Climate change modelling and analyses for Mozambique

Final report detailing the support provided to the Instituto Nacional de Gestão de Calamidades (INGC) adaptation to climate change project

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Executive summary

This report details the work and analyses undertaken as part of the INGC project to understand how climate change may impact the operations of INGC in the future and therefore which adaptation options may be of future benefit to the organisation. The work mostly involved producing downscaled climate change information and providing guidance and support on how to use the data. The following is a step by step summary of the major findings, problems that were encountered and recommendations for further work:

- The station network over Mozambique, whilst providing a reasonable coverage, has major geographical gaps especially in Gaza and Tete provinces – the stations used in this report provide approximately 1 station every 29000 km^2 (in South Africa this ratio is approximately 1 station every 1000 km^2). This limits the applicability of the data for downscaling the future climate and using it to suggest changes in other regions. Missing data limit its application for analyses of trends. The data requires rigorous quality control before using it for downscaling or trend analyses;
- Significant positive trends in temperature are found in the historical record over most of the country and in all four seasons. Statistically significant (at the 90% confidence level) trends in minimum temperatures are more spatially extensive than maximum temperatures. Trends in minimum temperatures for particular regions and seasons are higher than 0.03°C $year^{-1}$ indicating increases as high as 1.62°C (for central regions during winter) between 1960 and 2005. Changes in maximum temperature over the same period are highest in the north during the March-May and particularly September-November seasons (as high as 1.15°C). The number of cold nights and cold days has decreased between 1960 and 2005, whereas the number of hot nights and hot days has increased. This is most notable in the north where the number of hot nights has increased by 25% in DJF and the number of hot days has increased by 17% during SON;
- Significant trends in rainfall are not readily apparent though there are indications of a later start to the rainfall season, as well as an increase in dry day persistence and dry spell length in the northeast of the country during the March-May and September-November seasons. In the north the mean dry spell length during June-August is, on average, more than 7 days longer in 2005 than in 1960, increasing by up to 20 days for specific locations during September-November. During the same period the start of the rainfall season has been delayed by up to 45 days at some locations;
- Downscaled projections of climate change from 7 GCMs suggest an increase in December-May rainfall, with highest increases towards the coast and smaller increases inland. The spread between models is however large, with some models suggesting rainfall decreases and other models higher increases;
- By 2046-2065 increases in temperature are predicted by all 7 GCMs, with the median change being highest increases inland away from the coast and during the September-November (SON) period (up to +2.5 - +3°C in maximum temperature). Highest increases (+2.5 - +3°C) in minimum temperature are projected over the Limpopo and Zambezi valleys during SON;
- By 2081-2100 increases in temperature are projected to increase by as much as +5 to +6°C over the central regions suring SON;
- Calculated increases in potential evapotranspiration are dependent on the choice of calculation method. Even so and using a conservative method, increases of approximately 0.5 mm day^{-1} are apparent by 2046-2065 over the Limpopo and Zambezi valleys during SON. By the later 2080-2100 period this has increased to greater than 1 mm day^{-1} over central regions;
- Over all regions increases in evaporation will likely be greater than increases in rainfall during the winter and early summer (June-November) resulting in a drier dry season. This is especially apparent over the central region;
- Increases in rainfall will likely be greatest towards the end of the summer season, especially in the north and central regions;
- Over all regions there will be an increase in the likelihood of extreme maximum daily temperatures above 35°C of approximately 7% by 2046-2065 and 25-33% by 2080-2100.

The following was noted with respect to the impact modelling that was undertaken using the climate data:

- It was necessary to have the correct baseline data to add the climate change projections to for the purposes of crop-suitability modelling. This modelling is also susceptible to the assumptions made in the calculation of potential evapotranspiration;
- For the purposes of flood risk modelling the downscaled data is limited in spatial coverage as well as the simulation of maximum daily values under climate change. The former problem can

be accommodated through the use of satellite-derived gridded data. The latter represents a methodological problem which is hard to circumvent, though increases in the frequency of high flooding events can still be simulated and used as a proxy for maximum floods.

Given the results of the work undertaken so far and the requirements of INGC, the following is recommended for future work and analyses:

- Downscale other models using an alternative scenario (e.g. B1) to test the robustness of the results;
- Use a dynamical regional climate model to downscale estimates of changes in extreme (maximum) rainfall.
- Obtain information regarding the vulnerability of particular sectors to critical climate thresholds and tailor the climate information to provide estimates of changes in these thresholds;
- Look at developing scenarios of near-term climate change based on existing trends and knowledge of how the climate may change in the next 20 years. These should be developed as scenarios, rather than explicitly using GCMs to model the future climate;
- Identify specific regions and sectors for more detailed analyses and for which 'extreme' or 'outlier' scenarios of change (not the median change) may be important

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1 Introduction

Mozambique lies on the southeast coast of Africa between 10°S and 27°S. It has a long coastline which faces the tropical and sub-tropical Indian Ocean and which experiences a predominantly maritime climate. The climate of this coastal region is largely determined by the offshore warm waters of the Agulas current and the close proximity of tropical cyclones which pass mostly from the north to the south of the country. The mountainous region towards the northwest of the country, bordering Malawi, moderate the high temperatures usually found at these latitudes, whereas the deep wide valleys of the Zambezi and Limpopo rivers are regions of lower topography (see Figure 2b). Generally temperatures are warmer near the coast (and the warm offshore ocean current) and cooler inland at higher altitudes.

The most important weather systems that determine rainfall amounts and pattern over Mozambique are: (1) the Inter-tropical Convergence Zone (ITCZ); (2) Tropical Cyclones; (3) Thermal lows along the coast as result of the deepening of semi-permanent trough over Mozambique Channel; and (4) incoming easterly waves. There is a very clear annual variation in the amount of rainfall, with a rainy and hot season, lasting from October to April, and a dry and cooler season, from May to September. These seasonal variations are associated with the Inter Tropical Convergence Zone (ITCZ) and it's migration southward over the country; it starts to move south over the country during October and during the peak of the rainy season the ITCZ is in its most southerly position (approx 19°S) during January-February.

Over southern regions low intensity rainfall can also fall during the autumn, winter and spring seasons and may be associated with ridging anticyclones which bring moisture from the south. Rainfall is also influenced by local variations in altitude, with higher regions often experiencing more rainfall. Heaviest rainfalls are however associated with the passage of tropical cyclones which emanate from the tropical Indian Ocean and pass along the Mozambique channel usually from north to south, and can result is heavy floods such as those experienced in 2000.

During January – March the ITCZ becomes more active over the country. The tropical cyclone season is from November to April with the peak frequency centered within January – February. These systems are associated with southeasterly flow that cause periods of intense rain over the country.

Interannual variability of the climate of Mozambique is often associated with large scale global patterns of change such as the El-Niño Southern Oscillation (ENSO), the negative phase of which (El-Niño) usually results in drier conditions. Even so, Sea Surface Temperatures (SST) in the Indian Ocean (which sometimes are associated with El-Niño) exert a strong influence on the climate of Mozambique. Whilst warm SSTs in the Indian Ocean can lead to drier conditions inland (due to the offshore displacement of dominant rainfall producing systems), over coastal regions high SSTs in the Mozambique channel may increase humidity and rainfall.

This report details changes observed in the seasonal climate of Mozambique during the 1960-2005 period and presents downscaled future scenarios of climate over Mozambique, focussing on the mid-century (2046-2065) and late-century (2080-2100) periods. As such it provides additional information to that provided in other sources[1]. These scenarios were used as a basis for this report, as well as the flood and crop-suitability modelling undertaken as other components of this project. Whilst the results of the flood and crop-suitability modelling are presented elsewhere, details of the data production and enabling process is presented here as it involved significant time and resources. The main purpose of this report however is to understand how the climate of Mozambique may already be changing and how it may be expected to change in the future. It therefore serves as necessary background and context for the other studies undertaken as part of this project.

2 Global and regional climate trends

Box 1: What is climate change?

Climate change refers to a change in the average weather experienced in a particular region or location. The change may occur over periods ranging from decades to millenia. It may affect one or more seasons (e.g. summer, winter or the whole year) and involves changes in one or more aspects of the weather e.g. rainfall, temperature or winds. It's causes may be natural (e.g. due to periodic changes in the earth's orbit, volcanoes and solar variability) or attributable to human (anthropogenic) activities e.g. increasing emissions of greenhouse gases such as CO_2, land use change and/or emissions of aerosols. In contemporary society the term 'Climate change' often refers to changes due to anthropogenic causes.

It is widely recognized that there has been a detectable rise in global temperature during the last 40 years and that this rise cannot be explained unless human activities

[1] In particular see McSweeney et al. (2008) UNDP country profiles (http://country-profiles.geog.ox.ac.uk)

are accounted for[2]. The regional distribution of temperature increases is not however uniform and some regions have experienced greater change than others, especially the interior of continental regions such as southern Africa (see Figure 1). This is consistent with detected increases in annual temperatures found over southern Africa since 1900[3]. Additionally these changes in temperature are associated with decreases in cold extremes accompanied by increases in hot extremes[4]. Furthermore, the global average temperature indicates an increasing rate of change, such that temperature is rising quicker during the latter half of the 20th century (see Figure 1). Importantly, this increase in the rate of change is expected to continue, potentially resulting in more rapid changes of climate in the future.

Changes in rainfall are typically harder to detect due to its greater variability, both in time and space. Even so, changing rainfall patterns have been detected for many parts of the globe, including moderate decreases in annual rainfall over southern Africa. Where records are of sufficient length there have been detectable increases in the number of heavy rainfall events[5] and within the southern hemisphere there is evidence for a moistening of the tropics and subtropics[6]. This is consistent with regional studies over continental southern Africa which have shown trends for an increasing length of the dry season and increases in average rainfall intensity[4]. This has important implications for the seasonality of regional rainfall and together suggests a shorter but more intense rainfall season.

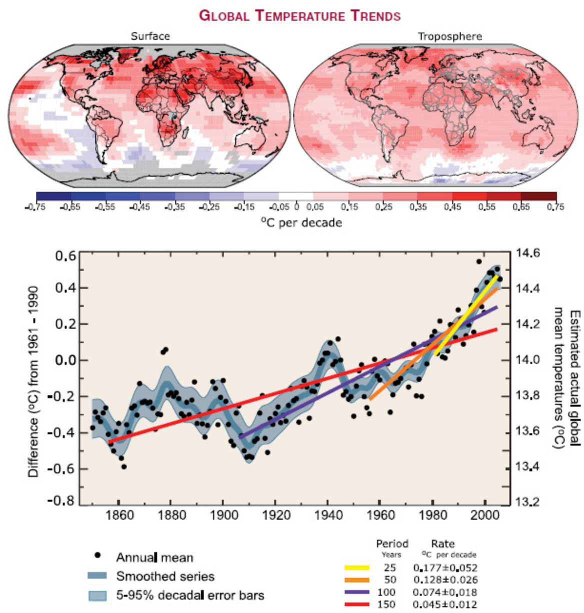


Figure 1: Distribution of global temperature trends (1979-2005) for the surface (left) and troposphere (right) from satellite records. Below: the average global temperature since 1850 indicating the increased rate of change during the later part of the 20th century[5].

Besides changes in temperature and rainfall, other aspects of global change are notable[2]:

- Increases in intensity and spatial extent of droughts since the mid-1970s;
- Decreases in northern hemisphere snow cover;
- Increases in the duration of heat waves during the latter half of the 20th century;
- Shrinking of the arctic sea ice pack since 1978;
- Widespread shrinking of glaciers, especially mountain glaciers in the tropics;
- Increases in upper-ocean (0-700m) heat content;
- Increases in sea level at a rate of 1.8 mm yr^{-1} between 1961 and 2003, with a faster rate of 3.1 mm yr^{-1} between 1993 and 2003.

There is therefore compelling evidence for climate change at the global level, attribution to human activities, as well as its effects on continental southern Africa. However, understanding how global climate change may affect individual countries and small regions within a country is still a matter of research and is inherently linked to issues of uncertainty (see Box 3). So whilst the observed global level changes serve to highlight that climate change is a reality and that we have confidence in continuing and potentially accelerating change, it is necessary to explore how local climates may already be changing as well as how they are expected to change in the future.

[2] IPCC (2007). Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK, New York, US, Cambridge University Press.

[3] Hulme, M., R. Doherty, T. Ngara, M. New and D. Lister (2001). African Climate Change: 1900-2100. *Climate Research* 17(2): 145-168.

[4] New, M., B. Hewitson, D. B. Stephenson, A.Tsiga, A. Kruger, A. Manhique, B. Gomez, C. A. S. Coelho, D. N. Masisi, E. Kululanga, E. Mbambalala, F. Adesina, H. Saleh, J. Kanyanga, J. Adosi, L. Bulane, L. Fortunata, M. L. Mdoka and R. Lajoie (2006). Evidence of trends in daily climate extremes over southern and west Africa. *Journal of Geophysical Research* 111. D14102, doi:10.1029/2005JD006289

[5] Solomon, S., D. Qin, M. Manning, R. B. Alley, T. Berntsen, N. L. Bindoff, Z. C. A. Chidthaisong, J. M. Gregory, G. C. Hegerl, M. Heimann, B. Hewitson, B. J. Hoskins, F. Joos, J. Jouzel, V. Kattsov, U. Lohmann, T. Matsuno, M. Molina, N. Nicholls, J. Overpeck, G. Raga, V. Ramaswamy, J. Ren, M. Rusticucci, R. Somerville, T. F. Stocker, P. Whetton, R. A. Wood and D. Wratt (2007). Technical Summary. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. S. Solomon, D. Qin, M. Manning et al. Cambridge, UK. New York, US, Cambridge University Press

[6] Zhang, X., F. W. Zwiers, G. C. Hegerl, F. H. Lambert, N. P. Gillett, S. Solomon, P. A. Stott and T. Nozawa (2007). Detection of human influence on twentieth-century precipitation trends. *Nature* 448: 461-465

Box 2: What causes climate change?

