Ecosystem-based Adaptation for Rural Resilience in Tanzania: Vulnerability and Impact Assessment

Climate Projections Report

UNIQUE forestry and land use

Ecosystem-based Adaptation for Rural Resilience in Tanzania: Vulnerability and Impact Assessment

Climate Projections Report

Client

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LIST OF ABBREVIATIONS

AOGCM	Atmospheric-Ocean Coupled Global Climatic Model
ARI	Average Recurrence Interval (aka 'return period')
BAU	'Business as Usual' (climate trends assuming no or minimal mitigation)
CMIP-5/6	Computer Model Inter-comparison Project, Generations 5 and 6.
COP25	Conference of the Parties (25th UN climate Change Conference, 2019)
EbARR	Ecosystem-based Adaptation for Rural Resilience (in Tanzania)
ECS	Equilibrium Climate Sensitivity
EIA	Environmental Impact Assessment
(E)VI	(Environmental) Vulnerability Index
GCMs	Global Climatic Model, generally an abbreviation of AOGCM
GHG	Greenhouse Gas(es)
IAV(%)	Inter-Annual Variability (usually precipitation)
IOD	Indian Ocean Dipole
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter-Tropical Convergence Zone
MAR	Mean Annual Rainfall
mamsl	metres above mean sea level
MAT	Mean Annual Temperature
NOAA	National Oceanographic and Atmospheric Administration (USA)
RCP	Representative Concentration Pathways
RH	Relative Humidity
RGMs	Regional Climatic Models
SRES	IPCC's Special Report Emissions Scenarios
SSTs	Sea Surface Temperatures
UNFCCC	United Nations Framework Convention on Climate Change
WBCCKP	World Bank Climate Change Knowledge Portal
WMO	World Meteorological Organization

SUMMARY

There is no longer any rational scope for 'climate-change skepticism'. Tanzania is sufficiently tropical that it will not suffer the extreme temperature changes expected in higher-latitude regions. Nevertheless, changes in temperature (air and water), rainfall (seasons, frequency and intensity), humidity, wind, evaporation, soil moisture and other parameters will have far-reaching consequences. Projections of evidence-based historic climate trends are valid for only one to two decades. Modelling projections are only calculated to the end of this century, and carry considerable uncertainties, especially beyond mid-century. The greatest uncertainty arises from the currently indeterminate human-induced greenhouse gas (GHGs) emissions. It must be appreciated that climate change will not stop at 2099. Thermodynamic inertia in the global climatic system will result in continued change for several centuries to come.

This climate assessment uses temperature, rainfall, and potential evapotranspiration as the dominant controlling factors for future planning. Temperature projections are very robust. Rainfall and ET_0 are less accurate because they compound more uncertainties. **Mean annual temperatures are expected to increase by between 0.9 and 1.3°C by mid-century, and by 1.8 to 2.4°C by the end of this century. Rainfall is expected to increase by between about 20 and 40 mm per year by mid-century, and by about 30 to 90 mm per year by the end of century.** This report exercises caution in assessment of rainfall because the variability (*not* average conditions) of rainfall determines viability of agriculture, livestock farming, etc. At present there is no reliable methodology for assessing future rainfall variability. Nevertheless, the variability of extreme rainfall, both in terms of flood and drought, will certainly increase towards the end of this century, possibly dramatically so.

Rainfall patterns will change. Rainstorms in Tanzania are associated with the annual migration of the inter-tropical convergence zone, causing a bimodal rainy season in the north, and a unimodal rainy season in the south. The timing and broad location of the ITCZ is unlikely to change. However, the nature of rainstorm generation will change, resulting in fewer but more intense rainstorms during the rainy season(s).

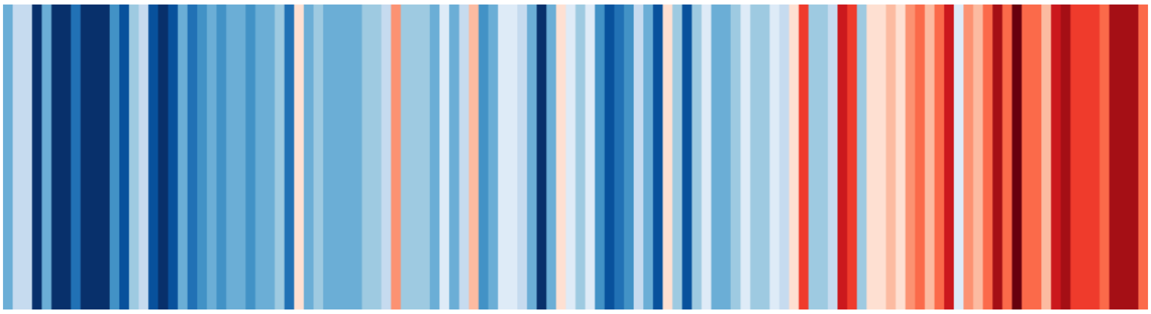
Reference Potential Evapotranspiration, 'ET_0' is the notional combination of evaporation and transpiration that would occur in exposed grassland under non-limiting conditions of moisture availability. Values in Tanzania currently vary between about 4.0 ± 0.9 and 5.0 ± 0.5. These values are expected to rise by up to 6% by mid-century, and by up to 12% by end of century. Moreover, this implied increase in crop-water requirements will coincide with higher crop-stresses, reduced soil-moisture retention, and reduced water resources availability. This combination of changed circumstances will tip some cropped areas and pasture across the threshold from viable to non-viable, and hence will require major socio-economic planned changes. Other factors and parameters are discussed or illustrated within the main report, for each of the five project regions of Zanzibar, Morogoro, Dodoma, Shinyanga and Manyara.

Zanzibar is a 'special case' because its climate is dominated by sea-surface temperatures. These SSTs are influenced by both climate change and by a quasi-decadal temperature oscillation between the western and eastern parts of the Indian Ocean. This oscillation is unrelated to climate change. Currently, it has greater influence upon Zanzibar's temperatures than global warming, but the relative importance is expected to change throughout this century.

1 INTRODUCTION: GLOBAL WARMING IN THE CONTEXT OF TANZANIA

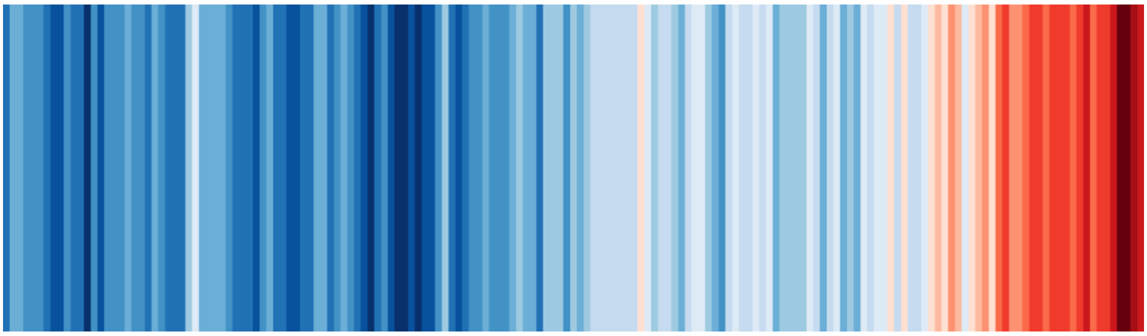
The country-wide and global mean annual temperatures are depicted visually in Figure 1 and Figure 2 respectively. In these diagrams, each vertical stripe represents the average temperature of that year, in which white is the overall mean, whilst progressively darker colors indicate progressively larger deviations from the mean. I.e. Blue = colder, Red = warmer.

Figure 1: Color-Coded Mean Temperature Change Spectra (Tanzania)



Tanzania MAT temperature change, 1901 to 2018: dark blue -1.5°C, dark red +1.5°C

Figure 2: Color-Coded Mean Temperature Change Spectra (Global)



Global average temperature change, 1901 to 2018: dark blue -1.5°C, dark red +1.5°C

Source: Berkeley Earth, NOAA, UK Met Office, MeteoSwiss, DWD. Graphics: Ed Hawkins, UoR, NCAR.

Three features in these two figures are immediately obvious. Firstly, whichever part of the time-series is considered, there are inter-annual fluctuations, or ‘anomalies’, which skew the short-term data, and which may even contradict the long-term trend. These anomalies are primarily driven by quasi-cyclic variations in sea surface temperatures (SSTs). In the case of Tanzania, the primary control is therefore SSTs in the Western Indian Ocean.

Secondly, notwithstanding short-term anomalies, there is an obvious temperature gradient over nearly 12 decades, with the most rapid positive temperature gradient since about the year 2000. The rate and gradient of this temperature change is very strongly validated.

Thirdly, and somewhat surprisingly - given its equatorial geography - the **temporal temperature change in Tanzania has exceeded that of the global average**. It is strongly suspected that this temporal temperature trend is related to the Indian Ocean Dipole (IOD), **an east-west temperature gradient which has, particularly in the last decade, resulted in exceptional warming of SSTs along the Tanzanian coastline**, which in turn strongly impacts the local synoptic conditions

An additional significant factor is the subtle changes in the annual oscillation of the inter-tropical convergence zone (ITCZ), and associated storm instability. The ITCZ is a feature of the Earth's obliquity, reaching a maximum southerly extent of 14°S to 16°S, in January, and a maximum northerly extent, of about 14°N in July. Associated rains may lag these solstice positions by a month or two. The ITCZ is essentially a low-pressure belt which generates tropical cloud and rain in a belt around the globe. Historically, the latitudinal amplitude of this oscillation is higher in East Africa than anywhere else on the planet; which is a function of the oceanic-continental distribution. The south-westerly half of Tanzania lies at or near the southernmost limit of the ITCZ, and hence there is only one main rainy season. Of the EbARR sub-project areas, only Dodoma and (perhaps Mpwapwa) lie in this unimodal rainfall region. All the other stations in north, central and northeast Tanzania are swept twice a year, by the ITCZ's southward and northward migration, and hence tend to approximate a more bimodal rainfall distribution.

Both historic satellite imagery and modelling of the ITCZ throughout this century, to 2100, indicates that climate change will not significantly affect the seasonal *location* of the ITCZ, but it *will* cause a narrowing and weakening of the ITCZ-associated cloud belt. This, combined with warmer air temperatures and disproportionate warming of the West Indian Ocean Dipole (IOD) will certainly change the rainfall patterns. There are expected to be fewer rainy days, combined with more intense rainstorms, which will have implications for water resources management, soil erosion and flood management.

Detailed projection of the ITCZ's future behavior is a subject of extensive contemporary research. Only its generalized features are currently well understood, and hence some caution must be exercised in interpreting current climate-model results regarding rainfall at specific locations.

2 METHODOLOGY

2.1 Climate-change Projections: Strengths and Weaknesses

There are two approaches to forward projections of the climate for planning purposes. The most widespread and data-intensive method is to run 'hindcast calibrated' atmospheric-ocean-coupled global climatic models, a.k.a. 'AOGCMs' or just 'GCMs'. The second method is to extrapolate trends from evidence-based field instrumentation from hydro-meteorological, synoptic and climatic stations. Both approaches have strengths and weaknesses. In this study the approach is, wherever possible, to utilize both methods. As in every country, the meteorological netzwork tends to be concentrated in relatively low-elevation heavily populated areas, in which the time-series of data typically spans some four to six decades. This is barely sufficient to estimate a pre-climate change baseline, and to discern distinct climate-change trends since about 1990.

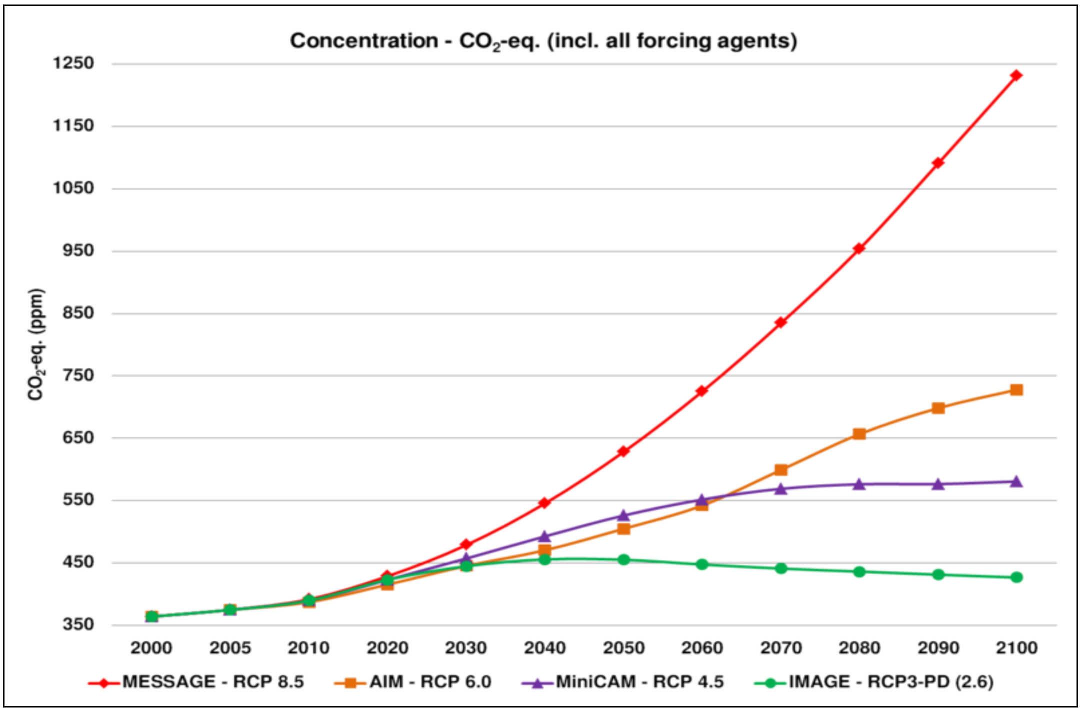
AOGCMs are essentially multi-layered spatially distributed solutions to a 'force and continuity' equation (*i.e.* the 'Navier-Stokes equation'), which seems to work reasonably well in projecting future temperatures, even though the subtleties of the equation are still not well understood. AOGCMs are limited in their scope because their parameterization procedures are necessarily simplifications of highly variable small-scale processes. Put simply, empirical evidence confirms that they are good at hindcasts and projections of temperature in terms of temperature trends. On the other hand, they were never designed for water resources work, even though that is how they are often used. AOGCMs are *not* strong in projecting rainfall, wind, humidity, soil-moisture, evapo-transpiration and other hydrology-related factors, a point which must be consistently kept in mind when considering the results of this report.

2.2 Choice of Carbon Emissions Scenario

All of the climate models used in this study are critically sensitive to future projections of GHG emissions, and in particular to the evolving atmospheric carbon dioxide in the atmosphere over the remaining century. Current scientific convention is to model climate projections upon the basis of four representative carbon pathways (RCPs). These are **RCPs 2.6, 4.5, 6.0 and 8.5**, in which the numbers indicate the range of radiative forcing values in the year 2100, relative to pre-industrial values, namely +2.6, +4.5, +6.0, and +8.5 W.m^{-2}, respectively. These RCPs supersede the SRES projections of 2000 (A1B, B1, B2, etc.). The CO_2 equivalent of GHG projections for all four scenarios is shown inFigure 3.

RCP 2.6 assumes that carbon emissions peak before 2025, and then decrease rapidly thereafter. That is, in order to achieve the RCP 2.6 pathway, the smoothed gradient of Figure 4 has to change from strongly positive to strongly negative within the next few years. As of mid-2019, this is clearly an impossible scenario. Indeed, there is no indication that the rate of increasing carbon emissions is slowing down, let alone decreasing. That is, there is still no flattening of the graph shown in the time-series shown in Figure 4. Therefore, in this assessment RCP 2.6, and consequently the target set by the 'Paris Accord', is ignored on the basis that it is effectively unachievable. Figure 4 is current to December 2018. For current updates, see the following: http://www.esrl.noaa.gov/gmd/ccgg/trends/full.html.

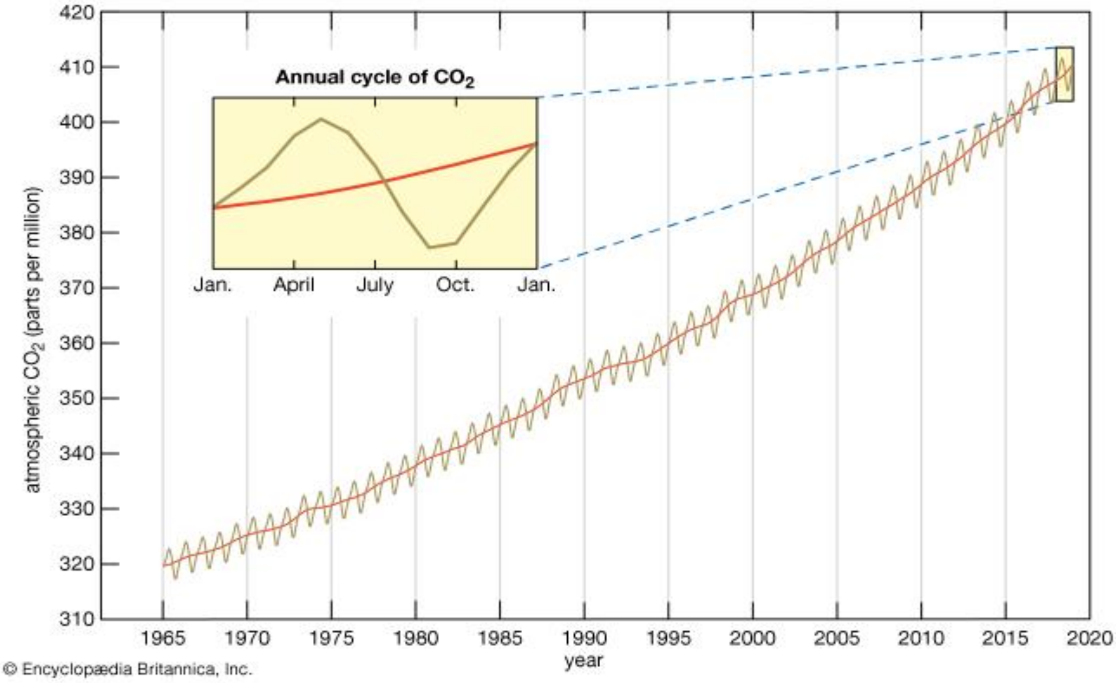
Figure 3: Concentrations of CO2-equivalent



Source: Wikipedia https://en.wikipedia.org/wiki/Representative_Concentration_Pathways

In the pessimistic scenario of RCP 8.5, the rate of emissions continues to increase at a disastrous rate. In this scenario, the impact of rising population effectively negates the 'carbon gains' of retiring fossil fuels and carbon-trading.

Figure 4: The 'Keeling Graph' of mean Atmospheric CO2-eq 1965-2018



Note: The highest annual increase in atmospheric CO_2, of 3.5 ppm, occurred in 2018, indicating no slowing down of emissions.

RCP scenarios 4.5 and 6.0 are characterized by peak emissions in 2040 and 2060 respectively, and then decline. Global carbon emissions during this century, 2000 to 2019, more or less track the equivalent of a hypothetical 'RCP 6.5', with a plausible argument that emissions may drop to less than the equivalent of RCP 6.0 by about 2035. Therefore, the remaining usable RCPs are 4.5 and 6.0, which are notionally considered in the following analysis to be the reasonable lower and upper bounds, respectively. In practical terms, these two curves only begin to diverge significantly beyond about 2070, and hence, on the time-scale of this study, there is not much difference between the RCP 4.5 and 6.0 outcomes.

In some of the following assessment, RCP 8.5 is included as a 'worst-case' scenario.

2.3 Model Generation

Temperature projections from modelling are predicated upon the 'equilibrium climate sensitivity' ('ECS'). This is the temperature increase resulting from a doubling of atmospheric $CO_{2\ (eq)}$, assuming sufficient time elapses for the Earth system to reach equilibrium. The ECS is subject to differing interpretations from various perspectives, namely theory, climate- modelling, paleo-climatic comparisons, instrumental trends, and combined methods.

This EbARR climate change report is heavily based upon CMIP-5 modelling outputs, which are currently available in their entirety. CMIP-6 outputs are about a year overdue. As of December 2019, only a small number of research groups have yet submitted their results. However, early results from CMIP-6 put the ECS some 21% higher than previous estimates, in which case temperature changes calculated for this report would be on the conservative side. On the other hand, some of the paleo-climatic and field instrumental trend results are ambiguous in their support of the early CMIP-6 conclusions on ECS.

2.4 Downscaling

Physiographic variation tempts some to argue in favor of downscaled modelling. This climate-change assessment strongly resists this approach on the grounds that: (a) the multi-model CMIP-5 assemblage of outputs is already 'as good as it gets'; (b) The apparent improvement in accuracy and precision is illusory, if not positively misleading, it is scientifically unsupportable; (c) Downscaled 'precision' becomes far less than the compounded error bounds, and is therefore meaningless; and (d) the difference in grid scale between the current generation of AOGCMs and downscaled models is not as great as formerly, and hence the distinction becomes increasingly unimportant.

2.5 AOGCMs Available

There are some 60 global AOGCMs in existence, generated by about 30 modelling groups or consortia in 14 countries. Many of these are variants of the same model, putting different emphases upon a range of aspects, and many use common slabs of code to process a much smaller set of global input data. These differ in such aspects as the mechanism of cloud formation, evolving monsoon strength and direction, evaporative mechanisms, ITCZ form and mobility, and in assumed sensitivities to global forcing mechanisms and feedback processes. These model differences account for the large scatter in the sub-tropical temperature estimates, such as those of the CMIP-5 outputs.

2.6 The World Bank's CCKP Ensemble of CMIP-5 AOGCMs

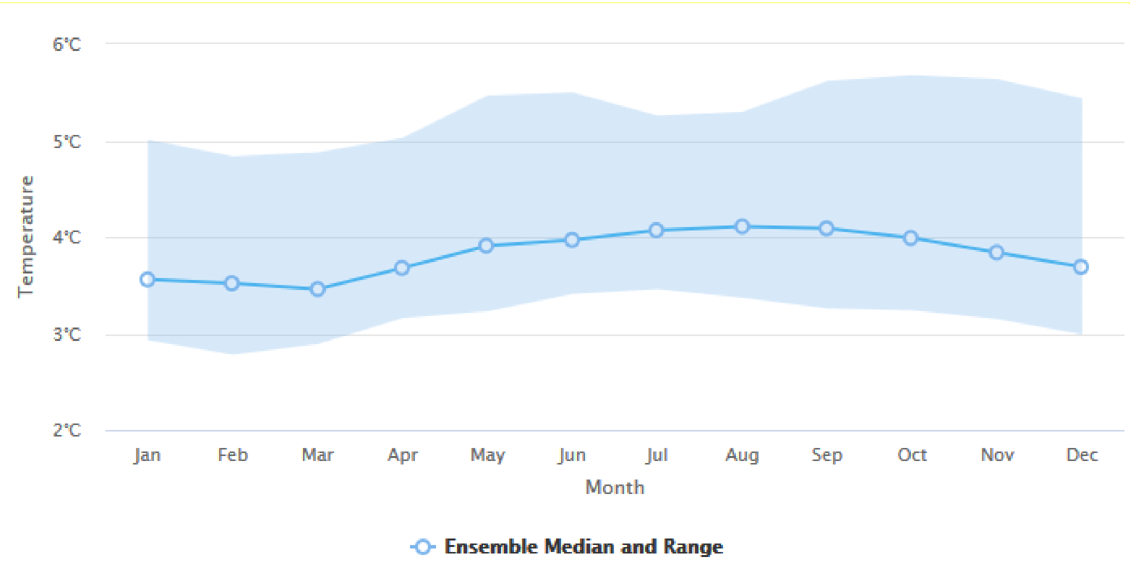
AOGCMs are complex representations of multi-parameter energy interchanges in which the ocean-atmosphere is modelled as areal grid units ranging in size from 64 to 320 km. Depending upon parameter, the model outputs may be very similar or highly divergent. Overall however, their climatic forecast capability is extremely powerful. The models typically occupy petabytes of computer space, and are generally not user-friendly or accessible to external users. Each model has its own biases, emphasis, regional or environmental applicability, strengths and weaknesses. None can be claimed to be 'definitively correct', or 'better' than the others.

An international initiative to attain clarity amongst the many model outputs is the '*Coupled Model Intercomparison Project*', or 'CMIP'. There are several phases to this project, such as CMIP-3 (which is now obsolete), CMIP-5 (which is the current phase for which the complete outputs are available), and CMIP-6, which is in transition from the experimental and design stage but which is not yet incorporated into the 'World Bank Climate-Change Knowledge Portal' (as of late 2019). CMIP-5 compares the outputs of 25 to 35 selected AOGCMs from around the world, including research consortia from many countries, in addition to international cooperative models. Other 'knowledge portals' using outputs from different model ensembles are also available, but their conclusions are essentially the same.

Throughout this report the accepted modelling results have been the ensemble *median* values. Figure 5, Figure 6 and Figure 7 are here included to illustrate the total spread of model outputs. These country-wide results put the median values into context. Similar spreads of results are derived for all specific locations.

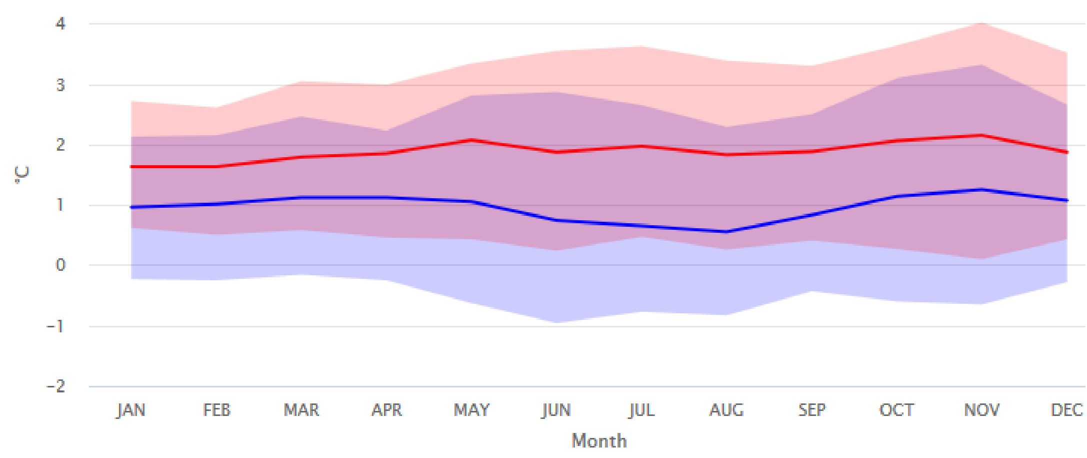
Figure 5: Projected Change in Monthly Temperature for Tanzania, 2080-2099

Various RCPs included. Ensemble 10-90th percentile range indicated in pale blue



Source: World Bank Climate Change Knowledge Portal, Country Summary

Figure 6: Example of Projected Change in Daily Maximum Temperature for Tanzania



Source: World Bank Climate Change Portal. Data for the time-slice 2040-2059.

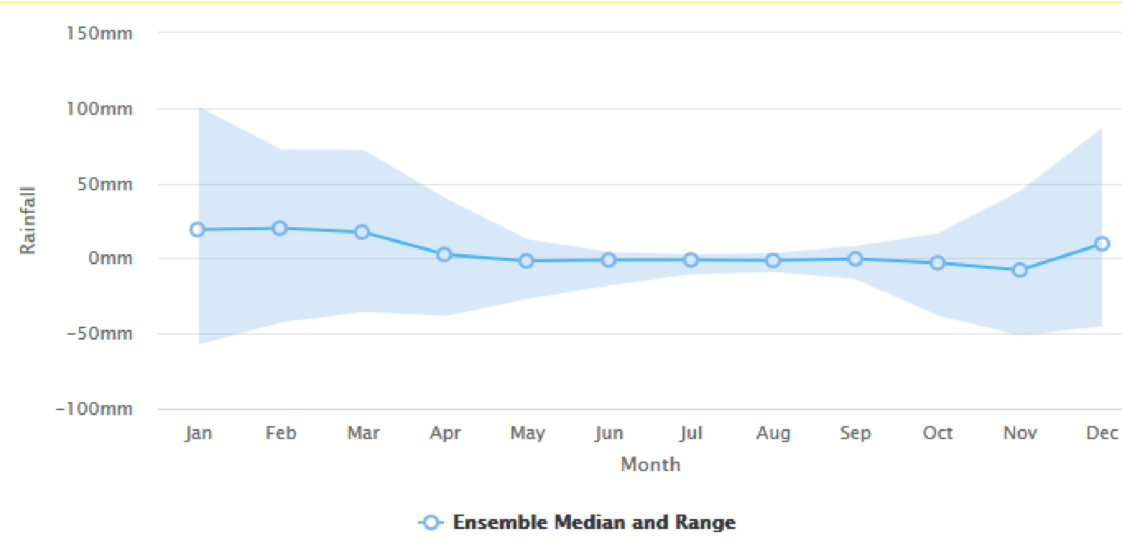
Blue line RCP 2.6 ensemble median; Shaded blue/mauve 10-90th percentile range.

Red line RCP 8.5 ensemble median; Shaded mauve/pink 10-90th percentile range.

As Figure 7 indicates, the projected country-wide *change* in modelled precipitation by 2080-99 is only marginally increased from zero, and even this small change is of low statistical significance. This is consistent with the historic instrumental record which, notwithstanding considerable inter-annual variation, does not yet indicate any significant rainfall trend in data, as of end of 2018. The modelled changes in *rainfall* should be treated with caution. Compounded implicit errors in model conceptualization, calibration, scaling, and physiographic bias, are at least as great, if not greater than, these small changes in rainfall.

Figure 7: Projected Change in Monthly Rainfall for Tanzania, 2080-99

Various RCPs included. Ensemble 10-90th percentile range indicated in pale blue.

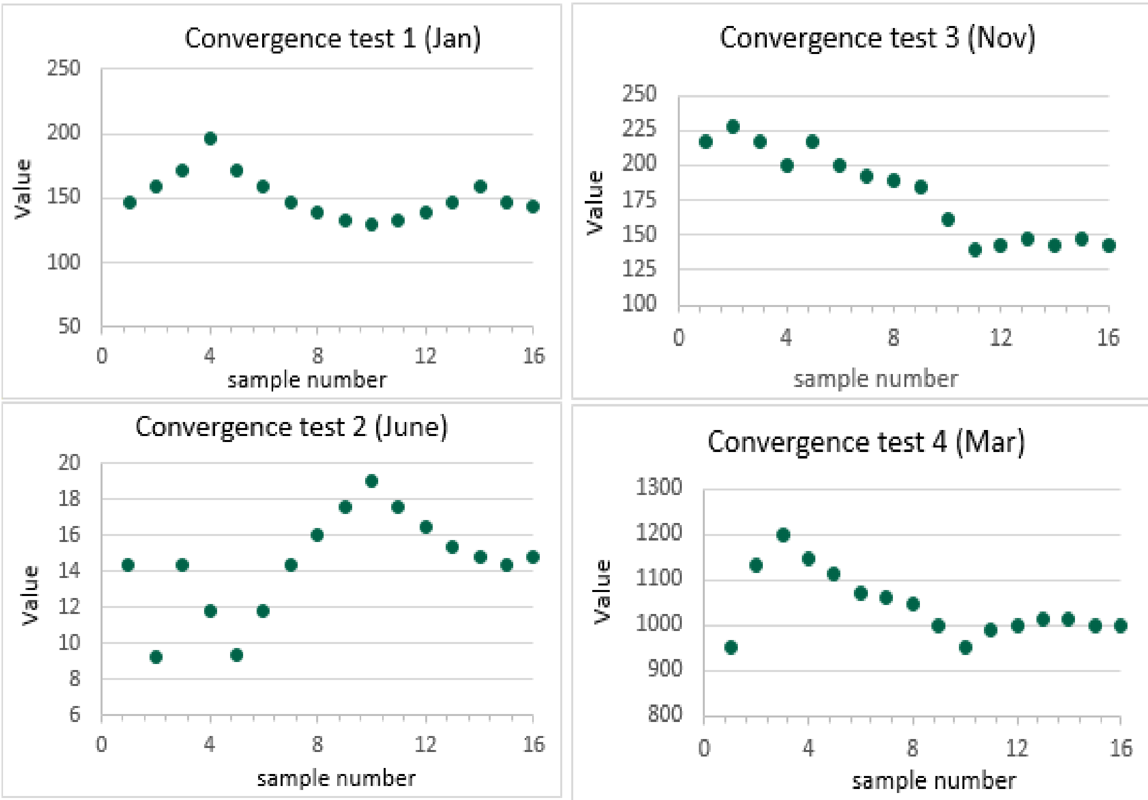


Source: World Bank Climate Change Knowledge Portal, Country Summary

2.7 How Many AOGCMs?

As the number of models increases, median projected values would be expected to converge upon an 'aggregate consensus value'. This raises the question of whether the number of model outputs presented on the World Bank Climate-Change portal is sufficient. Any set of forward projections could be used to test the hypothesis of 16 to 35-model sufficiency. Here, four tests tracked the convergence of median values of rainfall in the Shinyanga grid, north-western Tanzania (January, June, November and whole year) for RCP 4.5, 2080-2095. Reasonable convergence, to within 2 or 3%, was achieved in all four tests (Figure 8), with the conclusion that greater than 16-model outputs would be unlikely to significantly change the convergence values. On the other hand, 5 of the 16 models were variants of other models from the 'same stable', so not all of the 16 models were entirely independent. Plausible arguments could be advanced that a different, and more truly independent, set of AOGCMs might have been preferable, but the ease of accessibility and consistency of presentation were the overriding factors in choosing to use the WB portal's assemblage.

Figure 8: Convergence Tests with different numbers of model in the ensemble, based upon model cells near Shinyanga



Notes: 1) convergence is a measure of consistency. It is not necessarily a measure of accuracy. Only subsequent history-matching can confirm the ensemble median as being accurate.

