CLIMATE SYSTEM ANALYSIS GROUP, UNIVERSITY OF CAPE TOWN

Rekomitjie Climate Variability and Change

Final Scientific Report

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This report presents the climate analysis within the larger WHO/TDR funded projected entitled: Human African Trypanosomiasis: alleviating the effects of climate change through understanding human-vector-parasite interactions, headed by the DST/NRF Centre of Excellence in Epidemiological Modelling and Analysis (SACEMA) of the University of Stellenbosch.

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Abstract

This report explores how the climate at Rekomitjie research station in the Zambezi River Valley has changed over the recent past and how it is projected to change into the future due to anthropogenic climate change. The work is based primarily on data obtained from the manual weather station located at the Rekomitjie research station. A more general overview of the regional climate is presented using data from three nearby weather stations and the WFDEI gridded dataset. An ensemble of Global Climate Models (GCMs) is used to explore the future climate. Results from both the raw GCM data and empirically/statistically downscaled data are presented.

The local climate at Rekomitjie is driven by both local and remote forcing; Topography plays a key role in determining the temperatures, while remote drivers, such as the El Nino-Southern Oscillation (ENSO), influence both the temperature and rainfall at interannual timescales. Rainfall shows strong year to year variability but no discernible trends are evident. Minimum and maximum temperature show clear trends, especially during the warmest season (September – November) over the last few decades. These warming trends within the warmest months of the year have resulted in new extreme temperatures being recorded and these have been associated with more frequent and extended heat-spells. There is little consensus between Global Climate Models on whether the climate is projected to get wetter or drier into the future, however all models agree that it will get warmer and that the warming will be larger than the global average. The magnitude of the warming is less certain further into the future since it depends on the future greenhouse gas emission path and on the GCM selected. Even so, the projected warming of all models is sufficient to result in a local extinction of tsetse flies at Rekomitjie.

Introduction

The Rekomitjie research station located in the Zambezi River Valley has been the site of significant tsetse fly research since 1959. This research has highlighted the importance of climate, and specifically temperature as being a key driver of tsetse population dynamics. The Rekomitjie Research Station has recorded daily rainfall and temperatures since October 1959 providing a long and relatively complete record of the local weather and climate at this location. This report explores this dataset, focussing on trends and extremes of relevance to tsetse flies. It then presents how the climate may change into the future due to anthropogenic climate change and whether these changes may result in a local extinction of tsetse flies in the area.

The Rekomitjie research station is located in the Zambezi River Valley along the north-west border of Zimbabwe. The station is located within an area that is historically highly suitable for tsetse flies. Figure 1 shows how the suitability for tsetse flies is distributed across the larger region. It is clear that altitude is a critical determinant of the distribution of tsetse flies, with the lower, and therefore warmer, areas having a much higher probability of being suitable. Rekomitjie is located within the Mana Pools National Park which supports a large population of wild animals that provide a source of blood meals to tsetse flies, and also a reservoir for Human African Trypanosomaisis. Figure 1 also displays the location of three other weather stations included in this study; The Kariba station, which is also within the tsetse fly area, and the Karoi and Lusaka stations, which are located at higher elevation and are outside of the current tsetse fly region.

Regional circulation patterns

The seasonal climate of a location is strongly driven by the larger-scale circulation patterns and how these change from season to season. The basic pressure distribution and movement of air masses during austral summer (December, January and February (DJF)) are presented in Figure 2. During this season, the Atlantic and Indian high pressure systems move southwards and the Indian Ocean High is located well out to sea. The SE trade winds that originate from the South Indian high pressure bring moisture laden air over the east coast of southern Africa. The Inter Tropical Convergence Zone (ITCZ) is formed where the South Easterly Trades converge with the North Easterly Monsoon winds which cross the equator during this season. The ITCZ is a region of pronounced convective activity and is generally evident as a northwest to southwest band of clouds over the lower reaches of the Zambezi Valley in Mozambique. Summer heating of the subcontinent causes the development of a heat low over northern Angola/Zambia. Air curves clockwise around this low from the Atlantic over Angola/Zambia and these winds are known as the south west monsoons. Another region of enhanced convection, called the Congo Air boundary, is formed where the south west monsoon winds meet the south easterly trade winds.

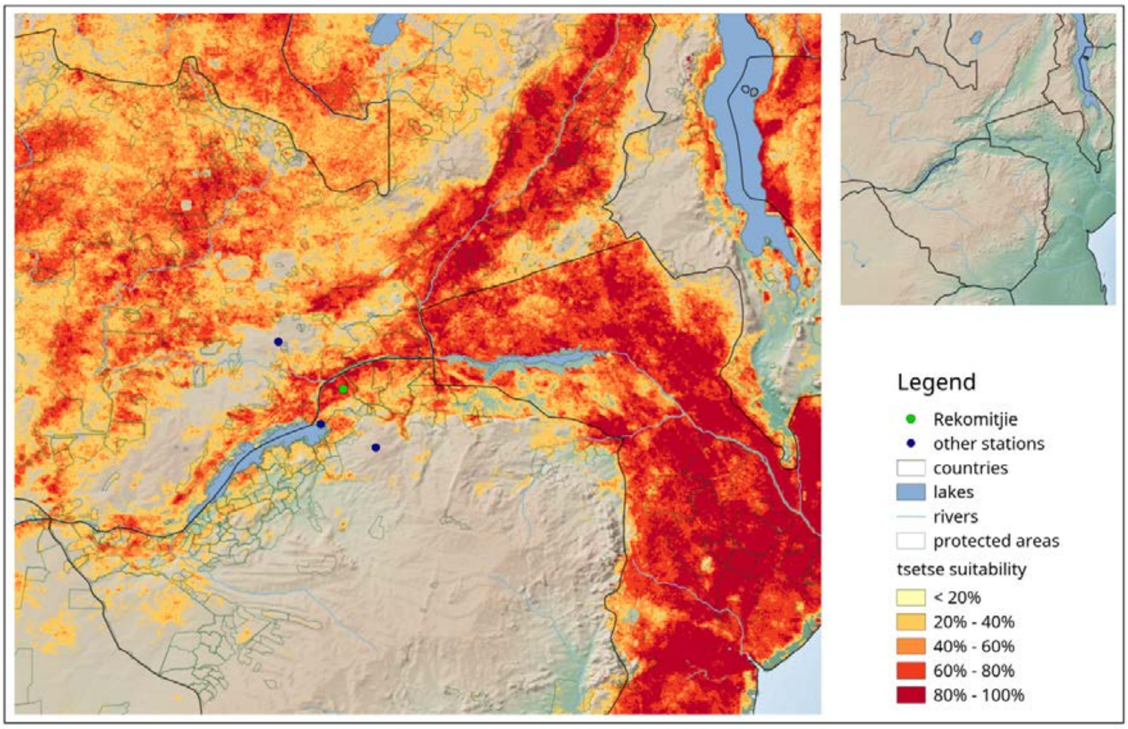
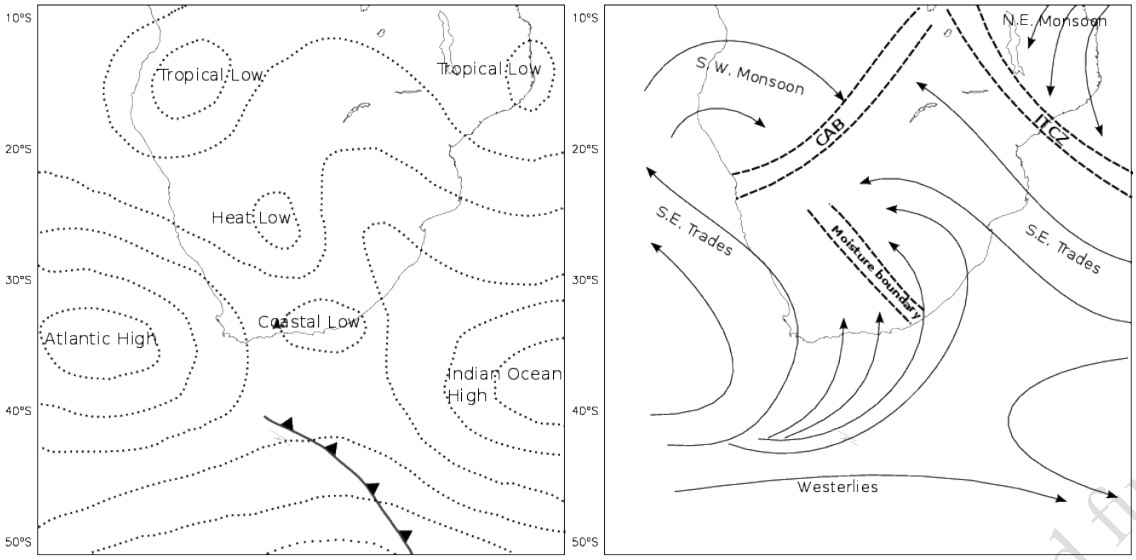


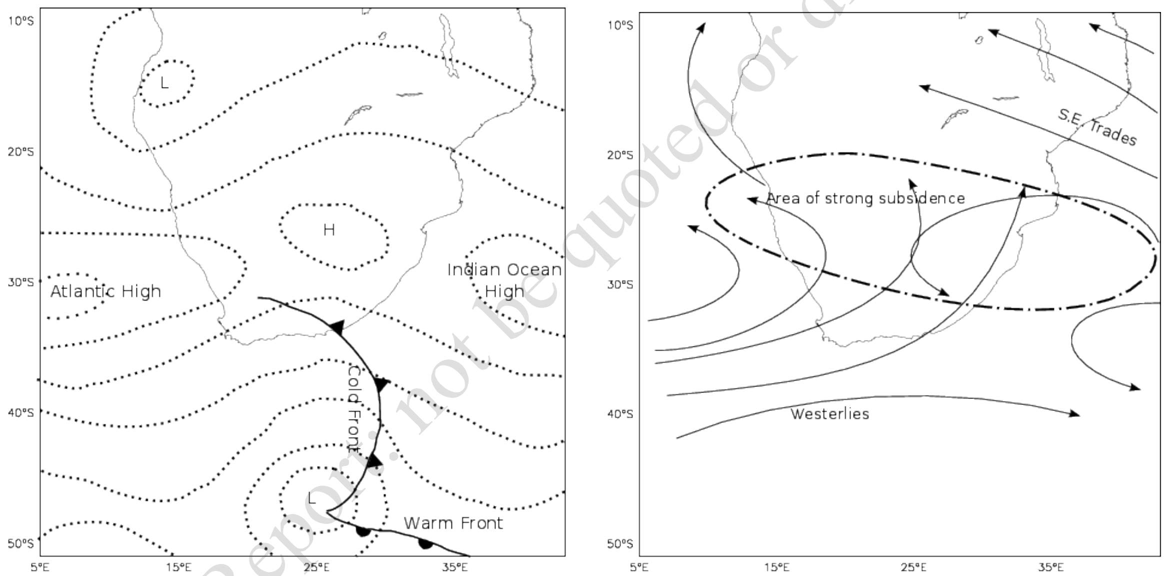
Figure 1: ***Tsetse fly suitability map.*** *Map showing the predicted areas of suitability for tsetse flies over the Zambezi valley. Tsetse fly suitability data from Wint and Rogers 2000. The location of the Rekomitjie station is presented in green, while the Lusaka, Kariba and Karoi stations are shown in blue.*

During winter the south Atlantic and Indian Ocean highs move north and the absence of a heat how over the interior often results in a linking of the two high pressures over the subcontinent. This high pressure and subsidence results in the clear skies and calm conditions experience over the interior of southern Africa during winter (Figure 3). The South Easterly trade winds still occur north of this belt of high pressure, However, no convergence and uplift occurs in the absence of the ITCZ and Congo air boundary which have moved north during austral winter.



(a) (b)

Figure 2: ***Features of the pressure distribution (a) and basin movement of air masses (b) over southern Africa during austral summer*** *(after Hurry and Van Heerden (1982))*



(a) (b)

Figure 3 ***Features of the pressure distribution (a) and basin movement of air masses (b) over southern Africa during austral winter*** *(after Hurry and Van Heerden (1982))*

Natural variability

Natural variability describes the year to year and decade to decade variations in the climate for a location or region and is a result of global scale oscillations. Local climate (i.e. rainfall at a location or region) is determined by a combination of a) large scale drivers, such as El Nino Southern

Oscillation (ENSO), North Atlantic Oscillation, and Indian Ocean Dipole, that influence the regional circulation patterns mentioned above; b) other local scale drivers such as regional Sea Surface Temperatures (SST), topography and water-bodies; and c) very local driver such as current vegetation or soil moisture conditions; and local stochastic effects such as the random location and track of a thunderstorm over a region.

The relative importance of different drivers of climate variability, from global scale oscillations, through to local stochastic processes, varies considerably from place to place. Typically, in relatively arid locations, where only a few convective rainfall events occur in a given rainfall season, local scale stochastic processes dominate. Indeed observations can show that locations less than 100km apart can experience above normal and below normal seasonal rainfall in the same season depending on the random location and track of particular rainfall systems that occur. In such regions, local water-bodies, vegetation and soil moisture feedbacks are also typically more important as they can become a significant moisture source, raising the atmospheric moisture levels sufficiently to allow convection, and thereby contribute towards the seasonal rainfall total.

In higher rainfall regions where rainfall events occur much more frequently, the local stochastic processes average out over more events and therefore there is far greater consistency between locations and inter-annual variability is typically lower and driven by larger scale processes.

Historical trends

Analysis of historical climate trends can provide useful insights into the current trajectory of various climate variables, as well as forming part of an understanding of the large scale drivers of regional climate. However, trend analysis is hampered wherever there is high variability in a time series, and/or short observational records. In such cases it becomes highly likely that the slope of any trend fitted to the time series, either visually, or analytically, is meaningless and very vulnerable to the particular time period used for the analysis. However, historical trends and variability can provide useful evidence pointing towards large scale climate drivers. In particular, the agreement between observed trends and trends simulated by a climate model strengthens confidence in climate model projections, as it suggests that the climate model is correctly capturing key processes and their influence on the regions climate.

The primary challenge in trend analysis is number and length of records. Unfortunately, for much of

Africa, there is a shortage of reliable records, and those that do exist are often short and suffer from poor data quality. This strongly limits the robustness of trend analysis of station observations. Gridded products bases on satellite derived estimates or merged satellite data and station observations can be used. But often variations in station coverage through time, and satellite sensor variance can introduce artificial trends in such datasets. It is therefore important to interpret trends, particular for high variance variables such as precipitation, with great caution. Where possible, multiple data sources should be compared.

Climate projections

Global Climate Models (GCMs) are the only feasible way to explore how the climate system might change into the future due to increasing green-house gas concentrations. They are widely used for this purpose, most significantly through the Coupled Model Inter-comparison Project (CMIP)[1], the multi-model ensemble suite that informs the Intergovernmental Panel on Climate Change (IPCC) reporting process.

There are two key considerations when deriving climate information from GCMs in the CMIP archives. Firstly, all the models included in the CMIP project are not equal. Primarily they differ in spatial resolution, and some models are more complex, use different or more sophisticated convection and radiation schemes, or have more complex ocean models. More sophisticated models are not necessarily more skilful, but it is important to know, when using GCMs to inform climate impacts, which models are capturing the key processes relevant to the region's climate. This is an area where there is little consensus on the best approaches and many argue for the standard one model one vote, ensemble statistics approach. However it becomes increasingly difficult, as demands for information escalate, to defend using a model that cannot capture a critical process on an equal footing as one that accurately represents that process.

Secondly, GCMs skill scale, that is to say the spatial scale at which we expect them to be realistic and at which we should consider their results as informative, is much larger than their grid scale. So while a GCM may operate on a spatial grid of 100km in size, its skilful scale is likely much larger, on the order of 500km. This is key when considering GCM results for small regions such as this, particularly if that region includes complex topography or ocean/continental boundaries and sharp climate

1 CMIP – cmip-pcmdi.llnl.gov

gradients are observed.

The fifth phase of the Coupled Intercomparison Project (CMIP5) is the latest set of coordinated climate model experiments (Taylor et al. 2012). This generation of GCMs make use of Representative Concentration Pathways (RCPs) (Moss et al., 2010) to dictate the concentrations of various greenhouse gases which were included within the simulated atmosphere of the models. This is in contrast to the previous generations of CMIP which used the Special Report on Emission Scenarios (SRES). RCPs are primarily based on different scenarios of atmospheric radiative forcing, rather than socio-economic scenarios which were used in SRES. Four RCPs were defined – one "low" scenario (RCP 2.6), two intermediate (RCP 4.5 and RCP 6) and one high (RCP 8.5). The number indicates the equivalent top of the tropopause change in radiative forcing in the year 2100.

The GCMs involved in the CMIP5 experiment operate at relatively low spatial resolution and therefore simulate the average conditions over a fairly large spatial area (roughly 200kmx200km). These models are able to capture the large scale shifts in circulation patterns and processes, however they are not accurate enough to represent the complexity of micro-climates within an area. This makes them unsuitable for direct use in local scale climate change assessments or impact modelling. For this, GCM data need to be downscaled using an appropriate method of downscaling. In spite of this, it is still important to look at the results from GCMs, firstly because they drive the downscaled output, but also because of the uncertainties introduced by downscaling. Looking at multiple sources of evidence, and their qualitative agreement, increase our confidence in the projections.

Downscaling

Downscaling seeks to add finer resolution information to GCM output and is seen as the only viable approach to achieve regional scale information consistent with the global and hemispheric forcing. Downscaling can be separated into two distinct classes; dynamical and statistical/empirical downscaling, with the latter being further separated into three subclasses. All have differing strengths and weaknesses. The dynamical downscaling is theoretically the most viable, but introduces notable structural uncertainty in the results, as well as additional stochastic variance and error from the parameterization schemes. As a result the multi-model spread can be broad. It is also unclear whether the increased complexity of nested models or high/variable resolution models actually adds to the signal. Statistical downscaling covers a broad range of methodologies and in principle can present a clearer picture of the first-order large scale forced signal at the local scale. Within the variants of statistical downscaling methods, weather generators need long time series to train the method, index/analogues are particularly vulnerable to stationarity issues, and transfer function approaches can miss the tails of the distribution. Most effective is thus a blended statistical approach, as is used here.

Self-Organizing Map based Downscaling (SOMD) is a leading empirical downscaling technique for Africa and provides meteorological station level or gridded response to global climate change forcing (Hewitson and Crane 2006). The downscaling of a GCM is accomplished by deriving the normative local response from the atmospheric state on a given day (predictors), as defined from historical observed data (predictants). The method recognises that the regional response is both stochastic as well as a function of the large scale synoptics. As such it generates a statistical distribution of observed responses to past large scale observed synoptic states. These distributions are then sampled based on the GCM generated synoptics in order to produce a time series of GCM downscaled daily values for the variable in question (in this case temperature and rainfall). Advantages of this method are that it is computationally much less expensive than dynamical downscaling, and that the relatively unskilled grid scale GCM precipitation is not used but rather the relatively high skilled large scale circulation (temperature, wind and humidity) fields are employed.

The SOMD methodology has undergone a number of important modifications over time. In the current version of the SOMD the observed daily atmospheric states, or predictors, are obtained from the ERA-Interim Reanalysis dataset for the period 1979-2010. The variables used include; near surface temperatures and winds, atmospheric temperature lapse rate, relative humidity and winds. The local responses to these states, or predictants, are characterised using daily rainfall and temperatures from the WATCH Forcing Data 20th Century Dataset ERA-Interim (WFDEI) which provides a spatially continuous – though relatively low resolution – historical record.

Materials and Methods

Climate data

Climate data from a number of sources are included in this project. Each has its own strengths and limitations. This section provides a brief overview of each of the datasets.

Station data

The primarily data used in this study was the daily meteorological records obtained from the manual weather station at the Rekomitjie research station in the Zambezi Valley of Zimbabwe (16.14° S 29.40° E 520 metres). Daily minimum and maximum temperature and rainfall were recorded for the period 9th October 1959 – 31st March 2016. The records were relatively complete (over 90% valid daily values) with most missing data occurring from March 1976 – June1978 and January 1979 – August 1980 when the research station was vacated due to the Zimbabwean civil war.

The data from this location of supplemented with that from three surrounding weather stations. These stations are: Kariba, Karoi and Lusaka. The Kariba station has the most similar climate to Rekomitjie since it is also located in the Zambezi valley, while the other stations are all located at higher elevations (see table 1 below).

Table 1: ***Summary table of weather stations used in this study***

Station Name	latitude	longitude	altitude	Period of record	Percentage valid		
					Tmax	Tmin	pr
Rekomitjie	-16.14	29.40	520	1959/10/09 - 2016/03/31	95	91	95
Kariba	-16.52	28.88	518	1963/05/01 – 2000/12/30	92	92	92
Karoi	-16.83	29.62	1343	1951/07/01 – 1990/02/27	93	93	93
Lusaka	-15.41	28.31	1252	1950/01/01 - 2013/06/29	84	85	90

The quality of the meteorological records were evaluated using a set of quality assurance tests based on those developed by the Global Historical Climatology Network (Durre et al. 2010) and then visually inspected to identify any further errors which were not identified by the automatic tests. Only a few erroneous values were identified and these were set to undefined. Details of the errors found in the Rekomitjie records can be found in Appendix A.

As mentioned above, the Rekomitjie station records had a number of gaps. But, a continuous temperature record was needed for some of the subsequent work, most notably Glyn Vales tsetse fly modelling work. Therefore an attempt was made to infill all periods of missing temperature data. In this instance, it was important to accurately replicate the monthly mean values, but also the day-to-day variance. Therefor a simple linear regression method was used. The correlation between the Rekomitjie station record and that of another predictor station was calculated for each month in the calendar year and the departures were used to bias correct the predictor station values for any period of missing data within the Rekomitjie record. The Kariba station temperature record was selected as the predictor dataset for a number of reasons; firstly, it has a long and relatively complete record that covers the majority of the Rekomitjie record; secondly, the station is located in a relatively close and similar environment to that of Rekomitjie, unlike other stations which are located outside of the Zambezi valley. And thirdly, the stations have similar climates, both in terms of the mean values, but also in terms of their variance (see table 2 below).

A few periods of missing data in the Rekomitjie minimum temperature record were after the end of the period covered by the Kariba station. During this time the Rekomitjie station did have valid maximum temperature values which were used as the predictor dataset. As one can see from the table below, the monthly variance in maximum temperature is often higher than that of minimum temperature and the correlations are therefore weaker than that between Rekomitjie and Kariba station records. Finally a few missing values were still present in the dataset. These values were infilled using the mean of the values on the day before and day after. Further details regarding the infilling can be found in Appendix B.

A number of derived statistics of relevance to tsetse flies were calculated from the daily records at monthly, seasonal or annual basis. Statistics for a month were only calculated if more than 90% of values within the month were valid, and annual statistics were only calculate if all 12 months were valid. Table 3 below provides a summary of the statistics used.

*Table 2: **Summary of monthly climatology for Rekomitjie and Kariba stations***

Month	Tmax				Tmin			
	Rekomitjie		Kariba		Rekomitjie		Kariba	
	mean	std	mean	std	mean	std	mean	std
Jan	32	2.83	31.30	2.33	21.87	1.52	21.87	1.24
Feb	31.83	2.57	31.16	2.27	21.79	1.44	21.61	1.33
Mar	32.23	2.53	31.52	2.29	21.54	1.67	20.92	1.62
Apr	31.61	2.53	31.00	2.24	19.91	2.20	18.73	2.32
May	29.86	2.56	28.93	2.29	16.79	2.42	14.70	2.66
Jun	27.80	2.31	26.78	1.87	14.28	2.31	11.73	2.55
Jul	27.56	2.30	26.65	1.85	13.67	2.23	11.54	2.49
Aug	30.31	2.62	29.25	2.32	15.87	2.69	14.40	2.30
Sep	33.92	2.89	33.29	2.71	19.90	3.11	19.50	3.38
Oct	36.26	3.20	35.41	3.13	23.29	2.86	23.30	2.98
Nov	35.76	3.94	34.48	3.80	23.65	2.63	23.84	2.60
Dec	33.02	3.48	31.79	2.92	22.41	1.90	22.33	1.69
Annual	31.88	3.88	30.97	3.66	19.58	4.09	18.71	4.90

Table 3: ***Summary of derived climate statistics***

Variable	Statistic	unit	Description
Tmax, Tmean, Tmin	means	°C	Average value per time period
Tmax, Tmean, Tmin, Pr	daysabove90%	days	The number of days where temperature is above the 90^{th} percentile
Tmean	daysbetween16-32	days	The number of days per period where the temperature is between 16 - 32° C
Tmean	spellbetween16-32	days	The mean number of consecutive days per period where the temperature is between 16 - 32°C
Tmean	daysabove32	days	The number of days per period where the temperature is above 32° C
Tmean	spellabove32	days	The mean number of consecutive days per month where the temperature is above 32° C
Pr	totals	mm	The sum of all rainfall per period excluding values less than 0.2mm/day
Pr	means	mm/day	The mean rainfall per rainday, where a rainday is defined as having at least 0.2 mm.
Pr	dryspell	days	The mean number of consecutive dry days per time period
Pr	wetspell	days	The mean number of consecutive wet days (pr > 0.2 mm). per time period

Sea Surface Temperature Index

The surface temperature of the ocean in a number of remote locations can play a critical role in determining the large-scale drivers of the regional climate. In this study we focus on the best studied and understood index, the El-Nino Southern Oscillation (ENSO) which records the periodic departures from the expected sea surface temperatures (SSTs) in the equatorial Pacific Ocean. The ENSO can be represented by the NINO 3.4 index which uses the area averaged SST anomaly over a region of the tropical Pacific (5°S-5°N and 170°-120°W) at a monthly timescale (Rayner et al. 2003). The index is calculated from the HadISST1 dataset which is a blend of historical SST and modern

SST records obtained both from satellite data and from observations. Values are presented as anomalies from the long-term mean (1951-2000) and were downloaded from NOAA's Working Group on Surface Pressure website[2].

Gridded data

There is not one "best" gridded dataset for this region. All differ in terms of the number of variables included, the spatial and temporal resolution and length of record. All have biases and may do better over some regions than others. It is therefore important to compare results from a number of datasets and to select the dataset that best suits ones needs. There are a number of suitable rainfall datasets which cover the African continent, but unfortunately far fewer temperature datasets.

The gridded dataset used in this project was the WATCH Forcing Data ERA Interim[3] which is a meteorological forcing dataset (based on ERA-Interim) for land surface and hydrological models and provides eight meteorological variables at 0.5° spatial resolution at 3-hourly or daily time resolution over the period 1979-2009 (Weedon et.al. 2014). Daily rainfall, maximum and minimum temperature, wind speed and specific humidity were used to characterise the regional climate over .The daily rainfall and maximum and minimum temperature were also used as inputs into the statistical downscaling to provide future projections over the larger region.

Global Climate Models data

Global Climate Models (GCMs) from the latest generation of the Coupled Model Inter-comparison Project (CMIP5) were used within this project. A set of synoptic variables from 11 models (Table 4) for the historical experiment and two future experiments (RCP 4.5 and RCP 8.5) were used to provide circulation predictors for the statistical downscaling. Rainfall, minimum and maximum temperatures results were also presented to illustrate the future change projected by the GCMs.

[2] https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/Nino34/
[3] WFDEI – www.eu-watch.org/data_availability

Table 4: ***CMIP5 Modeling Centres and models currently used in the statistical downscaling***

MODELING CENTRE (OR GROUP)	INSTITUTE ID	MODEL NAME
Beijing Climate Center, China Meteorological Administration	BCC	BCC-CSM1.1
College of Global Change and Earth System Science, Beijing Normal University	GCESS	BNU-ESM
Canadian Centre for Climate Modelling and Analysis	CCCMA	CanESM2
Centre National de Recherches Meteorologiques / Centre Europeen de Recherche et Formation Avancees en CalculScientifique	CNRM- CERFACS	CNRM-CM5
LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences	LASG-IAP	FGOALS-s2
NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL	GFDL-ESM2G GFDL-ESM2M
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC	MIROC5
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC	MIROC-ESM MIROC-ESM-CHEM
Meteorological Research Institute	MRI	MRI-CGCM3

Statistically downscaled data

The 11 CMIP-5 GCMs mentioned above were statistical downscaled using the Self-Organising Map based Downscaling (SOMD) methodology. Downscaled daily precipitation, maximum and minimum temperature time series were produced for the Historical experiment (1960-2005) and two future experiments, RCP 4.5 and RCP 8.5 (2006-2099) over the larger regional study area at 0.5° resolution.

The two future experiments lead on directly from the historical experiment and therefore the records can be concatenated together creating two 140-year records from 1960-2099. Note that the records are not identical over the historical period due to the way the downscaling samples the stochastic variance.

Results are presented both at the regional and local scale, where the values for the gridcell most closely located to Rekomitjie were extracted from each of the statistically downscaled models for each of the emission scenarios and each of the variables.

Tsetse fly cohort model

The model itself is not discussed here and the reader is referred to work done by Glyn Vale within the larger project.

Daily temperature and rainfall from the Rekomitjie Research station are used as primary input into the tsetse fly cohort model. This allows the model to simulate how the climate impacts the tsetse fly population dynamics over the historical period. Climate change projection data is needed in order to explore how climate change may impact the tsetse fly population into the future. Three GCMs were selected, from the 11-member ensemble of statistically downscaled CMIP5 models under the RCP 8.5 emission scenario, to represent the spread found within the model ensemble. The BCC-CM1-1 model projects no change in rainfall and a moderate increase in temperature into the future. MIROC-ESM-CHEM projects a very strong warming and drying trend while the MRI-CGCM3 model projects a slight drying and one of the lowest warming trends into the future. It is also based on the model with the finest resolution and may therefore do a better job at resolving the heterogeneous nature of the climates over this region.

Results

This report primarily explores the climate at the Rekomitjie Research station and the majority of this section will focus on the results for this location at a number of temporal scales from the diurnal to the interannual time scale. These results are compared to those obtained from three other weather stations located within the larger region and also to the output obtained from a gridded data product. The section then looks at how the climate is projected to change into the future due to anthropogenic climate change. Results from an ensemble of Global Climate Models (GCMs) are presented as well as results from these GCMs that have been statistically downscaled to a higher resolution. Finally the likely timing of tsetse fly extinction due to climate change is presented using the results obtained by running Glyn Vales tsetse fly cohort model driven by the statistically downscaled temperature and rainfall output.

The historical climate for the Rekomitjie Research Station over the last 56 years is presented in Figure 4. Rekomitjie can be classified as having a tropical savannah climate with three important seasons; The hot wet summer (December – February) in which the majority of the rainfall occurs and where temperatures are hot (~32 and 21° C for daily maximum and minimum temperatures respectively); Winters (June – August) are generally cool and dry with July recording zero rainfall and daily maximum and minimum temperatures dropping to a minimum of 27.5 and 13.5° C respectively; Spring (September – November) is characterises by very hot conditions, with daily maximum and minimum temperatures reaching their highest values during October, averaging over 36° C and 23° C respectively. The maximum daily value ever recorded (44° C) also occurred in this month.

At Rekomitjie, the largest variation in temperature is found at the diurnal time scale; the diurnal cycle, or difference between the daily maximum and daily minimum temperature, range between 10° C during summer to over 14° C in September and October. This is in contrast to the seasonal variability of maximum and minimum temperature that average 9.5° C and 10.7° C respectively. Interannual variability, represented by the difference between the hottest and coolest year on record, varies by about 5° C.

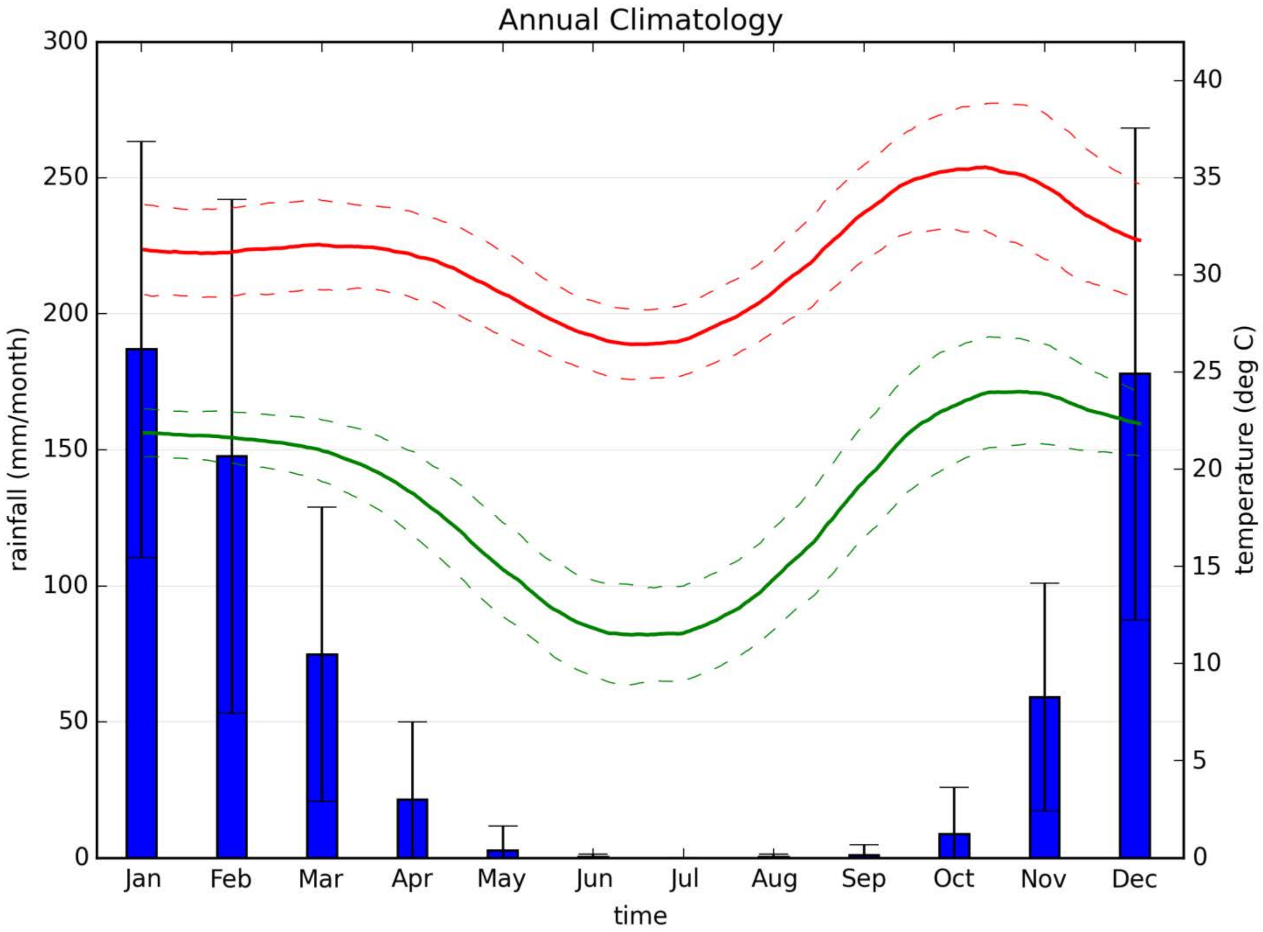


Figure 4: ***Historical Average Seasonality for the Rekomitjie Station.*** *Mean monthly total rainfall (mm) over the period 1960-2015 depicted as blue bars, whiskers show +- 1 standard deviation. 30-day smoothed mean daily maximum (minimum) temperature presented by the red (green) lines over the period 1960-2015. Dashed lines represent the +- 1 standard deviation around these means.*

Daily timescale

Figure 5 and table 5 below illustrate the frequency distribution of daily temperatures and rainfall values at the Rekomitjie research station. Maximum temperature is normally distributed with a median value of between ~32° C and values ranging from 18.5 to 44°C. Minimum temperature shows a slight bimodal distribution. The median value is 20.5°C, however a strong peak in frequency is evident for days with temperatures between 20° - 23° C. The spread of values (2 - 33°C) is slightly larger for minimum temperature than maximum temperature due to some extreme values on both tails. The distribution of rainfall is heavily right-skewed with a long tail and a number of outliers or extreme values.

