CLIMATE SYSTEM ANALYSIS GROUP, UNIVERSITY OF CAPE TOWN

Serengeti Climate Variability and Change

Final Scientific Report

Lisa van Aardenne, Piotr Wolski and Chris Jack

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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.

Contents

Abstract

This report explores how the climate in the Serengeti National Park, in northern Tanzania has changed over the recent past and how it is projected to change into the future due to anthropogenic climate change. The historic climate work is based on a number of different climate datasets, including both gridded- and station-based datasets. The analysis of the future climate makes use of an ensemble of Global Climate Models (GCMs) where results from both the raw GCM data and empirically/statistically downscaled GCM data are presented.

The Serengeti National Park is located at an altitude of roughly 1500 m above sea level, with the terrain generally increasing from west to east. The park is bounded by a number of other protected areas, most notably the Maasai Mara National Park in Kenya, and the Ngorongoro Conservation area to the east. Two tsetse fly species are found in this region, *Glossina swynnertoni* and *Glossina pallidipes*. However their distributions are quite different with *G swynnertoni* being the most common species within the park and at other higher elevation areas, while the distribution of *G pallidipes* is limited to lower elevation areas in and around the park.

The Serengeti is classified as having a tropical savannah climate. The daily maximum and minimum temperatures average around 29° C and 15° C respectively with very little seasonal variability in temperatures (~3° C), which means that the diurnal temperature variability (14° C) is the dominant mode of variability. The daily mean temperature over the region is within the ideal temperature range for tsetse flies (16 - 32° C) throughout the year, with the exception of the high mountainous and the Kenyan highlands. Rainfall is distributed through the year primarily in two rainy seasons; the short rains in November and December and the long rains from March to May, but, rainfall does also occur during January and February months, especially in the northern parts. The rainfall is generally convective in nature and associated with the seasonal migration of the Intertropical Convergence Zone (ITCZ) over the region.

There is some suggestion of an increasing trend in temperature in the recent past. However, this result was obtained from a single coarse-scale gridded product which is not able to provide information at the local scale which is of importance for tsetse fly research. No trend is evident in the rainfall record, but it does highlight the larger interannual and decadal variability of rainfall within this region.

There is some consensus between Global Climate that the climate over the Serengeti is projected to get wetter into the future, and this is supported by the downscaled climate change projections. The models do not agree on the magnitude of the change, with some models projecting no significant change while others project extreme wetting of up to 400mm/year by the end of the century. Models also agree that it will get warmer into the future and this warming will result in the climate shifting outside of the historical range of natural variability within the next few decades. 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 even the warmest model is not sufficient to shift the climate beyond the upper-limit of the ideal temperature range for tsetse flies, but it may be sufficient to allow tsetse flies to invade higher elevation areas like the Kenyan highlands.

Introduction

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 such as the Inter-Tropical Convergence Zone (ITCZ); 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 convective 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 the 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.

[1] CMIP – cmip-pcmdi.llnl.gov

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 when ocean/continental boundaries and sharp climate 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

There is not one "best" climate dataset for this region. All differ in terms of the type of data (station / gridded), 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 since together they provide a better understanding of the variability and projected change into the future for the Serengeti climate. This section provides a brief overview of each of the datasets.

Gridded data

Two gridded observed datasets are used in this analysis; the Tanzania Meteorology Agency (TMA) maproom monthly climate analysis[2] and the WATCH Forcing Data ERA Interim (WFDEI)[3] dataset.

The TMA maproom monthly climate analysis datasets are reconstructed rainfall and temperature datasets over land areas on a on a 0.0375˚ x 0.0375˚ lat/lon grid (about 4 km of resolution) at dekad (10-day) and monthly temporal resolution. The rainfall time series (1983 to 2014) was created by combining quality-controlled station observations with satellite rainfall estimates. Minimum and maximum temperature time series (1961 to 2013) were generated by combining quality-controlled station observations with downscaled reanalysis product. The dataset was produces by the International Research Institute for Climate and Society (IRI) ENACTS project[4]. The raw data is not publically available (the author attempted to obtain the data through numerous avenues), however a selection of derived information products /plots are available online and are used in this analysis.

The WATCH Forcing Data ERA Interim 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, mean and minimum temperatures were used to characterise the regional climate over the larger study area. The daily rainfall and maximum and minimum temperature were also used

[2] Monthly Climate Analysis http://maproom.meteo.go.tz/maproom/Climatology/Climate_Analysis/monthly.html
[3] WFDEI – www.eu-watch.org/data_availability
[4] IRI : ENACTS - https://iri.columbia.edu/resources/enacts/

as inputs into the statistical downscaling to provide future projections over the larger region.

Station data

No ideal station datasets is available for this study area. A station record just outside the park at Mwanza (-2.47N, 32,92E, 1140M) is available within the Global Historical Climatology Network – Daily (GHCN-D)[5] database covering the period 1973-2017. The data is made available via the KNMI Climate Explorer[6]. Unfortunately the data record has large periods of missing data which limit its usefulness.

A number of automatic weather stations were installed within the Serengeti National Park as part of the Serengeti Savannah Dynamics Project[7]. The data were made available to us by Dr Thomas Morrison and consisted of data for 12 stations, providing hourly reading for temperature, rainfall, relative humidity, solar radiation, wind and soil moisture for periods between mid-2012 to mid-2014. The shortness of the records limit their usefulness, especially since most of them have less than two years of data. However, they do provide some insight into what has happened in the recent past and allows for the comparison of the local climates at different places within the park. Results for 5 of the stations are used in this analysis, details of which can be found in Table 1 below.

Table 1: Summary of the five stations obtained from the Serengeti Savannah Dynamics Project

Weather station	Name	Region	Lat	Lon	Alt	Period
Ikoma Gate	ikoma	Center	-2.19	34.72	1300m	2012/11/18 – 2014/04/18
Kifaru Camp	kifaru	North	-1.19	35.02	1570m	2012/11/24 – 2014/03/04
Naabi Gate	naabi	South	-2.83	34.99	1710m	2012/12/04 – 2014/05/30
Simiyu Ranger Post	simiyu	South	-2.92	34.68	1550m	2012/07/06 – 2014/07/11
Soit Lemotonyi	soit	South	-257	35.11	1730m	2012/12/09 – 2014/07/01

Global Climate Model data

5 National Centers for Environmental Information - https://www.ncdc.noaa.gov/oa/climate/ghcn-daily/
6 KNMI Climate Explorer - https://climexp.knmi.nl
7 Anderson Lab - www.wfu.me/andersonlab

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 2) 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.

Table 2 CMIP5 modelling 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 (Hewitson and Crane 2006). 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

The Serengeti National Park is located in northern Tanzania at an altitude of roughly 1500 m above sea level, with the terrain generally increasing from west to east. The park is bounded by a number of other protected areas, most notably the Maasai Mara National Park in Kenya, and the Ngorongoro Conservation area to the east. Two tsetse fly species are found in this region, *Glossina swynnertoni* and *Glossina pallidipes* (figure 1). However their distribution is quite different with *G swynnertoni* being the most common species within the park and at other higher elevation areas, while the distribution of *G pallidipes* is limited to lower elevation areas in and around the park.

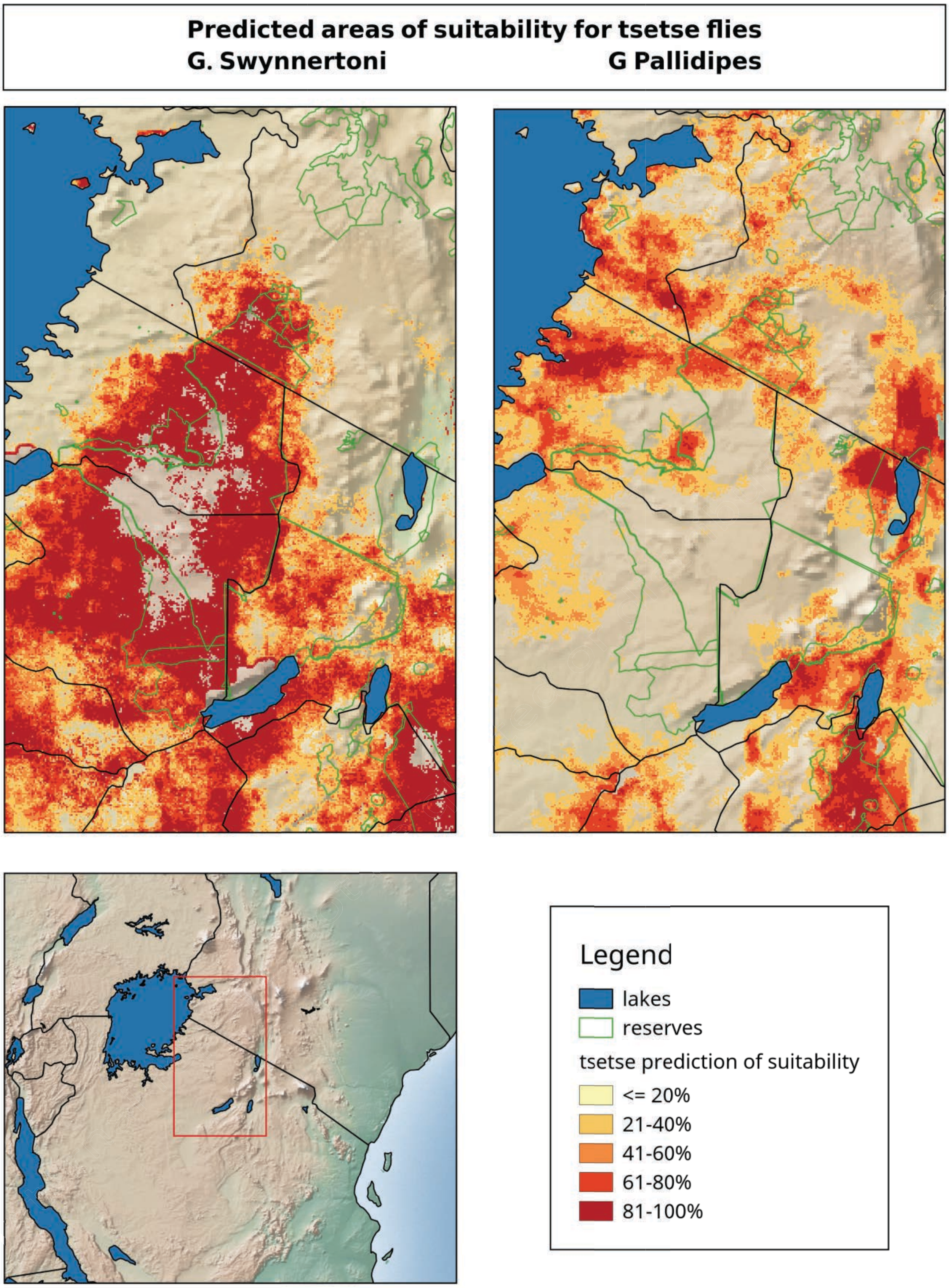

Figure 1: Tsetse fly suitability map. Map showing the predicted areas of suitability for tsetse fly species *G Swynnertoni* and *G. Pallidipes* over the larger Serengeti region. Tsetse fly suitability data from Wint and Rogers 2000. The boundaries of protected areas or reverses shown in green. Note: For the *G swynnertoni* map, the grey area within the Serengeti National Park represents areas with 100% suitability and not zero% suitability.

Historic climatology

The Serengeti National Park is classified as having a tropical savannah climate, with a dry and relatively cool season from June to August and a warm and still quite dry season in September and October. It has two wet seasons, the short rains from November to December and the long rains from March to May. Figure 2 presents the annual climate cycle averaged from 1983-2014 for the Serengeti District. Temperatures also show a bimodal seasonal cycle, maximum temperature has its first peak in February (29.5° C) and its second peak in October (30° C) which corresponds to just before the long and the short rains begin. This seasonal cycle of temperature is small, averaging only around 3° C for both maximum and minimum temperature and night time or daily minimum temperatures are quite low, averaging between 13 and 16° C, which is primarily due to the high elevation of this region. These relatively low minimum temperatures result in large average diurnal cycle of around 14° C.

Minimum and maximum temperatures in all months of the year show clear spatial variability across the larger region (Figure 3 and 4). Minimum temperatures are warmest over Lake Victoria and over other lower elevation areas, while the warmest maximum temperatures are located over the lower elevation land areas, and coolest temperatures are found over the high elevation areas primarily in Kenyan highlands but also the mountains of northern Tanzania. The minimum and maximum temperatures over the Serengeti National Park generally increase from east to west in relation to the general decrease in elevation.

The spatial pattern of rainfall is more complicated than that of temperatures and is primarily driven by the annual migration of the Intertropical Convergence Zone (ITCZ) back and forth over the region. During the June – September months, the ITCZ is located to the north of the region and generally only light rainfall occurs over the northern parts of the Serengeti. During November and December the ITCZ moves southwards over the region, resulting in the short rains, with heavier rains generally over the western parts of the region. During January and February, the areas does still received some rainfall, though the ICTZ is now located to the south of the region. During March – May the ITCS moves back over the region from the south resulting in the long rains over the Serengeti.

The TMA maproom monthly climate analysis dataset does not provide information on the daily mean temperature. Therefore this analysis relies on data from the coarser resolution WFDEI dataset. Figure 6 shows the seasonal average climatology of daily mean temperature over the region. This dataset confirms that the spatial variations are far stronger than the variations through the year. With the warmest daily mean temperatures occurring along the coast and especially over the north-east parts of Kenyan. The coolest temperatures occur over the Kenyan highlands around Nairobi. The seasonal average frequency of days where the mean temperature is within the ideal range for tsetse flies (16-32° C) is presented in figure 7. The climate for the vast majority of the regions falls within this temperature threshold for the entire year. It is just the cooler mountain in northern Tanzania and especially the Kenyan highlands where temperatures remain below the minimum threshold for much of the year.