Anthropogenic emissions of greenhouse gases (the main cause of anthropogenic climate change) have increased steadily since the industrial revolution. The rate of emissions, however, have been steadily increasing over time, and computer models of the earth's climate system (including both natural and human causes) are unable to simulate recent warming unless they include anthropogenic emissions of greenhouse gases. Computer models of the earth's climate which include only natural forcings (e.g. solar variability due to both internal and orbital variations, volcanic activity etc.) simulate a cooling of the earth after 1960, which is at odds with the observed warming (see Figure 1). This has led the Intergovernmental Panel on Climate Change (IPCC) to conclude recently that most of the warming of the last 50 years is attributable to human activities.

3 Station data used for the climate analyses

The data and analyses within this report show some of the changes noted in the historical records (trends) of climate in Mozambique and those changes projected for the future 2046-2065 and 2080-2100 periods from a suite of 7 downscaled GCMs. Both the historical trends and future projections were derived from daily (maximum and minimum) temperature and rainfall measurements since 1960 from 32 synoptic weather stations within Mozambique. These data were supplied by the Instituto Nacional de Meteorología de Mozambique (INAM). A list of the 32 stations, as well as their geographical locations, is provided in Table 1.

Due to constraints requiring a minimum of 10 years of daily data post-1979 for the statistical downscaling there were only 30 stations with sufficient rainfall data and 27 stations with sufficient temperature data. Therefore only the 27 stations with sufficient data for rainfall and temperature are used in the following analyses. Those stations provided by INAM and not meeting these criteria are highlighted in red in Table 1. Given Mozambique's land area of 784090 km^2 this provides an approximate station density of 1 station every 29000 km^2, which is much less than South Africa which has approximately 1200 stations over a land area of 1221040 km^2 (approx. 1 station every 1000 km^2).

Box 3: Understanding uncertainty and risk

The issue of uncertainty is crucial to understanding past and future climatic change, especially when designing adaptation strategies that will benefit both present and future socioeconomic situations. Uncertainty does not mean that we have no confidence in our projections of future climate. Indeed all climate projections, including seasonal forecasts, are couched in terms of the probability of particular climate conditions occurring in the future. This is a framework within which humans often operate, allowing an assessment of future risks, e.g. consideration of financial and investment opportunities.

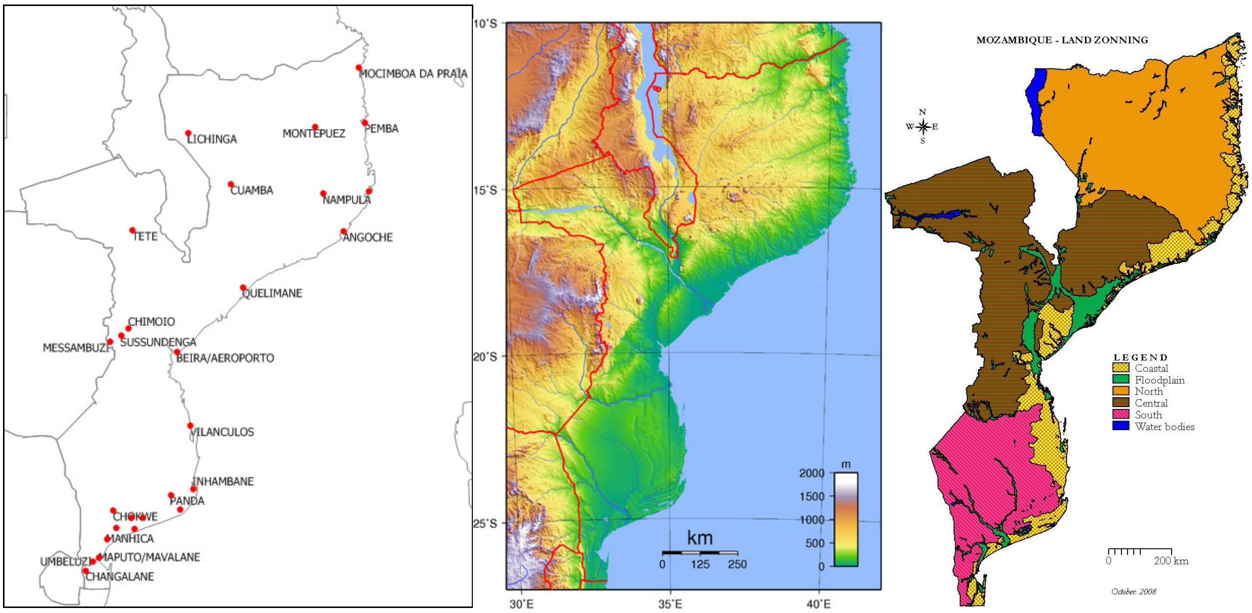
To be able to assess risk, one needs to consider all sources of information. It is therefore essential that a probabilistic framework is used to develop projections which should incorporate different sources of information. The IPCC define four sources of uncertainty that currently limit the detail of the regional projections:

1. Natural variability. Due to the limiting factor of observations (both in time and space) we have a limited understanding of natural variability. It is difficult to characterise this variability and the degree to which it may exacerbate or mitigate the expected background change in climate. This variability itself may change due to anthropogenic factors, e.g. increases in the frequency of droughts and floods;
2. Future emissions. Much of future projected change, at least in terms of the magnitude of change, is dependent on how society will change its future activity and emissions of greenhouse gases. Even so, the world is already committed to a degree of change based on past emissions (at least another 0.6ºC warming in the global mean temperature). Human responses to managing emissions may result in a projected global mean temperature change of between 1.5º and 5.6ºC;
3. Uncertainty in the science. This is further complicated within Africa because of limited understanding of the regional dynamics of the climate of the continent. There may be aspects of the regional climate system, which could interact with globally forced changes to either exacerbate or mitigate expected change e.g. land-use change. One consequence is the possibility of rapid nonlinear change, with unforeseen and sudden increases in regional impacts;
4. Downscaling – the term used to define the development of regional scale projections of change from the global models (GCMs). Downscaling tools can introduce additional uncertainty e.g. between downscaling using regional climate models and statistical techniques. Usually this uncertainty limits the confidence in the magnitude of the projected change with the pattern and sign of change often interpreted with greater certainty.

The location of the 27 stations meeting the criteria for downscaling are shown in Figure 2a. The stations are spread throughout Mozambique though they have a noticeable bias to be situated along the coast. Whilst this is not so noticeable in the north, the southern inland regions and to a lesser extent the central inland regions, have large areas without station measurements. This restricts how representive the following results can be for these inland regions, and for this reason it was

StationID	StationName	Latitude (°S)	Longitue (°E)	Elevation (m)
CD000013	MOCIMBOA DA PRAIA	-11.35	40.37	27.0
CD000014	MONTEPUEZ	-13.13	39.03	534.0
CD000022	MECUFI	-13.28	40.57	10.0
CD000034	PEMBA	-12.98	40.53	101.0
GZ008007	MANJACAZE	-24.72	33.88	65.0
GZ008010	MACIE	-25.03	33.10	56.0
GZ008032	XAI-XAI	-25.05	33.63	4.0
GZ008035	MANIQUENIQUE	-24.73	33.53	13.0
GZ008050	CHOKWE	-24.52	33.00	33.0
IB007003	INHAMBANE	-23.87	35.38	14.0
IB007004	INHARRIME	-24.48	35.02	43.0
IB007007	PANDA	-24.05	34.72	150.0
IB007010	VILANCULOS	-22.00	35.32	20.0
MN005015	CHIMOIO	-19.12	33.47	731.0
MN005032	MESSAMBUZI	-19.50	32.92	966.0
MN005045	SUSSUNDENGA	-19.33	33.23	620.0
MP009005	UMBELUZI	-26.05	32.38	12.0
MP009010	MANHICA	-25.37	32.80	35.0
MP009044	MAPUTO/MAVALANE	-25.92	32.57	39.0
MP009052	CHANGALANE	-26.30	32.18	100.0
NP002001	ILHA DE MOCAMBIQUE	-15.03	40.73	9.0
NP002006	RIBAUE/AGRICOLA	-14.98	38.27	535.0
NP002008	ANGOCHE	-16.22	39.90	61.0
NP002049	LUMBO	-15.03	40.67	10.0
NP002051	NAMPULA	-15.10	39.28	438.0
NS001002	CUAMBA	-14.82	36.53	606.0
NS001003	LICHINGA	-13.30	35.23	1,365.0
SF006053	BEIRA/AEROPORTO	-19.80	34.90	8.0
TT003002	TETE	-16.18	33.58	149.0
TT003053	ULONGUE	-14.73	34.37	1.0
ZB004001	QUELIMANE	-17.88	36.88	6.0
ZB004029	PEBANE	-17.27	38.15	25.0

Table 1: INAM synoptic weather stations for which daily rainfall and temperature measurements after 1960 were acquired. Stations marked in red were not used due to missing data.



(a) (b) (c)

Figure 2: a) Location of synoptic weather stations used in the analysis of historical trends and for downscaling the future climate; b) Topographic map of Mozambique[7]; c) Land zoning map of Mozambique (*Source: Instituto de Investigação Agrária de Moçambique*)

[7] http://en.wikipedia.org/wiki/Geography_of_Mozambique

necessary to use some station data from countries bordering Mozambique for both the preparation of the data for crop suitability modelling (see section 7) and the analysis of regional variations (see section 6).

Figure 2b shows the topographical variation within Mozambique, clearly showing the low lying coastal plain covering much of the country in the south and central regions (coloured green/blue). The higher mountains/plateaux inland and to the north are also clearly visible. Comparing Figure 2a and b indicates that the station network used in this anlysis misses potentially key areas such as the highland areas in Tete province (central west) and the low lying regions in Gaza province (southern inland). Figure 2c shows the regional zoning of Mozambique according to the Instituto de Investigação Agrária de Moçambique (IIAM), which was adopted for this study and is used for the regional analysis in section 6. It clearly shows that most of the stations are located in the coastal region, especially in the south where nearly all of the stations are in or close to the coastal region.

3.1 Quality control of station data

The data from each of the 27 stations underwent rigorous quality control, including checking for unrealistic rainfall and temperature values, as well as testing each timeseries for homogeneity. Suspicious data were set to missing values before proceeding with the tests for trends and using the data to downscaling the future climate scenarios (see section 5).

Any data collected at a weather station must undergo quality control procedures. Such quality control procedures are generally flexible and there are no hard and fast guidelines as to what should be implemented. For example, complex statistical techniques that detect discontinuities in timeseries (usually indicating the relocation or deterioration of a sensor) can be used with historical data. Or alternatively, some relatively simple quality control tests can be used:

- Remove negative rainfall, or rainfall above station-specific unrealistic values;
- Remove where maximum temperatures and less than minimum temperatures or either are within 3 - 6 standard deviations of the long-term mean.

In this analyses it was decided to use the following tests and data was removed if it failed any of them:

- checking for negative rainfall;
- rainfall > 500 mm in one day;
- minimum temperatures greater than maximum temperatures;
- minimum and maximum temperatures greater than 6 standard deviations from the long-term (full dataset) mean value;
- inhomogeneities due to changing instruments or location.

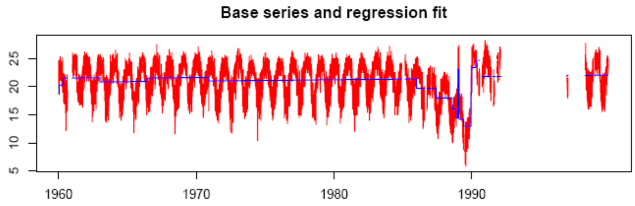


Figure 3: Timeseries of minimum temperature from Pebane station. Note the gradual degradation of the recordings from 1985 to 1990.

The first 4 steps were completed before undertaking the 5th step. The 5th test utilised software distributed by ETCCDMI[8][9]. Even so there were still a number of identified problems. These mostly appear to relate to sensor degradation an example of which is given in Figure 3. In this figure the measurements deteriorate between 1985 and 1990 – if the change was immediate and occurred only once then it could be due to a change of sensor or location but in this case it seems the sensor gradually degraded during the period. Whenever changes such as those in Figure 3 were discovered the data was set to NA (not available or not recorded).

4 Recent changes in the climate of Mozambique (1960-2005)

Studies of recent historical changes in climate within Mozambique are complicated by the significant regional variations in climate mentioned earlier, as well as natural variability on time scales of 10 years or longer. However, there is clear evidence that temperatures have increased, following the global trend and that the character of rainfall has changed appreciably. Whilst past trends are no guarantee of future change, especially in the context of uncertainty (Box 3), they are the foundation from which to assess current adaptation strategies to climate change and how they may be appropriate given future expected change.

To assess changes in climate the suite of seasonal and annual indices, developed under the STARDEX project, were calculated at each of the 27 INAM stations. These

[8] http://cccma.seos.uvic.ca/ETCCDMI/software.shtml
[9] Wang, X. L., Q. H. Wen, and Y. Wu (2007) Penalized maximal *t* test for detecting undocumented mean change in climate data series. *J. Appl. Meteor. Climatol.*, 46 (No. 6), 916-931. DOI:10.1175/JAM2504.1

indices represent a broad range of rainfall and temperature characteristics that capture most aspects of the climate that are likely to be affected by climate change. They do not, however, capture changes in seasonality associated with changes in the start/end of the rains which is dealt with in section 4.3. Average trends between 1960 and 2005 were calculated for each index, geographically located, and then interpolated (kriged) to a 0.5 degree grid. The suite of 57 indices for which these calculations were performed (annually and for each of the SON, DJF, MAM and JJA seasons) are given in Appendix A. Given that this represents for each of the 27 stations a set of 285 indices, only those indices representing significant and spatially consistent trends are presented here.