Table 5: ***Summary statistics of daily values at Rekomitjie****. Rainfall statistics are only calculated for*

those days on which at least 0.2mm rainfall fell.

	Tmax	Tmin	Rain	dtr	Tmean
count	19002	18185	2901	18181	18181
mean	31.85	19.55	12.28	12.29	25.7
std	3.87	4.09	14.48	3.24	3.63
min	18.5	2.2	0.2	0.5	13.9
10%	27	13.5	1	8	20.55
50%	31.7	20.5	7	12.5	26
90%	37	24	31	16.5	30.25
95%	38.5	25.5	44	17.5	31.65
max	44	33	96.5	25.6	37.5

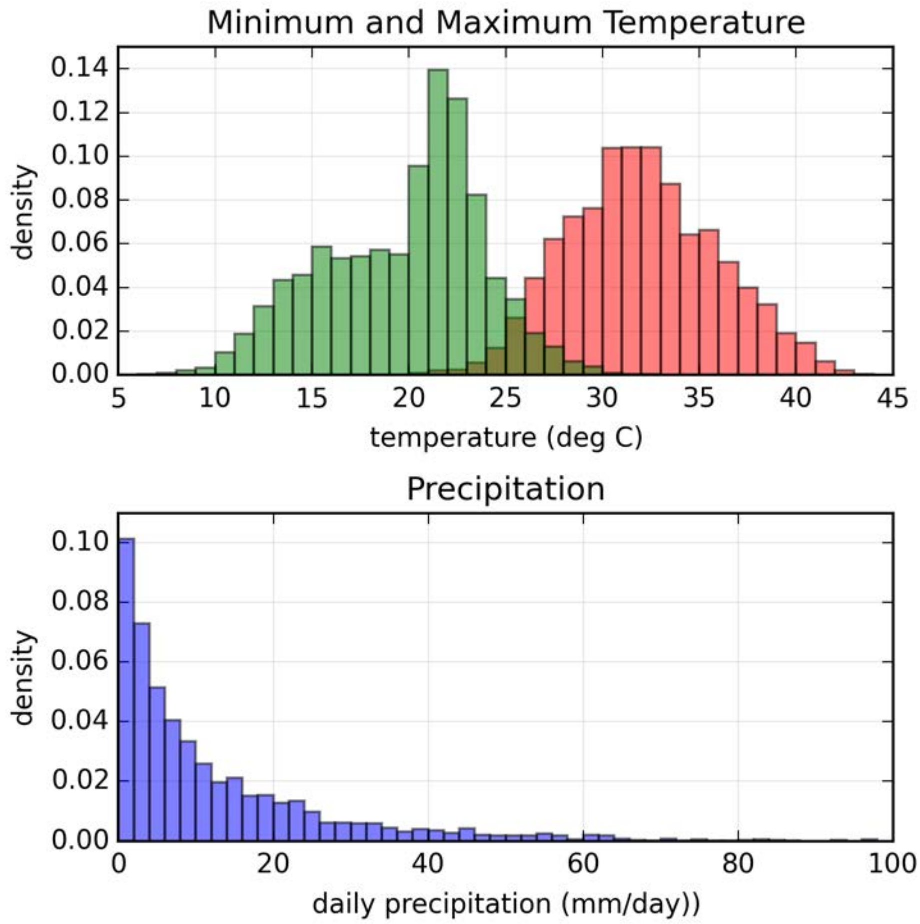


Figure 5: ***Histogram of daily minimum and maximum temperature and rainfall recorded at Rekomitjie 1960-2015****. Minimum temperature (green), maximum temperature (red) and daily precipitation (blue)*

The average daily maximum and minimum temperatures vary depending on the season, but so does the variability. Minimum temperatures are far more uniform during the rainy season (December – March) especially in January and February where over half the days recorded minimum temperatures between 22 and 24°C (figure 6). Daily maximum temperature shows quite similar range of variance in all seasons, with the exception of the hottest months where the distribution is left-skewed.

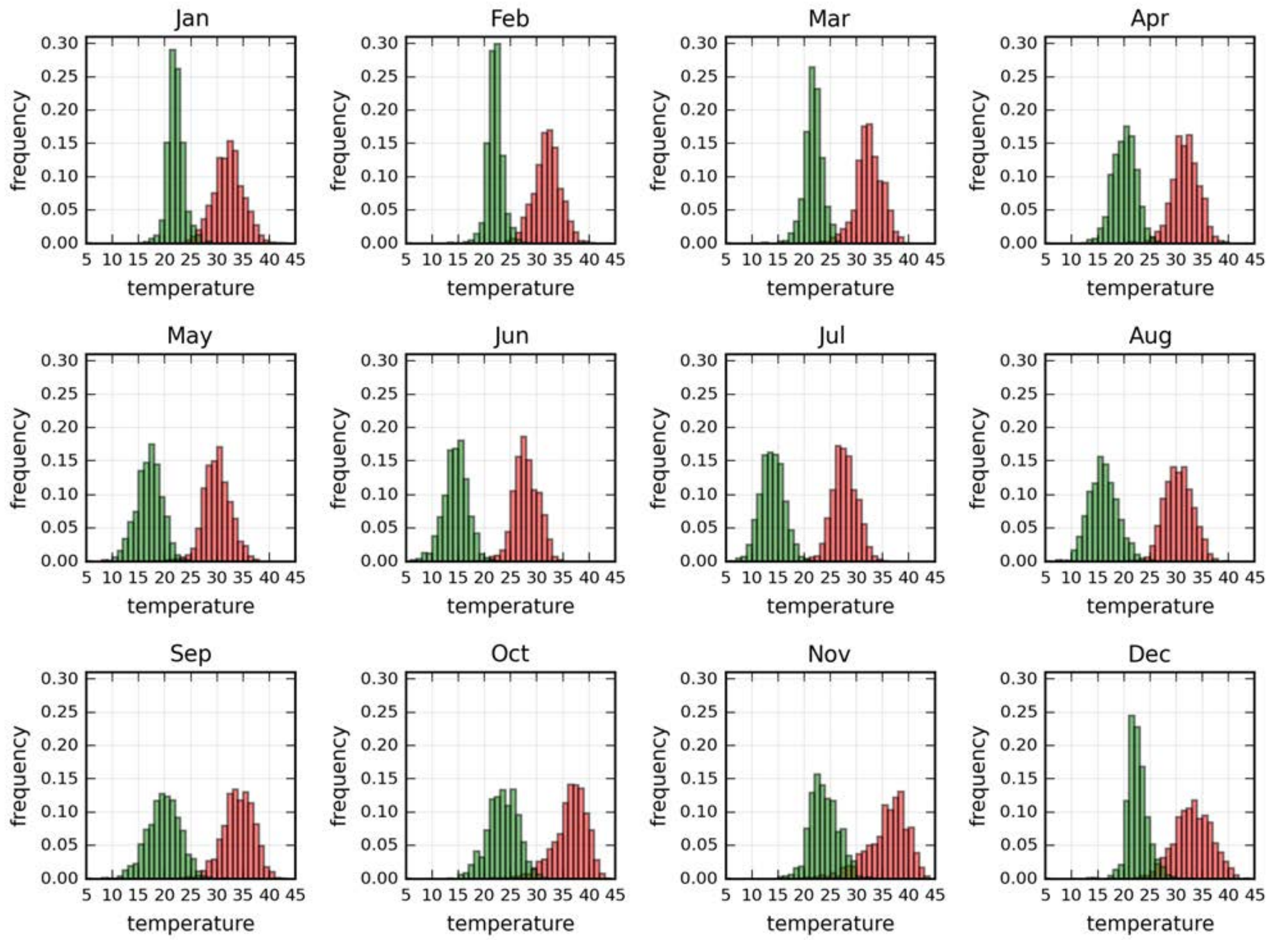


Figure 6: ***Histogram of daily minimum (green) and maximum (red) temperatures for each month of the calendar year 1960-2015 for Rekomitjie***

The time series of the three weather variables (figure 7) shows a number of things, firstly it highlights the periods of missing data, primarily from 1976 – 1981, but also 1963 and 2003 in the minimum temperature record. The time series show that the maximum temperature record is “messy” compared to that of minimum temperature, or in other words the day-to-day variance in maximum temperature is larger than that of minimum temperature. The bottom panel shows that the average intensity of rainfall is relatively low (~12 mm/day) during the summer season, but that a number of high rainfall events of up to 100 mm/day make a significant contribution to the total rainfall.

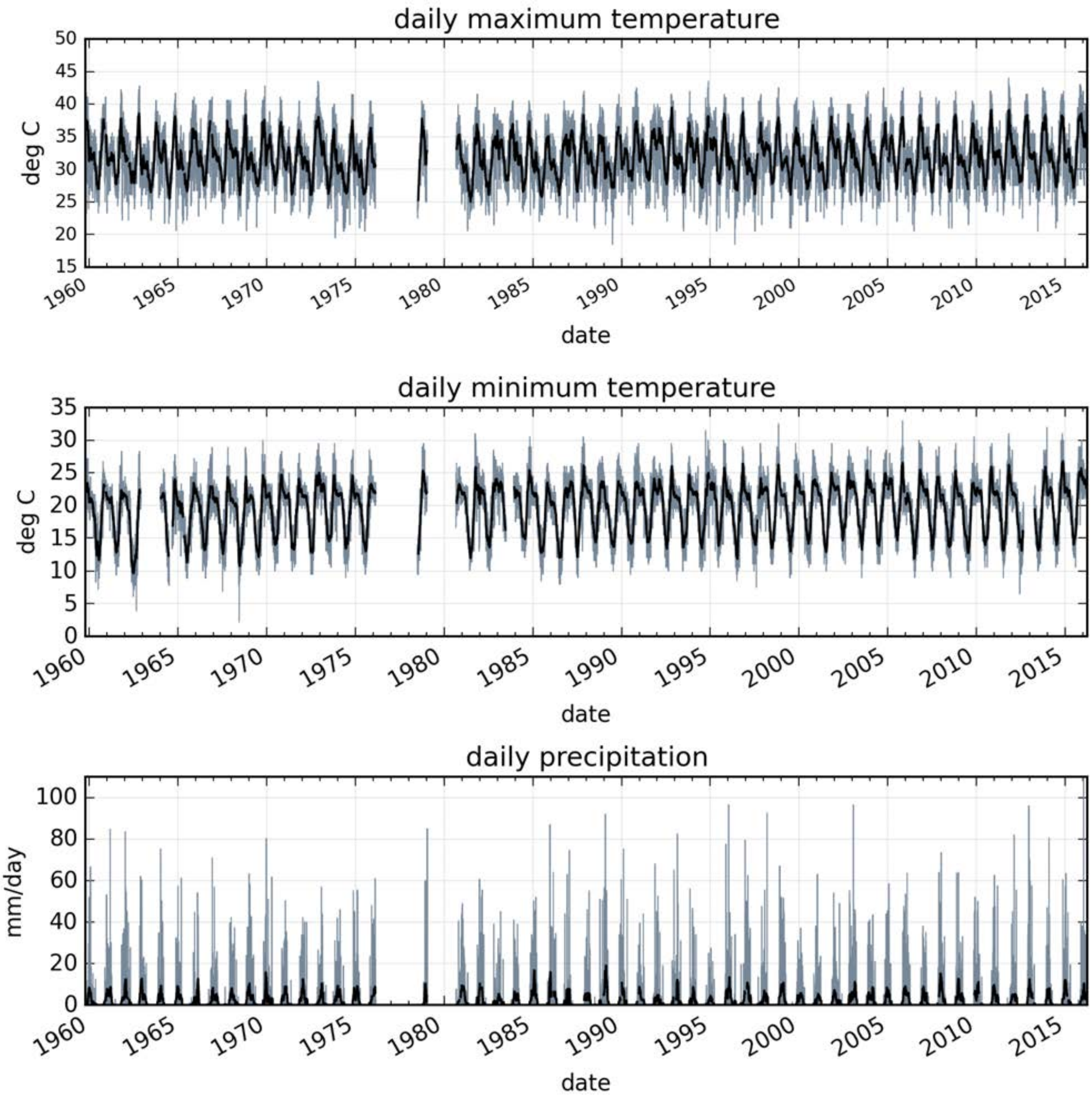


Figure 7: ***Time series of daily maximum and minimum temperature and rainfall for the Rekomitjie station****. Black line displays the 30-day moving average.*

Monthly timescale

Figure 8 displays the same data as that of Figure 7, however values have been converted to monthly time scale, with a 12-month running mean depicted by the coloured lines. It is clear that the seasonal variability is much larger than any variability from year to year. However, there does appear to be some interannual variability, primarily in maximum temperature during the late 1980 – 2000. This variability seems to disappear in the more recent past (from around 2009 onwards). This is in spite of the large-scale drivers of this variability still occurring, which may suggest an error or inconsistency has crept in over the last few years.

The aggregation to monthly scale makes it easier to identify the summer rainy season and also highlights the occurrence of months with extreme rainfall totals, for example the extreme months of December 1962 and February 1989, both of which recorded over 450 mm/month. The 1988-1989 rainy season was also the wettest season on record with just over 1100 mm/year being recorded. On the other extreme the 1994-1995 recorded the lowest rainfall total with only 308 mm/year. Strong inter-annual variability is also evident in the annual total rainfall record.

Table 6 presents the monthly climatology of the three primary variables (daily maximum temperature, daily minimum temperature, monthly total rainfall), but it also presents two derived variables; the diurnal temperature range and the daily mean temperature, both of which play an important role in determining the tsetse fly population dynamics at Rekomitjie.

*Table 6: **Monthly climatology for Rekomitjie**. Temperature values are long-term averaged per month, while rainfall is the long-term average monthly total values.*

month	Maximum Temperature	Minimum Temperature	Rainfall	Diurnal temperature range	Mean Temperature
1	31.9	21.8	186.9	10.1	26.9
2	31.8	21.8	147.6	10.0	26.8
3	32.2	21.5	74.8	10.7	26.9
4	31.6	19.9	21.3	11.7	25.8
5	29.9	16.8	2.7	13.1	23.3
6	27.8	14.3	0.3	13.5	21.1
7	27.6	13.7	0.0	13.9	20.6
8	30.3	15.9	0.2	14.5	23.1
9	33.9	19.6	1.1	14.2	26.7
10	36.2	23.3	8.6	12.9	29.8
11	35.8	23.7	59.1	12.0	29.7
12	33.0	22.4	177.9	10.7	27.8
annual	31.8	19.6	680.5	12.3	25.7

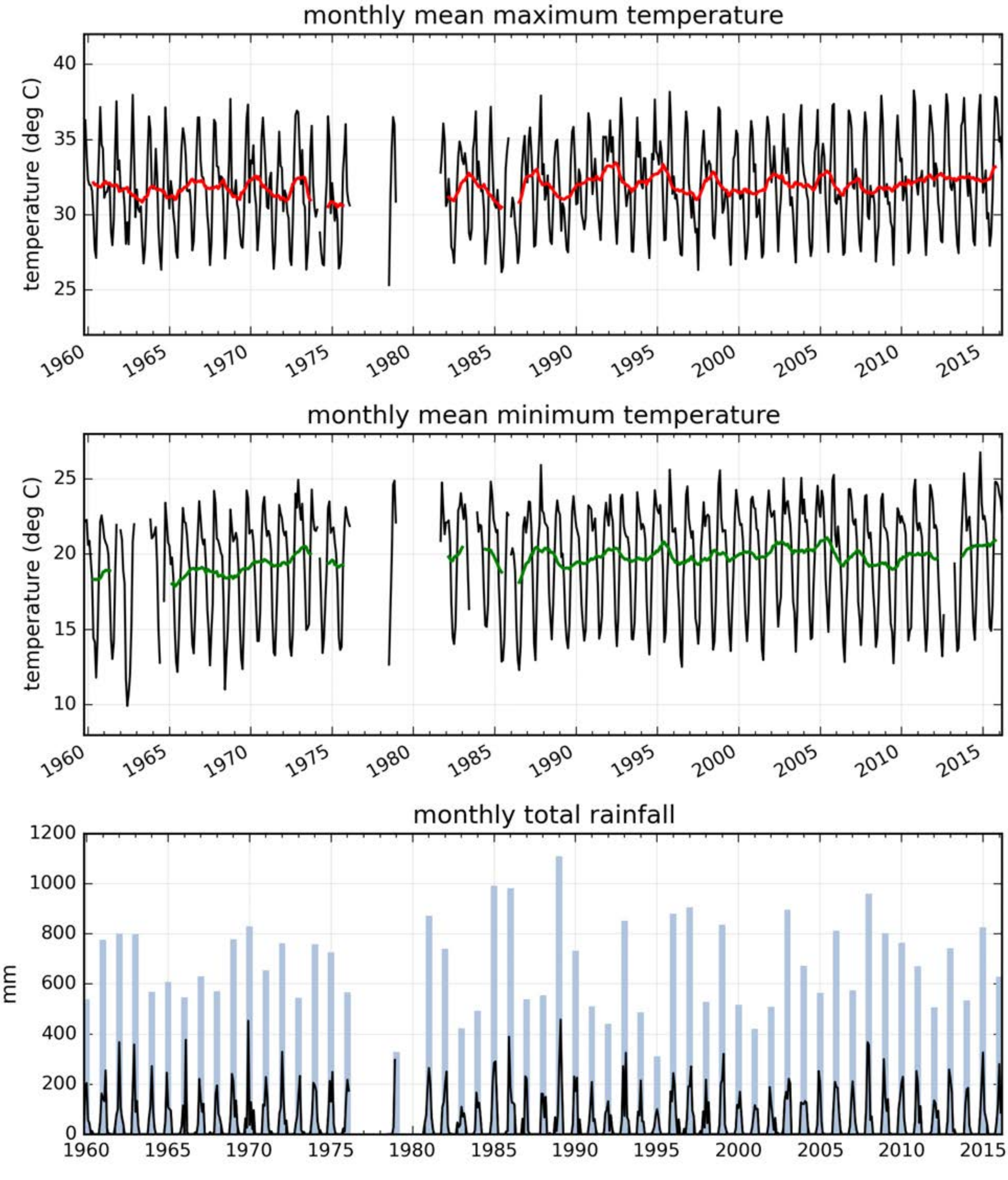


Figure 8: ***Time series of monthly mean maximum and minimum temperature and total rainfall for the Rekomitjie research station****, red and green coloured lines represent a 12 month running average for maximum and minimum temperature respectively. Light blue bars present the annual (July – June) total rainfall.*

ENSO influence on variability

A key remote driver of interannual variability is the El-Nino Southern Oscillation (ENSO) where the positive (El Nino) phase is generally associated with hotter drier conditions over the study area while the negative (La Nina) phase is associated with cooler and wetter conditions.

The ENSO is represented by the NINO 3.4 index which uses the area averaged Sea Surface Temperature anomaly over a region of the tropical Pacific (5°S-5°N and 170°-120°W) at a monthly timescale. Figure 9 presents a time series of the NINO 3.4 index along with the time series of monthly anomalies for maximum and minimum temperature, and annual (July-June) anomalies in total rainfall (mm/year). It is clear that variations in temperatures are strongly correlated with NINO 3.4, but with a lag; ENSO events are generally strongest during austral summer (December-February), while the strongest temperature anomalies are generally found during the following spring (September-November). Rainfall anomalies appear to be in phase with ENSO; with wetter years generally occurring during La Nina events (for example 1984-1985, 1988-1989 and 2007-2008), while dry years generally occur during El Nino events (1983-1984, 1991-1992, 1994-1995 and 1997-1998). However, the variability in rainfall and temperature is not fully explained by ENSO; some years, for example the 1995-1996 year was a relatively weak El Nino, but was associated with the lowest rainfall and one of the highest temperature anomalies on record at the Rekomitjie station. In contract the 1997-1998 El Nino, which was one of the strongest on recorded, failed to produce the predicted dry and hot conditions at Rekomitjie or over the larger region.

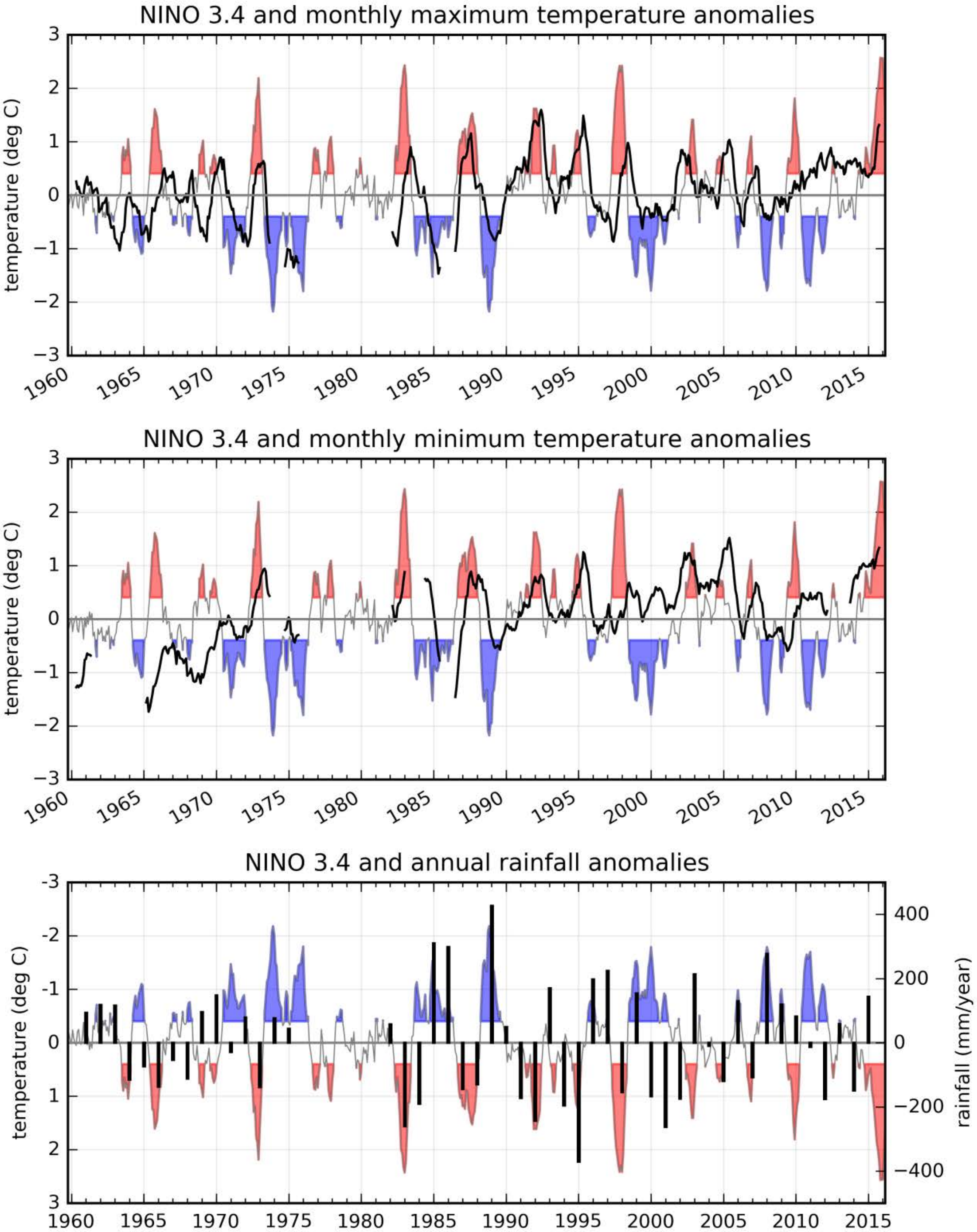


Figure 9: ***Association between ENSO and the climate at Rekomitjie through time.*** *Time series of the NINO 3.4 SST month anomalies is presented as the grey line; positive (El Nino) phases are coloured red, while negative (La Nina) phases are shaded in blue. Black line in top panel shows the monthly mean maximum temperature anomalies smoothed with a 12-value running mean. The second panel shows the same as above, but for minimum temperature. The black bars in the bottom panel show the annual (July-June) total rainfall anomalies (mm).*

Historic trends

The climate at Rekomitjie clearly shows variability at a number of different time scales, but trends are also evident in the temperature records. Figure 10 presents both the variance and the trend in mean maximum temperature for each month in the year. The magnitude of this variability changes through time and between months, seen by the larger or smaller spread of observations (blue dots) and also by the width of the confidence interval (dashed black lines). For example during May the magnitude of variance is reduced in the more recent past compared to the earlier period, but for November and especially December the magnitude of variability is larger in the early and late part of the record, but more constrained during the 1980s-1990s. A clear upward trend is found in months from August to December over the last 30 years. The trend in October is the strongest (median value of ~2°C) while a trend of over 1°C was found in the other months. No clear trends were evident in the other months. A negative trend was also apparent in the month of October during the 1960s to 1980s, however this negative trend is not evident in any of the surrounding station records (for example at the Kariba station) and may be due to local site conditions.

Figure 11 presents the results in another way using the Least Absolute Deviation method, but just for the period 1980-2015. It clearly shows strong and signficant warming trend during September, October and November of over 0.5°C per decade, while August shows a smaller and less significant positive trend. Other months show weaker and non-significant trends of both directions.

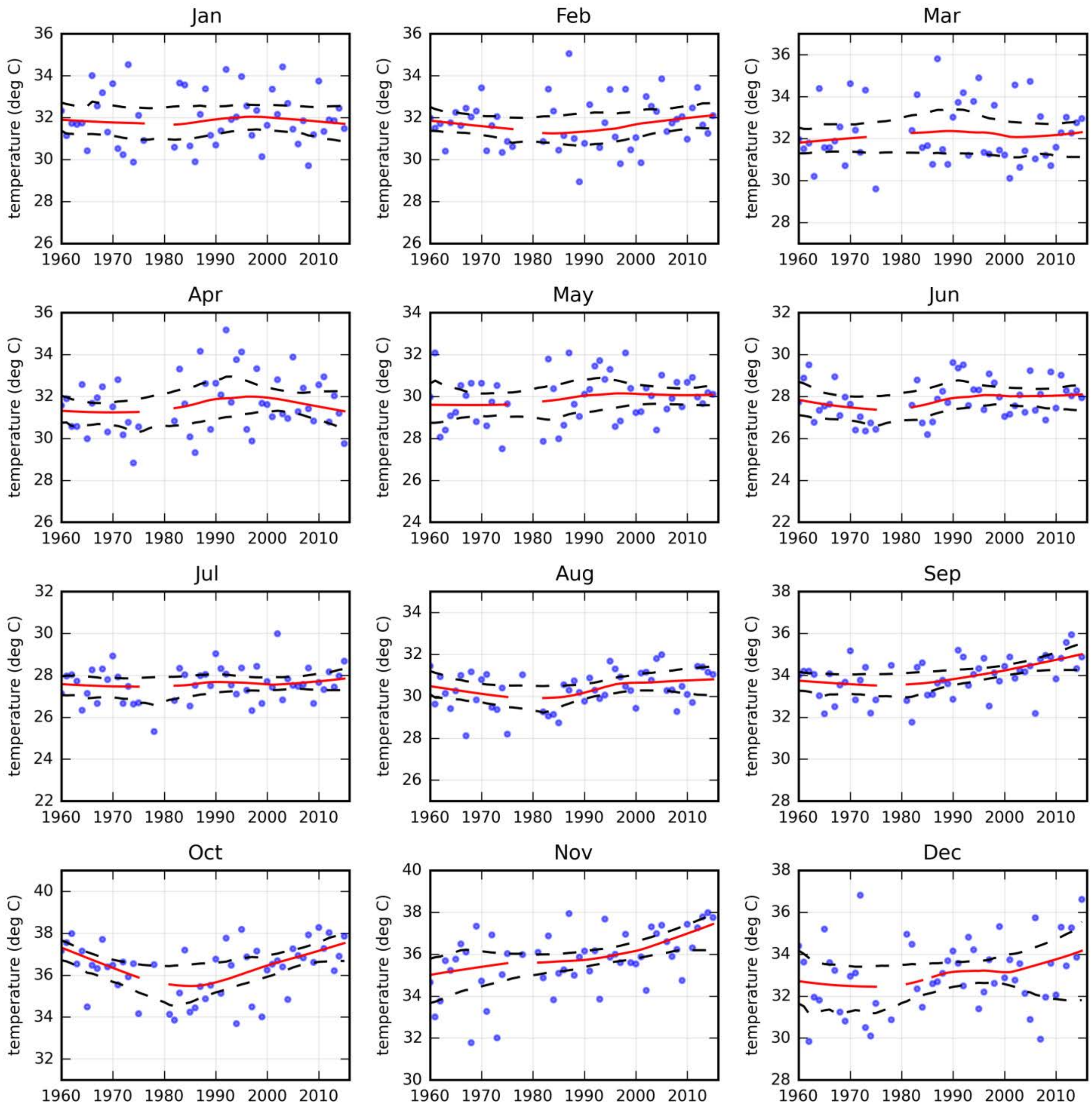


Figure 10: ***Observed time series and trend in maximum temperature at Rekomitjie station.*** *Time series of monthly mean maximum temperature (blue dots) presented for each month of the year. The red line shows the median trends calculated using lowess method, and the dashed lines show the range of the 95th confidence interval around the median.*

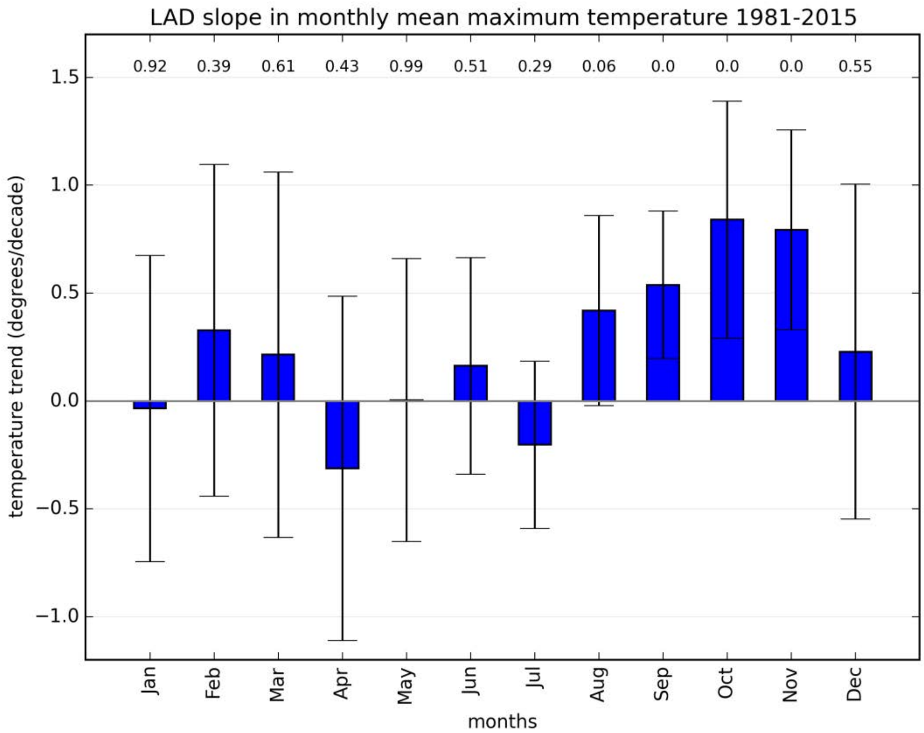


Figure 11: ***Observed trend in monthly mean maximum temperature at Rekomitjie station.*** *Trends calculated separately for each month for the period 1981-2015. The blue bar represents the slope (temperature change per decade) calculated using the Least absolute Deviation (LAD) The confidence interval is presented by the whiskers and the p values are presented above each column.*

Minimum temperature at Rekomitjie also shows strong variability and trends. The variability is generally smaller than that of maximum temperature, but also shows clear differences at different seasons. As mentioned before, the variability is generally low (less than 2°C during the wet season (December – March), slightly larger (between 2 and 2.5° C) during the dry winter season, and highest (2.5 - 3°C) during the hot dry season (September – November). A positive trend in minimum temperature is found in all months in the first 20 years (1960-1979) (Figure 12). This trend is not evident at any of the surrounding stations (see subsequent section), or in any gridded product that we have investigated, which leads us to believe that it may be due to local site conditions and it may not be representative of the climate of the larger area. That being said, a positive trend is evident since the mid-1980s in August to December (figure 13), but is only significant in October and November (~0.5°C change per decade) These trends appears to be more consistent with that of the larger area.

No trend is evident in the rainfall record for any months or in the annual totals (figure 14) and the year to year variability is very high, with the annual total rainfall varying by more than 900mm between a dry and a wet year.