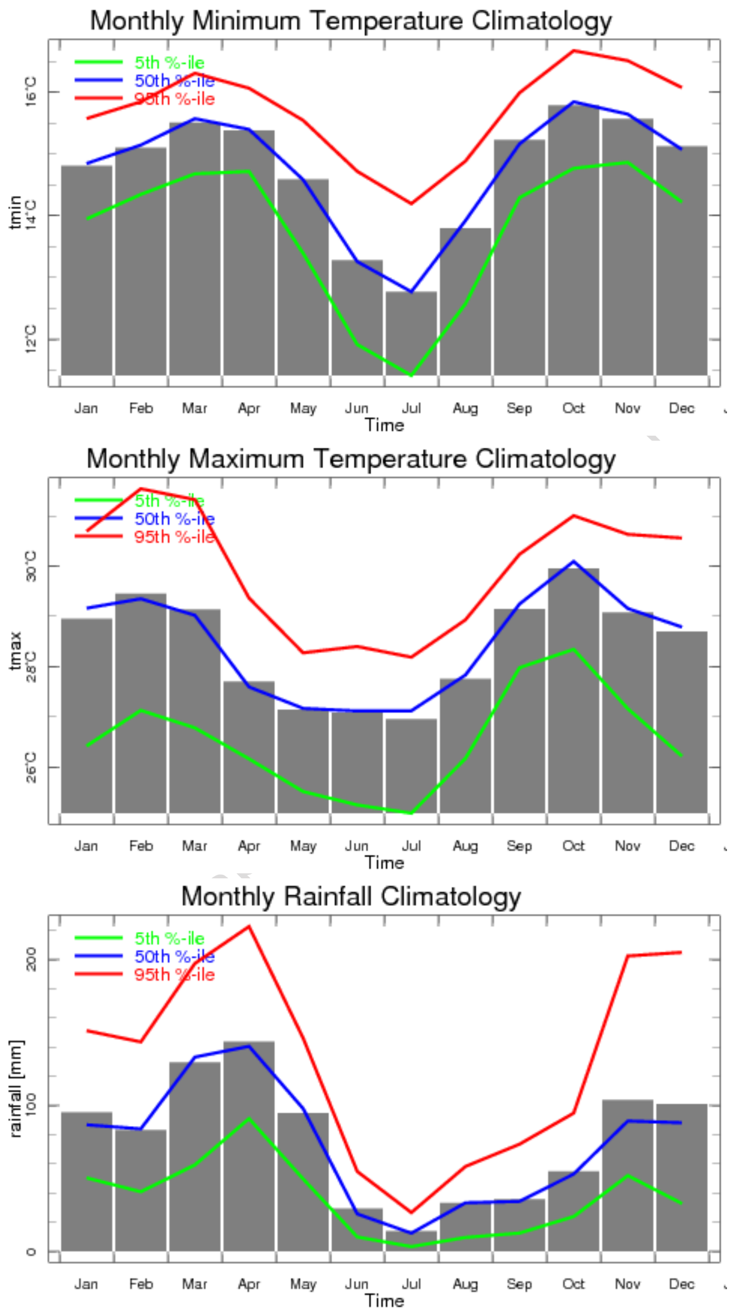

Figure 2: Seasonal cycle of daily minimum (top) maximum (middle) temperature and monthly rainfall (bottom) averaged for the Serengeti district. Data from the TMA maproom monthly climate analysis dataset.

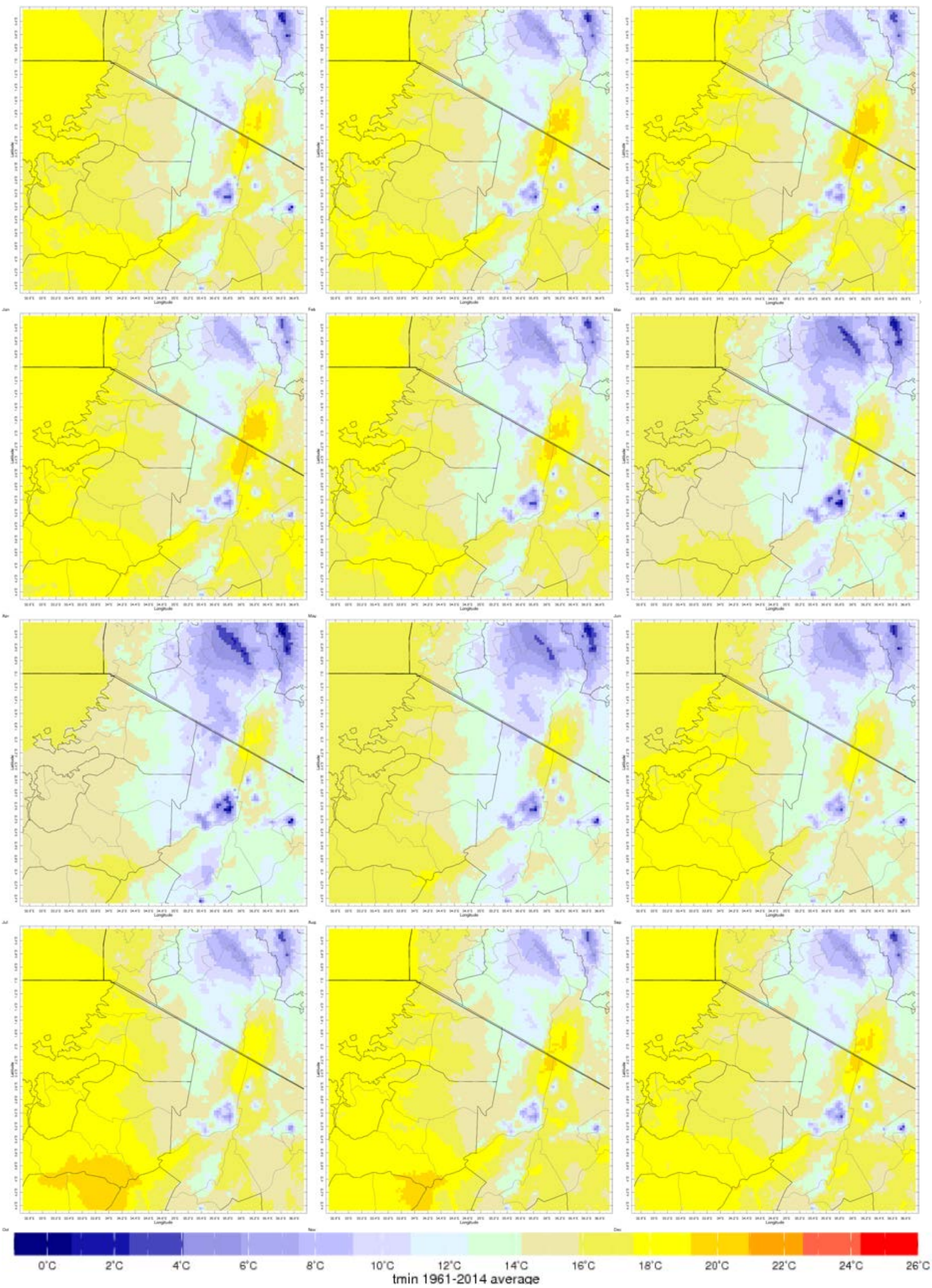

Figure 3 Monthly climatology of daily minimum temperature. Data from the TMA maproom monthly climate analysis dataset averaged over the period 1883-2010.

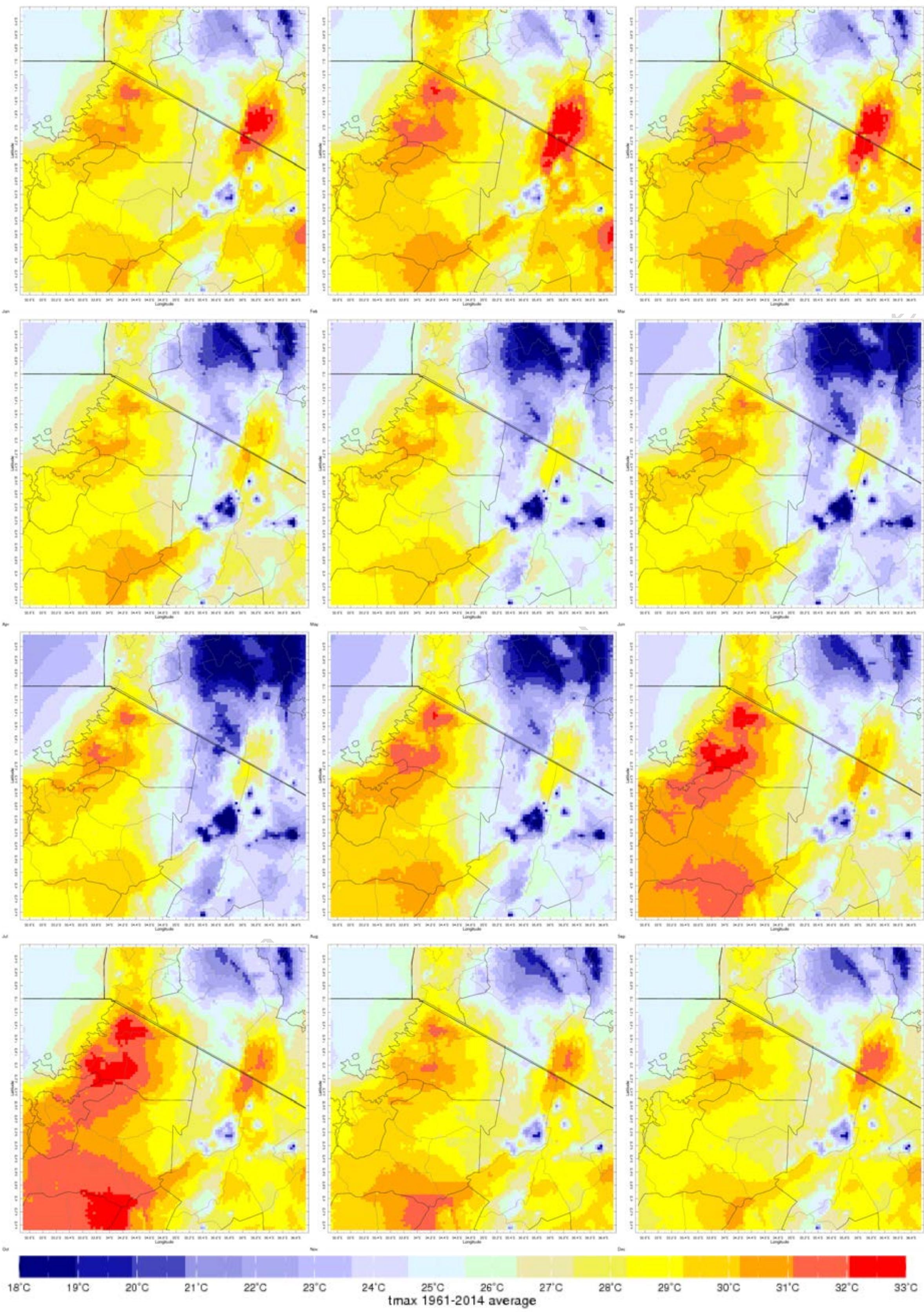

Figure 4: Monthly climatology of daily maximum temperature. Data from the TMA maproom monthly climate analysis dataset averaged over the period 1883-2010.

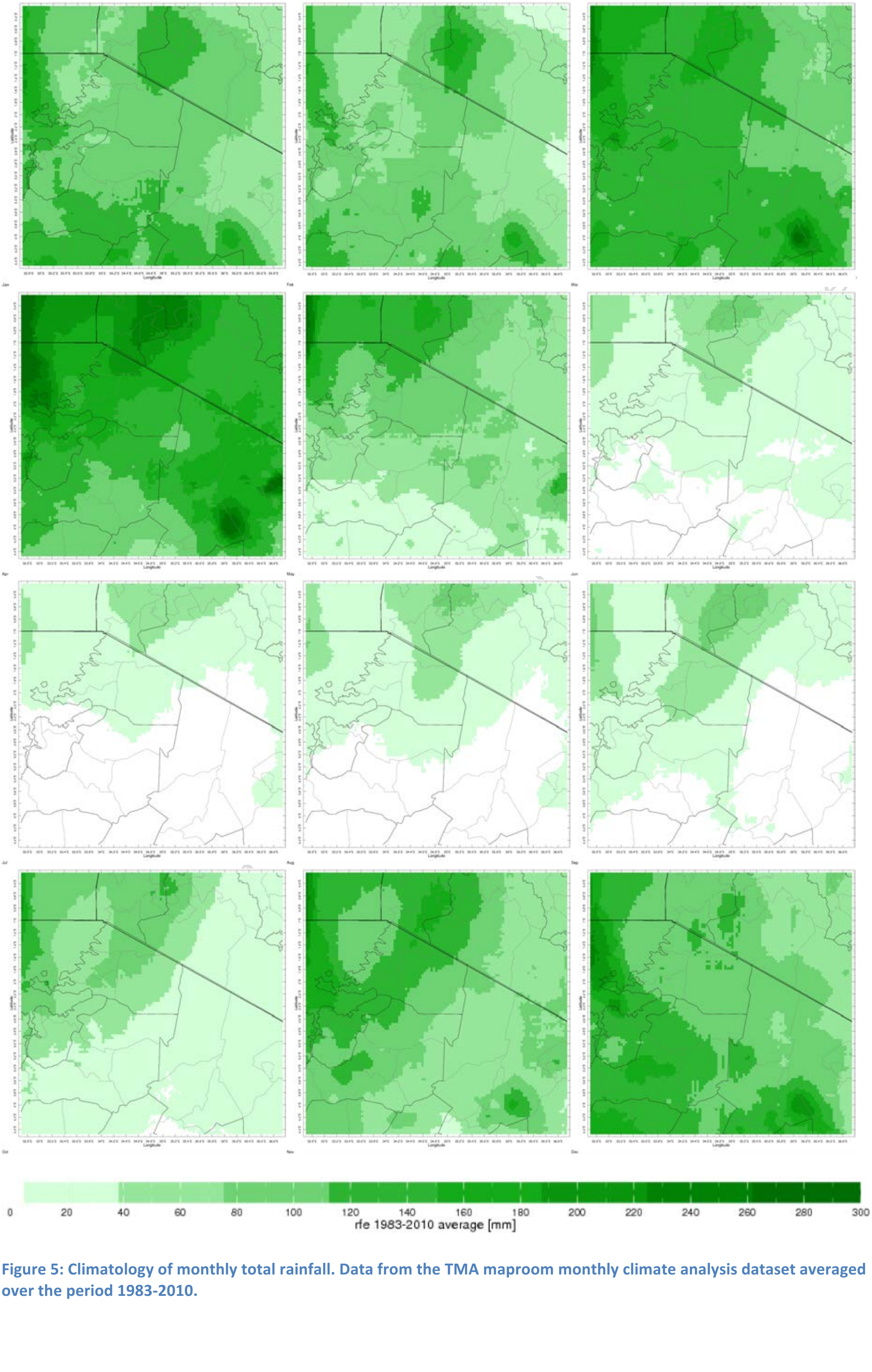

Figure 5: Climatology of monthly total rainfall. Data from the TMA maproom monthly climate analysis dataset averaged over the period 1983-2010.