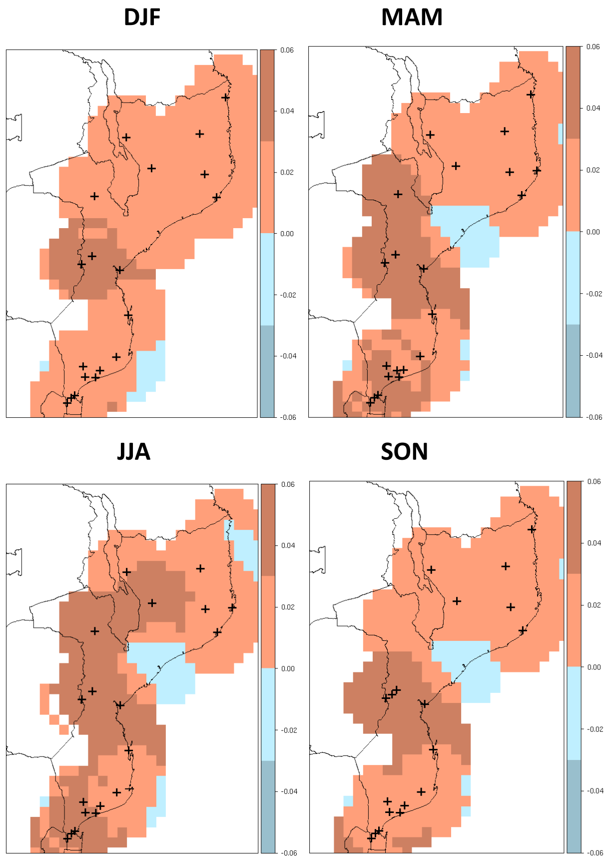


Figure 4: Trends in mean minimum temperature (1960-2005) for the four seasons DJF, MAM, JJA and SON (°C year^{-1}). "+"/"-" indicates positive/negative trends significant at the 90% confidence level.

4.1 Temperature

Not surprisingly the most consistent trends were found for indexes related to temperature; Figure 4 indicates trends in mean minimum temperatures for the four seasons (DJF: December to February; MAM: March to May; JJA: June to August and SON: September to Novemeber) whereas Figure 5 indicates the same for mean maximum temperatures. Significant trends (greater than 90 % confidence interval or p-value of less than 0.1) at each station are indicated by a "+"/"-", otherwise no symbol is used.

It is clear from these figures that most stations indicate significant increases in both mean minimum and mean maximum temperatures. The trends from individual stations were grouped according to the four regions defined in Table 5, representing the north, south, central and coastal areas and are shown in Table 2.

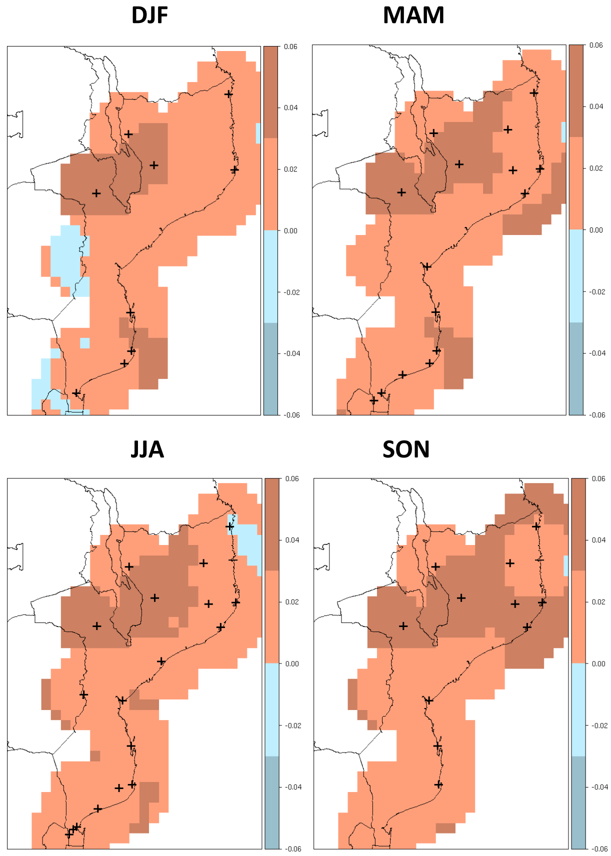


Figure 5: Trends in mean maximum temperature (1960-2005) for the four seasons DJF, MAM, JJA and SON (°C year^{-1}). "+"/"-" indicates positive/negative trends significant at the 90% confidence level.

Highest trends were greater than 0.03°C per year resulting in the highest average increase of 1.62°C during the 45 year period and over the central regions during JJA. Trends are particularly high for minimum temperatures during the late summer (MAM) and winter (JJA) periods, especially over the central and southern regions. Maximum temperatures indicate highest changes over the northern regions, particularly during the early (SON) and late (MAM) summer periods. Similar

	Average maximum temperatures					Average minimum temperatures				
	DJF	MAM	JJA	SON	Annual	DJF	MAM	JJA	SON	Annual
North	0.76	1.16	0.93	1.15	1.02	0.88	0.84	0.88	0.80	0.91
Central	0.40	0.98	1.11	0.95	0.92	1.12	1.38	1.62	1.15	1.21
South	0.50	0.98	0.90	0.65	0.77	0.69	1.27	1.35	1.14	1.17
Coastal	0.74	1.01	0.82	0.91	0.84	0.52	0.65	0.62	0.61	0.67

Table 2: Mean changes (per region) in average maximum and minimum temperatures (°C) between 1960 and 2005 for each of the four seasons and as an annual average.

	Frequency max. temp. above 90th percentile					Frequency min. temp. above 90th percentile				
	DJF	MAM	JJA	SON	Annual	DJF	MAM	JJA	SON	Annual
North	8.29	13.82	15.11	17.29	14.08	25.20	16.46	7.84	14.01	17.04
Central	4.89	6.17	9.32	6.88	7.26	17.61	10.41	11.06	10.54	12.21
South	1.52	7.03	8.69	3.39	5.12	6.44	10.25	11.49	9.66	9.38
Coastal	5.03	8.70	9.79	7.73	7.50	11.25	8.21	3.60	7.76	8.70

Table 3: Mean changes (per region) in the frequency with which maximum and minumum temperatures are in the hottest 10%. Changes are the difference (as a percentage) between the average frequency in 1960 and the average frequency in 2005.

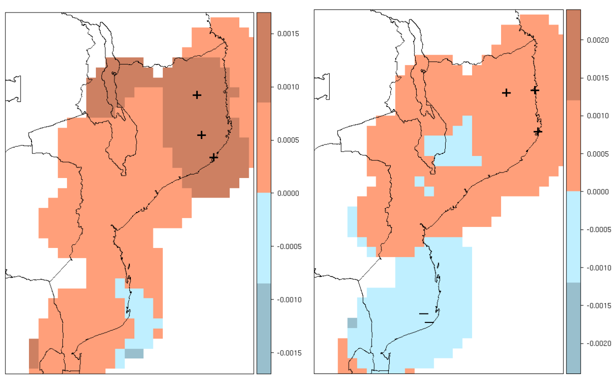
increases were also noted for the coldest (10th percentile) and hottest (90th percentile) nights (minimum temperatures) and days (maximum temperatures).

Spatially extensive and statistically significant increases in the duration of the longest heat waves were also noted, especially over the northern regions during SON (trends up to +0.2 days year^{-1} ≈ increase of 9 days between 1960 and 2005). It was also noted that the number of coldest nights and coldest days has been decreasing for all regions and all seasons (as much as 14% in MAM over central regions), whereas the number (frequency) of hot nights and hot days has been increasing (Table 3).

Broadly speaking the highest increases have been in the number of hottest nights, with annual increases greater than 12% in the north and central regions and the highest increase of 25% in the north during DJF. Even so the number of hottest days has also increased significantly over the whole of Mozambique, with the highest increases of 17% in the north during SON. This ties in with the changes in rainfall noted in the next section and is likely in part due to decreases in cloud cover, rainfall and evaporation, as well as increases in solar heating (due to less cloud cover).

4.2 Rainfall

Trends in rainfall indices were much more heterogeneous than those for temperature. Whilst there are statistically significant increases in some intensity related indices at specific locations and for specific periods, the most spatially consistent changes were found for indices related to rainfall frequency. Figure 6 shows trends in mean dry day persistence (the probability of having one dry day following another) for the spring and autumn seasons. The figure indicates that during these seasons over the north-eastern regions (Cabo Delgado/Nampula) the probability of consecutive dry days has been increasing. Consistent with these trends increases were also noted in mean dry spell length over these same regions. Trends in dry spell length are greatest in SON (Figure 7), increasing by as much as 20 days between 1960 and 2005, and which likely reflect a delay in the end of the dry season.



(a) **(b)**

Figure 6: Trends in mean dry day persistence (1960-2005): a) MAM; b) SON (days year^{-1})

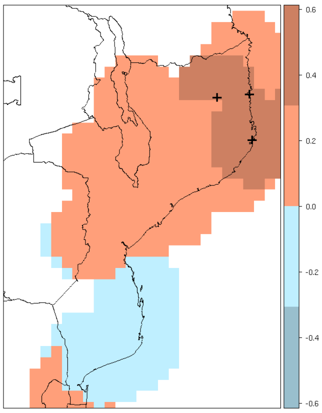
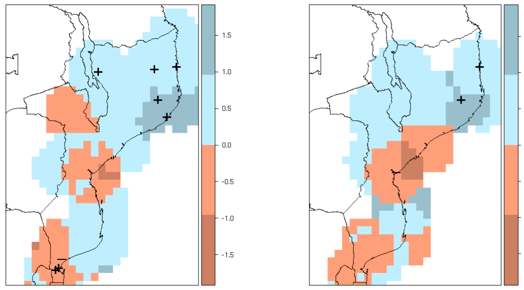


Figure 7: Trends (1960-2005) in mean dry spell length during SON (days year^{-1})

4.3 Changes in seasonal boundaries

As mentioned previously the STARDEX indices do not present information on potential changes in seasonal boundaries. We therefore developed indexes related to the start, end and duration of the season, based on rainfall as well as rainfall and potential evapotranspiration (PET; a measure of the evaporative potential of the atmosphere which increases as temperature increases). The rainfall only criteria assumed the season to have started when 45mm of rain fell in 30 days after August 1st and ended when less than 60mm fell in 30 days. The combined rainfall and PET criteria assumed that the start/end of the season was when the ratio of rainfall/PET was consistently above/below 0.5 for 30 days. Two criteria for defining seasonal boundaries were used as it is currently often the practise to use a rainfall only criteria whereas the rainfall/PET ratio more accurately reflects changes in moisture availability due to temperature changes, which will likely be a significant component under climate change. There are several methods for calculating PET, though due to data availability we were restricted to those approximate methods using only temperature. Both a modified Thornthwaite and Priestley-Taylor (P-T) method were tested with the P-T method eventually being used for the analysis (see discussion in section 5).

Very few spatially extensive and significant changes were detected in the seasonal boundaries. However, consistent with the changes noted in dry day persistence and dry spell length during SON there has been a trend for later starts to the rainfall season over the northern regions (see Figure 8a). These trends are as high as 1 day year^{-1} leading to changes of up to 45 days between 1960 and 2005. Whilst there were less obvious and consistent changes in the end and duration of the rainfall season, a simple index of moisture availability (rainfall – 0.5PET summed for each day between the start and end of the season), which approximately measures the potential rainfall–evaporation during the season, indicates that these northern regions have had steady increases in rainfall – 0.5PET, despite increases in temperature/PET and later starts to the season. This indicates that either the rainfall season has shifted later to a period when convective rainfall is normally more intense or there have been increases in the average intensity of daily rainfall. Consistent with other studies[4] we found non-statistically significant positive trends in mean daily rainfall intensity, but these were not clearly associated with the main rainfall season. Therefore it is likely the positive trends for moisture availability are mostly due to a shift of the rainfall season to a wetter period.



(a) **(b)**

Figure 8: Trends in: a) start of the rainfall season (days year^{-1}). Trends in some northern regions suggest that the start of the rains comes up to 45 days later in 2005 than in 1960; b) rainfall – 0.5PET (mm day^{-1} year^{-1}) during the rainfall season.

Box 4: Is one GCM better than another at projecting future change ?

Whilst some GCMs are better at simulating the present observed climate, this does not necessarily mean that they are better at simulating future *change*. Evaluating one GCM against another is also not an easy task; whilst one GCM may better simulate monthly mean rainfall and temperature it may not better simulate the daily frequency or diurnal cycle of rainfall. Another problem when trying to use a single GCM is that only a limited number of future scenarios can be used and this can sometimes create the impression of a narrowly determined future, which may not fully span the range of potential future change. It is therefore recommended that future change is expressed either as a range of future change or as an average statistic (e.g. median) with some measure or recognition of the spread of possible future states.

5 Future climate of Mozambique (2046 – 2065) from downscaled GCMs

General Circulation models (GCMs) are the fundamental tool used for assessing the causes of past change and projecting change in the future. They are complex computer models, which represent interactions between the different components of the climate system such as the land surface, the atmosphere and the oceans. In making projections of climate change, several GCMs and scenarios of future emissions of greenhouse gasses are used to predict the future (see **Box 4** and **Box 5**). This leads to a suite of possible futures, each of which is a valid representation of what the future climate may be. That there is a range of future possibilities is an important concept to understand clearly as it means that we can only suggest futures that may be more *likely* than others.

