with six General Circulation Models (GCMs), for example, gave conflicting results of the projected trend for the 21st century; 3 models indicated an increasing trend of positive events during the late rains, 2 models a decreasing trend and one model showing no change (Conway et al., 2007).

Observations

3.1 Data

The observed data was made available from the RMS databank; it consists of monthly station data of differing lengths and completeness of record. The data included cover the following meteorological variables:

- Precipitation
- Mean Temperature
- Average Maximum Temperature
- Average Minimum Temperature
- Relative Humidity
- Average Maximum Humidity
- Average Minimum Humidity
- Atmospheric Pressure
- Vapour Pressure
- Evaporation (pan)
- Evaporation (from the shade)
- Sunshine Duration

The number of stations and the completeness of the data records vary substantially between the variables; for some, such as sunshine duration, the record from the station at Kigali Airport is the only

Table 1: Decadal totals of start/finish dates of rainfall records

Decade	First record (no. of stations)	Last record (no. of stations)
1900s	1	0
1910s	2	0
1920s	15	0
1930s	24	0
1940s	6	0
1950s	13	1
1960s	34	1
1970s	49	5
1980s	29	16
1990s	5	100
2000s	6	10
2010s	3	54 (i.e. still recording)

Table 2: Summary of record lengths and completeness by variable

Variable	No. of records	Average % complete	Record length (years)			
			<10	1 Oct 2020	20-30	>30
Precipitation	187	85%	38	44	44	61
Mean Temp	65	72%	32	15	11	7
Max Temp	66	76%	31	12	15	8
Min Temp	71	75%	33	19	8	11
Rel Hum	16	66%	10	2	2	2
Max Hum	15	65%	9	2	2	2
Min Hum	15	65%	9	2	2	2
Atmos P	6	76%	1	1	2	2
Vapour P	14	66%	9	1	2	2
Evap (pan)	13	37%	9	2	1	1
Evap (shade)	16	51%	11	1	2	2
Sunshine Hrs	10	55%	7	2	0	1

record of note. There are substantially more station records for precipitation than any other of the meteorological variables. Many of the stations were set up in the 1920s and 1930s and the majority were added in the 1960s and 1970s; however, of the 187 stations included here, recording of data ended in the 1990s for 100 of them (see Table 1). Therefore, though there are a many stations recording data through the middle of the 20th century, many of those (and of the stations set up in the latter 20th century) were lost during the genocide. The result is that the more complete records of precipitation end in 1990s and there is a lack of data to assess more recent changes.

The locations of the meteorological stations are shown on the map in Figure 2, with comparatively fewer stations in eastern Rwanda than central and western areas. However, it should be noted that this figure shows all stations and doesn't discern which of those are still operational.

3.2 Quality Control

Before any of the data were used in the analysis they were first subject to several quality control tests. Firstly, in order to identify trends in each variable it is necessary to use data records of sufficient length, typically a minimum of 30-years in climate analyses. The majority of station records are substantially shorter than 30 years and this limits the number that is suitable for analysis. Table 2 shows the record lengths for each variable; with the exception of precipitation, there is a notable shortage of records of at least 30 years. In addition, the percentage completeness was considered (also included in Table 2); there are many instances where the records are incomplete, with missing months or years from the record.

An additional issue with precipitation records is encountered when summing monthly records into seasonal and annual totals. Where monthly data are missing in any year or season, a total value will be

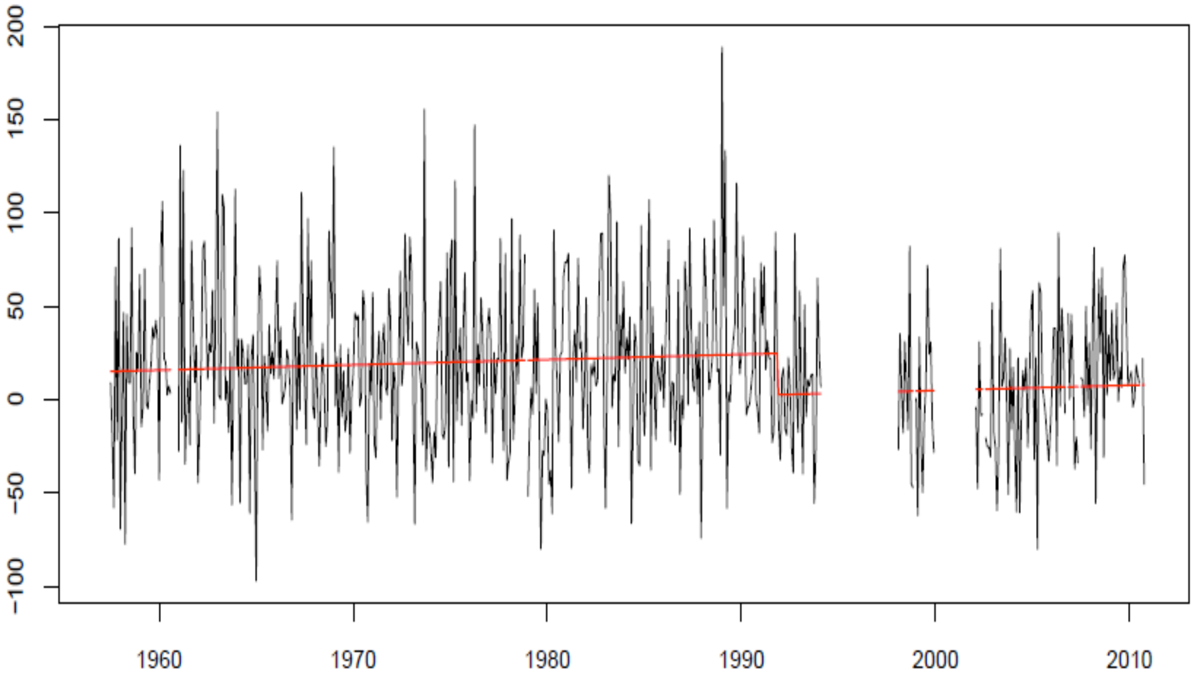


Figure 4: Example output from RHtestV3; identified changepoint in November 1991 (precipitation anomalies for Kamembe Airport).

lower than it would otherwise be, thus potentially affecting identification of a trend. Therefore, where monthly data are missing in an annual and seasonal record, that entire year or season is excluded from the analysis.

For the records of sufficient lengths and completeness it was then necessary to assess those records for homogeneity, to ensure that any variations in the records are the result of changes in climate rather than, say, changes to the station or how the data are collected. The homogeneity of the records was assessed using the RHtestV3 regression software, which analyses monthly (or daily) data and identifies step-changes in the record (Wang, 2008; Wang, 2003). An example of a step-change is shown in Figure 4. Identified step-changes may be actual changes in climate (e.g. El Niño events), in which case they can be identified in neighbouring records. However, there is little consistency between the step-changes found in the records analysed here and where step-changes are not found to be related to climatic events, the record is discounted and not used in the analysis.

3.3 Methods

Analysis of the meteorological records was undertaken using the Excel-based tool 'MAKESENS' (MAnn-KEndall test for trend and SEN'S slope estimates – Salmi et al. (2002)). The software combines two tests; the first is a nonparametric Sen's method for identifying the magnitude of any trend (Sen, 1968) and the second is a nonparametric Mann-Kendall test to identify the significance of any trend.

The software detects trends in annual values, so monthly values were either summed or averaged (as appropriate for the variable) to give an annual value. Where seasons are assessed, monthly data were summed or averaged into four seasons for the analysis: the two rainy seasons of March-April-May (MAM) and October-November-December (OND) and two dry seasons of January-February (JF) and June to September (JJAS).

For generating trends across a number of stations for a region or the country as a whole, the method followed the approach of Aguilar et al. (2009), which requires calculating anomalies at each station and then averaging anomalies across all stations of interest. No adjustment was made for periods or regions where more or fewer stations have data available, but it should be noted that only the station at Kigali Airport has records during the genocide. The stations were subjected to the same checks for homogeneity as those described earlier and those with unexplained changepoints were excluded. To be included in the analysis, a minimum threshold of 20 years was set for the number of complete years within the 30-year base period. The subsequent area-averaged time series were then assessed for trends and their significance using the MAKESENS software as described above.

It should be noted that all as the data are monthly rather than daily, it is not possible to ascertain information on changes in heavy rainfall events or the specific timing of the start and end of the rainy seasons (though it is possible to assess changes in seasonal totals with the monthly data available).

3.4 Results

The following section presents the results of the analysis of observed data. It should be noted that, in the text, trends in different variables are described with reference to their 'significance'; this is a statistical term that indicates the likelihood of that trend occurring by chance. Where a trend is described as 'significant' it will be followed in brackets by the level of significance (either 0.1, 0.05, 0.01 or 0.001 – i.e. the chance of that trend occurring by coincidence would be 10%, 5%, 1% or 0.1% respectively). Where a trend is not 'significant', it has a better than 10% chance of occurring by coincidence and therefore it cannot be ruled out that it happened by fluke. Where no significant trend is found, a corresponding graph will not have a trend line plotted.