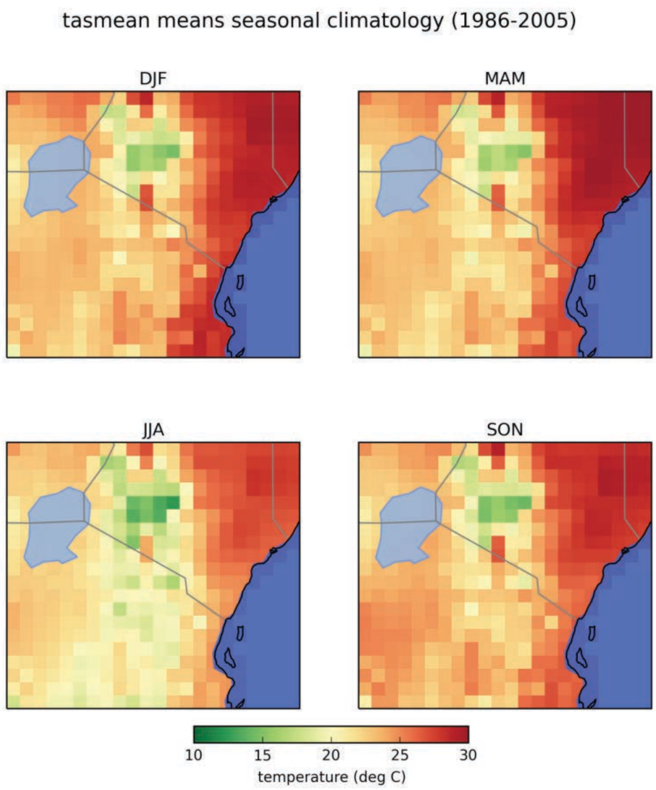

Figure 6: Climatology of seasonally averaged daily mean temperatures over the northern Tanzania / southern Kenya region. Data from the WFDEI dataset averaged over the period 1986-2005

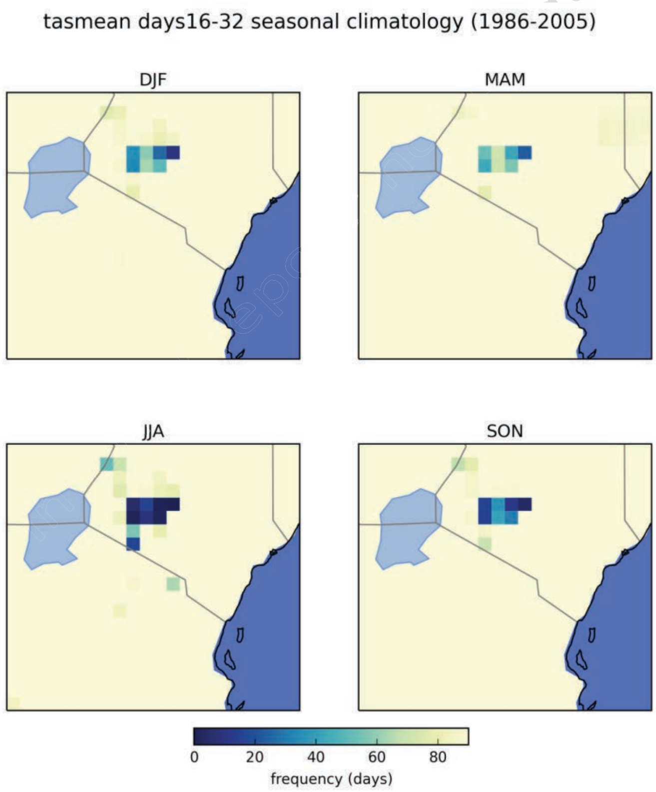

Figure 7: Climatology of seasonally average frequency of days with mean temperature between 16 and 32° C over the northern Tanzania / southern Kenya region. Data from the WFDEI dataset averaged over the period 1986-2005.

Historic variability and trends

Temperatures show clear interannual variability, but the magnitude and sign are not consistent for all months of the year or between variables. Figure 8-10 present the interannual variability of monthly averaged daily maximum, mean and minimum temperature respectively. The data is for the gridcell over the Serengeti from the WFDEI dataset covering the period 1979 – 2014. There is clear internannual variability in the three temperature records, but there is also an increasing trend in most months of up to 2° C. The warming trend is generally strongest during the 1990s, and in some months the warming trend flattens out in some of during some of the months of the year.

Figure 11 presents the frequency of extreme hot days, or days where the maximum temperature exceeds the 90th percentile (32° C). It is clear that at during the 1980s, this threshold was generally only exceed on around 4 to 5 days per month from December – March, but the frequency increases sharply from the mid-1990s, especially during February and October where the frequency over the more recent past is around 15 and 10 days respectively. Rainfall over this area exhibits strong interannual variability (Figure 12). For instance monthly total rainfall during March varies from less than 50 mm to around 300 mm. There is also clear multi-year or dedadal variability which makes it impossible to detect any trend in the data.

These results are obtained from a single data source and ideally should be compared to results obtained from other sources, such as station data. This was unfortunately not possible and therefore these results should be interpreted with caution.

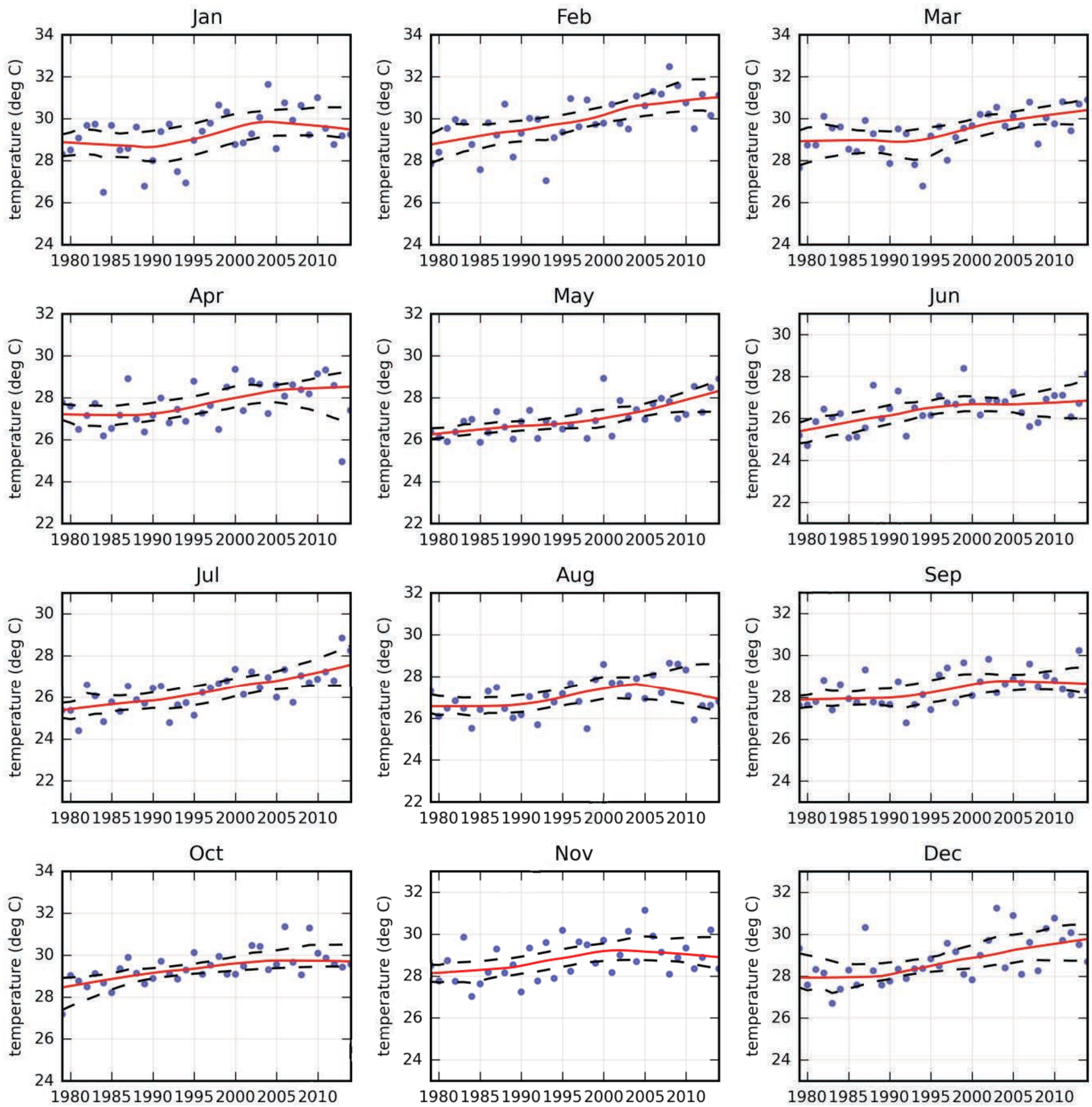

Figure 8: Observed time series and trend in daily maximum temperature for gridcell over Serengeti in the WFDEI dataset. Time series of monthly mean maximum temperature (blue dots) presented for each month of the year. The red line shows the median trends calculated using lowess method, and the dashed lines show the range of the 95th confidence interval around the median.

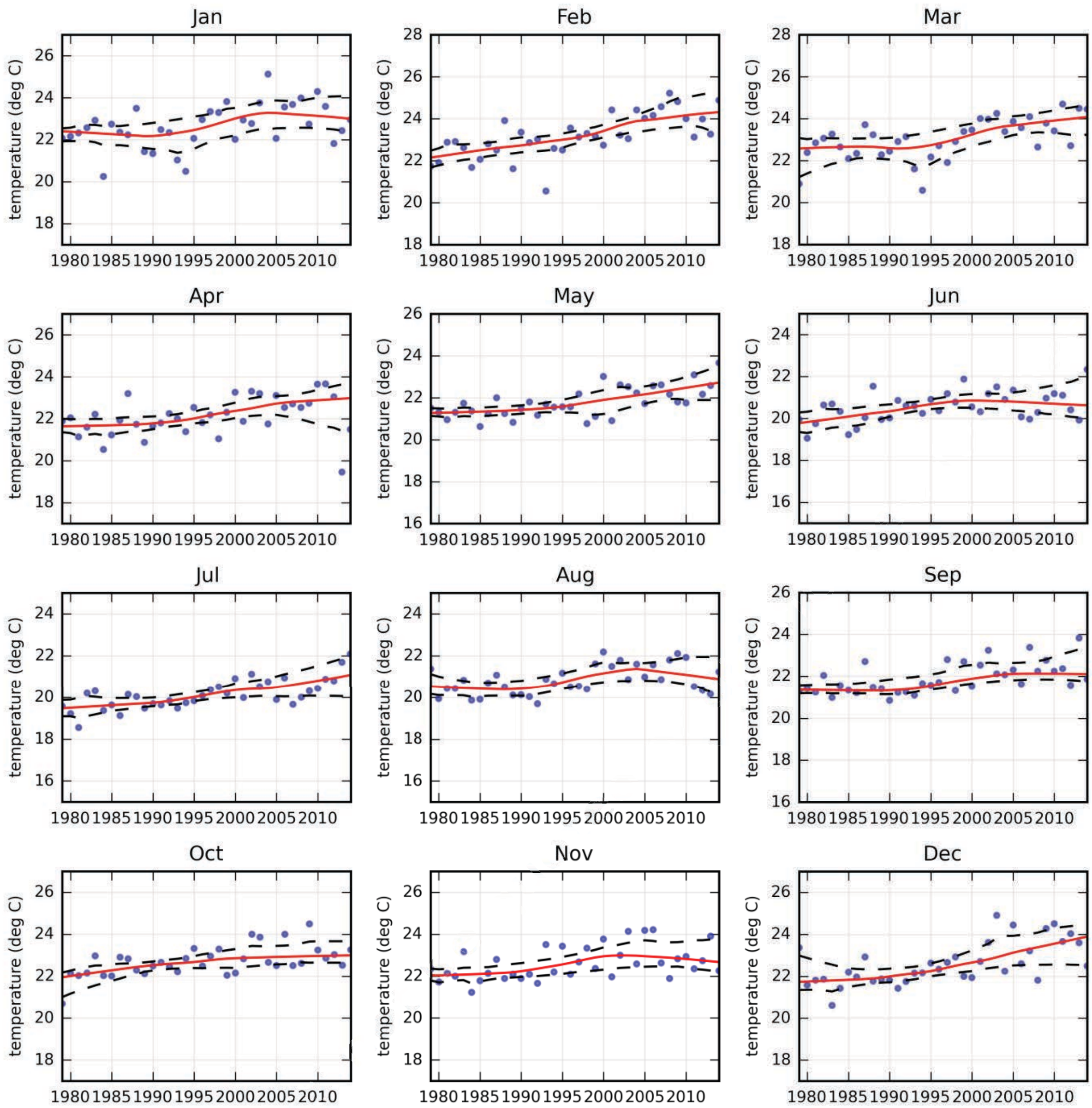

Figure 9: Observed time series and trend in daily mean temperature for gridcell over Serengeti in the WFDEI dataset. Time series of monthly mean maximum temperature (blue dots) presented for each month of the year. The red line shows the median trends calculated using lowess method, and the dashed lines show the range of the 95th confidence interval around the median.