Box 5: What is a scenario?

Scenarios describe potential futures, which can be based on either changes in the climate system, socio-economic circumstances or other potential future changes. In the context of climate change the IPCC published it's Special Report on Emissions Scenarios (SRES) which describe a range of possible scenarios based around four 'storylines': A1, B1, A2 and B2. These storylines assume different paths of development for the world, greater weight being given to environmental (B family) or economic (A family) considerations, and more global (A1, B1) or regional (A2, B2) development. Each of these scenarios have an associated emissions pathway for the period 2000-2100. These emission pathways describe the amount of greenhouse gases (and other atmospheric gases) emitted through human activity in the future. General Circulation Models (GCMs) can then use these future emissions (which define changes in the concentration of these gases in the atmosphere) to model the future climate.

GCMs typically work at a spatial scale of 200-300km, with the scales at which they have skill, i.e. at which they can usefully project the future, typically greater. Whilst this problem is greatest for projections of rainfall, it limits the application of GCM projections for assessments of change at the local scale. Therefore, the technique of 'downscaling' is typically used to produce projections at a finer spatial scale. Downscaling works because the GCMs are generally good at projecting changes in atmospheric circulation (high and low pressure) but do a poor job of translating that information into changes in rainfall. The projected changes in rainfall and temperature used in this project are therefore taken from the statistical downscaling of 7 GCMs downscaled to each of the station locations presented in Figure 2. All 7 GCMs were used in the IPCC 4th assessment report and forced with the SRES A2 emissions scenario[10] (which assumes that society will continue to use fossil fuels at a moderate growth rate, there will be less economic integration and populations will continue to expand). Details of the GCMs are provided in Table 4. It was decided to initially concentrate on a range of GCMs from one emissions scenario as this range is mostly larger than the range between scenarios, certainly until mid-century. The reason for this is that the concentration of greenhouse gases, especially CO_2, will continue to grow under all scenarios and will largely only change towards the middle of the 21st century[10].

Originating Group(s)	**Country**	**I.D.**
Canadian Centre for Climate Modelling & Analysis	Canada	CGCM3.1(T63)
Météo-France / Centre National de Recherches Météorologiques	France	CNRM-CM3
CSIRO Atmospheric Research	Australia	CSIRO-Mk3.0
Max Planck Institute for Meteorology	Germany	ECHAM5/MPI-OM
US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory	USA	GFDL-CM2.1
NASA / Goddard Institute for Space Studies	USA	GISS-ER
Institut Pierre Simon Laplace	France	IPSL-CM4

Table 4: GCMs used to downscale the projected climate for the 1960-2000, 2046-2065 and 2080-2100 periods[11]

The statistical downscaling used in this report is based on Self Organising Maps[12], the results of which have been used by the IPCC over Africa[13], and which will be referred to as the SOMD method[14]. The following figures show the differences in climate between the 1960-2000 and 2046-2065 periods, as simulated by the GCMs and downscaled via the SOMD method. Given the sparsity of stations in some regions, especially close to the borders with other countries, we included a range of stations from South Africa (provided by the Water Research

[10] IPCC (2000) IPCC special report emissions scenarios: Special report of IPCC working group III. Intergovernmental panel on climate change. pp 20.

[11] http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php

[12] Hewitson, B. C. and R. G. Crane (2006). Consensus between GCM climate change projections with empirical downscaling: precipitation downscaling over South Africa. *International Journal of Climatology* 26(10): 1315-1337.

[13] Christensen, J. H., B. Hewitson, A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R. K. Kolli, W.-T. Kwon, R. Laprise, V. M. Rueda, L. Mearns, C. G. Menéndez, J. Räisänen, A. Rinke, A. Sarr and P. Whetton (2007). Regional Climate Projections. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. S. Solomon, D. Qin, M. Manninget al. Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press

[14] climate data downscaled via SOMD is available via the website http://data.csag.uct.ac.za

Commission of South Africa), Swaziland, Zimbabwe, Zambia, Malawi and Tanzania (provided by the World Meteorological Organisation), all as close to the Mozambique border as was found in the relevent databases. Details of these extra stations are provided in Appendix B.

5.1 Rainfall

Figure 9 shows the median change in rainfall from the 7 GCMs and for the 4 seasons: DJF, MAM, JJA and SON (changes for each individual GCM are shown in Appendix C). The changes are interpolated (kriged) between stations. Any changes less than 0.1 mm day^{-1} are masked out as they are less than the increases in evapotranspiration (see section 5.3). Also shown on the figure is a "+"/"-" symbol at each station location which indicates if the median absolute deviation (a robust measure of standard deviation) of the variability from year to year increases or decreases in the future climate. This provides an approximate indication if seasonal rainfall variability can be expected to increase in the future.

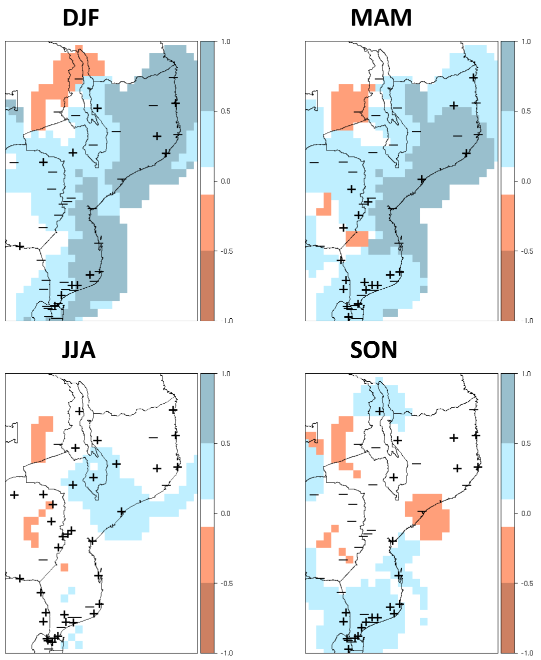


Figure 9: Median changes in future rainfall (mm day^{-1}) from 7 GCMs. "+"/"-" indicates whether seasonal variability is expected to increase/decrease in the future.

Figure 9 suggests that rainfall can be expected to increase over most of Mozambique during the DJF and MAM seasons whilst these increases are often less than approximate increases in evapotranspiration (0.1 mm day^{-1}) during the JJA and SON seasons. Higher increases in rainfall are simulated towards the coast, especially during the DJF season, with similar increases in coastal regions as well as towards Malawi during the MAM season. Seasonal variability both increases and decreases depending on location; over southern coastal regions there is often an increase in seasonal variability during all four seasons (though this is not true for all stations); most stations suggest an increase in variability over the whole country during JJA.

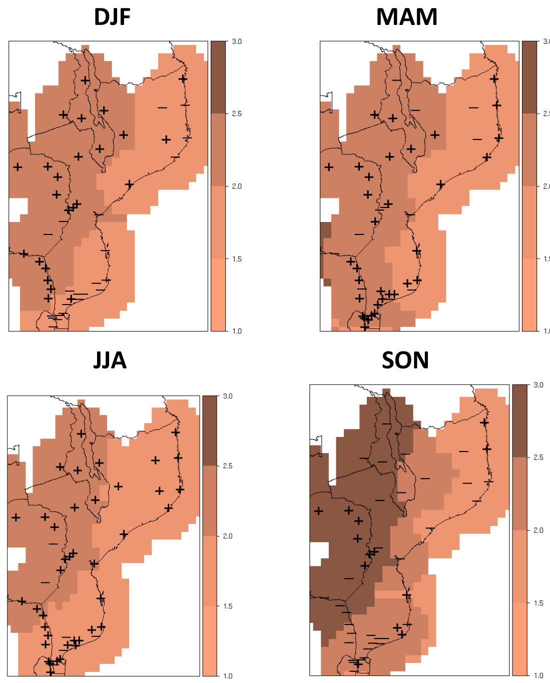


Figure 10: Median changes in future maximum temperature from 7 GCMs (2046-2065 period). "+"/"-" indicates whether seasonal variability is expected to increase/decrease in the future.

5.2 Temperature

Both minimum and maximum temperatures are projected to increase in all seasons by all 7 GCMs. Figure 10 shows the median model changes in maximum temperature (similar plots of changes in minimum temperatures can be found in Appendix D) for each of the 4 seasons, which clearly demonstrates that temperatures are expected to rise by 1.5 - 3°C by the 2046-2065 period. In all four seasons, maximum temperatures rise more towards the interior and less at the coast, partly due to the moderating influence of the ocean. Similar spatial patterns are present for changes in PET, highlighting that the interior regions will also suffer greater evaporation changes than those regions near the coast. It is also clear that the largest increases occur during the SON season, before the onset of the rains over much of the country. Changes in variability are mostly positive with clear suggestions that variability in maximum temperatures will decrease in the north during SON but increase over most of the country during MAM and JJA. Changes in variability in minimum temperatures (appendix D) suggest increases in variability in the north during MAM and JJA, with increases during SON in the south.

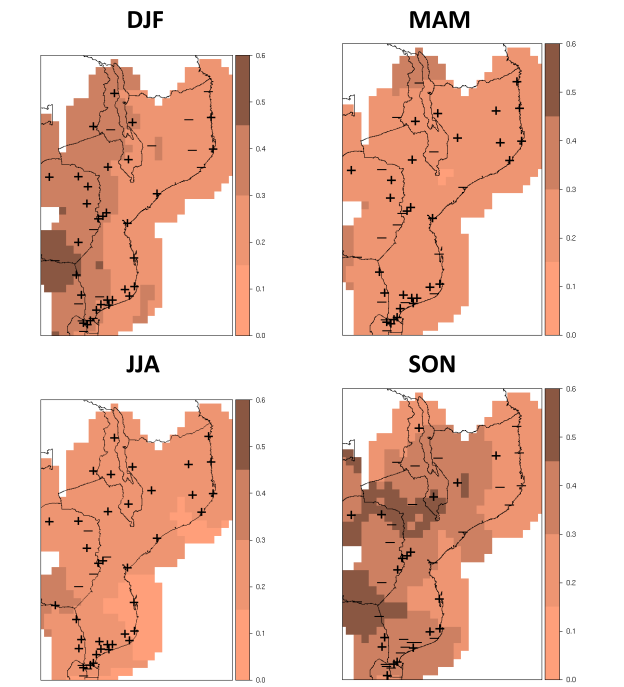


Figure 11: Median changes in future potential evapotranspiration (mm day^{-1}) from 7 GCMs (2046-2065 period). "+"/"-" indicates whether seasonal variability is expected to increase/decrease in the future.

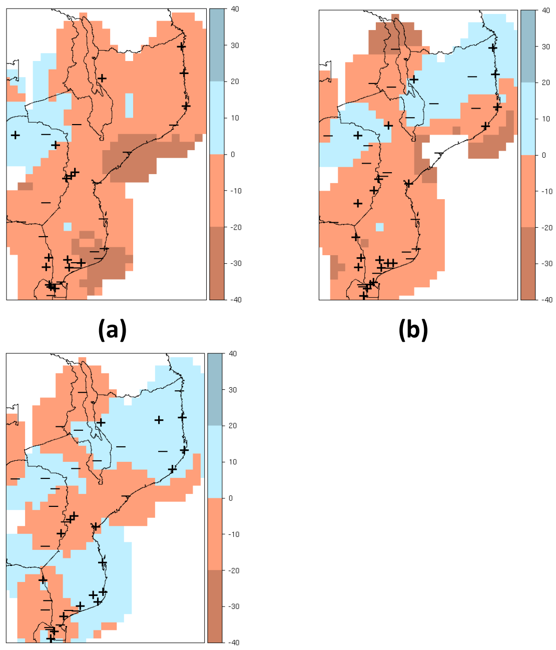
5.3 Potential evapotranspiration

As mentioned earlier the calculation of PET with data only for temperature requires the use of approximate methods. Both a modified Thornthwaite[15] (TW) and Priestly-Taylor[16] (P-T) method were tested with the TW method projecting greater increases in PET than the P-T method. However, given that the TW method is more appropriate for humid climates and that the P-T method is used more widespreadly within crop models over southern Africa, we use the P-T method in all calculations of PET in this report, though they may be considered conservative estimates. Even so, being temperature-only methods both TW and P-T do not account for potential changes in humidity and wind which would affect PET calculations using a standard Penman-Monteith method.

[15] Pereira, A. R. and W. O. Pruitt (2004). Adaptation of the Thornthwaite scheme for estimating daily reference evapotranspiration. *Agricultural Water Management* 66: 251-257.

[16] http://www.civil.uwaterloo.ca/Watflood/Manual/02_03_1.htm

Figure 11 shows the expected changes in PET for each season. It is clear that similar to increases in temperature, PET increases more inland away from the coast and that highest increases are found during SON, particularly over the Limpopo and Zambezi river valleys. This suggests that evaporation will increase significantly in these regions before the onset of the rainfall season, which, depending on changes in rainfall, could result in decreases in soil moisture before the main cropping season starts (this is investigated further in the following section). Besides these high increases in PET (which are also found during DJF in the western regions), increases in variability are suggested in the north during MAM and JJA, with increases in the south during DJF, MAM and JJA.



(c)

Figure 12: Median changes in future a) start, b) end and c) duration of the rainfall season from 7 GCMs (2046-2065 period). "+"/"-" indicates whether interannual variability is expected to increase/decrease in the future. Changes are given in days with negative values indicating an earlier start/end and reduced duration, whereas positive values indicate late start/end and longer seasons.