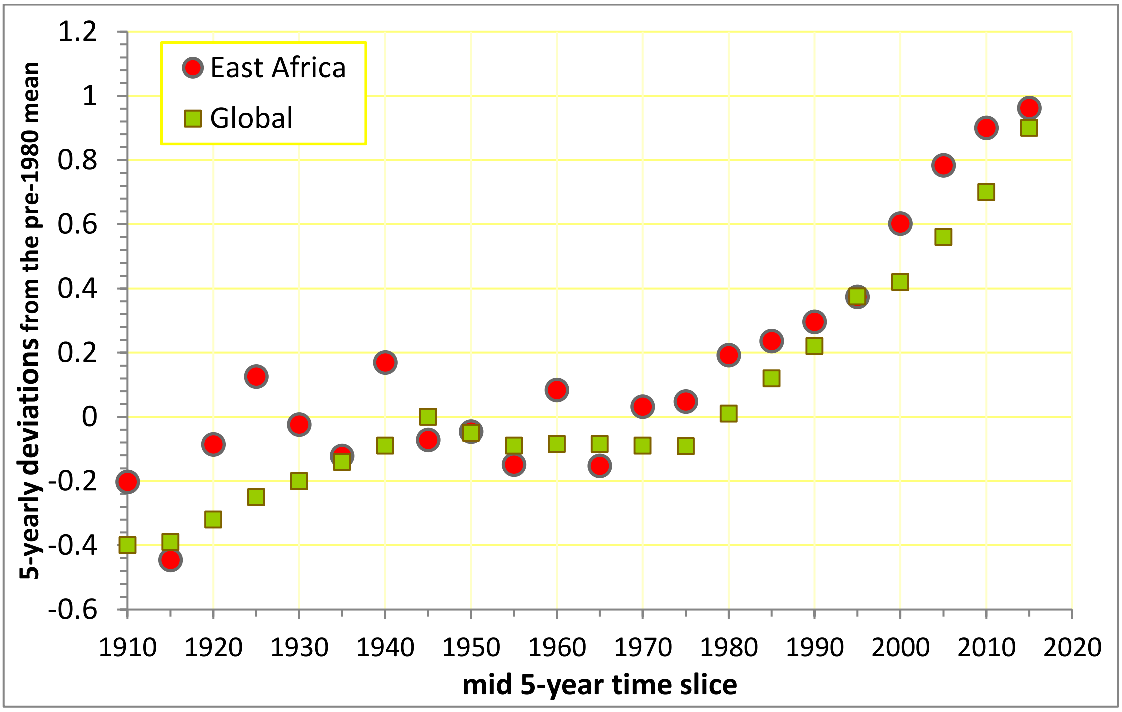
2) This test used the original World Bank published results for 16 models. Most of the data used in this report utilized the 2019 updated portal data, which is now based upon 35 models as used by the IPCCs 5th Assessment Report. The WBCCKP data are presented on an interpolated 1° x 1° global grid spacing. In Tanzania this is equivalent to a grid square of about 110 x 110 kilometers.

3 OVERVIEW OF RESULTS

3.1 Regional Climate-Change

Barring unexpectedly cold conditions in the last two months of 2019, the last five years 2015 to 2019 will have been the hottest five years since global records began in 1880. As an El-Niño year, 2016 was the hottest. Tanzania has a complex physiography, being 'continental' in the west, but strongly influenced by the Indian Ocean SSTs along its eastern coastline. East Africa has a regional warming trend which is slightly higher than that of the global average, as shown in Figure 9. Regionally, Global Climatic Models ('AOGCMs') all tend to reach the same general conclusion, that wet areas will become wetter, whilst dry areas will become drier. At a more local level, physiographic variations, such as the Kilimanjaro massif, the Rwenzori Watershed Mountains, and Lakes Malawi, Tanganyika and Victoria, all have important influences upon both temperature and rainfall. The local strong rainfall gradient around southern Lake Victoria is a case in point.

Figure 9: Historical Temperature Trends, Δ°C: East-African vs. Global



Sources: Merged data from NOAA global climate reports, Gebrechorkos et al., and combined multiple databases.

3.2 Country-Wide Climate Data Projections

Key projected climate trends, based on previous CMIP-5 outputs are summarized, below, in the country's 2nd communication to the UNFCCC (2014). The assumed emissions trajectory used in this assessment was not stated.

Temperature

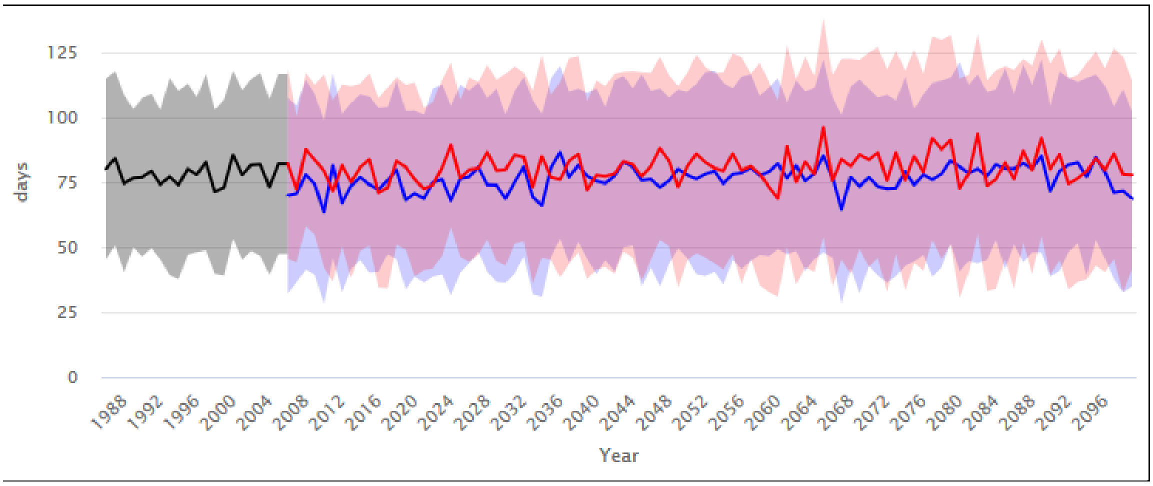
- More warming is projected over the Western side of the country, whereby a warming of up to 3.4ºC is projected by 2100.
- A warming of less than 1.76ºC for 2050 and 3.28ºC for 2100 is projected over parts of the northern coast regions and north-eastern highlands.
- A warming in excess of 1.77ºC for 2050 and 3.3ºC for 2100 is projected over the Lake Victoria zone.
- A warming in excess of 1.39ºC for 2050 is projected in central Tanzania zone.
- And a warming of 3.18ºC for 2100 is projected for the southern coast including Mtwara and Lindi regions.

Precipitation

- Rainfall projections indicate that some parts of the country may experience an increase in mean annual rainfall of up to 18-28% by 2100, particularly over the Lake Victoria Basin and North-Eastern Highland.
- The South Western Highlands and Western Zones of the country are projected to experience an increase in annual rainfall by up to 9.9% in 2050 and by up to 17.7% in 2100.
- The North Coast Zone is projected to have an increase of about 1.8% in 2050 and 5.8% in 2100 while the Central Zone is projected to have an increase of up to 9.9% in 2050 and up to 18.4% in 2100.
- The Southern Coast Zone is projected to have a decrease of up to 7% in 2050 and an increase of annual rainfall of about 9.5% in 2100.

Model projections indicate that, for most parts of Tanzania, there will be little change in the *median* number of consecutive dry days, but there will be a noticeable increase in the duration of the 10th to 90th percentile range. That is drought intensities with an *average* recurrence interval of 10 years will be extended by about 10 days.

Figure 10: Generalized Maximum Number of Consecutive Dry Days across Tanzania Historic (grey) and Projected (pink)



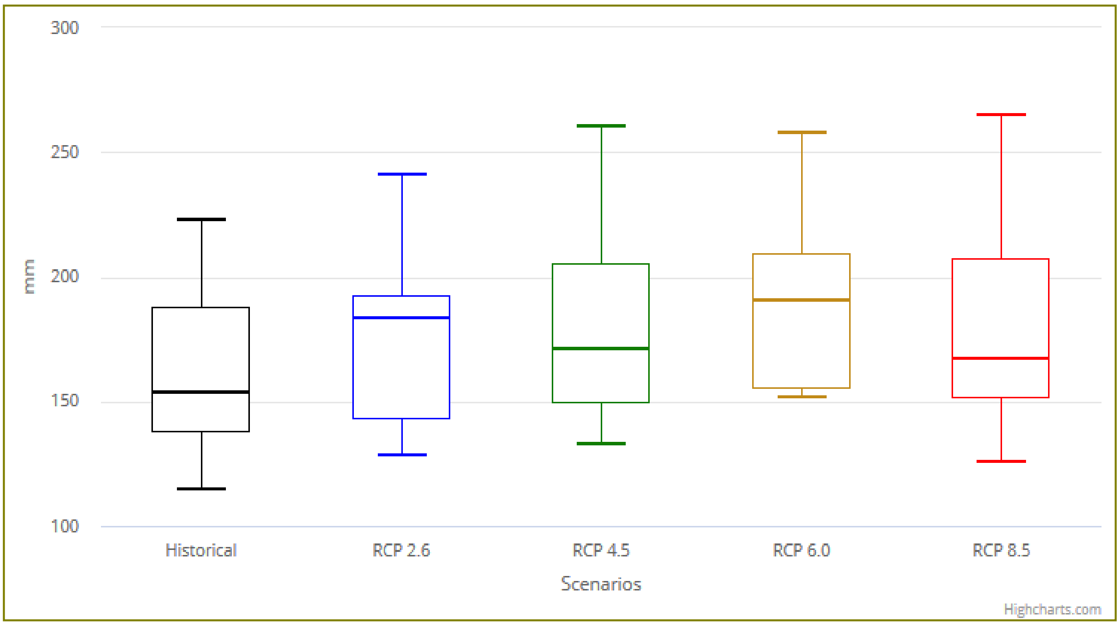
Source: World Bank Climate Change Portal. Blue line RCP 2.6 median, blue shading 10-90th percentile range: Red line RCP 8.5 median, pink shading 10-90th percentile range.

3.3 Extreme Precipitation and Runoff

The 'precipitable moisture' in the atmosphere is closely linked to temperature, but cloud formation, cloud-top temperatures, and storm advection are all poorly constrained by the model, and hence extreme event rainfalls cannot be estimated either at any given location, or at any particular time of year, with a high degree of confidence. On the other hand, generalized rainfall extremes can be estimated, and are presented in Figure 11. The most extreme precipitation is only about 5% greater than those of the historic record. However, higher frequency/lower intensity events could be up to about 30% more intense than in the historic record.

Note that the runoff is not directly proportional to the rainfall, so an increase of only 10% in extreme rainfall can, and almost certainly will, result in a much higher proportion of runoff, resulting in greatly enhanced quickflow (flash flooding). In addition, the erosive power of quickflow is approximately proportional to the fourth power of the runoff velocity, so a small increase in extreme rainfall will have a disproportionate impact upon hill-slope, soil and embankment erosion.

Figure 11: Generalized Extreme Rainfall Projections in Tanzania for 2040-2059



Source: World Bank Climate Change Portal

Notes: The Extreme Event Modelled is the 5-day rainfall at an average recurrence interval of 10 years. Symbols are maximum, upper quartile, median, lower quartile and minimum.

3.4 Growing Season, Rainfall Seasonality and Crop Yields

In Tanzania, the potential growing season (>5°C) is essentially all year round, and hence there is no change to the duration of the temperature-governed growing season, even under the most pessimistic climate change projections. However, there *are* changes in both the intensity of photosynthesis and in the duration of excess heat stress.

The rainfall seasonality index measures the standard deviation of monthly rainfall against the mean rainfall. The larger the value, the more variable is the rainfall across the year. The smaller the value, the more evenly distributed is rainfall across the seasonal cycle. Under most RCP scenarios there is a slight decrease in rainfall seasonality in coastal and near-coastal districts, and either no-change or a slight increase in rainfall seasonality in more inland areas. Either way the modelled average effects are minimal. The change in standard deviation is dwarfed by the 10th to 90th percentile range of the model ensemble. The *CMIP-5 model* changes in rainfall seasonality are therefore statistically indeterminate. On the other hand, process studies and projections at regional level, particularly in respect of the ITCZ behavior, suggest some degree of rainfall intensification, concentrated over a shorter time-frame (Byrne et al. 2018a). That is, more rain is expected to fall throughout shorter rainy seasons, both in the 'long rains' and 'short rains'.

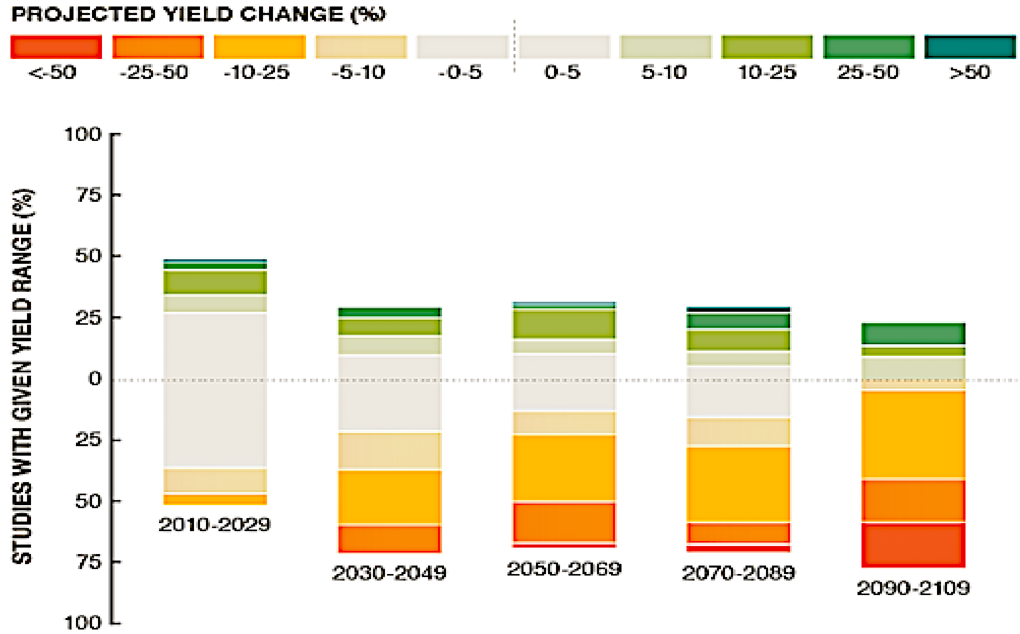
The World Bank has developed projections in the change in yield for various crops, an example of which is shown below, in Figure 12 (for maize). This serves to indicate the local variability to be expected in an *average* year. Farming viability, however, is determined not in average years, but by years of extreme conditions. Hence, such maps must be used with caution.

Figure 12: Crop Yield Projections for Low-Input Rain-fed Maize, 2080

Source: WBCCP Agricultural Impacts

Some crops, such as some varieties of maize, beans and bananas, may actually benefit from climate-change impacts, at least in the short- to medium-term. However, the majority of modelling studies conclude that negative impacts will prevail from about the 2030s onwards. Beyond about 2050, a broad spectrum of crop yields will decrease by more than 10%. Higher CO_2 concentrations and warmer temperatures will lead to greater biomass production, but probably at the expense of crop quality and nutrition (Figure 13 below).

Figure 13: Generalized Multi-Study Outlook for Crop Yields, by Time-slice



3.5 Evapotranspiration

3.5.1 Evapotranspiration: Wind-run

An input of wind-run, in units of km per day, is an important component of the Penman-Monteith equation for calculating the potential evapotranspiration, which is in turn a necessary part of the drought-risk estimate.

All five key met stations have wind-run records starting in 1988. That is, yielding only 30 years of data, mostly with an unbroken record of monthly mean data, as summarized in

Figure 14. Second order regressions have been fitted to each station's data, none of which are very convincing. All the continental stations (i.e. excluding Zanzibar) show a distinct wind-strengthening over the most recent seven years.

Unfortunately, AOGCMs do not reliably capture either hindcast or forward projections of wind-run, whilst climate change is only one of three possible long-term influences, the other two being El-Nino knock-on effects, and the Indian Ocean Dipole. The IOD has an import impact upon winds and drought in Australia, but its effect upon winds and rain in East Africa is unclear, except to note that IOD-influenced drought in Australia corresponds to excess rains in East Africa. Recent decades have seen an increased frequency of IOD events.

Beyond a generalized tendency for warmer conditions to generate stronger winds, the current state of research is inadequate to quantify forward projections of wind. Here we suggest a 'guesstimate' of 5% increased wind-run by 2050, and a 10% increase by 2090, for all stations except Zanzibar.

There is substantial variation in seasonal wind-run between the five stations. They tend to follow a consistent pattern of maximum winds in September and October, with the exception of Zanzibar whose wind pattern is dominated by the Indian Ocean monsoonal winds.

Figure 14: Historic Mean Monthly Wind-Run at all Five Stations (2nd order regressions)

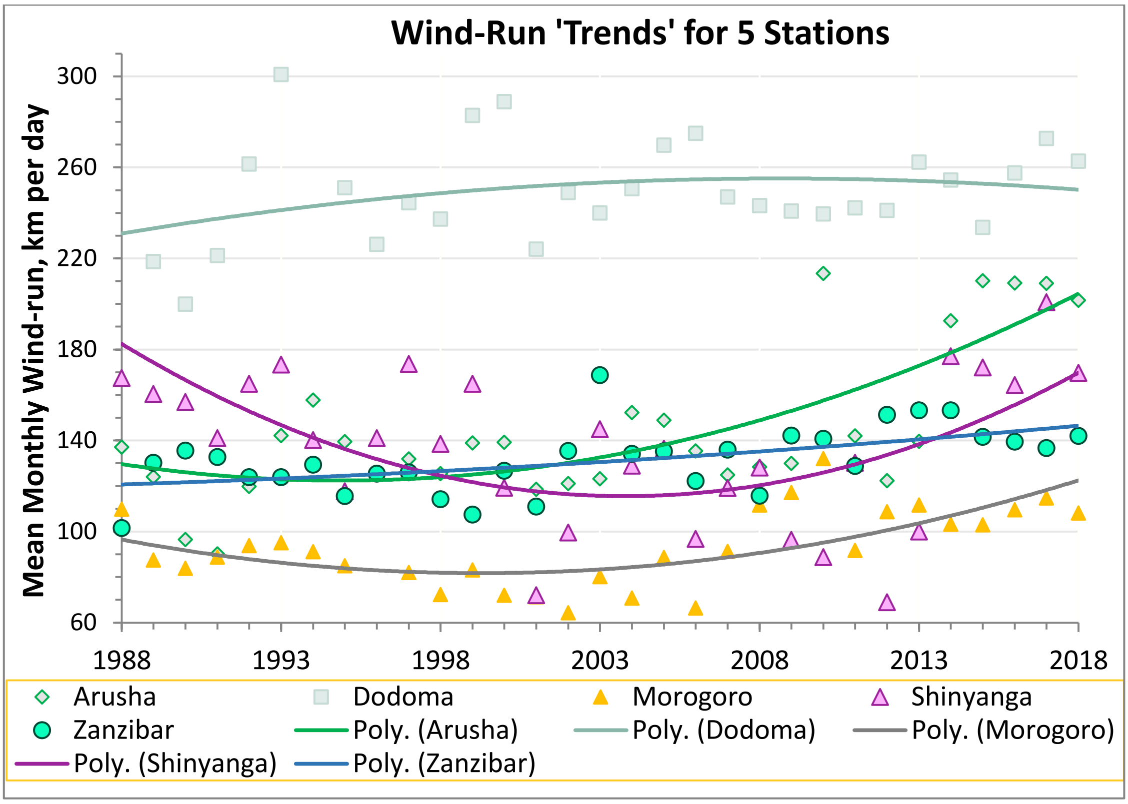
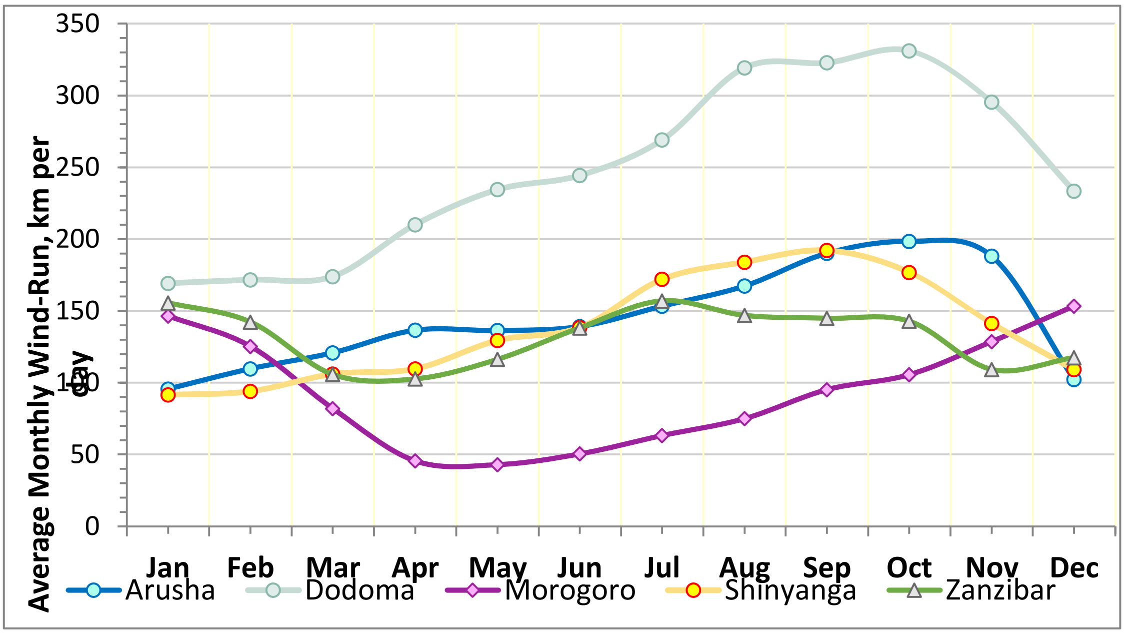


Figure 15: Mean Monthly Wind-Run at the EbARR sub-project areas



3.5.2 Evapotranspiration: Sunshine Hours

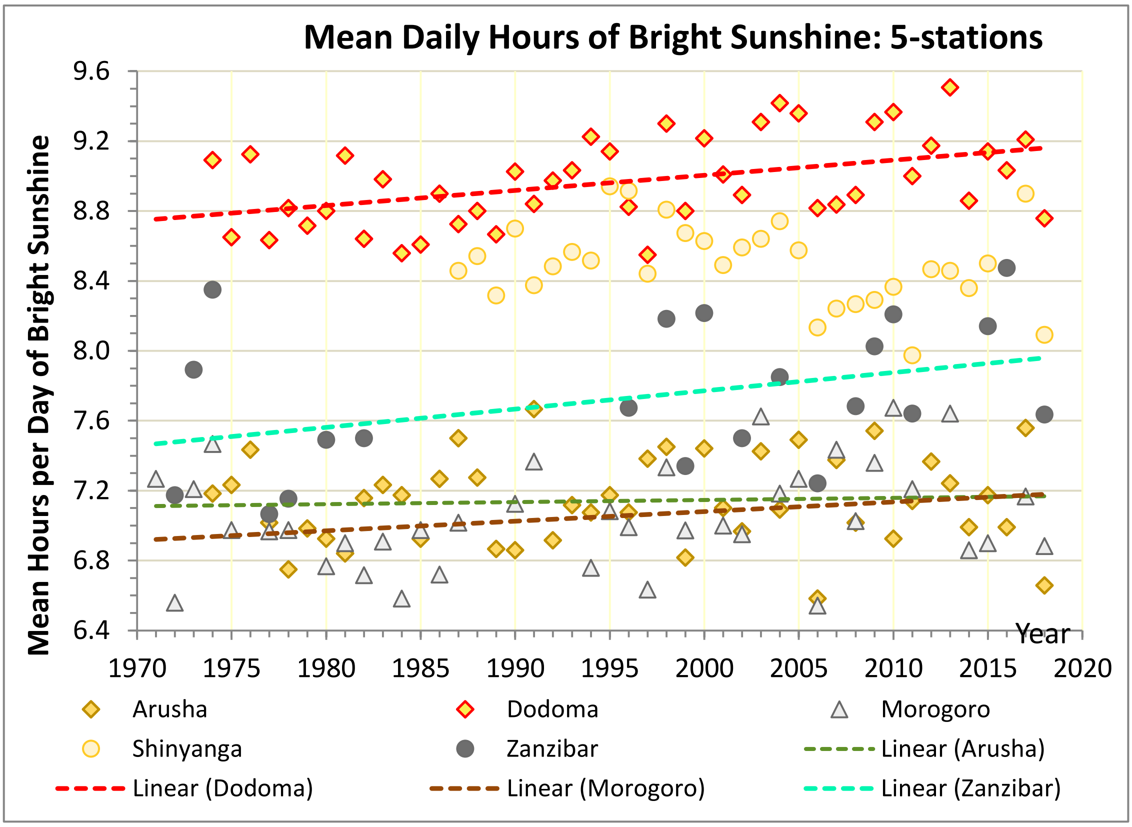
Four of the five main meteorological stations record 'daily hours of bright sunshine' from the early 1970s. The time series from Shinyanga is too short to determine any meaningful trend.

Otherwise, three stations, Dodoma, Zanzibar and Morogoro, all exhibit a distinct increase in bright sunshine hours, averaging 0.39 hours per day over the time series, or 5.1 minutes per day per decade. Sunshine hours / cloudiness at Arusha remains more or less unchanged.

All five stations incurred minor gaps which have been adjusted with synthetic data. The percentages of synthetic data at each station are: Arusha 0.4, Dodoma 1.7, Morogoro 2.2, Shinyanga 3.0 and Zanzibar 7.9. The implicit errors of data synthesis are very unlikely to significantly change any of the assessed trends.

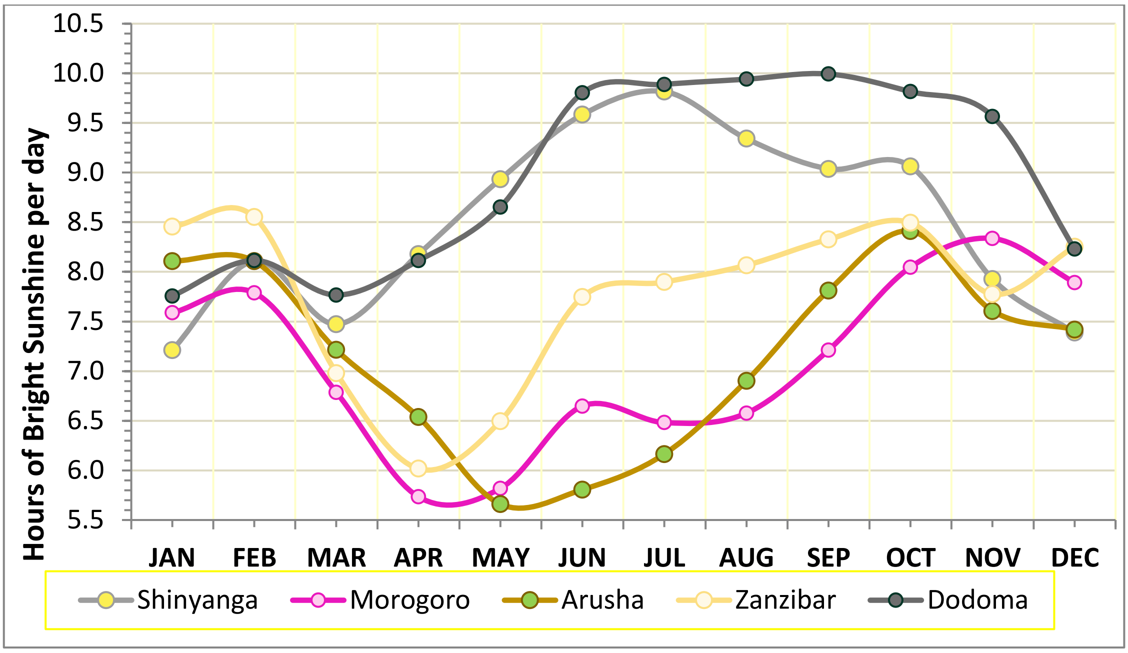
Mean annual time-series are compared in Figure 16. Future projections of these apparently linear trends are very unlikely to continue, and there is no existing methodology to estimate future sunshine hours beyond about 2025. Unfortunately, computer modelling is insufficiently sensitive to capture such subtle changes. However, the trends are real, and point to future increases in potential evapotranspiration, and hence to increased crop-water requirements.

Figure 16: Annual Mean Sunshine Hours at the main EbARR stations



Note: Years with more than two months of missing data are not included in the above summary. Short term gaps in the record have been interpolated with synthetic data, but make no appreciable difference to the trends illustrated.

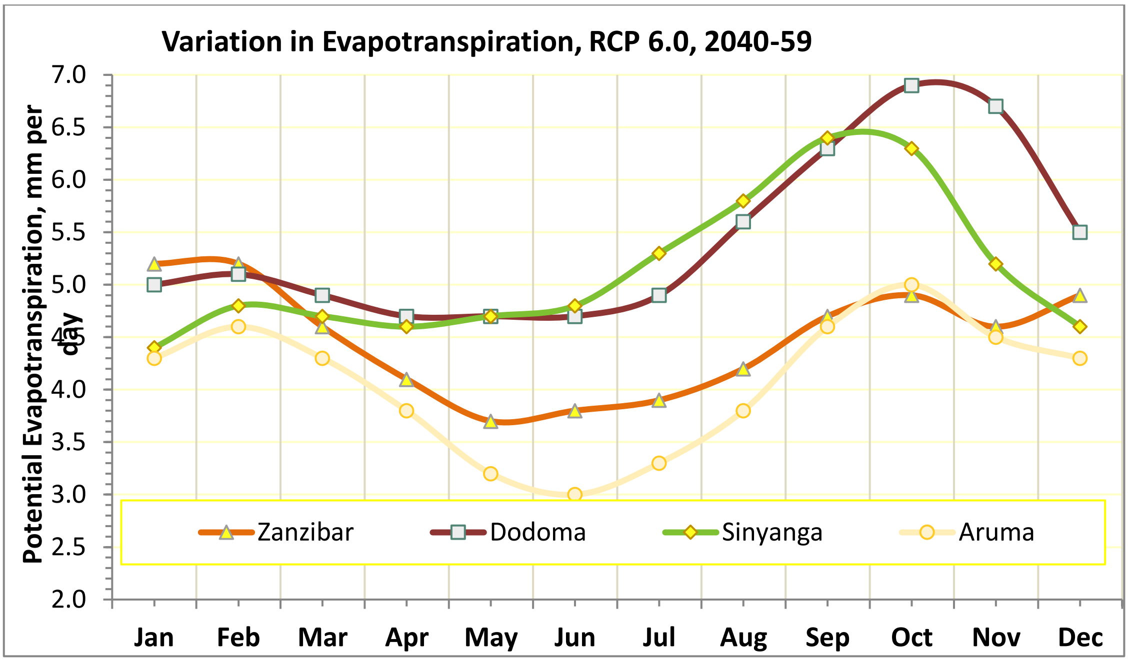
Figure 17: Sunshine Hour Seasonality at the main EbARR stations



Most of the seasonal variation in sunshine hours occurs during the dry season of April to September.

3.5.3 Evapotranspiration: Regional Variation

Figure 18: Calculated Variations in Potential Evapotranspiration at EbARR Stations

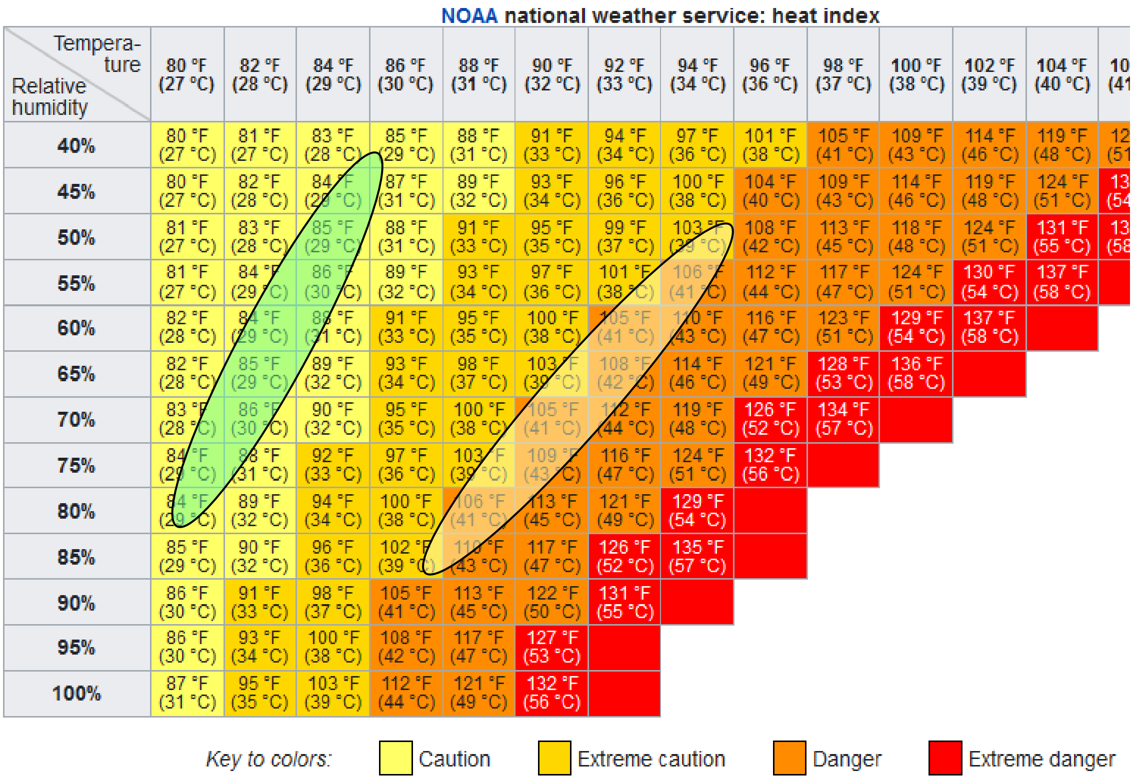


Note: ET_0 values for Morogoro were not calculated, but will be intermediate between Zanzibar and Dodoma, i.e. corresponding to the approximate median of the above data. There were insufficient data to calculate ET_0 for either Mpwapwa or Babati. Mpwapwa is expected to be very similar to Dodoma, whilst Babati will be very similar to Arusha.

3.6 Heat Stress

An assessment of prolonged exposure to heat stress, of a month or more, was made by comparing RCP 6.0 hottest and most humid month projections onto the American NOAA heat stress chart of temperature vs humidity, as shown in Figure 19. Under no climate-change scenarios does this prolonged heat-humidity combination become dangerous to humans. The likely range for prolonged exposure is approximated by the green ellipse. The projected range is within the ‘exercise caution’ zone, defined as 27-32°C, in which “fatigue is possible with prolonged exposure and activity. Continuing activity could result in heat cramps.”[1] For relatively *short-term* exposure, of a few days, there will be occasional excursions into the ‘extreme caution’ or ‘danger zone’, as indicated by the grey ellipse of Figure 19. Under such conditions, heat cramps and heat exhaustion are possible whilst heat-stroke could result from over-exertion. Naturally, the impact of high humidities will be most noticeable in Zanzibar. Also, note that exposure to full sunshine without a hat can effectively increase the heat index by up to 8°C.