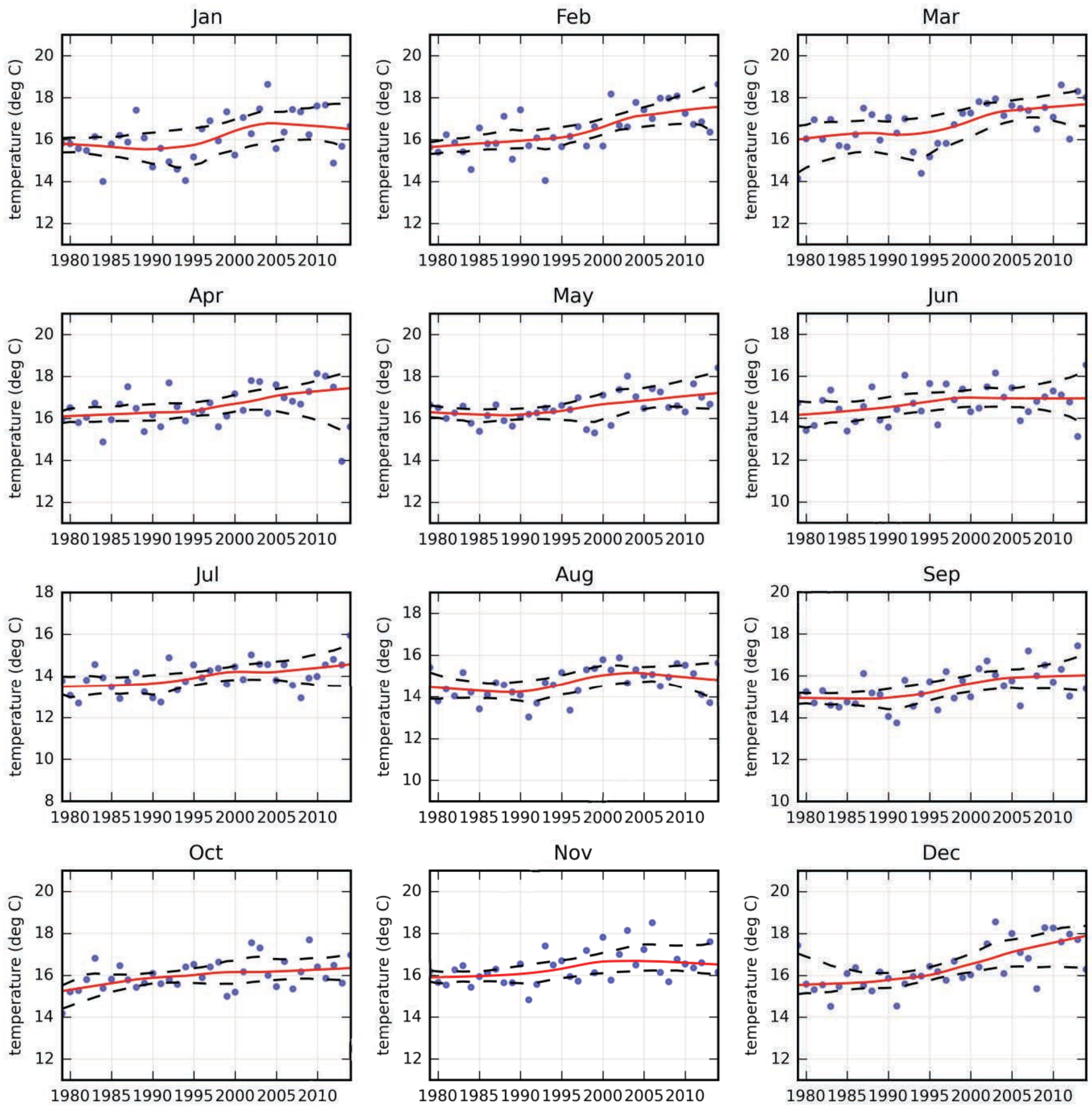

Figure 10: Observed time series and trend in daily minimum temperature for gridcell over Serengeti in the WFDEI dataset. Time series of monthly mean maximum temperature (blue dots) presented for each month of the year. The red line shows the median trends calculated using lowess method, and the dashed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

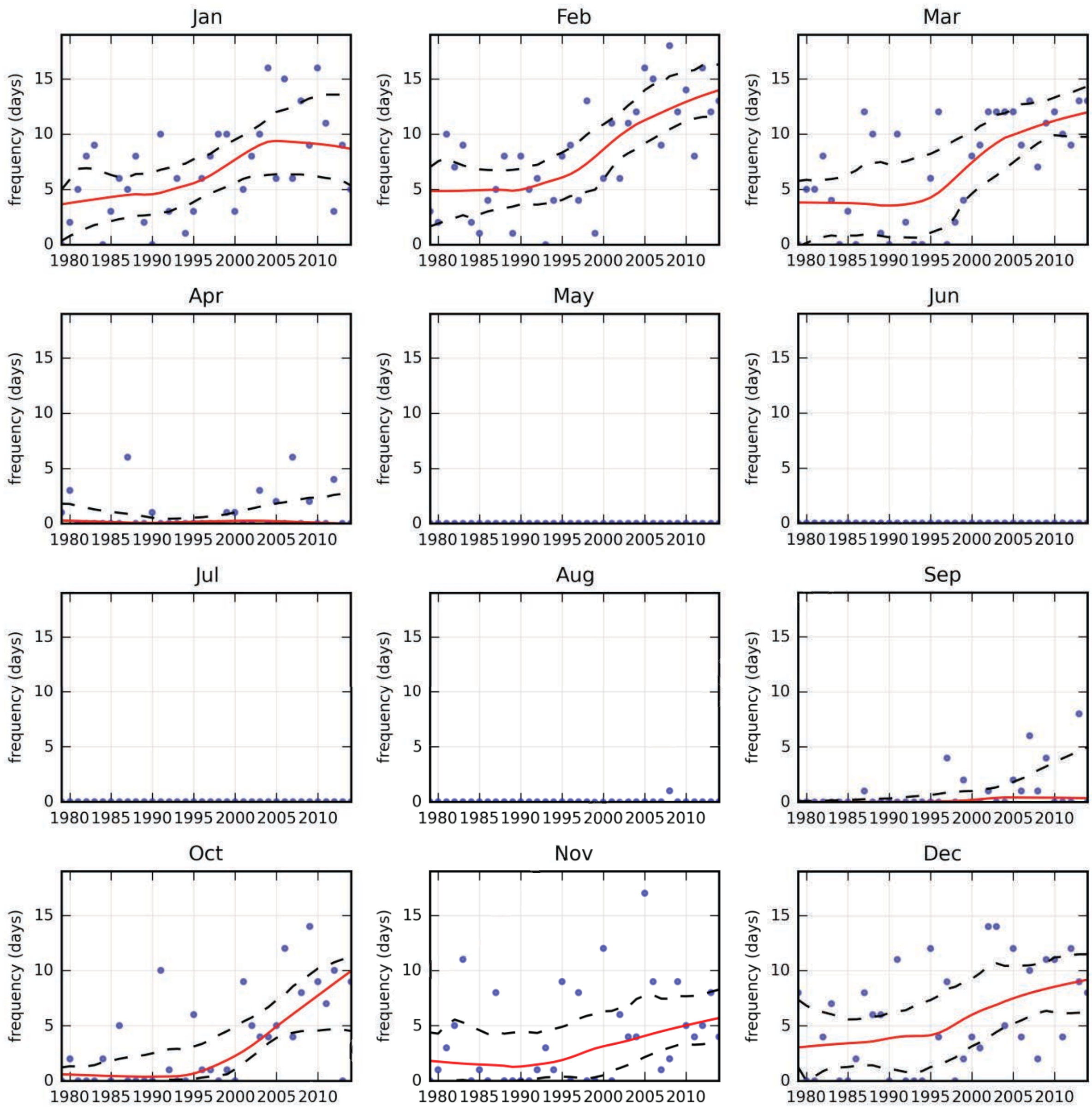

Figure 11: Observed time series and trend in the frequency of extreme hot days (days above the 90th percentile / 32° C) for the gridcell over Serengeti in the WFDEI dataset. Time series of monthly mean maximum temperature (blue dots) presented for each month of the year. The red line shows the median trends calculated using lowess method, and the dashed lines show the range of the 95th confidence interval around the median.

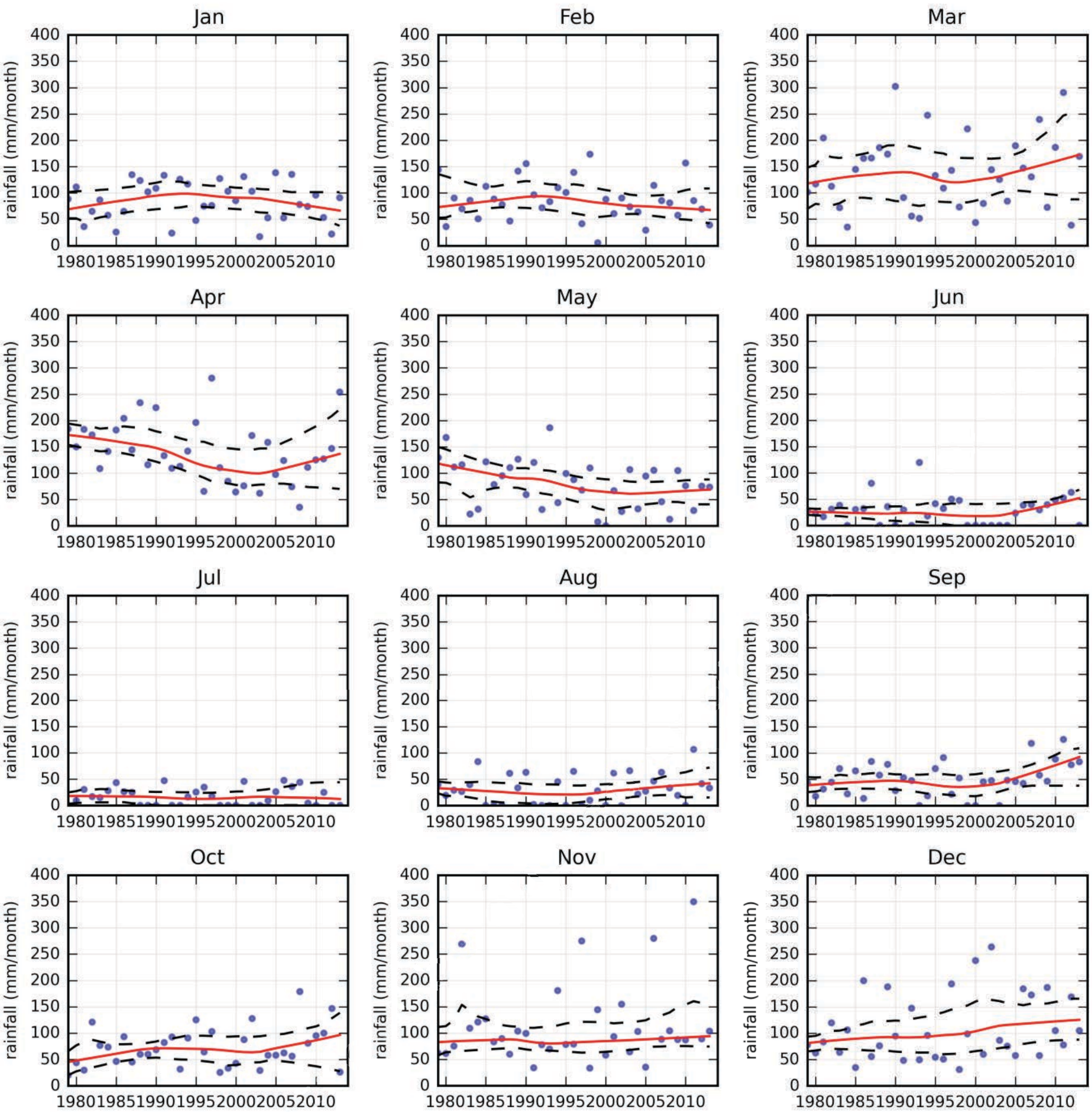

Figure 12: Observed time series and trend in monthly total rainfall for the gridcell over Serengeti in the WFDEI dataset. Time series of monthly mean maximum temperature (blue dots) presented for each month of the year. The red line shows the median trends calculated using lowess method, and the dashed lines show the range of the 95th confidence interval around the median.

Station Data

The only publically available weather station within the Serengeti area is the Mwnza station, located just outside the park. The rainfall record extends from 1950-1990 and the temperature records start in 1973 and continue to the present. Unfortunately the quality of the temperature data is very poor with very large gaps in the records, most notably from around 1983 – 2000, but also spread throughout the record. That being said the temperature records after 2000 is of better quality than during the earlier periods.

Figure 13 presents the average climatology of daily maximum and minimum temperature and rainfall, but it duplicates the annual cycle twice. At this station the maximum temperatures average around 28° C, however there is strong variability ranging between 20 and 38° C. No clear seasonal cycle is evident in the record. The strong variability and lack of clear seasonal cycle are most probably the result of the very poor quality of the data record. Minimum temperatures are shown to vary between around 15° C in July and around 18° C from October to May. Very strong variability is also evident in the minimum temperature record, which ranges from 8 - 23° C which is again probably due to the poor quality of the data. The rainfall is presented as daily mean values rather than monthly total values, however, it is still possible to identify the two rainy seasons. The record also highlights the strong variability of rainfall and that heavy rainfall events are evident even in the dryer months.

Figure 14 presents the time series of daily mean maximum and minimum temperature and daily rainfall over the full periods of the records. The gaps and the poor quality of the temperature records are clearly evident, which makes it impossible to identify any decadal variability or trends in the records. The rainfall record is almost complete, however, it ends in 1990 and it is hard to detect any trend within the daily record.

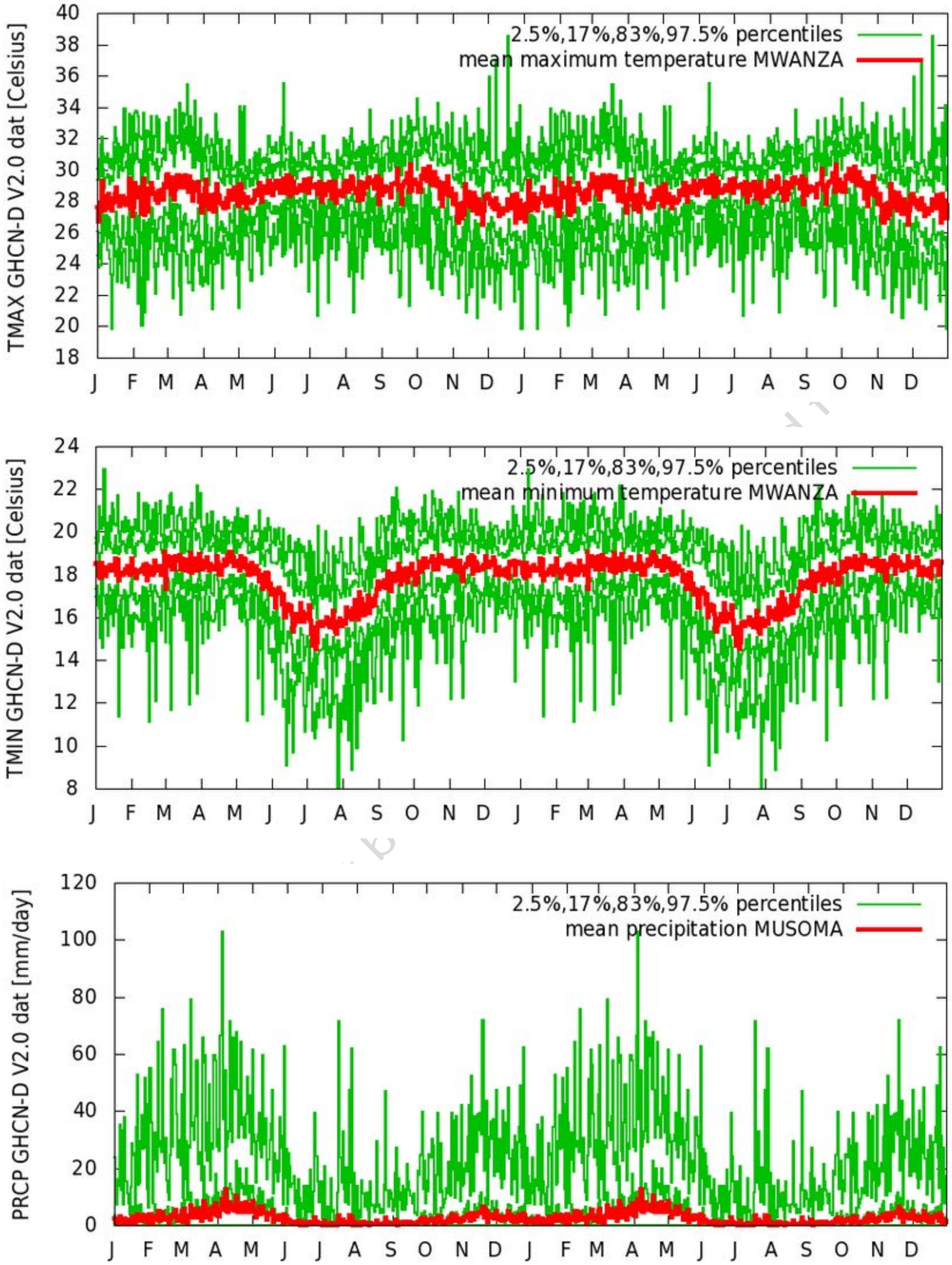

Figure 13: 24-month climatology of daily values at Musoma. Daily maximum temperature (top panel), daily minimum temperature (middle panel) and daily mean rainfall (bottom panel). GHCN-D v2 data obtained from the Climate Explorer.