5.4 Seasonal and agrometeorological conditions

As mentioned in section 4.3 the start, end and duration of the season was calculated for the historical record, based on both rainfall-only and rainfall/PET criteria. These same criteria were used to calculate the projected changes in the start/end and duration in the future climates of the 7 downscaled GCMs. Because the rainfall/PET criteria (rainfall/PET > 0.5 marks the rainfall season boundaries) is more robust to climate change

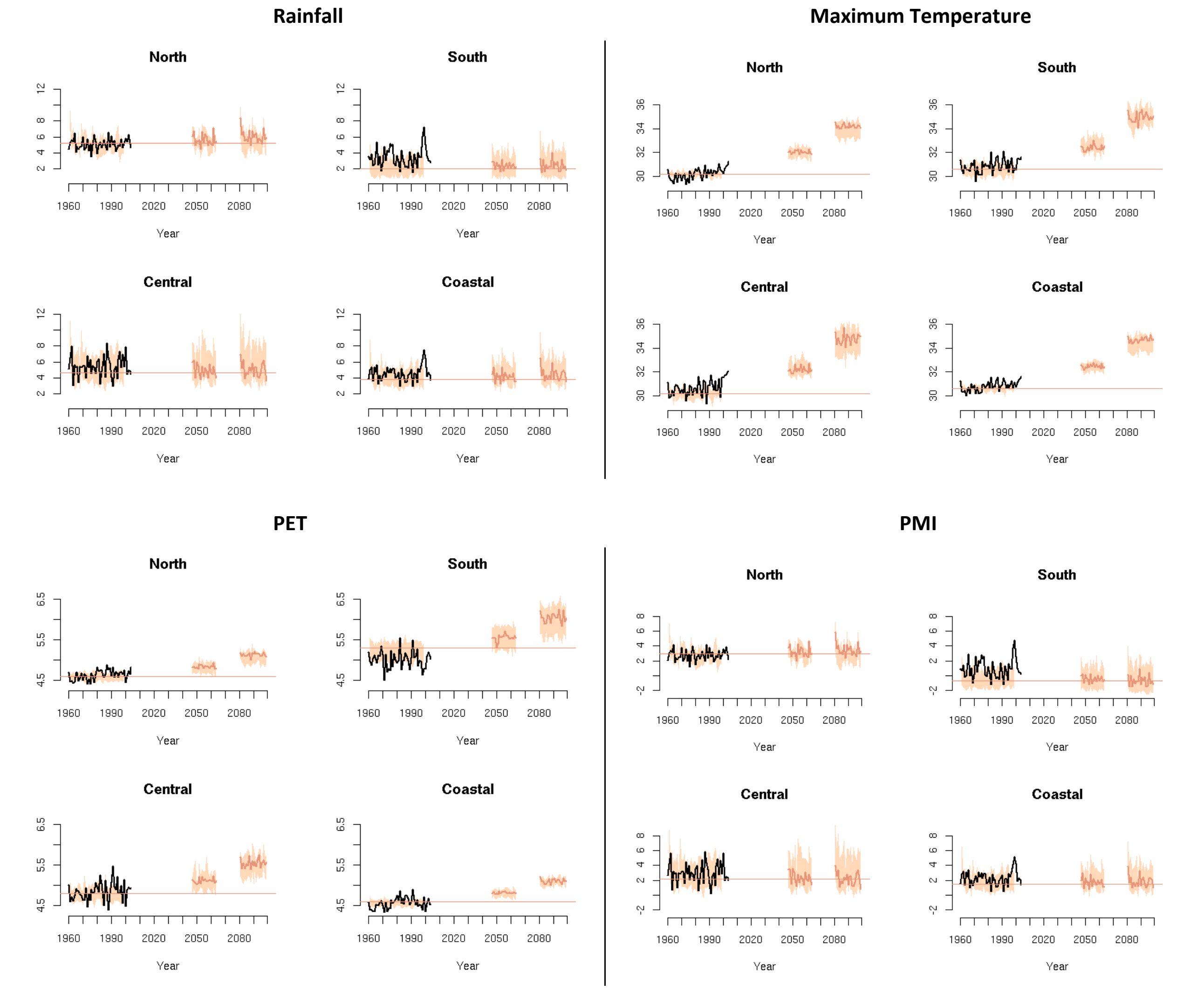


Figure 13: Interannual variability for the November-April season for each of the 4 regions: a) Rainfall (mm day^{-1}); b) Maximum temperature (°C); c) PET (mm day^{-1}) and d) Rainfall – (0.5*PET) (PMI) (mm day^{-1}). Orange shading is the GCM intermodel range, dark orange is the median of the models and the black line is the station observations. Horizontal orange line is the mean of the 7 GCM control climate simulations.

(due to increases in evaporation) we only show the results of these calculations, which are presented in Figure 12.

Figure 12a demonstrates that according to these criteria the rainfall season may be expected to start earlier over most of the country, though it is also expected to end earlier in the south and later in the far north (Figure 12b). This results in longer rainfall seasons in the north and southern regions towards the coast, but decreases in seasonal duration over the central regions and Zambezi valley (Figure 12c). Whilst this provides an indication of these seasonal changes in the start, end and duration of the season it should be noted that the results are highly dependent on the calculation of PET – here we have used the method which estimates the least increases in PET and therefore provides the most favourable estimates of changes in these seasonal characteristics. The following section provides further information on these modelled changes.

6 Changes in regional climate

Given the shifting changes in climate demonstrated for different locations in the previous section and the need to understand change from a more regional perspective we calculated rainfall, minimum and maximum temperature, PET as well as indices for the start, end and duration of the season for the four regions identified in Figure 2 (“North”, “Central”, “South” and “Coastal”). These data were taken as the means of all stations that fell in the following latitude bands: -15.5°S > North, -21°S < Central< -15.5°S, -21°S > South, with the Coastal region

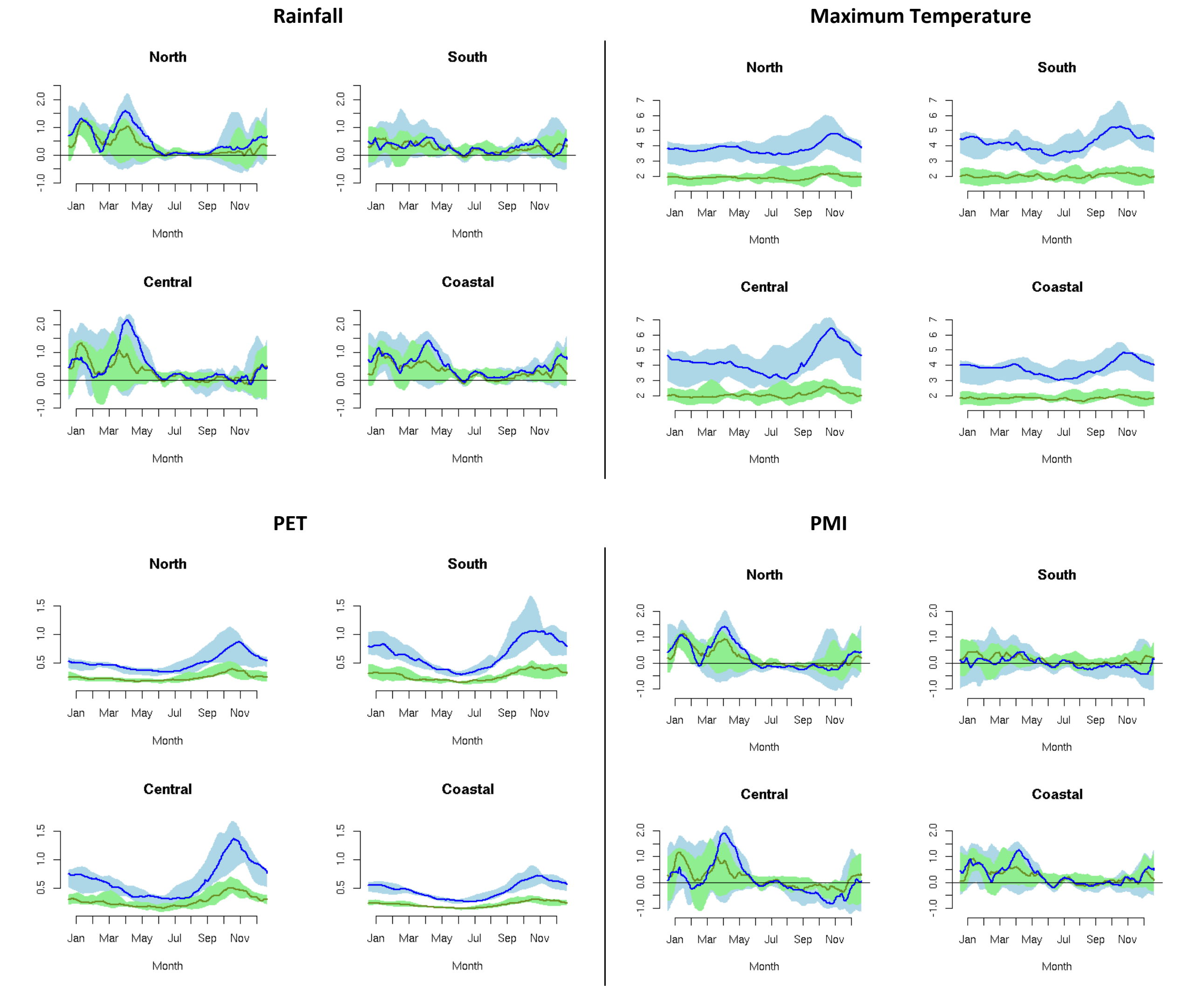


Figure 14: Changes in the annual cycle of a) Rainfall (mm day^{-1}); b) Maximum temperature (°C); c) PET (mm day^{-1}) and d) Rainfall – (0.5*PET) (PMI) (mm day^{-1}) simulated by 7 GCMs for the north, central, southern and coastal regions. Green shading indicated the range (olive line the median) for the 2046-2065 period, blue shading the range (blue line the median) change for the 2080-2100 period.

compromising a subset of the 27 stations found only on the coast. This led to the grouping of stations shown in Table 5.

Region	Stations
North	Cuamba, Lichinga, Mocimboa da Praia, Montepuez, Pemba, Lumbo, Nampula
Central	Angoche, Beira Aeroporto, Chimoio, Messambuzi, Quelimane, Sussengenga, Tete
South	Changalane, Chockwe, Inhambane, Inharrime, Macie, Manhica, Maniquenique, Manjacaze, Maputo Mavalane, Panda, Umbeluzi, Vilanculos, Xai-Xai
Coastal	Mocimboa da Praia, Pemba, Lumbo, Angoche, Quelimane, Beira Aeroporto, Vilanculos, Inhambane, Inharrime, Xai-Xai, Manhica, Maputo Mavalane

Table 5: Grouping of INAM stations into regions

As nearly all the stations in the southern region are found towards the coast it was found that the results for the coastal region closely resembled those for the south, though this is clearly inconsistent with the different climate found in the inland regions of Gaza province. Therefore to better represent these regions in the results for the south it was decided to add those stations from South Africa and Zimbabwe, shown in appendix B, that lay between 21°S and 26.2°S.

6.1 Changes in rainfall, temperature, PET and potential moisture index

Figure 13 presents regionally averaged rainfall, maximum temperature, PET and (Rainfall – (0.5*PET)) (taken as an index of potential surface moisture "PMI") for the station observations (black line), modelled range (orange shading) and modelled median change (dark orange line) for the November-April season during the past (1960-2000) and for two future periods (2046-2065) and (2080-2100). When looking at the 1960-2000 period, the modelled range of climates can be seen to correspond to the observed climate (black line) providing confidence that the downscaled models are simulating the most important aspects of Mozambique climate (besides a detectable bias for simulating too little rainfall in the south). Most of the noticeable trends in the observations (black lines) are related to temperature, with obvious increases in maximum temperatures and PET in the central region. These changes are simulated to increase in the future with higher increases for the 2080-2100 period than the 2046-2065 period, consistent with the observed trends. There are no obvious changes in mean rainfall (Figure 13a) during the 1960-2000 period, though there is noticeably higher interannual variability in the southern and central regions. In the future periods it can be seen that the median simulated change is close to mean of the control climate simulations (horizontal orange line), indicating that both negative and positive rainfall changes are simulated. PMI (Figure 13d) clearly shows that most regions have 6 month means that are positive during the 1960-2000 period, demonstrating that during this period there is mostly more rainfall than evaporation (negative values indicate potentially more evaporation than rainfall, whereas positive values indicate potentially more rainfall than evaporation). The exception is the south which is clearly a region that often has negative PMI and therefore is more prone to drought. Again however, these calculations rely on the method of calculating PET and so are likely an optimistic estimate. Furthermore these changes are shown for the November-April main rainfall season (similar figures for the four main seasons are given in Appendix E) and ignore seasonal fluctuations which change how rainfall, temperature and PET interact at different points in the seasonal cycle. In particular, evaporation is often greater than rainfall in the winter and early summer period. The following section therefore looks in closer detail at the timing of these rainfall increases/decreases and when the water balance is likely to be positive/negative.

6.2 Changes in the seasonal cycle of rainfall, temperature, PET and potential moisture index

To elaborate on changes in seasonality, Figure 14 shows the changes in rainfall, maximum temperature, PET and PMI on an annual basis for each of the 4 regions. Most models (and the median model) in all 4 regions suggest increases in rainfall during most of the rainfall season in both future periods. The largest increases occur during the late summer, particularly in the central, northern and coastal areas, with higher increases during the later 2080-2100 period. Increases in maximum temperature and PET are apparent all year round and are particularly high between September and November before the main rainfall season starts. These sharp increases in PET are partly reflected in the negative changes in PMI during this period (Figure 14d), despite the slight increases in rainfall during the same period (Figure 14a). These negative changes are more negative in the central region and during the 2080-2100 period in all regions. Altogether they suggest that the winter dry season will become drier everywhere in the future, more so during the 2080-2100 period.