Figure 19: Tmax- RH Ranges of Potential Heat Stress for EbARR Stations



NOAA national weather service: heat index

Temperature / Relative humidity	80 °F (27 °C)	82 °F (28 °C)	84 °F (29 °C)	86 °F (30 °C)	88 °F (31 °C)	90 °F (32 °C)	92 °F (33 °C)	94 °F (34 °C)	96 °F (36 °C)	98 °F (37 °C)	100 °F (38 °C)	102 °F (39 °C)	104 °F (40 °C)	10 (41
40%	80 °F (27 °C)	81 °F (27 °C)	83 °F (28 °C)	85 °F (29 °C)	88 °F (31 °C)	91 °F (33 °C)	94 °F (34 °C)	97 °F (36 °C)	101 °F (38 °C)	105 °F (41 °C)	109 °F (43 °C)	114 °F (46 °C)	119 °F (48 °C)	12 (51
45%	80 °F (27 °C)	82 °F (28 °C)	84 °F (29 °C)	87 °F (31 °C)	89 °F (32 °C)	93 °F (34 °C)	96 °F (36 °C)	100 °F (38 °C)	104 °F (40 °C)	109 °F (43 °C)	114 °F (46 °C)	119 °F (48 °C)	124 °F (51 °C)	13 (54
50%	81 °F (27 °C)	83 °F (28 °C)	85 °F (29 °C)	88 °F (31 °C)	91 °F (33 °C)	95 °F (35 °C)	99 °F (37 °C)	103 °F (39 °C)	108 °F (42 °C)	113 °F (45 °C)	118 °F (48 °C)	124 °F (51 °C)	131 °F (55 °C)	13 (58
55%	81 °F (27 °C)	84 °F (29 °C)	86 °F (30 °C)	89 °F (32 °C)	93 °F (34 °C)	97 °F (36 °C)	101 °F (38 °C)	106 °F (41 °C)	112 °F (44 °C)	117 °F (47 °C)	124 °F (51 °C)	130 °F (54 °C)	137 °F (58 °C)	
60%	82 °F (28 °C)	84 °F (29 °C)	88 °F (31 °C)	91 °F (33 °C)	95 °F (35 °C)	100 °F (38 °C)	105 °F (41 °C)	110 °F (43 °C)	116 °F (47 °C)	123 °F (51 °C)	129 °F (54 °C)	137 °F (58 °C)		
65%	82 °F (28 °C)	85 °F (29 °C)	89 °F (32 °C)	93 °F (34 °C)	98 °F (37 °C)	103 °F (39 °C)	108 °F (42 °C)	114 °F (46 °C)	121 °F (49 °C)	128 °F (53 °C)	136 °F (58 °C)			
70%	83 °F (28 °C)	86 °F (30 °C)	90 °F (32 °C)	95 °F (35 °C)	100 °F (38 °C)	105 °F (41 °C)	112 °F (44 °C)	119 °F (48 °C)	126 °F (52 °C)	134 °F (57 °C)				
75%	84 °F (29 °C)	88 °F (31 °C)	92 °F (33 °C)	97 °F (36 °C)	103 °F (39 °C)	109 °F (43 °C)	116 °F (47 °C)	124 °F (51 °C)	132 °F (56 °C)					
80%	84 °F (29 °C)	89 °F (32 °C)	94 °F (34 °C)	100 °F (38 °C)	106 °F (41 °C)	113 °F (45 °C)	121 °F (49 °C)	129 °F (54 °C)						
85%	85 °F (29 °C)	90 °F (32 °C)	96 °F (36 °C)	102 °F (39 °C)	110 °F (43 °C)	117 °F (47 °C)	126 °F (52 °C)	135 °F (57 °C)						
90%	86 °F (30 °C)	91 °F (33 °C)	98 °F (37 °C)	105 °F (41 °C)	113 °F (45 °C)	122 °F (50 °C)	131 °F (55 °C)							
95%	86 °F (30 °C)	93 °F (34 °C)	100 °F (38 °C)	108 °F (42 °C)	117 °F (47 °C)	127 °F (53 °C)								
100%	87 °F (31 °C)	95 °F (35 °C)	103 °F (39 °C)	112 °F (44 °C)	121 °F (49 °C)	132 °F (56 °C)								

Key to colors: Caution · Extreme caution · Danger · Extreme danger

Green ellipse: Approximate RCP 6.0, 2099 range for prolonged exposure. Grey ellipse: Approximate RCP 6.0, 2099 range for short- to medium-term exposure.

Differences in temperature between historic and projected conditions are typically up to 2°C (RCP 6.0) or over 3°C (RCP 8.5). In many cases these temperature differentials will significantly change the heat stress conditions from ‘caution’ to ‘extreme caution’, or from ‘extreme caution

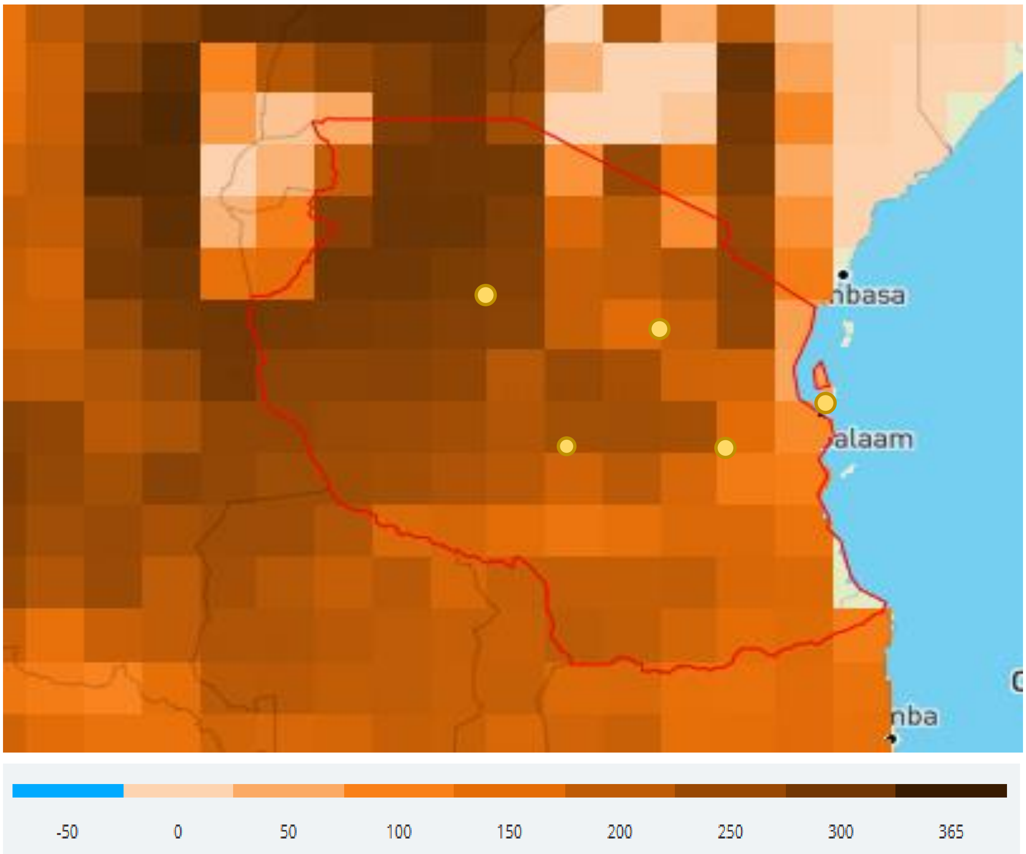
[1] Cited from: https://en.wikipedia.org/wiki/Heat_index

to ‘danger’, both for humans and livestock. The threat of heat stress to livestock is sensitive to species and varieties, and hence local farming expertise should be consulted.

Figure 20 indicates the worst-case geographic projection for changes in tropical nights above 20 degrees C by end of century. This may be more realistic for the next century. However, a more useful ‘ΔT’ map would use a more moderate RCP, such as 4.5 or 6.0, for the time slice 2040-59, and for temperatures of >25°C, i.e. the night-time temperature above which heat stress recovery is severely retarded. However, the generation of such a map is beyond the scope and resources available to EbARR.

In Figure 20, the 1°x1° pixels are interpolated to compare differing resolutions of the CMIP-5 ensemble. The two inland pale areas, *i.e*. cool areas with little or no change in temperatures above 20°C, reflect higher altitudes in the Rwenzori mountains and the East-African Highlands, (respectively northwest and northeast of Tanzania). The darkest area, in northern Tanzania, is caused by higher heat-retention (heat capacity and thermal inertia) in the relatively shallow waters of Lake Victoria. The 5 EbARR project sub-area locations are indicated roughly by green spots.

Figure 20: Projected RCP 8.5, change in tropical nights (nights of Tmin >20°C), relative to 1986-2005, for the Tanzanian region, for the time-slice 2080-2099

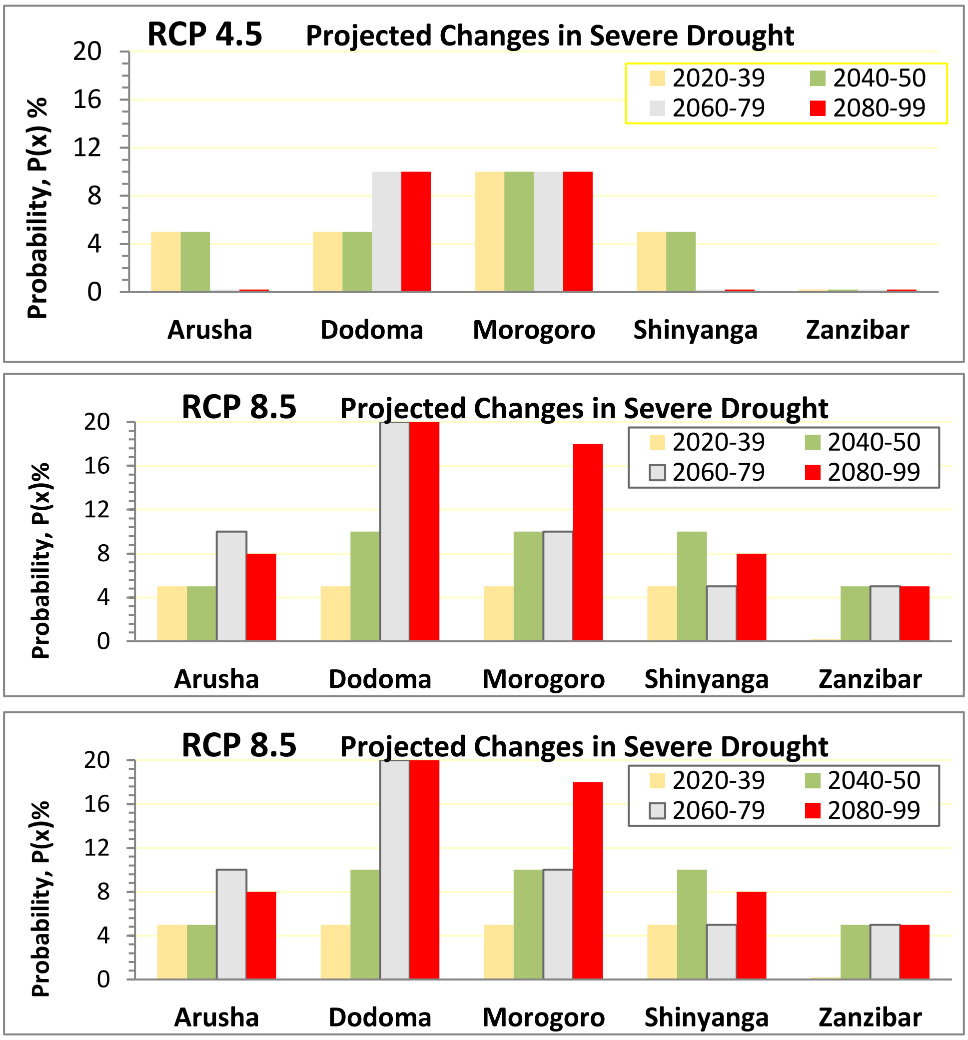


3.7 Changes in Drought

None of the AOGCMs yield reliable quantitative assessments of drought probability. There are so many dependent variables with implicit uncertainties, each compounding the error- bounds, that any assessment of drought conditions will, at best, be only semi-quantitative. Here, the projected changes in annual severe drought for all five project areas are compared using the 3 standard emissions scenarios:

In Figure 21, rough estimates of the *probabilities of severe droughts* are computed by using the 'standardized precipitation evapotranspiration index' (SPEI), which is only one of several possible ways of representing drought, and which incurs moot assumptions in estimating both rainfall and evapotranspiration. In most locations the ensemble projections range from 0% to 40%, with no negative values. The exception is Zanzibar, where the change in probability of drought varies from about -5% to +20%. As a first approximation and as expected, higher probabilities of extreme drought are inversely related to the mean annual rainfall. That is, already dry areas risk more extreme future droughts whereas wet areas, notably Zanzibar, are projected to be more or less unaffected by changing drought conditions. Other physiographic factors, such as altitude or distance from the sea, seem to have little or no impact on the evolving drought probability.

Figure 21: Ensemble Median Estimates of Increasing Drought Probability, by Location



3.8 Specific District-level Analyses

3.8.1 Background to District-level Analysis

Meteorological Stations and Metadata

The location of EbARR districts in relation to the available representative meteorological stations, are shown in Figure 22. The corresponding metadata is tabulated in Table 1.

Figure 22: Meteorological Station Locations in Relation to the Five Sub-Project Areas

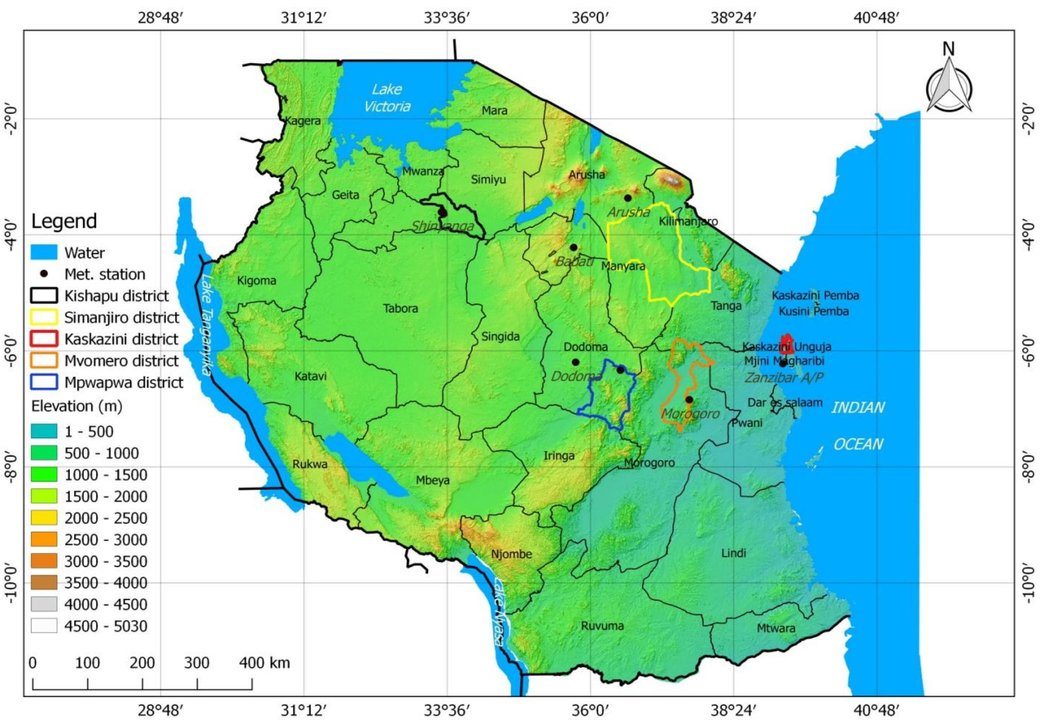


Table 1: Station Information of Met Sites Selected for EbARR analysis

EbARR District	Met Stn.	Latitude (south)	Longitude (east)	Alt. metres	Est.	Years
Simanjiro Manyara region	a) Arusha b) Babati	3°22'03.1" 4°13'4.1"	36°37'33" 35°43'03.5"	1388 1416	i 1971	59 32
Mpwapwa Dodoma region	a) Dodoma b) Mpwapwa	6°10'10.3" 6°19'58.7"	35°45'02" 36°30'00"	1121 1027	ii 1926	60 84
Mvomero Morogoro region	Morogoro	6°50'29"	37°39'20"	535	iii	48
Kishapu Shinyanga region	Shinyanga	3°36'29"	33°30'10.1"	1175	1987	32
Kaskakini A, Zanzibar	Zanzibar A/P	6°13'14"	39°13'37"	15	iv	66

Notes on Table 1:

- *Est = year of establishment; 1st year of full data.*
- *'Years' = number of years of complete data set. Not all climatic parameters were established simultaneously:*
  a. *1959 except for RH 1972, sunshine hours 1973 and wind-run 1988.*
  b. *pptn 1935, temp 1958, sunshine 1974, RH 1986 and wind-run 1988.*
  c. *1971 except for sunshine 1970 (7.8 incomplete), RH 1972 and wind-run 1988*
  d. *pptn 1952, temp 1957, RH and sunshine 1971, wind-run 1988.*

Apart from Babati and Mpwapwa (rainfall only) all stations have the following parameters: T_{max}, T_{min}, precipitation, Relative Humidity, Hours of bright sunshine, and wind-run.

3.8.2 Modelled Annual and Monthly Rainfall for the Districts

The ensemble median modelled changes in rainfall are summarized in Table 2. The ensemble median modelled change in monthly rainfalls are given in Table 3, where the pink shaded cells indicate that there will be a monthly rainfall deficit compared to the historic data (to 2016). In short, the wet months will become wetter by *up to* about 14%, whilst the dry season becomes even dryer.

Table 2: Annual Rainfall Parameters; historic and changes for RCPs 4.5. 6.0 and 8.5

Station		Arusha	Babati	Dodoma	Mpwapwa	Morogoro	Shinyanga	Zanzibar
N*		60	32	84	83	48	34	67
MAR** mm		818	807	570	710	826	818	1630
IAV%***		33.4	33.8	29.4	23.5	27.5	24.1	26.1
By 2050	4.5	+44	+44	-15	-15	0	+24	+9
	6.0	+37	+37	28	28	+32	+38	+21
	8.5	+30	+30	-9	-9	+4	+17	+14
By 2100	4.5	+69	+69	+14	+14	+6	+93	+28
	6.0	+81	+81	+32	+32	+22	+92	+49
	8.5	+88	+88	+30	+30	+4	+97	+61

** N= Years of complete data. **MAR= Mean Annual Rainfall. ***IAV=Inter-Annual Variability*

Note that the changes in precipitation, here expressed as model ensemble medians, in mm per year, are nearly all positive but are sufficiently close to the estimated error bounds as to incur significant uncertainty.

Interpretation of Table 3 requires some caution. Credible research indicates that the CMIP-5 model ensemble tends to *under-estimate* the long rains and *over-estimate* the short rains, (Yang et al, 2014). That is, the change in rainfall of January to March rains may be somewhat higher than indicated, whilst the November-December rains may be less than indicated.

Also consider that AOGCM conceptualizations adequately capture neither the west-Indian Ocean's evolving trends in SSTs, nor the ITCZ narrowing/intensifications yet, both of which will certainly affect Tanzania's rainfall régime. Therefore, conclusions regarding the late 21st century's rainfall must be regarded as only provisional.

Table 3: Modelled Monthly Changes in Rainfall, in mm, for RCPs 4.5, 6.0 and 8.5

Arusha, Babati	RCP	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
By ~2050	4.5	11.3	9.7	2.8	-0.5	2.8	-0.3	0.3	-0.8	-1.5	-2.0	10.6	11.1	**43.5**
	6.0	9.2	9.3	2.1	1.0	-1.3	-1.1	-0.8	-1.4	-0.2	-4.1	5.2	19.2	**37.1**
	8.5	4.1	9.6	2.4	-0.6	-3.2	1.3	-1.2	-1.8	-0.6	-3.8	0.8	22.9	**29.9**
By ~2090	4.5	15.1	6.2	4.1	9.1	0.9	3.0	-1.4	-1.9	-1.2	-2.4	10.2	27.6	**69.3**
	6.0	13.6	12.9	11.0	8.7	-0.6	2.9	-1.3	-1.4	0.0	-1.0	4.3	32.0	**81.1**
	8.5	27.7	14.0	9.8	1.0	2.2	-0.3	-3.8	-2.8	-1.3	-2.1	5.8	37.5	**87.7**
Dodoma, Mpwapwa	**RCP**	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**Annual**
By ~2050	4.5	5.3	1.0	1.2	-2.2	-3.0	-0.3	0.0	-1.1	-1.5	-2.8	-9.8	-1.3	**-14.5**
	6.0	13.7	12.6	2.4	3.2	0.2	-0.7	-0.7	-1.0	-0.3	-4.8	-9.7	13.5	**28.4**
	8.5	2.5	11.5	0.9	-0.4	-8.3	1.6	-0.8	-1.5	-1.3	-2.9	-11.3	1.1	**-8.9**
By ~2090	4.5	18.5	-0.1	5.9	0.3	-3.5	1.0	-0.9	-1.5	-1.2	-2.1	-12.3	9.9	**14.0**
	6.0	17.1	9.2	7.7	-1.9	-2.5	0.3	-1.5	-2.0	-0.5	-3.0	-9.8	19.1	**32.2**
	8.5	18.8	13.1	16.5	-0.8	-3.0	-2.4	-2.2	-1.9	-2.0	-5.1	-16.6	15.4	**29.8**
Morogoro	**RCP**	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**Annual**
By ~2050	4.5	3.5	4.7	9.8	-4.2	-6.9	-1.5	-1.6	-1.2	-2.0	-2.6	-0.7	2.3	**-0.4**
	6.0	7.6	2.2	6.6	-3.6	0.3	-0.5	-0.4	-2.0	-0.3	-0.3	3.3	18.8	**31.7**
	8.5	10.1	8.1	8.5	-4.8	-14.7	2.5	-1.6	-1.9	-1.8	-4.4	-6.5	10.8	**4.3**
By ~2090	4.5	17.9	3.5	10.5	-1.3	-8.3	2.2	-1.6	-1.5	-3.2	-1.0	-3.8	6.3	**19.7**
	6.0	24.3	13.3	19.5	-8.0	-2.6	2.1	-2.6	-2.5	-1.7	-3.3	-8.7	22.3	**52.1**
	8.5	18.4	18.9	19.2	-20.8	-5.7	-3.0	-2.4	-5.6	-2.2	-6.5	-5.7	4.0	**8.6**
Shinyanga	**RCP**	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**Annual**
By ~2050	4.5	13.8	8.9	-1.9	2.8	0.0	-0.2	-0.3	0.0	-0.2	-3.9	1.0	3.9	**23.9**
	6.0	16.9	8.4	-8.8	3.9	0.5	-0.3	-0.4	0.1	1.2	-3.9	3.0	17.0	**37.6**
	8.5	0.7	11.0	-2.9	0.9	-1.5	-0.6	-0.5	-0.2	0.0	-1.8	-4.9	16.4	**16.6**
By ~2090	4.5	34.6	4.6	11.8	8.2	1.1	0.0	-0.3	0.2	0.8	1.4	7.7	23.1	**93.2**
	6.0	23.9	14.6	2.4	12.8	1.1	0.0	-0.5	0.0	1.4	-1.5	7.0	30.9	**92.1**
	8.5	21.6	22.4	10.1	8.6	3.1	-1.1	-0.6	-0.3	0.5	0.9	2.6	29.5	**97.3**
Zanzibar	**RCP**	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**Annual**
By ~2050	4.5	9.6	5.3	13.5	-7.6	-8.0	-1.9	-2.7	-1.1	-0.9	-2.9	4.6	1.0	**8.9**
	6.0	6.1	0.1	4.4	-9.8	1.3	-0.9	-1.5	-2.7	-0.8	-0.9	3.5	22.5	**21.3**
	8.5	11.1	4.9	8.8	0.0	-15.3	0.5	-4.0	-2.5	-1.0	-3.4	-3.0	17.5	**13.6**
By ~2090	4.5	15.5	4.0	14.0	-3.0	-8.0	0.7	-3.0	-1.3	-1.4	-0.2	0.5	10.6	**28.4**
	6.0	23.1	8.9	20.6	-2.1	-2.2	0.0	-4.3	-2.5	-1.0	-0.7	-7.3	16.7	**49.2**
	8.5	29.3	19.0	17.9	22.6	-8.4	-6.7	-5.5	-4.7	-1.6	-7.2	1.2	5.2	**61.1**

Chapters 4 to 8 present regional, and where possible, district level climate change analyses.

4 PROFILE: KASKAZINI A (ZANZIBAR)

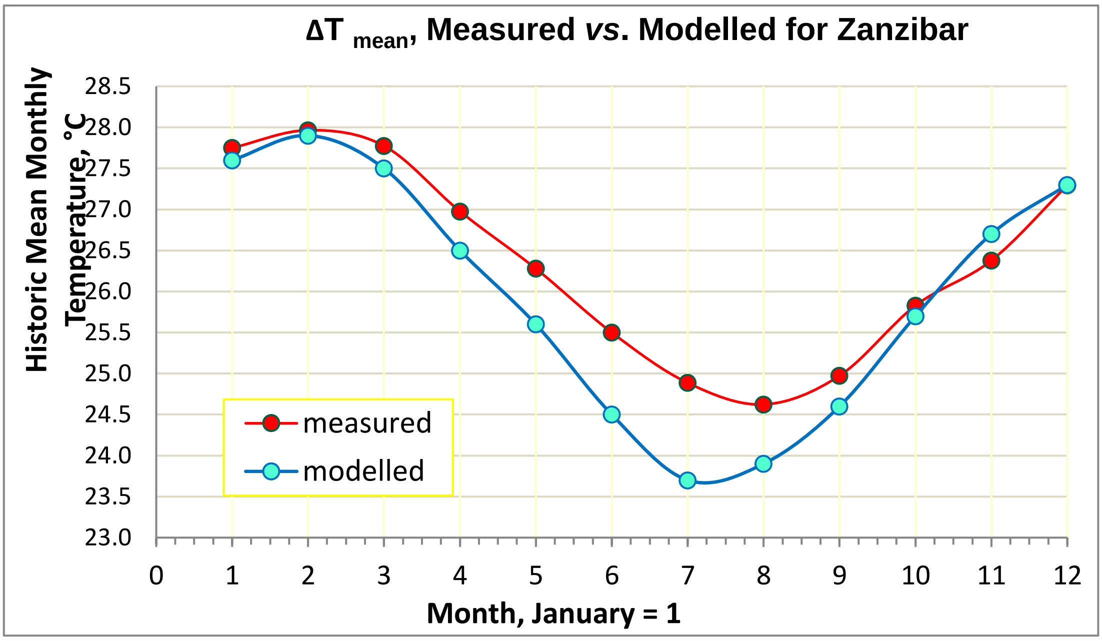
4.1 General

The working dataset is for Zanzibar airport, located at 39° 13' 17.3" E, 6° 13' 12" S, and is considered to be of high quality. The station lies some 33 km SSW of Kaskazini-A Shehia. It has an elevation of 16 metres above mean sea level ('mamsl') and was opened in 1951 with the first full year of data collected in 1952. The percentages of missing data are Tmax 1.8, Tmin 0.8, RH 1.5, sunshine 11.0, wind-run 0.0.

4.2 Temperature

There is inevitably a small discrepancy between historic temperatures as computed, as opposed to 'as measured'. The *computed* temperatures are the median of the model ensemble outputs, as averaged over the entire grid cell. The *measured* temperatures are for the specific location, in this case Zanzibar airport. These monthly discrepancies are shown in Figure 23, below. For the purposes of climate change this mean discrepancy, the 'bias correction', is taken as 0.4°C. That is, for climatic projections, $T_{final} = T_{modelled} + 0.4$.

Figure 23: The Bias Correction for mean monthly temperatures at Zanzibar



Zanzibar's mean annual temperature was historically 26.4°C. The median projected temperatures (bias corrected) range from about 27.0°C in the 2020-39 time-slice, to 29.4°C by the end of the century, with substantial variation according to the carbon emissions scenario. The change estimates are shown in Figure 24. If somewhere between RCP 4.5 and 6.0 is regarded as the most likely, then the end of century temperature increase relative to the present will only be about 1.6°C, yielding a mean annual temperature of 28°C by century end. Such a modest increase is to be expected given Zanzibar's maritime position, and the controlling influence of the local SSTs.

Figure 24: Ensemble Model Projections of Changing Temperature in Zanzibar

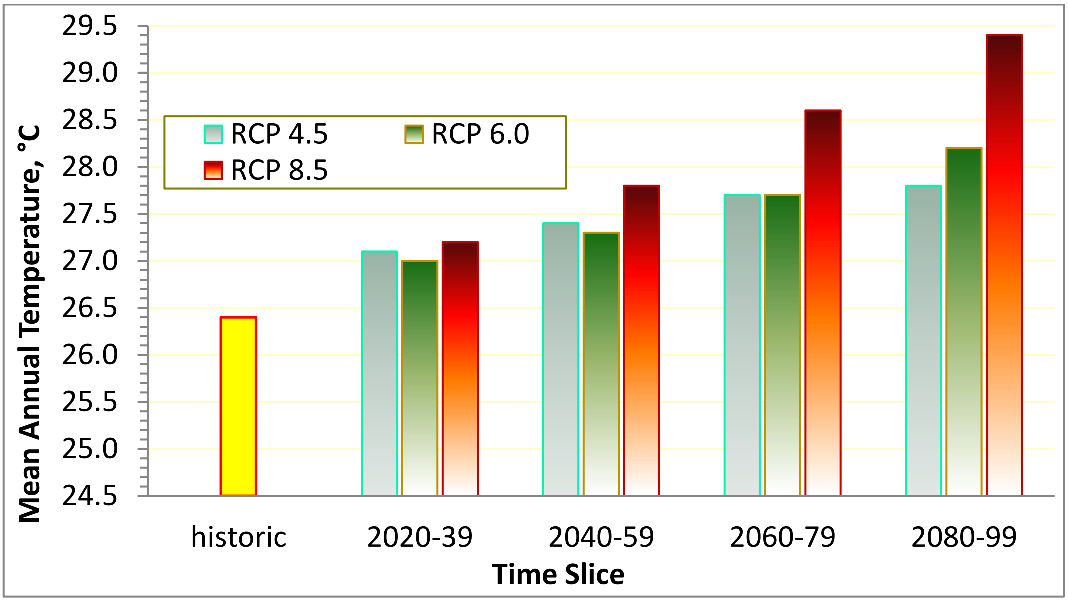
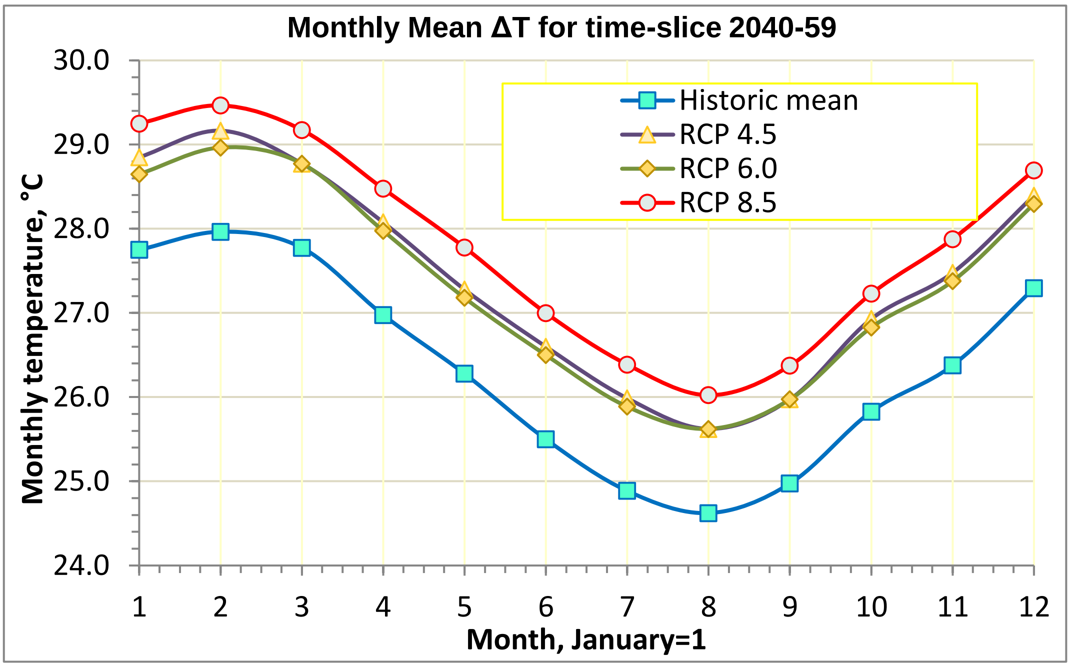


Table 4: Median Ensemble Mean Annual Temperature Change Projections, °C

CMIP-5 data for Zanzibar (Bias Corrected)

Station	Historic mean	RCP	2020-39	2040-59	2060-79	2080-99
Zanzibar	26.40°C N=61	4.5	27.10	27.40	27.70	27.80
		6.0	27.00	27.30	27.70	28.20
		8.5	27.20	27.80	28.60	29.40

Figure 25: Projected Seasonal Changes in Temperature for Zanzibar



Note: Figure 25 is just one example. Other time-slices show a similar pattern but with different offsets relative to the historic record.

Public perceptions of an increase in the historic temperatures are confirmed by the frequency of maximum and minimum daily temperatures, as shown in the histogram of Figure 26 and Figure 27. Climate modelling indicates that this trend will continue, as in Figure 5. However, there is a mismatch between the measured trend and projected rates of change. Even conservative non-linear extrapolation of the instrumental trend would imply that, by century end, the number of additional days >35°C will more closely approximate the modelled maximum than the modelled median.