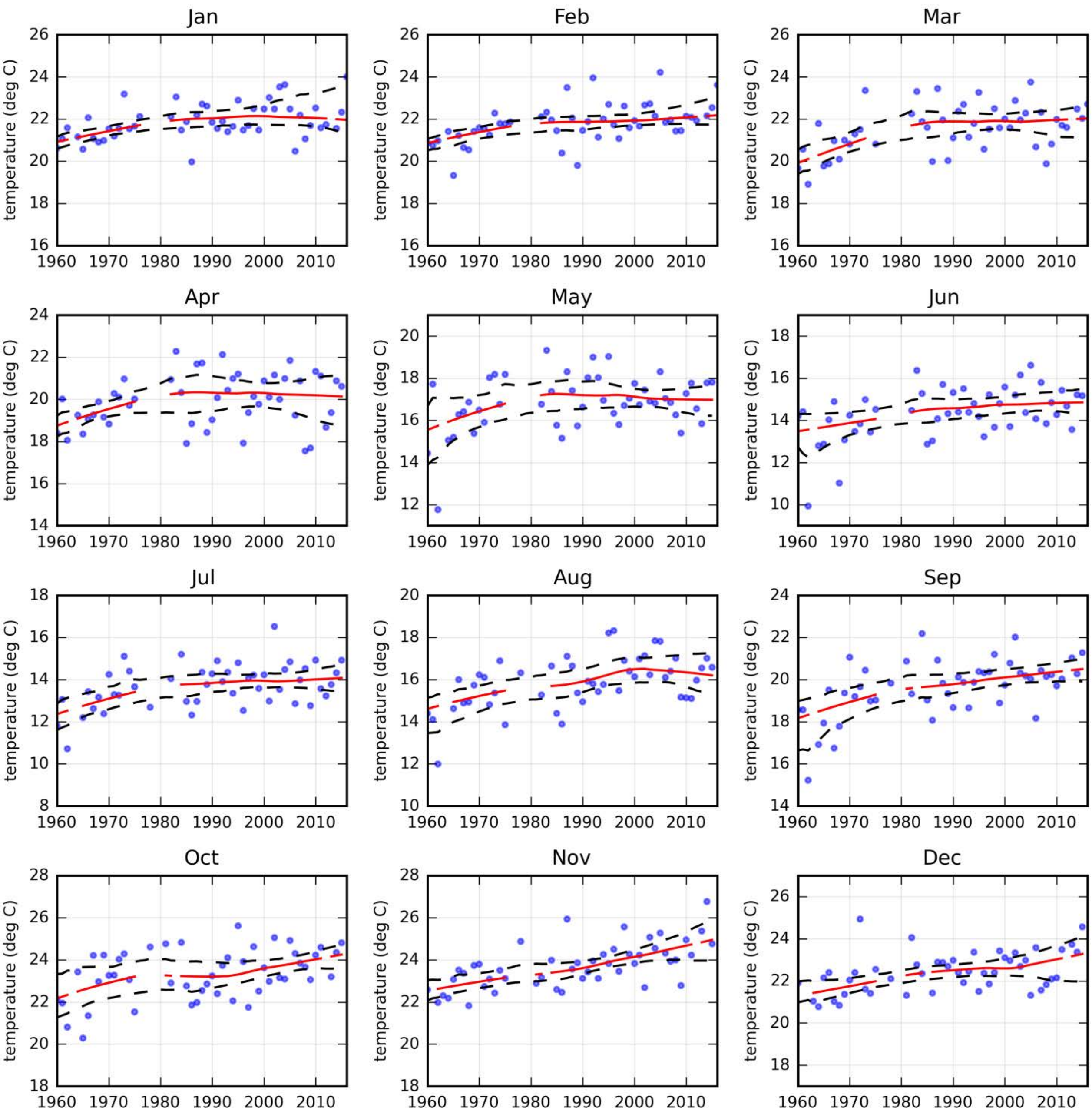


Figure 12: ***Observed time series and trend in minimum temperature at Rekomitjie station.*** *Time series of monthly mean minimum temperature (blue dots) presented for each month of the year. The red line shows the median trends calculated using lowess method, and the dashed lines show the range of the 95th confidence interval around the median.*

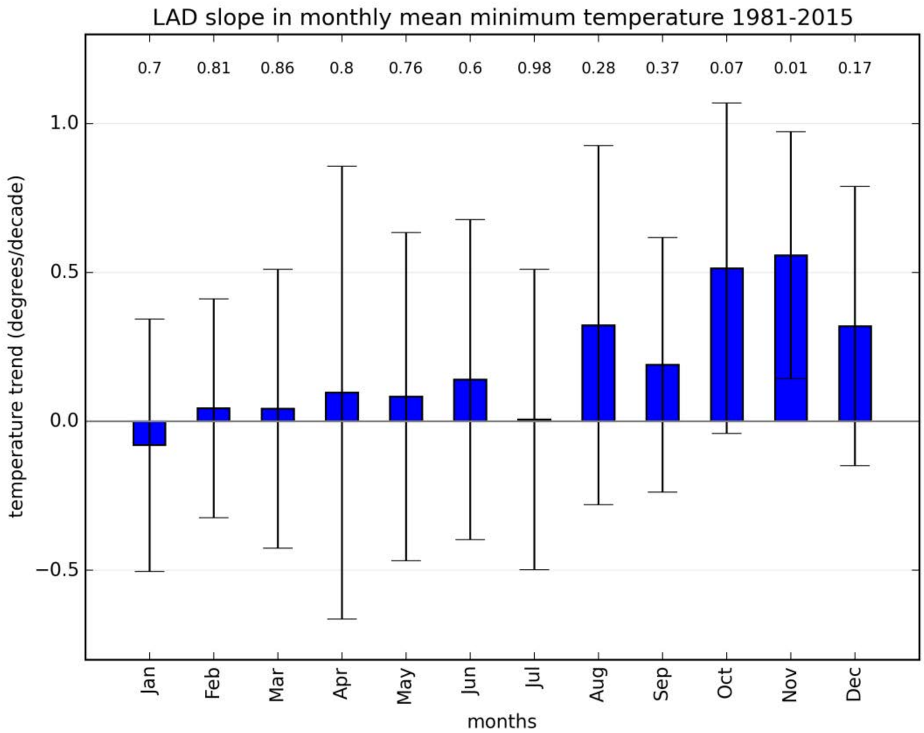


Figure 13: ***Observed trend in monthly mean minimum temperature at Rekomitjie station.*** *Trends calculated separately for each month for the period 1981-2015. The blue bar represents the slope (temperature change per decade) calculated using the Least absolute Deviation (LAD) The confidence interval is presented by the whiskers and the p values are presented above each column.*

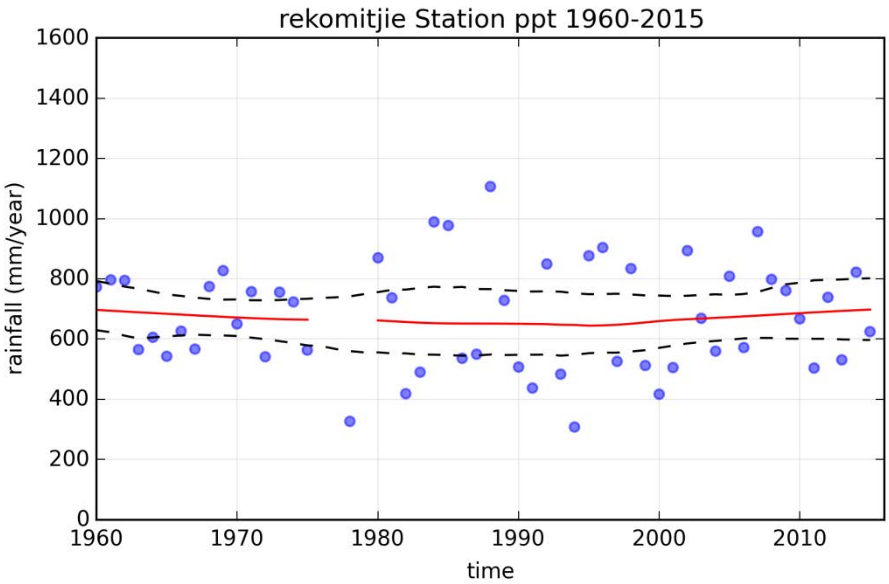


Figure 14: ***Observed time series and trend in annual total rainfall at Rekomitjie station.*** *Time series of annual (July-June) total rainfall (blue dots) presented for each year of the record. The red line shows the median trends calculated using lowess method, and the dashed lines show the range of the 95th confidence interval around the median.*

Extreme events

Tsetse flies are sensitive to temperature and they have an optimal temperature range of between 16 – 32° C. The daily mean temperature at Rekomitjie generally falls within this range, however the recent increasing trend in both maximum and minimum temperatures during the hot dry season (September – November) has resulted in the daily mean temperatures exceeding the 32° C upper threshold on a more regular basis. Figure 15 presents a time series of monthly mean daily average temperature, the frequency of hot days and the mean hot spell duration. The majority of extreme hot days occur during the September – November season and there are clearly some periods with more frequent extremes, for example in the mid 1990's and from 2010 to the present. 32°C is an extreme value for daily mean temperature at Rekomitjie (~95th percentile of daily values) and it is very rare for the average monthly temperature to reach this, however, during November 1987, October 1995 and November 2013, the mean temperature came close (above 31.5°C) and in November 2014 it exceeded this threshold for the first time (32.38° C). November 1987 was also the first time that half of the days per month exceeded this threshold. However these heat spells only lasted on average 4 days. A similar pattern was found in October 1995, where 15 days exceeded the threshold and the heat spells lasted for an average of 3 days.

For tsetse flies it may be there average duration of the hot spell that plays the most significant role. December 1966, October 1992, November 1997 and November 2013 experienced the most protracted hot spells of 7 or more consecutive days per month. December 1966 and November 1997 are probably of less importance since there was only a single spell above the threshold in the whole month. October 1992 and November 2013 experienced more than one heat spell with over 15 and 18 days exceeding the threshold and a maximum heat spell length of 9 and 13 days respectively.

Tsetse fly population dynamics are traditionally been associated with daily mean temperature, but it is also worth looking at the extreme events in daily maximum and minimum temperature and rainfall. Figure 16 presents the monthly mean daily temperature anomalies along with the number of days per month where the daily maximum temperature is above the 90th percentile (37° C) and the average length of these hot spells. The top panel highlights the strong interannual variability evident in maximum temperature. The months with the largest positive anomalies are spread through the record; December 1972, February and March 1987,February and April 1992, December 2015 and February 2016 were all at least 3° C warmer than their monthly climatological mean. The majority of hot days occur during October and November, with more 20 or more hot days occurring in October 1961, 1962 and 1968, November 1994, October 1995, 2008, 2010 and 2012 and then most recently in November 2014 and 2015. The mid 1990s experienced a number of protracted heat spells during October and November, but these hot temperatures were also experienced in the subsequent summer months, especially in 1992 and 1995.

Figure 18 presents a number of rainfall statistics. The top panel shows the time series of monthly total rainfall anomalies (difference from the monthly climatology). The second panel presents the number of days per month with very heavy rainfall (rainfall over 31mm/day). The third panel shows the average length of dry spells. As one would expect, the positive rainfall anomalies are clearly associated with months that experience a higher number of heavy rainfall events. For example February 1966, December 1969, December 1985 and February 1989 all recorded over 200 mm above their monthly climatological mean and at least 4 days of very heavy rainfall. The most extreme negative anomalies occurred in January 1966 and 1970, December 1982, February 1987 and 1992 and December 1997 and were generally associated with El-Nino and extreme dry years (see figure 9). The average dryspell duration highlights years where the dry season was long and uninterrupted. 1963, 1964 and 1998 displayed very long and interrupted dry seasons, while a number of years in the mid-1990s (1984, 1985, 1987, 1989) and in the recent past (2012 2013, 2014) also display long continuous dry seasons, however they are not generally associated with drier than average summer conditions.

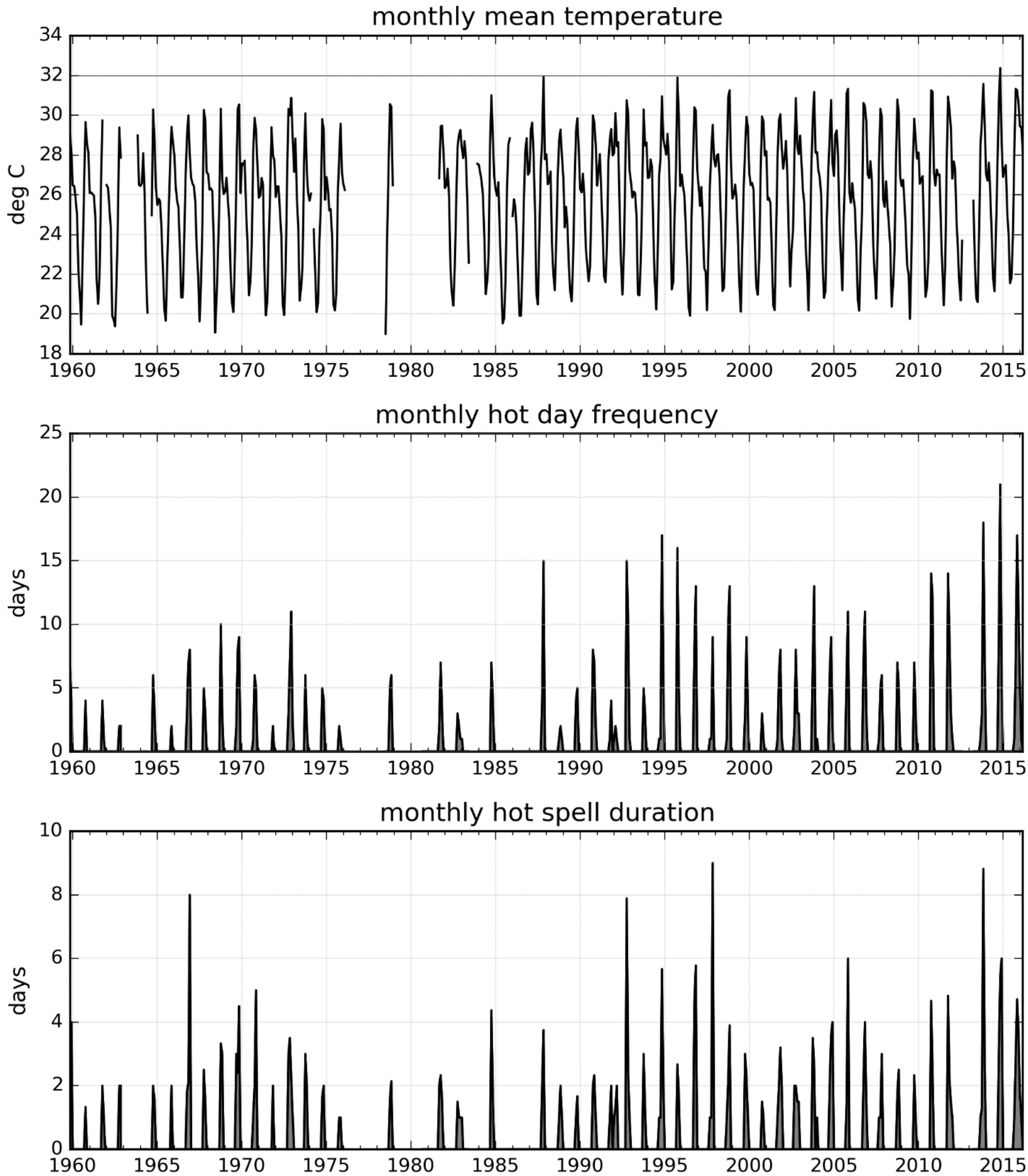


Figure 15: ***Time series of extreme events at Rekomitjie station.*** *Monthly averaged daily mean temperature (top panel). The monthly hot day frequency or the number of days per month where the mean temperature exceeds 32° C (middle panel). The monthly hot spell duration or the average number of consecutive days where the mean temperature exceeds 32° C per month (lower panel)*

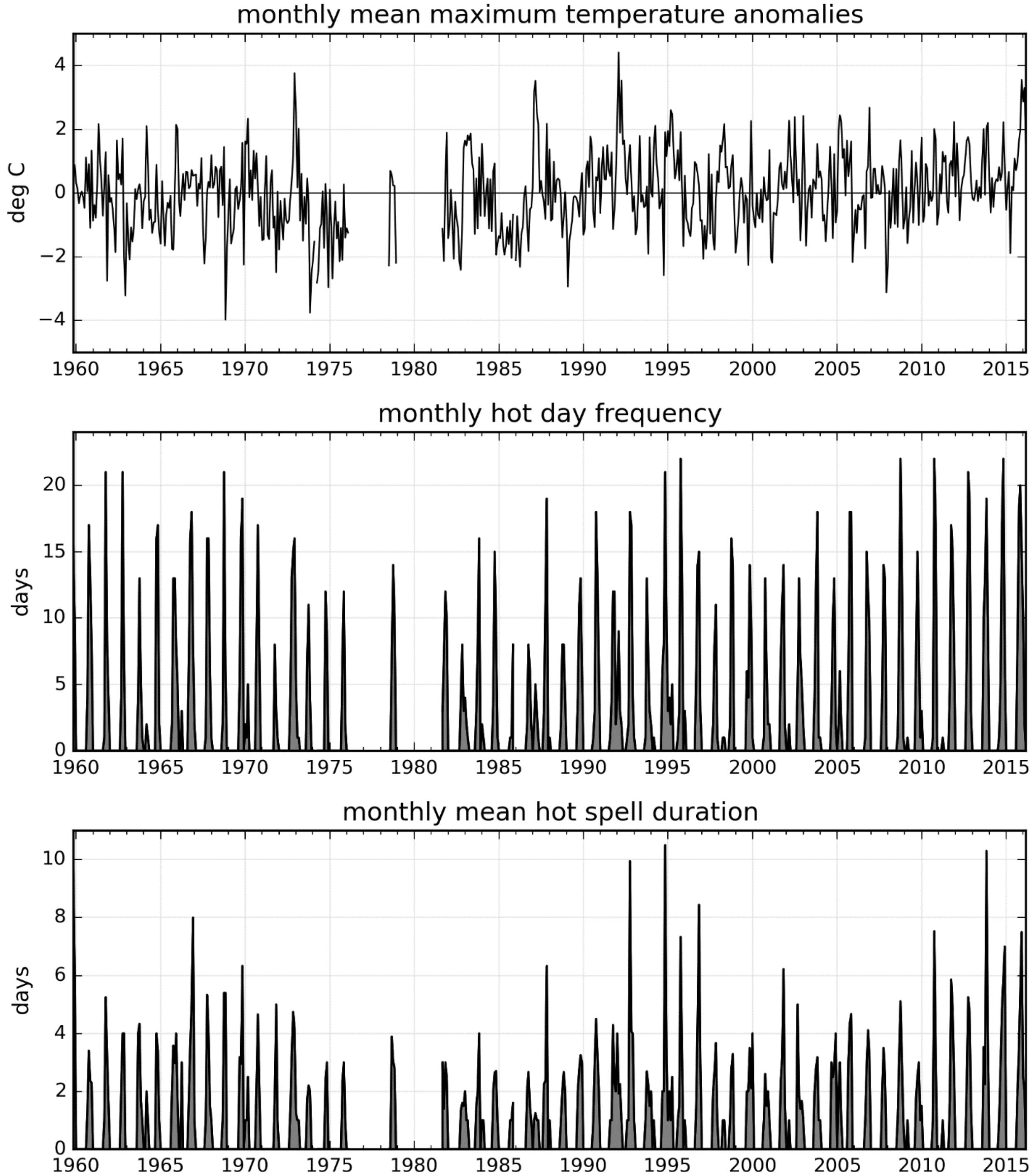


Figure 16: ***Time series of daily maximum temperature monthly statistics****. Monthly mean maximum temperature anomalies (top panel), number of days above the 90th percentile (37° C) per month (middle panel) and the mean number of consecutive days above the 90th percentile per month.*

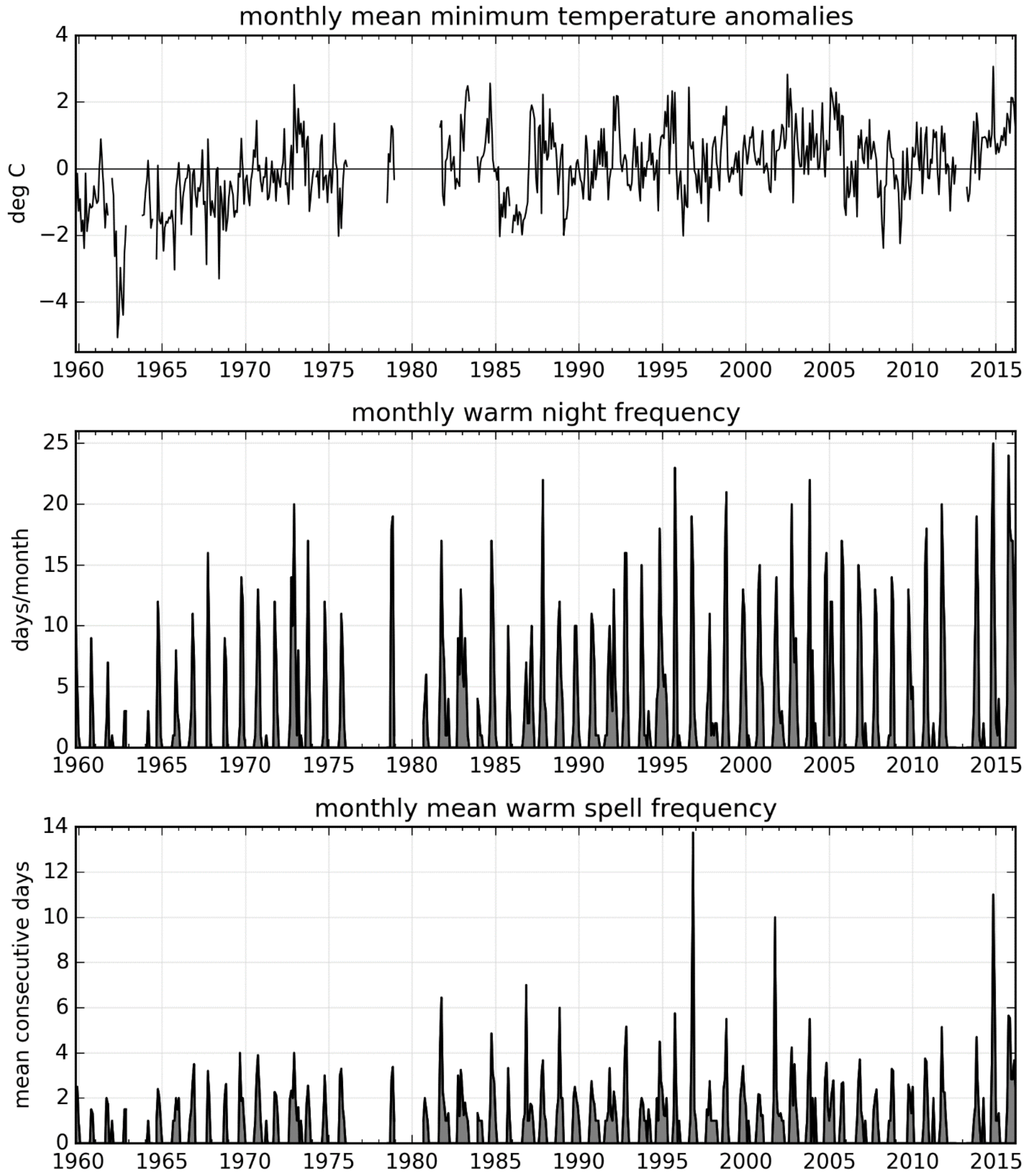


Figure 17 : ***Time series of daily minimum temperature monthly statistics****. Monthly mean minimum temperature anomalies (top panel), number of days above the 90th percentile (24° C) per month (middle panel) and the mean number of consecutive days above the 90th percentile per month.*

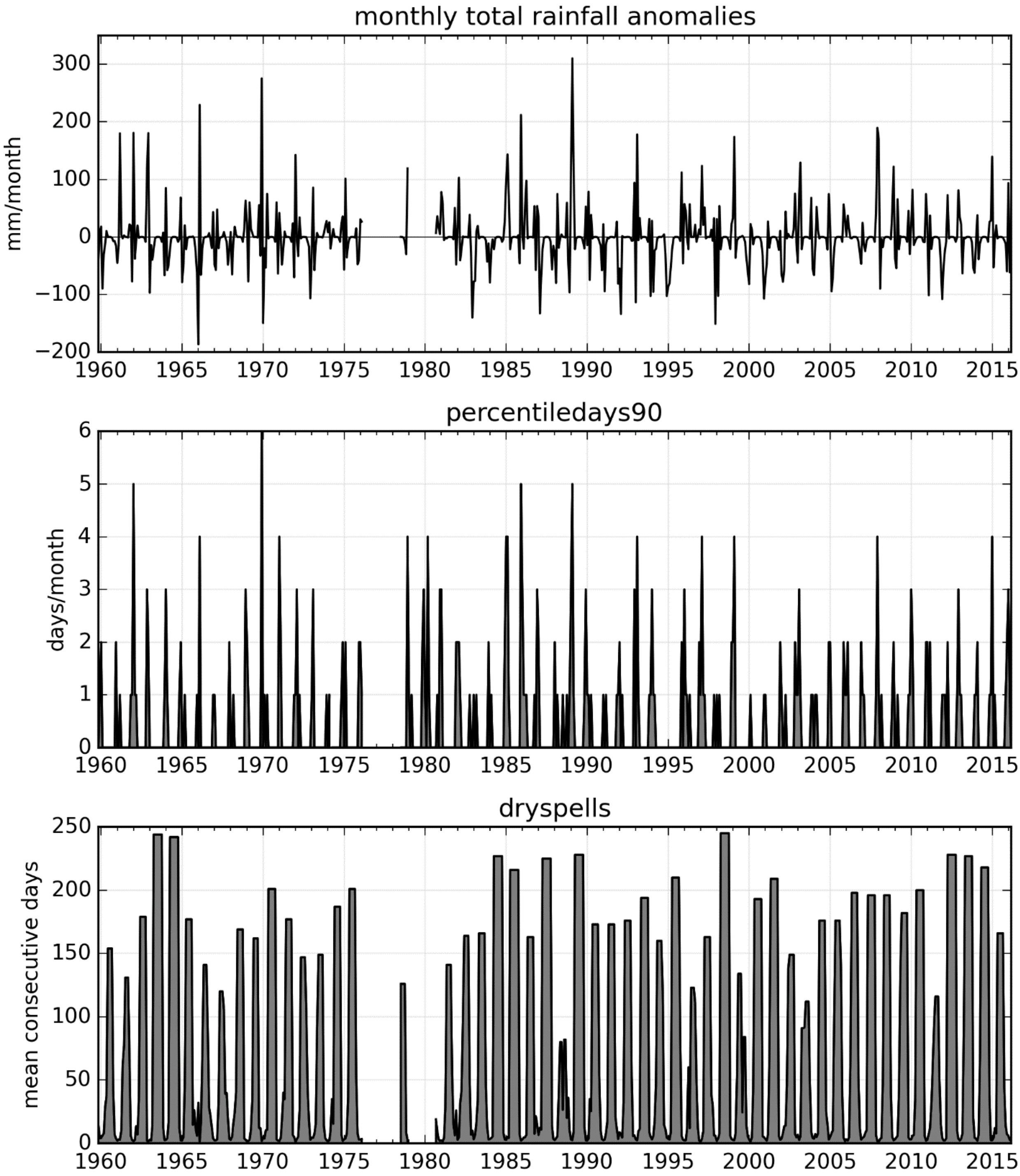


*Figure 18: **Time series of monthly rainfall statistics**. Monthly total rainfall anomalies (top panel), number of days above the 90th percentile (31mm) per month (second panel).The mean number of consecutive dry-days (bottom panel).*

Other weather stations

Three other weather stations are located within the wider region surrounding Rekomitjie. This section provides a brief overview of their climates. Figure 19 presents the historical average seasonality of the three stations from 1960 until the end of their records. All three stations display the same basic seasonality with a single summer rainfall season and dry winters. All have the coolest temperatures during winter and warmest temperatures during September – November season. The climate of the Kariba station is the most similar to that of Rekomitjie. However, the maximum temperatures are just slightly cooler than those at Rekomitjie throughout the year, while minimum temperatures are similar during the summer, but cooler from March – September. Rainfall is also slightly higher, especially during the shoulder seasons (740 mm/year vs. 678 mm/year). The climates at Karoi and Lusaka are more dissimilar to that of Rekomitjie, primarily because they are located outside of the valley at higher elevations. Temperatures at Karoi (Lusaka) are generally 6° C (5° C) cooler than at Rekomitjie, and minimum temperatures at Karoi do not show the peak during September – November, this may in part be due to the fact that the Karoi record only extends up to 1990, while the Kariba records ends in 2000 and the Lusaka station in 2012. Rainfall totals are quite a lot higher at these stations with Karoi receiving on average 823 mm/year and Lusaka recording 815 mm/year.

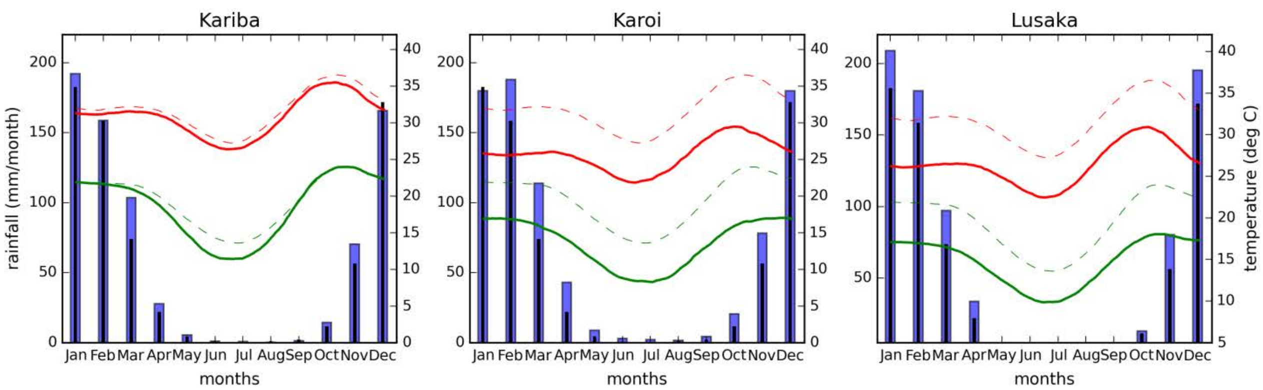


Figure 19: ***Historical average seasonality for the Kariba, Karoi and Lusaka stations.*** *Mean monthly total rainfall (mm) depicted as blue bars. 30-day smoothed mean daily maximum (minimum) temperature presented by the red (green) lines. Dashed lines show the minimum and maximum temperatures and the narrow black bars show rainfall for the Rekomitjie station as a reference.*

Focusing on the Kariba station, it is clear that there has been a positive trend in maximum temperature in all four seasons, however this warming has not been evident or consist in all decades (figure 20). The warming was strongest during the late 1970 to the end of the 1980s after which the rate of warming decreased, except during September – November season. A decreasing trend is evident during March – May during the 1960, but the spread of values is so large that this suggest that it may be due to instrument error rather than a real trend.

A similar message is seen in the minimum temperature record for Kariba (figure 21). The largest warming is seen during the late 1970 to the end of the 1980s after which there is a light decrease in all seasons except summer. Again, the large variance at the beginning of the record makes it difficult to interpret the validity of any trend during this period. Strong interannual variability is found in the rainfall (Figure 22), but rainfall values appeared to increase through the 1960s to the mid 1970 after which it decreased during the 1980 to the 1990s. The large warming temperature trend is probably associated with the drying conditions.

The Karoi station (Figure 23- 25) provides just less than 30-years of data with the record ending in 1990. It therefore does not provide any information on how the local climate has changed over the recent past, however it does support the findings at Kariba that show a slight negative trend in minimum temperature during winter and not clear trends in other months. This is in contract to the strong warming trend seen in the Rekomitjie station minimum temperature record during this earlier period.

The Lusaka station has a relatively long and complete record, and like the Kariba station, it shows the strongest rate of daytime warming occurring in the 1980s and that it is only during the September – November period that this warming is evident through the full period (figure 26). Minimum temperature shows warming trends in all seasons except summer, with the strongest rate of warming occurring during the 1980s (figure 27). No clear trend is evident in the rainfall time series (Figure 28).

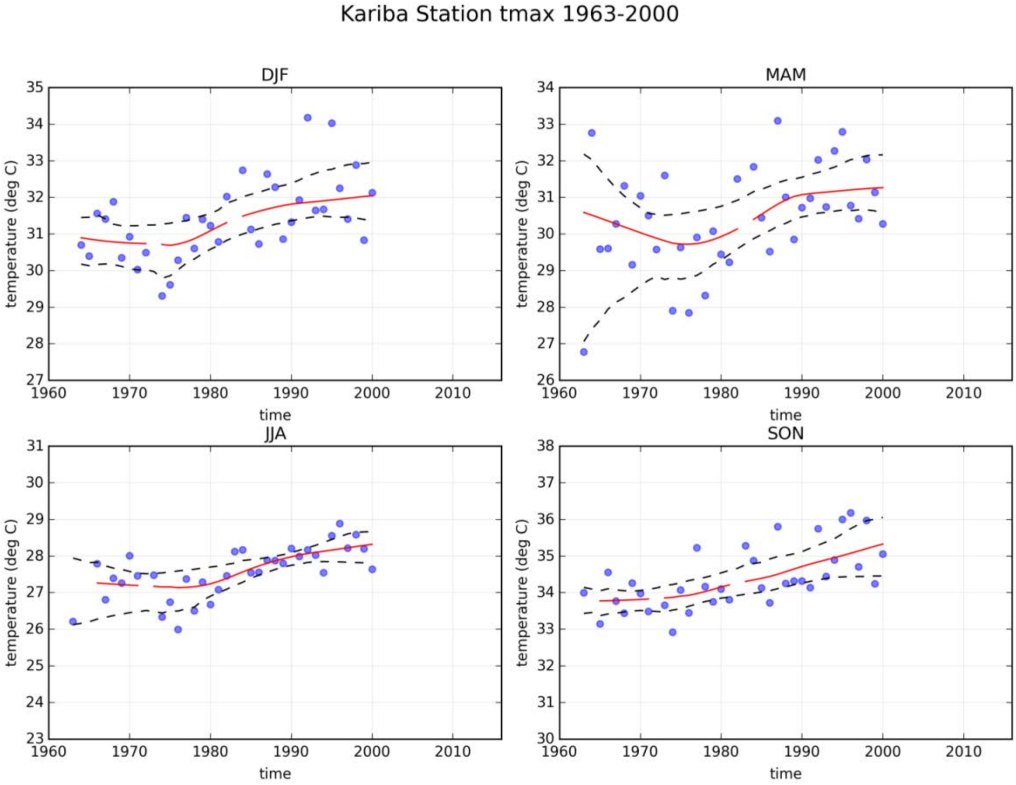


Figure 20: ***Observed time series and trend in maximum temperature at Kariba station.*** *Time series of seasonal mean maximum temperature (blue dots). The red line shows the median trends calculated using lowess method, and the dashed lines show the range of the 95th confidence interval around the median.*

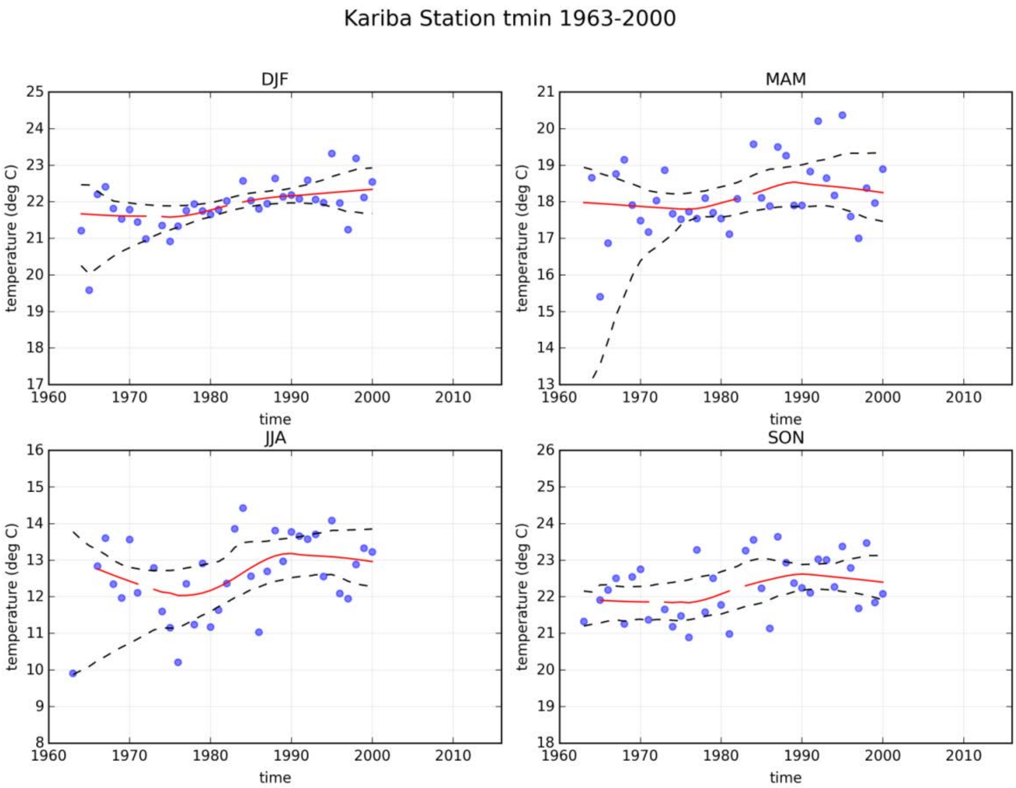


Figure 21: ***Observed time series and trend in minimum temperature at Kariba station.*** *Time series of seasonal mean minimum temperature (blue dots). The red line shows the median trends calculated using lowess method, and the dashed lines show the range of the 95th confidence interval around the median.*

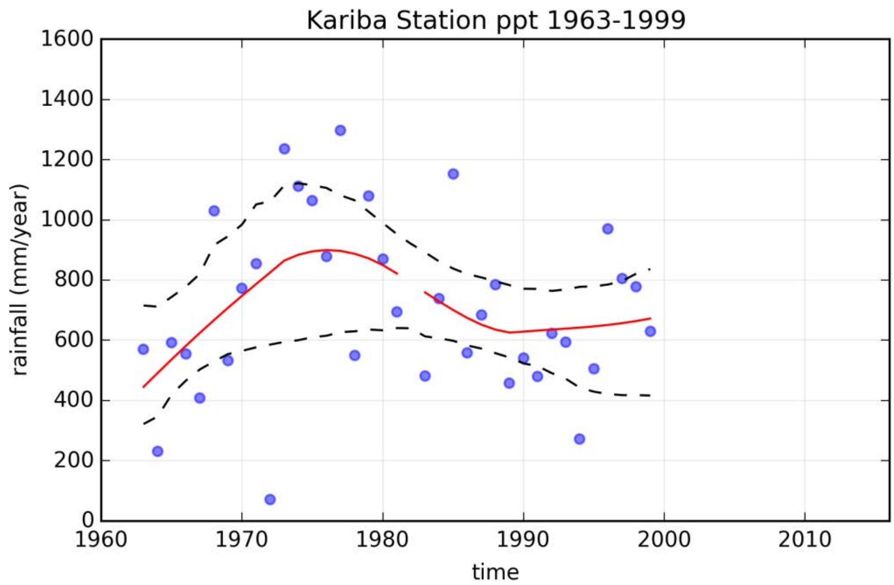


Figure 22: ***Observed time series and trend in annual rainfall at Kariba station.*** *Time series of annual total rainfall (blue dots). The red line shows the median trends calculated using lowess method, and the dashed lines show the range of the 95th confidence interval around the median.*