6.3 Thresholds and frequencies of extreme temperatures

Given the increases in average temperature simulated for the future climates it is expected that the frequency with which daily maximum temperatures will exceed critical thresholds will increase in the future. This is clearly demonstrated in Figure 15 which shows for each region and period the simulated frequency (1 minus the cumulative probability) with which maximum daily temperature exceeds 35°C. In each plot the observations for the region are shown as the black line and in each case this can be seen to closely follow the simulated control periods of the GCMs (orange line), providing confidence that the GCM simulations are realistic during this period. The probability/frequency with which this critical threshold is exceeded ranges between 0.02 (for

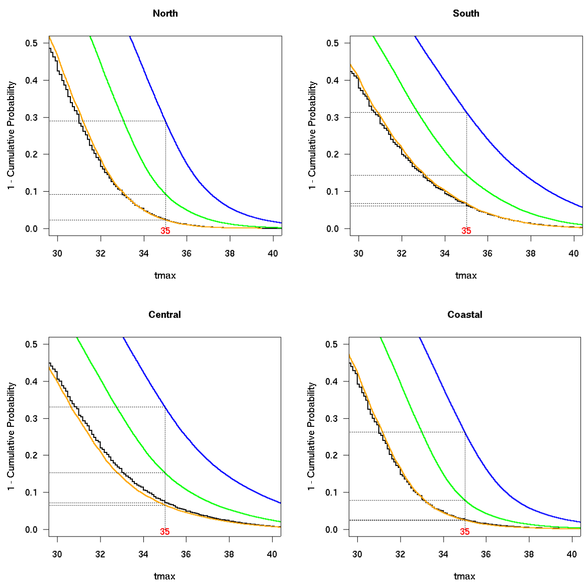


Figure 15: Frequency (1 – cumulative probability) with which maximum daily temperature exceeds 35°C in the observations (black line), simulated 1960-2000 (orange line), 2046-2065 (green line) and 2080-2100 (blue line) periods, for each of the four regions. The cumulative distributions are an amalgamation of the downscalings from all 7 GCMs.

the coastal and northern regions) and 0.07 (for the central and southern regions). There is an approximate increase to between 0.08 and 0.14 respectively during the simulated 2046-2065 period, representing an increase in the likelihood of this extreme temperature by approximately 7%. In the far future 2080-2100 period the increase in the likelihood of attaining this temperature is greater than 25% in all regions (as high as 33% in the central region). Given the seasonal cycle of these changes presented in the previous section and that maximum temperatures often occur during the September-November period before the rains, it is to be expected that many of these exceedance days will occur during this period in the future.

7 Climate change scenarios for flood and crop-suitability modelling

The scenarios developed as part of this component of the INGC project are not a standalone component and the expectation was that they would be used downstream as inputs into further impact modelling. This impact modelling had two components: 1) crop-suitability modelling undertaken by IIAM and 2) Flood risk modeling undertaken by Ara-Sul and another international consultant. Both of these components had specific requests when it came to data requirements and formats to run the flood-risk and crop-suitability models. This aspect of the project took a long time to work out and required a lot of consultation via emails and telephone conversations for the author to understand the specific requirements of the impact modellers, as well as for the impact modellers to understand the peculiarities of the climate science, models and data. It should be noted that the author is not an expert in either of these models and therefore may (accidently) misrepresent some of the complexities. Here we provide a summary of the pertinent points that came to light during the course of the project for future reference when undertaking this type of work.

7.1 Crop-suitability modelling

The crop suitability modelling undertaken by IIAM utilised an agroecological model based on principles established by the United Nations Food and Agricultural Organisation. These are in some ways similar to the ways in which the start and end of the season has been defined in this report (using a ratio of rainfall/PET of 0.5 to define the seasonal boundaries). However, the model uses monthly mean data and uses crop-specific coefficients and soils data to define water use and land suitability. Whilst the end product and information is presented in the form of GIS maps, most of the calculations are done in excel using baseline data from 135 agromet and synoptic stations scattered around Mozambique. This presented a problem in that the climate change scenarios were only for the 27 INAM stations mentioned previously.

Therefore the initial step was to take the INAM stations and interpolate (using a kriging algorithm) their projected changes in monthly mean rainfall, maximum and minimum temperatures and PET to the locations of the 135 IIAM stations. As the baseline data from the 135 stations wasn't readily available, the projected changes in climate were added to a baseline created by interpolating the INAM observations. However, it was realised at a late stage that this baseline data was unrealistic (largely because there are no INAM stations in

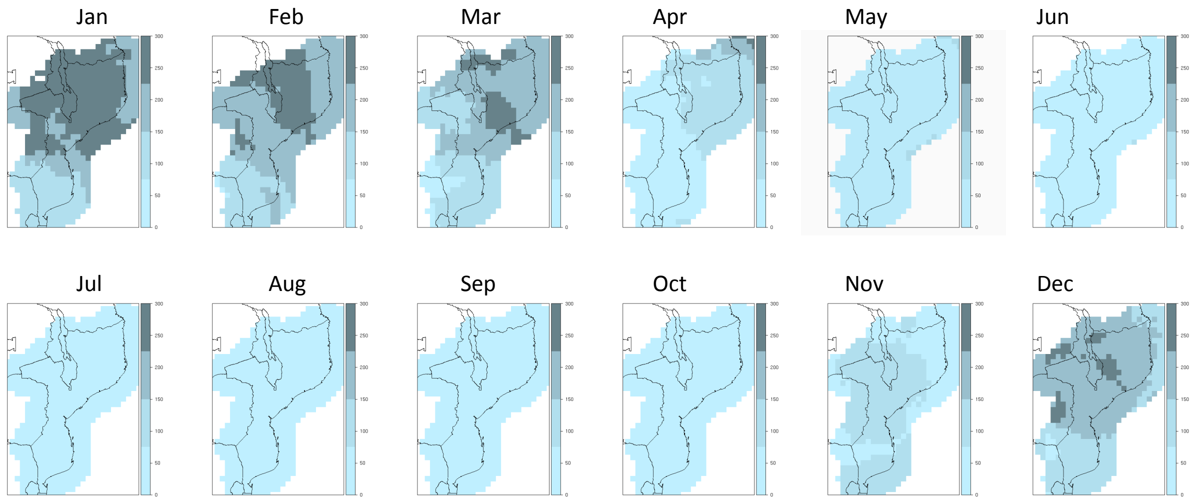


Figure 16: IIAM baseline rainfall for each month, created from the 135 IIAM stations.

the central southern regions and so the created baseline largely reflected the coastal stations used to create the data). Therefore it was decided that IIAM should digitise the baseline data for the 135 stations (shown in Figure 16), which was sent to the author who then added the climate change data to this original baseline.

Even so this still presented a logistical problem of running the crop-suitability model with 135 stations for each of 7 downscaled GCMs (representing data for 945 stations). IIAM indicated that this was not feasible and so it was decided to run with only 3 GCMs representing a dry, medium and wet model. This is a very crude approximation as each model will only be dry, medium or wet at specific times of the seasonal cycle and so may miss some of the major impacts. Even so there was no real alternative and so this is how the modelling proceeded. Finally the last hurdle was to import all the climate change scenarios into excel as manually importing the data was not feasible. This was accomplished via a routine written using the R software.

7.2 Flood risk modelling

The flood risk modelling represents a major step forward in the modelling of climate change impacts in southern Africa. It was mostly feasible as it builds on much of the work implemented by FEWS-NET within the region for flood risk monitoring – largely a response to the 2000/1 floods in Mozambique. Even so developing a downscaled climate change dataset for this work was a challenge. Station data could not be used as the flood model requires gridded data and for larger regions e.g. the watersheds of the Limpopo and Zambezi rivers which stretch across large parts of southern Africa.

Eventually it was decided to try and downscale the GCMs using the satellite based Rainfall Estimates (RFE) as the observed training data. These satellite data are currently used by the model for monitoring purposes. However, there have only just become available a long enough daily timeseries for use as the training data (a minimum of 10 years of data is required) and the the problem was to adapt the data or downscaling code to work with the geographic projection the data came on. To get around this problem the flood modellers took the RFE estimates and used them to produce daily estimates of rainfall at each sub-basin centroid as well as the geographic location of each sub-basin centroid. These data were then used in the downscaling in a similar manner to the station data, though due to the large dataset it took 48 hours of continuous calculations to run the downscaling. Whilst the rainfall data used for this modelling is a different observational source than the INAM (+ other country) station data used for the analysis in this report and the IIAM modelling, it can be expected to produce estimates of change that will be spatially consistent with these other downscaled data. This stems from the fact that the same spatial patterns in the GCM data are used to resample the observed data in each case. There may be differences in the magnitude of estimated changes, especially where the satellite-based RFE data may be biased with respect to observations on the ground, but the RFE observations have the advantage that they are valid for spatially gridded regions. Assumptions regarding the spatial representivity of point measurements, such as are made when kriging the station data, are not required for the RFE data.

The output downscaled data files were then reformatted to the same format that the data were given as and then sent back to the flood modellers. It was decided that the flood modelling would undertake to use all 7 downscaled GCMs to get a clear handle on the range of projected changes.

One important drawback of this proposed modelling approach was that the statistical downscaling methodology is currently based on historical observations and so is unable to project daily rainfall intensities beyone what is currently experienced at a particular location. It therefore underestimates the maximum potential floods in a future climate, though it can capture changes in the frequency of large floods. Current research is seeking to address this issue in the near future.

8 <u>Reconciling observed and expected future change</u>

The projected changes in rainfall and temperature for the middle and end of the 21st century that have been presented here are linked to physical changes in the regional climate system, which offers a way to reconcile observed trends and future projected change where they are different. Consistently projected future change is a consequence of the following physical changes:

1. Increase in temperature, which promotes convective activity, especially during mid-late summer
2. Increase in humidity, which increases the amount of moisture available for rainfall once it is triggered.
3. Retreat of the mid-latitude storm systems and increases in the continental high pressure system during winter (and potentially autumn and spring)

However, these changes in the physical system will interact and couple in a non-linear manner and individually manifest themselves at different periods in the future. The regional expression of change is therefore dependent on which mechanisms, which may compete with each other (e.g. increases in rainfall may offset decreases in rain days), are dominant at any particular time. Unlike the temperature signal due to climate change, which is currently observable, the rainfall signal (as estimated from low variability GCM data and therefore likely a conservative estimate) is not expected to be observable for several decades.

Reconciling these past and future changes is a difficult, yet necessary challenge, if climate science is to better inform those involved in planning disaster risk reduction and adaptation activities. Where current (statistically significant) trends are in line with projected change, and the physical mechanism related to both is understood, planning and adaptation related to such changes have firm grounds for moving ahead. However, where there are observed statistically significant trends at most stations within a given area, but future projections (all models) either disagree on the sign of the change or are inconsistent, then further investigation is required as observed changes may be due to natural variability. In the case when there are no consistently observed significant trends, but projections suggest a change that is physically plausible, further monitoring is necessary to detect any such changes if and when they happen in the future.

From the data presented in this report, increases in temperature are already apparent across Mozambique and much of this increase has happened since 1990. Changes in rainfall are, however, much harder to detect due to it's spatial and temporal heterogeneity. Indeed it is possible that multidecadal variability will dominate any climate change signal in the rainfall record in the near future. Even so this does not mean that human and ecological systems are not moving beyond critical thresholds and many of the changes noted here need to be evaluated within their specific social, economic and/or ecological settings. A good example of this would be cropping/farming systems which are currently close to critical thresholds of either water availability or seasonal duration (for growing specific crops). Increases in temperature alone (with no significant change in rainfall) could make the cultivation of particular crops unviable. This may be an immediate problem facing farmers in semi-arid regions. The projected increases in rainfall which are simulated by the climate models in the far future and which could offset some of these difficulties are not immediately relevent as these beneficial changes have yet to occur. Therefore the scenarios presented in this report are quite possibly optimistic from this viewpoint.

9 Recommendations for further work and analyses

One obvious recommendation for future work would be to use more downscaled GCMs to better capture the potential range of climate changes in the future (including using data for another scenario e.g. the B1 SRES emissions scenario). However several other important aspects of the modelling process, as well as the scientific limitations and application of the data for the purposes required by INGC, present themselves. To summarise the most pressing problems:

1. There is a lack of information regarding the vulnerability of society to critical climate thresholds. If such thresholds are provided then the climate information can be tailored to be more relevent to particular sectors and impacts;
2. Potential increases in maximum daily rainfall are not simulated in the present methodology. One way to overcome this would be to use the output of a dynamical regional climate model to better understand changes in maximum rainfall and hence maximum floods;
3. Determining when in the future rainfall increases may offset the negative impacts of increases in temperature is a key question. This is unlikely to resolve itself with more climate change modelling, therefore it is recommended that the project look at developing scenarios of near-term climate change based on existing trends and knowledge of how the climate may change in the next 20 years. These should be developed as scenarios, rather than explicitly using GCMs to model the future climate;
4. Linked to points 1 & 3, it would be useful to identify specific regions and sectors for more detailed analyses and for which 'extreme' or 'outlier' scenarios of change (not the median change) may be important.

Whilst some of these issues have been touched on during the course of the project, much more work is needed to adequately address the information requirements of INGC.

Acknowledgements

We wish to acknowledge the STARDEX[17] team and ETCCDMI[18] for making available the software for calculating the extreme indices and testing for homogeneity of the station data. We are also grateful to INAM for providing the station data and Prof Bruce Hewitson of the University of Cape Town for allowing his downscaling code to be used. The downscaling code uses the CMIP3 dataset and we wish to acknowledge the

[17] http://www.cru.uea.ac.uk/projects/stardex/
[18] http://cccma.seos.uvic.ca/ETCCDMI/software.shtml

modeling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the WCRP's Working Group on Coupled Modelling (WGCM) for their roles in making available the WCRP CMIP3 multi-model dataset. Support of this dataset is provided by the Office of Science, U.S. Department of Energy.