Figure 26: Historically Increasing Frequency of Hot Days, >35°C in Zanzibar

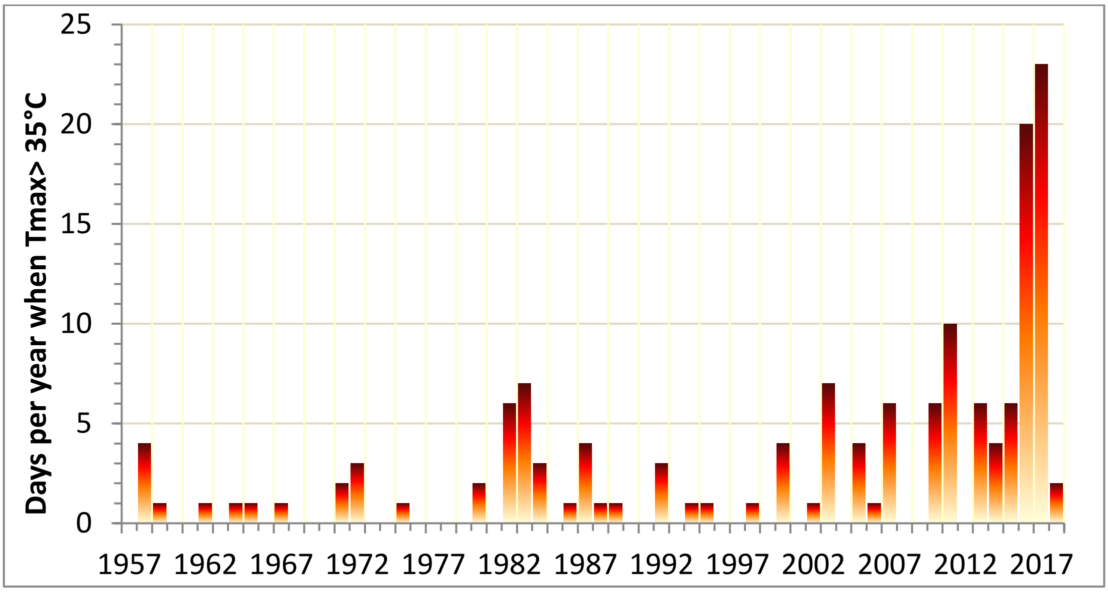


Figure 27: Historic Minimum Night-time Temperatures >25°C, Zanzibar

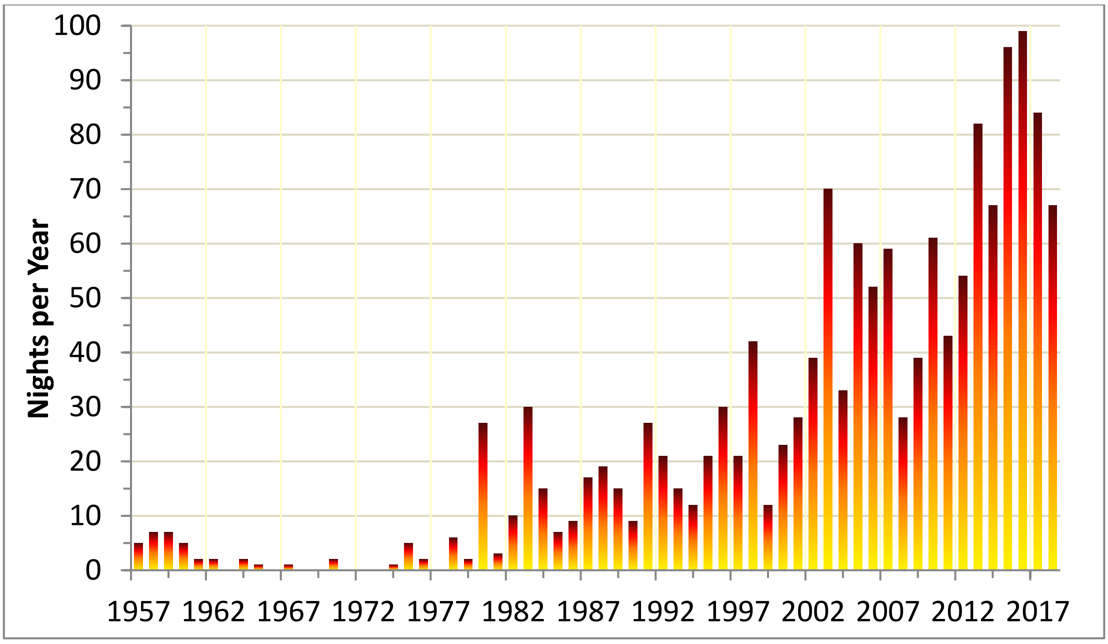


Table 5: Modelled number of additional days of >35°C by 2080-99 at Zanzibar

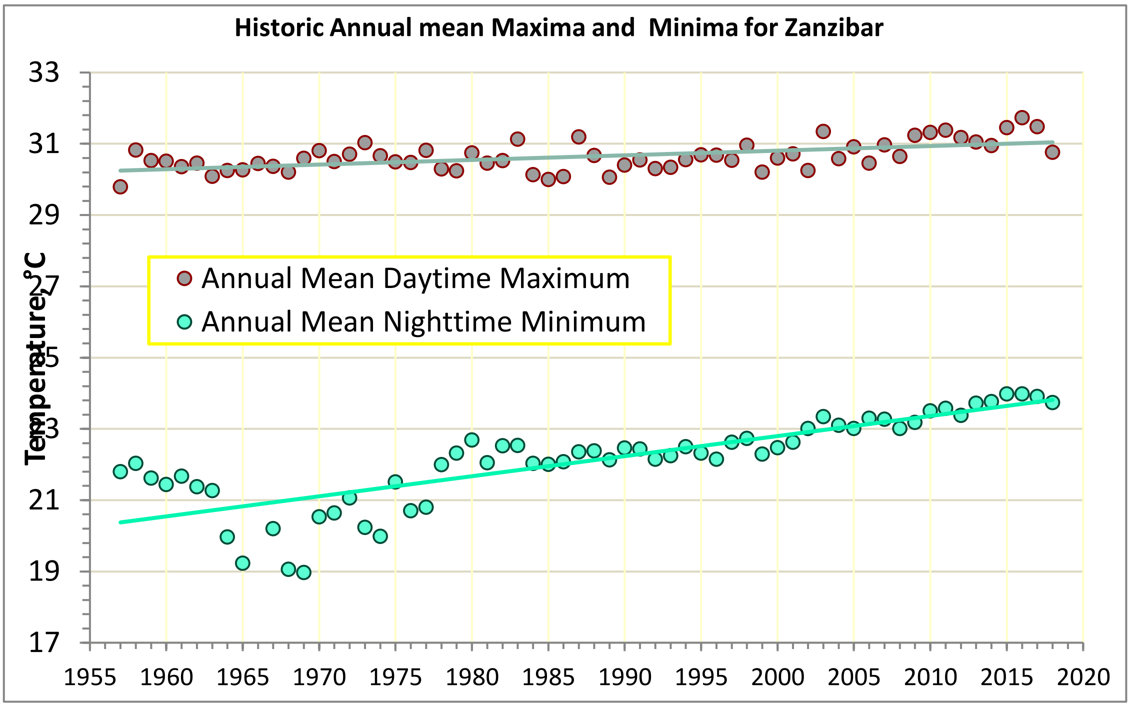
RCP	Median number of days/year	Maximum number of days/year
4.5	+2	+8
6.0	+3	+10
8.5	+14	+24

The ameliorating influence of SSTs will ensure that there will be few, if any, additional days of >40°C in Zanzibar, whatever the emissions trajectory.

From the perspective of heat stress in both humans and livestock, by far the biggest impact will be the rapid increase in night-time minimum temperatures which, from the 1980s onwards, has consistently risen at about three times the rate of maximum day-time temperatures. This is shown in Figure 28, with increasing night-time temperatures occurring most notably from May to November.

Over most of Tanzania the heat index-35 is insignificant, the only possible exception being the coastal zone, under the most extreme scenario (RCP 8.5 by 1980-99). In practice, this is unlikely to be of serious concern throughout this century.

Figure 28: Night-time minima warming faster than day-time maxima



4.3 Rainfall

The mean annual rainfall is 1627 mm with an inter-annual variability of 26.5%. The monthly/ seasonal rainfall distribution is shown in Figure 29 indicating long rains predominantly from March to May, and short rains from October to December.

Figure 29: Historic Mean Daily Rainfall in Zanzibar, mm

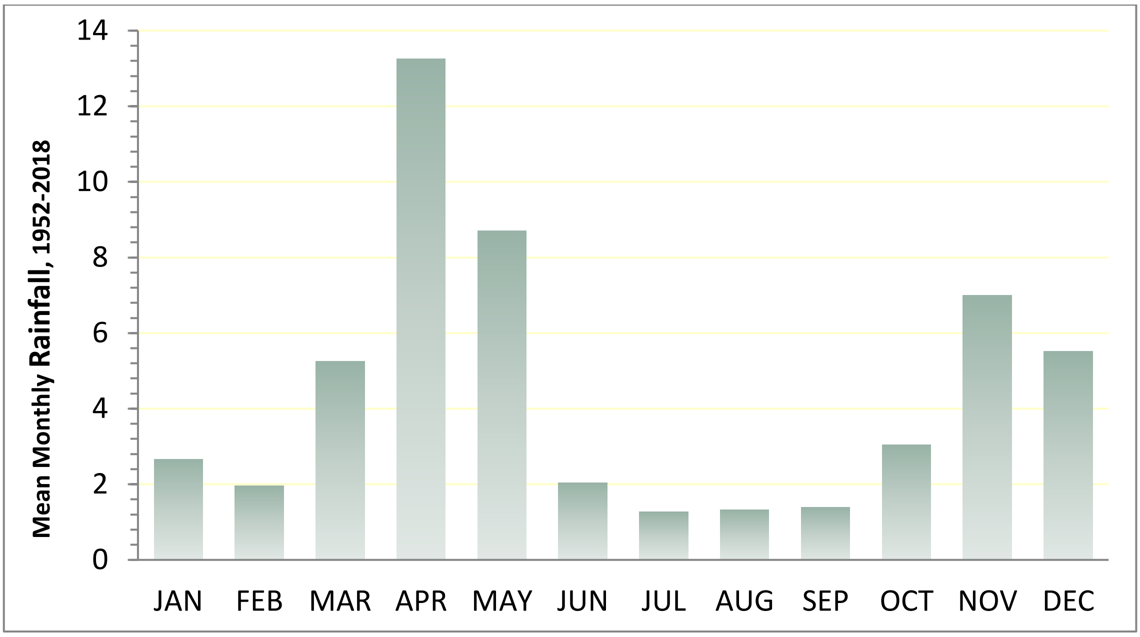


Figure 30 shows that he historic dataset is statistically homogeneous and stationary, both in respect of annual rainfall and 24-hour rainfall intensity (>30 mm). That is, there has been no discernible change over time, prior to 2018.

Figure 30: Annual Rainfall Distribution at Zanzibar

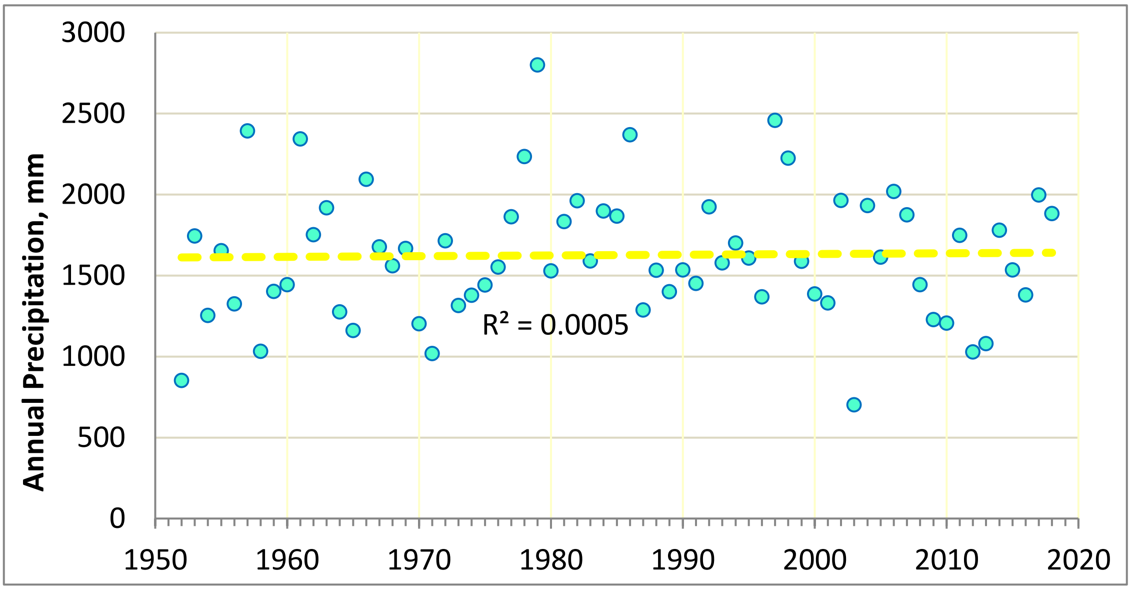


Figure 31: Rainfall Intensity at Zanzibar; by just one of several definitions

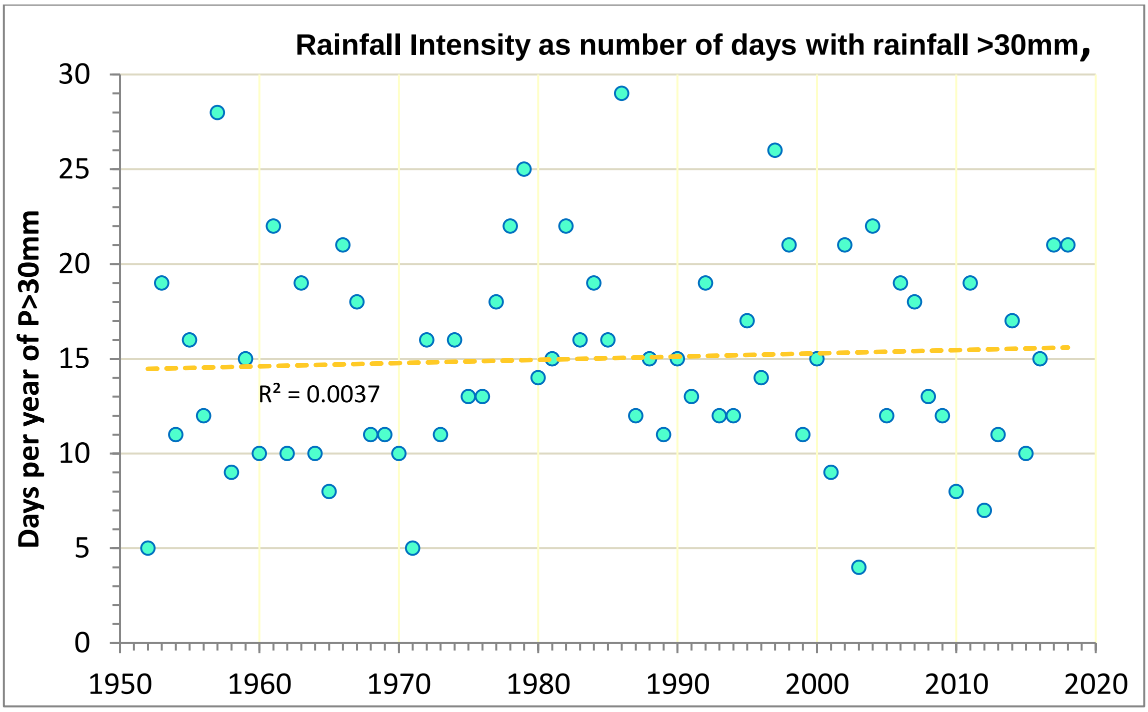
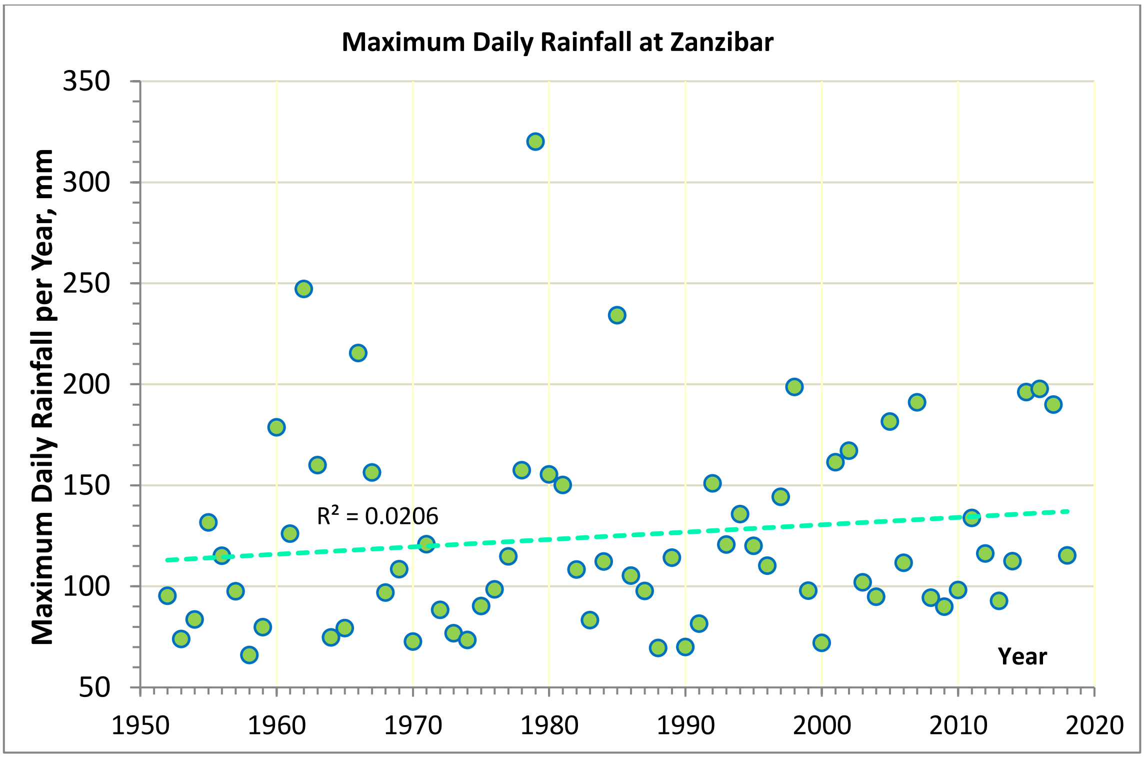


Figure 32: Maximum Daily Rainfall per Year, mm, at Zanzibar



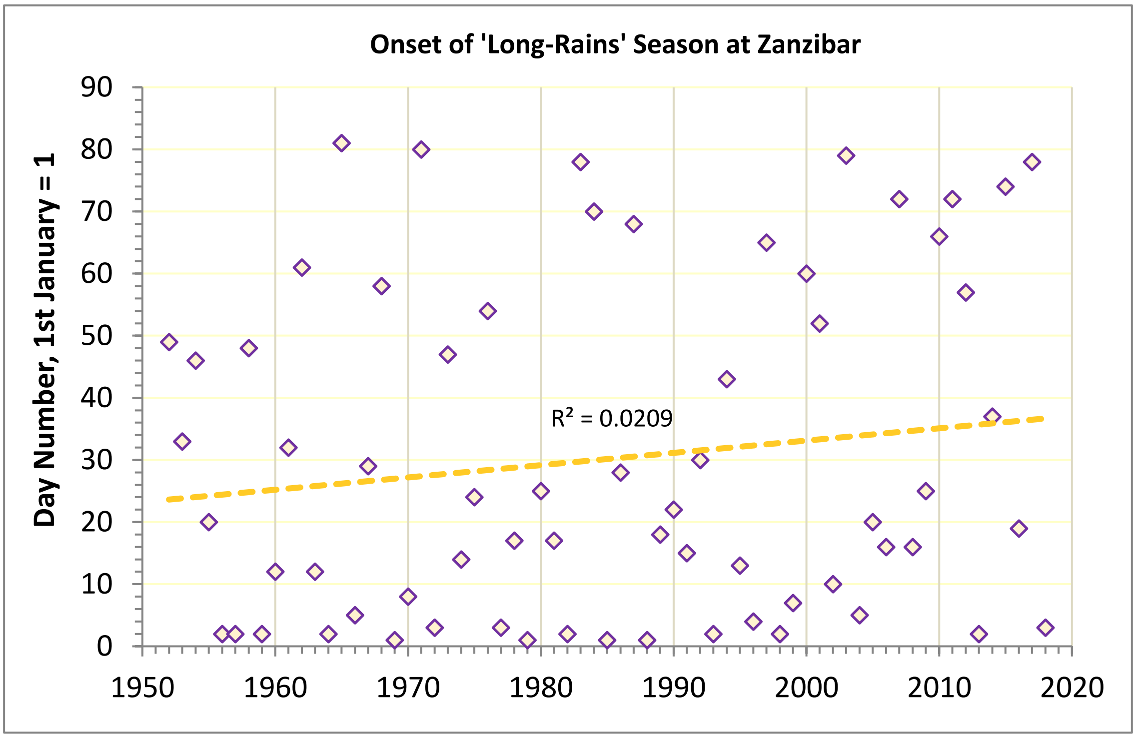
4.4 Rainy Season Onset

Onset of the rainy season, i.e. the 'long rains', is not well-defined. For assessment purposes it is here taken as *the first significant rain of ≤5 mm which is not followed by 10 or more days without rain*. Other definitions are possible, the most appropriate of which is entirely subjective.

As indicated in Figure 33, there is a weak statistical trend towards the onset of the main rainy season ('long rains'), currently occurring about 10 days later than in the mid- 20th century – *on average*. However, this trend is largely masked by strong inter-annual variability in which the onset can occur anywhere within the first 10 weeks of the year.

Within the Indian Ocean rainy seasons are controlled by SSTs and the annual migratory locus of the inter-tropical convergence zone ('ITCZ'). Within continental East Africa, this is not the case (Yang et al, 2014). Rather, the rainfall is predominantly a function of low-to mid-level tropical storm instability. Zanzibar is at the boundary of these two climatic régimes, and hence it is not possible to predict whether or not this weak trend in rainfall delay will intensify.

Figure 33: Effective Onset of the 'Long-Rains'



CMIP-5 ensemble projections of the changes in rainfall are, at most, about +5% (see Table 6), and are well within the implicit error bounds of computation. Hence, they can't be relied upon except to indicate the general trend of existing models. It is quite possible that the CMIP-6 generation will see a significant shift in the projected changes, either positive or negative.

Table 6: Median Ensemble Mean Time-slice Rainfall Projections, mm

CMIP-5 data for Zanzibar (Bias Corrected)

Historic mean, mm	RCP	Incremental Additions, mm			
		2020-39	2040-59	2060-79	2080-99
1630	4.5	14	13	35	62
	6.0	13	39	43	80
	8.5	18	26	40	89
		Projected Average Total Rainfalls			
	4.5	1644	1643	1665	1692
	6.0	1643	1669	1673	1710
	8.5	1648	1656	1670	1719

4.5 Rainfall Variability

The statistical spread of historic monthly rainfall at Zanzibar is shown in Figure 34 (projected future dry-season trends are indicated by the arrows), and is listed in Table 7, below.

Figure 34: Historic Wet and Dry Year Contrasts in Zanzibar

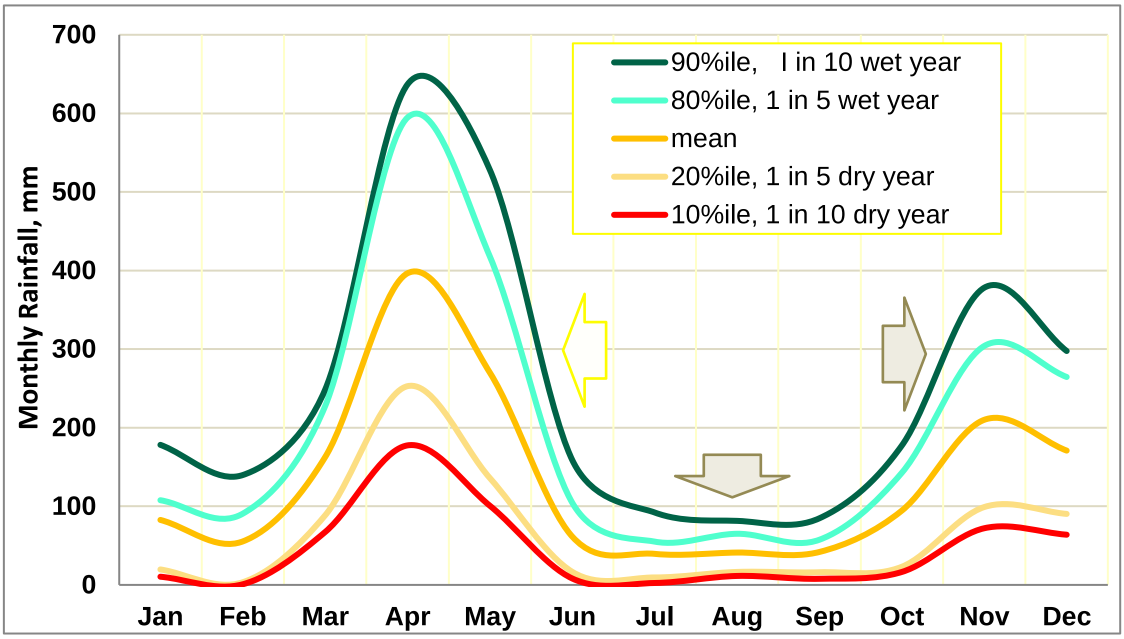


Table 7: Historic wet and dry year contrasts at Zanzibar, mm

ZANZIBAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
90%ile, I in 10 wet year	178	140	249	637	528	159	92	81	85	177	378	298	**3002**
80%ile, 1 in 5 wet year	108	91	228	595	418	104	55	65	58	143	304	265	**2432**
mean	83	55	163	397	270	61	39	41	42	95	210	171	**1627**
20%ile, 1 in 5 dry year	20	3	89	253	136	17	10	17	16	23	99	90	**772**
10%ile, 1 in 10 dry year	10	1	67	178	101	8	2	11	8	16	72	64	**539**

The CMIP-5 modelling consistently indicates that the long dry season will become longer, with more intense droughts. There is some ambiguity / lack of clarity regarding rainfall trends during the 'between season' of December to February.

It is strongly emphasized that agricultural viability is not determined by mean or median conditions, but by the crop-water shortfall during dry years. Historically, there has been a more than three-fold variation in, for example, the I-in-5 dry year and I-in-5 wet year. Regardless of which carbon trajectory eventuates, this inter-annual variability is expected to deepen throughout the remainder of this century.

Because of its maritime position Zanzibar has by far the highest dry-season rainfall of any of the EbARR project areas.

4.6 Projected Climatic Trends

Figure 35: 35-Model Median Projected Change in Rainfall for Zanzibar, RCP 4.5, 2020-39

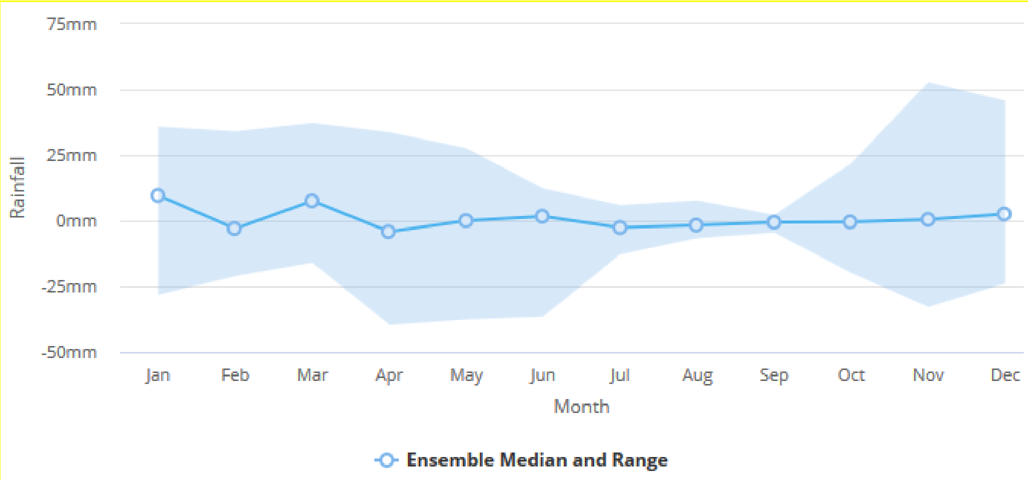
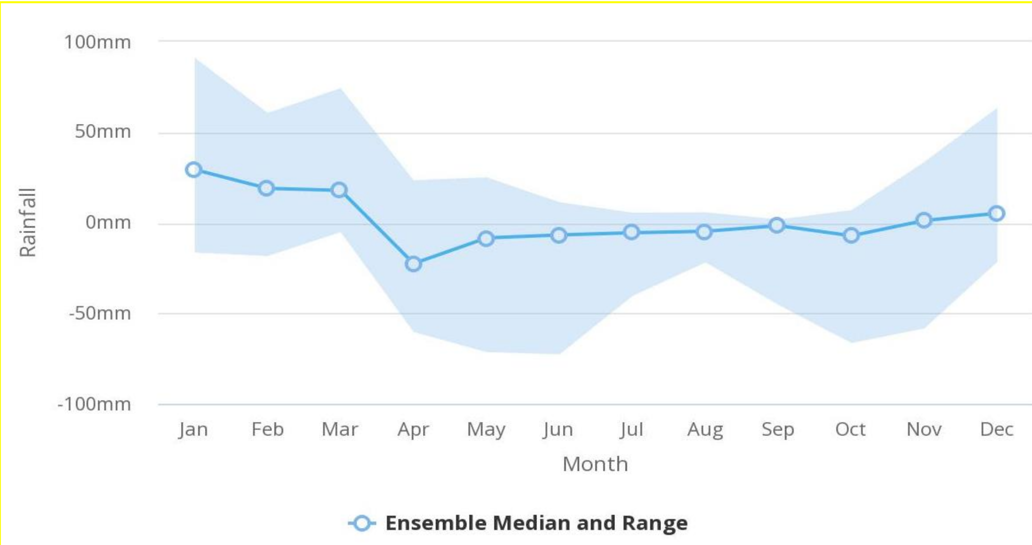


Figure 36: 35-Model Median Projected Change in Rainfall, Zanzibar, RCP 8.5, 2080-99



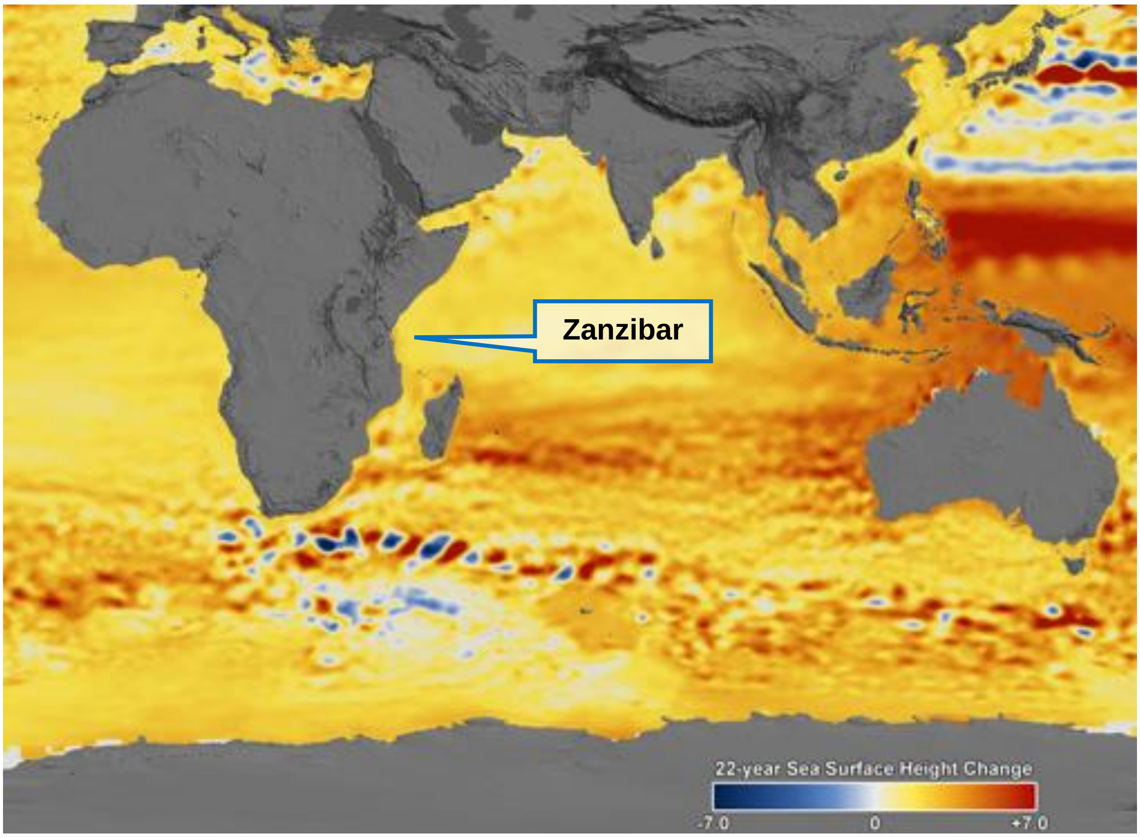
Source: WBCCP – Risk Assessment

4.7 Sea Level Rise

Perhaps counter-intuitively, sea level rise differs substantially with location in response to ocean currents, thermal redistribution and isostatic adjustments. In the case of Zanzibar sea level rise, since satellite monitoring commenced in 1992, has been very slightly less than average (Figure 37). This slow response is *not* expected to continue because the IOD is expected to create thermal expansion in the western Indian Ocean much more frequently in the future.

Numerous projections of the likely sea level rise have been published, and all have an unfortunately large margin for error due to the numerous implicit uncertainties of emissions scenario and poorly calibrated feed-back processes.