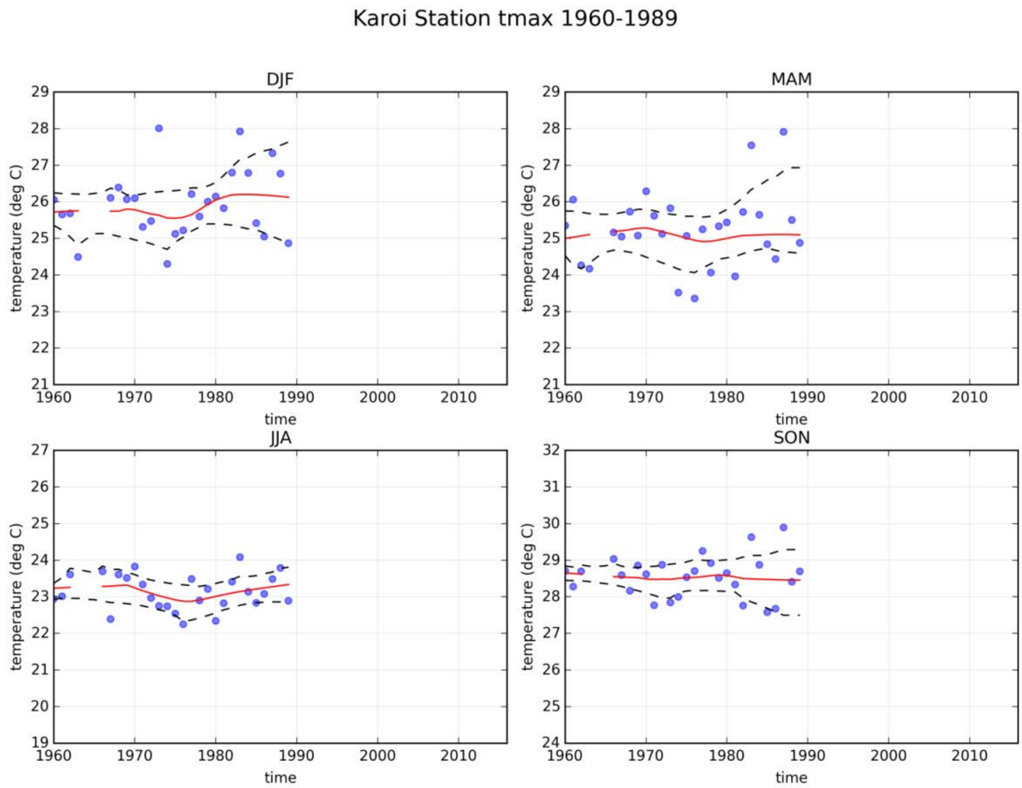


Figure 23: ***Observed time series and trend in maximum temperature at Karoi station.*** *Time series of seasonal mean maximum temperature (blue dots). The red line shows the median trends calculated using lowess method, and the dashed lines show the range of the 95th confidence interval around the median.*

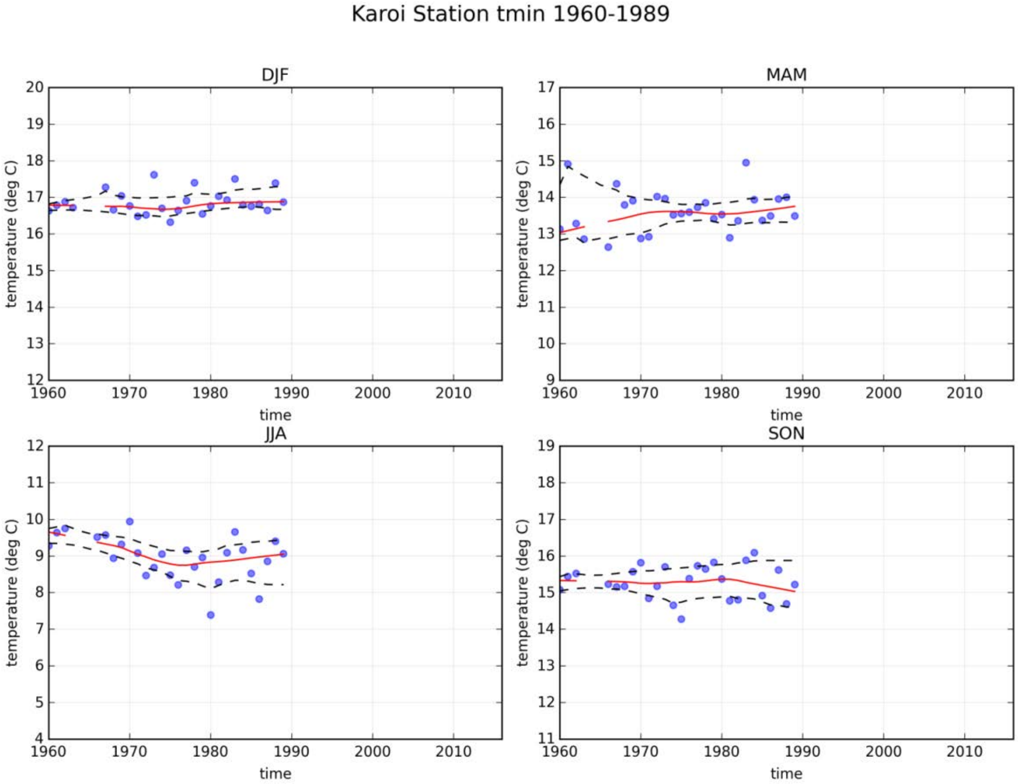


Figure 24: ***Observed time series and trend in minimum temperature at Karoi station.*** *Time series of seasonal mean minimum temperature (blue dots). The red line shows the median trends calculated using lowess method, and the dashed lines show the range of the 95th confidence interval around the median.*

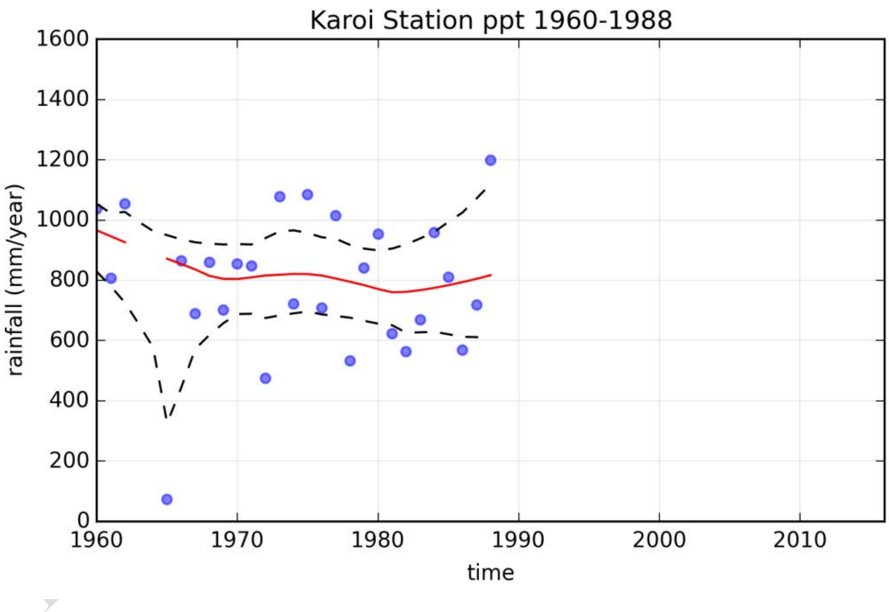


Figure 25: ***Observed time series and trend in annual rainfall at Karoi station.*** *Time series of annual total rainfall (blue dots). The red line shows the median trends calculated using lowess method, and the dashed lines show the range of the 95th confidence interval around the median.*

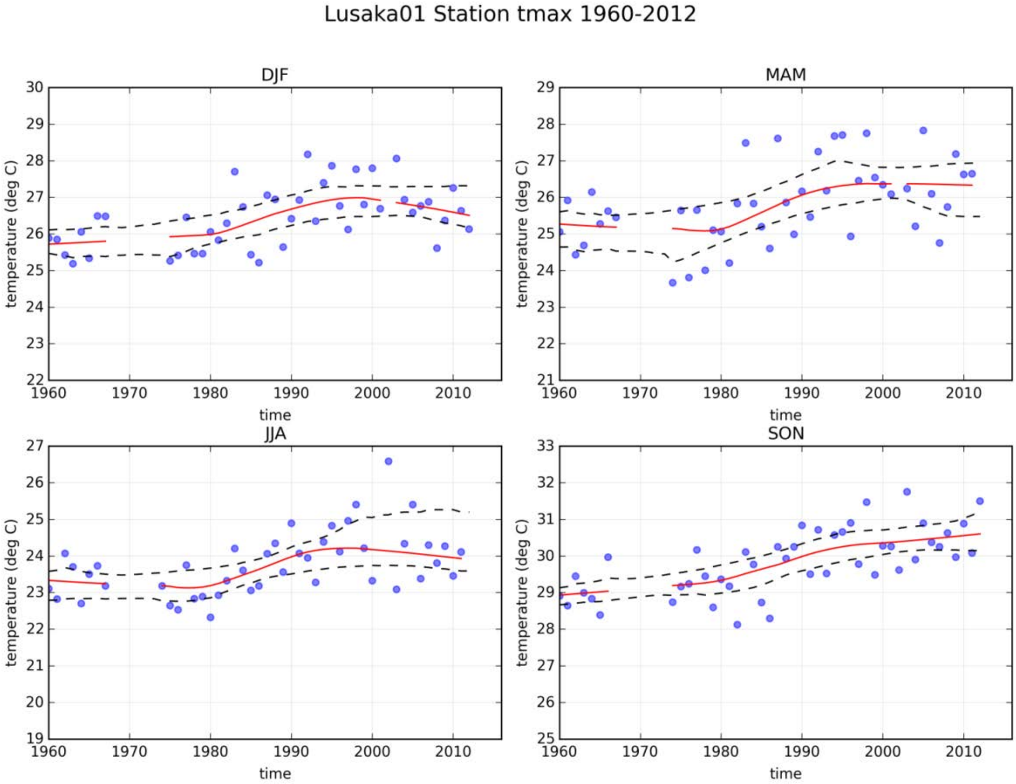


Figure 26: ***Observed time series and trend in maximum temperature at Lusaka station.*** *Time series of seasonal mean maximum temperature (blue dots). The red line shows the median trends calculated using lowess method, and the dashed lines show the range of the 95th confidence interval around the median.*

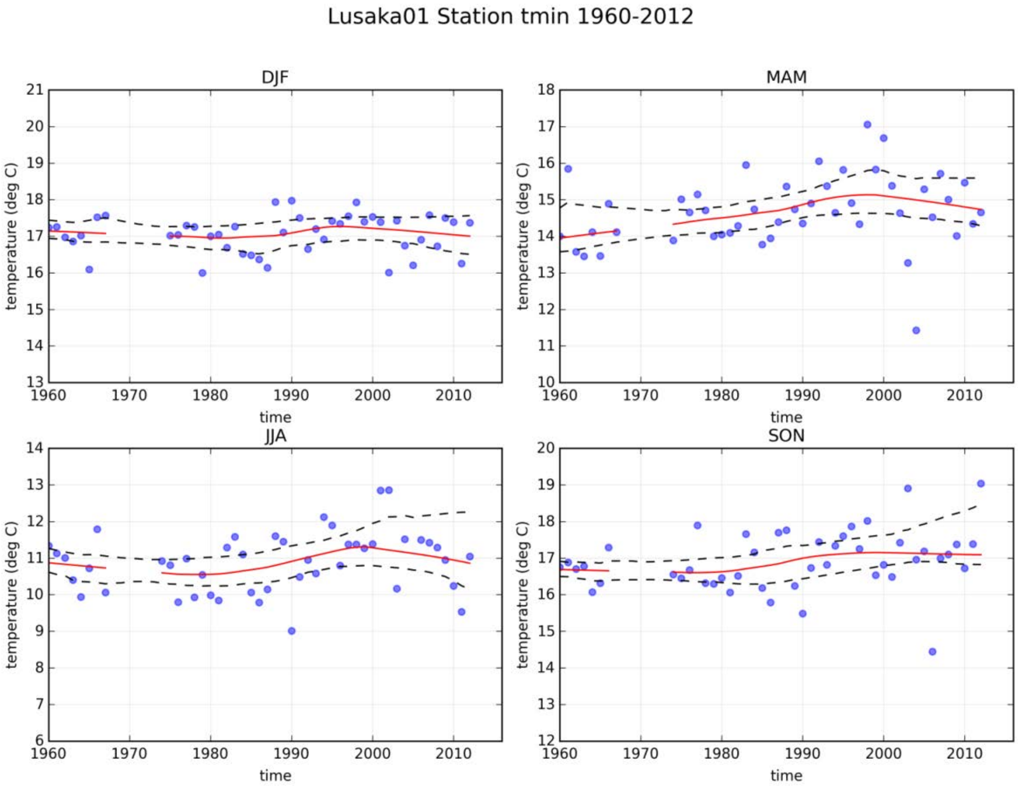


Figure 27: ***Observed time series and trend in minimum temperature at Lusaka station.*** *Time series of seasonal mean minimum temperature (blue dots). The red line shows the median trends calculated using lowess method, and the dashed lines show the range of the 95th confidence interval around the median.*

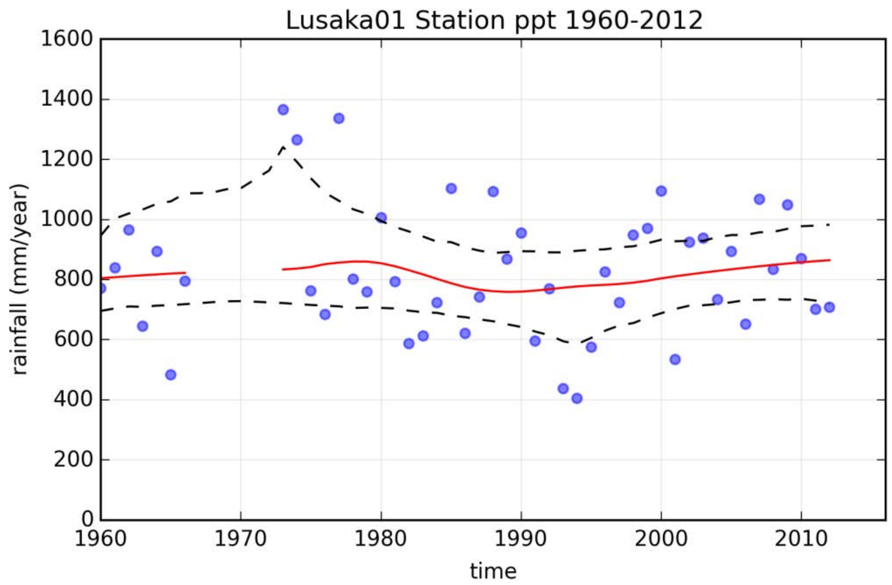


Figure 28: ***Observed time series and trend in annual rainfall at Lusaka station.*** *Time series of annual total rainfall (blue dots). The red line shows the median trends calculated using lowess method, and the dashed lines show the range of the 95th confidence interval around the median.*

Regional climate

It is useful to understand the local climate at Rekomitjie in light of the larger regional climate surrounding it. The WFDEI gridded dataset is used to provide an overview of the regional climate. It is important to recognise that this dataset has a coarse resolution and that each gridcell value represents an area of roughly 50 × 50 km and therefore will not closely match the point values from a weather station. This is illustrated in Figure 29 below which compares the historical average seasonality of the gridpoint value and those for the Rekomitjie station. Figure 30 presents the same data, but in a different way, showing the frequency distribution of minimum and maximum temperatures and rainfall between these two different datasets.

The seasonality of maximum and minimum temperatures are relatively similar between the gridcell value and that of the Rekomitjie station, except the climate of the gridcell is around 2° C cooler. This is primarily because the gridcell represents an average for a larger area which includes slightly cooler / higher elevation areas to the south-east of Rekomitjie. The distribution of the minimum temperature gridded product is also slightly left-skewed relative to the station record, meaning that it has a slightly larger (smaller) proportion of cooler (warmer) nights compared to the station record.

The rainfall from the WDFEI dataset is slightly higher than that at Rekomitjie during the core rainy season, but lower at the end of the rainy season. Also the gridded product records a far higher proportion of very light rainfall values (less than 1mm) and does not capture the very long tail and extreme values found in the station record. The differences found in rainfall between the gridded and station products can again be explained by the differences between point and area average values.

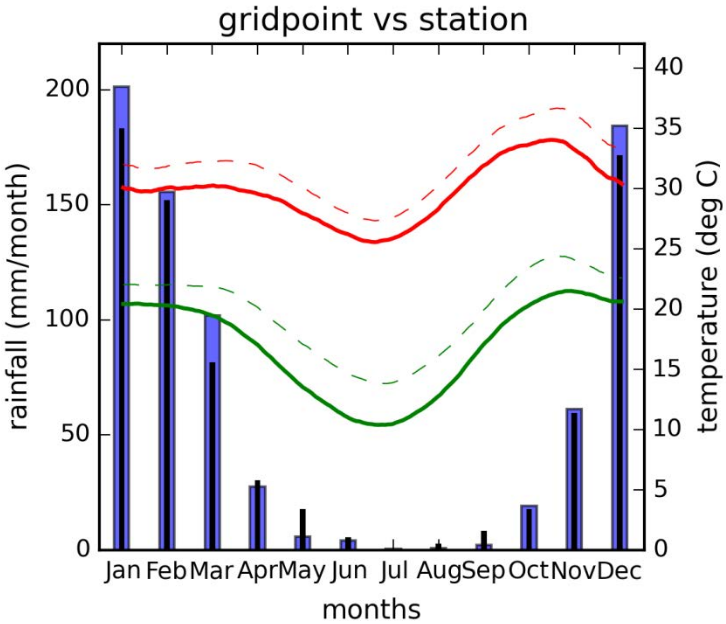
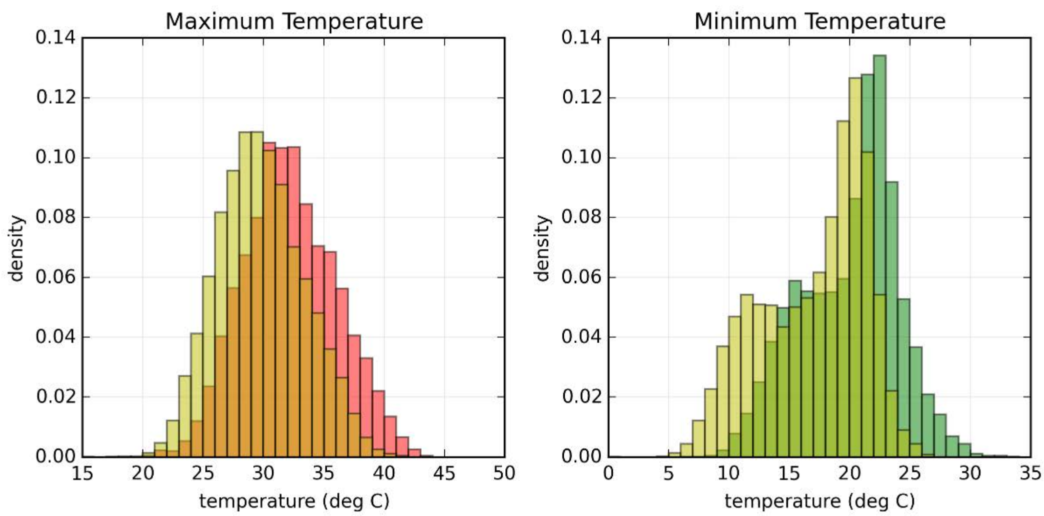


Figure 29: ***Historical average seasonality for the WFDEI gridcell value.*** *Mean monthly total rainfall (mm) depicted as blue bars. 30-day smoothed mean daily maximum (minimum) temperature presented by the red (green) lines. Dashed lines show the minimum and maximum temperatures and the narrow black bars show rainfall for the Rekomitjie station as a reference.*



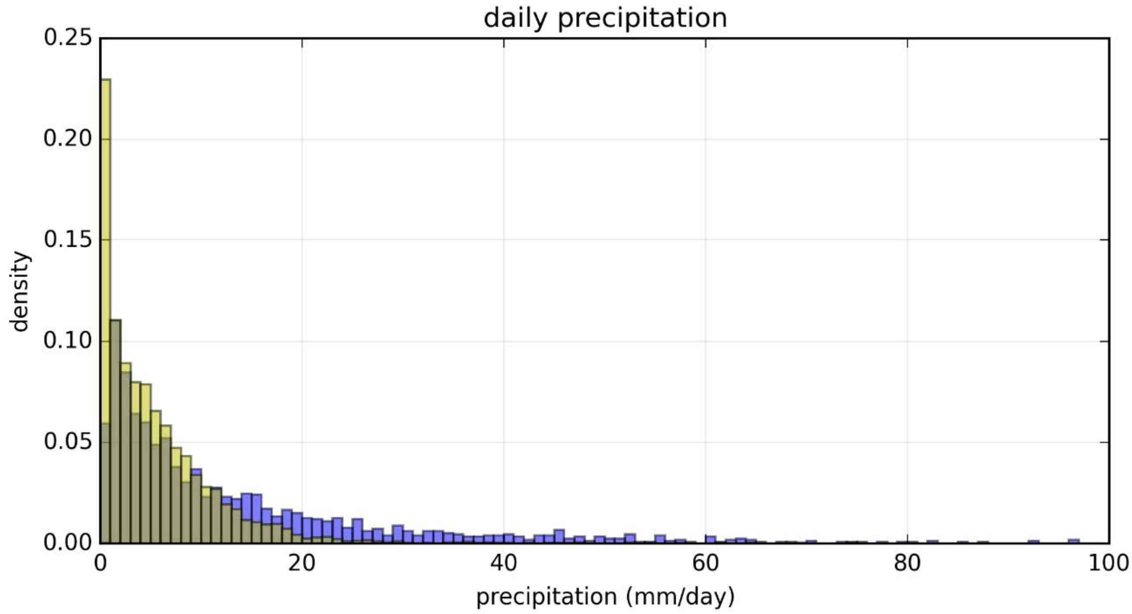


Figure 30: ***Comparison of values between the station record and gridcell value over Rekomitjie****. Histogram of daily maximum and minimum temperature and rainfall for the Rekomitjie station (red, green and blue respectively) and the gridcell values at centred on -16.25, 29.25 from the WFDEI dataset (yellow) for the period 1979-2014.*

It is clear that the topography of the region plays a leading role in determining the spatial temperature pattern. Temperatures are generally warmer over the lower elevation areas of the Zambezi Valley and cooler over the higher topography, especially over the Highveld of Zimbabwe (Figure 31 and 32). Figure 33 presents the extreme hot values, or the 90^{th} percentiles, for minimum, mean and maximum daily temperatures. It shows that the extreme values of temperature are closely tied to the mean climatologies. Figure 34 displays the average number of days per season, where the daily mean temperature is within the ideal temperature range for tsetse flies (16 - 32° C). It is clear that during summer, autumn and spring the temperatures are almost always within this ideal range over the full domain. However, during winter the average temperatures are too low over the higher elevation areas, especially over the Zimbabwe Highveld.

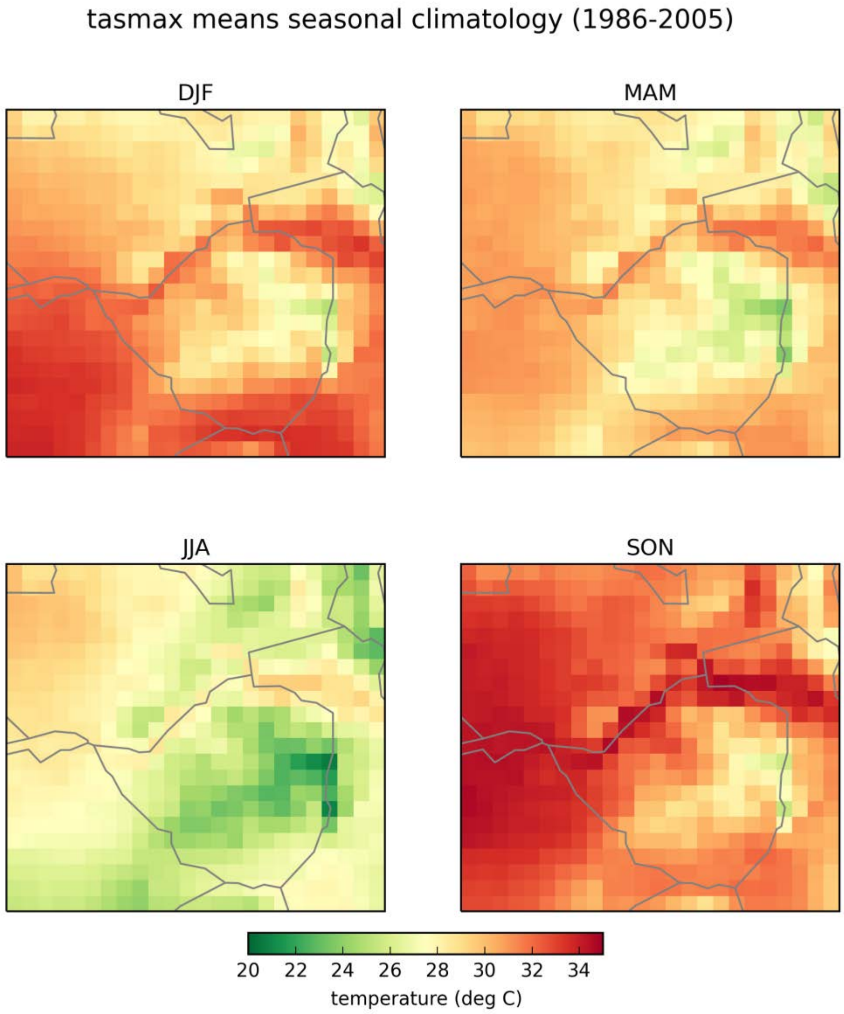


Figure 31: ***Climatology of seasonally averaged maximum daily temperatures over the Zimbabwe region.*** *Data from the WFDEI dataset averaged over the period 1986-2005.*

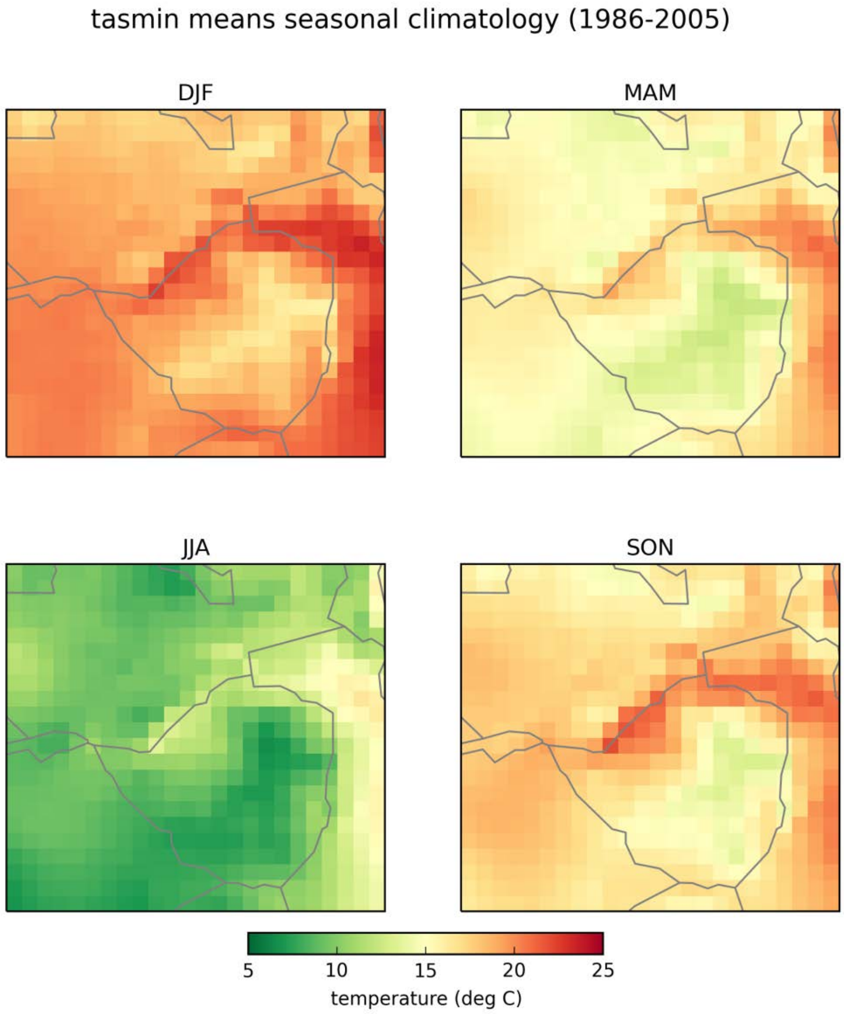


Figure 32: ***Climatology of seasonally averaged minimum daily temperatures over the Zimbabwe region.*** *Data from the WFDEI dataset averaged over the period 1986-2005*

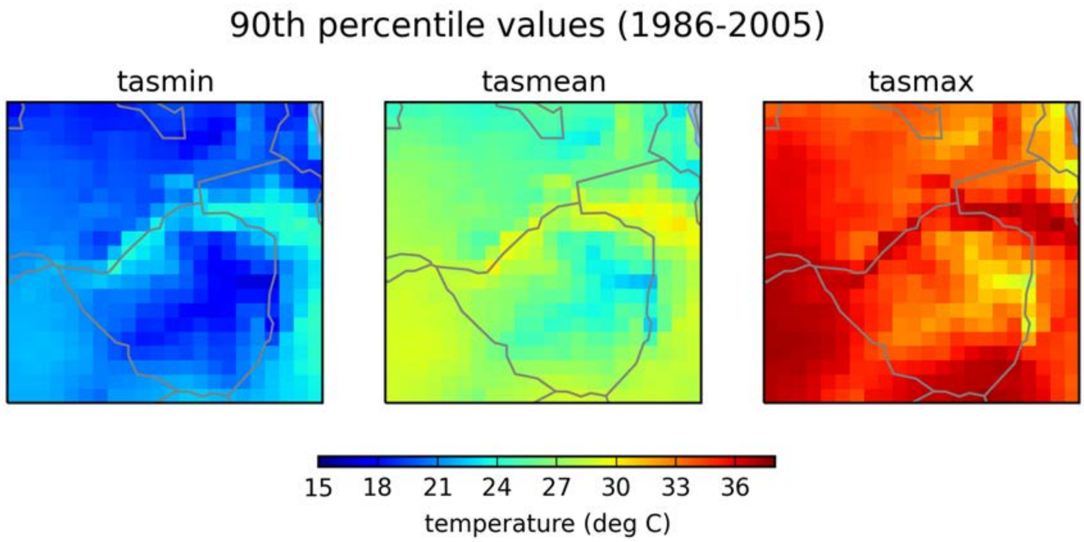


Figure 33: ***90th percentile values for daily maximum, mean and minimum temperatures over the Zimbabwe region.*** *Data from the WFDEI dataset averaged over the period 1986-2005*

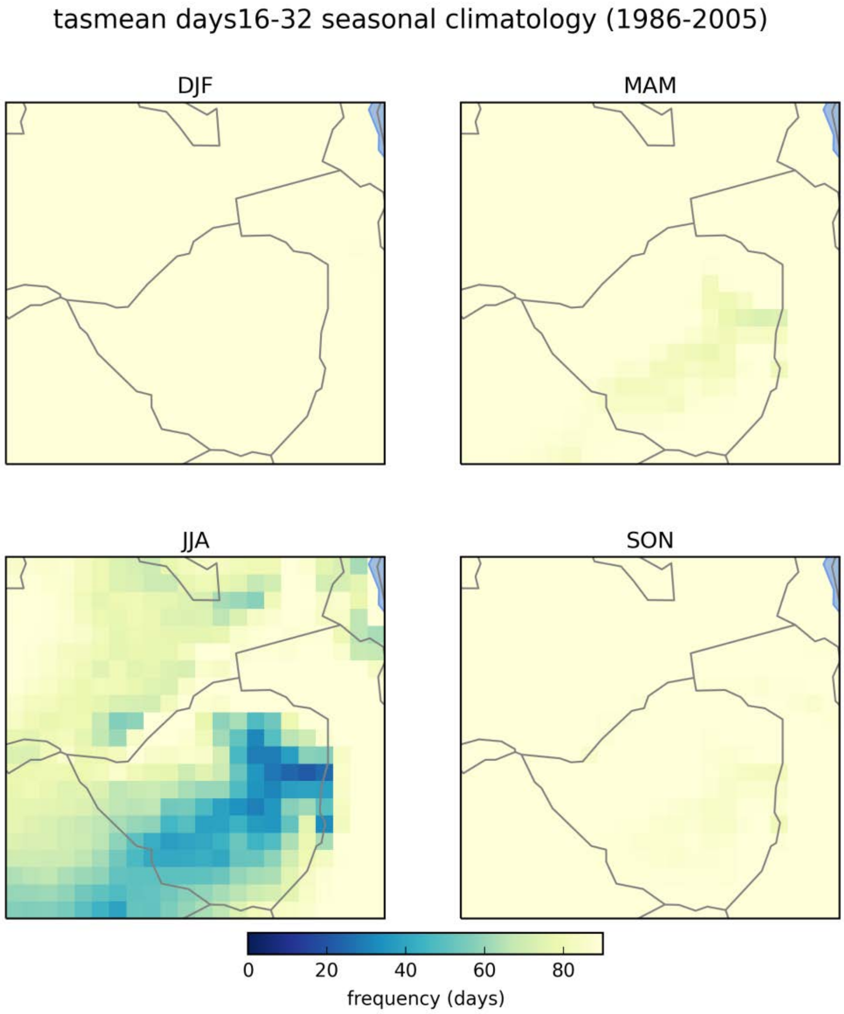


Figure 34: ***Climatology of seasonal frequency of days within the ideal tsetse fly temperature range over the Zimbabwe region.*** *Average number of days per season where daily mean temperatures are between 16°-32° C. Data from the WFDEI dataset averaged over the period 1986-2005*

Climate projections

This section presents the future climate for the Rekomitjie area, as well as for the larger region, projected by an ensemble of Global Climate Models (GCMs) from the CMIP5 archive. It then presents the results obtained by statistically downscaling the GCMs using the Self-Organising Map based downscaling method. The analysis focuses on seasonally averaged daily maximum minimum and mean temperatures and annual total rainfall under two different emission scenarios; the moderate RCP4.5 scenario and the more extreme RCP 8.5 emission scenario.

Global Climate Model projections

Figure 35 presents the temporal evolution of seasonal mean daily maximum temperature for the gridcell over Rekomitjie projected by a 15-member ensemble of CMIP5 GCMs for RCP 4.5 emission scenario. It shows that daily maximum temperature is projected to increase into the future and that the change will be large enough that the climate change signal should emerge beyond the range seen in historical natural variability within the next few decades. The models agree on the sign of change, however, there is disagreement in the magnitude of warming especially into the far future. The rate of warming is slightly higher during September – November, and lowest during June – August, suggesting that warmer temperatures may increase faster than the cooler temperatures. Figure 36 also depicts the time evolution of daily maximum temperature, but under the more severe RCP8.5 emission scenario. Under this scenario, the projections is for a more rapid warming, but still there is a large spread in the range of projected temperature of between 2° - 7° C by the end of the century. A similar message is seen in daily minimum and daily mean temperature (Figure 37-40).