3.4.1 Kigali Airport

The most complete meteorological station record for recent history is at Kigali Airport, where

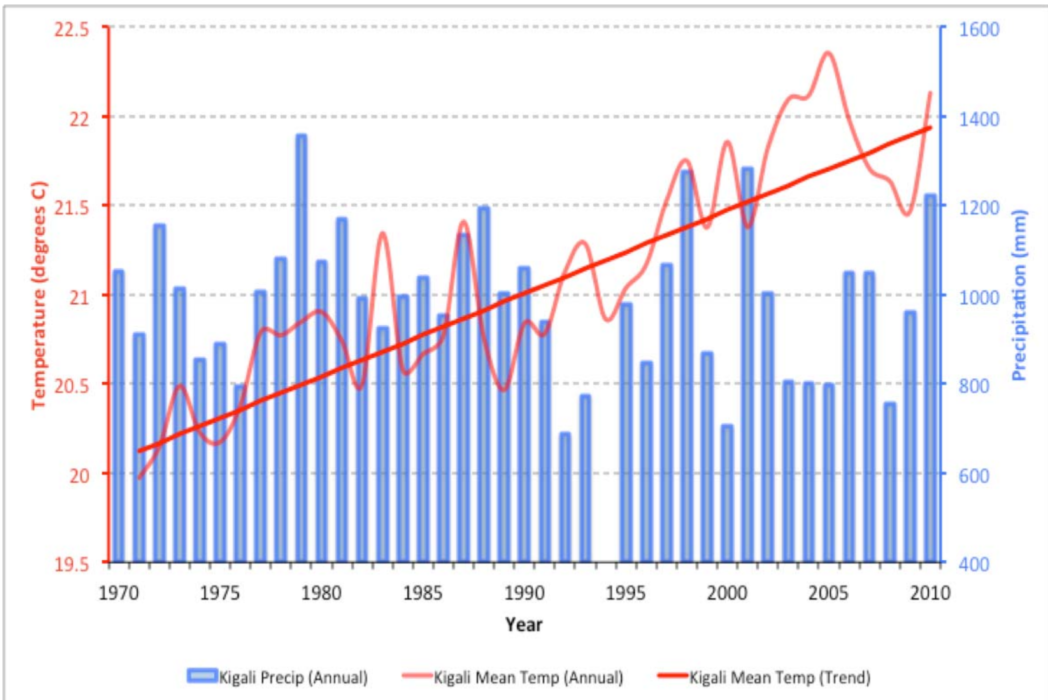


Figure 5: Annual trend in mean temperature (left-hand axis) and precipitation (right-hand axis) for Kigali Airport (1971-2010)

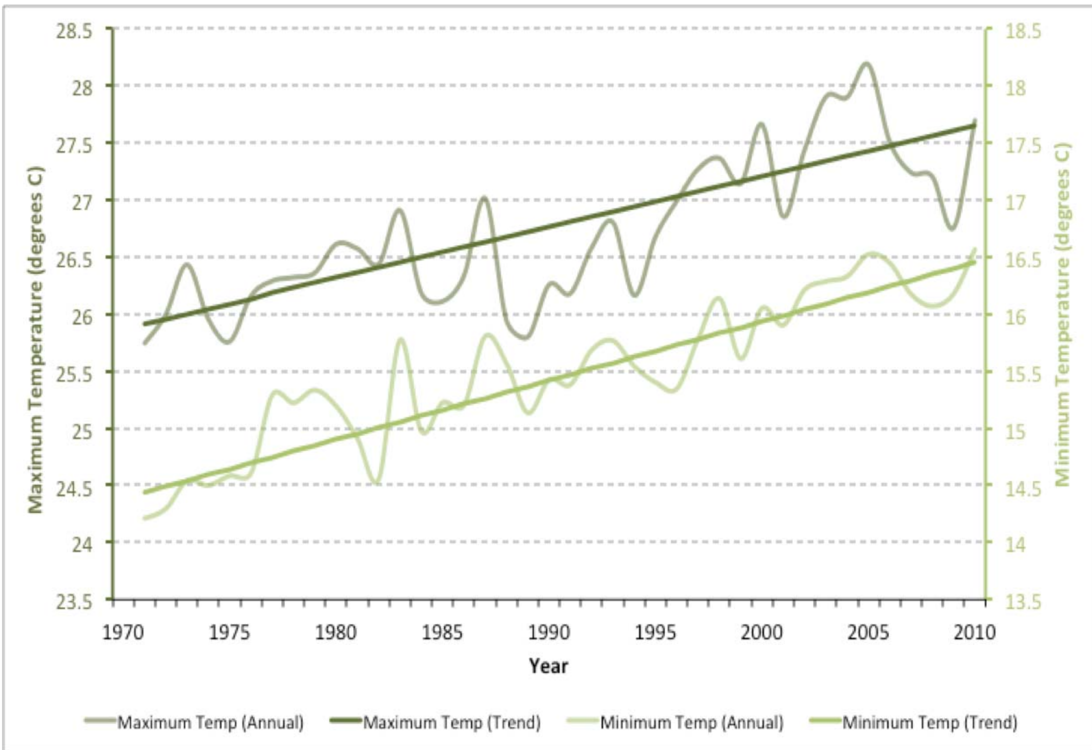


Figure 6: Annual trend in maximum temperature (left-hand axis) and minimum temperature (right-hand axis) for Kigali Airport (1971-2010)

rainfall and temperature records are available from 1964 and 1971 respectively. It is the only station for which records are available during the genocide (excluding rainfall records in 1994 from May to September, inclusive). As the results presented in this section are for one station only, they cannot be assumed to be representative of the whole of Rwanda.

Figure 5 shows annual average data and the linear trend for annual mean temperature and precipitation between 1970 and 2010. Mean temperature shows a significant increase (0.001) of almost half a degree per decade (0.47°C), taking average annual temperature towards 22°C in 2010. This trend is more rapid than the global observed average reported in the most recent IPCC report (between 0.19 and 0.32°C per decade for 1979-2005, Trenberth et al., 2007).

Rainfall, by contrast, shows a slight decrease over the same period; however, this trend is not significant. This plot also demonstrates the difference between interannual variability and long-term trend. From year-to-year temperature or rainfall may be particularly high or low, yet it is necessary to

Table 3: Increase per decade in mean and maximum temperature for each season, for Kigali Airport 1971-2010)

Season	Mean Temp	Significance	Max Temp	Significance
JF	0.57	0.001	0.50	0.001
MAM	0.42	0.001	0.42	0.001
JJAS	0.48	0.001	0.44	0.001
OND	0.45	0.001	0.41	0.001

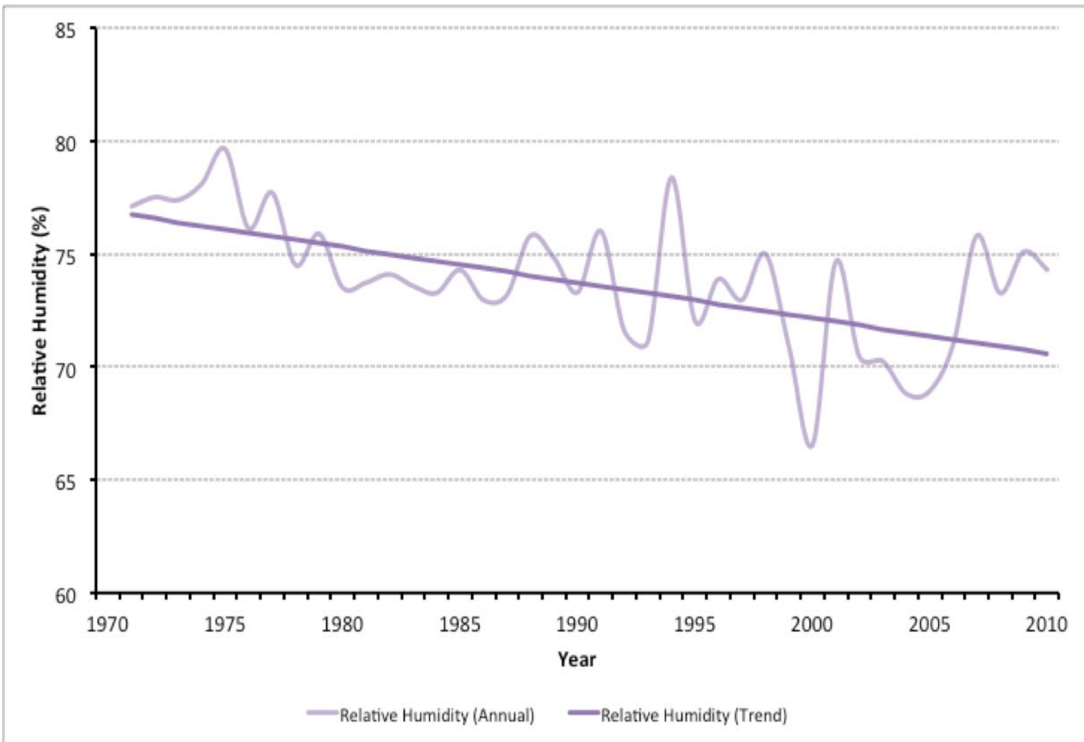


Figure 7: Annual trend in relative humidity for Kigali Airport (1971-2010)