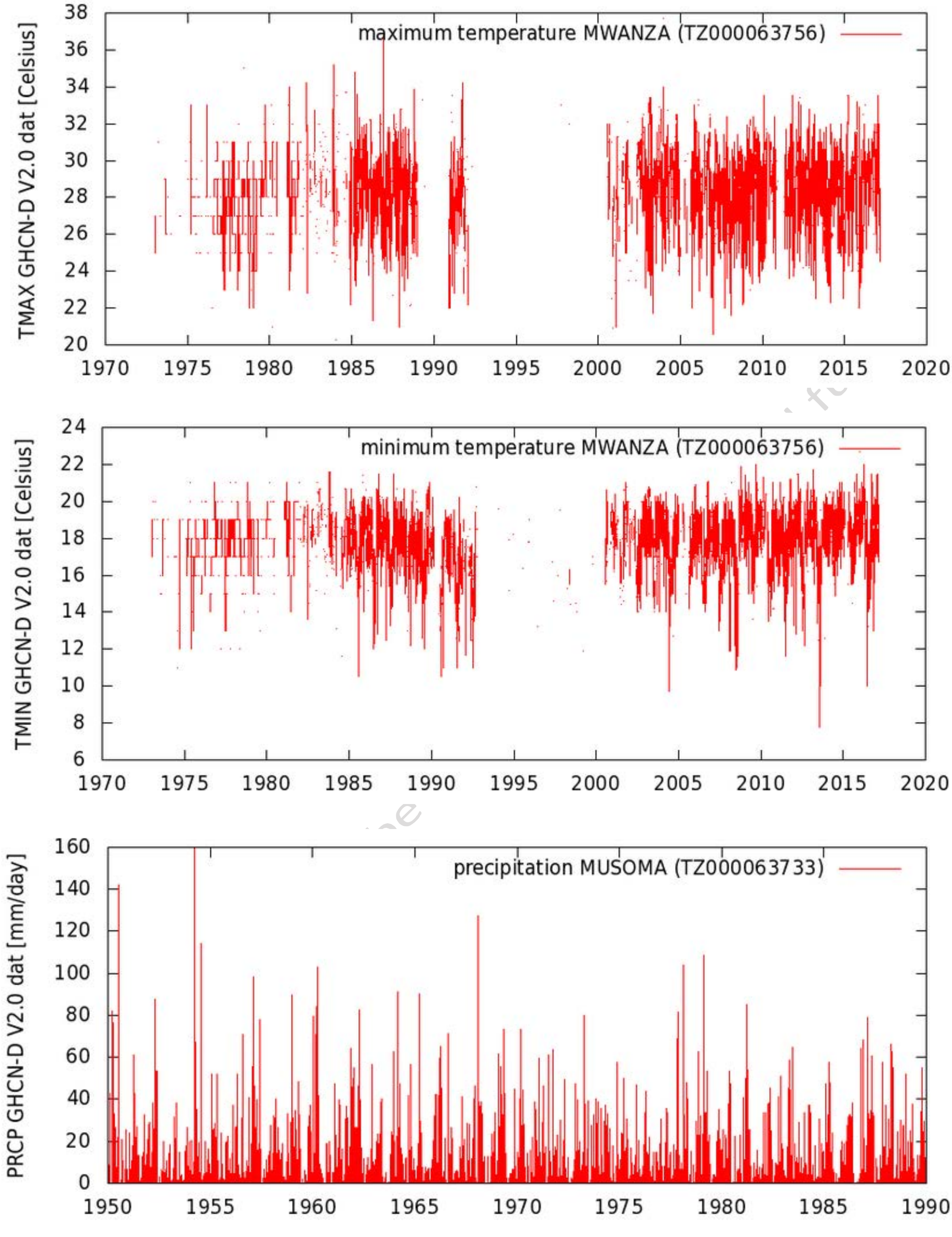

Figure 14: Time series of daily values at Musoma. Daily maximum temperature (top panel), daily minimum temperature (middle panel) and daily mean rainfall (bottom panel). GHCN-D v2 data obtained from the Climate Explorer.

The weather station records obtained from the Serengeti Savannah Dynamics Project just provide a snapshot of the local climates at different locations in the Serengeti National Park (Figure 15 and 16). They cannot be used to calculate a climatological means or extremes and they also do not provide any information on how the local climates have changed over time. What they do highlight is the spatial differences in the climate across the park. It is important to recognise that the results for this very short period may not be representative of the long-term climate and any messages taken from this analysis are at best tentative.

The lowest elevation station (Ikoma Gate) has the warmest climate, while the highest elevation stations (Naabi and Soit) have the coolest climates. The temperatures at all stations appear to track one another which suggest that the large-scale and local forcing at each station are the similar and that the differences are primarily due to variations in altitude.

Rainfall shows stronger spatial differences across the park. All stations show minimum rainfall during June- August season, but they vary on the rainfall amounts during the remainder of the year. The Simiyu station, which is located in the south, did not display the peak associated with the short rains in November-December in either of the two years, and the monthly totals are generally lower than all the other stations. The two most northern stations, Ikoma Gate and Kifaru, generally display the highest rainfall totals of the stations.

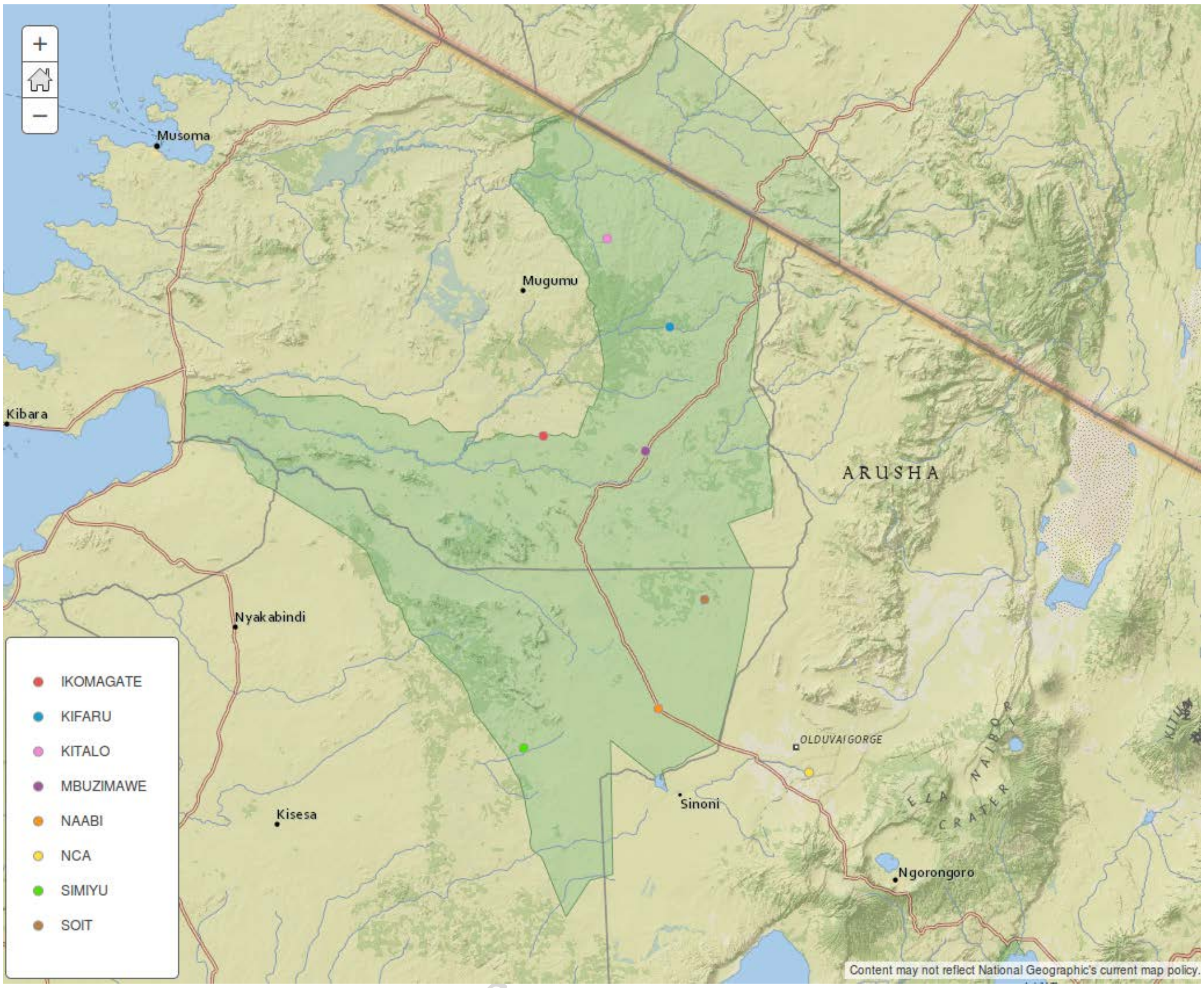

Figure 15: Spatial map showing the extent of the Serengeti National Park and the location of the automatic weather stations from the Serengeti Savanna Dynamics Project

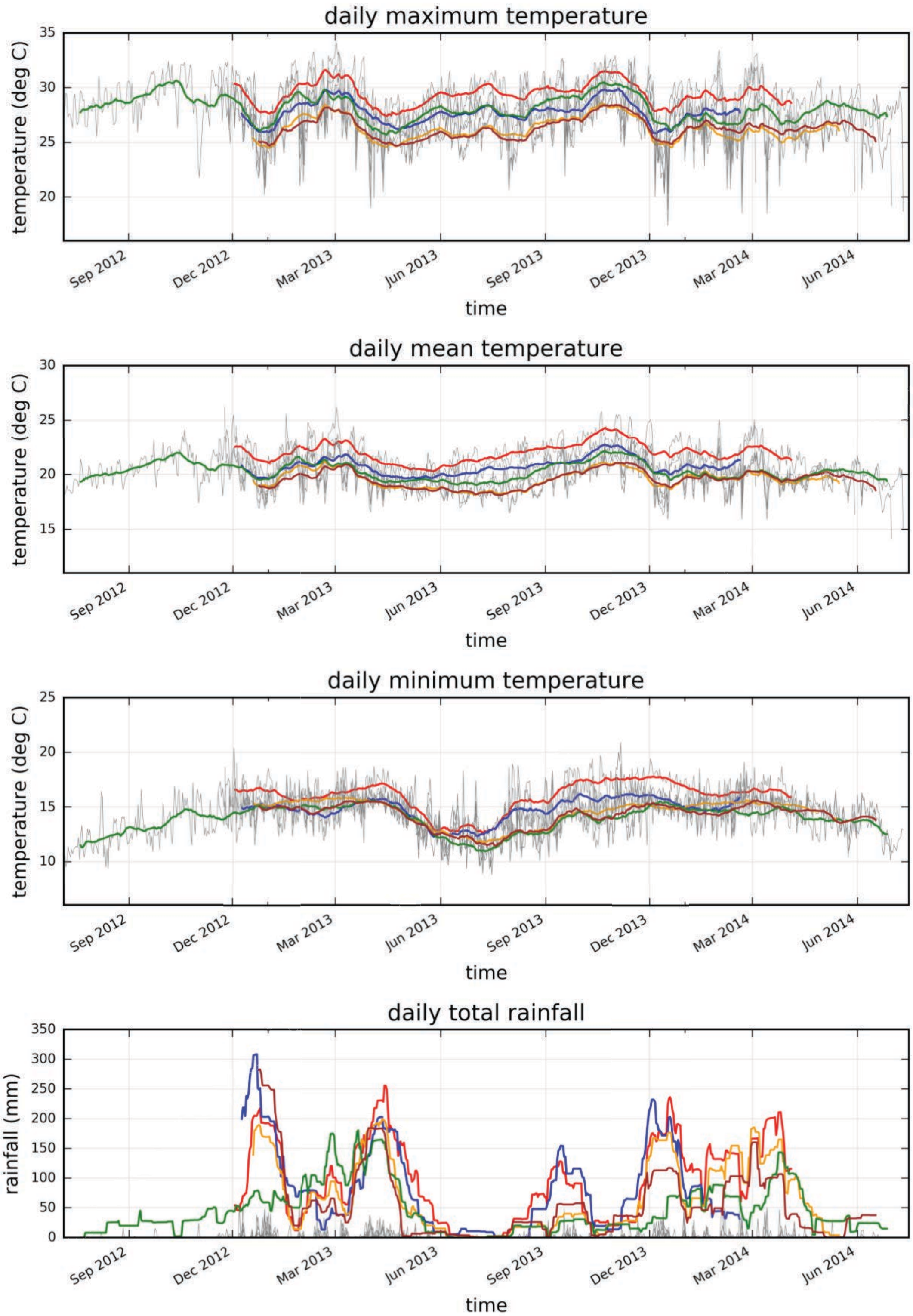

Figure 16: Time series of daily maximum, mean and minimum temperature and rainfall for 5 stations within the Serengeti National Park. Daily values shown in grey, coloured lines show the 30-day running mean for temperature and the 30-day running total for rainfall (line colours are same as those used in Figure 2 above. Ikoma gate – red, Kifaru- blue, Naabi – orange, Simiyu – green, Soit - brown)

Climate projections

This section presents the future climate for the Serengeti National park, 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 annual and seasonally averaged daily maximum, minimum and mean temperatures and total rainfall under two different emission scenarios; the moderate RCP4.5 scenario and the more extreme RCP 8.5 emission scenario. Results presented in this report are just a subset of those produced by the analysis and focus on the more extreme, and arguably more realistic, RCP 8.5 emission scenario.

Global Climate Model projections

Figure 17 and 18 present the projected change in maximum and minimum temperature over the larger region by the end of the century under the RCP8.5 emissions scenario. The results show that the projected changes in temperatures 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. Generally, the intermodal spread in temperature is larger than the spatial variability within a model. This is primarily due to the very coarse scale of these models, which limits their usefulness at representing any regional or local scale climate messages.