10 Appendix A: extreme indices

Extreme indices calculated at each synoptic station annually and for the SON, DJF, MAM, JJA seasons:

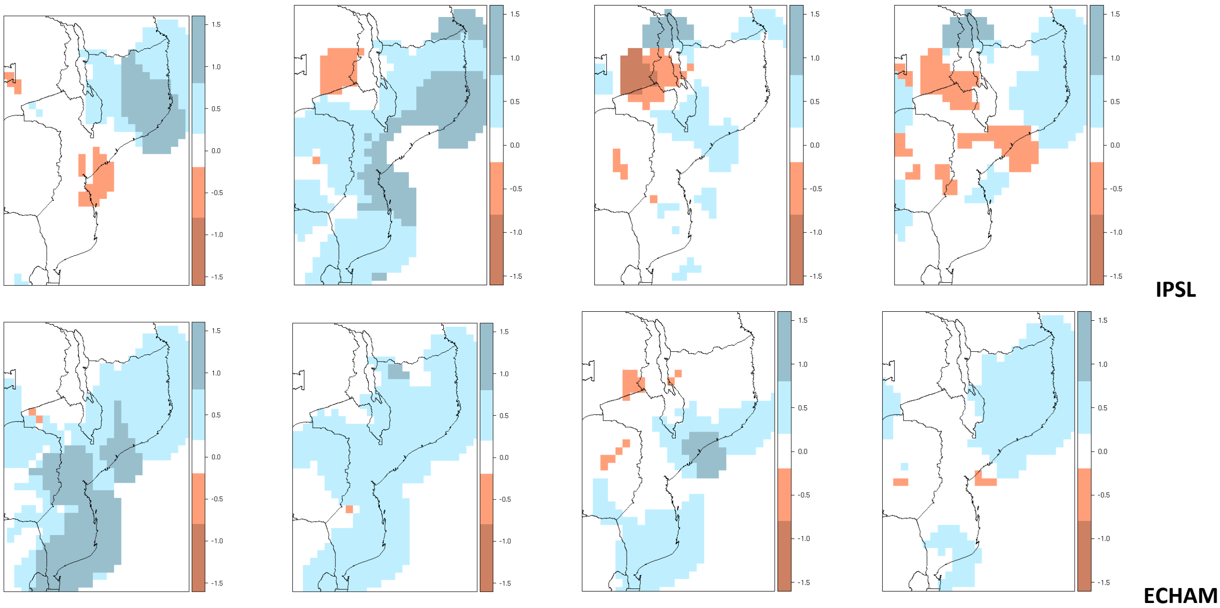
txav	Mean Tmax
tnav	Mean Tmin
tav	Mean Tmean
trav	mean diurnal temperature range
trq10	10th percentile diurnal temperature range
trq90	90th percentile diurnal temperature range
txq10	Tmax 10th percentile
txq90	Tmax 90th percentile
tnq10	Tmin 10th percentile
tnq90	Tmin 90th percentile
tnfd	Number of frost days Tmin < 0 degC
txice	Number of days without defrost (ice days) Tmax < 0 degC
tgdd	Growing degree days > threshold
tiaetr	Intra-annual extreme temperature range
tgsl	Growing Season Length
txhwd	Heat Wave Duration
txhw90	90th Percentile Heat Wave Duration
tncwd	Cold Wave Duration
tncw10	10th Percentile Cold Wave Duration
tnfsl	Frost Season Length (0 degC)
txf10	% days Tmax < 10th percentile
txf90	% days Tmax > 90th percentile
tnf10	% days Tmin < 10th percentile
tnf90	% days Tmin > 90th percentile
pav	Mean climatological precipitation (mm/day)
pq20	20th percentile of rainday amounts (mm/day)
pq40	40th percentile of rainday amounts (mm/day)
pq50	50th percentile of rainday amounts (mm/day)
pq60	60th percentile of rainday amounts (mm/day)
pq80	80th percentile of rainday amounts (mm/day)
pq90	90th percentile of rainday amounts (mm/day)
pq95	95th percentile of rainday amounts (mm/day)
pf20	Fraction of total precipitation above annual 20th percentile
pf40	Fraction of total precipitation above annual 40th percentile
pf50	Fraction of total precipitation above annual 50th percentile
pf60	Fraction of total precipitation above annual 60th percentile
pf80	Fraction of total precipitation above annual 80th percentile
pf90	Fraction of total precipitation above annual 90th percentile
pf95	Fraction of total precipitation above annual 95th percentile
pn10mm	No. of days precip >= 10mm
pxcdd	Max no. consecutive dry days
pxcwd	Max no. consecutive wet days
ppww	Mean wet-day persistence
ppdd	Mean dry-day persistence
ppcr	Correlation for spell lengths
pwsav	mean wet spell lengths (days)
pwsmed	median wet spell lengths (days)
pwssdv	standard deviation wet spell lengths (days)
pdsav	mean dry spell lengths (days)
pdsmed	median dry spell lengths (days)
pdssdv	standard deviation dry spell lengths (days)
px3d	Greatest 3-day total rainfall
px5d	Greatest 5-day total rainfall
px10d	Greatest 10-day total rainfall
pint	Simple Daily Intensity (rain per rainday)
pfl90	% of total rainfall from events > long-term 90th percentile
pnl90	No. of events > long-term 90th percentile

11 Appendix B: stations outside Mozambique used in the analysis

Station ID and locations of station data outside Mozambique used to provide a regional perspective of scenarios and interpolate to regions with sparse data coverage within Mozambique.

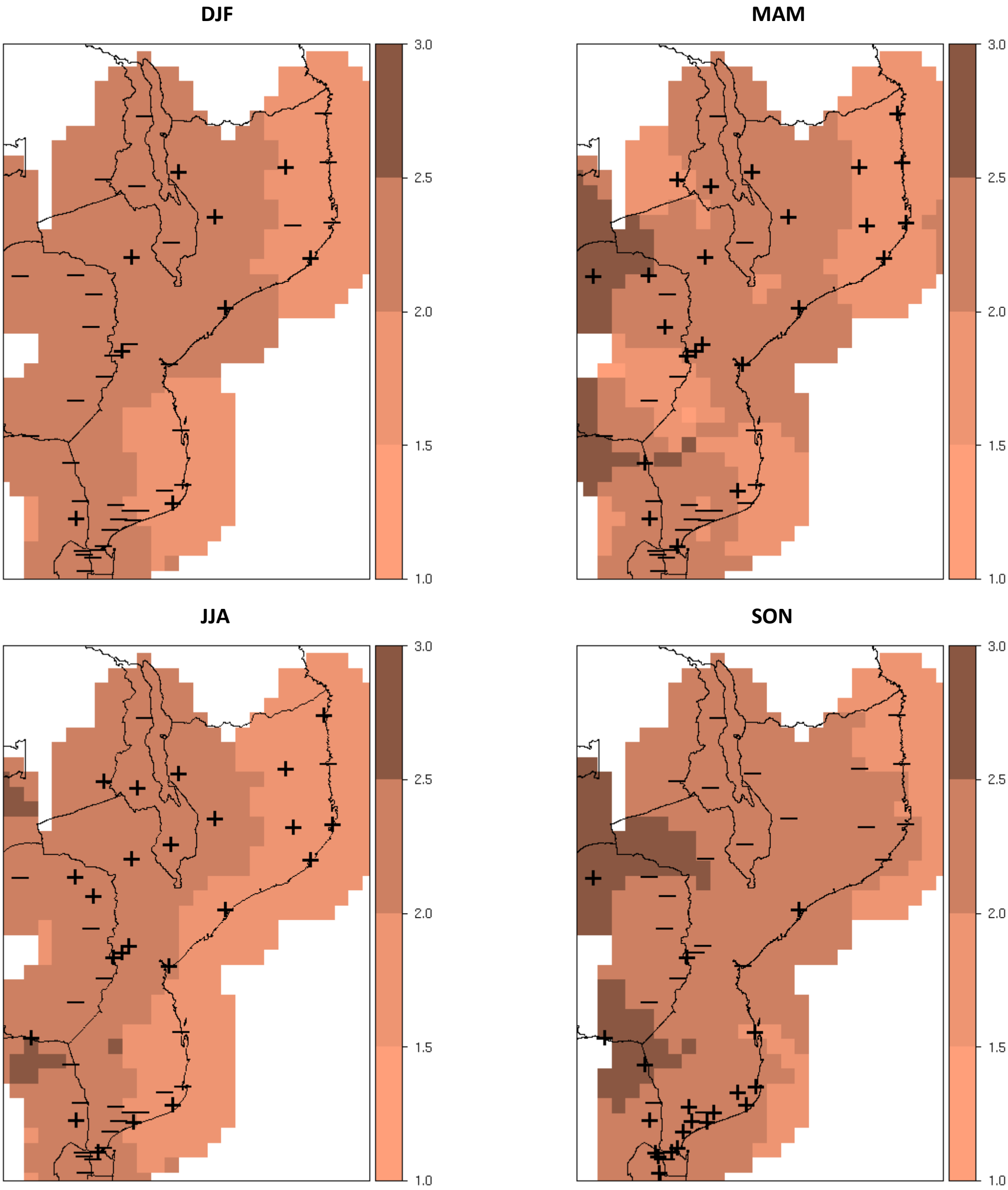
Station ID	Latitude	Longitude
WMO stations		
68496	-28.50	32.40
68296	-24.98	31.60
67991	-22.22	30.00
67977	-21.02	31.58
67983	-20.20	32.62
67881	-18.53	32.13
67781	-17.42	32.22
67779	-16.78	31.58
67765	-16.83	29.62
67665	-15.32	28.45
67663	-14.45	28.47
67581	-13.55	32.58
67693	-15.68	34.97
67586	-13.78	33.77
67489	-11.45	34.02
WRC stations		
0725756AW	-23.10	31.43
0639474_W	-24.40	31.77
0483545_S	-26.08	31.82
0446766_S	-26.77	31.93
0483702_S	-26.20	31.90

12 Appendix C: changes in rainfall for each GCM



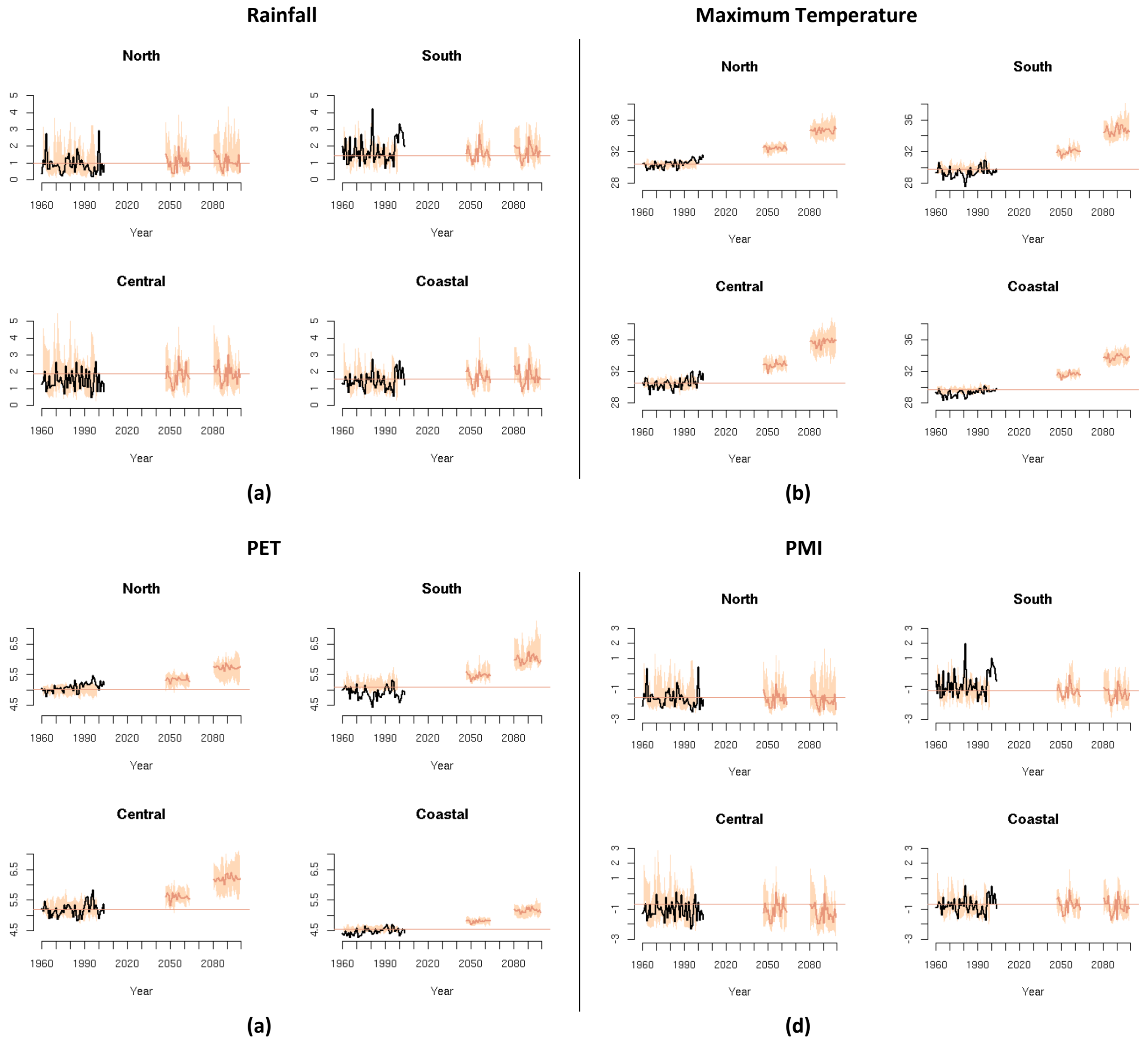
Downscaled seasonal changes in future rainfall (mm day^{-1}) for each of the 7 GCMs.