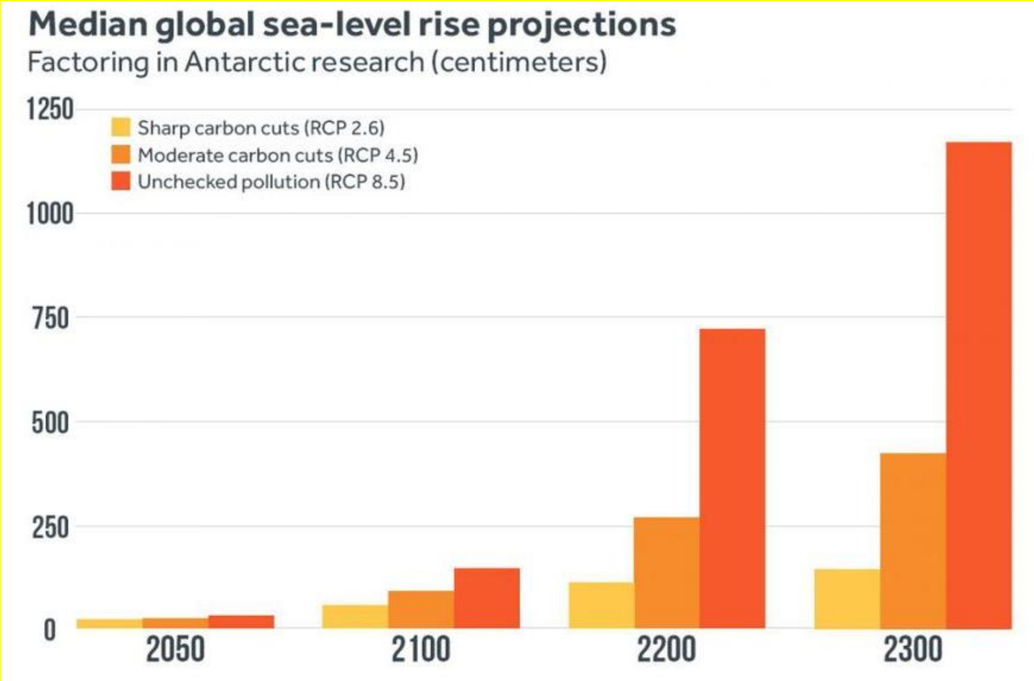
Figure 37: 22 years of global sea level change



Source: NASA Scientific Visualization Studio, Data from OPEX/Poseidon, Jason-1 and Jason-2 satellite altimeters.

Several important points must be considered. Over the last decade, IPCC estimates of the rate of sea level rise have been consistently superseded by faster rates, such that the former worst case scenario now looks like the optimistically best-case scenario. As of September 2019, the sea level rise of 2100 appears to be in the range 85 ± 25 cm. Whatever the century-end sea level rise will be, the rate of sea level rise will still be accelerating, resulting in much worse sea level rises in subsequent centuries, as shown in Figure 38 below. The ultimate sea level rise, perhaps millennia into the future, cannot be less than about 7 meters. This being the case, *the entire* current coastal and near-coastal infrastructure is ultimately unsustainable.

Figure 38: Median Global sea-level rise projections (in cm)



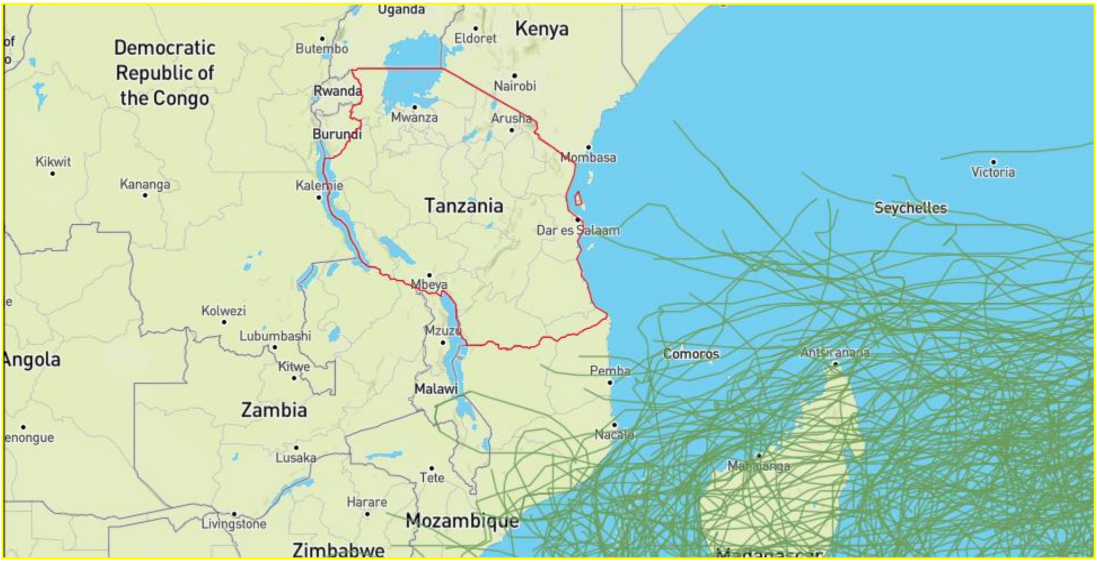
Source: Climate Central

4.8 Tropical Storms

Sea surface temperatures (SSTs) are certainly set to increase east of Tanzania. Some modelling puts the SST by 2100 as high as 30°C. Since an SST of >27°C is a pre-requisite for the development of tropical storms / hurricanes, some concern has been expressed regarding the future potential for such storms. Two factors run counter to this concern. Firstly, the low latitude of Tanzania ensures that there is insufficient spin to 'kick-start' the tropical storm[2]. This is apparent from the historic loci of tropical storms and hurricanes, shown in Figure 39 below.

[2] The law of 'conservation of angular momentum' does not allow rising tropical air to begin spinning significantly until the Coriolis effect becomes substantial, at about 6 to 8°S.

Figure 39: Historic Cyclone tracks in the Western Indian Ocean



Secondly, as global warming progresses wind-shear intensifies, and hence disruption of convective cell complexes tends to break up tropical storms before they evolve further. The net effect is that the future frequency and location of tropical storms is unlikely to change much from the historic picture'.

Zanzibar is close to the theoretical northern limit of tropical storm locations. There is a small risk of tropical storm damage across the whole island, but the future risk is unlikely to be much different from historic conditions. For the rest of this century the south-eastern-most tip of Tanzania will incur a slightly elevated hurricane risk which could cause severe damage to areas within about 30 to 40 kilometers from the coast.

4.9 Evapotranspiration

Reference potential evapotranspiration ('ET_0' in mm.day^{-1}) was calculated for the mean monthly historic data, and for the projected scenarios of RCP 4.6, 6.0 and 8.5, both for 2060-80 and for 2080-2100 time-slices. This procedure used the FAO's online ET_0 calculator, version 3.2, based upon the Penman-Monteith equation, see http://www.fao.org/land-water/databases-and-software/eto-calculator/en/. The results are given in Table 8, Table 9 and Table 10 below.

Table 8: Summary and output of monthly historic (1957-2018) climatic data for calculating daily potential reference evapotranspiration, ET_0, at Zanzibar

Parame-ter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
M max T °C	32.1	32.8	32.2	30.4	29.6	29.1	28.8	29.2	30.2	30.9	30.9	31.6
M min T °C	23.4	23.2	23.4	23.5	22.9	21.9	21.0	20.0	19.7	20.7	21.9	23.0
R.H. %	78.7	77.8	82.0	85.4	83.8	79.6	78.6	78.9	78.5	79.4	82.6	81.9
Wind-run	156	142	106	103	116	138	157	147	145	143	109	118
Hrs brt sun	8.5	8.6	7.0	6.0	6.5	7.7	7.9	8.1	8.3	8.5	7.8	8.3
ET_0, mm	**5.0**	**5.1**	**4.4**	**3.7**	**3.5**	**3.6**	**3.8**	**4.1**	**4.5**	**4.7**	**4.5**	**4.7**
									Mean Annual ET_0			**4.3**

Table 9: Summary and output of monthly projected climatic data for calculating daily evapotranspiration, ET_0, at Zanzibar. RCP 6.0; 2040-59, bias corrected

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
MmaxT °C	33.1	33.7	33.1	31.4	30.6	30.2	29.8	30.2	31.2	32.0	31.9	32.5
MminT °C	24.3	24.2	24.4	24.7	23.9	22.9	21.9	21.0	20.7	21.7	22.9	24.0
R.H. %	78.8	77.9	82.1	85.5	83.9	79.7	78.7	79.0	78.6	79.5	82.7	82.0
Wind-run	176	162	126	123	136	158	177	167	165	163	129	138
Hrs sun	8.7	8.8	7.2	6.3	6.7	8.0	8.1	8.3	8.6	8.7	8.0	8.5
ET_0, mm	**5.2**	**5.2**	**4.6**	**4.1**	**3.7**	**3.8**	**3.9**	**4.2**	**4.7**	**4.9**	**4.6**	**4.9**
									Mean Annual ET_0			**4.5**

Table 10: Summary and output of monthly projected climatic data for calculating daily evapotranspiration, ET_0, at Zanzibar. RCP 6.0; 2080-99, bias corrected

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
MmaxT °C	33.8	34.7	34.0	32.2	31.5	31	30.7	31	32.1	32.8	32.8	33.3
MminT °C	25.2	25.2	25.3	25.5	24.8	23.8	22.9	21.7	21.4	22.4	23.7	24.8
R.H. %	78.9	78.0	82.2	85.6	84.0	79.8	78.8	79.1	78.7	79.6	82.8	82.1
Wind-run	196	182	146	143	156	178	197	187	185	183	149	158
Hrs sun	9.0	9.1	7.5	6.5	7.0	8.2	8.4	8.6	8.8	9.0	8.3	8.8
ET_0, mm	**5.4**	**5.6**	**4.8**	**4.1**	**3.9**	**4.0**	**4.0**	**4.4**	**4.9**	**5.2**	**4.9**	**5.1**
									Mean Annual ET_0			**4.7**

The evapotranspiration, 'ET_0', is significant in several respects. Firstly, when combined with growing-season crop factors ('K_c'[3]) and taking account of local drainage conditions, it indicates

[3] Such as those supplied by FAO, http://www.fao.org/3/X0490E/x0490e0b.htm

the crop-water requirement. Whether the crop is rain-fed or irrigated changes in the mean annual ET_0, as calculated in the tables above, indicate an *increased* water requirement of 4.5% by mid-century, and more than 9% by end-century. This must be factored into the water resources demand in addition to increased domestic water demand (warmer temperatures, population growth), and decreased recharge of groundwater. Increased evaporative losses from reservoirs must also be considered.

Secondly, the increased crop-water demand will be concurrent with increased seasonal soil-moisture deficits between soil surface and the base of the root zone, especially during April to November.

Thirdly, even small changes in ET_0 will have a disproportionate impact upon the effective rainfall. This latter may be crudely approximated as positive values of daily rainfall less daily evapotranspiration, which is essentially the water available for runoff and infiltration.

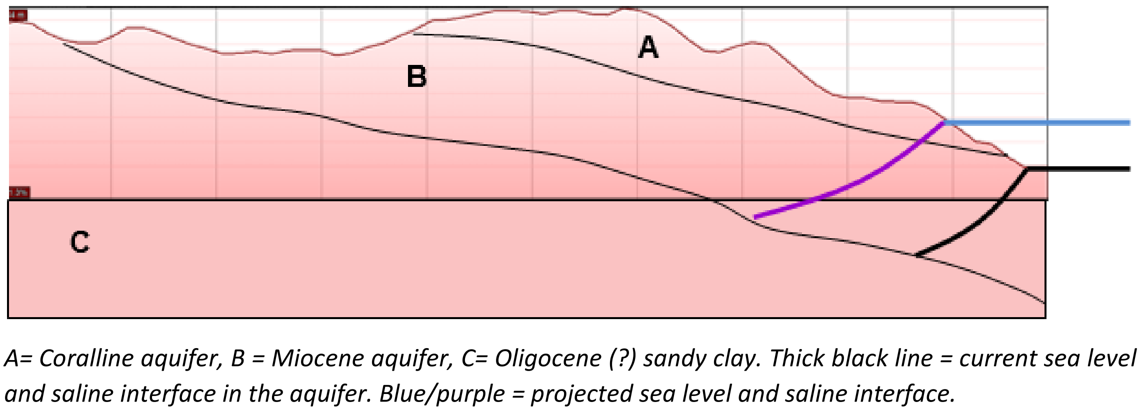
4.10 Groundwater

The geology of north-east Zanzibar consists of recently uplifted coralline limestone overlying more thoroughly lithified Miocene limestone, which in turn overlies relatively impervious sandy clay and marl. This sequence has a gentle easterly dip such that the limestone coastline is in hydraulic continuity with the Indian Ocean. Copyright prevents reproduction of the geological map and section, but it may be accessed on page 4 of Hardy et al (2015).

There is almost no surface drainage on the limestone areas although some perennial flow occurs in the drainage divide area, on the sandy-clay 'bedrock'. Otherwise, both the coralline and Miocene limestones are permeable, with the development of sub-karstic to eukarstic conditions.

Groundwater recharge is generated by both runoff from the island divide, and by direct vertical infiltration. A quantitative assessment is impossible without field hydrogeological investigations. However, qualitatively, it is obvious that climate-change will stress the groundwater resource by reducing the effective rainfall (and hence the recharge), and by rising sea level inducing saline intrusion into the limestone aquifer.

Figure 40: Conceptual 5 km E-W section of the North-East Coast of Zanzibar



A= Coralline aquifer, B = Miocene aquifer, C= Oligocene (?) sandy clay. Thick black line = current sea level and saline interface in the aquifer. Blue/purple = projected sea level and saline interface.

There is a clear double climate-change threat to the existing aquifer in the north-east of the island. Therefore, if the freshwater aquifer is to be preserved, then it becomes imperative for action to be taken in the near future. Such action is expected to include:

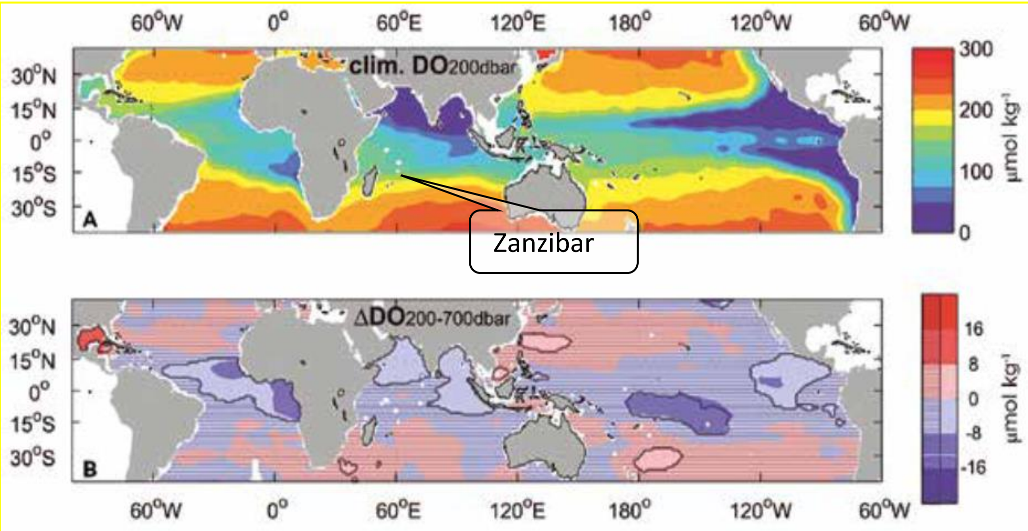
- Hydrogeological mapping with particular regard to karstic development.
- More precise assessment of the aquifer dimension and boundaries
- Emplacement of observation wells (monitored piezometers) to analyze recharge, recession, seasonal fluctuations in the piezometric surface, and to characterize the configuration and stability of the saline interface.
- An inventory of current groundwater usage and projected future demands.
- Strict limitation of borehole extraction rates to within safe sustainable limits.

4.11 SSTs and Ocean Acidification

Fish catches off the Tanzanian coast increase when the SSTs and humidity are below normal, and vice versa. Sea Surface Temperatures ('SSTs') are only partly controlled by climate change. They are mainly a function of phases in the quasi-decadal IOD and related currents. In a general sense, and other factors being equal, one might expect the overall trend of rising SSTs to decrease fishery productivity towards the end of the century.

The issue of Ocean Acidification was recently highlighted in the COP25 meeting (Madrid, December 2019). Global warming will create both gains and losses in dissolved oxygen at regional level. However, "relatively warm equatorial ocean waters and eastern ocean coastal margins with productive upwelling systems are less oxygen rich relative to higher latitude and western ocean basins, and this difference in dissolved oxygen levels is expected to widen in coming decades".

Figure 41: Oxygenation and Deoxygenation status of the Oceans



Note: The upper diagram indicates the historic mean oxygen concentrations of seawater at 200 dbar, which is dominated by the latitudinal temperature control. The lower diagram indicates projected changes in oxygen concentration between 200 and 700 dbars. Data modified from Stramma et al (2010). See also Laffoley and Baxter (2019).

As Figure 41 indicates, the waters off Tanzania can expect to see a slight reduction in oxygen concentration of up to 8 $\mu mol.kg^{-1}$ O_2. This is equivalent to a decrease of about 5%. It is expected that this will adversely affect pelagic fish stocks with a high metabolic rate, such as sharks, tuna and marlin, whilst jellyfish and benthic low-metabolic fish stocks will increase.

Overall, the combined effects of rising ocean temperatures, falling oxygen levels, and changing nutrient availability will have complex ecological knock-on effects. Historically, the global annual fish catch has remained approximately constant since about the mid-1980s, whilst aquaculture / fish farming has increased continuously and substantially. In places like the western Indian Ocean projections of the future wild fish catch are likely to see a decline, albeit with major short-term fluctuations. Hence, the trend is increasingly towards the development of aquaculture.

4.12 Additional Considerations

On land, the ecological and water resources impacts of a 2 to 3°C warming will have further consequences in such areas as disease vector mobility, photosynthetic efficiency in crops, heat-stress in livestock, groundwater recharge and availability, and surface water storage requirements. These all require further research as a matter of urgency.

5 PROFILE: SIMANJIRO (AT ARUSHA/BABATI, MANYARA)

5.1 General

The closest meteorological station to Simanjiro district, and hence the primary dataset is for Arusha airport, at 3°22’03.1” south, 36°37’33” east, at an altitude of 1388 meters, and is considered to be of high quality, with a station record of about 59 years. Arusha is some 130 Km NW of Simanjiro.

Babati station, at an elevation of 1416 meters, is 159 km west of Simanjiro (elevation 1287 meters), but only has rainfall data and a dataset duration of 26 years. However, the physiographic setting of Babati may be closer to that of Simanjiro.

Simanjiro is 230 km from the coast, and hence has little or no climatic influence from the Indian Ocean.

5.2 Temperature

Projected temperatures are modelled on a mean monthly basis, shown in Figure 42, for 2050 and 2090, and for RCPs 4.5, 6.0 and the worst case 8.5. The most likely increase of about 1.5°C, relative to recent historic temperatures, is about normal for a tropical to sub-tropical environment.

Figure 43 illustrates the historic increased frequency of hot days in Arusha. Currently, the available data do not justify anything more than a linear approximation, but over the next century or two it is likely that this trend will conform to an error function (sigmoidal), whose upper bound is currently indeterminate, and which is likely to remain indeterminate until at least mid-century.

Figure 42: Seasonal Temperatures at Arusha: Historic vs. Projected

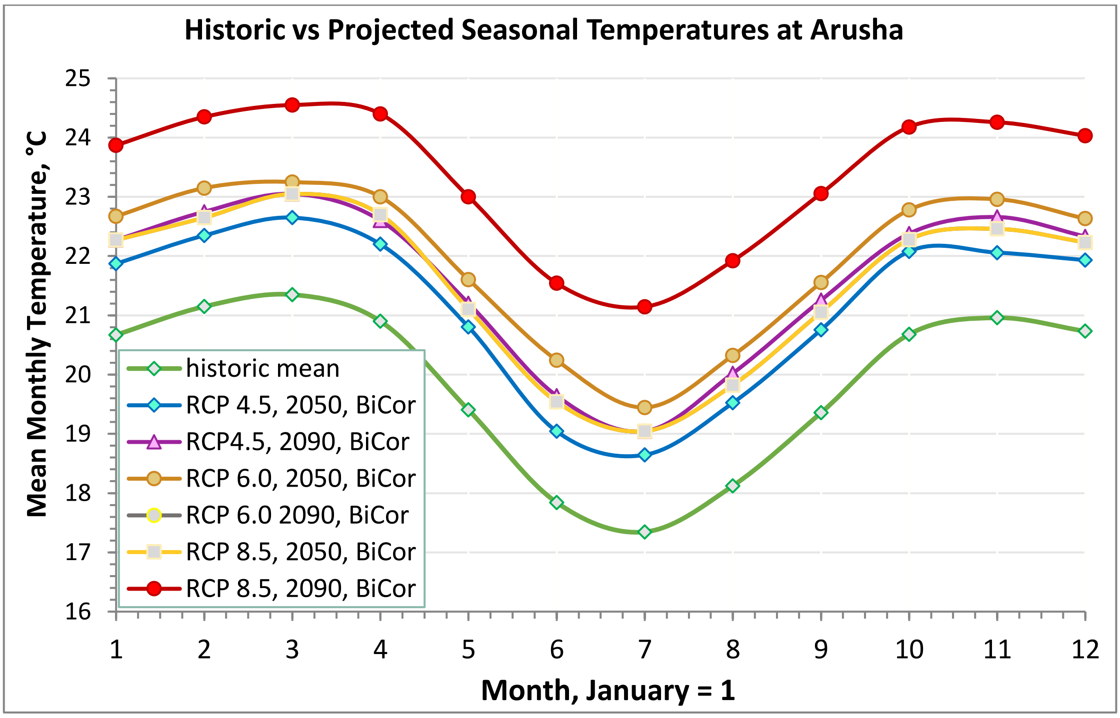


Figure 43: Increasing frequency of hot days in Arusha

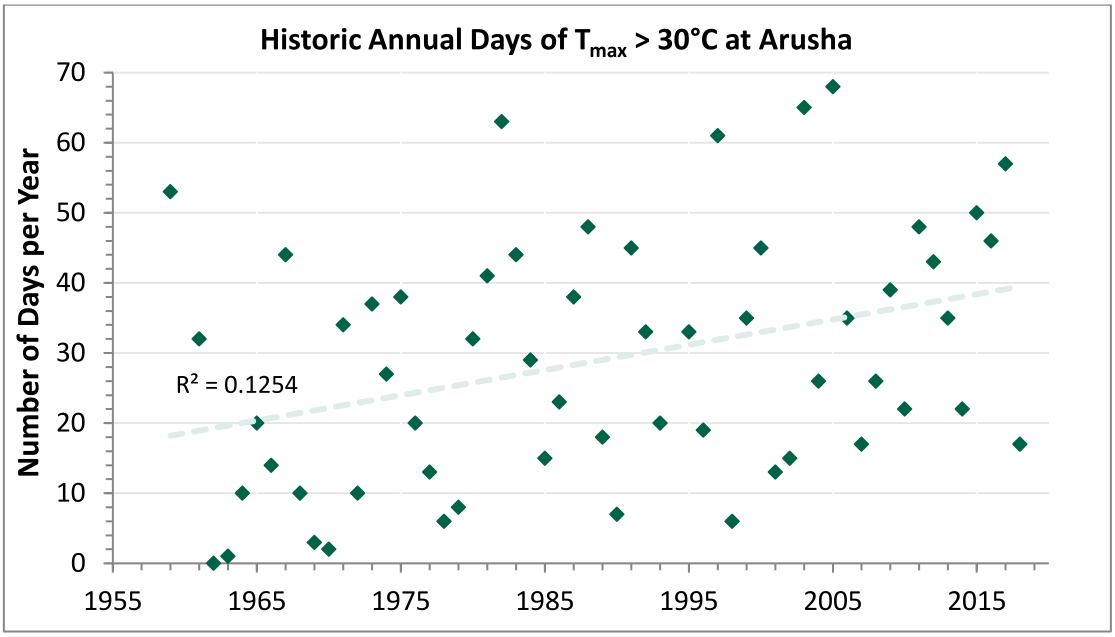


Figure 44 indicates the historic increases in maximum daytime temperature, and the minimum night-time temperature. In common with most regions, the increase in night-time minima is roughly three times the rate of increase in day-time maxima. This has implications for human health as the resilience to day-time maxima is seriously compromised by the reduced capacity to cool down during the night. The implications for crops and livestock is currently unclear.

Figure 44: Historic Drifts in Night-time Minima and Day-time Maxima

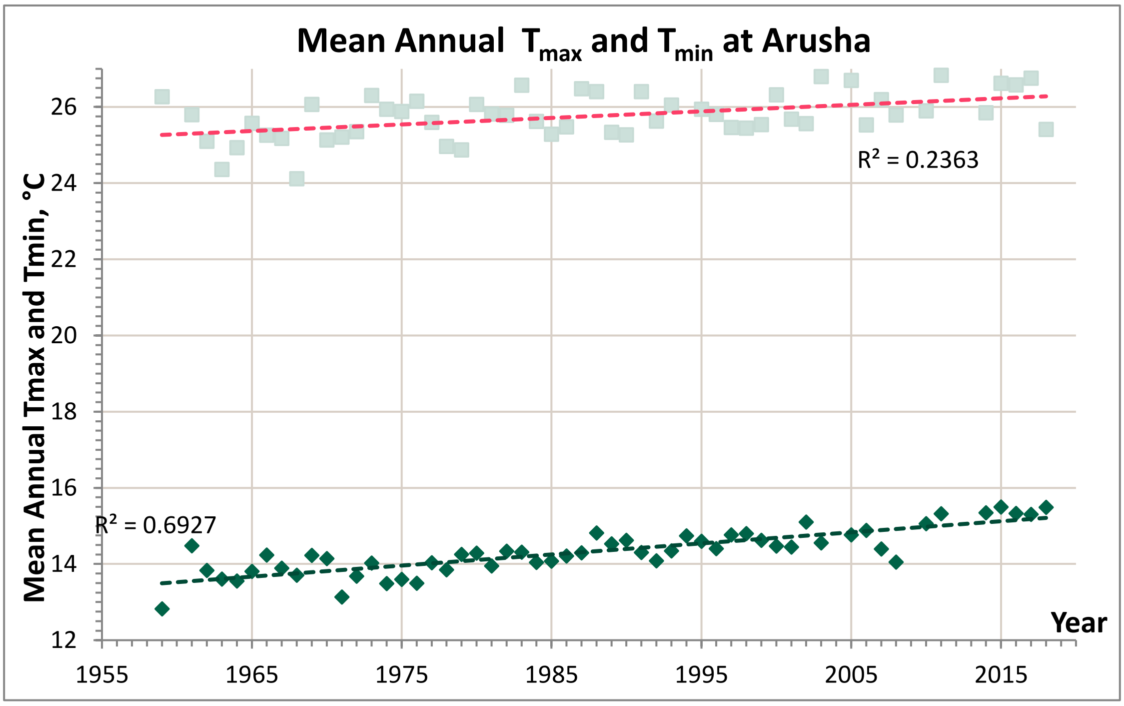
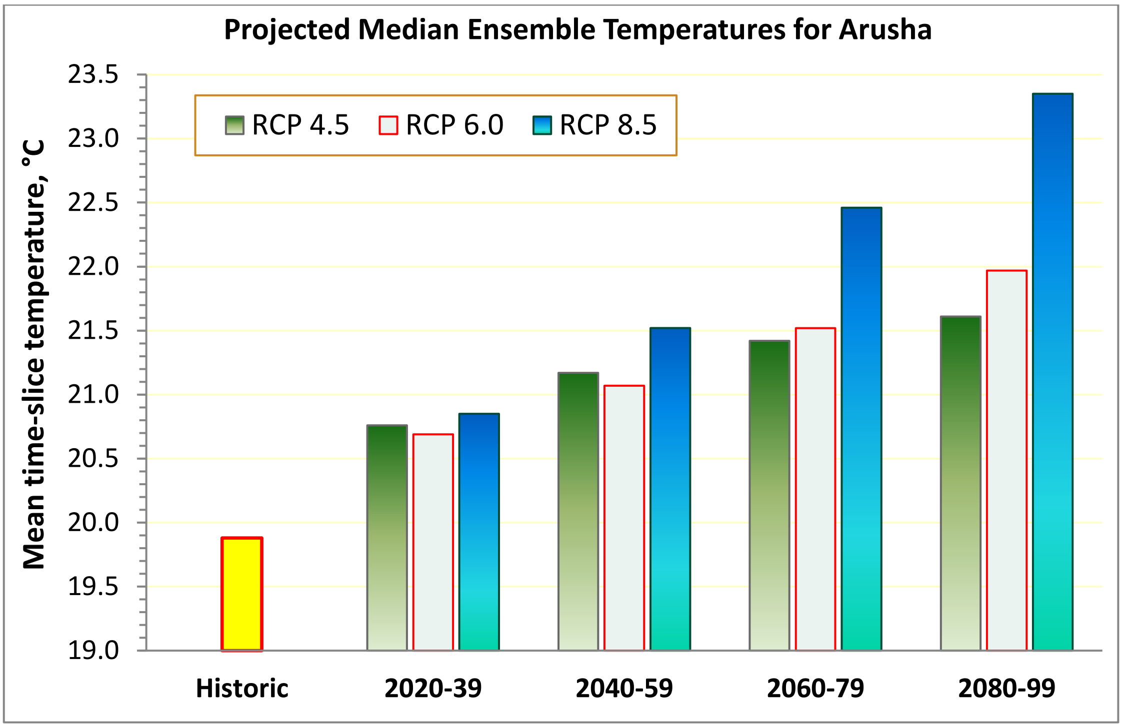


Figure 45: 20-year time-slice temperature projections for Arusha



For numerical comparison the data of Figure 45 are compared in Table 11. Note that mean annual temperatures are presented 'as computed', to two decimal places. This does *NOT* imply either accuracy or precision to two decimal places! Note also that the forward projections are in 20-year time-slices, whereas the historic data are effectively a 60-year time-slice. The CMIP-5 data for Arusha are bias-corrected for that station.

Table 11: Median Ensemble Mean Annual Temperature Change Projections, °C, Rainfall

Station	Historic mean	RCP	2020-39	2040-59	2060-79	2080-99
Arusha	19.88°C N=54	4.5	20.76	21.17	21.42	21.61
		6.0	20.69	21.07	21.52	21.97
		8.5	20.85	21.52	22.46	23.35

Figure 46 and Figure 47 present the historic rainfall picture for Arusha/Babati. The 59-year rainfall record for Arusha yields no significant evidence of a change in the onset of the long-rains.

Figure 46: Historic Mean Monthly Rainfalls at Babati and Arusha

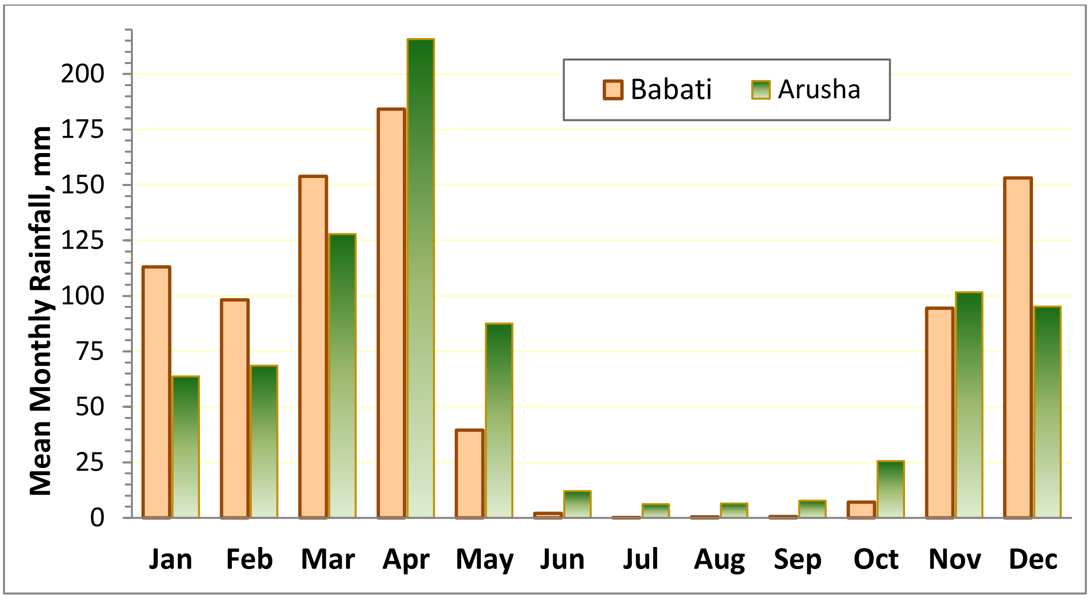


Figure 47: Statistically Weak Annual Rainfall Decline at Arusha

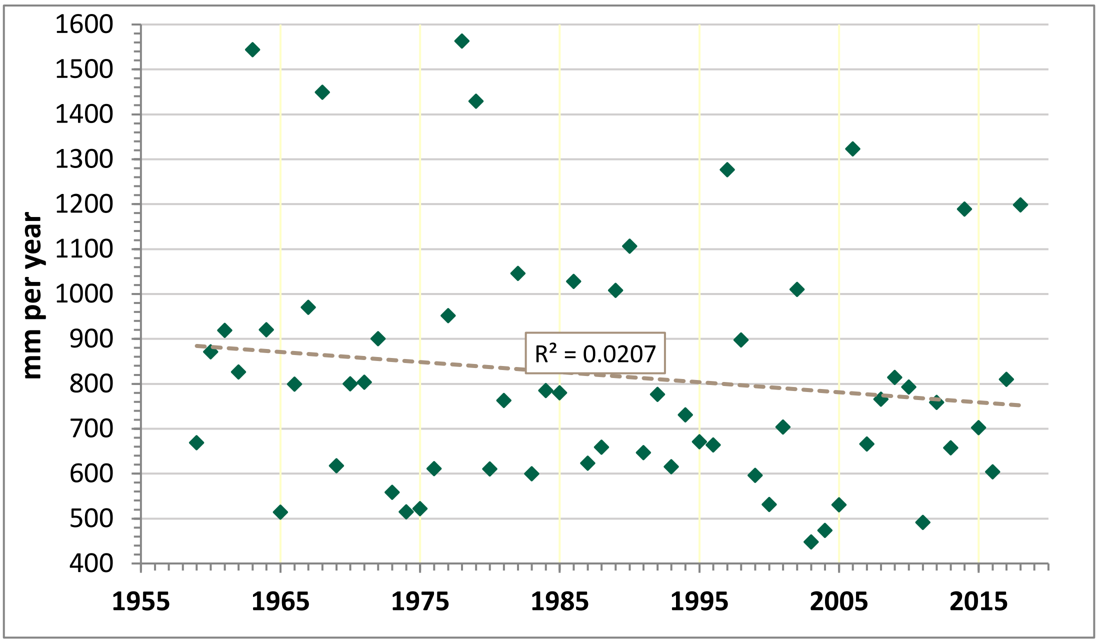
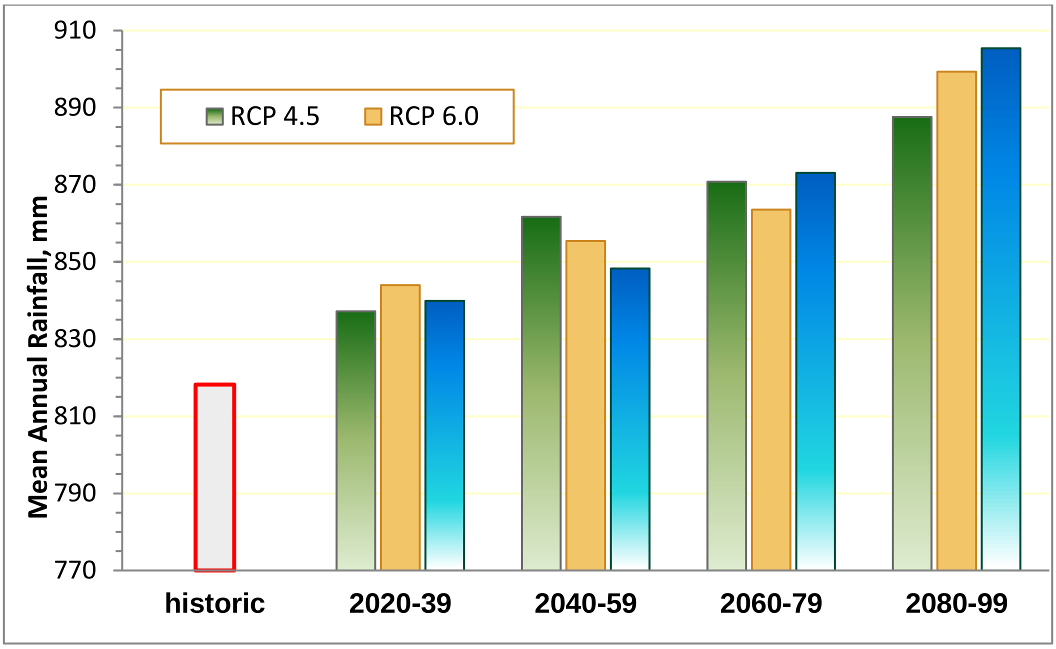


Figure 48: Historic and Projected Mean Time-slice Rainfalls at Arusha



Note: The above projected rainfalls are all bias corrected for Arusha met station.