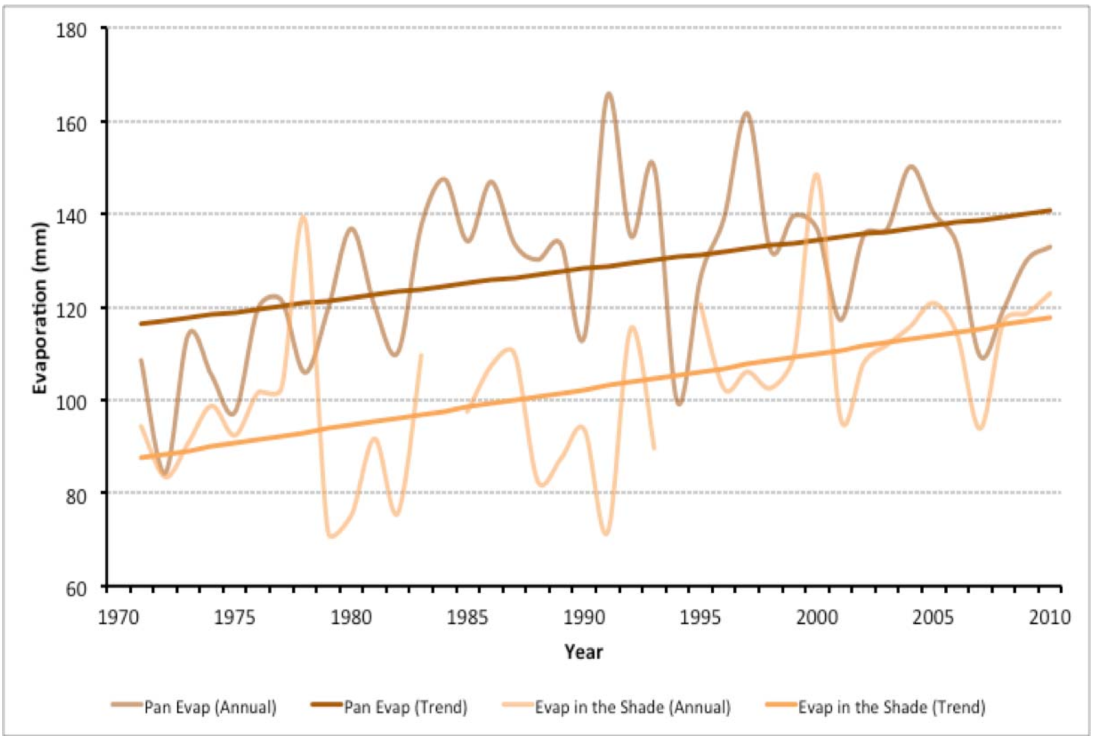


Figure 8: Annual trend in pan evaporation and evaporation in the shade for Kigali Airport (1971-2010)

consider changes in climate over a longer time period to identify any trend. Therefore, although – for example – Rwanda may experience cooler years, the trend shows a gradual increase in mean temperature. Conversely, with rainfall, though there are years where rainfall is unusually low or high, there is no significant trend in how rainfall is changing at this station since 1971.

In a similar plot, Figure 6 shows the trend in both average daily maximum and minimum temperatures. As with mean temperature, the records for maximum and minimum temperature show a significant (0.001) increase of around half a degree per decade (0.45°C and 0.52°C respectively), rising to an average of approximately 27.5°C and 16.5°C by 2010 respectively. With a larger increase in minimum temperature than maximum, this implies a reduction in diurnal temperature range (DTR). As with mean temperature, these are larger increasing trends than the global observed average, which for both maximum and minimum temperature is 0.29°C per decade over 1979-2005 (Trenberth et al., 2007). The global trend over 1950-2004 for minimum temperature was larger than that of maximum temperature, with a corresponding reduction in DTR; however, the equivalent assessment for 1979 to 2004 shows no trend in DTR globally (ibid).

Table 3 shows the increase per decade in mean and maximum temperature for the four seasons for Kigali (1971-2010), and the significance of the trends. There is no one season that dominates the annual trend in temperature increase; rather a similar increase is seen all seasons, with a largest in the JF dry season.

The equivalent analysis for precipitation across the seasons (not shown) indicates that while the small decreases identified in annual rainfall are concentrated in the two rainy seasons, no significant trends were found in any of the four seasons.

Of the records of other meteorological variables, there is no significant trend in number of hours of

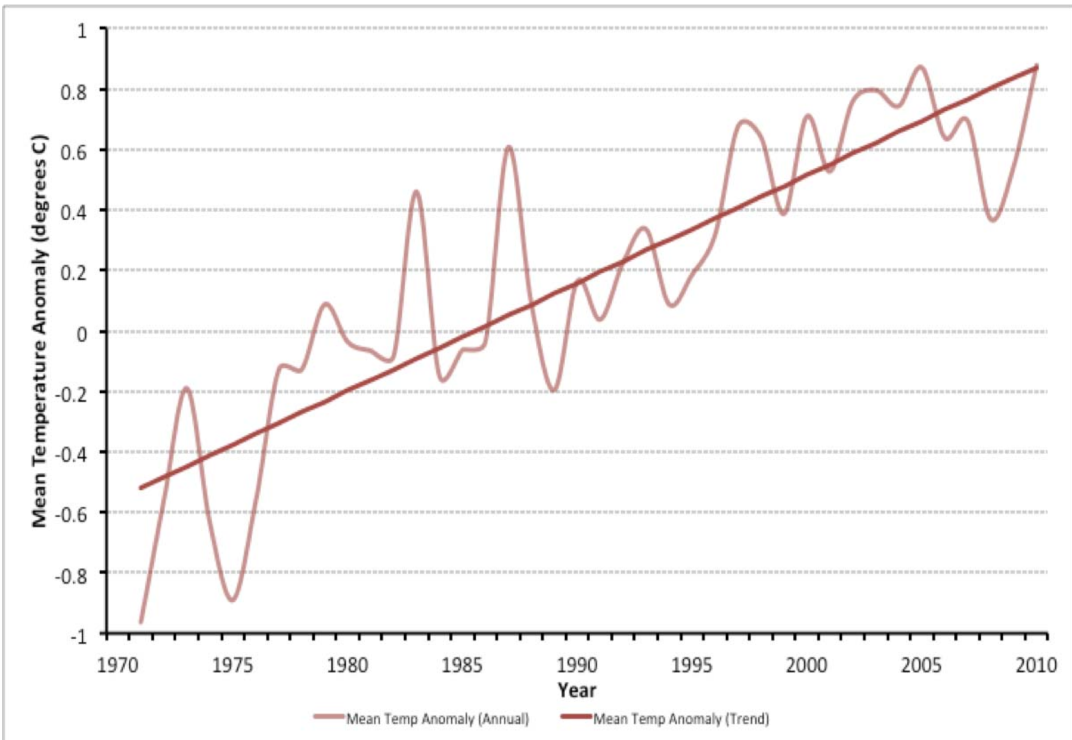


Figure 9: Annual anomaly and trend for mean temperature for Rwanda (1971-2010 against a baseline of 1971-2000); from 4 stations.

sunshine, or in atmospheric or vapour pressure. Data for relative humidity suggest a reduction over the 1971-2010 period, with a significant reduction (0.001) of just over one and a half per cent per decade (1.58%) over the period of 1971 to 2010 (see Figure 7). Associated significant decreases are also found in maximum and minimum humidity over the same period – 1.11% and 1.24% per decade respectively (at 0.001 and 0.01 respectively; graph not shown). As humidity has an (non-linear) inverse relationship with temperature, this decreasing trend is expected with the increase in temperature described earlier.

With increasing temperature and decreasing humidity, an increase in evaporation is expected, and this what the data suggest. Significant trends are found in pan evaporation (0.05) and evaporation in the shade (0.001); however, the trend in pan evaporation is relatively weak. As shown in Figure 8, both show increases over the 1971-2010 period – 6mm per decade and 8mm per decade for pan evaporation and evaporation in the shade respectively.