The number of days where the daily mean temperature exceeds 32° C is projected to increase into the future under both emission scenarios (Figure 41-42). Days exceeding this threshold in the historical record represent a very rare extreme event with direct implications for tsetse fly population dynamics. The projections suggest that by the end of the century this threshold could be exceeded on up to 40 days during spring and may even start to occur during the summer season under the RCP 4.5 scenario. Under the RCP8.5 scenario these extreme hot days are projected to increase to as much as 65 days in spring and 30 days during summer and may even start to occur in the other seasons by the end of the century.

The projected change in rainfall into the future varies strongly between the models under both emission scenarios (Figure 43 and 44). Some models project wetting, some project drying, while others project no statistically significant change from the historical range of interannual variability.

Figure 45 – 49 present the projected change in temperature and rainfall over the larger region by the end of the century under the RCP8.5 emissions scenario. The results show that the projected changes in temperature are positive and statistically significant (stippling shows where the change is statistically significant). However, the magnitude of change is strongly dependent on the model, with some models showing a relatively moderate warming of around 2° C over the full area, while other models project a very strong warming of between 4 – 9° C depending on the location. The figures also highlight the very coarse scale of these models, which limits their usefulness at representing any regional or local scale climate messages.

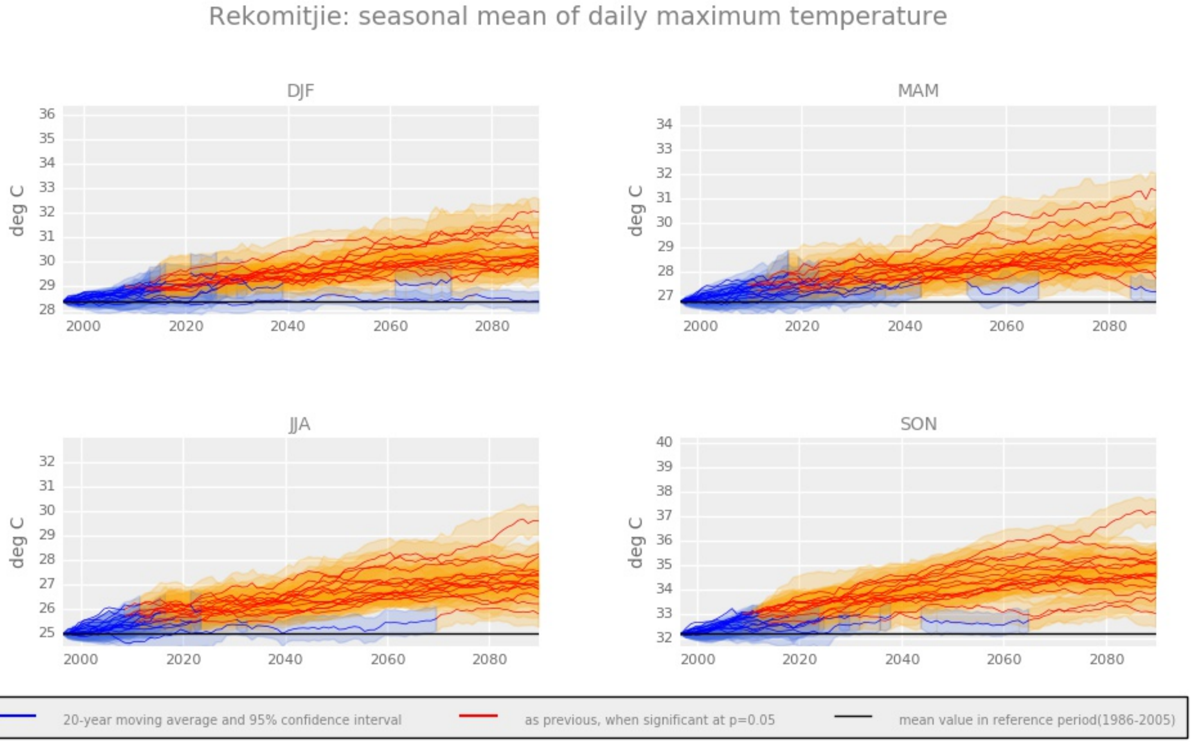


Figure 35: ***CMIP5 projected changes in seasonal mean daily maximum temperature under the RCP 4.5 concentration pathway for Rekomitjie****. The black line shows the multi-model mean value across all models in the reference period 1986-2005. The coloured lines show the 20-year moving average of results from each model and the shading around each line shows the 95% confidence range around those model results. Where the line and associated shading changes from blue to red/orange indicates when 20-year moving average moves outside of the 95% confidence range of the reference period.*

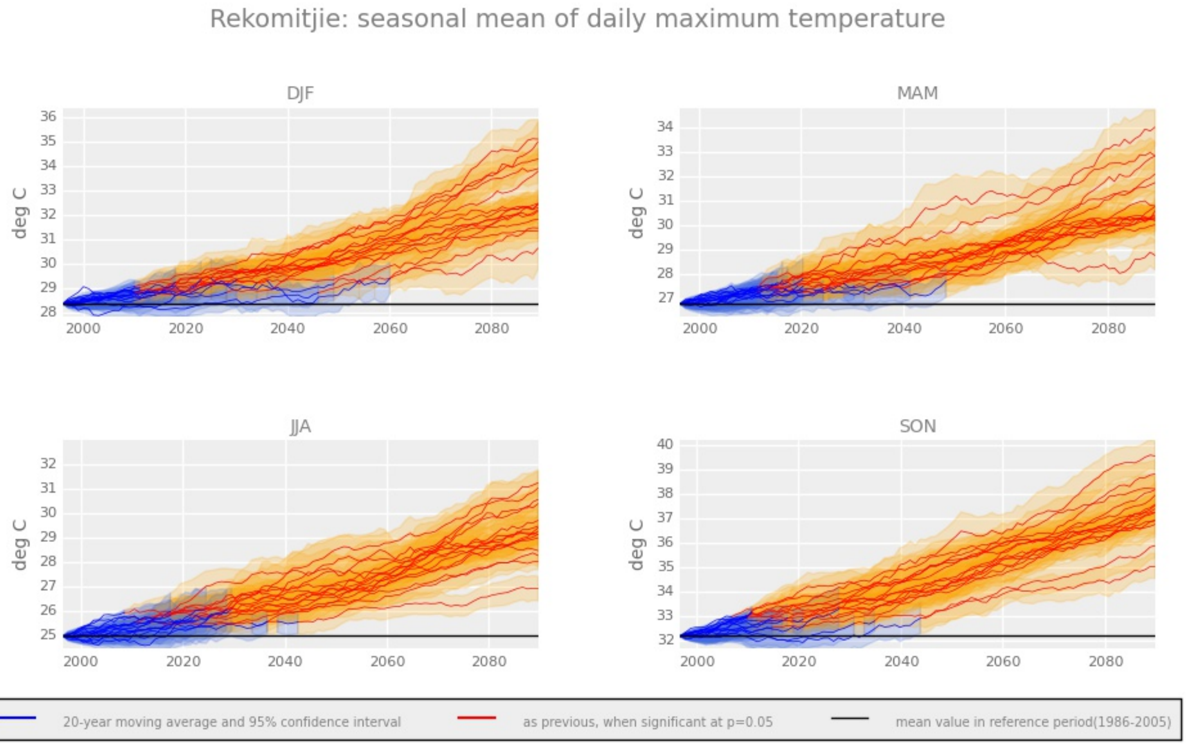


Figure 36: ***CMIP5 projected changes in seasonal mean daily maximum temperature under the RCP 8.5***

***concentration pathway for Rekomitjie*.**

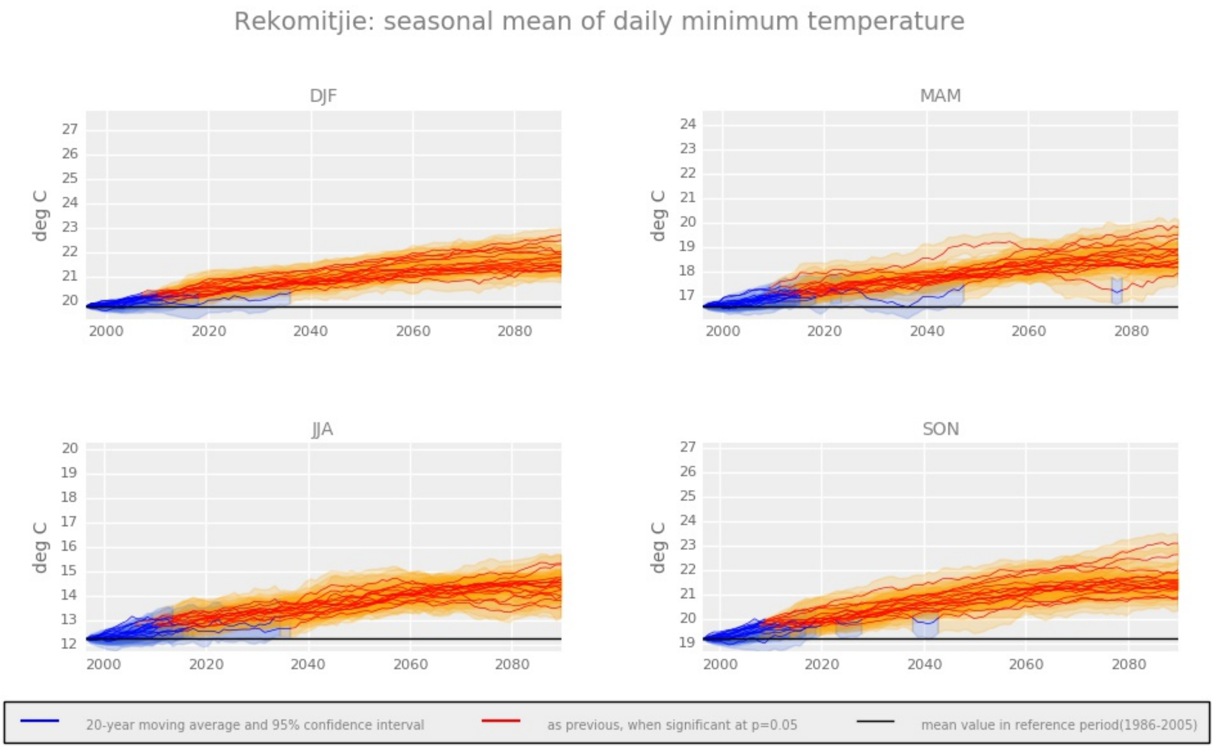


Figure 37: ***CMIP5 projected changes in seasonal mean daily minimum temperature under the RCP 4.5 concentration pathway for Rekomitjie***

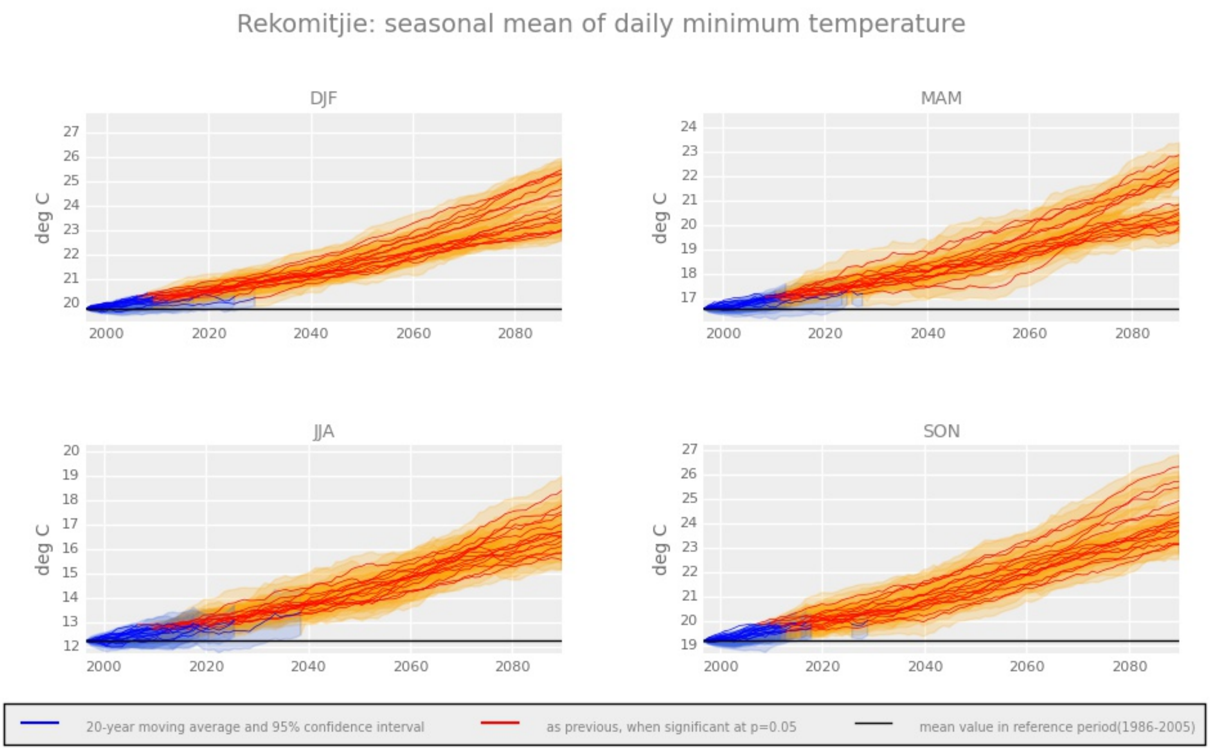


Figure 38: ***CMIP5 projected changes in seasonal mean daily minimum temperature under the RCP 8.5 concentration pathway for Rekomitjie***

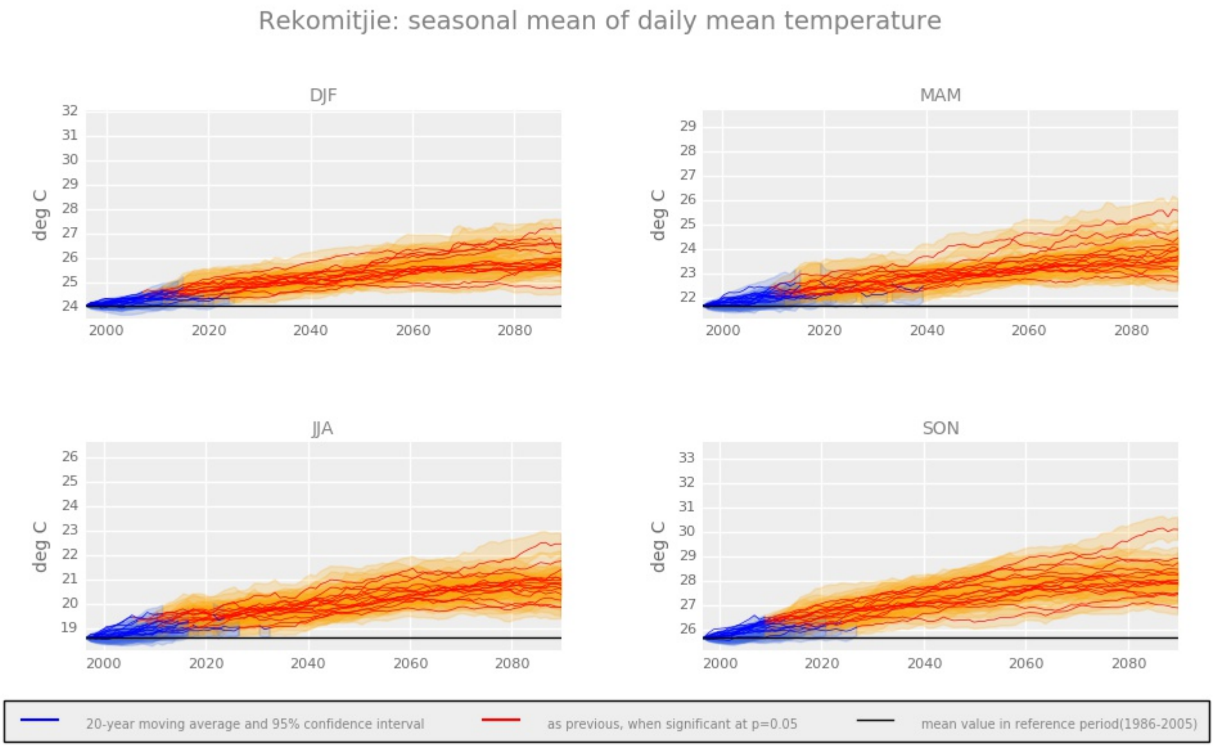


Figure 39: ***CMIP5 projected changes in seasonal mean daily mean temperature under the RCP 4.5 concentration pathway for Rekomitjie***

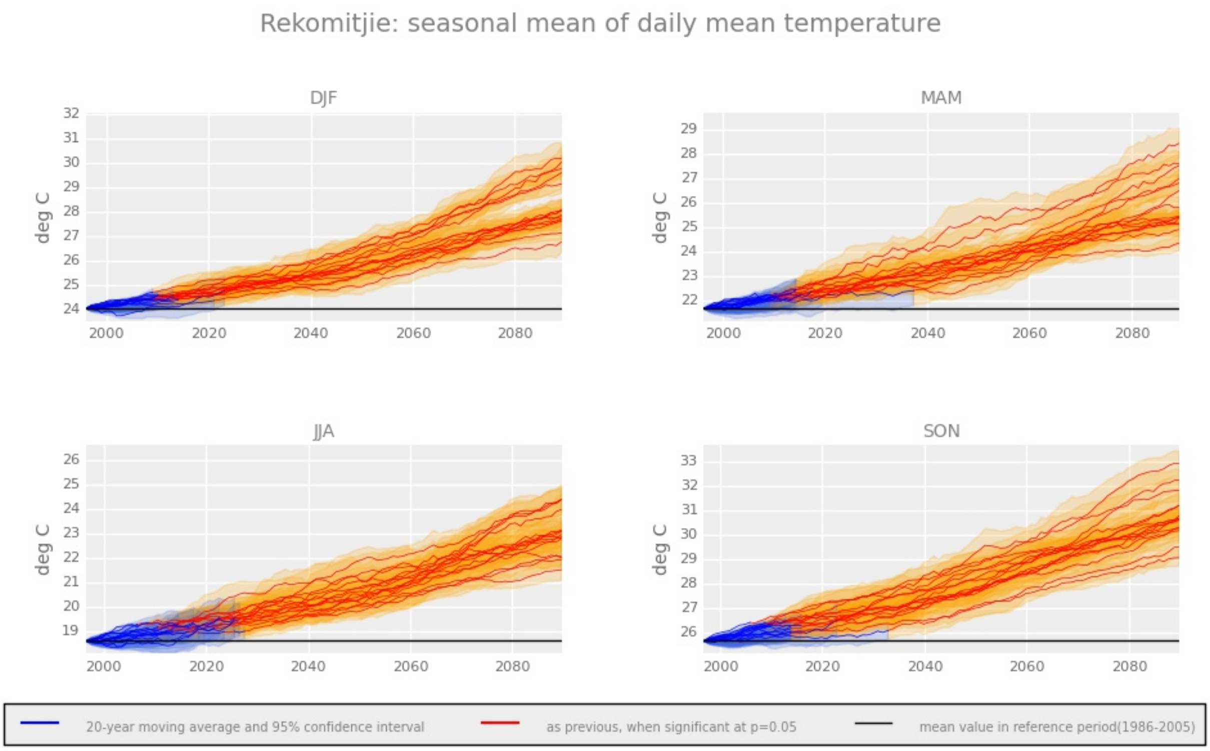


Figure 40: ***CMIP5 projected changes in seasonal mean daily mean temperature under the RCP 8.5 concentration pathway for Rekomitjie***

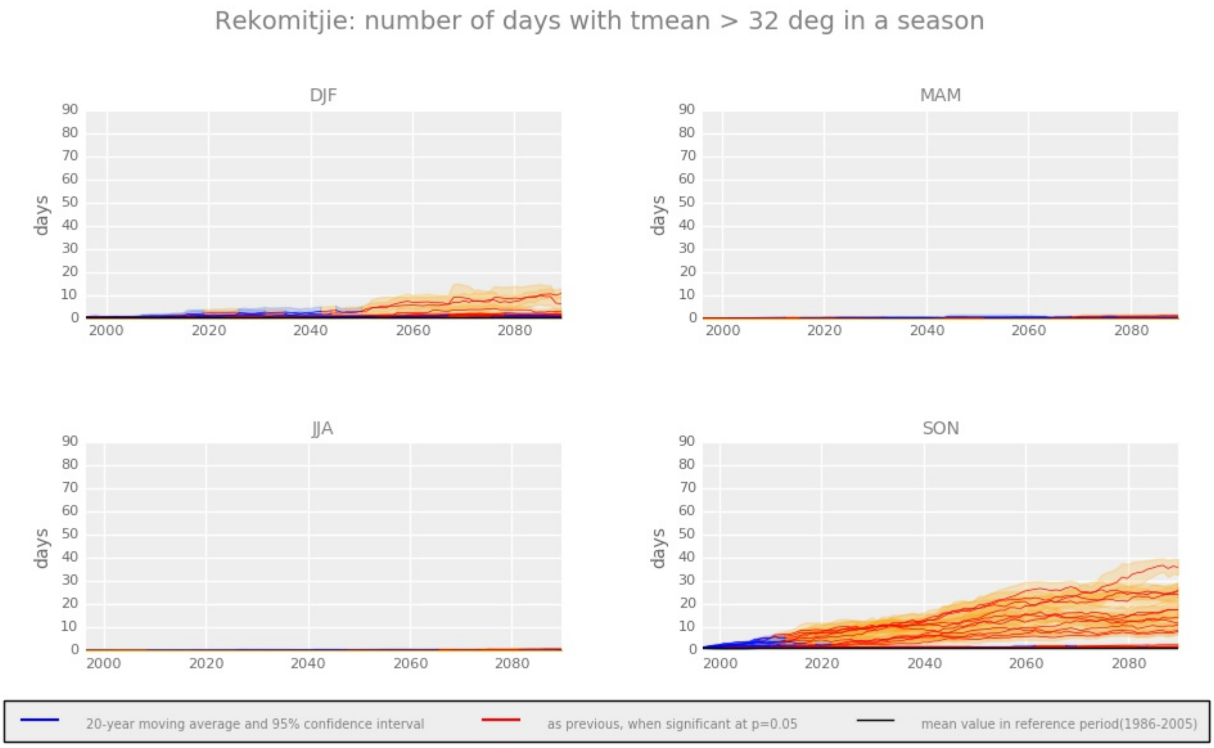


Figure 41: ***CMIP5 projected changes in seasonal mean number of days with daily mean temperature over 32° C under the RCP 4.5 concentration pathway for Rekomitjie***

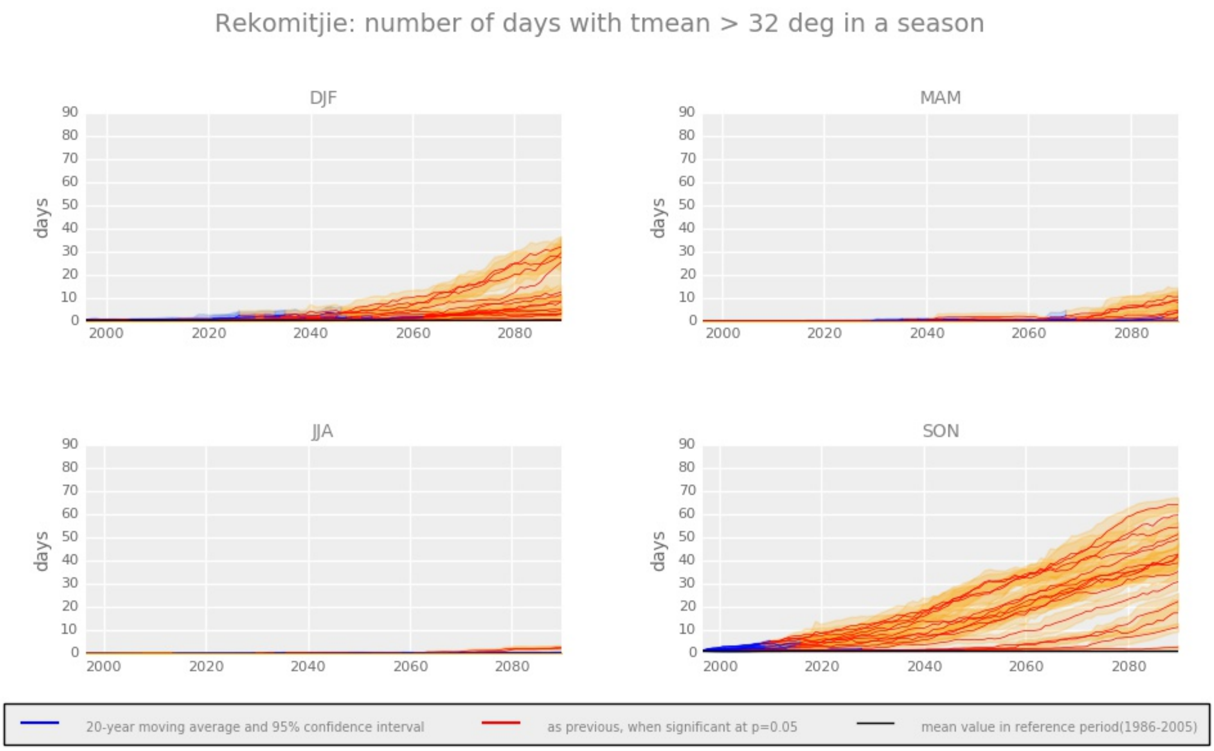


Figure 42: ***CMIP5 projected changes in seasonal mean number of days with daily mean temperature over 32° C under the RCP 8.5 concentration pathway for Rekomitjie***

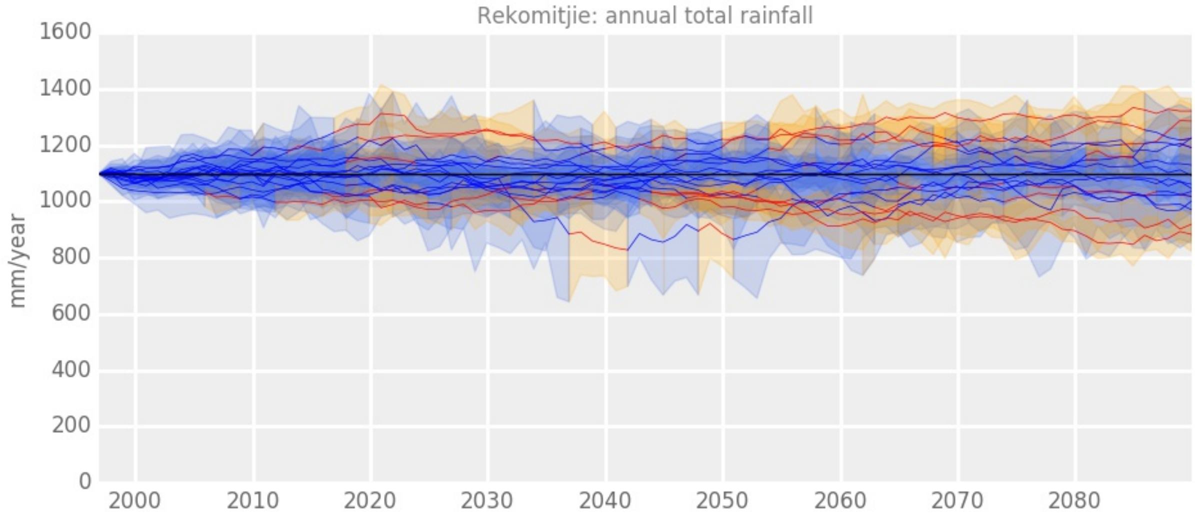


Figure 43: ***CMIP5 projected changes in annual total rainfall under the RCP 4.5 concentration pathway for Rekomitjie***

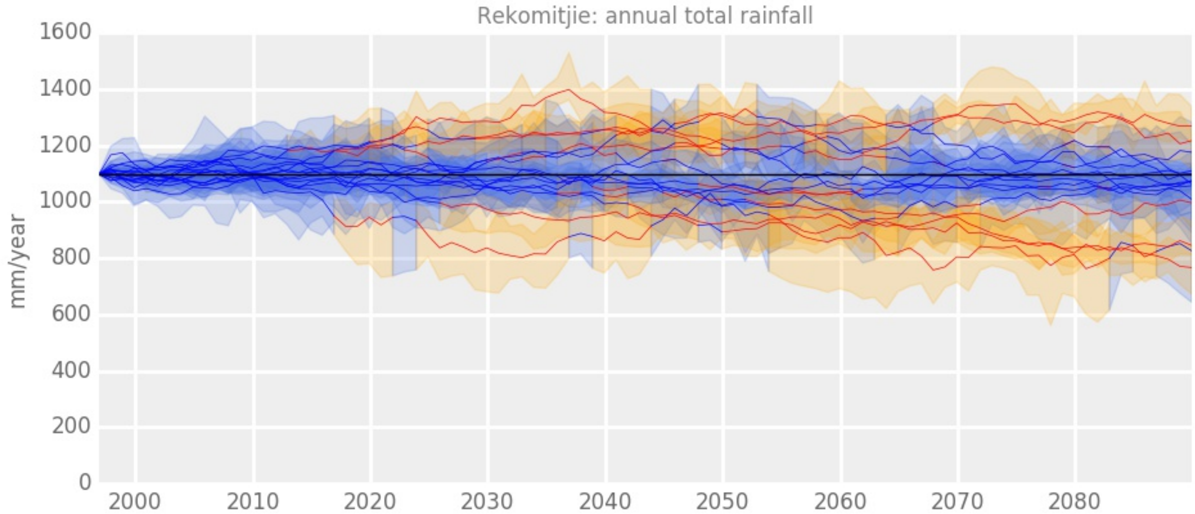


Figure 44: ***CMIP5 projected changes in annual total rainfall under the RCP 8.5 concentration pathway for Rekomitjie***

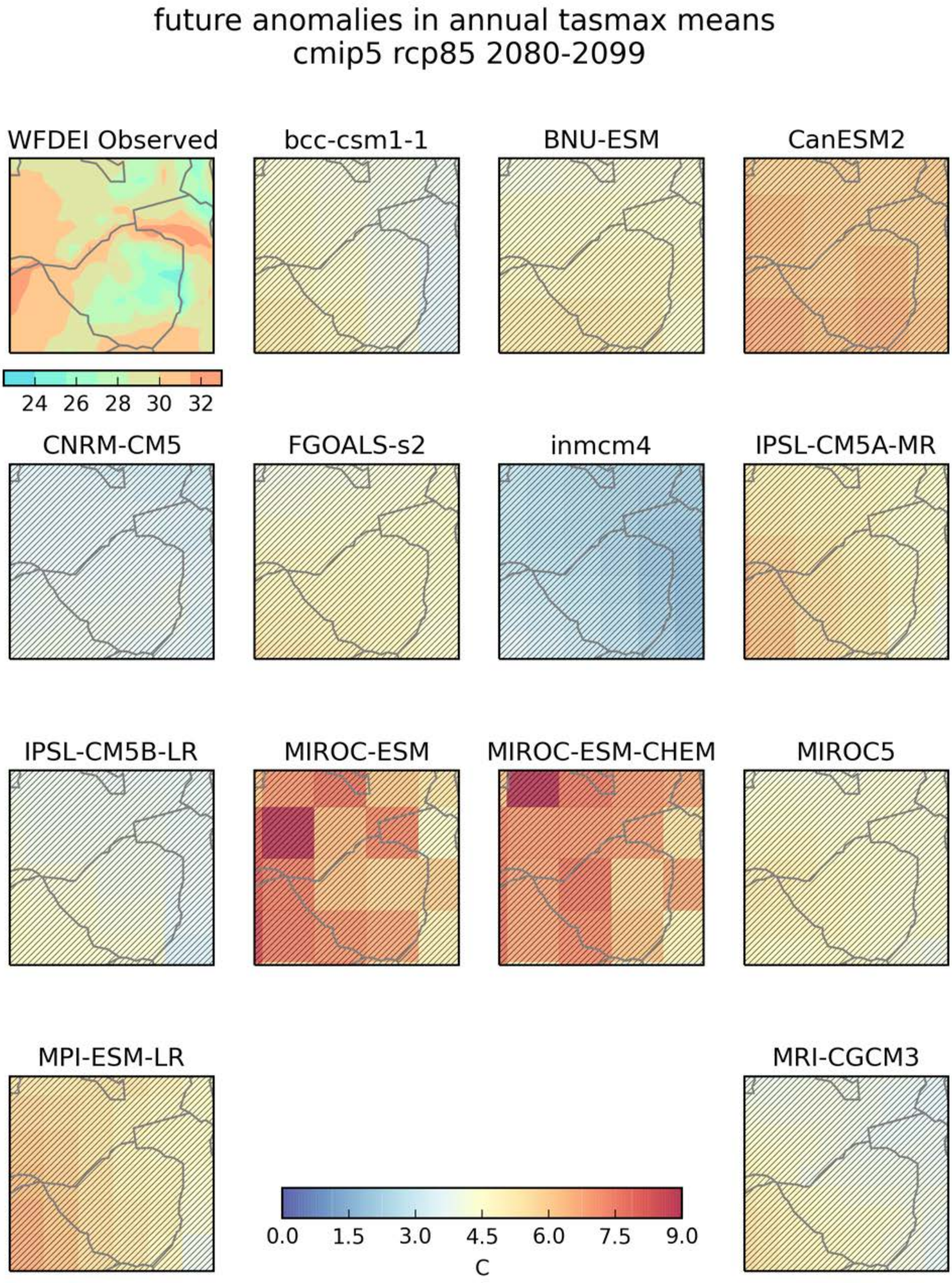


Figure 45: ***CMIP5 projected change in annual mean maximum temperature by the end of the century under the RCP 8.5 emission scenario.*** *Change presented as the difference between the future period 2080-2099 and the historical period 1986-2005. Stippling shows where the change is statistically significant. The top left panel presents the observed historical climatology from the WFDEI dataset.*

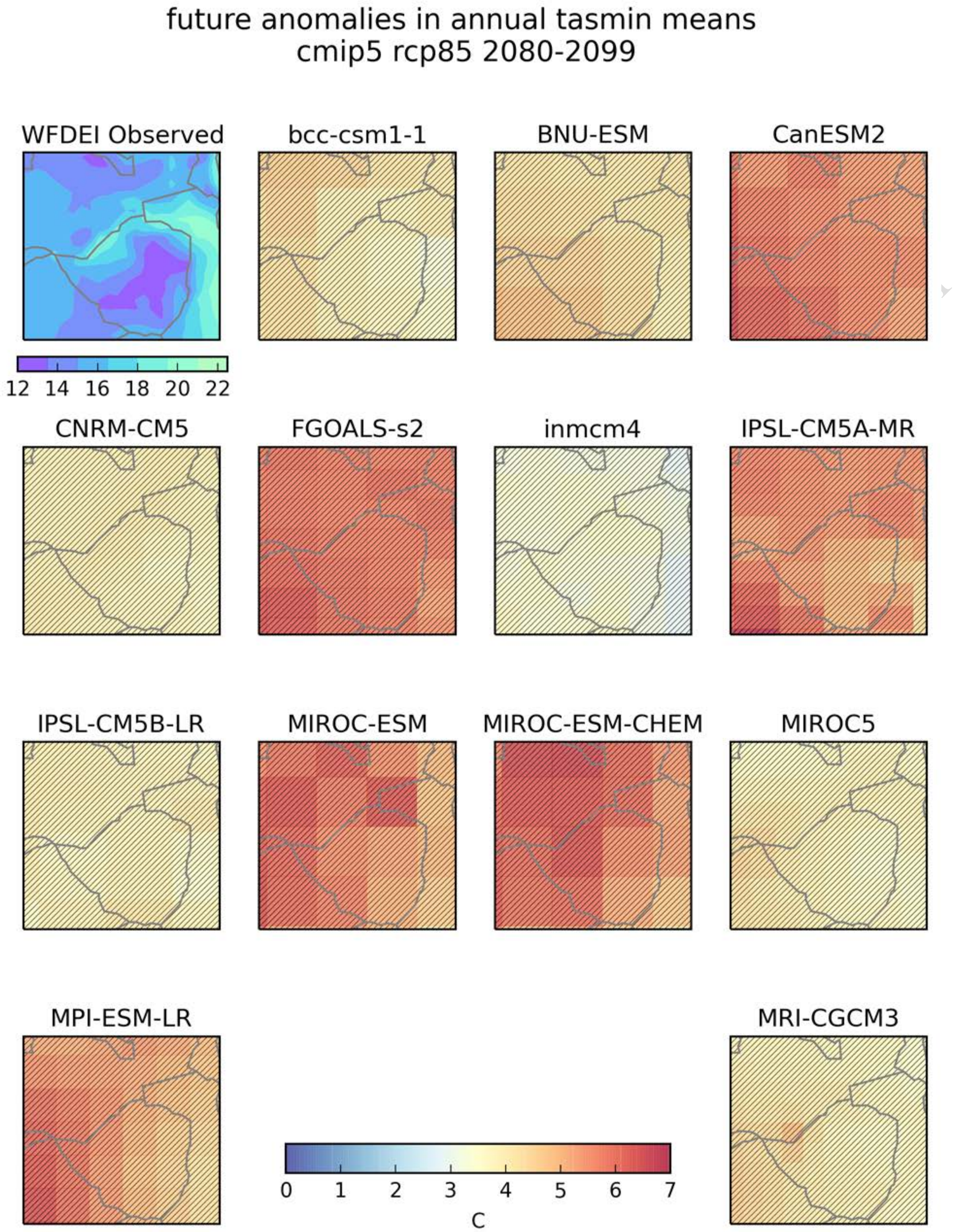


Figure 46: ***CMIP5 projected change in annual mean minimum temperature by the end of the century under the RCP 8.5 emission scenario.*** *Change presented as the difference between the future period 2080-2099 and the historical period 1986-2005. Stippling shows where the change is statistically significant. The top left panel presents the observed historical climatology from the WFDEI dataset.*