The future projections for rainfall are less confident than for temperature, most models do project a wetting into the future over the Serengeti area, but the magnitude of the change varies between models and is not statistically different from that seen in the interannual variability during the historical period in a number of models (figure 19). Rainfall over this region is highly heterogeneous and the spatial scales of the models limit their usefulness in providing the regional or local representation of the large scale climate signal.

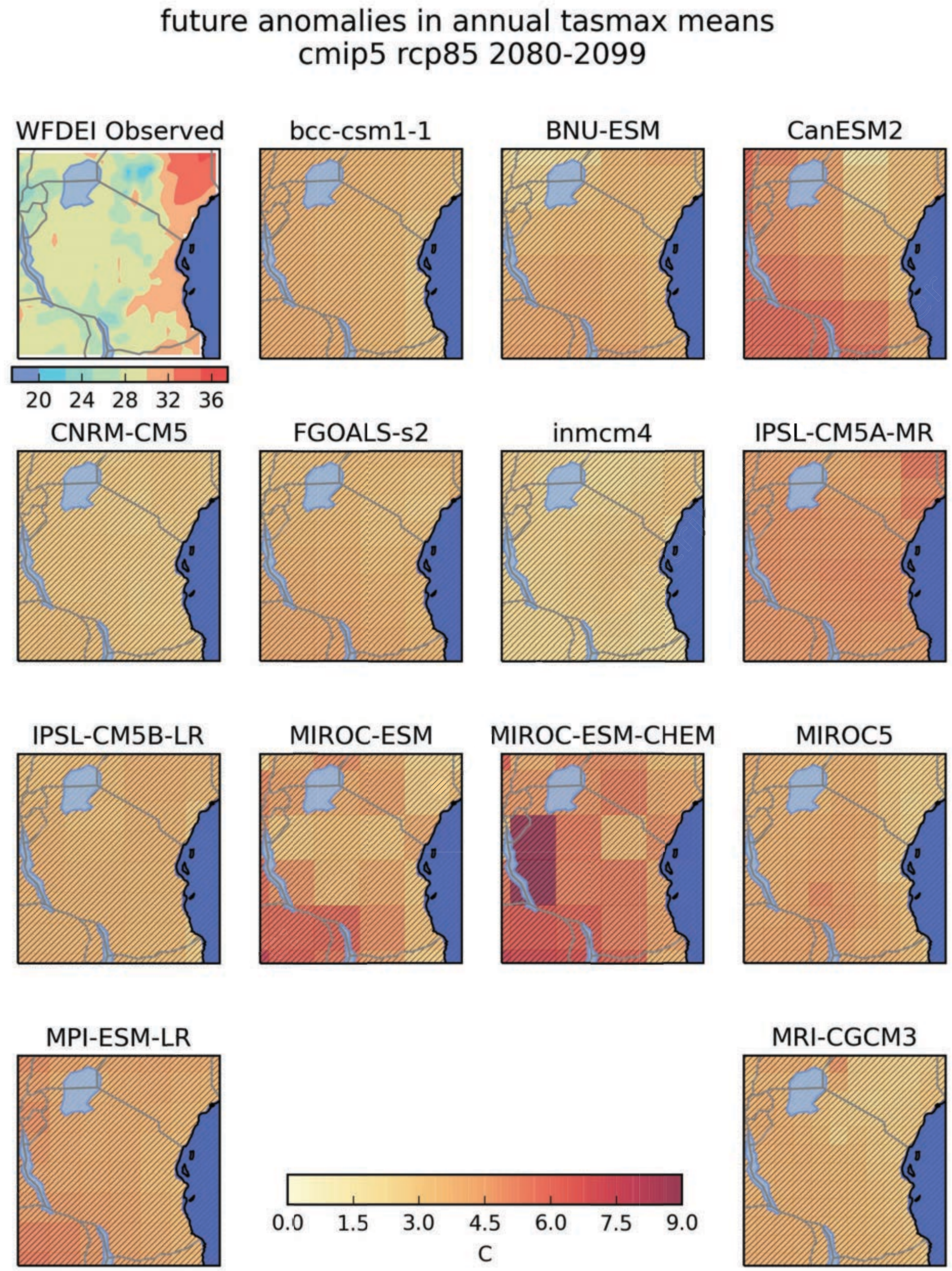

Figure 17: CMIP5 projected change in annual mean daily maximum temperature by the end of the century under the RCP 8.5 emission scenario. Change presented as the difference between the future period 2080-2099 and the historical period 1986-2005. Stippling shows where the change is statistically significant. The top left panel presents the observed historical climatology from the WFDEI dataset.

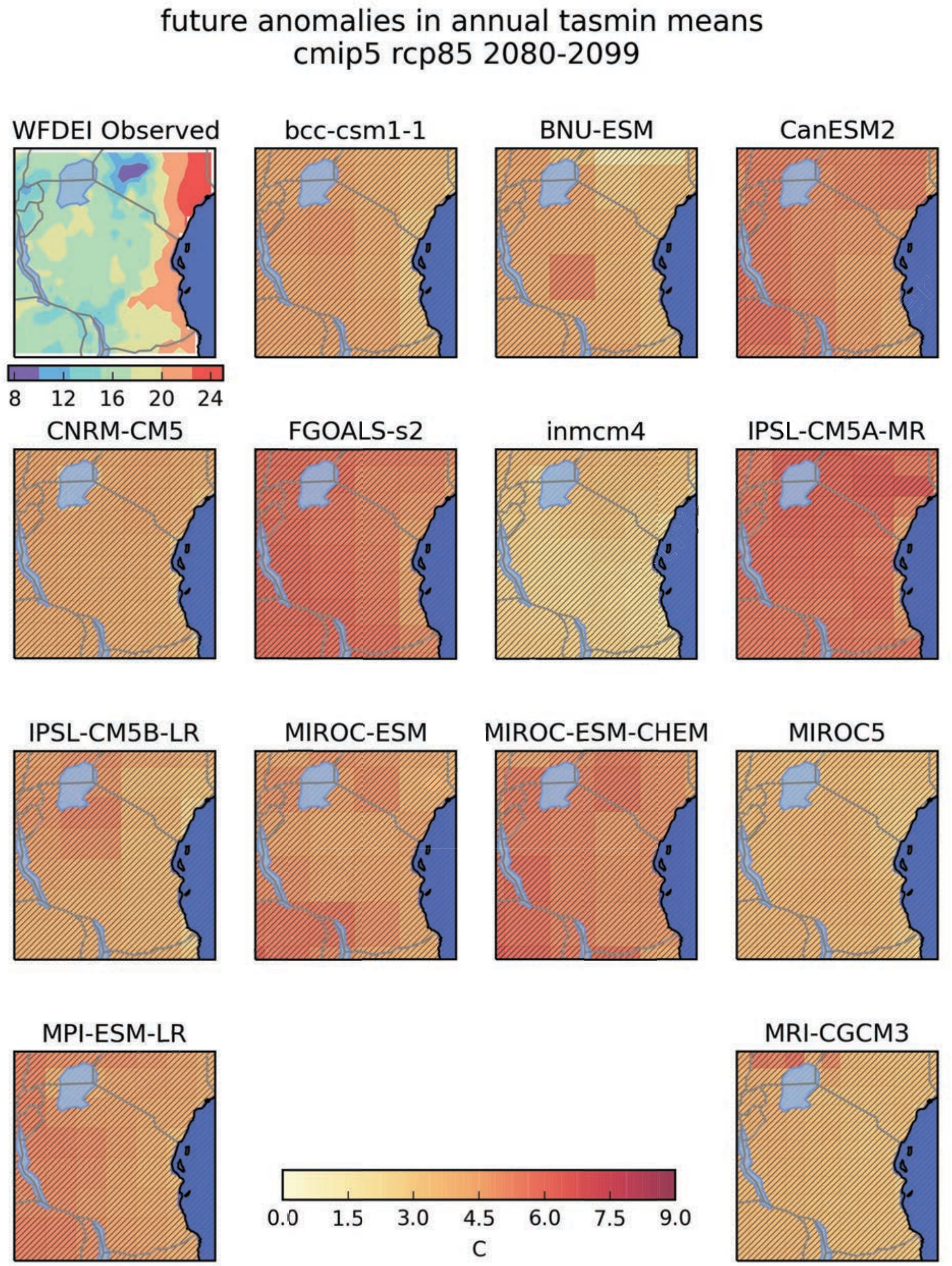

Figure 18: CMIP5 projected change in annual mean daily minimum temperature by the end of the century under the RCP 8.5 emission scenario. Change presented as the difference between the future period 2080-2099 and the historical period 1986-2005. Stippling shows where the change is statistically significant. The top left panel presents the observed historical climatology from the WFDEI dataset.

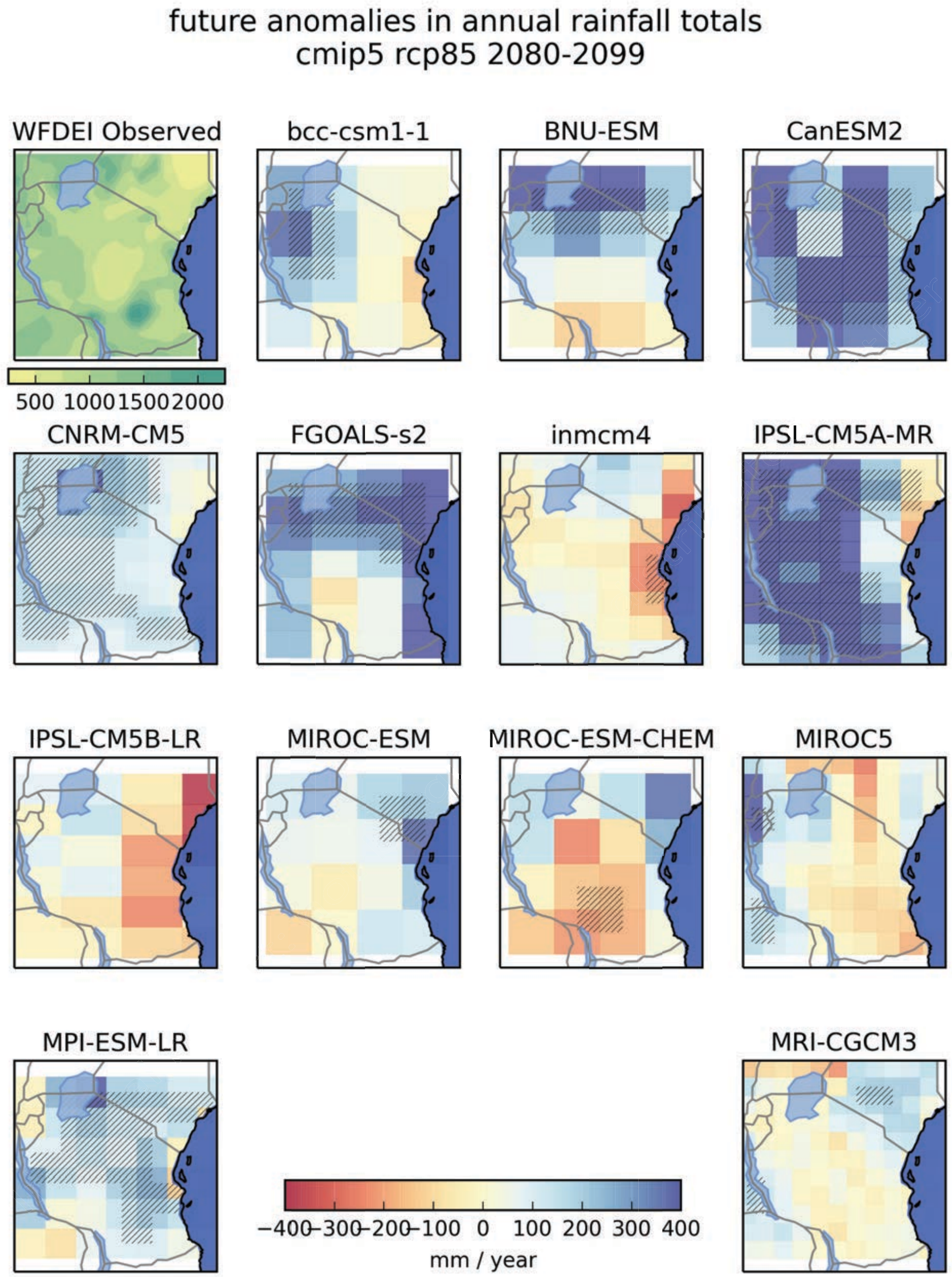

Figure 19: CMIP5 projected change in annual mean total rainfall by the end of the century under the RCP 8.5 emission scenario. Change presented as the difference between the future period 2080-2099 and the historical period 1986-2005. Stippling shows where the change is statistically significant. The top left panel presents the observed historical climatology from the WFDEI dataset.

Statistically downscale projections

Figure 20-23 present the projected time evolution of seasonal mean daily maximum, mean and minimum temperature respectively over the Serengeti National Park for 11 models under the RCP8.5. These results support the findings seen in the raw GCMs that the daily temperatures 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. Some models do appear to group according to more / less severe warming especially by the end of the century. Focussing on daily mean temperature (Figure 21), the current climate is simulated to be around 20.5 – 22.5° depending on the season, and is project to increase to between 24 – 28° C by the end of the century, depending on the season and on the model selected. This suggests that even with the strong anthropogenic warming, the climate within the Serengeti will not exceed the upper threshold of the ideal temperature range for tsetse flies by the end of the century.

The downscaled projections of annual total rainfall over the larger area (Figure 25) generally agree with those found in the GCM analysis. Most models project an increase in rainfall over the Serengeti National Park, but now the change in most models is statistically different from the historic natural variability. The strongest wetting is generally located to the north of the park, with a consistent drying change projected along the coast and to the south-east. There is still very large disagreement in the magnitude of change, which varies from very slight drying to an increase in rainfall of up over 400mm/year. Looking specifically at the Serengeti National Park at the seasonal time-scale (figure 26), it is clear that with the exception of the June – August season, many of the models project a statistically significant change in rainfall long before the end of the century especially during the DJF and SON seasons.

Figure 27 displays the mean climatology for the last two decades of the 21^{st} Century and shows that all models project that the spatial pattern will not change dramatically, but that the relatively uniform increase in temperature will shift the climate so that the full region will be between 18 and 34° C. The projected increase in temperature will change the frequency of days with daily mean temperatures between 16 and 32° C (Figure 28). The results project an increase in frequency over the Kenyan highlands and a decrease over the north-east parts of Kenya, but little change over the rest of the region. This change in the frequency of days between 16 - 32° C may result in the climate over the Kenyan highlands becoming more favourable for tsetse flies, but is insufficient to shift the climate over the rest of the study area outside the temperature range by the end of the century, even under this more extreme RCP 8.5 scenario (Figure 29).