3.4.2 National and Regional Trends

Mean Temperature

Though the earliest temperature record for Rwanda began in 1930, there are few records that documented temperature consistently through the 20th century. Of these few, only one – Kibuye (in western Rwanda on the coast of Lake Kivu) – is homogenous and sufficiently complete to be suitable for identifying a trend. However, analysis of the 1955-93 record shows no significant trend and so no conclusions can be taken.

As described earlier, there is a stark contrast in the number of station records for temperature and rainfall, which limits the ability to create a countrywide assessment of the changes in mean temperature. Only four records are of sufficient length and are homogenous – those of Kigali, Kamembe, Gisenyi and Ruhengeri airports – however records are only available for these

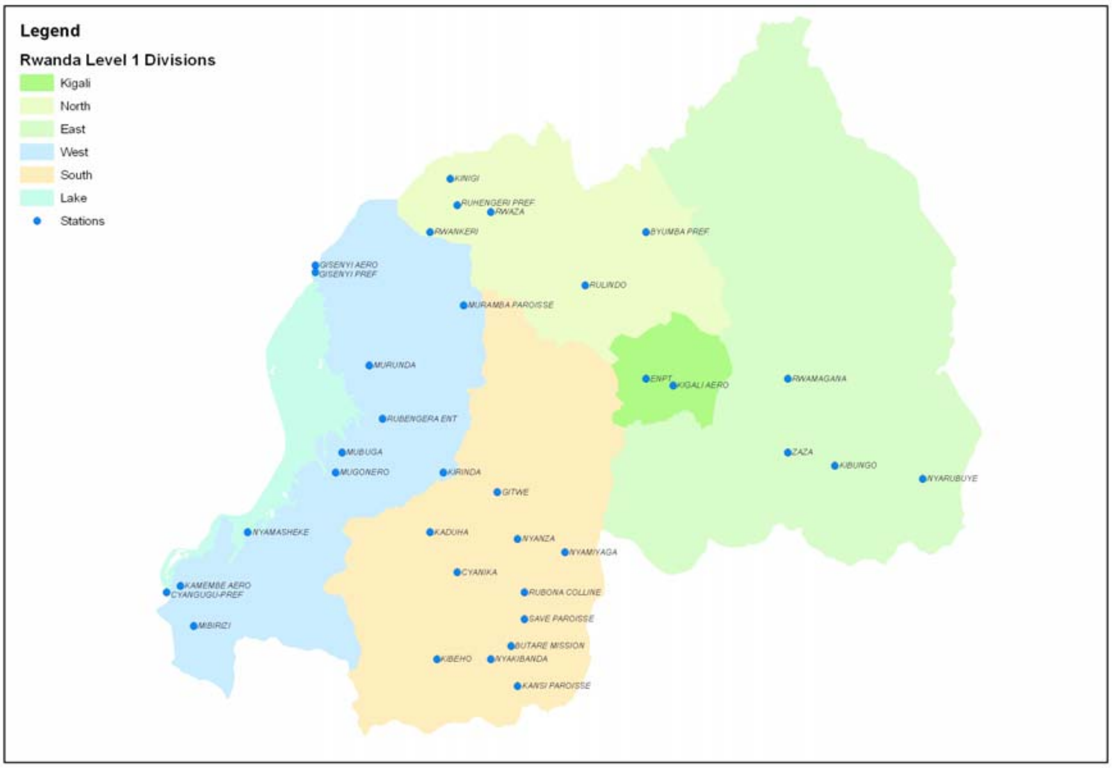


Figure 10: Map of precipitation stations used in this analysis and the regions of Rwanda

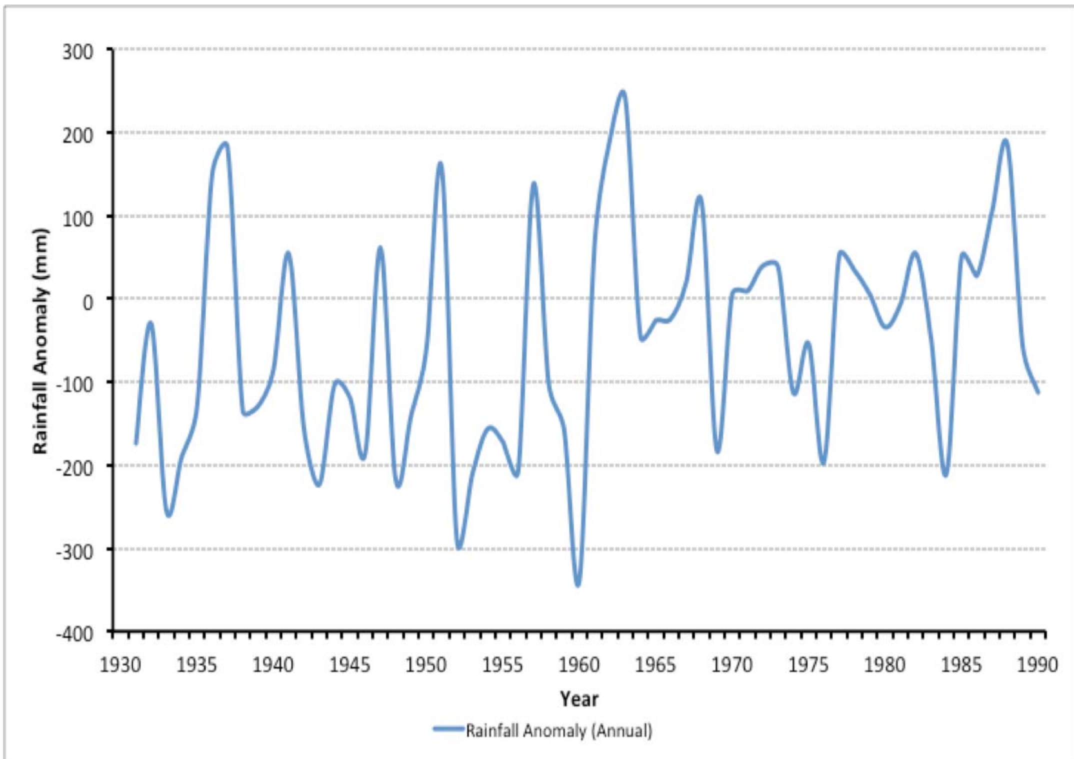


Figure 11: Annual anomaly for precipitation for Rwanda average (1931-90 against a baseline of 1961-90); from 26 stations.

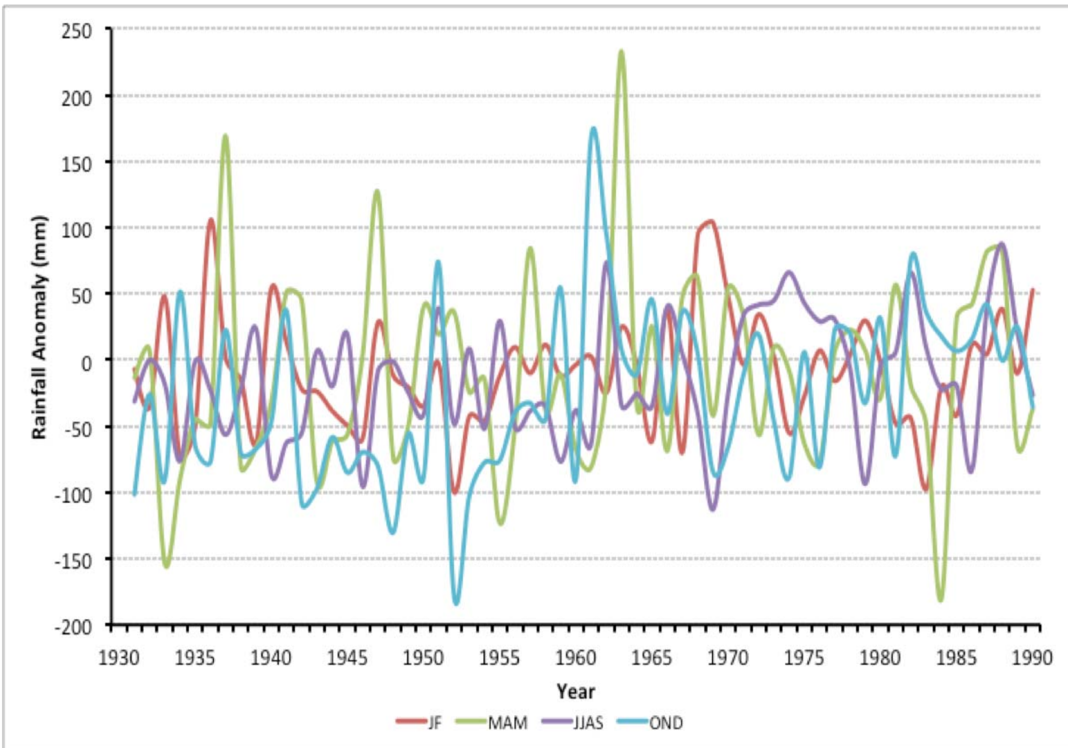


Figure 12: Seasonal anomalies for precipitation for Rwanda average (1931-90 against a baseline of 1961-90); from 26 stations.