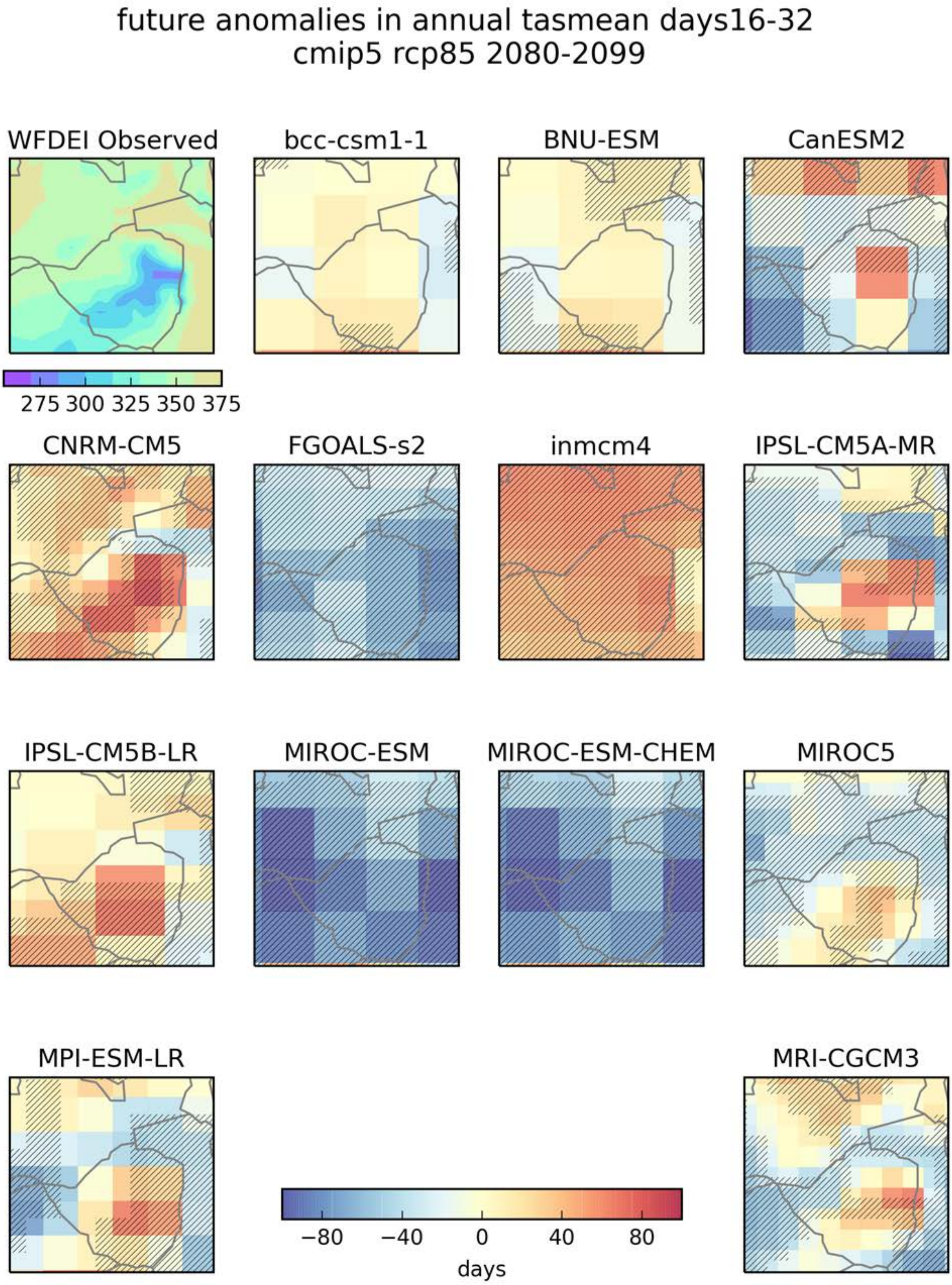


Figure 47: ***CMIP5 projected change in the number of days with mean temperatures between 16-32° C by the end of the century under the RCP 8.5 emission scenario.*** *Change presented as the difference between the future period 2080-2099 and the historical period 1986-2005. Stippling shows where the change is statistically significant. The top left panel presents the observed historical climatology from the WFDEI dataset.*

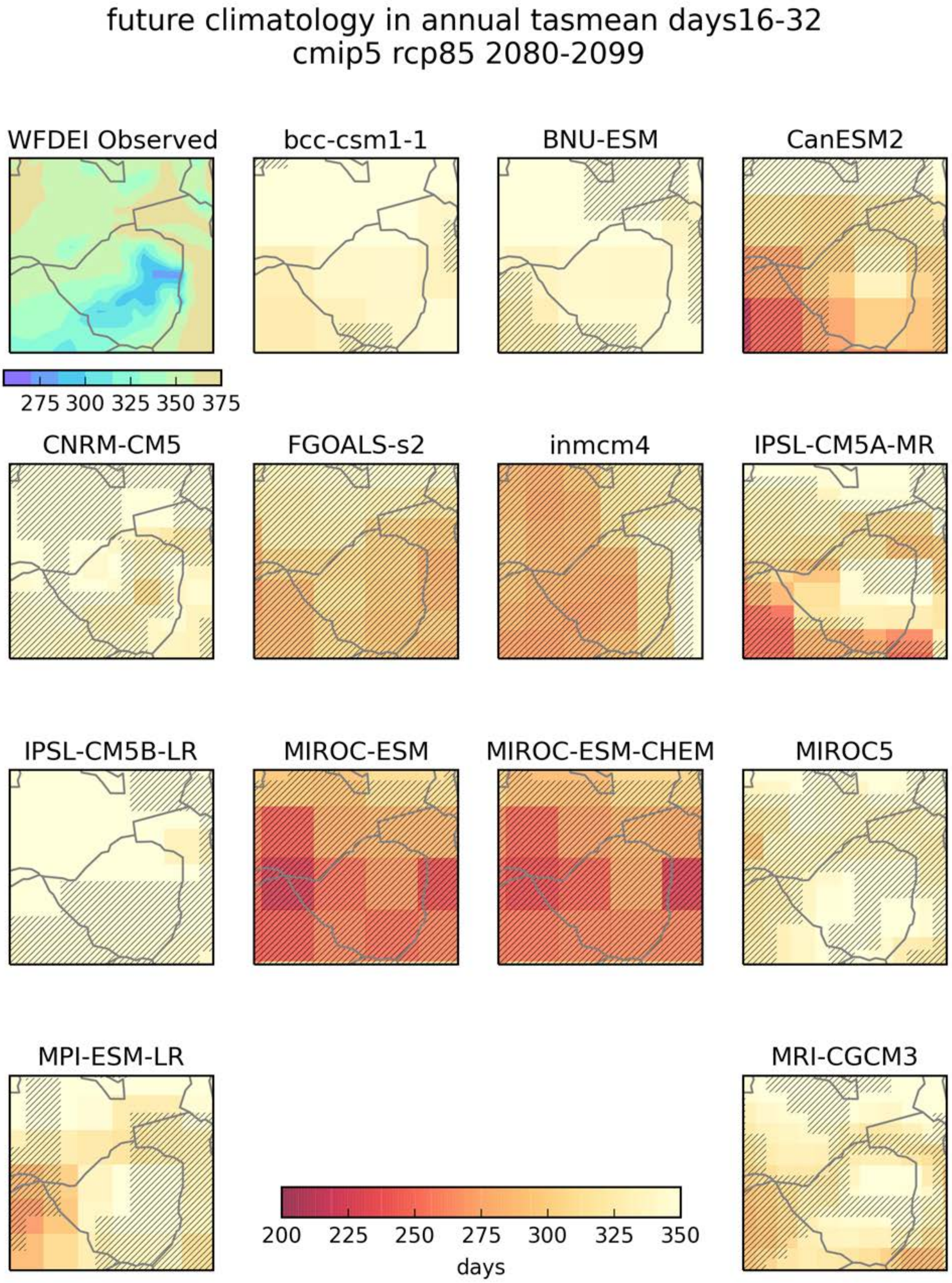


Figure 48: ***CMIP5 projected climatology in the number of days with mean temperatures between 16-32° C by the end of the century under the RCP 8.5 emission scenario.*** *Climatology presented as the mean for the future period 2080-2099. Stippling shows where the change between this period and the historical period is statistically significant. The top left panel presents the observed historical climatology from the WFDEI dataset.*

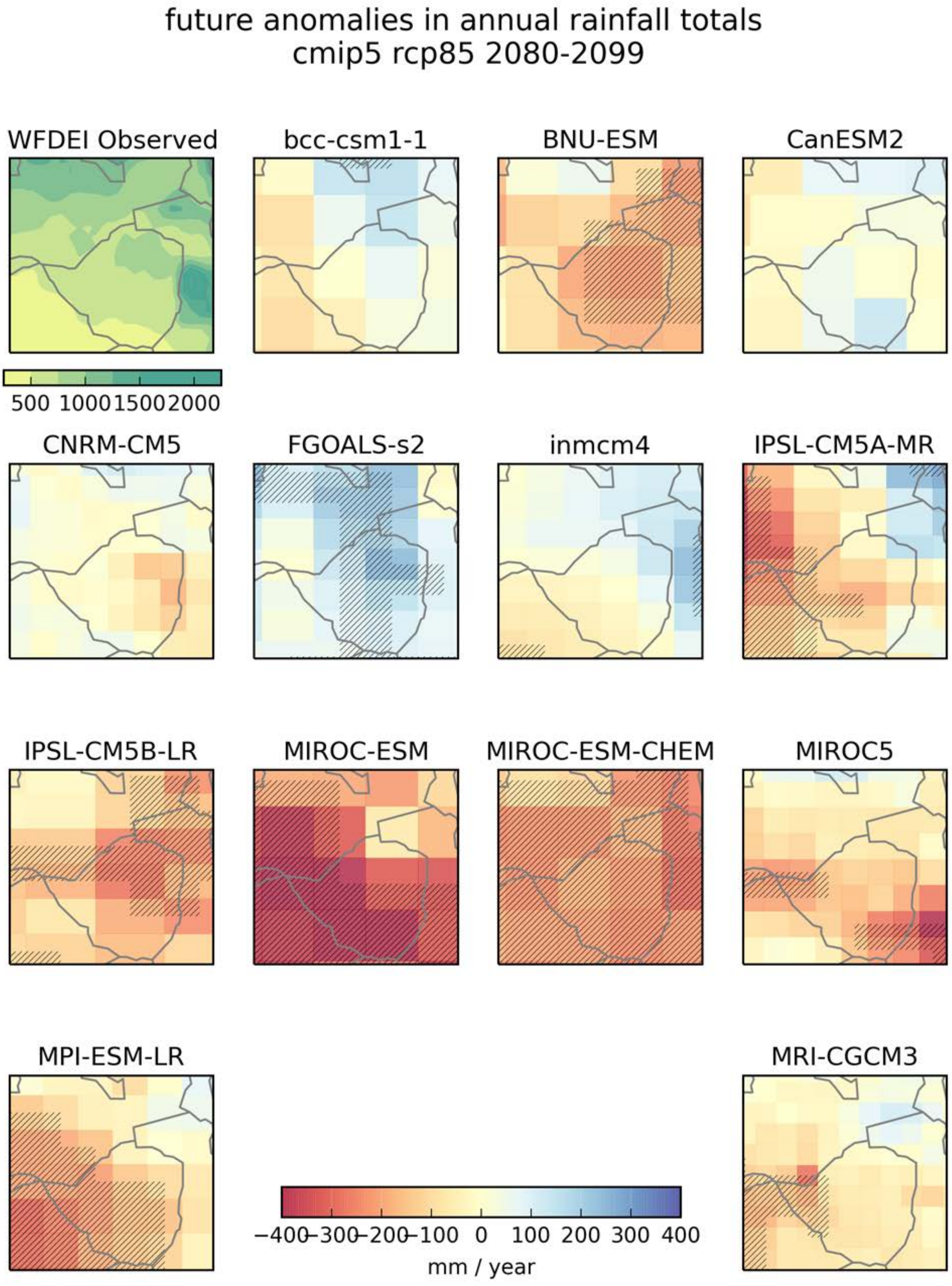


Figure 49: ***CMIP5 projected change in annual total rainfall by the end of the century under the RCP 8.5 emission scenario.*** *Change presented as the difference between the future period 2080-2099 and the historical period 1986-2005. Stippling shows where the change is statistically significant. The top left panel presents the observed historical climatology from the WFDEI dataset.*

Statistically downscaled projections

Results from the statistical downscaling are presented in the same way as those of the raw GCMs. Figure 50 and 51 present the projected time evolution of seasonal mean daily maximum temperature for 11 models under the RCP4.5 and RCP8.5 scenarios respectively. These results support the findings seen in the raw GCMs that the daily maximum temperature is projected to warm significantly into the future and that this warming will shift the climate beyond the historical range of variability within the next few decades. There is still clear disagreement between models, though the range is slightly reduced, and the magnitude of change is far larger under the RCP8.5 emission scenario than under the more moderate RCP 4.5 scenario. Some models do appear to group according to more / less severe warming especially by the end of the century under the RCP8.5 scenario.

Very similar results are seen for daily minimum and daily mean temperature (Figure 52-55). Daily mean temperatures are projected to increase by between 1 – 3 °C by the end of the century under the RCP 4.5 and by 3 – 6 ° C under the RCP 8.5 scenario during summer, autumn and winter, and by up to 4 or 7° C during spring. This results in half of the models projecting an average daily temperature of at least 32° C during spring by the end of the century. This warming shifts the whole distribution of temperatures and what currently is an extreme temperature (32° C) is projected to become a relatively common temperature. This is seem in Figure 56-57 which show that the number of days exceeding this threshold are projected to increase to between 30 – 70 days during spring, and by up to 50 days during summer.

The downscaled projections of annual total rainfall (Figure 58-59) generally show no significant change, or project a slight drying into the future especially under the RCP 8.5 scenario.

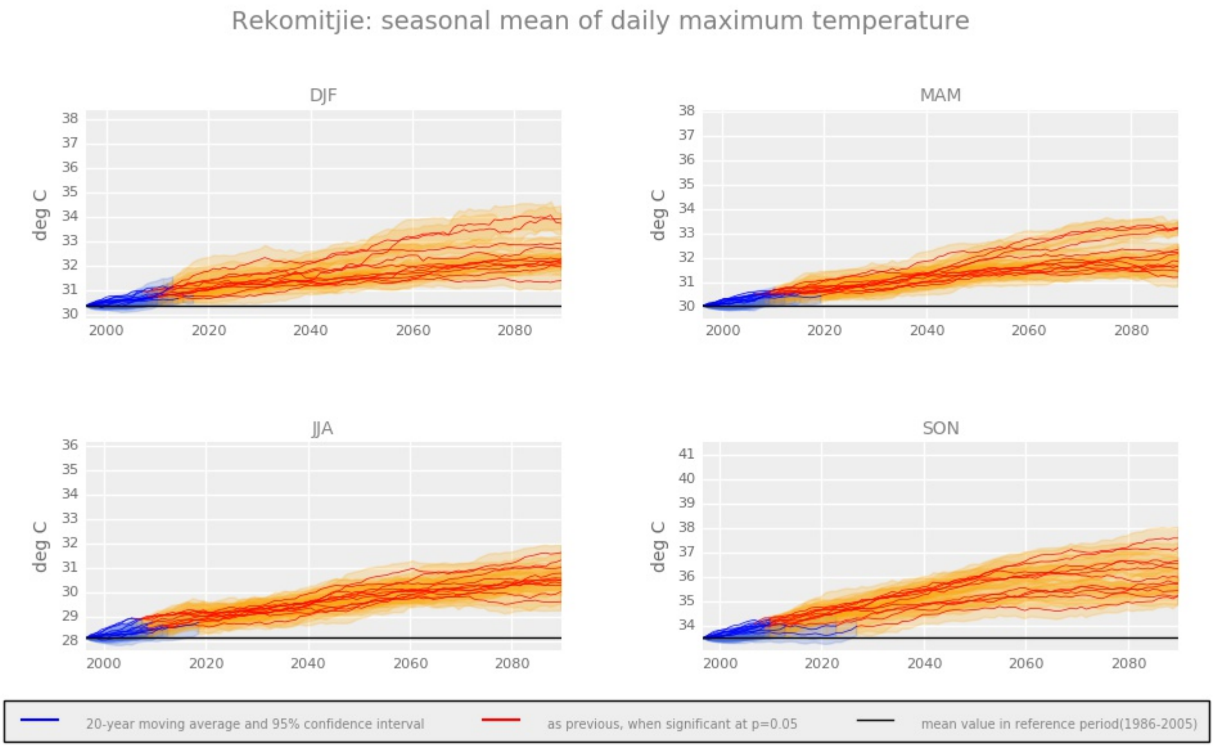


Figure 50: **SOMD projected changes in seasonal mean daily maximum temperature under the RCP 4.5 concentration pathway for Rekomitjie**

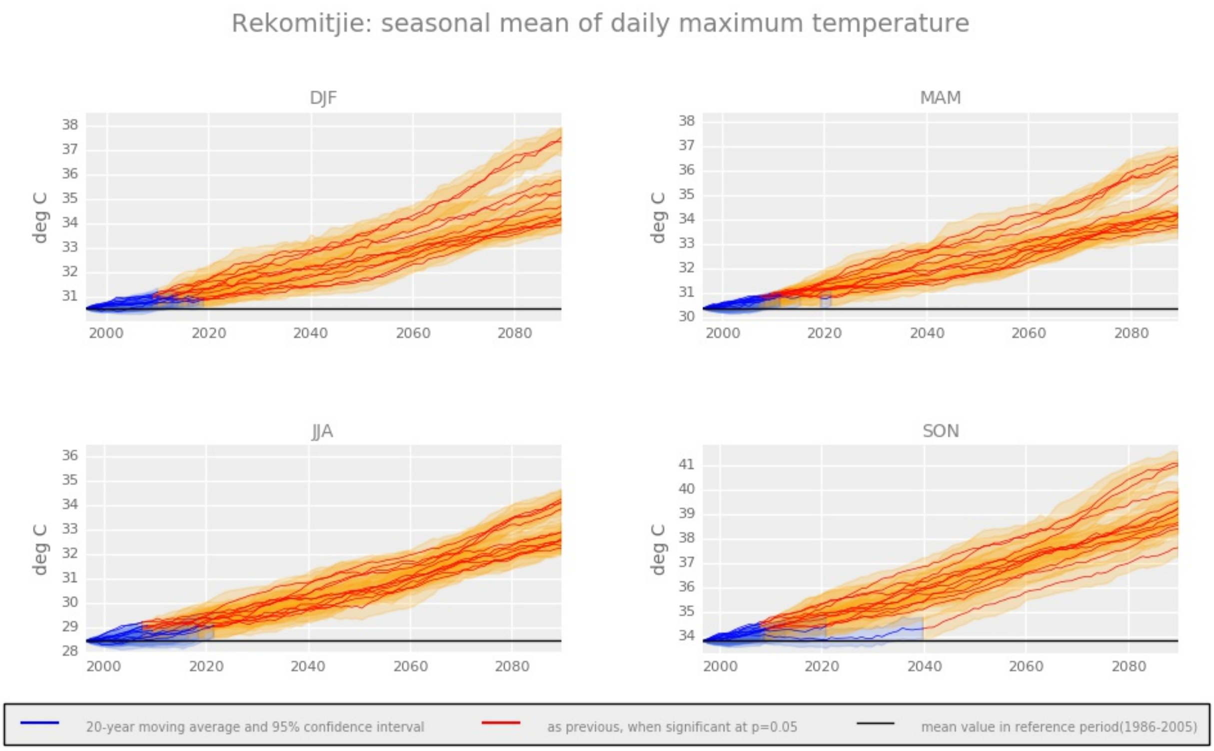


Figure 51: **SOMD projected changes in seasonal mean daily maximum temperature under the RCP 8.5 concentration pathway for Rekomitjie**

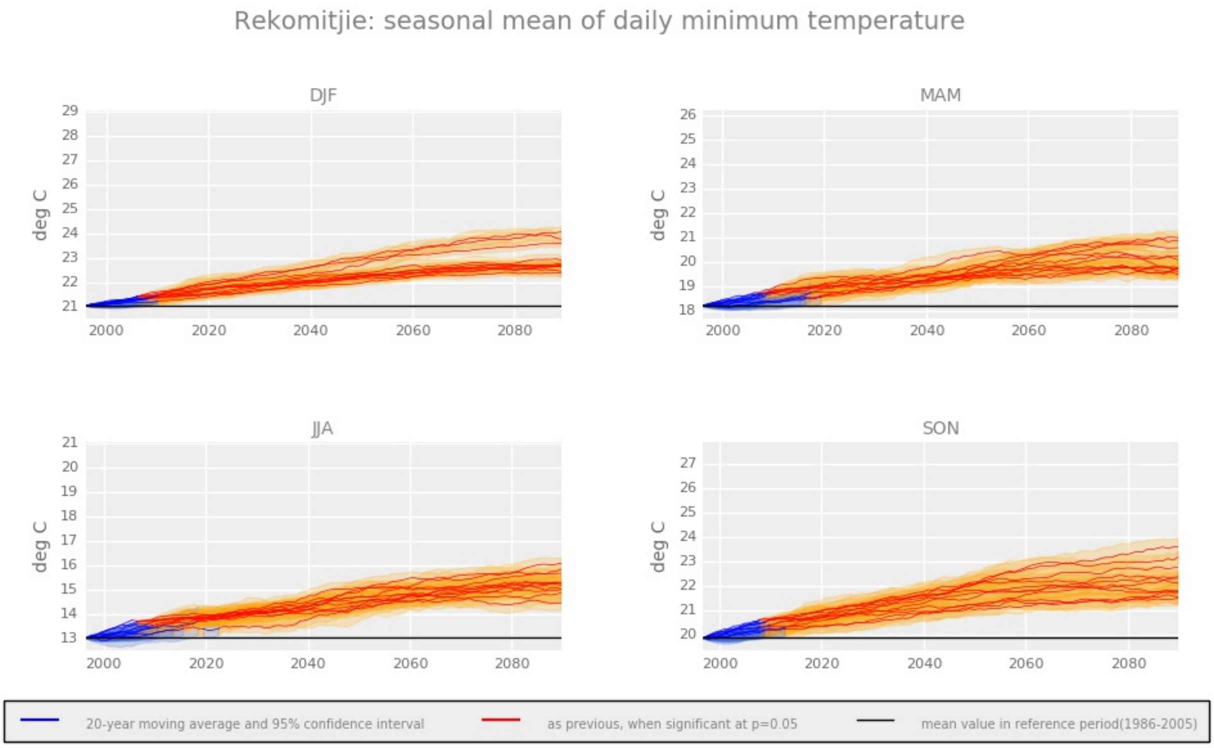


Figure 52: **SOMD projected changes in seasonal mean daily minimum temperature under the RCP 4.5 concentration pathway for Rekomitjie**

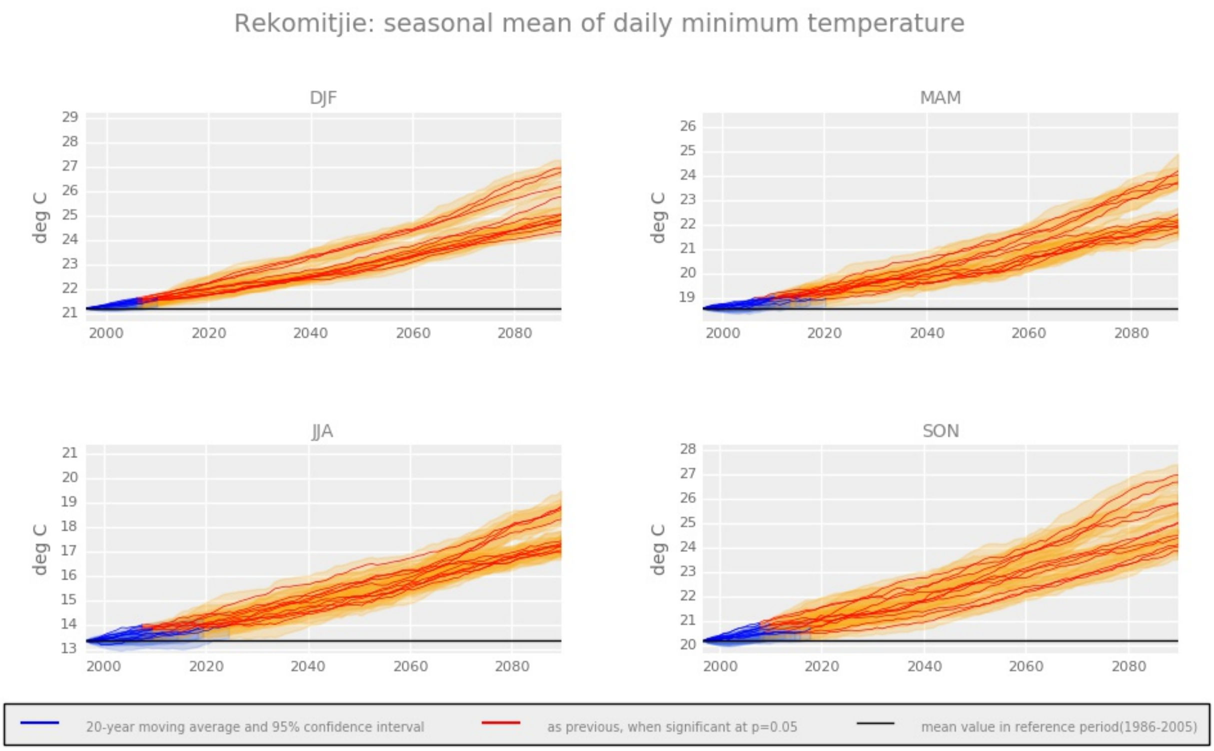


Figure 53: **SOMD projected changes in seasonal mean daily minimum temperature under the RCP 8.5 concentration pathway for Rekomitjie**

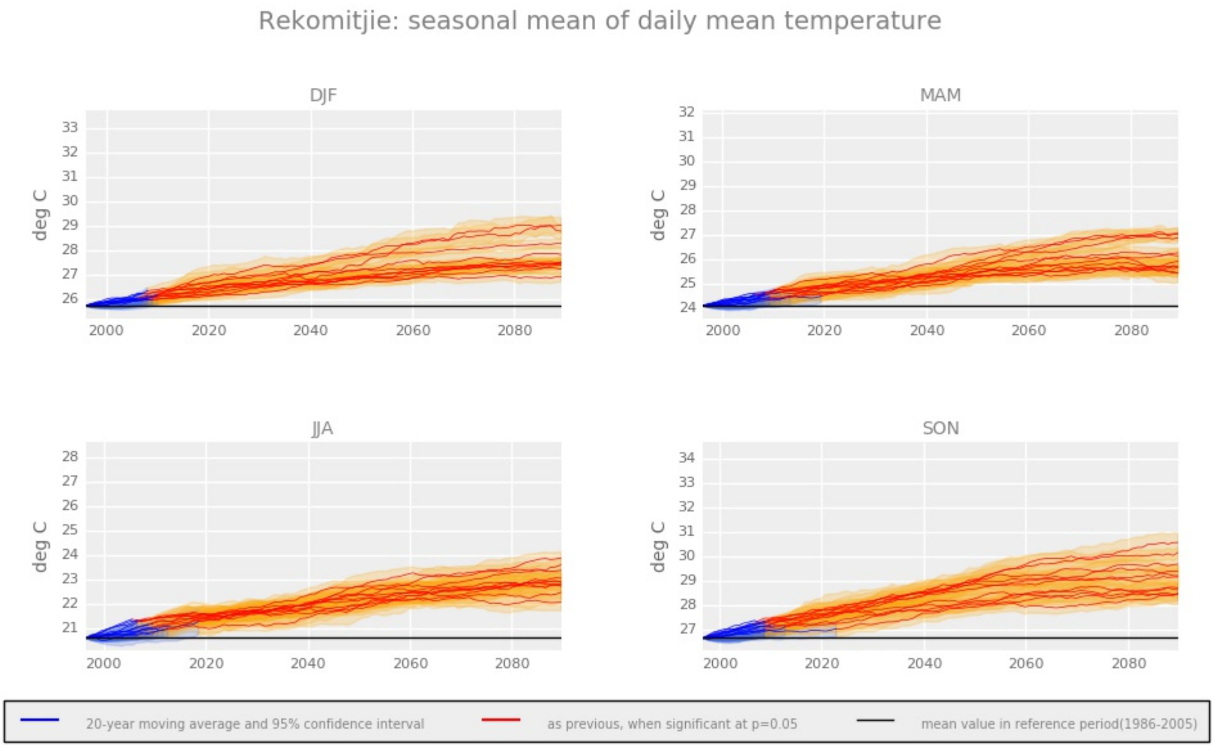


Figure 54: **SOMD projected changes in seasonal mean daily mean temperature under the RCP 4.5 concentration pathway for Rekomitjie**

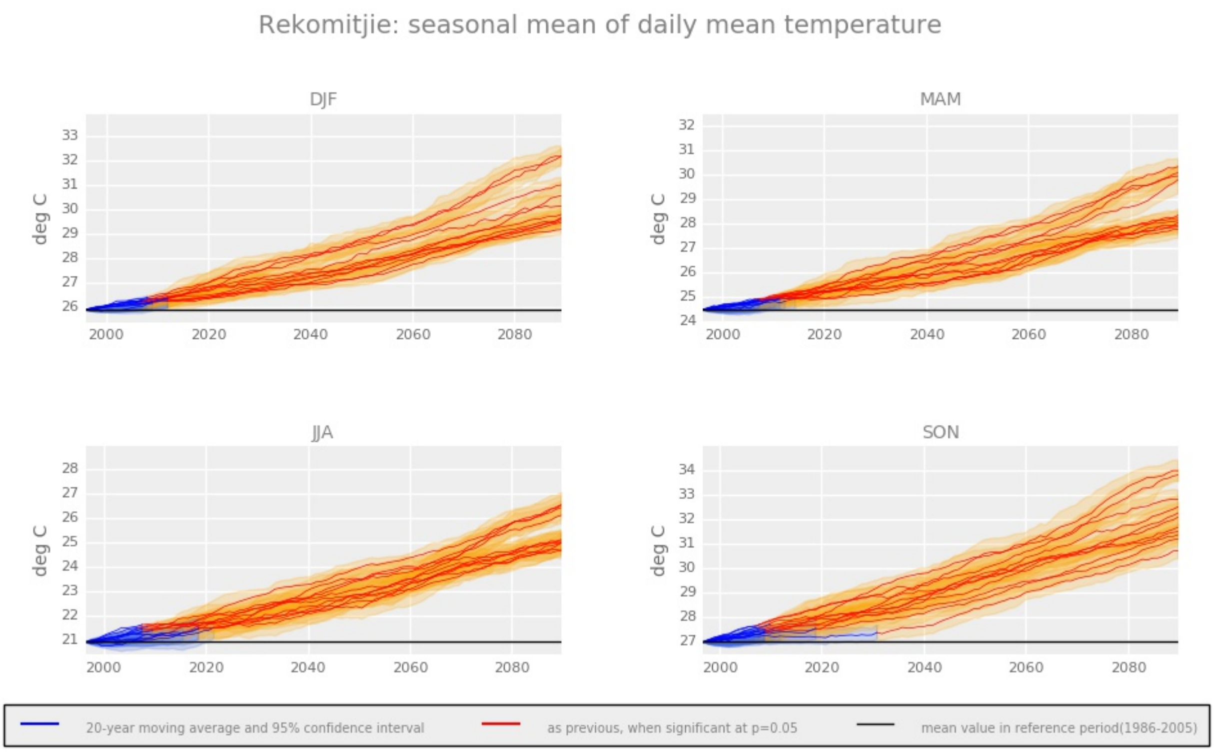


Figure 55: **SOMD projected changes in seasonal mean daily mean temperature under the RCP 8.5 concentration pathway for Rekomitjie**

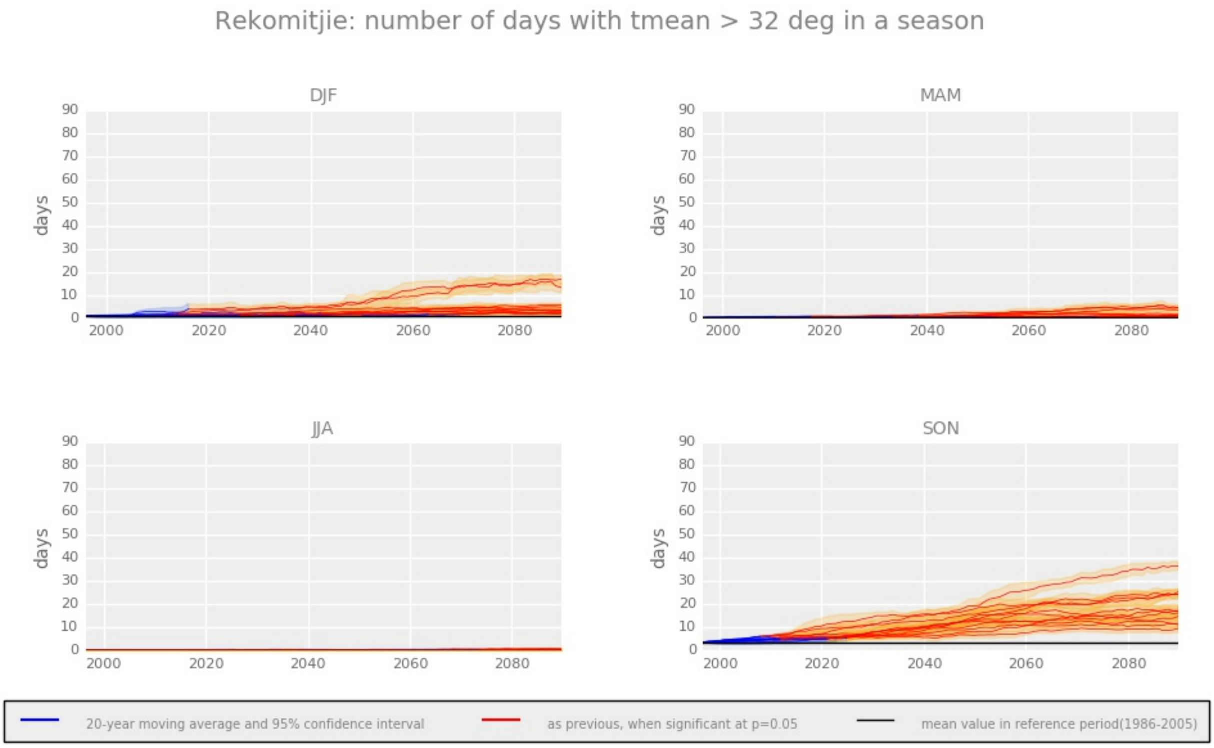


Figure 56: **SOMD projected changes in the number of days where the mean temperature exceeds 32°C temperature under the RCP 4.5 concentration pathway for Rekomitjie**