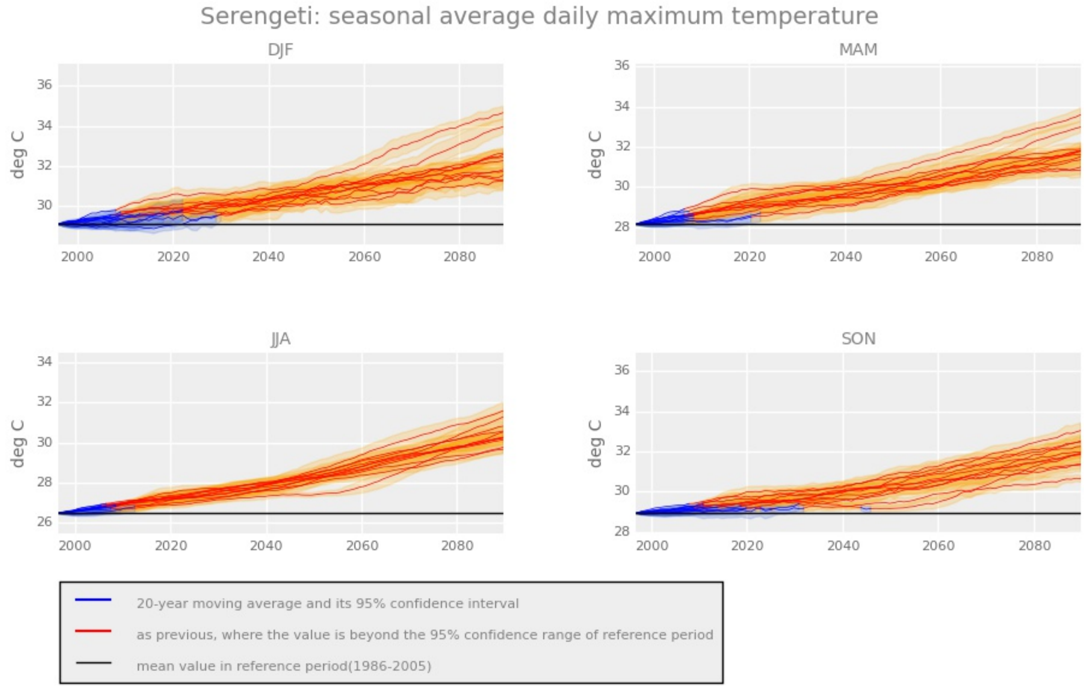

Figure 20: SOMD projected changes in seasonal mean daily maximum temperature under the RCP 8.5 concentration pathway for the gridcell centred on the Serengeti. The black line shows the multi-model mean values across all models in the reference period 1986-2005. The coloured lines show the 20-year moving average of results from each model and the shading around each line shows the 95% confidence range around the model mean. Where the line and associated shading changes from blue to orange indicates where the 20-year running mean moves outside the 95% confidence range of the reference period.

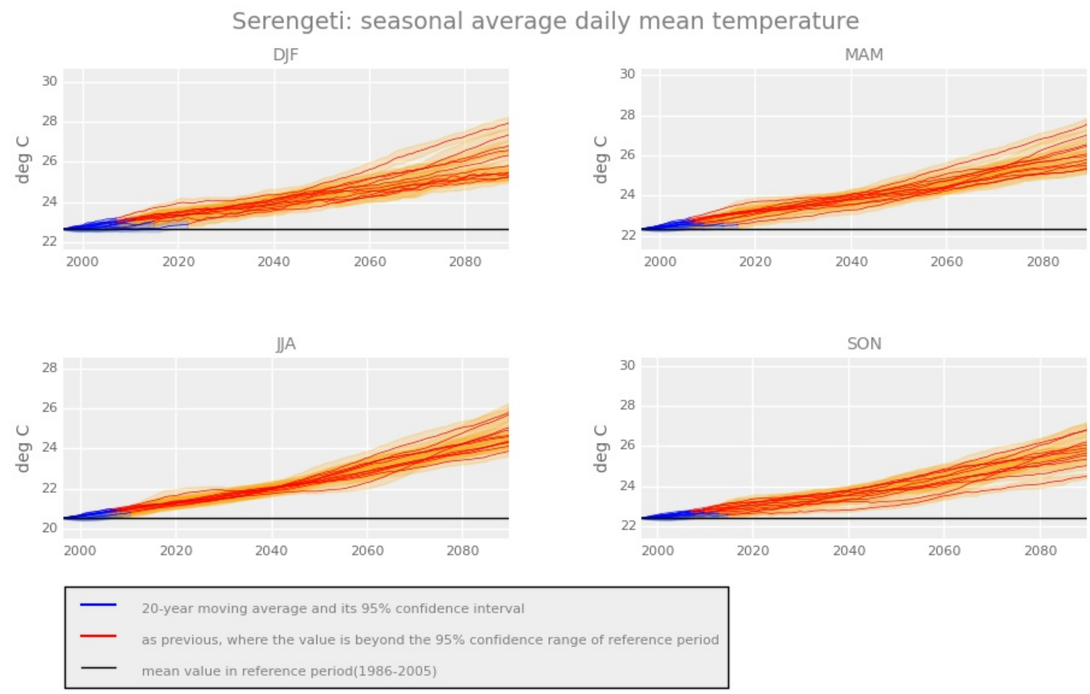

Figure 21: Figure 22: SOMD projected changes in seasonal mean daily mean temperature under the RCP 8.5 concentration pathway for the gridcell centred on the Serengeti.

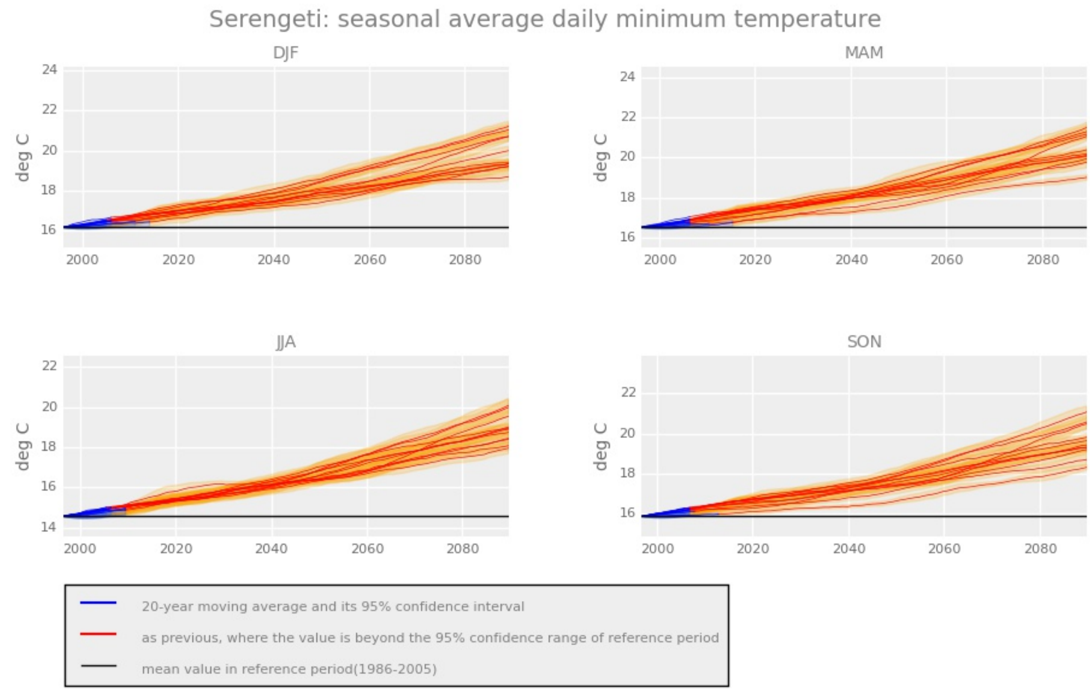

Figure 23: Figure 24: SOMD projected changes in seasonal mean daily minimum temperature under the RCP 8.5 concentration pathway for the gridcell centred on the Serengeti.

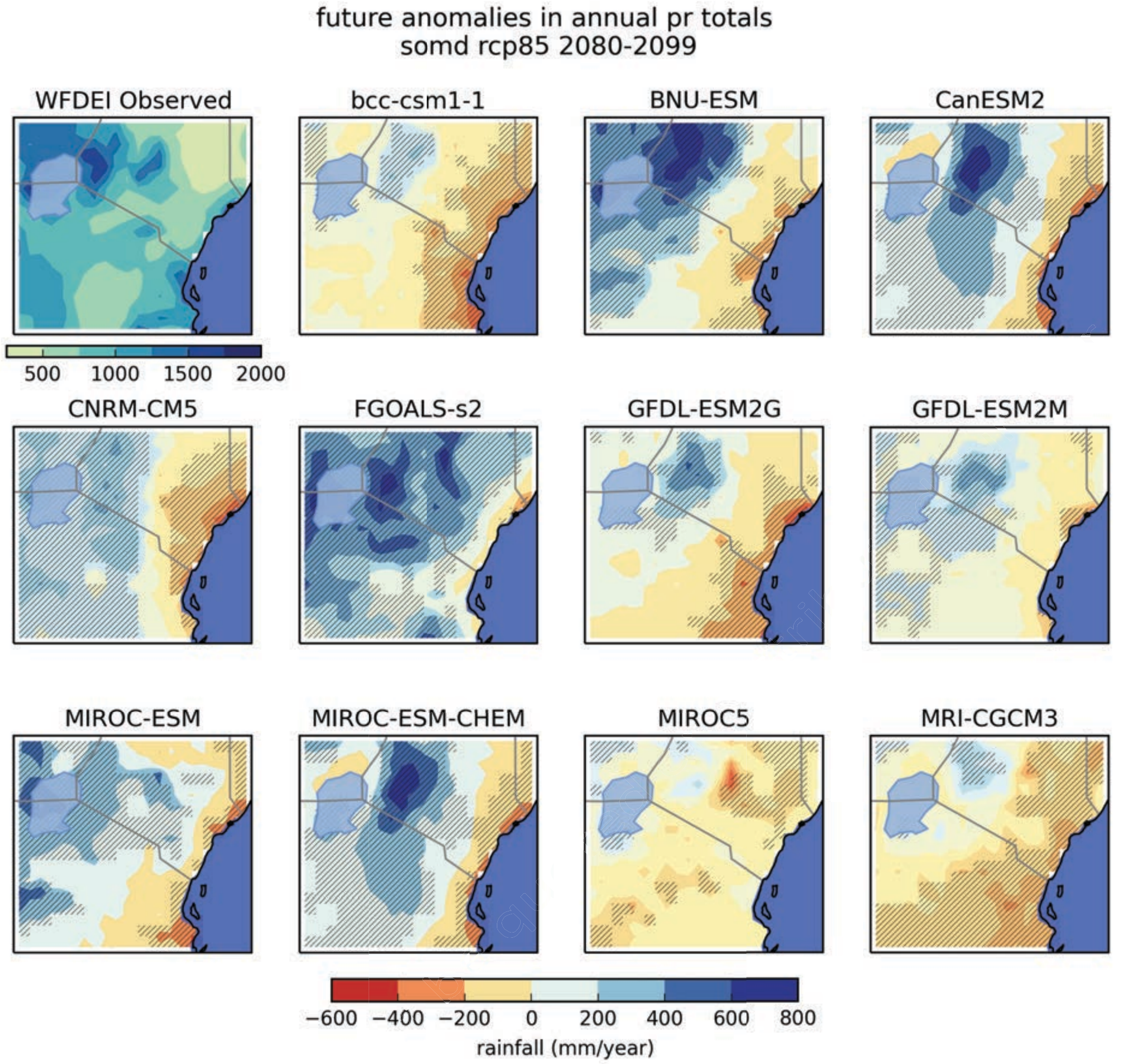

Figure 25: SOMD projected change in annual total rainfall by the end of the century under the RCP 8.5 emission scenario. Change presented as the difference between the future period 2080-2099 and the historical period 1986-2005. Stippling shows where the change is statistically significant. The top left panel presents the observed historical climatology from the WFDEI dataset.

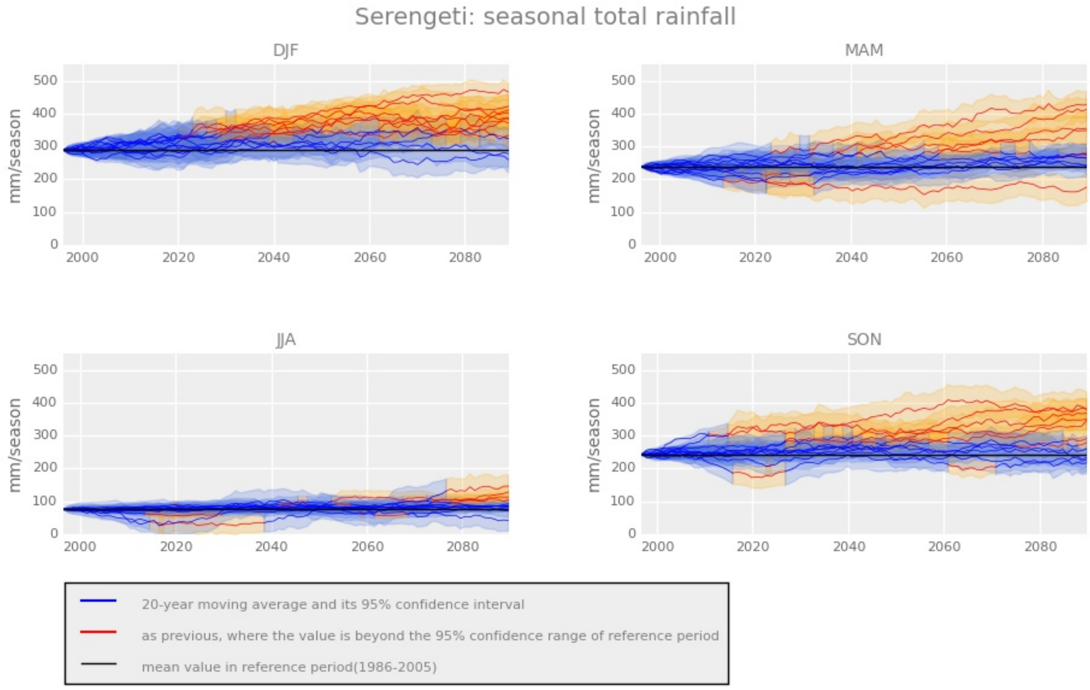

Figure 26: SOMD projected changes in seasonal total rainfall under the RCP 8.5 concentration pathway for the gridcell centred on the Serengeti.