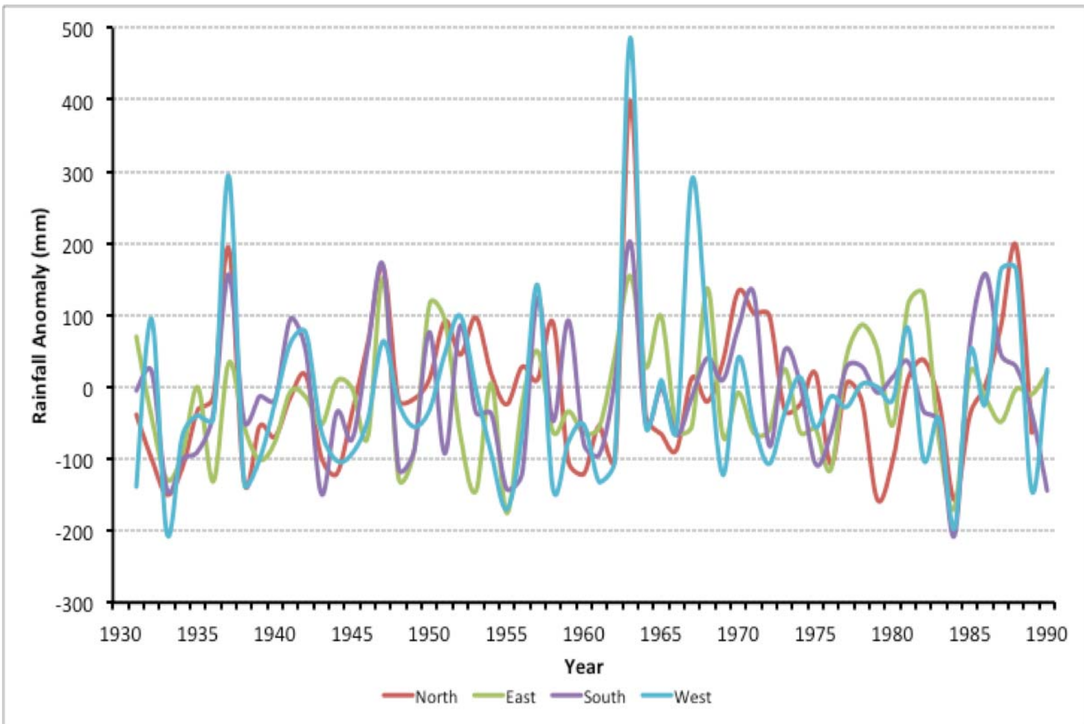


Figure 13: MAM anomalies for precipitation for regions of Rwanda average (1931-90 against a baseline of 1961-90); from 26 stations.

stations since the 1970s. Using these four stations to create a single record omits the eastern region of the country and so any conclusions should be made with caution.

An average 1971-2010 record in mean temperature anomalies was calculated using a baseline period of 1971-2000. Figure 9 shows the resulting significant (0.001) trend of an increase of 0.35°C per decade for annual data. A similar analysis of the individual seasons showed significant (0.001) increasing trends in all seasons, with the largest increase in January-February of 0.47°C per decade.

Mean Precipitation

There are a substantially greater number of records for precipitation than there are for the other variables; this allows trends in rainfall to be assessed for the regions of Rwanda as well as a national view. Figure 10 shows the stations that were used in developing national and regional trends in precipitation.

Unfortunately, there are few records that continue beyond the mid-1990s and Kigali Airport is the only station that passes the quality control tests. This has been analysed in the earlier section, therefore the analysis presented below is for the period 1931-90.

No significant trend is found for rainfall over the period 1931-1990 (see Figure 11). The plot highlights the high interannual variability of rainfall in Rwanda, with annual rainfall anomalies of up to approximately ±25% over the 1961-90 average. Also notable in the plot is the step-change to slightly higher annual rainfall totals in the early 1960s, which reflects a similar shift identified in the levels of many lakes across East Africa (see Conway, 2002). However, it should be noted that this shift could instead reflect a change in how rainfall data were recorded or collected in Rwanda. There are no metadata available for these data that would help confirm whether this was the result of a climate shift.

On a seasonal basis, no significant trends are found; however, again the high interannual variability can be seen, predominantly for the two rainy seasons (see Figure 12). No significant trends are identified when analysed by region, although Figure 13 is included here to illustrate the differences in variability between the five regions of Rwanda. The plot shows rainfall anomalies for the MAM rainy season; the greatest variability is found in the West of Rwanda.

3.5 Discussion

The station at Kigali Airport provides the most complete record many of the meteorological variables. Analysis of these records over the past 4 decades shows an increasing temperature trend, identified in mean, minimum and maximum temperature. However, it should be noted that the trends are higher than the globally observed average, which may bring into question the quality of the data. Without equivalent data from other stations to support these findings, any conclusions made from these data should be made with caution.

Analysis of three other stations over the same period showed an increase that was closer to that of the global average. With the increases in temperature, the data from Kigali show a corresponding reduction in humidity and increase in evaporation. However, this assessment is limited to a single station and so conclusions should be made with caution. No significant trends were identified in any of the other variables, including rainfall.

For precipitation, no significant trends have been found for the period 1961-90; there are insufficient records to assess the most recent two decades of rainfall with these stations. Though no trends have been identified, the analysis has revealed a high interannual variability for rainfall across Rwanda in all regions.

Projections

4.1 Data

The data used in the projections are taken from an ensemble of 19 General Circulation Models (GCMs) from the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project 3 (CMIP3). CMIP is a programme that brings together output from GCMs from modelling centres across the world. Using a range of climate models gives an indication of the uncertainty in the projections. No single model is 'right' and to limit analysis to one or few models could yield misleading results. The CMIP3 output was used by Working Group I of the IPCC in the production of the Fourth Assessment Report (AR4).

In running the models, different scenarios or 'pathways' of future greenhouse gas (GHG) emissions are used to assess their differing impact on global climate. The IPCC developed a range of six models to describe potential development pathways of society through the 21st century, known as 'SRES scenarios' by virtue of their IPCC 'Special Report on Emission Scenarios' in which they were published (see Nakicenovic & Swart (2000) for more information). Each scenario has a pathway of GHG concentration and temperature rise associated with it. There are no probabilities associated with the SRES scenarios (there isn't a higher chance of one being correct than another), but rather they provide a set of driving forces that climate institutions can use to allow direct comparisons of their model outputs. The scenarios used for the results here are as follows (see Nakicenovic & Swart, 2000):

- A2 – used here as a 'high' emissions scenario (28.9 Gigatonnes of Carbon/year by 2100). A2 describes a world of continually increasing global population with less international cooperation than in the other scenarios. Trade and transfer of technology and information is focused on a regional, not global, level.
- A1B – used here as a 'medium' emissions scenario (13.1 GtC/year by 2100). A1B describes a world where the global population peaks mid-century and then decreases. Economic growth is rapid but with a balance of fossil fuel and renewable energy sources.
- B1– used here as a 'low' emissions scenario (5.2 GtC/year by 2100). The population growth pattern is a similar to A1B; however, B1 describes a more resource-efficient world with clean technology and an economy built around information and services rather than material use.

4.2 Methods

4.2.1 Monthly data

CMIP3 mean temperature and precipitation data were extracted from an ensemble of 19 GCMs for the grid cells covering Rwanda specifically. Monthly time series of precipitation and mean temperature were used to derive annual and seasonal changes for three SRES scenarios (A2, A1B and B1) against a baseline of 1970-99.

Changes for three future 30-year 'timeslices' were calculated, each referred to according to the decade around which it is centered: 2020s (2010-2039), 2050s (2040-2069) and 2080s (2070 – 2099). Projected changes in precipitation (in percent) were plotted against changes in mean temperature (in °C) for all three timeslices for each SRES scenario in turn.

4.2.2 Daily data

Daily maximum temperature and heavy rainfall events are assessed using the same CMIP3 data as described above, which has been downscaled for Butare in Rwanda rather than being a country average (for 9 of the 19 models in the CMIP3 ensemble).

GCMs run at a low spatial scale, simulating changes on grid cells of perhaps several hundred kilometers square, which limits the information they can produce on regional or local scales. Downscaling is the process of generating local or regional climate information from the output of a GCM. It is also used to generate data at a higher temporal scale, such as using monthly GCM output to produce daily data.