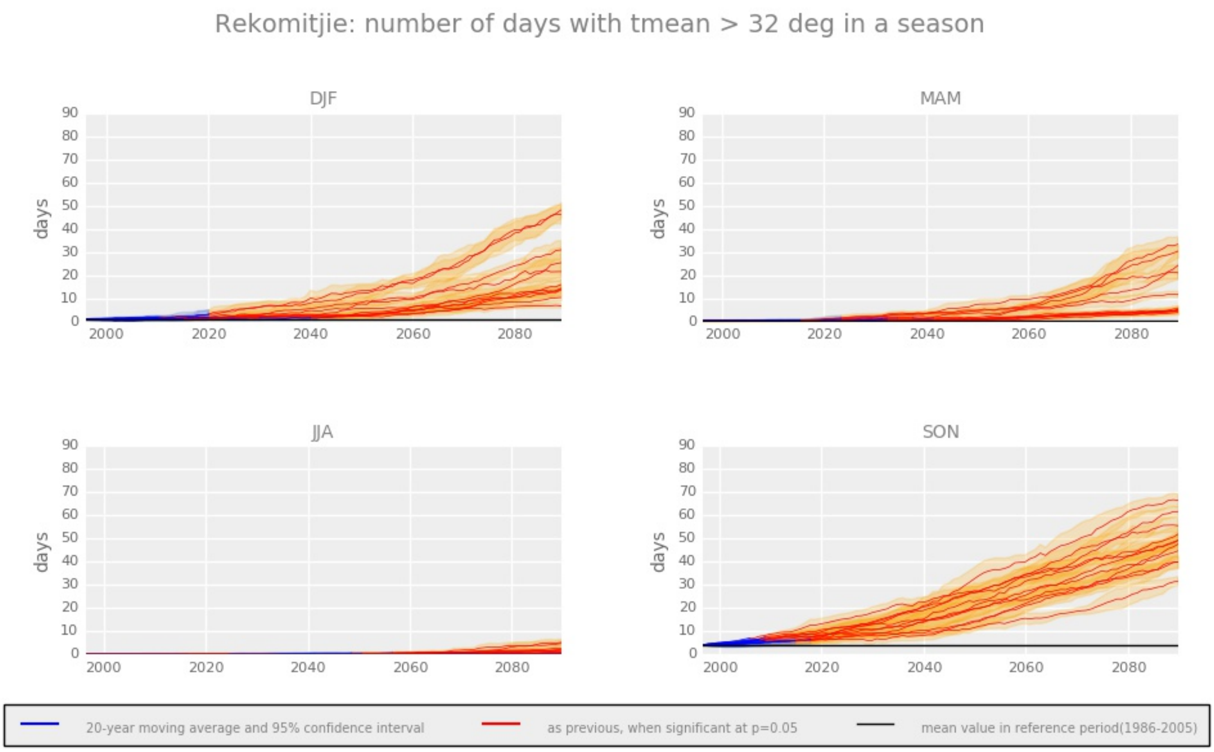


Figure 57: **SOMD projected changes in the number of days where the mean temperature exceeds 32°C temperature under the RCP 8.5 concentration pathway for Rekomitjie**

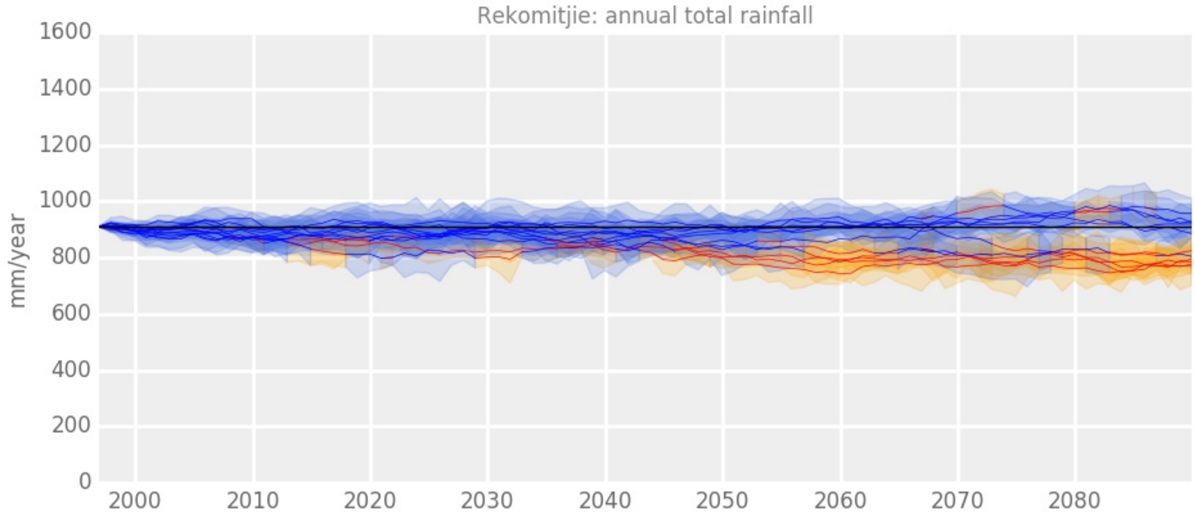


Figure 58: **SOMD projected changes in annual total rainfall under the RCP 4.5 concentration pathway for Rekomitjie**

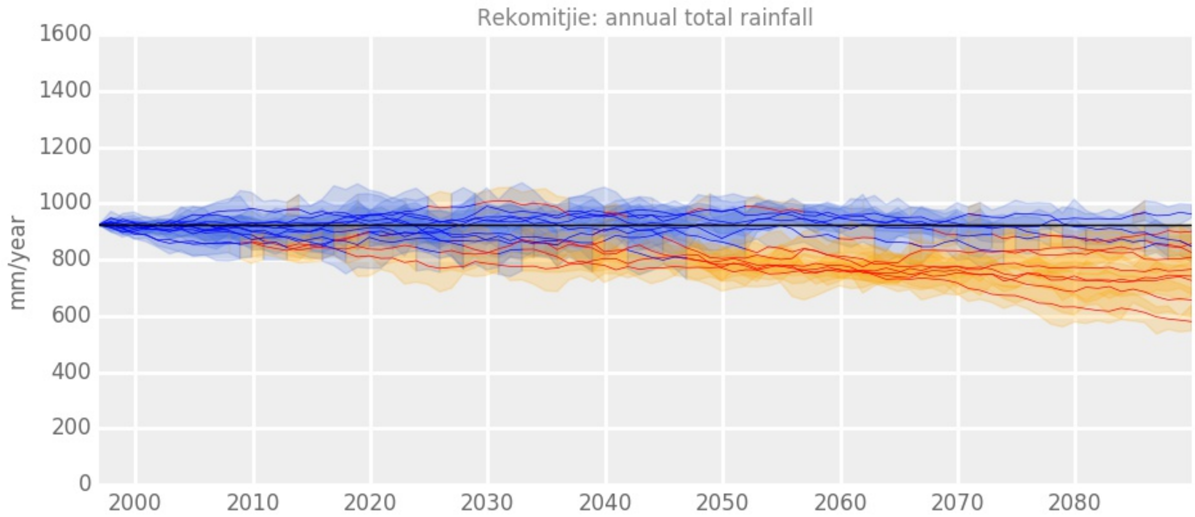


Figure 59: **SOMD projected changes in annual total rainfall under the RCP 8.5 concentration pathway for Rekomitjie**

The statistically downscaled projections can also be presented as spatial maps covering the larger region. In this section we focus only on the output from the more severe RCP 8.5 emission scenario looking primarily at the projected change by the end of the century. The resolution of the downscaled output is far finer than that of the driving GCMs, but still the most significant differences are found between models rather than spatially within a model (Figure 60 and 61).

However, the use of a specific temperature threshold highlights the spatial pattern that this rather uniform warming can introduce. Figure 62 presents the change in the number of days per year where the daily mean temperature is projected to be between 16 and 32° C by the end of the century under the RCP 8.5 scenario. The top left panel present the observed climatology from the WFDEI dataset and it shows that temperatures are generally within this range in the Zambezi Valley and over Mozambique throughout the year, but temperatures over the higher elevation areas, especially over the Zimbabwe Highveld, are generally too cool during some period of the year. The projected increase in temperature results in a negative change over the warmer areas where temperatures get too hot and exceed the upper threshold on up to 100 days per year (primarily during spring), while positive changes are seen over the cooler / higher elevation areas where a larger proportion of the days mean temperature falls within the ideal range. The climatology of the number of days per year within this temperature range by the end of the century is presented in Figure 63. It shows that the warmer areas within the Zambezi River valley, over Mozambique and over northern Botswana are all projected to be too warm by the end of the century and therefore exceed the upper threshold during a significant part of the year. The climate over the majority of the Zimbabwe Highveld and Zambia are projected to become within this ideal temperature range over the full year. The un-stippled areas represent areas where the increase in temperature does not significantly change the frequency these days within this ideal range.

Figure 64 and 65 present the winter (June – August) mean climate projected by the downscaled models under the RCP 8.5 scenario for the mid-century (2046-2065) and the late-century (2080-2099) respectively. By the mid-century it is only the highest / coolest parts of Zimbabwe where the mean climate is still below the lower threshold of ideal temperature range while the climate within the rest of the region falls within the ideal range. By the end of the century even the highest elevation areas have a mean winter climate that is within the ideal range. Figure 66 and 67 present the same results, but for the spring season (September – November). During this season for the mid-21st Century most models project that the mean climate will remain within the ideal range, with the exception of the Zambezi Valley. By the end of the century, a much larger area is projected to have an average spring climate which exceeds the upper threshold. This area covers the north-western Botswana and south-western Zambia and the full Zambezi river valley.

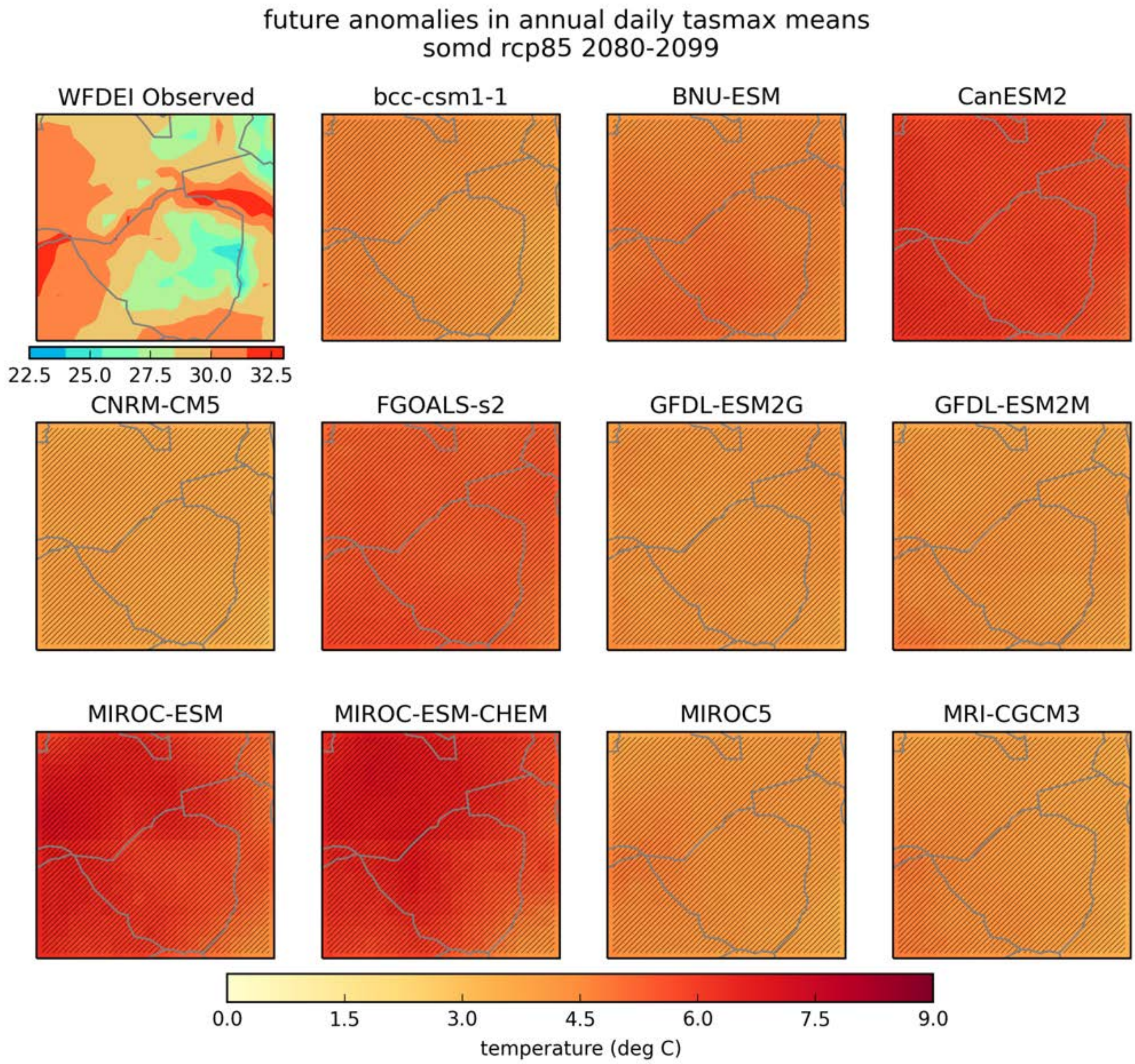


Figure 60: ***SOMD projected change in annual mean maximum temperature by the end of the century under the RCP 8.5 emission scenario.*** *Change presented as the difference between the future period 2080-2099 and the historical period 1986-2005. Stippling shows where the change is statistically significant. The top left panel presents the observed historical climatology from the WFDEI dataset.*

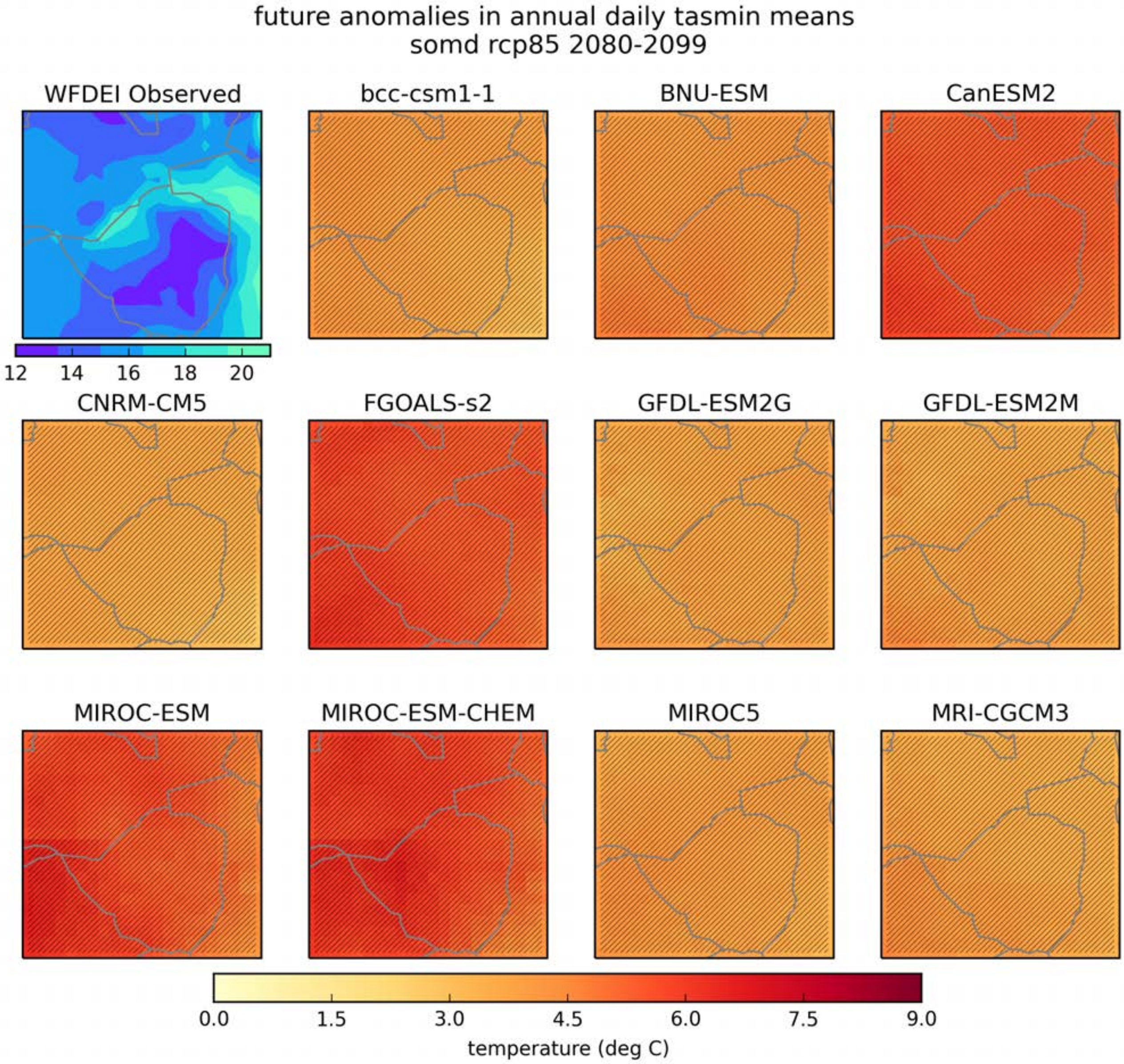


Figure 61: ***SOMD projected change in annual mean minimum temperature by the end of the century under the RCP 8.5 emission scenario.*** *Change presented as the difference between the future period 2080-2099 and the historical period 1986-2005. Stippling shows where the change is statistically significant. The top left panel presents the observed historical climatology from the WFDEI dataset.*

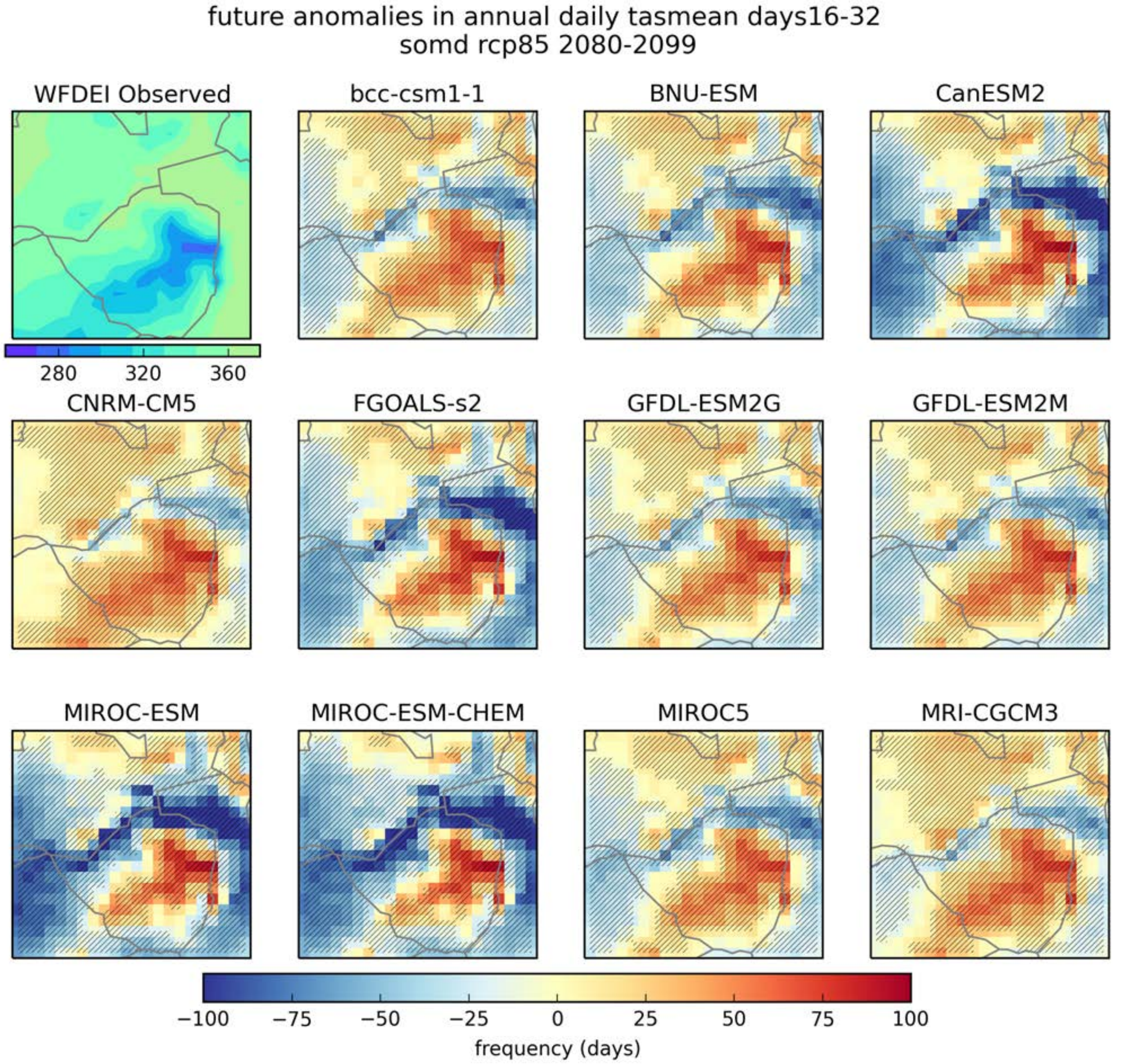


Figure 62: ***SOMD projected change in number of days where the mean temperature is between 16-32° C by the end of the century under the RCP 8.5 emission scenario.*** *Change presented as the difference between the future period 2080-2099 and the historical period 1986-2005. Stippling shows where the change is statistically significant. The top left panel presents the observed historical climatology from the WFDEI dataset.*

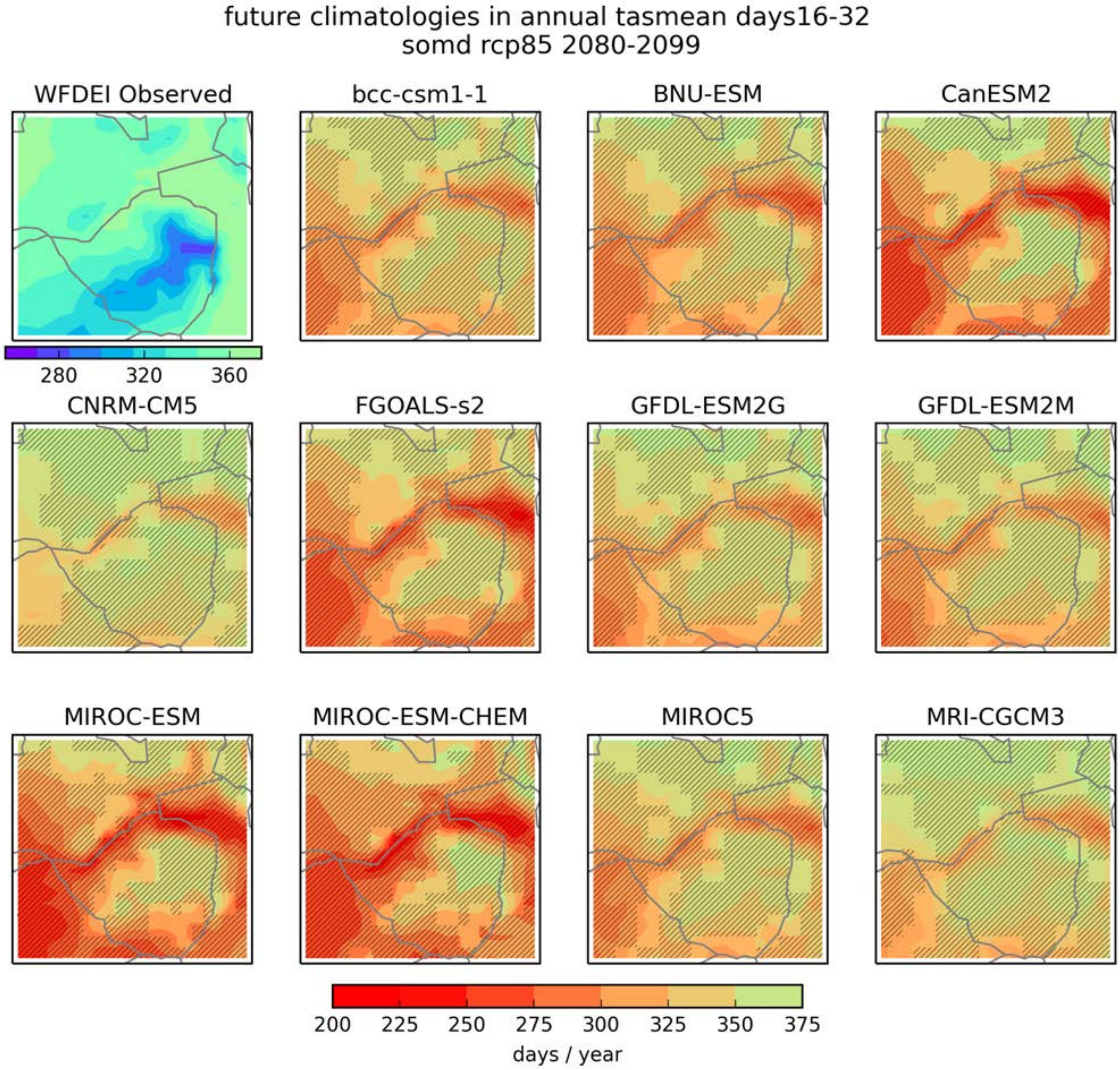


Figure 63: ***SOMD projected climatology in the number of days with mean temperatures between 16-32° C by the end of the century under the RCP 8.5 emission scenario.*** *Climatology presented as the mean for the future period 2080-2099. Stippling shows where the change between this period and the historical period is statistically significant. The top left panel presents the observed historical climatology from the WFDEI dataset.*

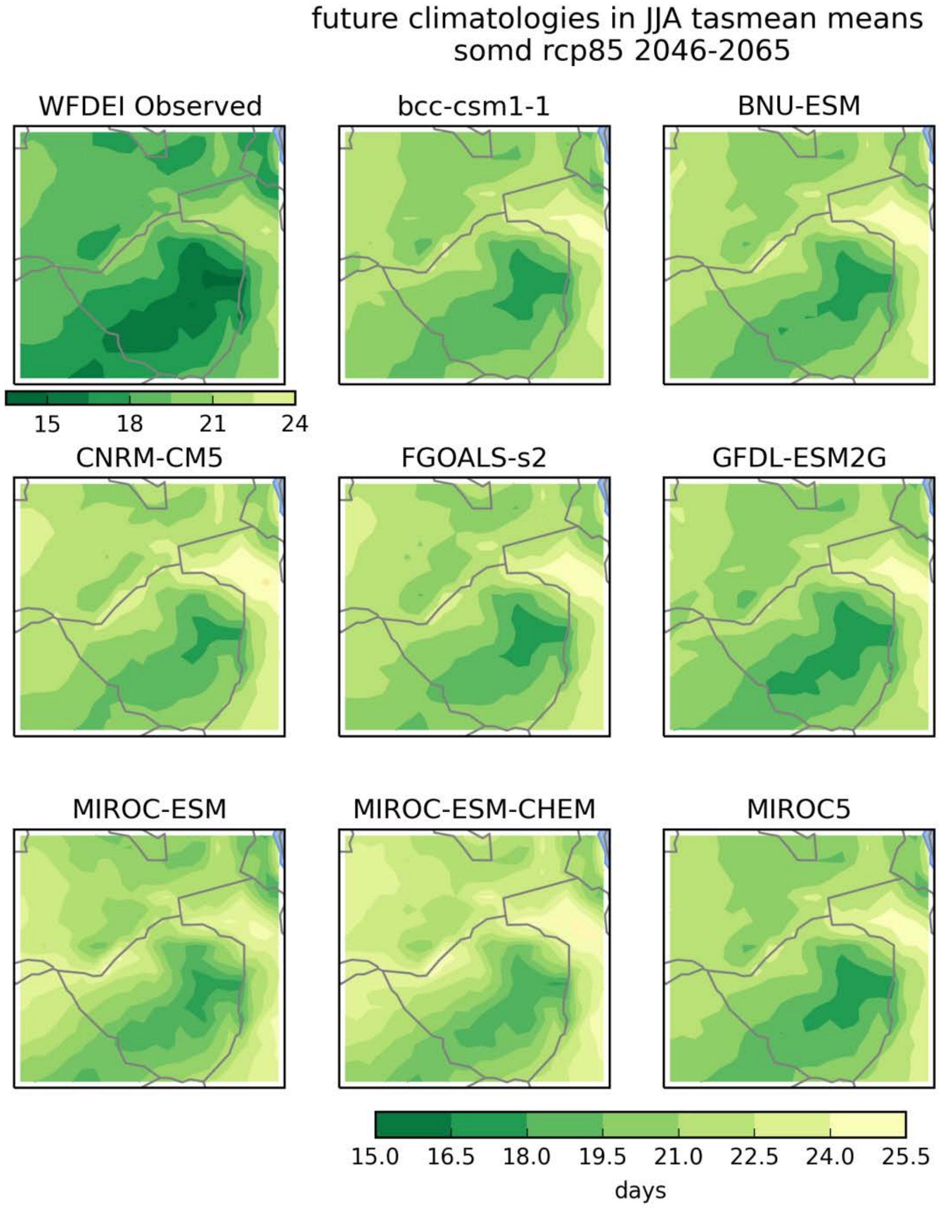


Figure 64: ***SOMD projected climatology in average June – August daily mean temperatures by the mid-century under the RCP 8.5 emission scenario.*** *Climatology presented as the mean for the future period 2046-2065. Values over the full domain are statistically significant*

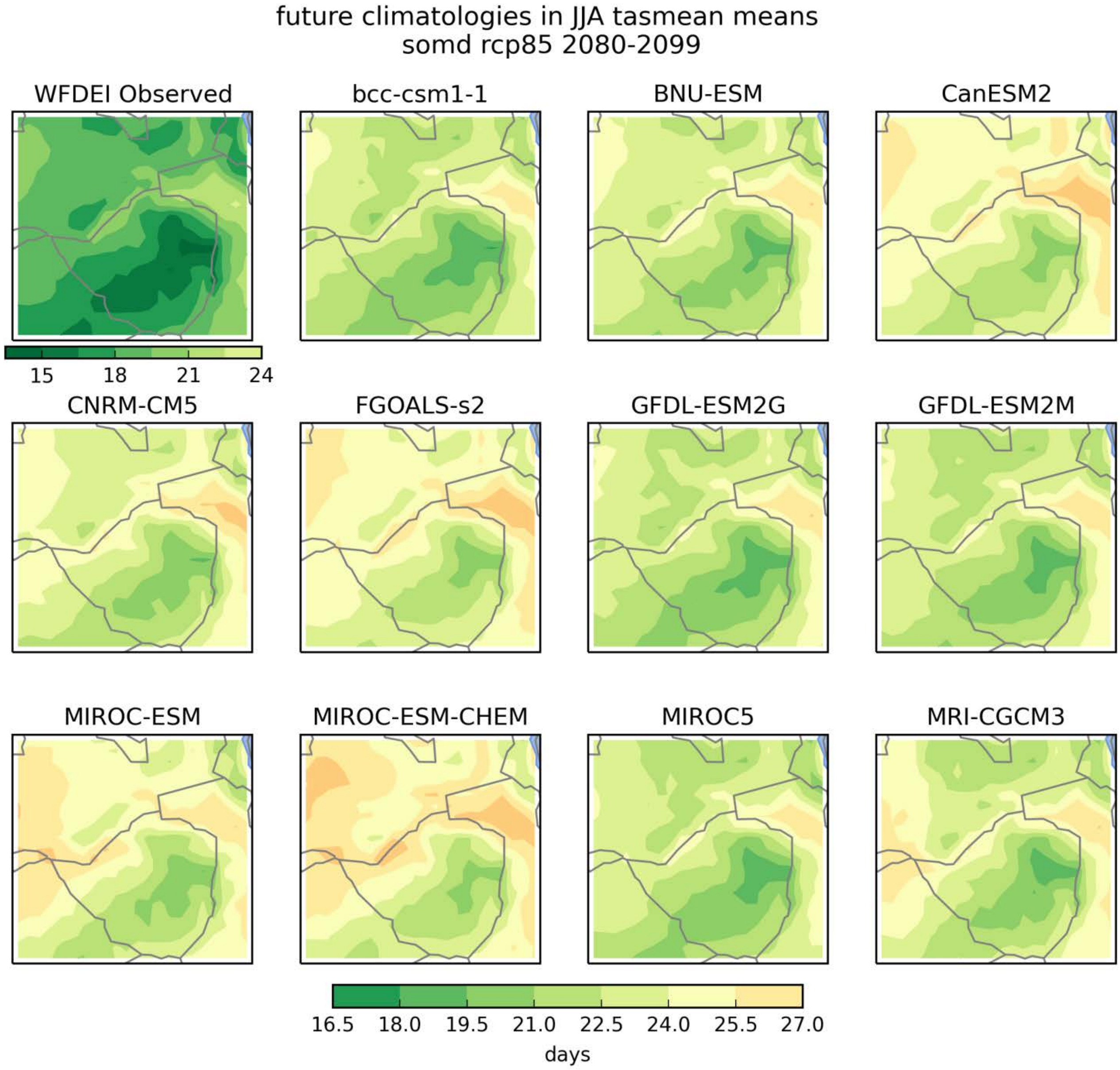


Figure 65: ***SOMD projected climatology in average June – August daily mean temperatures by the late-century under the RCP 8.5 emission scenario.*** *Climatology presented as the mean for the future period 2080-2099. Values over the full domain are statistically significant*