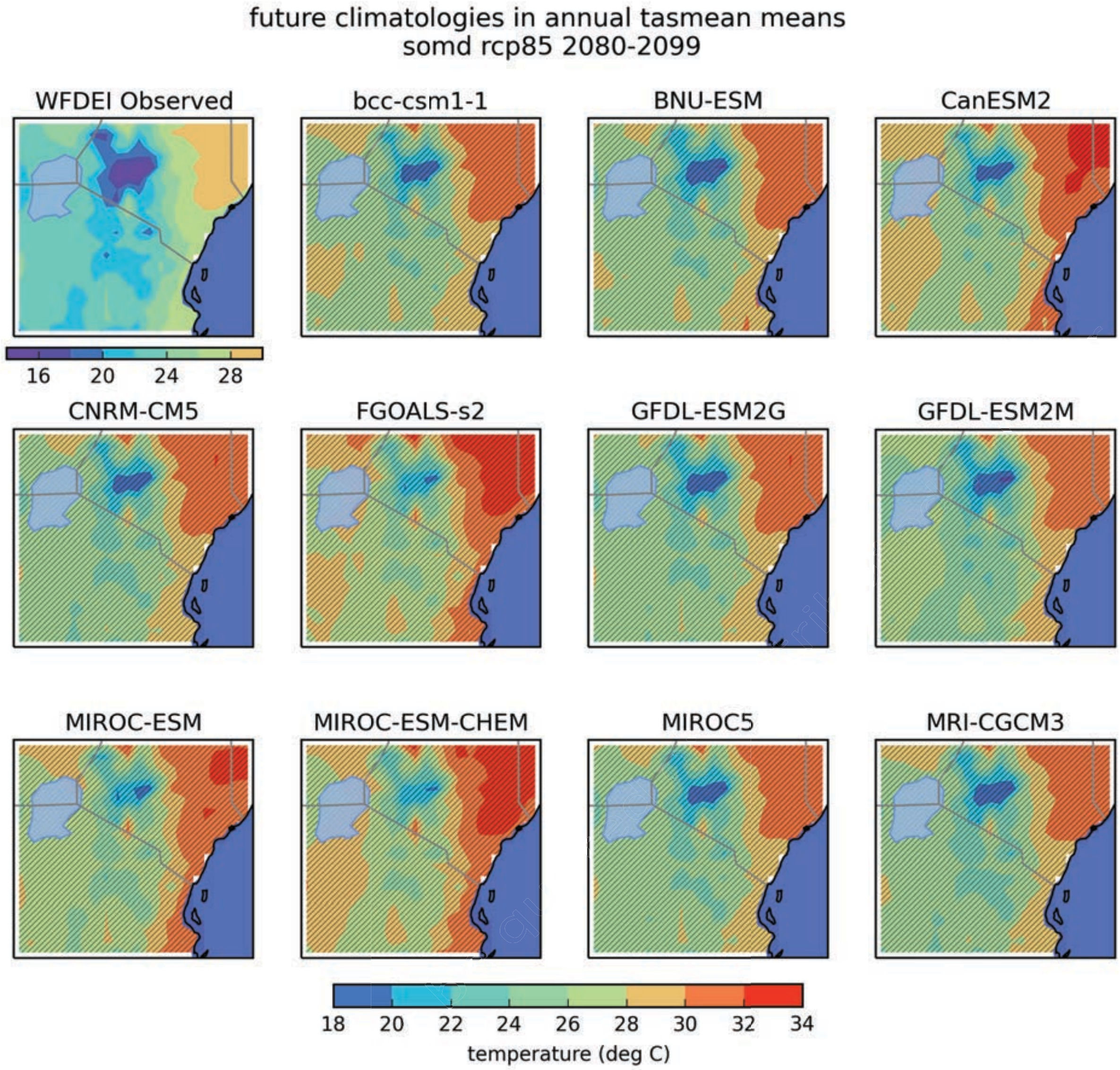

Figure 27: SOMD projected climatology daily mean temperatures by the end of the century under the RCP 8.5 emission scenario. Climatology presented as the mean for the future period 2080-2099. Stippling shows where the change between this period and the historical period is statistically significant. The top left panel presents the observed historical climatology from the WFDEI dataset.

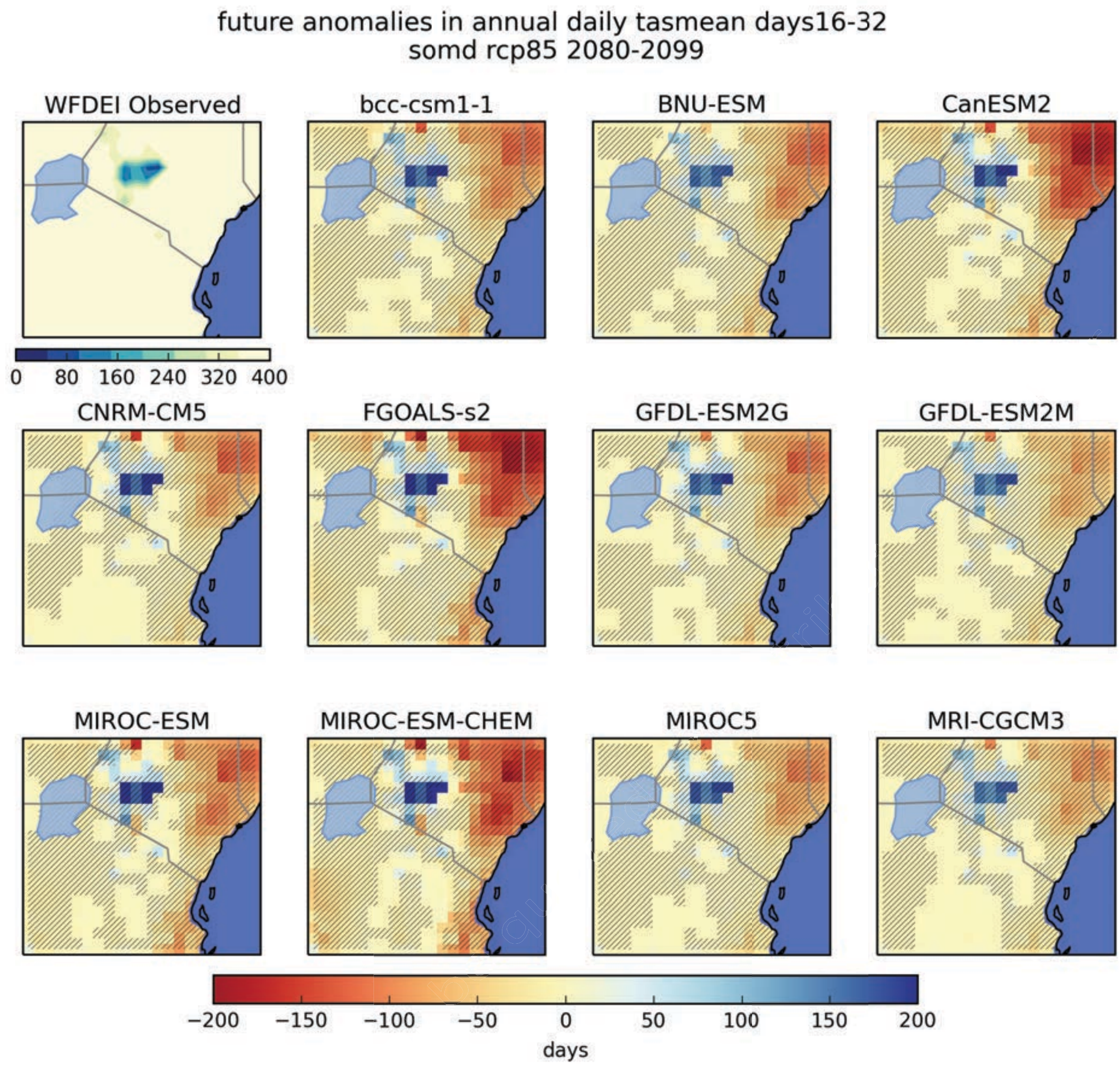

Figure 28: SOMD projected change in annual frequency of mean temperatures between 16 - 32°C by the end of the century under the RCP 8.5 emission scenario. Change presented as the difference between the future period 2080-2099 and the historical period 1986-2005. Stippling shows where the change is statistically significant. The top left panel presents the observed historical climatology from the WFDEI dataset.

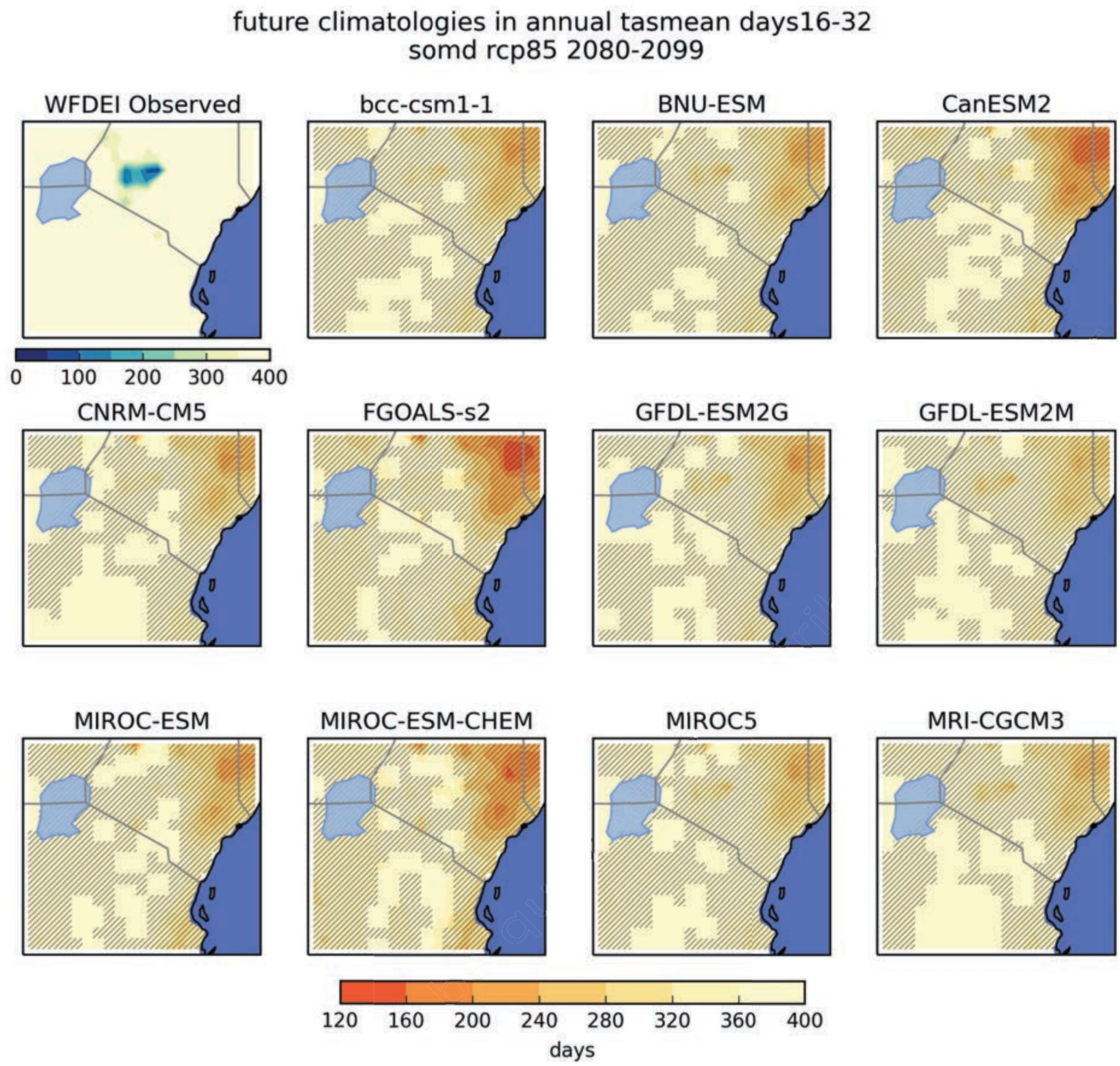

Figure 29: SOMD projected climatology in the number of days with mean temperatures between 16-32° C by the end of the century under the RCP 8.5 emission scenario. Climatology presented as the mean for the future period 2080-2099. Stippling shows where the change between this period and the historical period is statistically significant. The top left panel presents the observed historical climatology from the WFDEI dataset.

Discussion and Conclusion

This analysis explores the historic variability in the climate of the Serengeti and how it is projected to change into the future due to anthropogenic climate change. The Serengeti National Park is situated at roughly 1500 m above sea level. The park is bounded by a number of other protected areas, most notably the Maasai Mara National Park in Kenya, and the Ngorongoro Conservation area to the east. Two tsetse fly species are found in this region, *Glossina swynnertoni* and *Glossina pallidipes.* However their distributions are quite different with *G swynnertoni* being the most common species within the park and at other higher elevation areas, while the distribution of *G pallidipes* is limited to lower elevation areas in and around the park.

This analysis of the Serengeti climate was hindered by a lack of suitable climate data. The only free and publically available station record within the areas was of such low quality that little could be done with it. This record was supplemented with five very short records from the Serengeti Savannah Dynamics Project, which provided some spatial information across the park, but the records were too short to determine any climatic mean or extremes and obviously could not be used for any trend analysis. The most promising dataset was the TMA maproom dataset, which is a very high resolution blended station and reanalysis dataset at dekad or monthly timescale. Unfortunately all attempts to gain access to this data proved futile and we had to rely on the basic online monthly climatology maps. In the end, much of the historical analysis relied on the very coarse resolution (~50km) WFDEI dataset. Thankfully each dataset adds something to the analysis and it is possible to weave the results together to obtain a relatively good understanding of the climate of this region.

The Serengeti is classified as having a tropical savannah climate. The daily maximum and minimum temperatures average around 29° C and 15° C and therefore these is a diurnal cycle is roughly 14°, which is much larger than the season variability of minimum and maximum temperatures which are only around 3° C. The daily mean temperatures over the region are within the ideal temperature range for tsetse flies (16 - 32° C) throughout the year, with the exception of the high mountainous and the Kenyan highlands. Rainfall is distributed through the year primarily in two rainy seasons; the short rains in November and December and the long rains from March to May, but, rainfall does also occur during January and February months. The rainfall is generally convective in nature and associated with the seasonal migration of the Intertropical Convergence Zone (ITCZ) over the region. There is some suggestion of an increasing trend in temperature in the recent past, but no trend is evident in the rainfall record which is dominated by strong interannual variability.

There is some consensus between Global Climate that the climate over the Serengeti is projected to get wetter into the future, and this is supported by the downscaled climate change projections. The models do not agree on the magnitude of the change, with some models projecting no significant change while others project extreme wetting by the end of the century. Models also agree that it will get warmer into the future and this warming will result in the climate shifting outside of the historical range of natural variability within the next few decades. 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 even the warmest model run is not sufficient to shift the climate beyond the ideal temperature range for tsetse flies, but it may be sufficient to allow tsetse flies to invade higher elevation areas like the Kenyan highlands.

Acknowledgements

We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modelling groups (listed in Table 4 of this report) for producing and making available their model output. For CMIP the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals

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