Downscaling usually follows one of two methods; 'dynamical' downscaling typically uses Regional Climate Models (RCMs), which work in a similar way to GCMs, but at a higher resolution (i.e. smaller grid cells). RCMs use output from GCMs to drive the model, and then add information on local conditions (e.g. topography) to generate projections on a higher spatial scale. 'Statistical' downscaling, in contrast, involves using observed data to develop empirical relationships between GCM output and local meteorology. It should be noted that while downscaling may add information on a regional or local scale, it does not add to the accuracy or reduce the uncertainty in the data. Downscaled data should therefore not be considered to be more reliable than GCM data.

The daily data used here was downscaled by the Climate Systems Analysis Group (CSAG) at the University of Cape Town. CSAG have developed a statistical downscaling method known as Self-Organising Maps (SOM), which uses observed daily data to downscale GCM data to the daily timestep (see Hewitson & Crane, 2006). Data were provided for maximum temperature and precipitation for two SRES scenarios – B1 ('Low') and A2 ('High') and for two 20-year future timeslices, 2046-65 (2050s) and 2081-2100 (2090), against a baseline of 1961-2000.

The maximum temperature data are used to assess the frequency of 'Hot' days. This metric refers to the daily maximum temperature that is exceeded on the highest 10% of days in that season for the baseline period (McSweeney et al., 2010). The frequency that this threshold is exceeded is then found for each season for the two future time periods.

The approach used to assess the change in heavy rainfall events follows the method presented in Osborn et al. (2000). Daily rainfall from a season is sorted into ascending order and collected into 10 classes, each accounting for 10% of the total rainfall of that season. For example, the first class ('T1') are all the days of lightest rainfall until 10% of the seasonal total is reached; the other classes are then filled in the same way, each amounting to 10% of total rainfall, up until the class of heaviest rainfall 'T10'. The number of days rainfall required to reach 10% gradually reduces from T1 through to T10. These classes are then expressed as a percentage of the total number of wet days. This distribution of rainfall is then compared between the baseline and future periods.

4.3 Results

4.3.1 Monthly data

The following graphs show the projected changes in mean annual temperature and precipitation for the 2020s, 2050s, and 2080s and for 'Low' (B1), 'Medium' (A1B) and 'High' (A2) emissions scenarios. All 19 models are plotted for each timeslice, which indicates the spread in the projections (the shaded areas are there to aid identification of this spread). The uncertainty increases as the projections extend further into the 21st century. The range of projections for annual

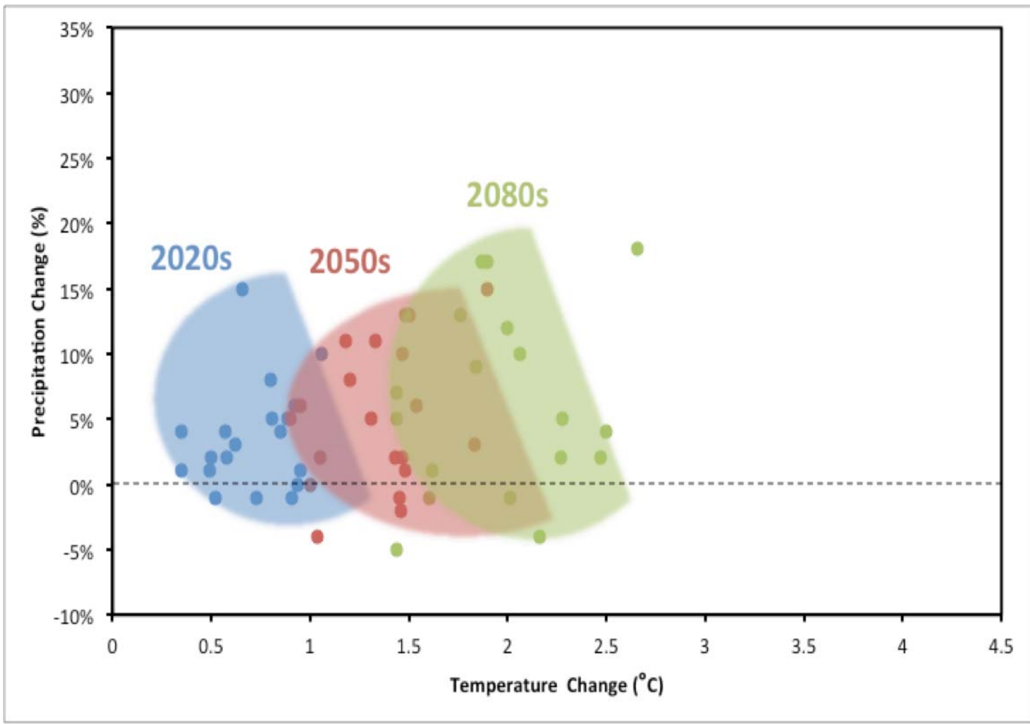


Figure 14: Projected annual change in temperature (degrees C) and precipitation (%) for Rwanda for the 2020s (blue), 2050s (red) and 2080s (green) for the B1 SRES scenario. Dots show individual GCMs; shading indicates spread of results.

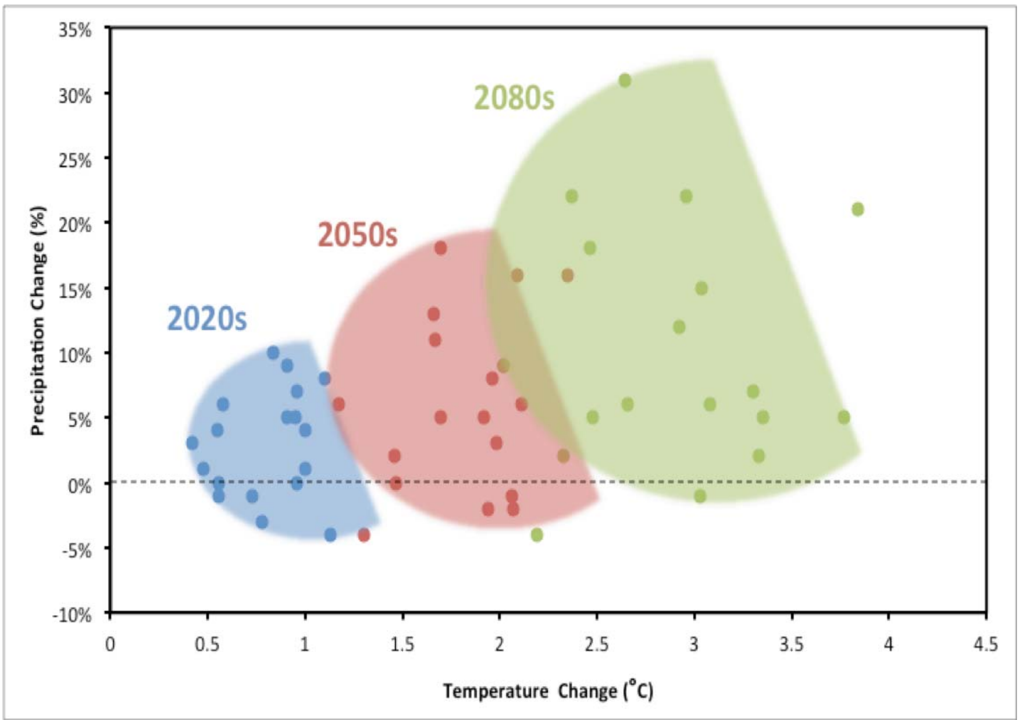


Figure 15: Projected annual change in temperature (degrees C) and precipitation (%) for Rwanda for the 2020s (blue), 2050s (red) and 2080s (green) for the A1B SRES scenario. Dots show individual GCMs; shading indicates spread of results.

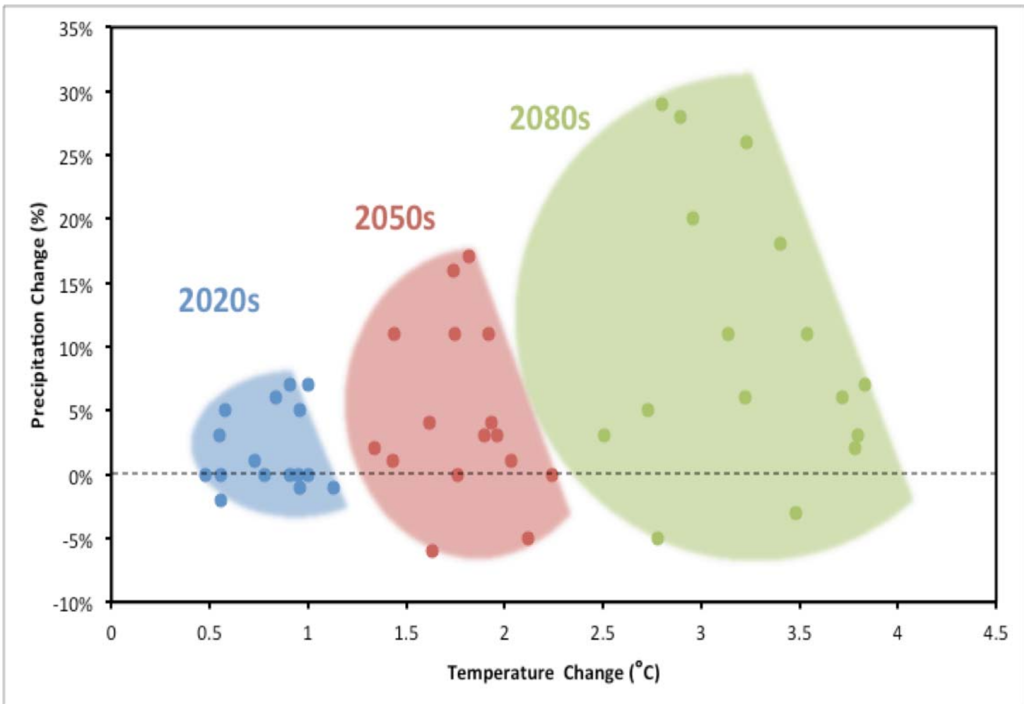


Figure 16: Projected annual change in temperature (degrees C) and precipitation (%) for Rwanda for the 2020s (blue), 2050s (red) and 2080s (green) for the A2 SRES scenario. Dots show individual GCMs; shading indicates spread of results.