Cautions:

i. The computed gain in total rainfall is contradicted by both field perceptions of farmers, and by recent instrumental trends. The latter indicates a medium-term *decrease* in rainfall over the decade prior to 2018, which is most probably an artefact of the IOD rather than of long-term climate-change.

ii. There is good evidence to suggest that the CMIP-5 ensemble median rainfall under-estimates the long rains, and over-estimates the short rains. This implicit error is, potentially, at least as great as the above changes.

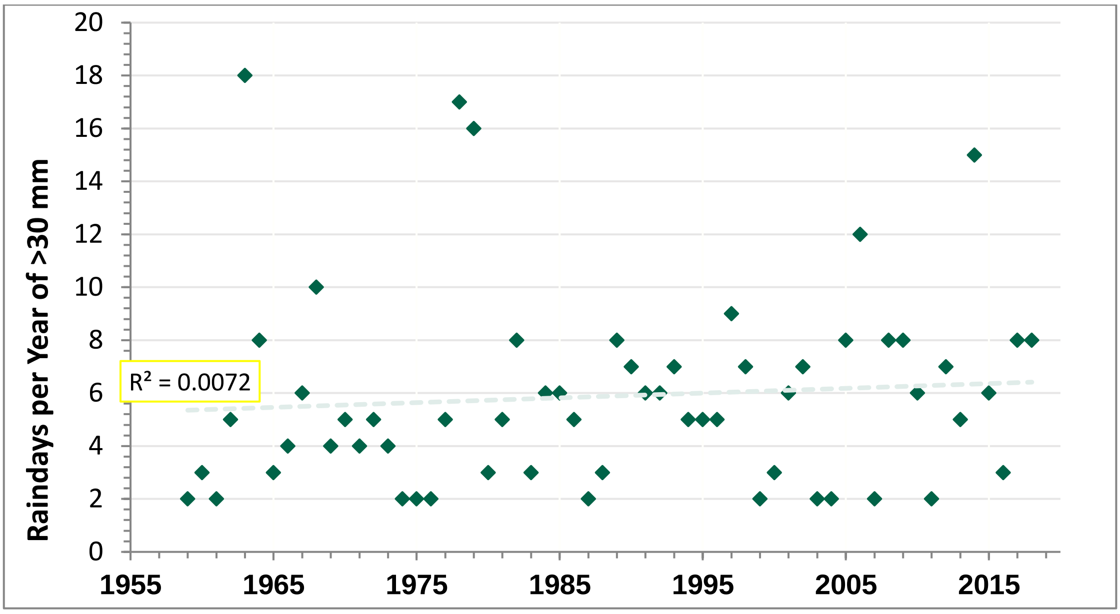
i. The above is the modelled *average* annual rainfall. Even if this aspect of the modelling is correct, the strongly increased inter-annual variability, towards the mid- to end century, will cause some years of rainfall to be *less* than those of the historic record.

ii. Note the origin of the above histogram. The most likely end of century scenario yields an actual modelled *increase* of less than 11%, which is within plausible error bounds.

Table 12: CMIP-5 data (bias corrected) Median Ensemble Mean Rainfall Projections, mm

Station	Historic mean, mm	RCP	Incremental Additions, mm			
			2020-39	2040-59	2060-79	2080-99
Arusha	818	4.5	19	44	53	69
		6.0	26	37	45	81
		8.5	22	30	55	87
			Projected Average Total Rainfalls			
		4.5	837	862	871	888
		6.0	844	855	864	899
		8.5	840	848	873	905

Figure 49: Historic Frequency of High Rainfall, >30 mm per day, at Arusha



Eventually it is expected that narrowing and intensification of the ITCZ will result in fewer and heavier rainstorms during the rainy season. However, there is as yet no statistically convincing evidence of this trend in Figure 49.

5.3 Rainfall Variability

Historic variability in the annual rainfall at Arusha, shown in Figure 47, can also be recast as monthly rainfall probabilities, as shown in Figure 50, and in tabular form, Table 13.

Figure 50: Historic Annual Rainfall Distribution at Arusha

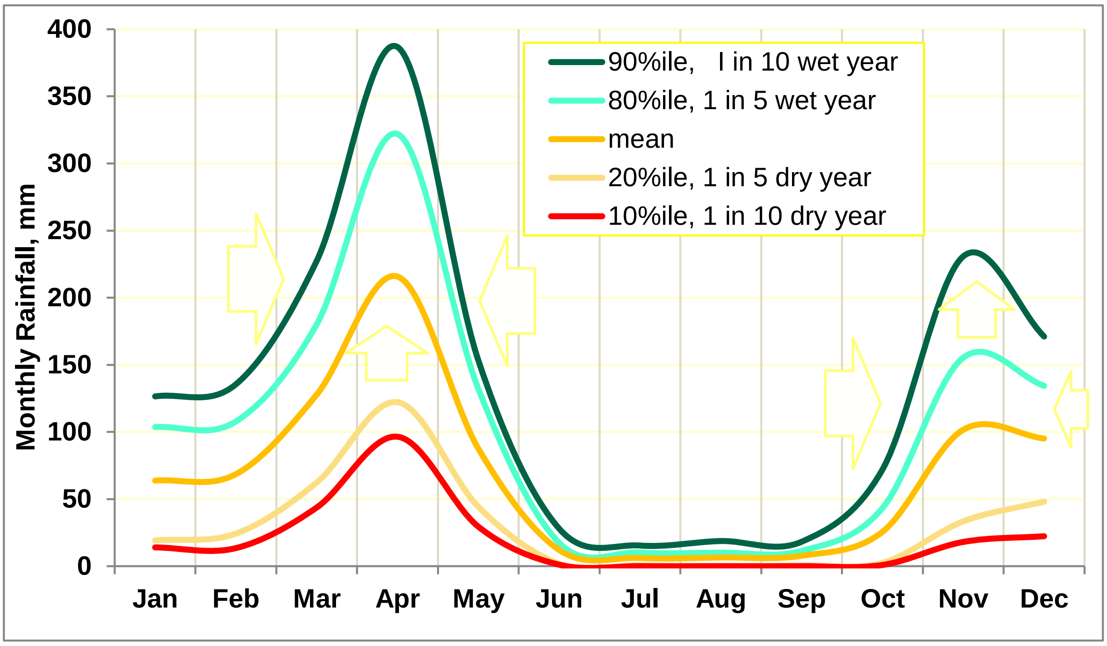


Table 13: Historic Wet and Dry-Year Contrasts in Rainfall at Arusha, mm

ARUSHA	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
90%ile, I in 10 wet year	126	135	227	387	153	28	15	19	18	72	231	171	**1584**
80%ile, 1 in 5 wet year	104	108	180	322	132	17	10	10	11	43	155	134	**1227**
mean	64	69	128	216	88	12	6	6	8	26	102	95	**818**
20%ile, 1 in 5 dry year	19	24	62	122	44	2	1	0	0	2	33	48	**359**
10%ile, 1 in 10 dry year	14	13	44	96	29	1	0	0	0	1	18	22	**239**

Climate-change is expected to influence this frequency distribution in several respects. Firstly, the histogram will broaden in both directions; right and left arrows of Figure 50. Secondly, even though the *average* rainfall will increase from 818 mm to about 855 mm by mid-century, there will be relatively fewer years with about 850 mm of rainfall. Thirdly, the overall pattern of rainfall distribution will become less regular. That is, it is less likely to resemble the 'bell-shape with tail'.

5.4 Evapotranspiration

The parameters and output data used for calculating potential evapotranspiration, 'ET_0', are listed in Table 14, Table 15 and Table 16. Mean monthly maximum and minimum temperatures are the median CMIP-5 values for Arusha. Other parameters are less tractable.

As temperatures rise the *specific* humidity ($g.kg^{-1}$) will certainly increase. There is less clarity over the *relative* humidity, which could either stay much the same as historic values, or decrease slightly. The Relative Humidity is not well-captured in AOGCMs.

Generalized historic data for tropical and sub-tropical continental regions indicate a decrease from about 1980, and particularly from the mid- to late 90s. Here the regional average rate of decrease in RH is taken to be -0.22% per decade (Byrne and O'Gorman, 2018). This will not be true of Zanzibar, but is likely to be close to reality for the rest of Tanzania. This amounts to ~1% by the 2040-59 time-slice or ~2% by the 2080-99 time-slice.

Wind is another parameter that is poorly captured by computer modelling. Projections for Arusha vary from 'no change' to between 1 and 5 fewer days of noticeable wind (on average) between November and April.

In the following three tables, note that T_{max} and T_{min} are the median outputs from CMIP-5 modelling, adjusted to match the local historical meteorological data at Arusha (that is, adjusted by bias correction). The R.H trend is assumed to be a linear projection of the last 40 years of regional data. The wind run correction is minor, but is the least reliable of the modelled projected parameters. Values taken from the modelling indicate a small seasonal *reduction*, which is counter-intuitive. As the tropics warm, it is entirely possible that stronger winds will prevail, in which case these ET_0 estimates would be conservative, that is under-estimating the change. In the absence of cloud-cover projections (indeterminate) it is assumed that, by ~2090, mean daily hours of bright sunshine for each month will be unchanged. This could be a false assumption in either direction.

Table 14: Summary and output of monthly historic (1959-2018) climatic data for calculating daily reference evapotranspiration, ET_0, at Arusha/Babati

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
M max T °C	28.5	29.0	28.1	25.3	23.3	22.2	22.1	23.3	25.5	27.4	27.4	27.5
M min T °C	14.0	14.3	15.6	16.5	15.4	13.4	12.7	12.9	13.2	14.3	15.1	14.5
R.H. %	67	65	69	79	81	77	73	70	66	64	69	70
Wind-run	95.6	109.	120.	136.	136.	139.	153.	167.	190.	198.	188.	102.
Hrs sun	8.1	8.1	7.2	6.5	5.7	5.8	6.2	6.9	7.8	8.4	7.6	7.4
ET_0, mm	**4.4**	**4.6**	**4.3**	**3.7**	**3.1**	**2.9**	**3.1**	**3.6**	**4.4**	**4.9**	**4.5**	**4.0**
											Average ET_0	**4.0**

Table 15: Summary and output of monthly projected climatic data for calculating daily evapotranspiration, ET_0, at Arusha/Babati. RCP 6.0; 2040-59, bias corrected

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
MmaxT °C	28.3	29.1	28.1	26.5	24.6	23.5	23.3	24.7	26.8	28.3	27.7	27.9
MminT °C	15.2	15.6	16.7	16.5	16.6	14.6	14.0	14.1	14.4	15.5	16.3	15.7
R.H. %	66	64	68	78	80	76	72	69	65	63	68	69
Wind-run	88.5	98.4	104	130.7	136.3	139.1	153.4	167.3	190.1	198.4	178.7	97.3
Hrs sun	8.1	8.1	7.2	6.5	5.7	5.8	6.2	6.9	7.8	8.4	7.6	7.4
ET_0, mm	**4.3**	**4.6**	**4.3**	**3.8**	**3.2**	**3.0**	**3.3**	**3.8**	**4.6**	**5.0**	**4.5**	**4.3**
											Average ET_0	**4.1**

Table 16: Summary and output of monthly projected climatic data for calculating daily evapotranspiration, ET_0, at Arusha/Babati. RCP 6.0; 2080-99, bias corrected

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
MmaxT °C	29.2	29.8	28.9	27.3	25.7	24.5	24.2	25.8	27.8	29.2	28.8	28.9
MminT °C	16.1	16.5	17.7	18.6	17.6	15.7	14.8	15.1	15.2	16.3	17.0	16.6
R.H. %	65	63	67	77	79	75	71	68	64	62	67	68
Wind-run	95.6	109.4	119.3	136.6	136.3	139.1	153.4	167.3	190.1	197.7	186.2	101.4
Hrs sun	8.1	8.1	7.2	6.5	5.7	5.8	6.2	6.9	7.8	8.4	7.6	7.4
ET_0,	**4.5**	**4.7**	**4.5**	**3.9**	**3.3**	**3.2**	**3.4**	**3.9**	**4.7**	**5.1**	**4.7**	**4.2**
											Average ET_0	**4.2**

5.5 Effective Rainfall

Without detailed process studies and field calibration within the catchment(s) of interest it is impossible to quantify the likely climate-change impacts upon surface runoff and aquifer recharge. Nevertheless, by using a ‘proxy variable’ we may simulate an approximation by using the 'effective rainfall', defined as all positive values of daily rainfall reduced by the reference daily evapotranspiration.

Strictly, the runoff and recharge components of rainfall are not directly proportional to the 'effective rainfall', especially in forested areas, but we may nevertheless take the effective rainfall as a rough, semi-quantitative indicator of likely impacts.

The modelled historic vs projected (RCP 6.0, 2080-99) monthly values are given in Table 17 and in Figure 51.

Table 17: Effective Monthly Rainfall, mm (positive values of 'pptn-ET_0') at Arusha

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
39	44	90	164	58	5	2	3	4	13	71	64
38	44	89	162	57	5	2	3	4	13	70	62
47	52	97	168	57	6	1	2	4	12	73	84

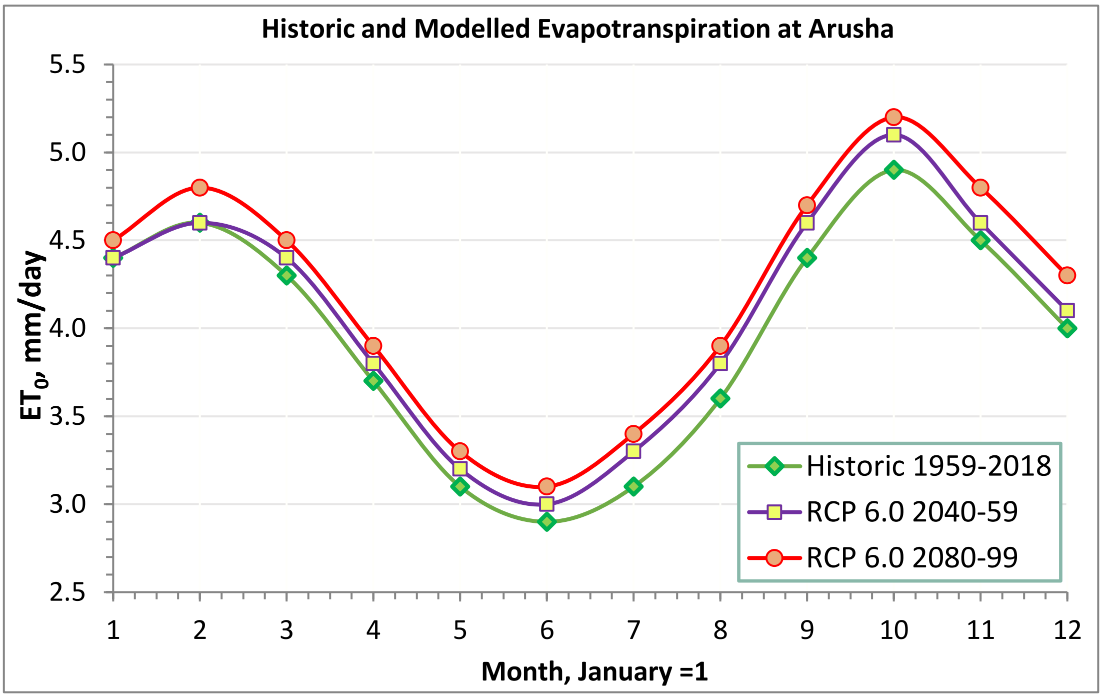
First row: Historic rainfall with historic evapotranspiration.

Note: Second row: Historic rainfall with projected evapotranspiration (RCP 6.0, 2080-99)

Third row: Projected rainfall with projected evapotranspiration (RCP 6.0, 2080-99) and other adjustments

Caution: this table is indicative only. Compounded implicit assumptions of future rainfall, relative humidity, wind-run and sunshine hours used to generate this table leave scope for significant future deviation.

Figure 51: Modelled changes in Reference Evapotranspiration at Arusha

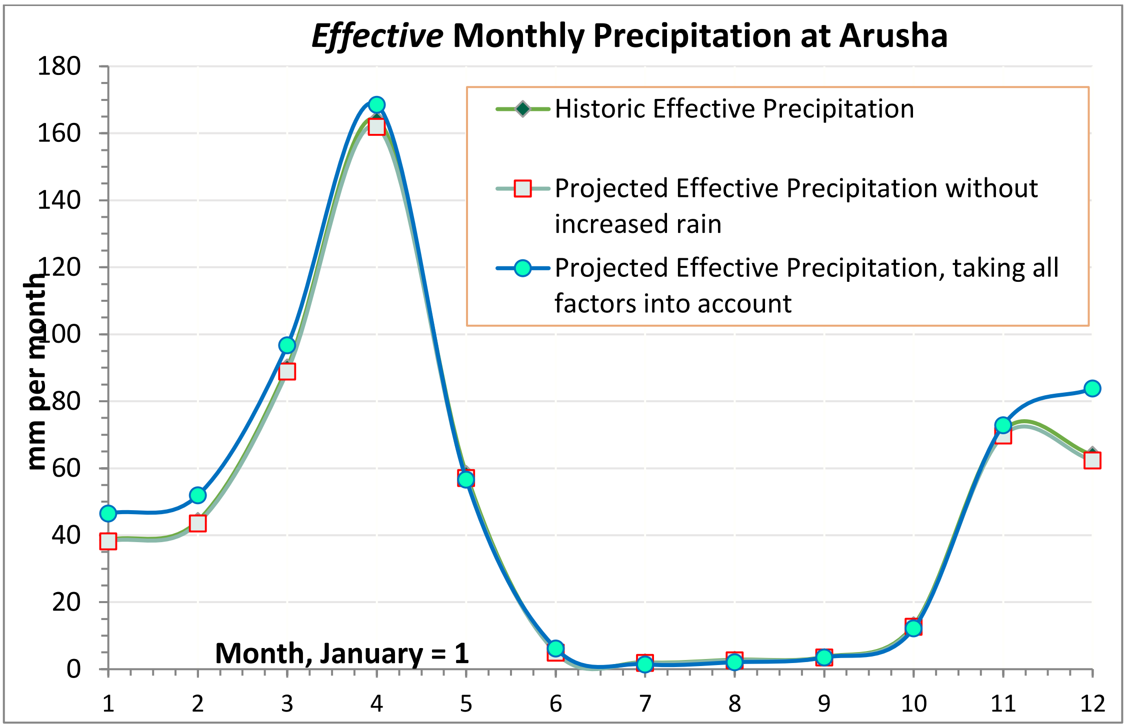


The essential conclusion of the modelling is that there *appears* to be a small net gain in the future overall water balance, in which increased rainfall slightly exceeds the increased future losses from enhanced evapotranspiration. However, there are several important caveats to be noted:

- The computed gain in both total and effective rainfall is contradicted by instrumental trends over the past decade. This divergence of results is probably a regional feature of the Indian Ocean Dipole, acting on a quasi-decadal time-scale. It is not attributable to climate change. Nevertheless in general, when modelling and measured instrumental projections are at variance, always believe the latter (evidence-based).
- The water balance is very much a derived parameter in which the compounded errors could easily exceed 10%
- The *effective rainfall,* as here defined is, frankly, a simplistic concept, and does not take into account either crop factors or soil-moisture deficits.
- For the purposes of water resources assessment, the only truly reliable trends are those obtained from field process measurement. That is, from stream gauging and from groundwater level monitoring.

Figure 52: Monthly aggregate of 'daily rainfall – evapotranspiration'

Positive values only



6 PROFILE: KISHAPU (SHINYANGA)

6.1 General

Kishapu, (1138 m altitude), is 35 km east of Shinyanga meteorology station, the latter having 24 years of unbroken temperature data. This is too short a record to detect the onset of any significantly increasing temperature change. Both Shinyanga and Kishapu are about 150 km south of Lake Victoria, and lie at the southernmost limit of climatic influence from the Lake.

6.2 Temperature

Figure 53: Increasing mean daily Tmax and Tmin at Shinyanga

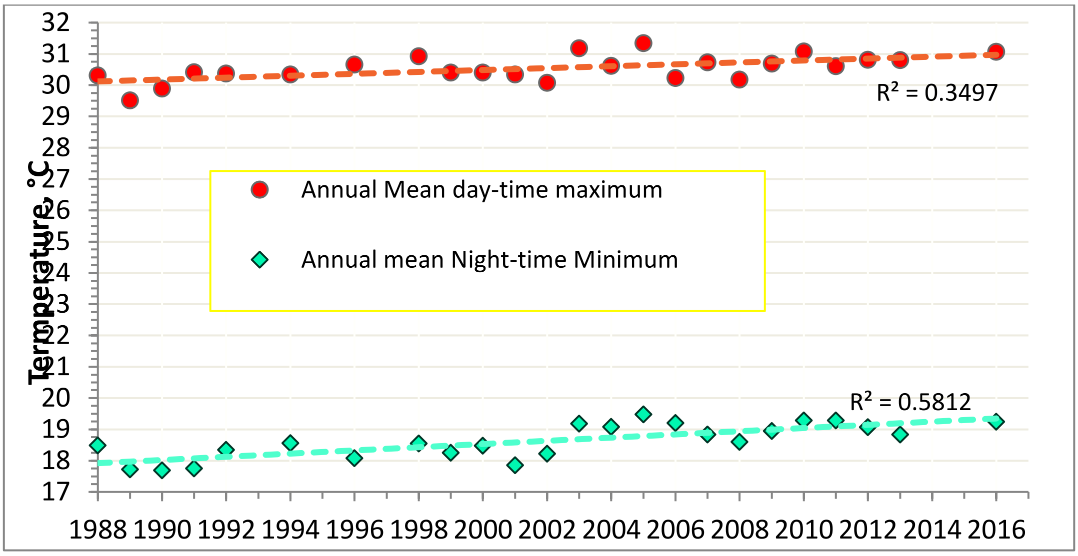


Figure 54: Historic and Projected Seasonal Temperatures at Shinyanga

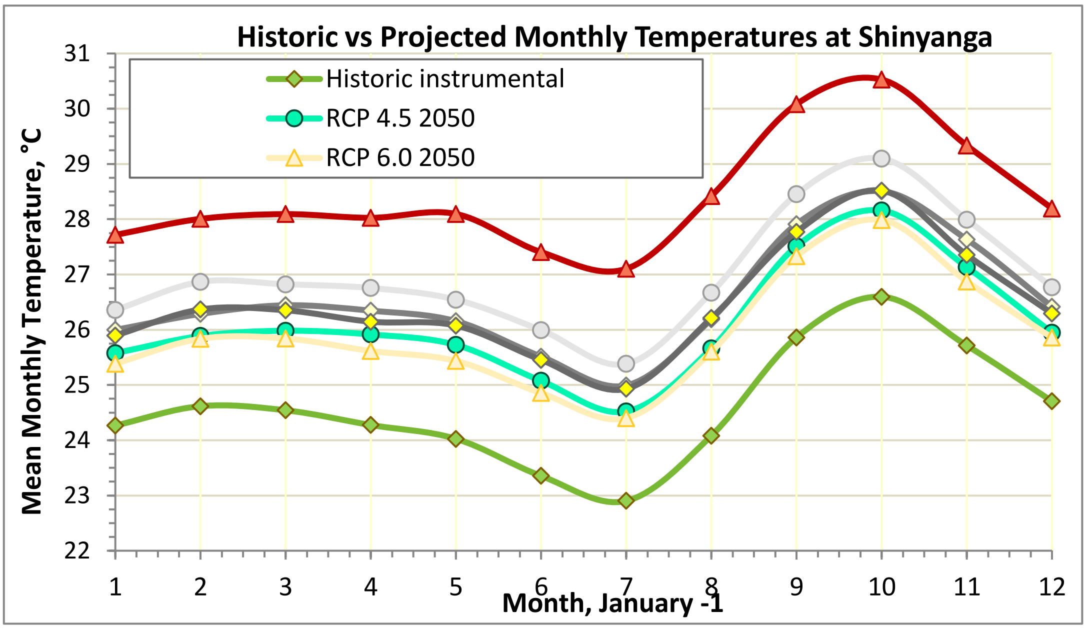
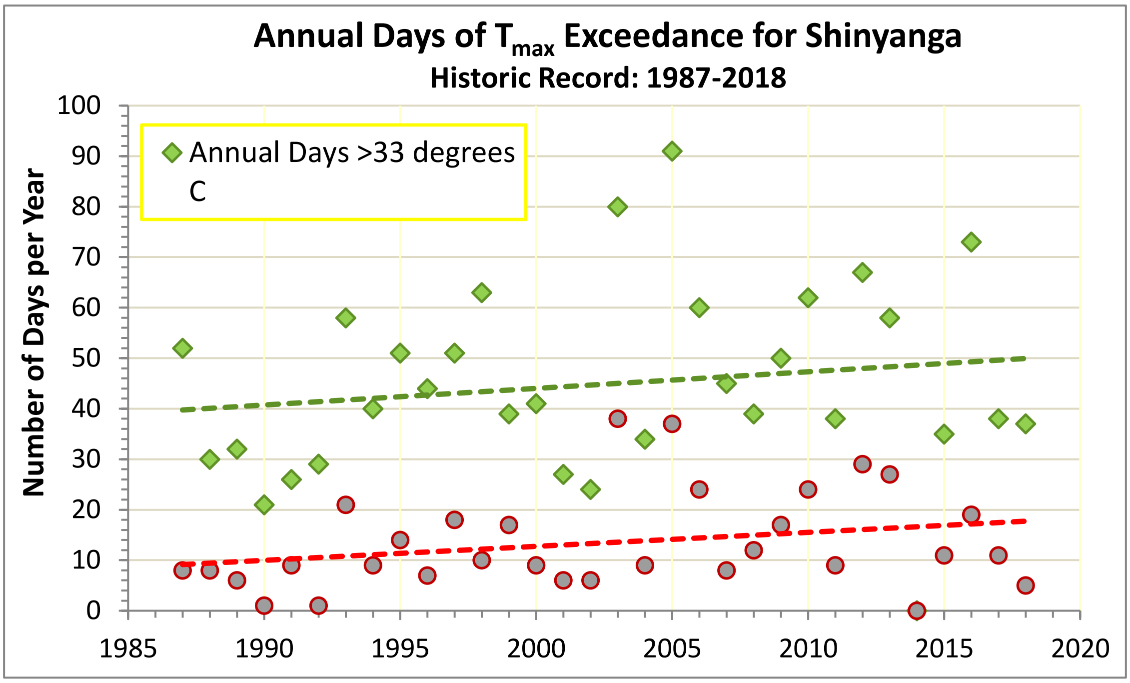


Figure 55: Historic Frequency of Hot Days at Shinyanga



The long-term trends in the number of hot days per year will most probably be greater than the linear trends shown. This is because, over the relatively short time-series of data available, the IOD depression of temperatures between 2008 and 2018 has been disproportionately represented.

Across the 34-year rainfall record for Shinyanga there is no statistically valid evidence of a change in the onset of the long-rains.

Figure 56: Historic vs. Projected Temperature Changes at Shinyanga

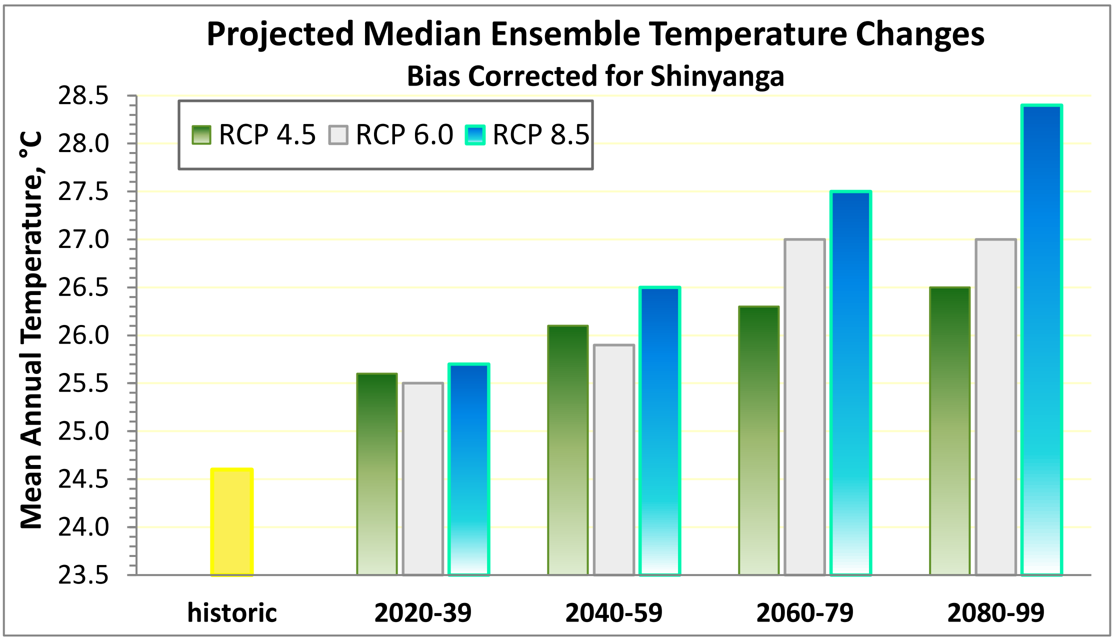


Table 18: Median Ensemble Mean Annual Temperature Change Projections, °C

CMIP-5 data for Shinyanga (Bias Corrected)

Station	Historic mean	RCP	2020-39	2040-59	2060-79	2080-99
Shinyanga	24.6°C N=32	4.5	25.6	26.1	26.3	26.5
		6.0	25.5	25.9	27.0	27.0
		8.5	25.7	26.5	27.5	28.4

6.3 Rainfall

Although the rainfall record at Shinyanga is of high quality the limited time-series, of only 33 years, is too short to discern any meaningful shift in the onset of the long rains.

Table 19: Median Ensemble Mean Time-slice Rainfall Projections, mm

CMIP-5 data for Shinyanga (Bias Corrected)

Station	Historic mean, mm	RCP	Incremental Additions, mm			
			2020-39	2040-59	2060-79	2080-99
Shinyanga	818	4.5	14	24	65	92
		6.0	28	37	75	92
		8.5	29	17	76	96
			Projected Average Total Rainfalls			
		4.5	832	842	883	910
		6.0	845	855	893	910
		8.5	847	834	894	914

Figure 57: Statistically weak rainfall decline at Shinyanga

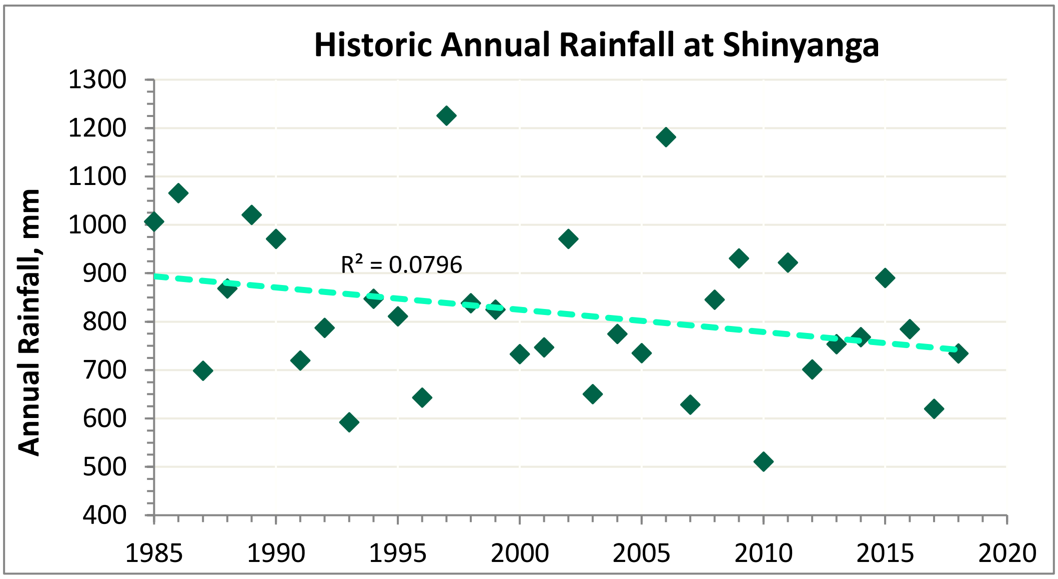


Figure 58: Historic vs. Projected Rainfall at Shinyanga

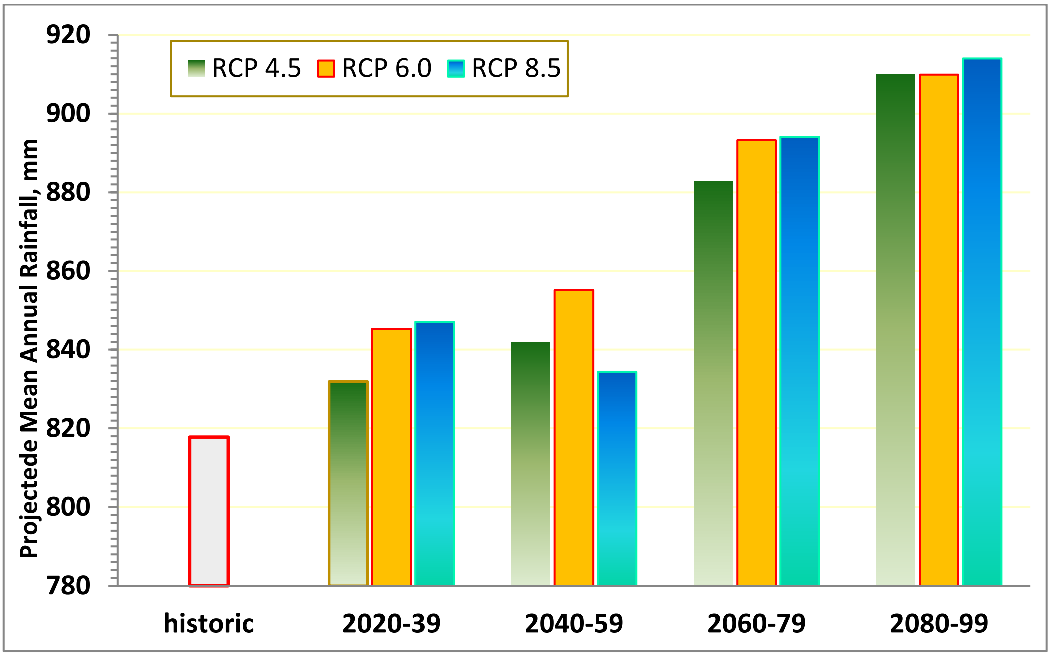


Figure 59: Mean Annual Wind Run at Shinyanga

With only 30 years of record, it is difficult to interpret the future trend in wind-run at Shinyanga. Over the first 20 years of record there has been a dramatic decline in windiness, whilst, in the most recent decade, there was an abrupt increase of about 80 km per day.