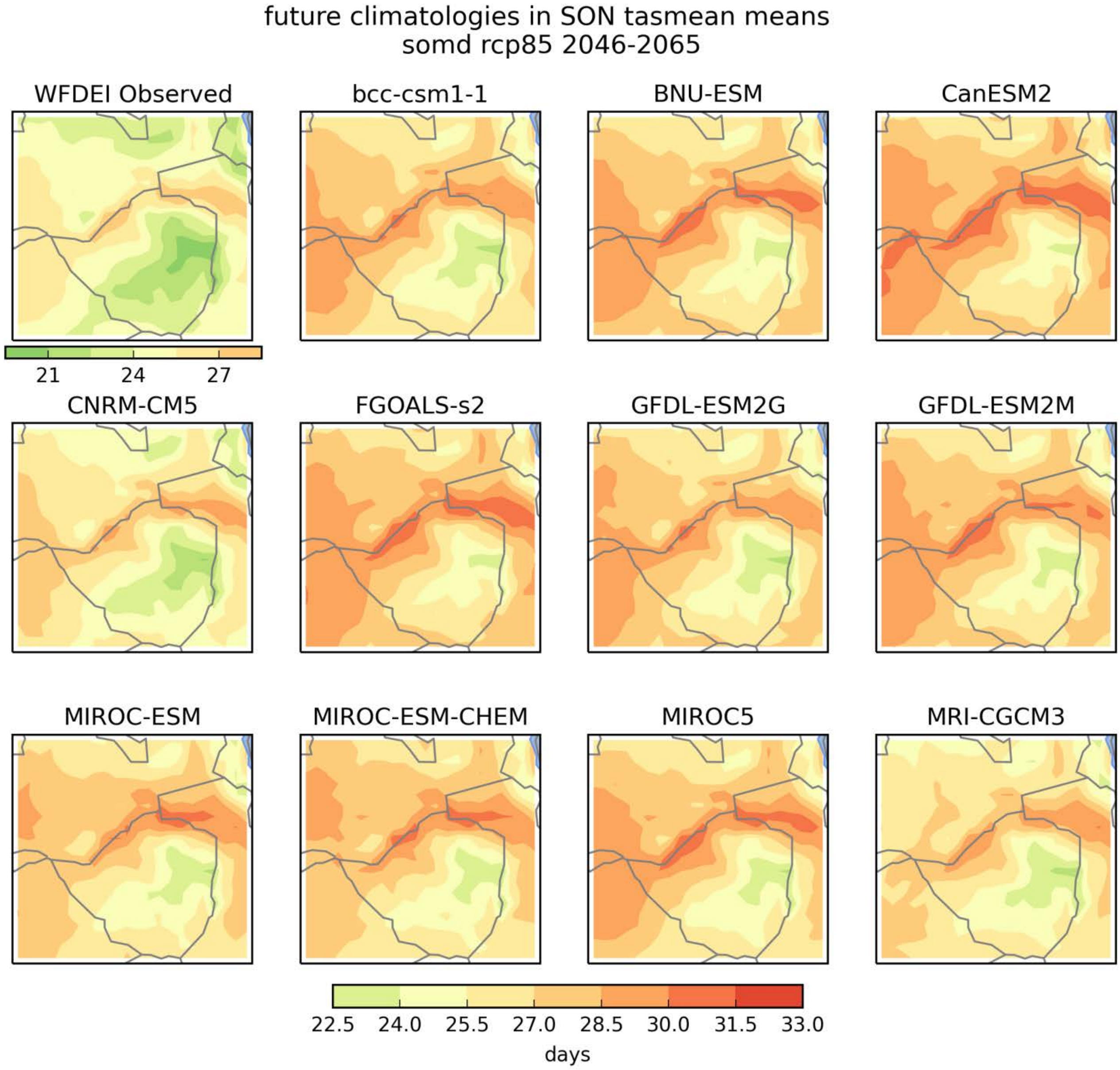


Figure 66: ***SOMD projected climatology in average September - November daily mean temperatures by the mid-century under the RCP 8.5 emission scenario.*** *Climatology presented as the mean for the future period 2046-2065. Values over the full domain are statistically significant*

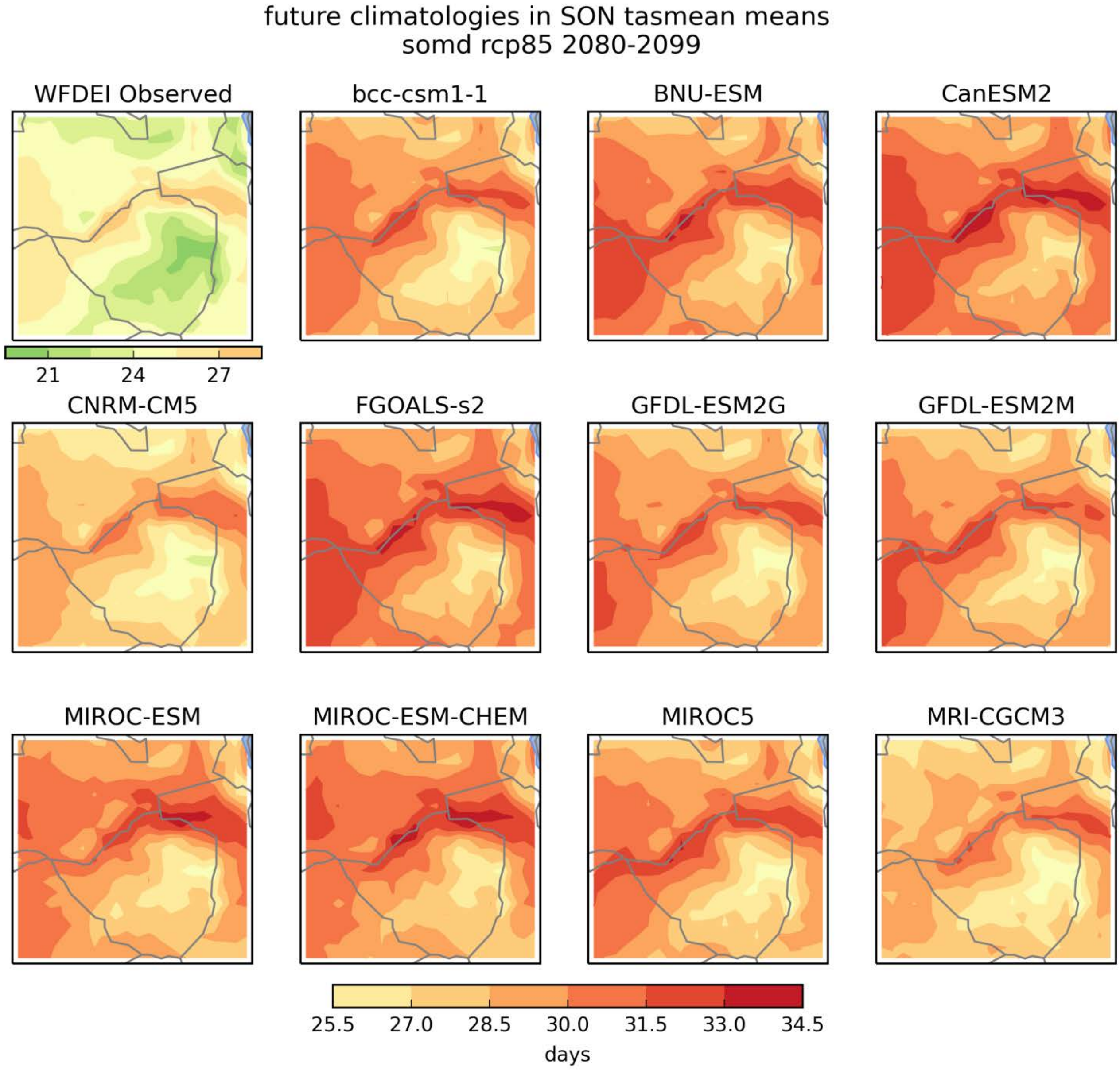


Figure 67: ***SOMD projected climatology in average September - November daily mean temperatures by the end of the century under the RCP 8.5 emission scenario.*** *Climatology presented as the mean for the future period 2080-2099. Values over the full domain are statistically significant*

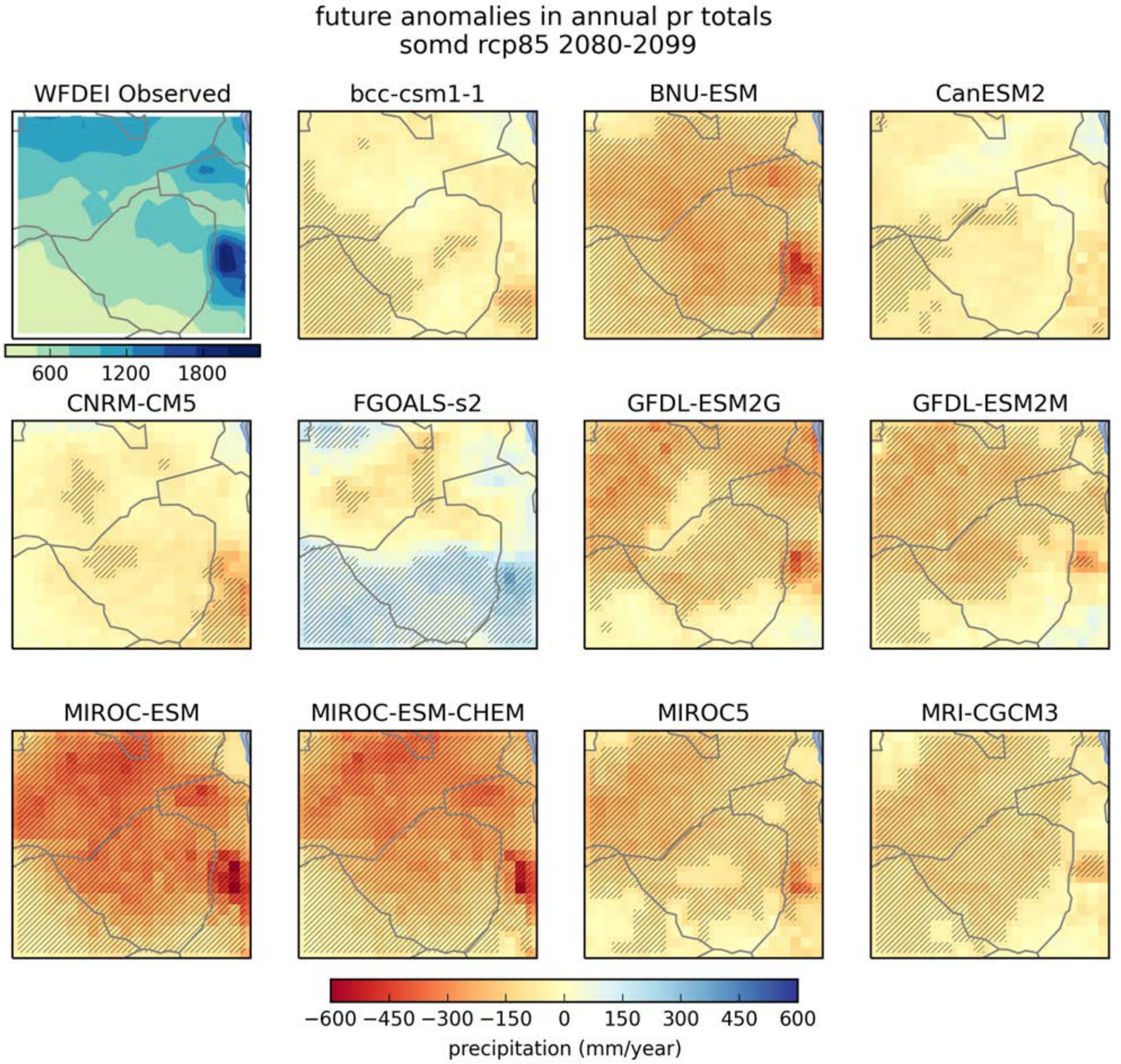


Figure 68: ***SOMD projected change in annual total rainfall by the end of the century under the RCP 8.5 emission scenario.*** *Change presented as the difference between the future period 2080-2099 and the historical period 1986-2005. Stippling shows where the change is statistically significant. The top left panel presents the observed historical climatology from the WFDEI dataset*

Future tsetse population

The tsetse fly model was run using the observed temperature and rainfall records from Rekomitjie Research Station and the results are presented in the top panel of figure 69. The red line depicts the time series of annual average daily temperature, while the blue line shows the mean simulated tsetse fly (*Glossina morsitans)* population size (using the number of female flies per square kilometre). The blue coloured envelope represents the range given by the minimum and maximum tsetse fly population size. The relationship between temperature and tsetse population size is clearly evident with the population decreasing as the temperature increases. The current population is simulated to be around 700 flies per square kilometre.

The simulations run using the three statistically downscaled GCMs are presented in the lower panels. In each instance the time series of annual mean daily maximum temperature projected by the model is shown in red, while the mean tsetse fly population is presented by the black lines. All three models simulate a slightly cooler climate than what is found at Rekomitjie, this is because they are based on a WFDEI gridcell value and not the station value. This has the result that the initial tsetse population size is larger in the downscaled model runs than for the observation run. The MIROC-ESM-CHEM model is slightly warmer than the two other models and this results in a slightly lower initial tsetse fly population size. The strong warming simulated by this model (~5° C by the end of the century) results in the tsetse fly population decreasing rapidly once the annual mean maximum temperature exceeds 33° C and the population goes extinct once the temperature hits 34° C for the first time. This same relationship seems to be evident in the other models. However, due to their more moderate rate of warming, the time of extinction is shifted further into the future, with BCC-CM1-1 projecting this to occur on the mid 2060s and MRI-CGCM3 projecting extinction to occur in the early 2070s.

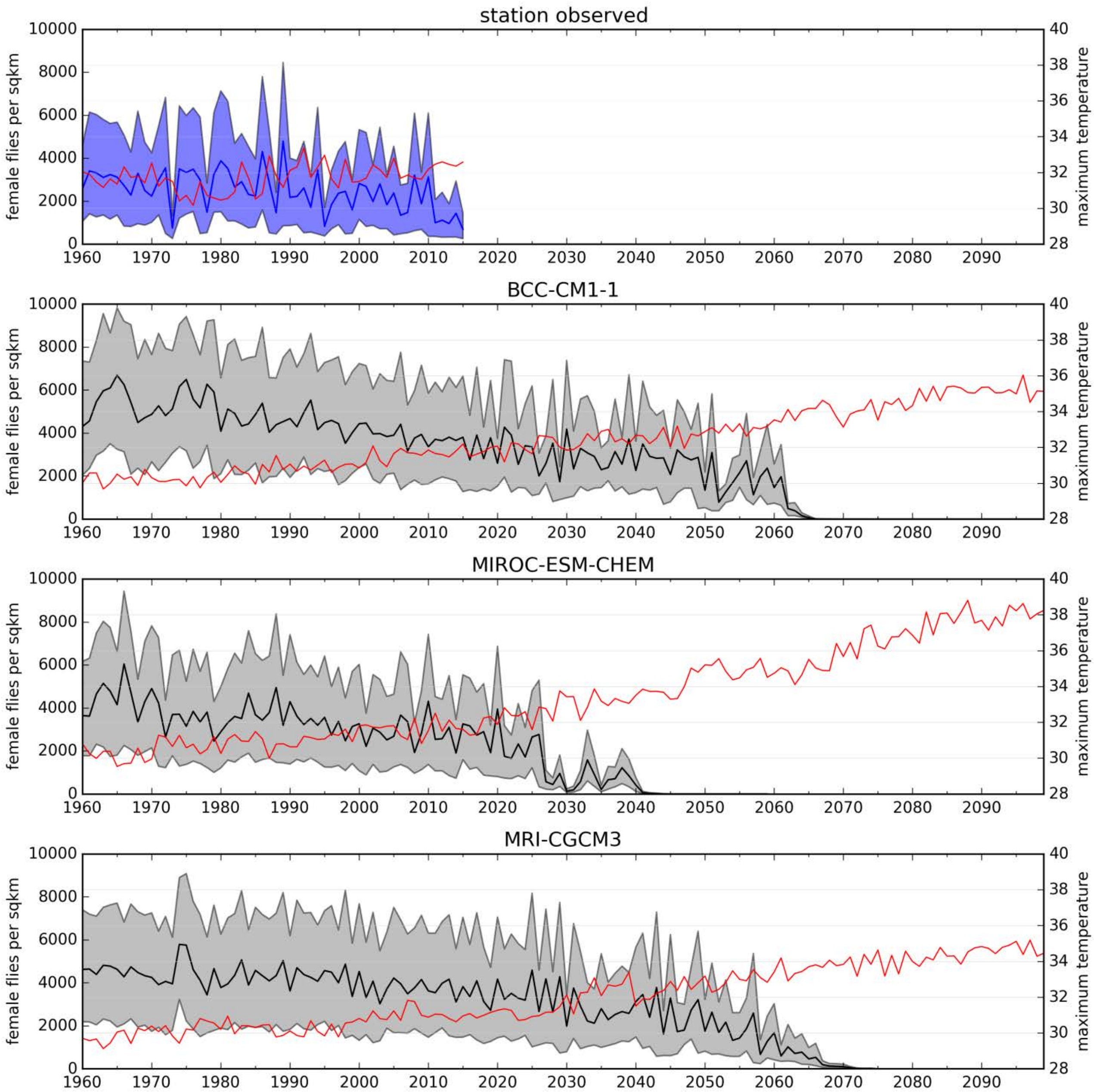


Figure 69: ***Projected tsetse fly population size using observed temperatures and projected temperatures from three SOMD models.*** *Top panel displays the observed daily mean temperature record (red), the mean female population of Glossina morsitans (blue line) and full range (blue envelope). The next three panels show the same but for three statistically downscaled GCM models.*

Discussions

The climate at Rekomitjie research station in the Zambezi Valley has a tropical savannah climate and is characterised by strong variability at a number of time scales. An important, though often overlooked scale is the diurnal cycle. The difference between the minimum temperature and the maximum temperature within a day is often larger than the average seasonal cycle. However, tsetse flies are well adapted to this daily variability and have coping strategies to deal with this (for example resting in the shade during the warmest parts of the day and feeding in the cooler evening hours). There is strong seasonality in the Rekomitjie climate. Summers (December – February) are characterised by hot conditions, maximum temperature averaging around 32° and minimum temperature of around 22° C, and convective rainfall events which account for a seasonal total of just over 500 mm. During this season, the daily mean temperatures are generally within the ideal temperature range for tsetse flies, there is sufficient shade and the soil temperatures are cool enough that tsetse flies are not restricted in where they deposit their larvae. Winters (June – August) are dry and warm (maximum temperatures average 28.5° C and minimum temperatures average 14° C). At these lower temperatures tsetse fly metabolic processes occur at a slower rate which generally reduces the size of the fly population. The spring season is characterised by clear, dry and very hot conditions (35 and 22° C for maximum and minimum temperature respectively) and relatively low rainfall. It is during this season that tsetse flies become the most stressed, since their metabolic rates are high, but the temperatures are often too hot to fly. The availability of shade, suitable locations to deposit their larva are limited at this time of year.

Clear interannual variability is seen in both temperature and rainfall at Rekomitjie. A key remote driver of this variability is the El-Nino Southern Oscillation (ENSO) where the positive (El Nino) phase is generally associated with hotter drier conditions over the study area while the negative (La Nina) phase is associated with cooler and wetter conditions. ENSO events are generally strongest during austral summer and the rainfall anomalies appear to be in phase with this, while the strongest temperature anomalies are generally found during the following spring. ENSO is only one of the remote drivers of interannual variability and it does not fully explain the variation in temperature and rainfall at Rekomitjie. More work needs to be undertaken to better understand how ENSO interacts with other ocean and atmospheric processes and how this translates into what is experienced on the ground at Rekomitjie.

There is no clear or significant trend in rainfall, but temperatures at Rekomitjie have increased over time. There is some doubt regarding the validity of the strong warming trend found in the minimum temperature record during the 1960s and 1970s, since there is no evidence of this warming trend at any neighbouring stations, or over the general region. It may instead be a local phenomenon, due to changes in the site conditions as the research station grew and developed over these first two decades. When this earlier period is disregarded, there are still strong and significant warming trends in both maximum and minimum temperature of around half a degree per decade during spring. These warming trends, occurring during the warmest time of the year resulted in new extreme values being recorded and exceeded through time. The increasing trend in temperatures have had a direct impact on the tsetse fly population dynamics, since it pushes the daily mean temperature beyond the ideal temperature range for tsetse flies more frequently and for a more protracted period which can cause tsetse fly population to crash.

The climate at Rekomitjie may be representative of the climate along the Zambezi Valley, but not of the larger region. The spatial differences in rainfall and especially temperature are strongly related to altitude, with decreasing temperatures at increasing elevations. There is a clear temperature gradient from the hot Zambezi Valley up the Zimbabwean escarpment, where the temperatures are currently too cool for tsetse flies during at least some part of the year.

The climate is projected to warm into the future due to anthropogenic climate change. The rate of warming is primarily dependent on which developmental pathway society chooses to follow, but is also dependent on which Global Climate Model is selected. However, all models show that temperatures are projected to increase into the future and that the change will be large enough that the climate change signal should emerge beyond the range seen in historical natural variability within the next few decades. This conclusion is supported by the strong warming trend that is already evident in the observed climate during spring. There is no agreement on how rainfall is projected to change into the future.

The results from the statistically downscaled GCMs generally agree with those from the raw GCMs, however, the range between models is slightly reduced. The finer resolution (~50 km x 50 km) helps resolve the spatial differences in temperature. Daily mean temperatures at Rekomitjie are projected to increase by between 1 – 3 °C by the end of the century under the RCP 4.5 and by 3 – 6 ° C under the RCP 8.5 scenario during summer, autumn and winter, and by up to 4 or 7° C during spring. This means that half of the models projecting an average daily temperature of at least 32° C during spring by the end of the century. This warming shifts the whole distribution of temperatures, and especially the upper tail, and what currently is an extreme temperature (32° C) is projected to become a relatively common temperature. This has huge implications for tsetse flies, since the average spring temperature by the mid to late 21st Century may be outside of what they can tolerate. This is illustrated using the results from Glyn Vale's tsetse fly model run with climate information from three different statistically downscaled GCMs. The local tsetse fly population at Rekomitjie is projected to go extinct before the end of the century, irrespective of which model was used. The only difference is the timing of the extinction.

The statistically downscaled results over the larger region suggest that the climate will become too warm within the Zambezi Valley, but that ideal temperatures will slowly migrate up the escarpment and that by the end of the century most of the Zimbabwe Highveld will have a climate within the ideal temperature range for tsetse flies. This conclusion, comes with a number of important caveats, firstly, climate is a necessary but not sufficient factor in determining the areas suitable for tsetse flies. Other important factors include vegetation type and land use and also the availability of animals on which to feed. The tsetse flies would also need to follow "corridors" of suitable conditions since a new colony would require many years of immigration from the current tsetse areas before their populations would be fully established. During this time, tsetse control measures would also be very effective in keeping the population below sustainable levels.

Conclusion

This report shows that the climate at Rekomitjie research station in the Zambezi Valley has changed over the recent past and that it is projected to change into the future due to anthropogenic climate change. The local climate at Rekomitjie is driven by both local and remote forcing; topography plays a key role in determining the temperatures, while remote drivers, such as the El Nino-Southern Oscillation (ENSO), influence both the temperature and rainfall at interannual timescales. Rainfall shows strong year to year variability but no discernible trends are evident. Minimum and maximum temperature show clear trends, especially during the warmest season (September – November) over the last few decades. These warming trends within the warmest months of the year have resulted in new extreme temperatures being recorded and these have been associated with more frequent and extended heat-spells. There is little consensus between Global Climate Models on whether the climate is projected to get wetter or drier into the future, however all models agree that it will get hotter, especially during the warmest time of the year. The magnitude of the warming is less certain further into the future since it depends on the future greenhouse gas emission path and on the GCM selected. Even so, the projected warming of all models is large enough that it extends beyond the range of natural variability and results in extreme heat events becoming more frequent and protracted. These results suggest that it is likely that tsetse flies will go extinct at Rekomitjie; however, there they also suggest that the area with ideal temperatures range for tsetse flies will slowly migrate up the escarpment and that it will include most of the Highveld of Zimbabwe by the end of the century.

Acknowledgements

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Appendix A: Error checks

1. Tmax < = Tmin

Date	Tmin	Tmax
1960/11/23	24.44	24.44
1962/03/17	22.22	22.22
1965/04/30	18.89	17.78
1966/11/09	27.78	23.89
1966/11/19	26.67	24.44
1994/12/15	22.00	21.50
1997/09/15	21.50	20.00
2004/12/28	25.50	25.50
2008/01/18	22.50	22.50

2. Variable: Temperature, Test: 15-day standard deviation check

Date	Variable	Value	Std dev	Mean	Lower bound	Upper bound
2009/07/26	tmax	14.00	2.33	28.19	14.21	42.16
1968/02/29	tmin	32.78	1.80	21.55	10.78	32.33

1. Variable: pr, Date: 1962-03-17, Value: 174.75.
not only is this value almost 100 mm higher than next highest value, but also the tmin and tmax values are identical on this date provides further support to this being a miss-recording of the value. All three values set to undefined

2. Variable: tmax, Date: 2009-07-27, Value 14.50

Depending on the threshold set, this values also fail the climatological outlier check. Values set to undefined

3. Variable: pr, Date: 1988-07-20, Value 55.00
This is the only above zero July rainfall value found in the full record. Value set to undefined.

4. Variable: tmin, Dates: 2012-09-01 : 2013-03-31
Clear step-jump in timeseries, with values roughly 3 to 5 degrees lower than monthly climatological norm. Values set to undefined.

5. Variable: pr, Dates: ~1959 - 1969
Much larger number of light intensity rainfall events (pr<2mm) than in later period. ~ 200 events in the 1960s with between 75 - 100 events in other decades. This is probably due to a decrease in the accuracy of logging / reporting these light rainfall events (no measures were taken to correct this, however, trend analysis should focus on rainfall values greater than 2mm/day).

6. Variables: tmax, tmin, Dates: ~1959 - 1969
Clear "rounding up" of values found in the data (unusually low frequency of values such as 9, 14, 19, 24, 29ºC etc.)

Appendix B: Station data infilling

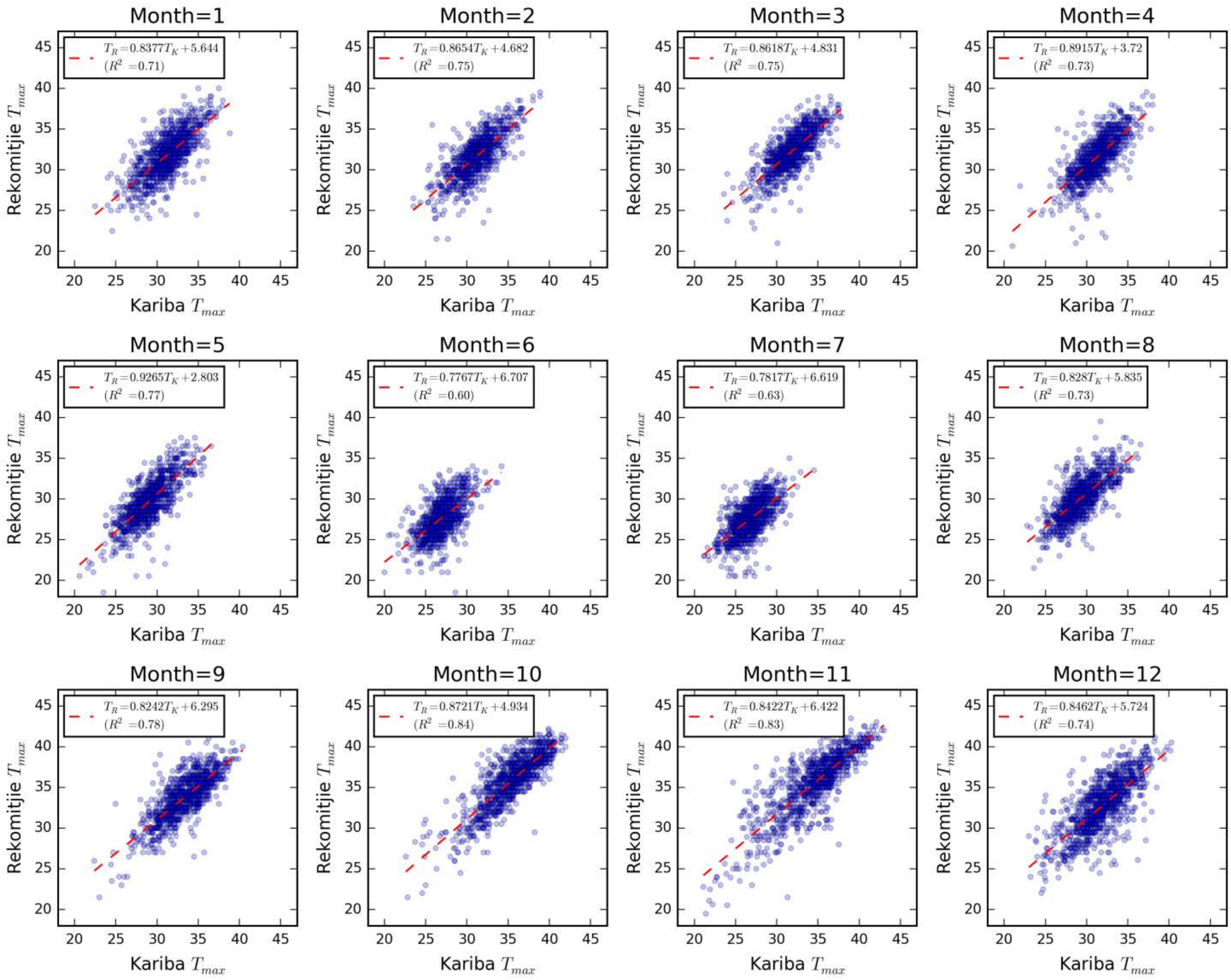

Figure 70: ***Correlation between daily maximum temperature at Rekomitjie and Kariba stations***

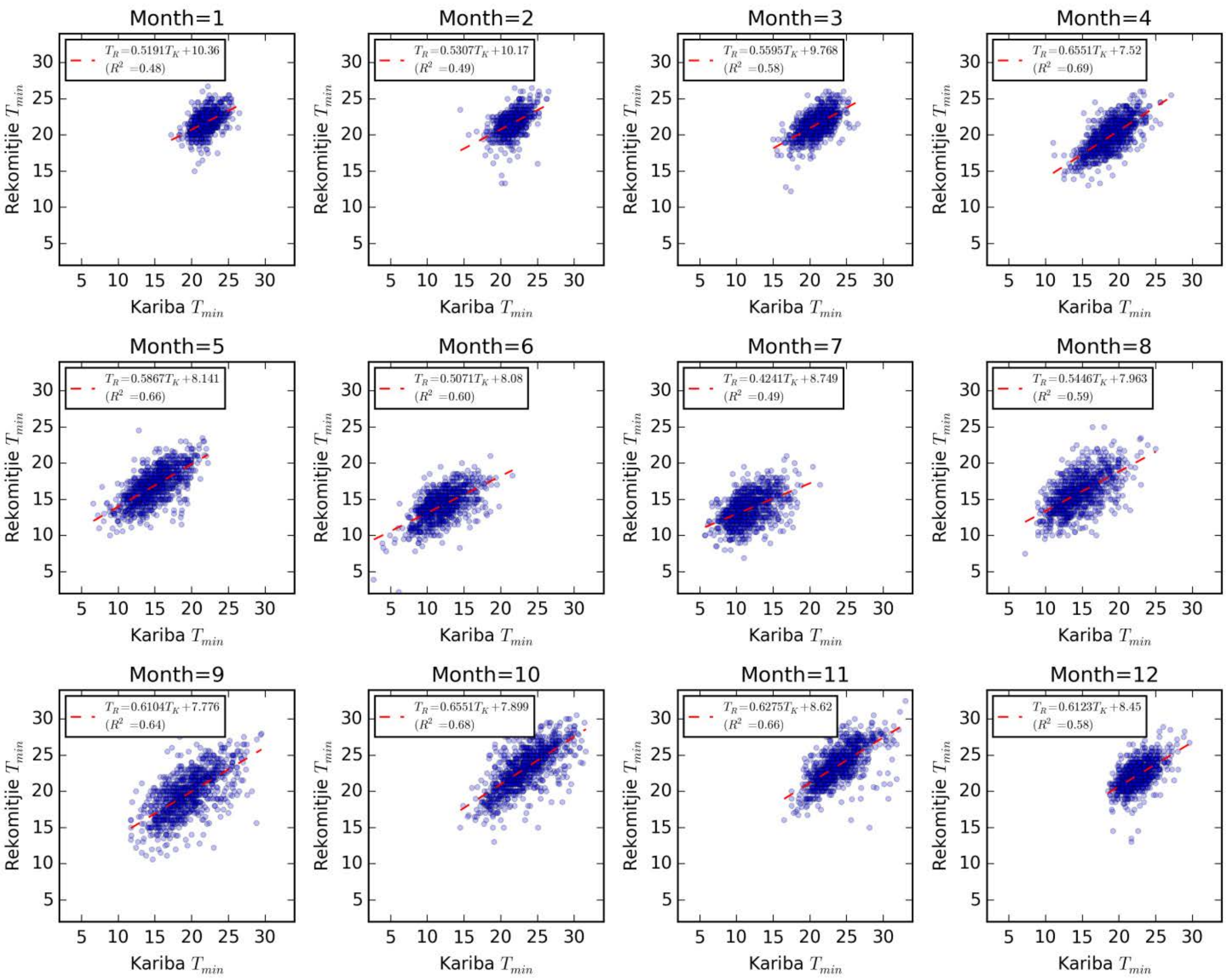

Figure 71: ***Correlation between daily minimum temperature at Rekomitjie and Kariba stations***

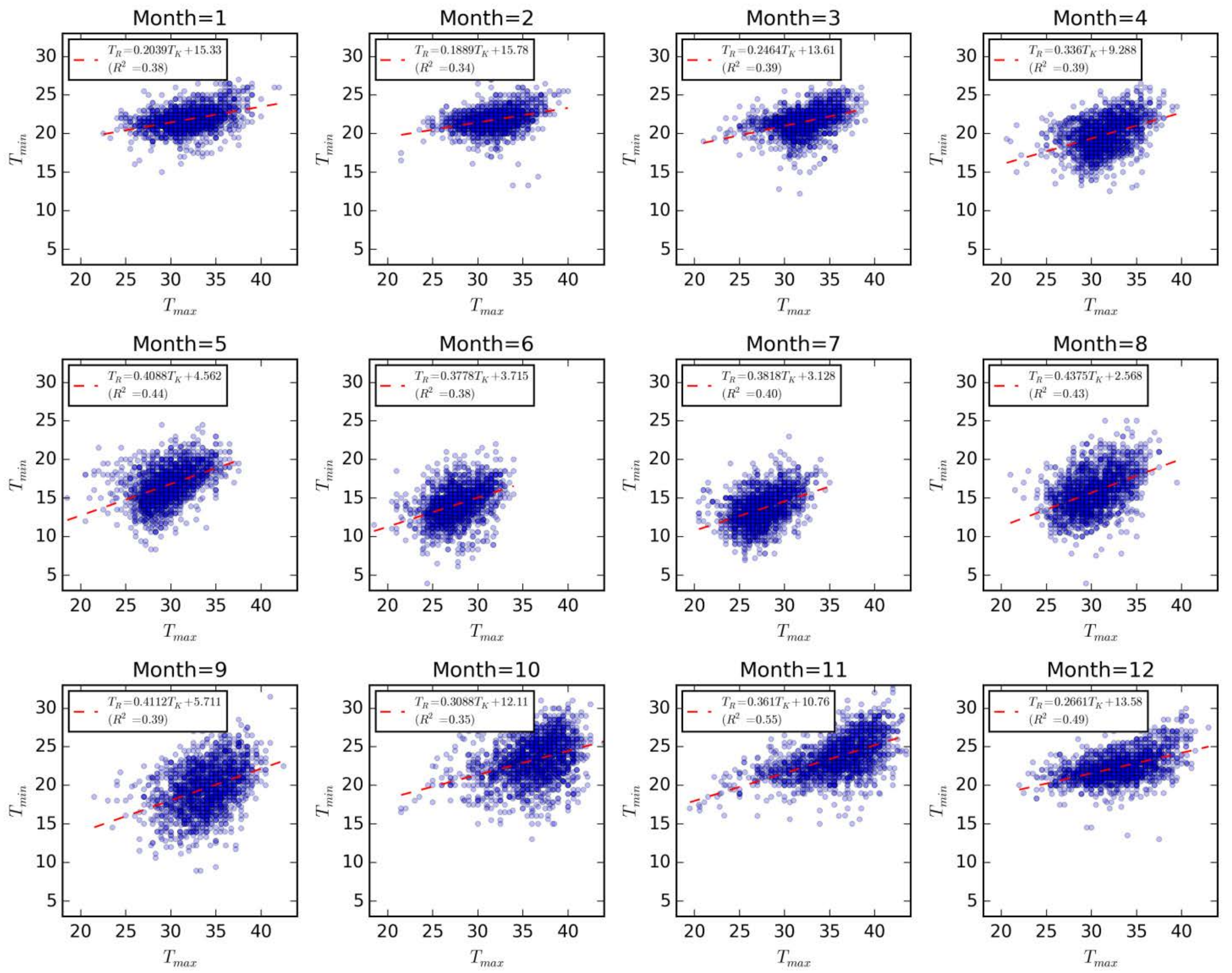

Figure 72: ***Correlation between daily maximum and minimum temperature at the Rekomitjie station***