changes in temperature and precipitation are summarised in Table 4. Projections show increases for temperature, and predominantly show increases for precipitation as well. Median projections of temperature show a rise of around 1°C by the 2020s, 1.5-2°C by the 2050s and 2-3°C by the 2050s. Median projections for precipitation (of up to 7% increase by the 2080s under A2) are small relative to the interannual variability currently experienced in Rwanda.

Table 4: Summary of median (minimum to maximum in brackets) projections for annual changes in rainfall and mean temperature for each SRES scenario and timeslice.

Scenario	2020s	2050s	2080s
Rainfall			
B1	+3 (-1 to +15)	+5 (-4 to +15)	+5 (-5 to +18)
A1B	+4 (-4 to +10)	+6 (-4 to +18)	+7 (-4 to +31)
A2	0 (-2 to +7)	+3 (-6 to +17)	+7 (-5 to +29)
Mean Temperature			
B1	0.7 (0.4 to 1.1)	1.4 (0.9 to 1.9)	1.9 (1.4 to 2.7)
A1B	0.9 (0.4 to 1.1)	1.9 (1.2 to 2.4)	2.9 (2.0 to 3.8)
A2	0.9 (0.5 to 1.0)	1.8 (1.3 to 2.2)	3.2 (2.5 to 3.8)

Table 5: Summary of median (minimum to maximum in brackets) projections for annual percentage changes in seasonal rainfall for MAM and OND for each SRES scenario and timeslice

	2020 (%)	2050 (%)	2080 (%)
MAM Rainfall			
B1	+2(-8 to +24)	+5 (-9 to +22)	+8 (-8 to +30)
A1B	+1 (-6 to +18)	+7 (-6 to +24)	+7 (-11 to +42)
A2	+3 (-11 to +16)	+9 (-10 to +19)	+12 (-8 to +40)
OND Rainfall			
B1	+3 (-3 to +9)	+4 (-4 to +12)	+6 (-5 to +23)
A1B	+2 (-3 to +11)	+4 (-1 to +17)	+6 (-1 to +43)
A2	+1 (-4 to +9)	+3 (-7 to +19)	+7 (-4 to +36)

On a seasonal basis, the largest temperature increases are projected for the JJAS dry season, with median increases of 0.9°C, 1.9°C and 3.1°C for the 2020s, 2050s and 2080s respectively for the A1B scenario. Projected precipitation changes for the two rainy seasons are shown in Table 5, and show predominantly increases in rainfall in both seasons. However, the median projected changes are again small relative to interannual variability; the upper end of the projections show more substantial increases, though the uncertainty of these projections is high. Projections for the JF and JJAS dry seasons reveal small increases (not shown). Analysis of monthly data does not allow any assessment of changes to heavy rainfall; however, another study for East Africa found an increasing proportion of rainfall in heavy events for both rainy seasons using the A1B scenario for CMIP3 data (Shongwe et al., 2011).

4.3.2 Daily data

It should be noted that the daily data presented in this section refer to downscaled data for the Butare station only, and therefore do not represent projected changes for Rwanda as a whole.

Hot Days

High frequencies in the number of days that would be classed as 'Hot' in the current climate is found for all seasons under both B1 and A2 SRES scenarios, particularly JJAS. Table 6 shows median percentage frequency of 'Hot' days (with minimum and maximum in brackets) from the ensemble of 9 GCMs. The frequencies predicted are large, which is likely a result of Rwanda's low intra-annual variability of temperature. Consequently the threshold for a 'Hot' day (the highest 10% of daily maximum temperatures in current climate) is not substantially higher than the mean daily maximum (approximately 1.5°C higher). It is therefore frequently surpassed in a warmer future climate.

Heavy Rainfall Events

Figure 17 shows the projected changes in daily rainfall intensity across the ten classes of rainfall (as described in the 'Methods' section above) for the OND season. Each set of three columns shows the percentage of total wet days that contributes 10% of total rainfall, from the heaviest events ('T10') in the leftmost columns to the lightest events ('T1') in the rightmost columns. Of most interest are the heavier events towards the left of the graph; the heavier the daily rainfall, the smaller the percentage of wet days required to achieve 10% of total rainfall.

These data show little change to the intensity of rainfall for Rwanda; the 10 classes have very similar percentages across the baseline and the 2050s and 2090s. 'T10' events (i.e. the heaviest) in particular show no change. Little change is also found in heavy rainfall events for the MAM season (not shown).

In contrast, analysis of the same CMIP3 data as part of a United Nations Development Programme (UNDP) project found increases in 'heavy' rainfall (classified as daily rainfall amount exceeded by the 5% of heaviest events in a season) for the grid cell over Rwanda (McSweeney et al., 2008). Median

Table 6: Projected frequency of 'Hot' days in each season, under B1 and A2 SRES scenarios and for 2050s and 2090s timeslices, against a baseline of 1961-2000. Median percentage frequency of 'Hot' days are given with minimum and maximum range in brackets; from 10 GCMs of CMIP3, downscaled to Butare station only.

Season / Scenario	2050s (% of 'Hot' days)	2090s (% of 'Hot' days)
JF		
B1	55 (46 – 60)	68 (52 – 80)
A2	66 (48 – 72)	97 (81 – 99)
MAM		
B1	59 (47 – 71)	74 (58 – 88)
A2	75 (54 – 85)	99 (89 – 99)
JJAS		
B1	63 (57 – 77)	78 (63 – 88)
A2	76 (63 – 85)	98 (92 – 99)
OND		
B1	51 (44 – 57)	98 (92 -99)
A2	66 (50 – 71)	97 (87 – 99)

annual heavy rainfall events were found to increase by 6% for the A2 scenario by the 2090s, with a range of 0 to +15% across the ensemble of models (ibid).

That there is a difference between the projections is likely a result of the different spatial scales of the data and the processes used to produce them. The UNDP project used the GCM data directly, which at a 2.5° resolution, uses a single grid cell that entirely encompasses Rwanda; the downscaled data, by contrast, has been downscaled to Butare specifically. Neither therefore incorporates the variation in topography and climate across Rwanda. In addition, the ability of GCMs to represent convectional rainfall is poor, and so large uncertainties into how heavy rainfall in the Tropics will change are not uncommon.

4.4 Discussion

Climate projections for Rwanda reveal a warmer climate with a likely increase in rainfall, though some of the models do project a decrease. The temperature projections from the 19 models show an increase of around 2-3°C by the 2080s. The median projections for precipitation are small (around 7% by the 2080s) compared to interannual variability. Projections for seasons show increases in rainfall for all seasons, with the larger changes projected for the two rainy seasons. However, the median changes are also found to be relatively small compared to interannual variability.

Analysis of daily data for Butare shows a projected increase in the number of days that would be classed as 'Hot' in the current climate. Projected changes are large (>50%), which is a result of the low intra-annual in temperature in Rwanda. The daily precipitation data show no projected change in heavy rainfall events; this is in contrast to other studies using the same CMIP3 data.