6.4 Rainfall Variability

Shinyanga is arguably the most 'typical' of the inland EbARR stations, having an historic dry season lasting six to seven months, between a bimodal rainfall pattern. This dry season is, on average, expected to lengthen.

Attention is again drawn to the 1 in 5 or 1 in 10 dry years in which projected future drought conditions could be extend for at least an additional month. It is these dry years that will determine agricultural viability in the area.

Figure 60: Historic Wet and Dry-Year Rainfall Contrasts Rainfall at Shinyanga, mm

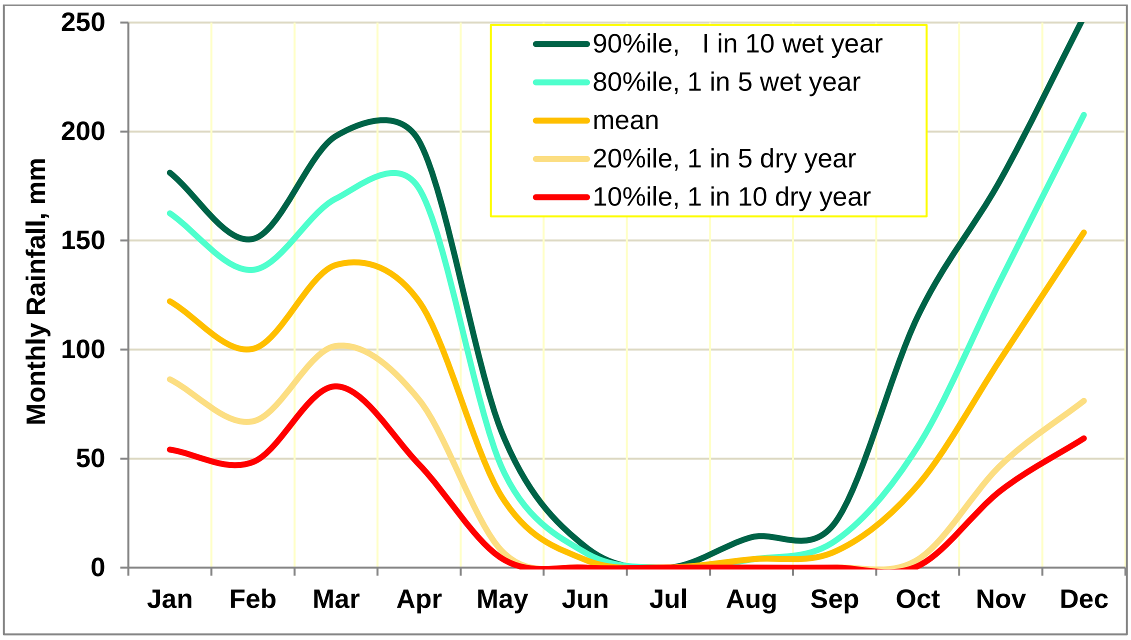


Table 20: Historic Wet and Dry Year Rainfall Contrasts at Shinyanga, mm

SHINYANGA	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
90%ile, I in 10 wet year	181	151	198	196	62	10	0	14	20	115	178	253	**1377**
80%ile, 1 in 5 wet year	163	137	169	174	46	7	0	4	12	55	132	208	**1106**
mean	122	100	139	122	32	4	0	4	7	38	96	154	**818**
20%ile, 1 in 5 dry year	86	67	102	77	7	0	0	0	0	4	47	77	**467**
10%ile, 1 in 10 dry year	54	48	83	47	4	0	0	0	0	1	35	59	**333**

6.5 Potential Evapotranspiration

Table 21: Summary and output of monthly historic (1987-2018) climatic data for calculating daily reference evapotranspiration, ET_0, at Shinyanga

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
M max T °C	29.5	30.3	30.1	29.7	29.9	30.0	29.9	30.8	32.4	32.8	31.3	29.8
M min T °C	19.1	19.0	19.0	18.8	18.2	16.7	15.9	17.3	19.3	20.4	20.1	19.6
R.H. %	67.7	65.2	67.8	68.4	59.9	49.6	45.0	43.2	41.0	45.0	56.6	64.3
Wind-run	91.6	94.0	106	110	130	138	172	184	192	177	141	109
Hrs sun	7.2	8.1	7.5	8.2	8.9	9.6	9.8	9.3	9.0	9.1	7.9	7.4
ET_0, mm	**4.3**	**4.7**	**4.6**	**4.5**	**4.5**	**4.6**	**5.1**	**5.5**	**6.1**	**6.1**	**5.1**	**4.5**
											Average ET_0	**5.0**

Table 22: Summary and output of monthly projected climatic data for calculating daily evap-otranspiration, ET_0, at Shinyanga. RCP6.0; 2040-59, bias corrected

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
MmaxT °C	30.6	31.5	31.4	31.1	31.3	31.5	31.4	32.4	33.9	34.2	32.4	31.0
MminT °C	20.2	20.2	20.3	20.2	19.6	18.2	17.4	18.8	20.8	21.8	21.3	20.7
R.H. %	67.6	65.1	67.7	68.3	59.8	49.5	44.9	43.1	40.9	44.9	56.5	64.2
Wind-run	96	99	111	115	136	145	181	193	202	186	148	115
Hrs sun	7.0	7.9	7.3	8.0	8.7	9.4	9.6	9.1	8.8	8.9	7.7	7.2
ET_0, mm	**4.4**	**4.8**	**4.7**	**4.6**	**4.7**	**4.8**	**5.3**	**5.8**	**6.4**	**6.3**	**5.2**	**4.6**
											Average ET_0	**5.1**

Table 23: Summary and output of monthly projected climatic data for calculating daily evap-otranspiration, ET_0, at Shinyanga. RCP6.0; 2080-99, bias corrected

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
MmaxT °C	31.5	32.5	32.4	32.2	32.4	32.6	32.4	33.4	35.0	35.3	33.6	31.9
MminT °C	21.2	21.2	21.2	21.3	20.7	19.4	18.4	19.9	21.9	22.9	22.4	21.7
R.H. %	67.4	64.9	67.5	68.1	59.6	49.3	44.7	42.9	40.7	44.5	56.4	64.0
Wind-run	101	103	117	121	142	152	189	202	211	195	155	120
Hrs sun	7.0	7.9	7.3	8.0	8.7	9.4	9.6	9.1	8.8	8.9	7.7	7.2
ET_0, mm	**4.5**	**5.0**	**4.8**	**4.8**	**4.8**	**5.0**	**5.5**	**6.0**	**6.6**	**6.5**	**5.4**	**4.7**
											Average ET_0	**5.3**

In the absence of any reliable objective methodology to estimate future relative humidities and wind-run, it is here assumed that higher temperatures will result in a uniform reduction of relative humidity of 0.1% by 2050, and 0.3% by 2090. The wind run is 'guesstimated' to increase in Shinyanga by +5% to 2059, and by +10% to 2099. These two educated guesses are justified on the basis that the ET_0 is determined mainly by temperatures (which *are* well constrained) whereas changes in RH, wind-run and hours of bright sunshine are *relatively* minor adjustments, and hence can accommodate some error in estimation without seriously affecting ET_0 values.

7 PROFILE: MPWAPWA (DODOMA)

7.1 General

Mpwapwa has an excellent 84 year old rainfall record, but somewhat more microclimatic variation than Dodoma. Remaining meteorological met are all from Dodoma, some 85 Km further west. Dodoma is about 50 meters higher than Mpwapwa.

7.2 Temperature

Figure 61: Historic Mean Monthly Temperature Variation at Dodoma

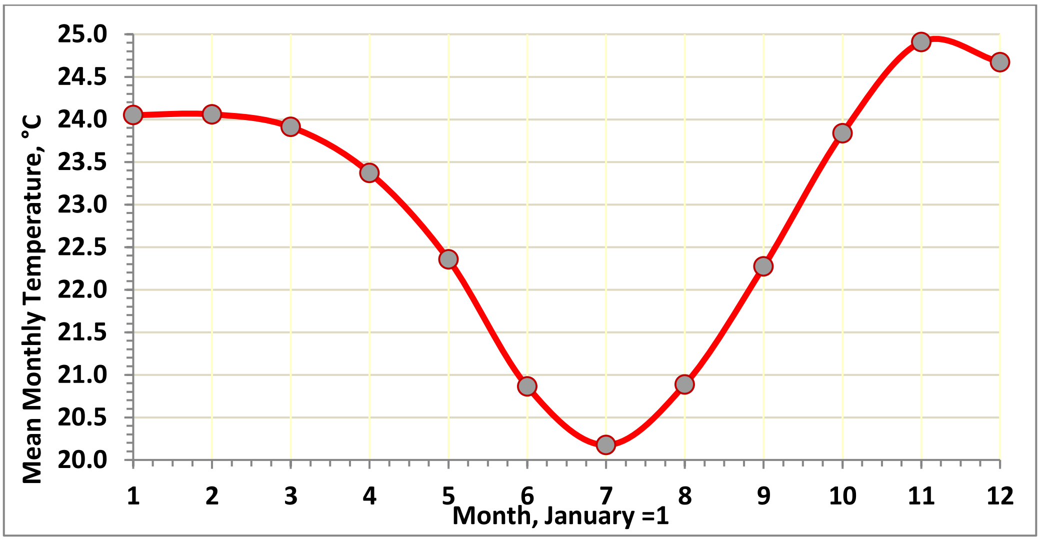
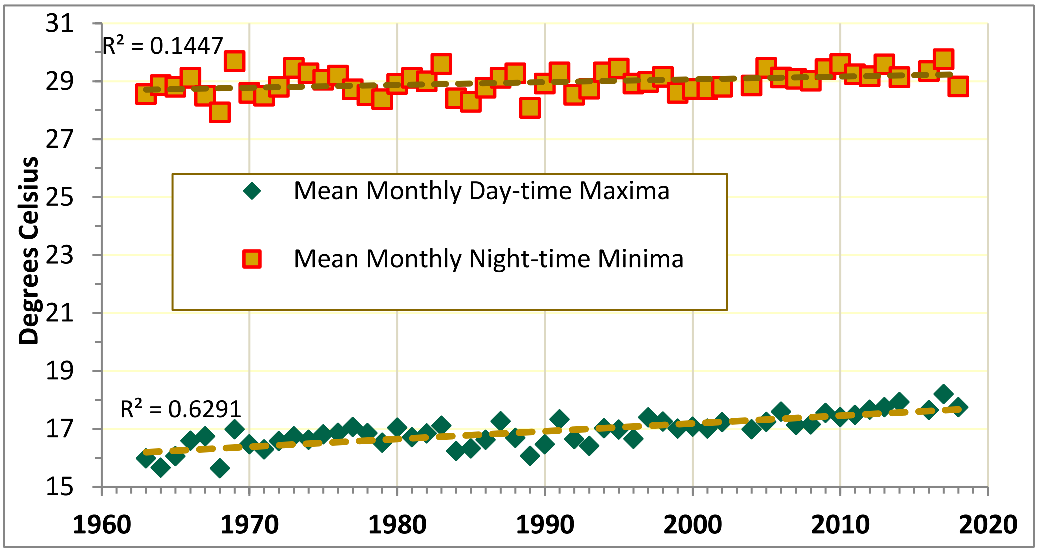
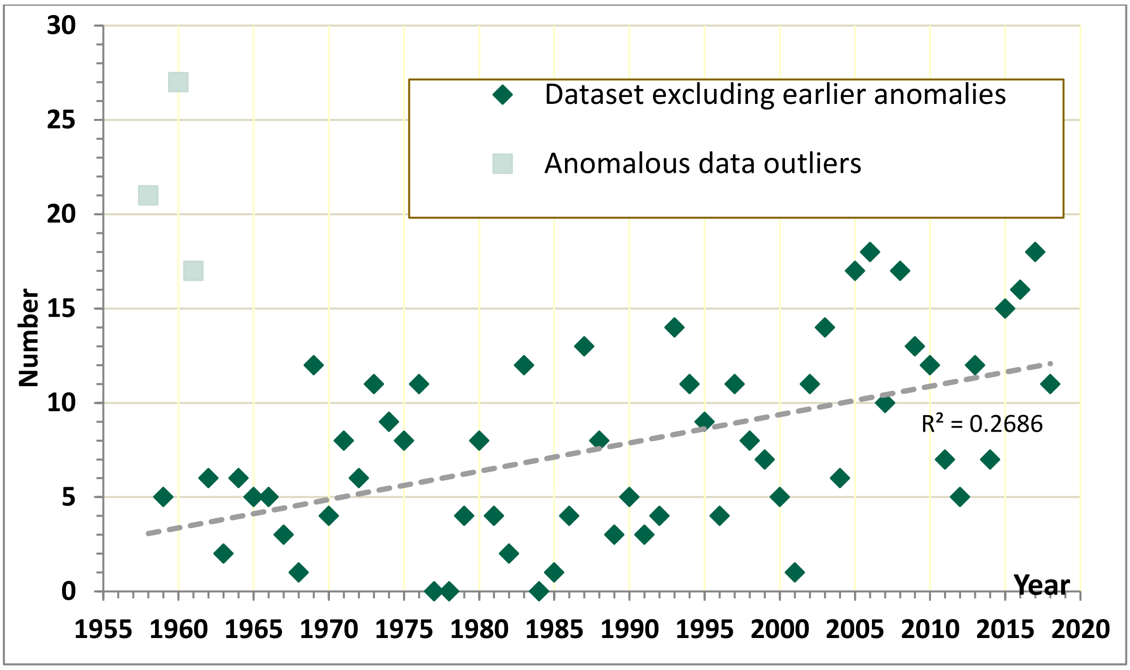


Figure 62: Historic Mean Annual Tmax and Tmin Variations at Dodoma



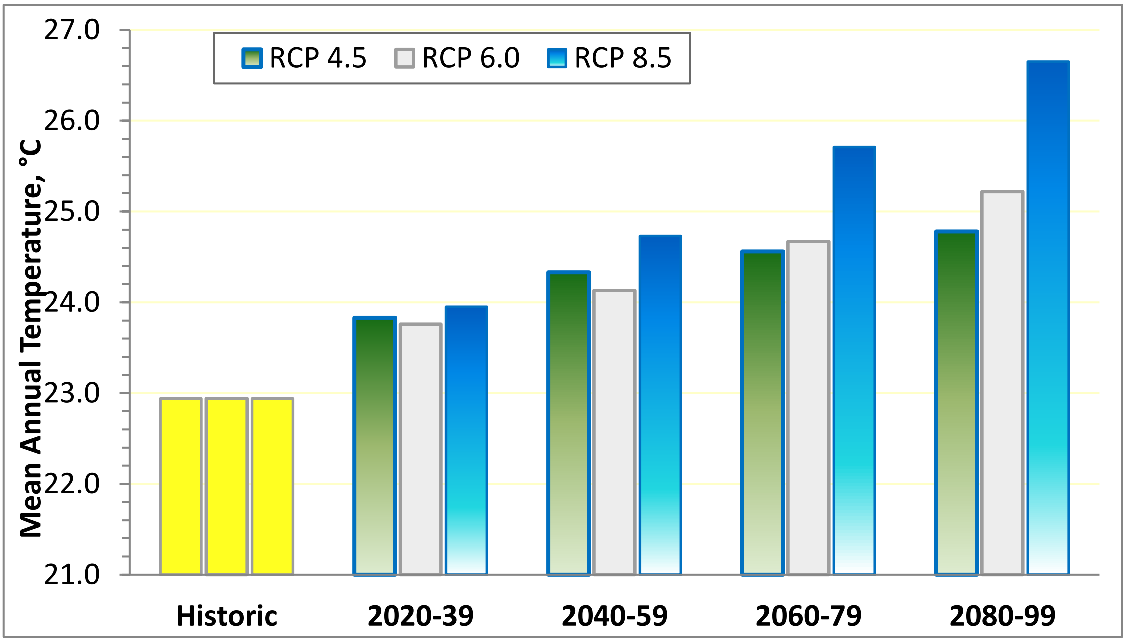
The overall rate of warming of night-time minima is 2.3 times the rate of warming of day-time maxima.

Figure 63: The growth in annual Days Exceeding 33°C



The anomalies of hot days in 1958, 1960 and 1961 are unexplained. It is not clear whether these are real, instrumental or observational problems. Otherwise, there is a very clear trend of increasing numbers of days per year > 33°C. This trend is expected to continue for many decades to come. Only two days in the 60-year record have exceeded 35°C, and none have yet attained 40°C.

Figure 64: Median CMIP-5 Ensemble Temperature Change Projections for Dodoma



All data bias corrected for Dodoma

Table 24: Median Ensemble Mean Annual Temperature Change Projections, °C

CMIP-5 data for Dodoma (Bias Corrected)

Station	Historic mean	RCP	2020-39	2040-59	2060-79	2080-99
Dodoma	22.94°C N=59	4.5	23.83	24.33	24.56	24.78
		6.0	23.76	24.13	24.67	25.22
		8.5	23.95	24.73	25.71	26.65

7.3 Rainfall

Figure 65: Historic Mean Monthly Rainfall at Mpwapwa and Dodoma

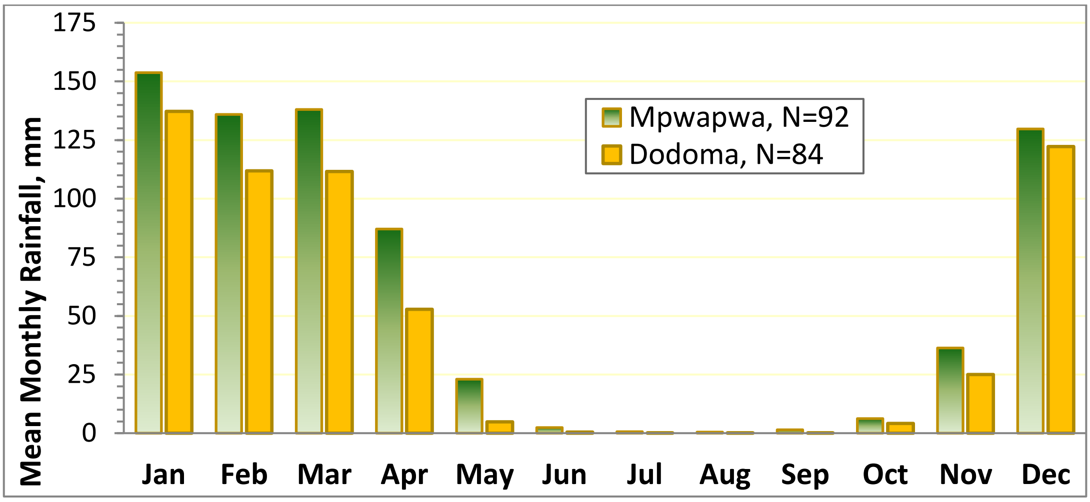


Figure 66: Maximum Daily Rainfall per Year at Dodoma

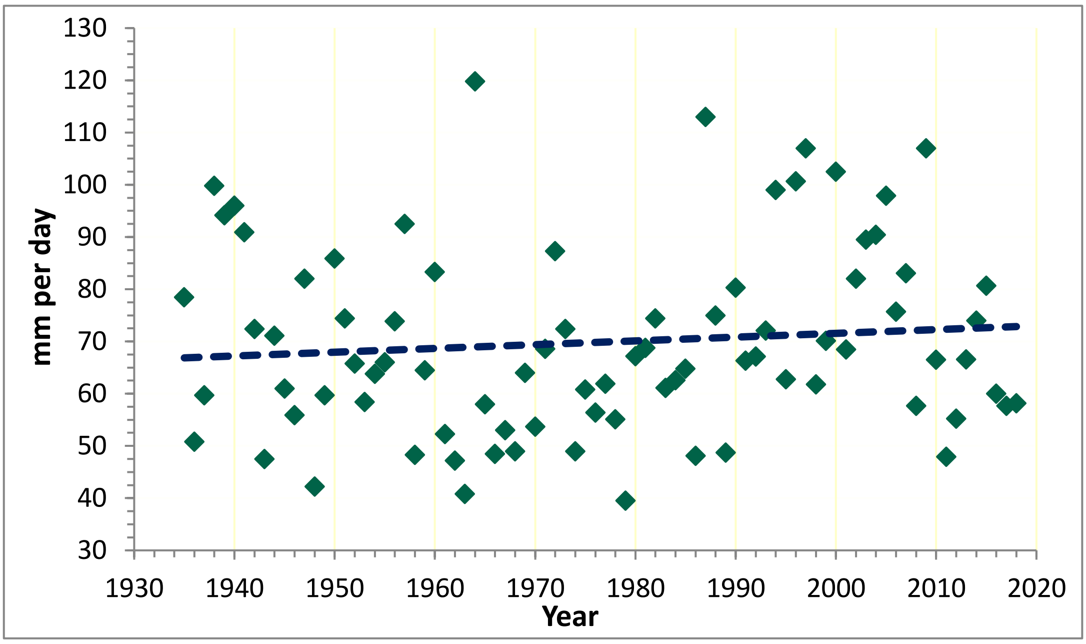


Figure 67: Mean Annual Rainy days, >10mm, at Dodoma

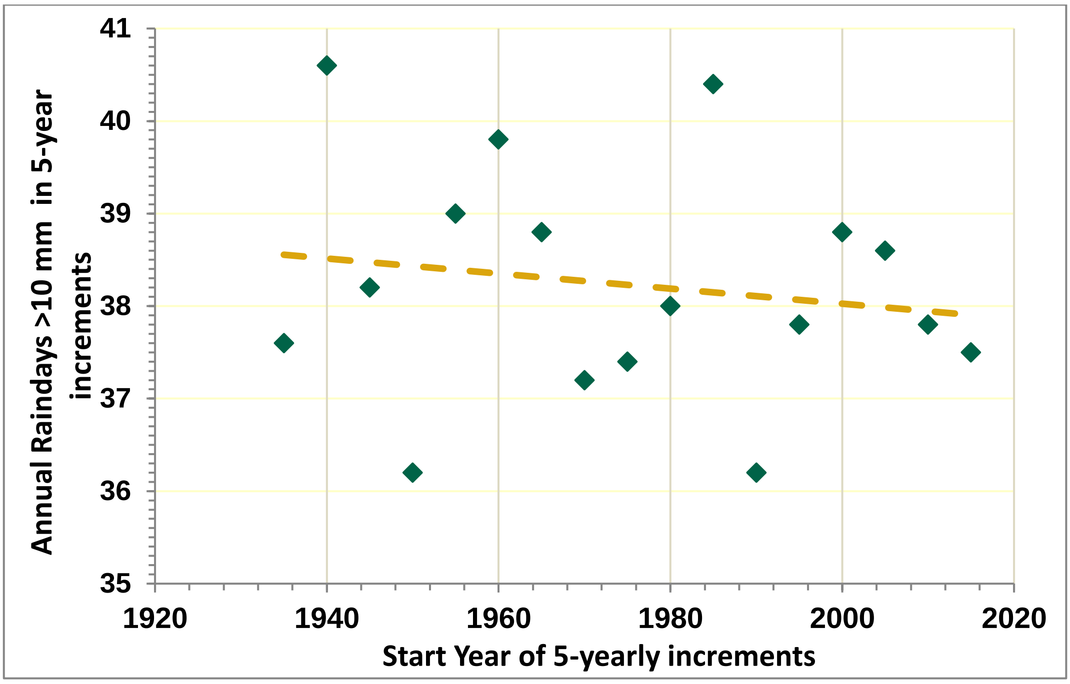


Figure 68: Annual Rainfall Variation at Dodoma

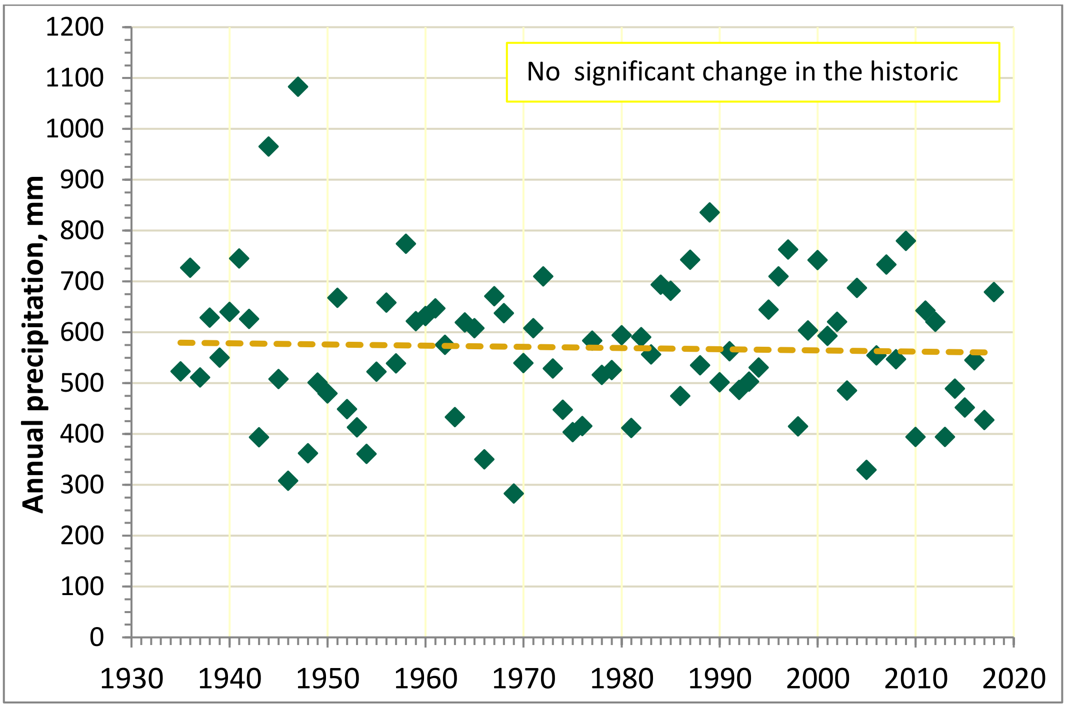
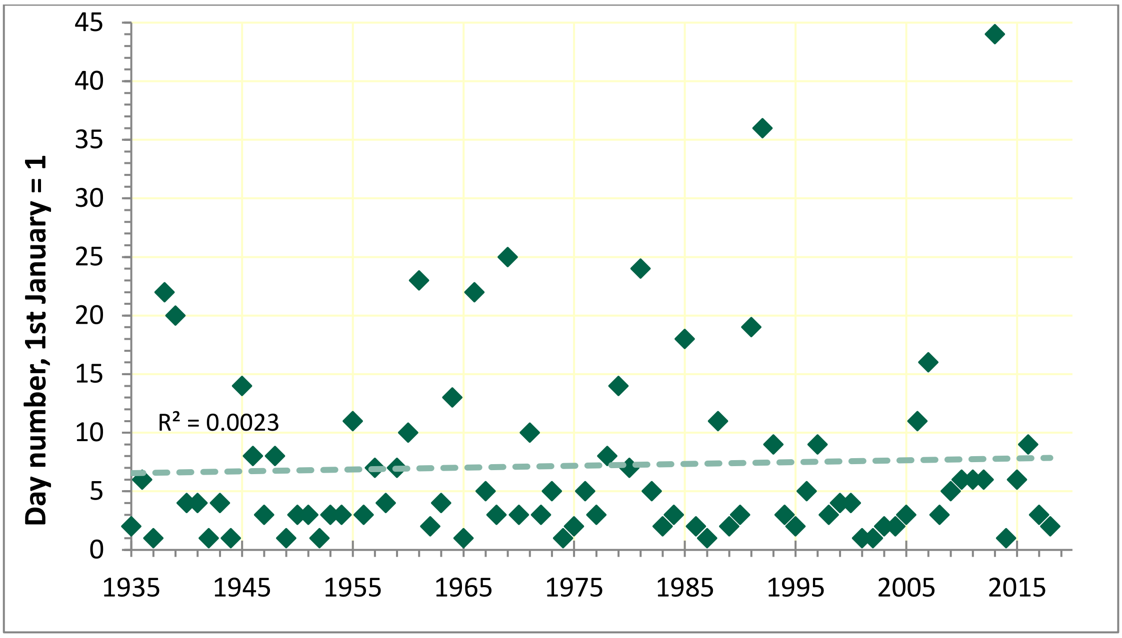


Figure 69: Historic Onset of Long Rains at Dodoma



The onset of long rains at Dodoma is distinctly bimodal. During most years, there is no change from the historic norm, but there are also outliers in the dataset in which the long rains are delayed by an interval of three to six weeks. This delay has the appearance of getting longer over time, but this is currently a statistically weak feature, which could change significantly with the addition of one or more outliers.

Figure 70: Projected Changes in Rainfall at Dodoma and Mpwapwa

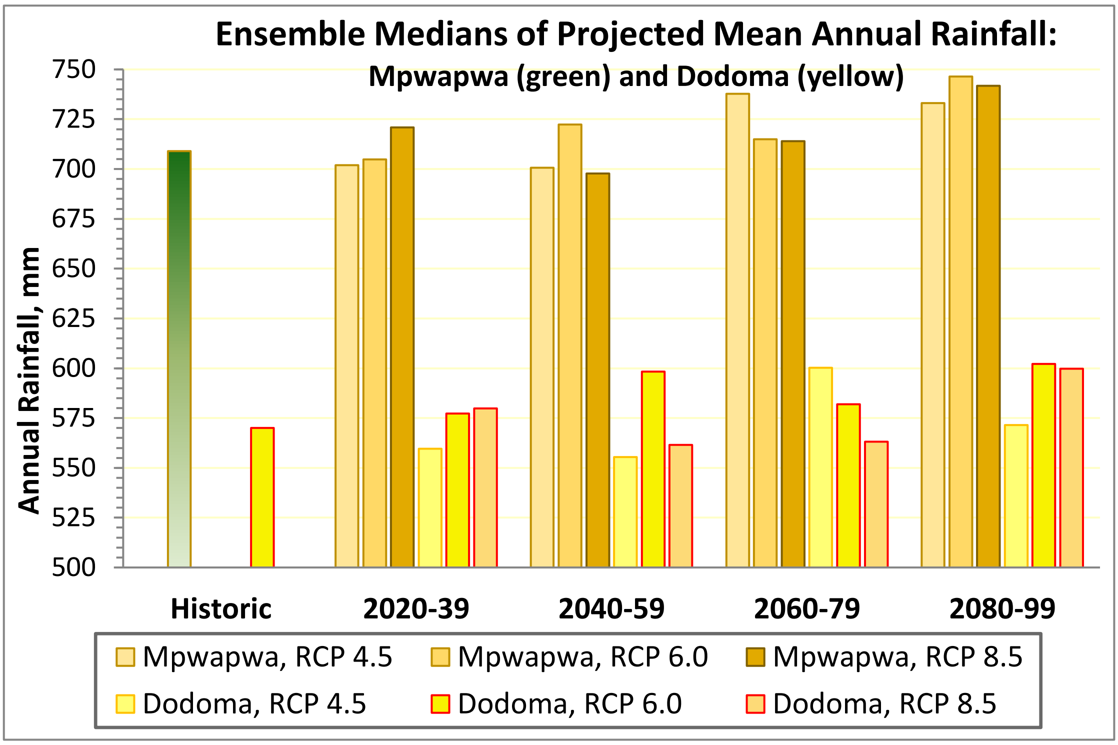


Table 25: Median Ensemble Mean Time-slice Rainfall Projections, mm

CMIP-5 data for Dodoma and Mpwapwa (Bias Corrected)

Station	Historic mean, mm	RCP	Incremental Additions, mm			
			2020-39	2040-59	2060-79	2080-99
Dodoma	570	4.5	-10	-15	30	2
		6.0	7	28	12	32
		8.5	10	-9	-7	30
		Projected Average Total Rainfalls				
		4.5	560	555	600	572
		6.0	577	598	582	602
		8.5	580	562	563	600
Mpwapwa	710	**Incremental Additions, mm**				
		4.5	-7	-8	29	24
		6.0	-4	13	6	38
		8.5	12	-11	5	33
		Projected Average Total Rainfalls				
		4.5	702	701	738	733
		6.0	705	722	715	747
		8.5	721	698	714	742

7.4 Rainfall Variability

A ubiquitous conclusion to climate change projections is that rainfall will become progressively more variable as the climate warms, and hence becomes more energetic. The commonly used parameter for expressing this is the 'inter-annual variability', or IAV(%), determined from the time-series of annual rainfall. The IAV is defined as $\Sigma|x_{i-1}-x_i|.100/(\mu(n-1))\%$ where μ is the mean, n is the number of data points, and x_i is the 'ith' value of the data set.