13 Appendix D: changes in minimum temperature

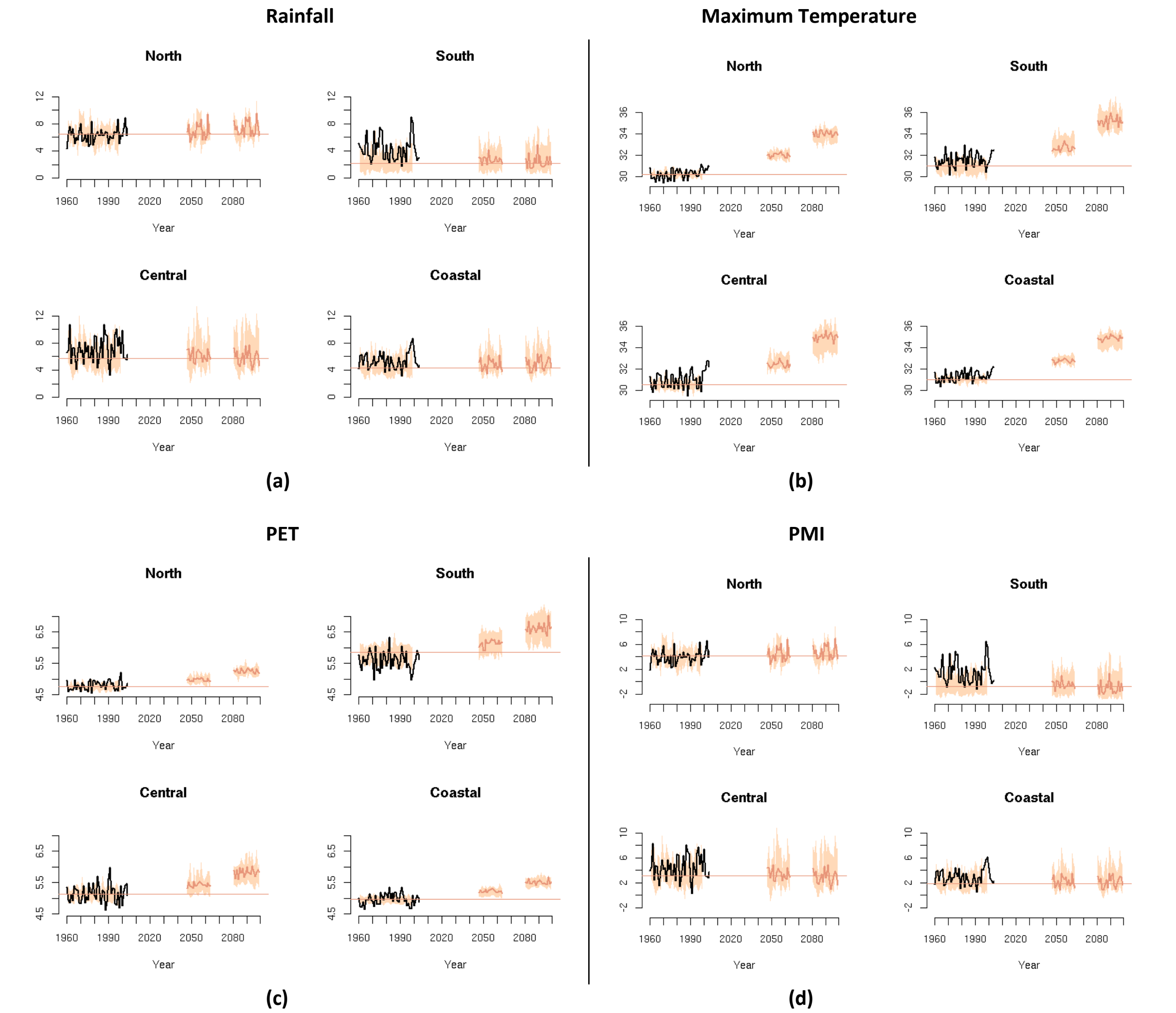


Median changes in future minumum temperatures from 7 GCMs (2046-2065 period). "+"/"-" indicates whether seasonal variability is expected to increase/decrease in the future.

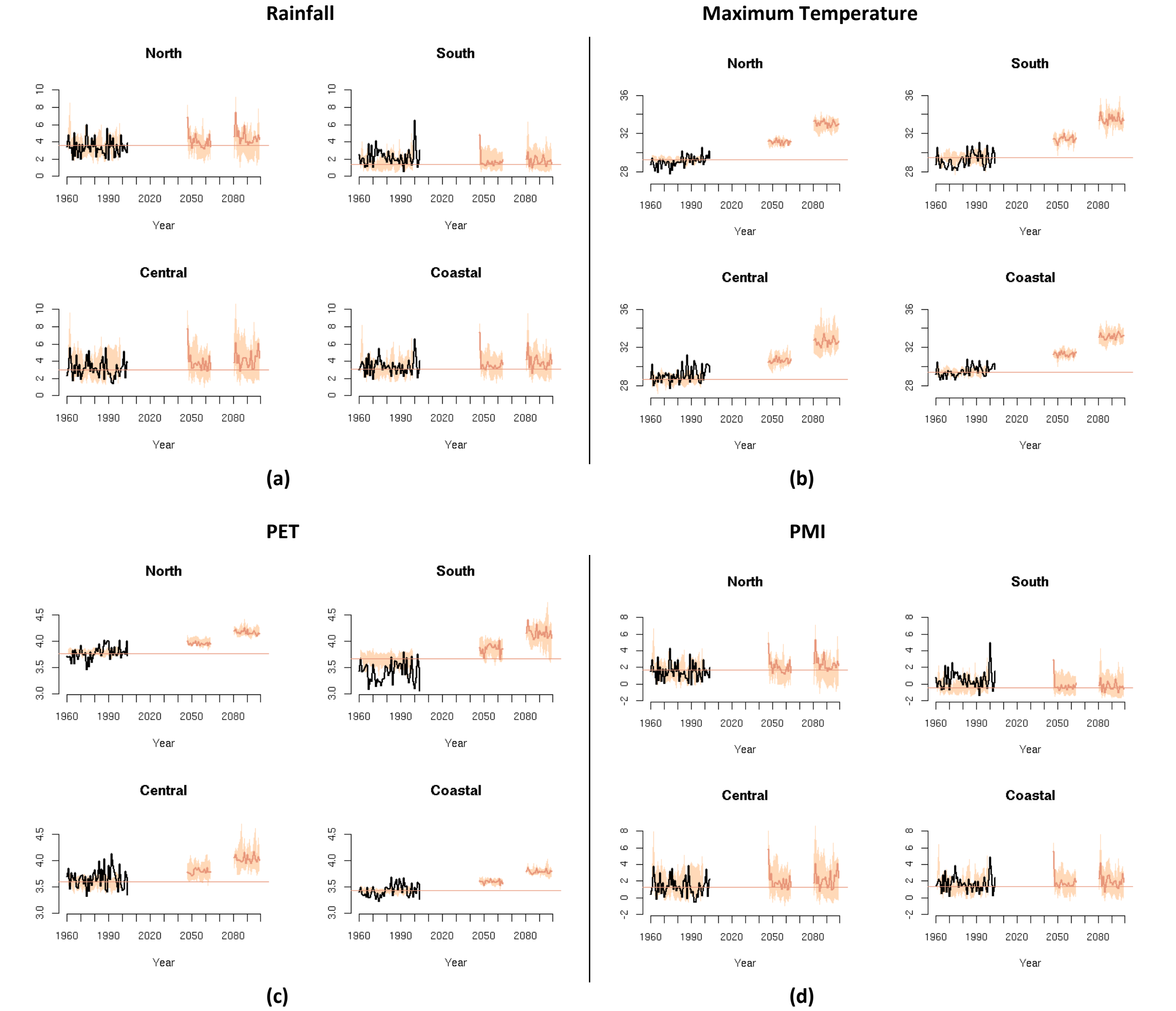
14 Appendix E: regional changes in rainfall, temperature and PET per season



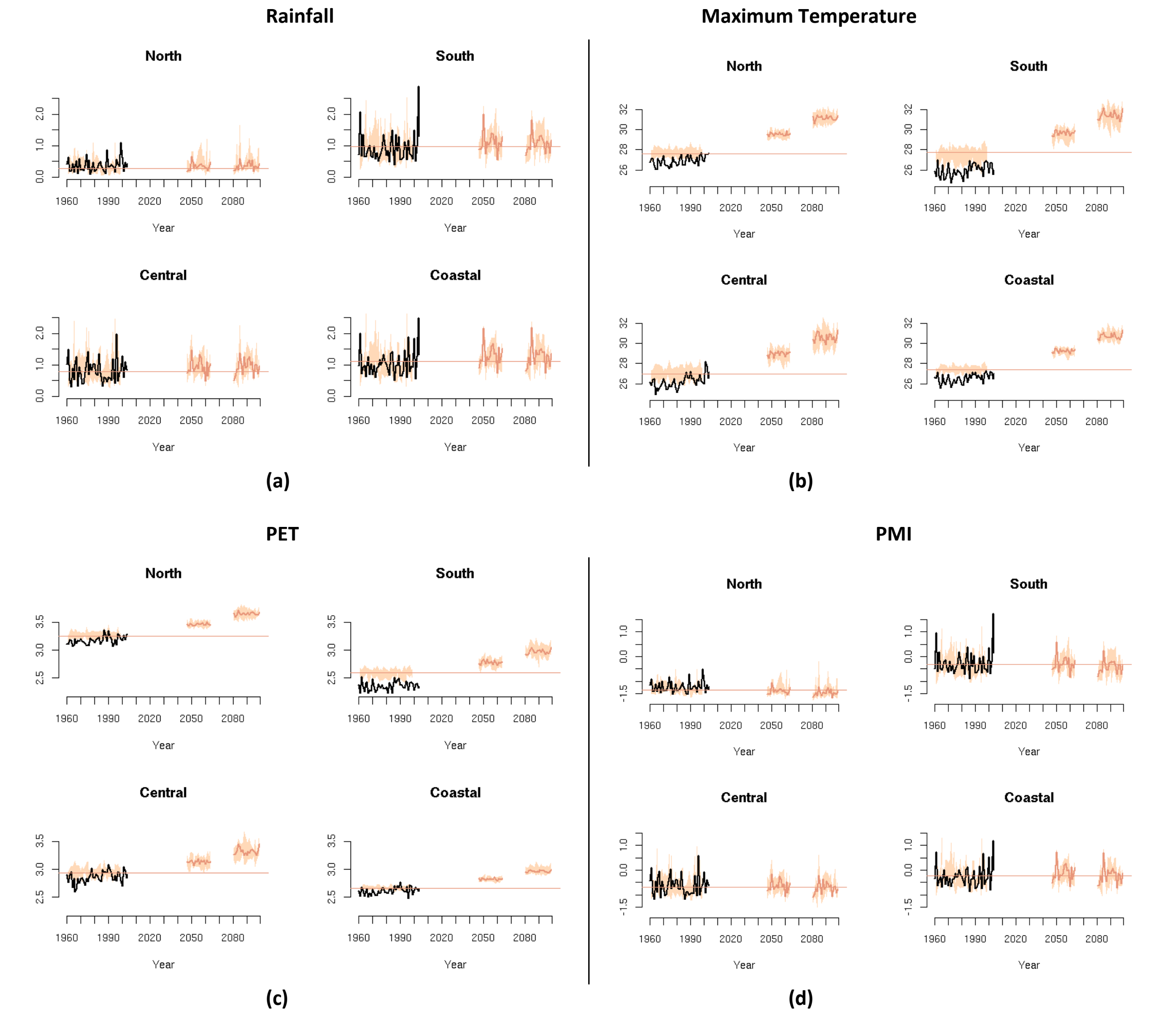
Interannual variability for the SON season for each of the 4 regions: a) Rainfall (mm day^{-1}); b) Maximum temperature; c) PET (mm day^{-1}) and d) Rainfall – (0.5*PET) (PMI) (mm day^{-1}). Orange shading is the GCM intermodel range, dark orange is the median of the models and the black line is the station observations. Horizontal orange line is the mean of the 7 GCM control climate simulations.



Interannual variability for the DJF season for each of the 4 regions: a) Rainfall (mm day^{-1}); b) Maximum temperature; c) PET (mm day^{-1}) and d) Rainfall – (0.5*PET) (PMI) (mm day^{-1}). Orange shading is the GCM intermodel range, dark orange is the median of the models and the black line is the station observations. Horizontal orange line is the mean of the 7 GCM control climate simulations.



Interannual variability for the MAM season for each of the 4 regions: a) Rainfall (mm day^{-1}); b) Maximum temperature; c) PET (mm day^{-1}) and d) Rainfall – (0.5*PET) (PMI) (mm day^{-1}). Orange shading is the GCM intermodel range, dark orange is the median of the models and the black line is the station observations. Horizontal orange line is the mean of the 7 GCM control climate simulations.



Interannual variability for the JJA season for each of the 4 regions: a) Rainfall (mm day^{-1}); b) Maximum temperature; c) PET (mm day^{-1}) and d) Rainfall – (0.5*PET) (PMI) (mm day^{-1}). Orange shading is the GCM intermodel range, dark orange is the median of the models and the black line is the station observations. Horizontal orange line is the mean of the 7 GCM control climate simulations.