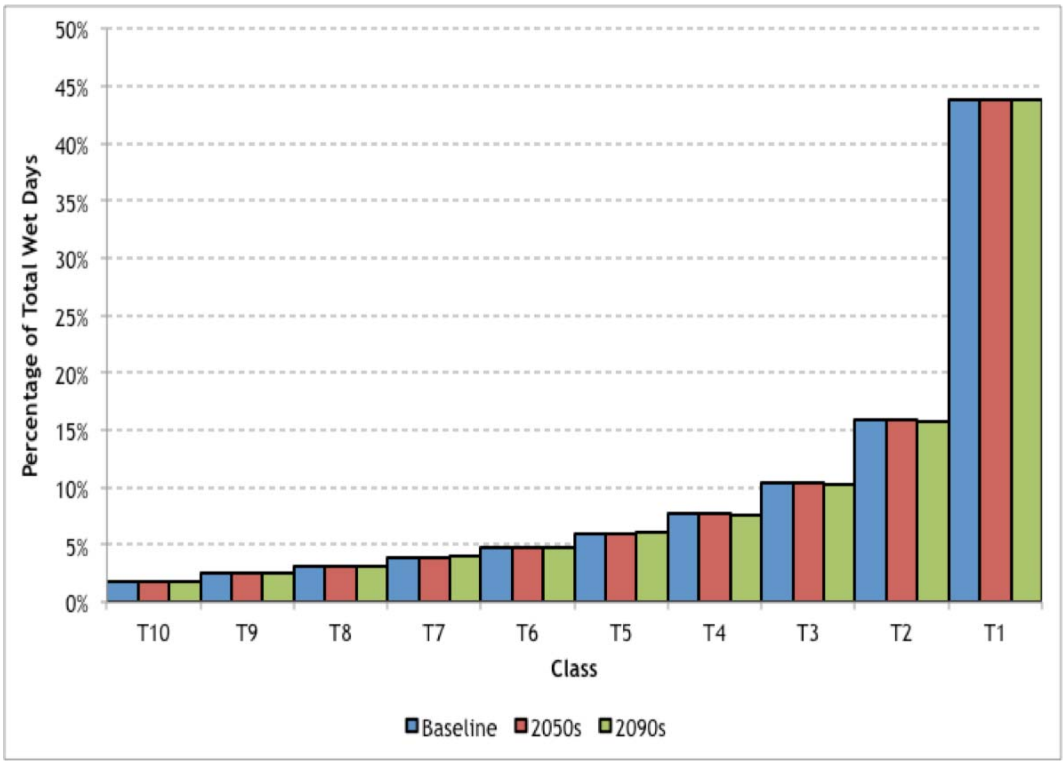


Figure 17: Median projected changes in daily OND rainfall intensity across the ten classes of rainfall. Under A2 SRES scenario for 2050s and 2090s timeslices, against a baseline of 1961-2000; from 10 GCMs of CMIP3, downscaled to Butare station only.

Conclusions

The ability to draw conclusions on the changes to Rwanda's climate during the 21st century is limited by the quantity and the quality of the observed data available. There are few temperature records extending back earlier than 1970, while precipitation data are lacking since the genocide. As such, the data problem is a conclusion in itself and highlights the importance of developing the station network in Rwanda and strengthening the data collection and verification processes.

The observed data assessed here suggest that mean temperatures have increased in Rwanda over the past 40 years, with associated increases in minimum and maximum temperatures. Other variables show changes associated with increasing temperature, namely a reduction in relative humidity and an increase in evaporation. However, the quality and quantity of these data should be noted as data from stations other than Kigali Airport are not available to support these findings. A greater quantity of precipitation records allows a more complete assessment of rainfall changes during the 20th century; however, the records show no significant trend between 1931 and 1990. There are not sufficient records to assess changes since 1990.

Analysis of projections for Rwanda's climate through the 21st century indicates a trend towards a warmer, wetter climate. Increases in mean temperature are projected under all models and all emissions scenarios, while the majority of models also indicate increases in annual rainfall totals, though a few show small reductions. The increases in rainfall are generally small relative to the interannual variability currently experienced in Rwanda. Analysis of daily data for Butare specifically suggests an increase in the frequency of days that would be characterised as 'Hot' in the current climate. The projected changes to heavy rainfall events are less conclusive, with daily data for Butare showing little change for the 2050s or 2090s, while other published research using CMIP3 data has found increases in heavy rainfall for Rwanda. This reflects the uncertainty in projections for heavy rainfall in climate models.

Acknowledgements

The observed meteorological data were kindly provided by the Rwanda Meteorological Service. The downscaling of the daily projections was carried out by Chris Jack at the Climate Systems Analysis Group (CSAG) at the University of Cape Town.

References

Aguilar, E., Aziz Barry, A., Brunet, M., Ekang, L., Fernandes, A., Massoukina, M., Mbah, J., Mhanda, A., do Nascinmento, D.J., Peterson, T.C., Thamba Umba, O., Tomou, M. and Zhang, X. 2009. Changes in temperature and precipitation extremes in western central Africa, Guinea Conakry, and Zimbabwe, 1955-2006, J. Geophys. Res., 114, D02115, doi:10.1029/2008JD011010.

Black, E. 2005. The relationship between Indian Ocean sea-surface temperature and East African rainfall, Phil. Trans. R. Soc., 383: 43-47.

Camberlin, P. and Philippon, N. 2002. The East African March–May rainy season: Associated dynamics and predictability over the 1968–1997 period. J. Climate, 15: 1002–1019.

Conway, D. 2002. Extreme Rainfall Events and Lake Level Changes in East Africa: Recent Events and Historical Precedents In E.O. Odada (ed.) The Second International Symposium on the Limnology, Climatology and Palaeoclimatology of the East African Lakes. Kluwer.

Conway, D., Hanson, C., Doherty, R. and Persechino, A. 2007. GCM simulations of the Indian Ocean dipole influence on East African rainfall: Present and future, Geophysical Research Letters, 34.

Godwin, O. 2005. The impacts of ENSO in Africa, In: Low, P.S. (Ed). Climate change and Africa, Cambridge University Press, Cambridge, 369pp.

Hewitson, B.C. and Crane, R.G. 2006. Consensus between GCM climate change projections with empirical downscaling: precipitation downscaling over South Africa, Int. J. Climatol., 26: 1315-1337.

McGregor, G. and Nieuwolt, S. 1998. Tropical climatology, Wiley, Chichester, 339pp.

McSweeney, C., New, M. and Lizcano, G. 2008. UNDP Climate Change Country Profiles: Tanzania, Available at http://country-profiles.geog.ox.ac.uk/UNDP_reports/Tanzania/Tanzania.hires.report.pdf [Accessed 20/7/2011].

McSweeney, C., New, M. and Lizcano, G. 2010. UNDP Climate Change Country Profiles: Documentation, School of Geography and Environment, University of Oxford. Available at: http://country-profiles.geog.ox.ac.uk/UNDPCCCP_documentation.pdf [Accessed 20/7/2011].

Nakicenovic, N and Swart, R. (eds). 2000. Special report on Emissions Scenarios. A special report of the Intergovernmental Panel on Climate Change, IPCC, Cambridge University Press, UK, 5099pp.

Nicholson, S. and Kim, J. 1997. The relationship of the El Niño-Southern Oscillation to African rainfall, Int. J. Climatol., 17: 117-135.

Osborn, T.J., Hulme, M., Jones, P.D. and Basnett, T.A. 2000. Observed trends in the daily intensity of United Kingdom precipitation. Int. J. Climatol,. 20: 347–364.

Saji, N., Goswami, B., Vinayachandran, P. and Yamagata, T. 1999. A dipole mode in the tropical Indian Ocean, Nature, 401: 360-363.

Saji, N. and Yamagata, T. 2003. Possible impacts of Indian Ocean dipole mode events on global climate, Climate Research, 25: 151-169.

Salmi, T., Määttä, A., Anttila, P., Ruoho-Airola, T. and Amnell, T. 2002. Detecting trends of annual values of atmospheric pollutants by the Mann–Kendall test and Sen's slope estimates – the Excel template application MAKESENS, Publications on Air Quality No. 31, Finnish Meteorological Institute, Helsinki.

Sen, P. K. 1968. Estimates of the Regression Coefficient Based on Kendall's Tau, Journal of the American Statistical Association, 63(324): 1379-1389.

Shongwe, M.E., van Oldenborgh, J.G., van den Hurk, B. and van Aalst, M. 2011. Projected changes in mean and extreme precipitation in Africa under global warming, Part II: East Africa, Journal of Climate, submitted.

Trenberth, K.E., P.D. Jones, P. Ambenje, R. Bojariu, D. Easterling, A. Klein Tank, D. Parker, F. Rahimzadeh, J.A. Renwick, M. Rusticucci, B. Soden and P. Zhai. 2007. Observations: Surface and Atmospheric Climate Change. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Wang, X. L. 2003. Comments on “Detection of Undocumented Changepoints: A Revision of the Two-Phase Regression Model”, J. Clim., 16(20): 3383-3385.

Wang, X. L. 2008. Accounting for Autocorrelation in Detecting Mean Shifts in Climate Data Series Using the Penalized Maximal t or F Test, Journal of Applied Meteorology and Climatology, 47(9): 2423-2444.

Smith School of Enterprise and the Environment
University of Oxford
Hayes House
75 George Street
Oxford
OX1 2BQ
United Kingdom
www.smithschool.ox.ac.uk