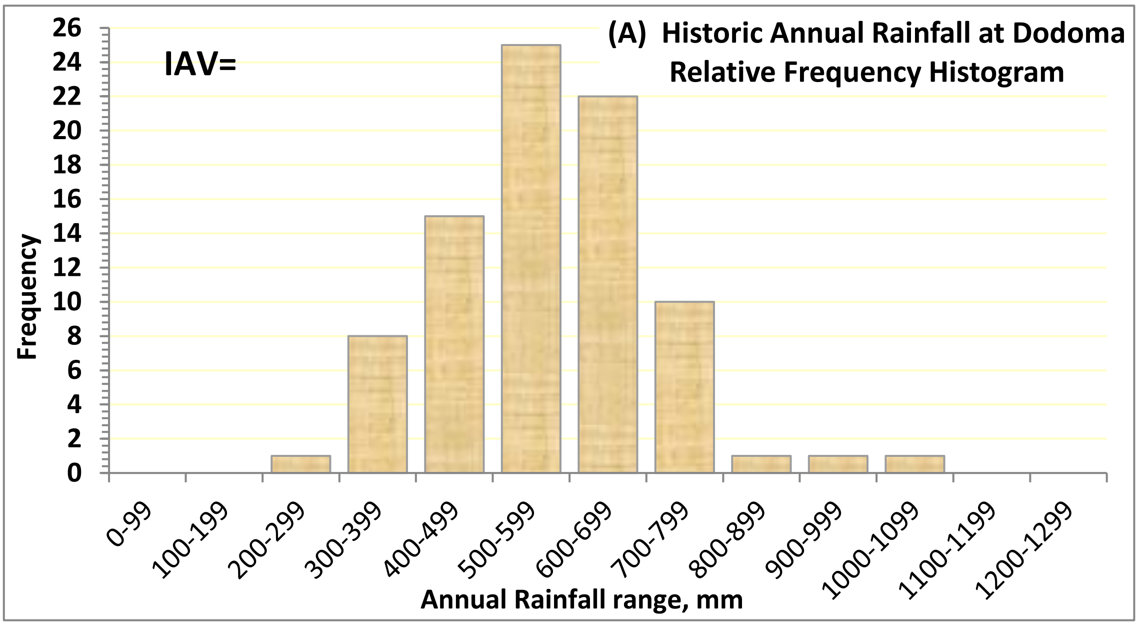
Unfortunately, there is no satisfactory methodology to calculate reliable IAVs from forward projections of AOGCMs. Here, an alternative approach is to assume a plausible IAV based upon the range of analogous conditions within the historic record of tropical and subtropical environments. Specifically, we have used the historic rainfall record of Dodoma, with an IAV of 29.4%, and assumed that this station's IAV will increase to about 43% or 44% by mid century, that is within the time-slice 2040 to 2059. Such an increase in variability is certainly plausible, although an argument *could* be advanced that the evolution of such variability may take longer than 30±10 years, in which case our assumptions may be more applicable to later in the century, rather than mid-century.

Dodoma was the station chosen for this analysis, partly because it is the longest continuous time-series available to EbARR, of 84 years, and partly because its IAV is more or less in the mid-range of Tanzanian stations. That is, Dodoma's historic IAV is 29.4% as compared to the typical range of 24% to 35%.

Dodoma's annual rainfall can be recast as a relative frequency histogram, approximating a skewed Gaussian distribution, as shown in Figure 69. In order to simulate the mid-century annual rainfall distribution a two-stage process was applied. First, the projected rainfall changes were adjusted for RCPs 6.0 and 4.5[4], Figure 71, Figure 72 and Figure 73 respectively. Secondly, synthetic increased variabilities were applied in such a way as to yield an IAV in the range 43% to 44%. By this means two annual rainfall distributions were simulated. These may be regarded as optimistic and pessimistic (but not worst case) examples of the sort of rainfall distributions to be expected. Comparing these to the historic data, Figure 71, it is apparent that extremes of wet or dry years, (<300mm or >1100mm), increase in frequency from about 5% to 25% by mid-century, or possibly a few decades later than mid-century.

An alternative perspective considers annual rainfall of ≤600 mm; that is 17% less than the average annual rainfall in the historic time-series. Historically, ≤600mm fell in about 29% of years, whereas for the mid-century projections, ≤600 mm is likely to fall in some 33% to 40% of years, even though the mean annual rainfall may increase. This has obvious implications in respect of the future need for increased over-year water storage.

Figure 71: Relative frequency histograms of rainfall at Dodoma, with associated IAVs; historic



NB. See Figure A1, Appendix A for a comparative distribution for Arusha.

[4] The projected rainfall changes being median values of the Dodoma grid cell outputs from CMIP-5 models.

Figure 72: Relative frequency histograms of rainfall at Dodoma, with associated IAVs; optimistic projection

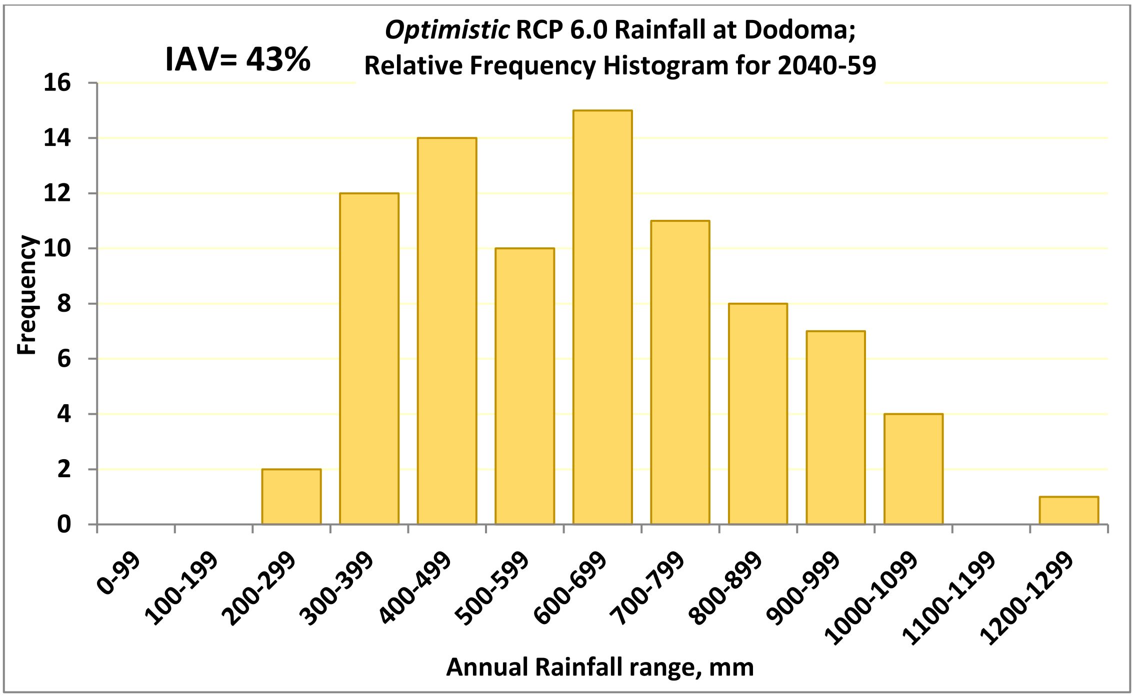
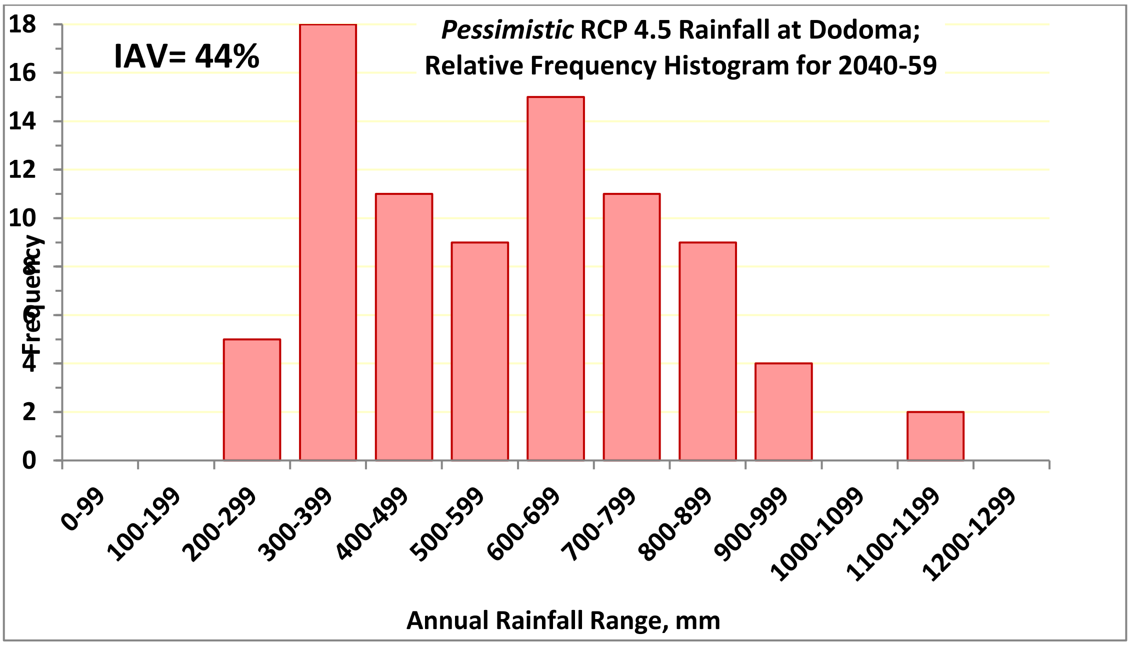


Figure 73: Relative frequency histograms of rainfall at Dodoma, with associated IAVs; pessimistic projection



To facilitate comparison with other EbARR station, reported above, the historic rainfall variability has also been recast as wet and dry-year contrasts, Figure 74, and in tabular form, Table 26.

Figure 74: Wet and Dry Year Historic Rainfall Distributions for Dodoma

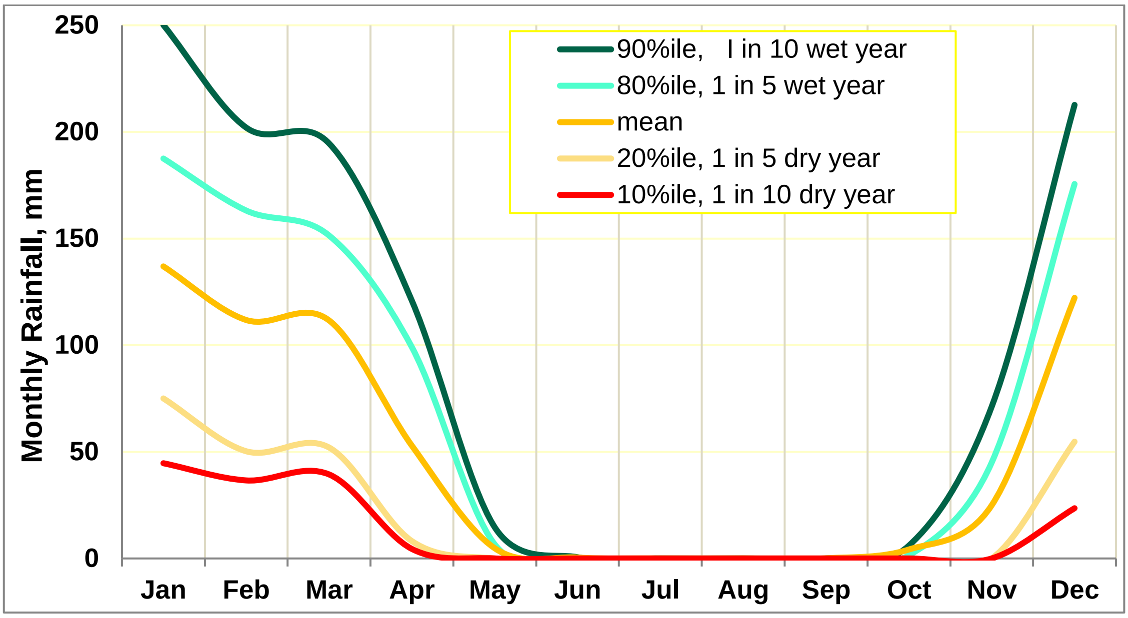


Table 26: Historic Wet and Dry-Year Contrasts in Rainfall at Dodoma, mm

DODOMA	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
90%ile, I in 10 wet year	250	202	195	121	15	1	0	0	0	6	71	213	**1073**
80%ile, 1 in 5 wet year	188	163	151	99	7	0	0	0	0	2	45	176	**830**
mean	137	112	112	53	5	0	0	0	0	4	25	122	**570**
20%ile, 1 in 5 dry year	75	50	52	8	0	0	0	0	0	0	0	55	**240**
10%ile, 1 in 10 dry year	45	37	39	4	0	0	0	0	0	0	0	24	**149**

Of all the EbARR stations, Dodoma is the closest to a unimodal rainy season. The dry season already has essentially zero rain, but as temperatures increase, so also will the soil moisture deficit, so at break of the rainy season, the runoff is likely to be less than the historic discharges.

7.5 Potential Evapotranspiration

On the basis of station-specific and regional historic trends, and allowing for decadal IOD adjustments, the following assumptions were used to calibrate the above ET_0 calculations: The mean monthly RH is expected to reduce by -0.1% by 2050, and by -0.3% by 2100.The wind run is projected to increase by 5% and 10% in the same time slices These are all conservative estimates. The mean daily hours of bright sunshine are expected to increase by +0.2 hours per day by 2050, and by +0.4 hours per day by 2100. These latter are somewhat speculative, based upon assumed evolution of the ITCZ configuration.

Table 27: Summary and output of monthly historic (1958-2018) climatic data for calculating daily potential reference evapotranspiration, ET_0, at Dodoma

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
M max T °C	29.4	29.4	29.4	28.7	28.2	27.2	26.6	27.4	29.1	30.7	31.4	30.4
M min T °C	18.7	18.7	18.5	18.0	16.5	14.5	13.7	14.4	15.4	17.0	18.4	19.0
R.H. %	71.2	70.8	72.8	72.8	67.6	63.3	61.1	61.4	58.7	55.7	58.5	65.9
Wind-run	169	172	174	210	234	244	269	319	323	331	295	233
Hrs brt sun	7.8	8.1	7.8	8.1	8.7	9.8	9.9	9.9	10.0	9.8	9.6	8.2
ET_0, mm	**4.7**	**4.9**	**4.7**	**4.5**	**4.5**	**4.5**	**4.7**	**5.2**	**6.0**	**6.5**	**6.3**	**5.3**
									Mean Annual ET_0			**5.1**

Table 28: Summary and output of monthly projected climatic data for calculating daily evapotranspiration, ET_0, at Dodoma. RCP 6.0; 2040-59, bias corrected

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
MmaxT °C	30.6	30.6	30.4	29.9	29.3	28.5	27.9	28.8	30.6	32.3	32.9	31.5
MminT °C	19.9	19.9	19.6	19.2	17.6	15.6	14.9	15.6	16.7	18.2	19.7	20.2
R.H. %	71.1	70.7	72.7	72.7	67.5	63.2	61.0	61.3	58.6	55.6	58.4	65.8
Wind-run	177	181	183	221	246	256	282	335	339	348	310	245
Hrs sun	8.0	8.3	8.0	8.3	8.9	10.0	10.1	10.1	10.2	10.0	9.8	8.4
ET_0, mm	**5.0**	**5.1**	**4.9**	**4.7**	**4.7**	**4.7**	**4.9**	**5.6**	**6.3**	**6.9**	**6.7**	**5.5**
									Mean Annual ET_0			**5.4**

Table 29: Summary and output of monthly projected climatic data for calculating daily evapotranspiration, ET_0, at Dodoma. RCP 6.0; 2080-99, bias corrected

parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
MmaxT °C	31.4	31.4	31.4	30.8	30.7	29.7	29.1	29.9	31.7	33.3	34.1	32.6
MminT °C	20.9	20.8	20.7	20.2	18.8	16.9	16.0	16.7	17.7	19.2	20.6	21.2
R.H. %	70.9	70.5	72.5	72.5	67.3	63.0	60.8	61.1	58.4	55.4	58.2	65.6
Wind-run	186	189	191	231	257	268	296	351	355	364	325	256
Hrs sun	8.2	8.5	8.2	8.5	9.1	10.2	10.3	10.3	10.4	10.2	10.0	8.6
ET_0, mm	**5.1**	**5.3**	**5.1**	**4.9**	**5.0**	**5.0**	**5.2**	**5.8**	**6.6**	**7.3**	**7.0**	**5.8**
									Mean Annual ET_0			**5.7**

Both the absolute and projected change in ET_0 is higher in Dodoma than those calculated for other stations. For example, compare the ΔET_0 (RCP 6.0 – historic 2080-99): Dodoma 0.6, Shinyanga 0.3, Arusha 0.2 and Zanzibar 0.4. This is due to the combination of higher temperatures, lower humidities and differing wind-run estimates.

Figure 75: ET_0 Variation for Historic and RCP 6.0 time-slices

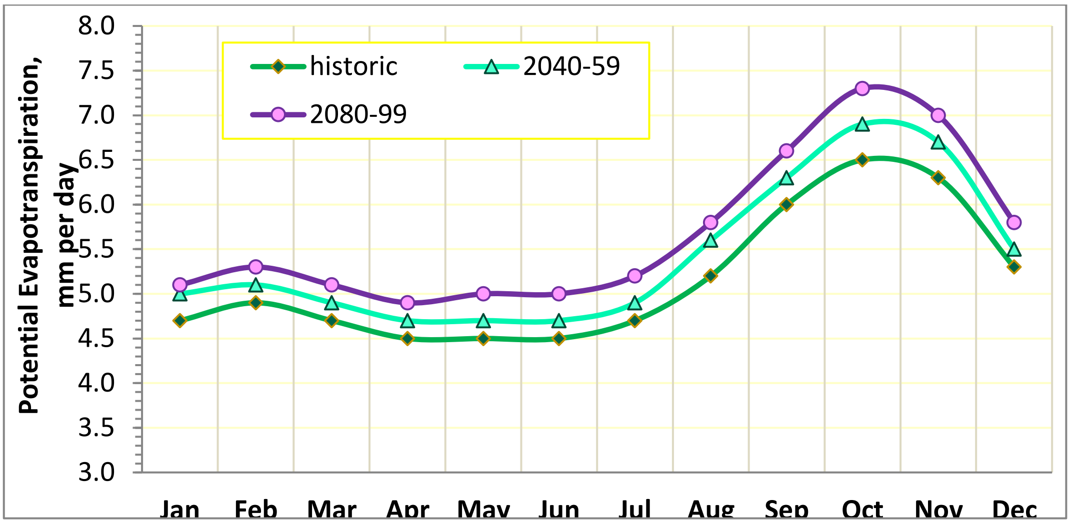
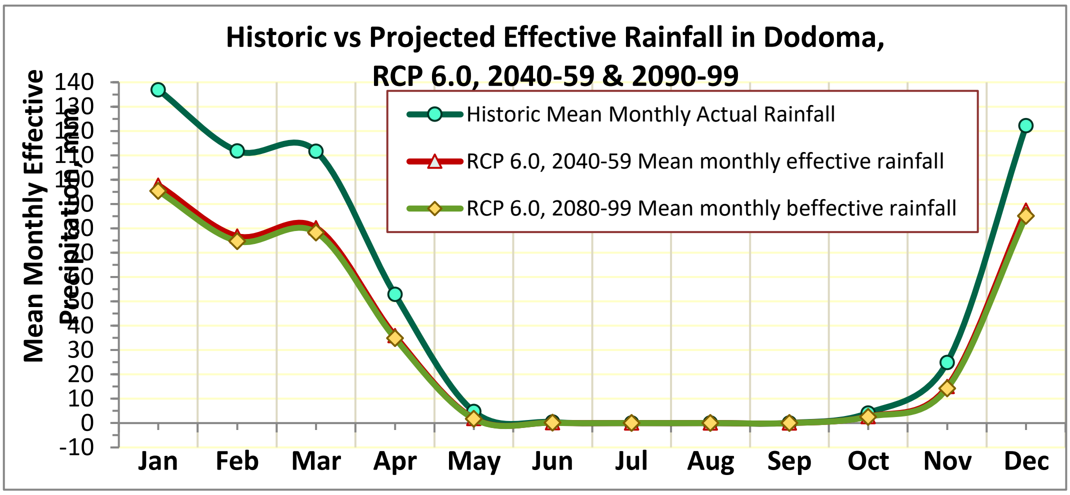


Figure 76: Contrasted Historic and Projected Effective Rainfall at Dodoma



Although the total rainfall is projected to rise for most of this century, increased rainfall, especially in the second half of the century, is negated by the increased evaporative loss. Whatever the time-slice or RCP, the *effective* rainfall more or less stabilizes at about 68% of the actual rainfall. This constancy of 68%, whatever the RCP (Figure 76), is purely coincidental.

As a *separate issue*, the increased rainfall variability, longer dry-season and changing rainfall patterns (fewer but more intense storm events) will have huge implications for less reliable run-off, reduced aquifer recharge, and groundwater availability.

Modern runoff data were not available but historic data from Dodoma[5], from 1929-40, indicates runoff, as a percentage of the total rainfall, of only 6.5 ± 3.8 % (1σ). This is a low runoff fraction by any standards, and underlines the need for efficient and rigorous water conservation and management in the future.

[5] Annual Reports of the Geological Survey of Tanganyika

8 PROFILE: MVOMERO (MOROGORO)

8.1 Temperature

The highest historic temperature at Morogoro was 38.8°C. Most projections have maximum temperatures seldom exceeding 40°C by the end of century. Curiously, the normal trend of night-time minima warming much faster than day-time maxima, does not appear to apply in Morogoro, as is evident from Figure 77.

Table 30: Median Ensemble Mean Annual Temperature Change Projections, °C

CMIP-5 data for Morogoro (Bias Corrected)

Station	Historic mean	RCP	2020-39	2040-59	2060-79	2080-99
Morogoro	24.79°C N=44	4.5	25.57	25.98	26.2	26.63
		6.0	25.51	25.81	26.42	27.06
		8.5	25.69	26.39	27.56	28.1

Figure 77: Trends in Annual Mean monthly Tmax and Tmin at Morogoro

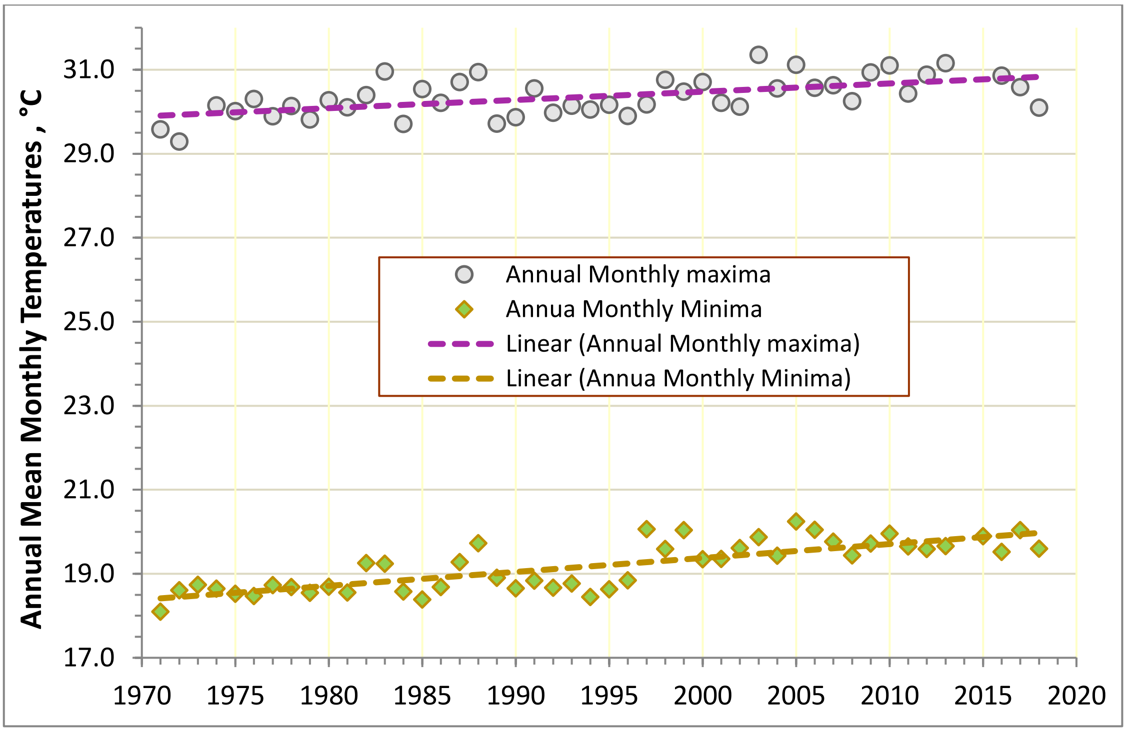


Figure 78: Seasonal Temperature Variations at Morogoro

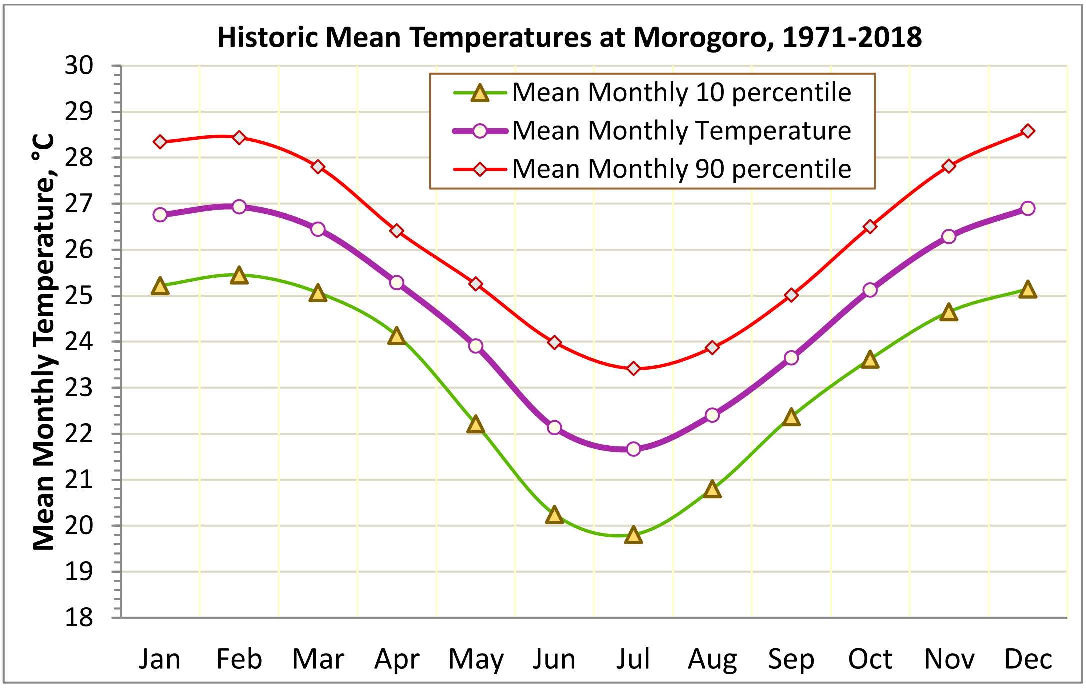
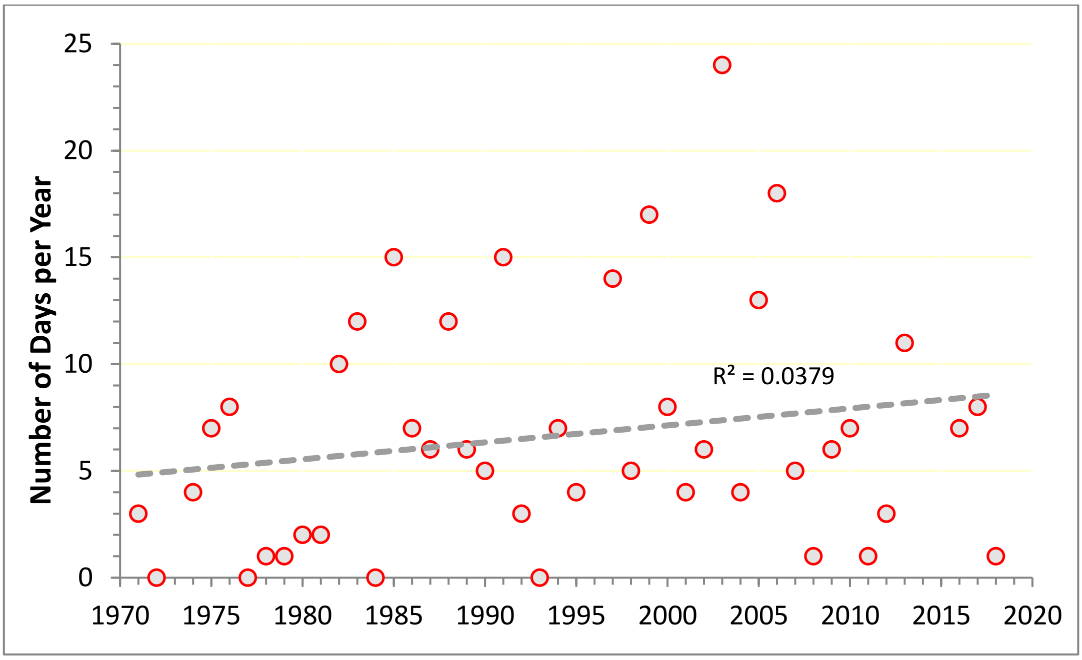
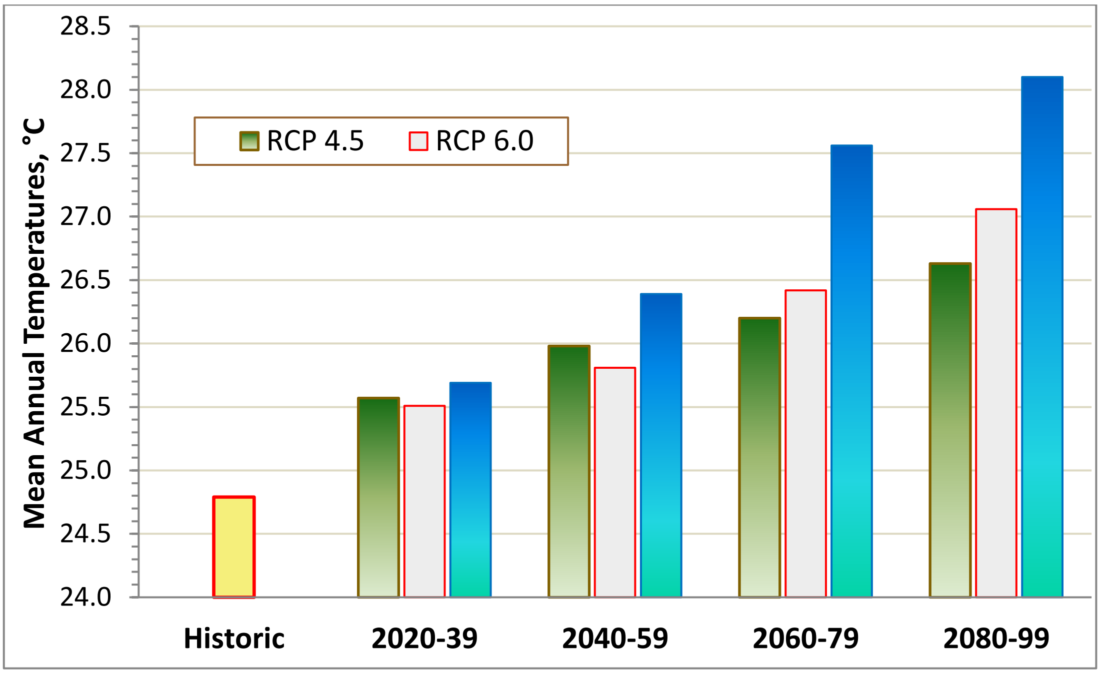


Figure 79: Historic Annual Days Exceeding 35°C at Morogoro



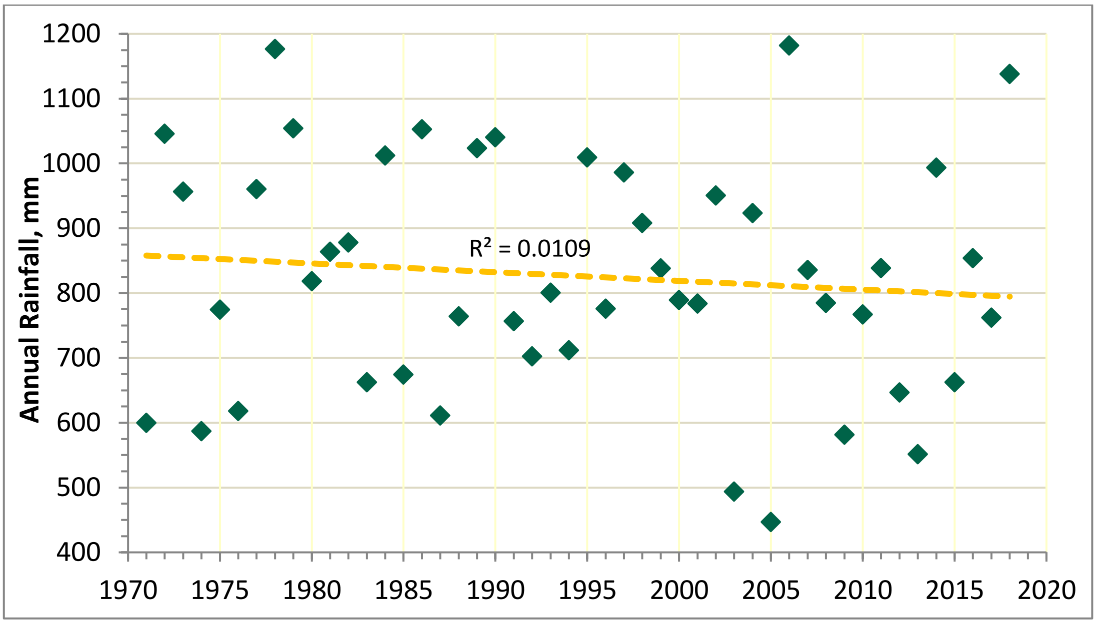
The regression in number of hot days at Morogoro has a statistically weak R^2 value, but is nevertheless consistent with expected trends.

Figure 80: Historic and Projected Temperature Changes at Morogoro



8.2 Rainfall

Figure 81: Historic Annual Rainfall Variation at Morogoro



The scatter of data is too great to determine any reliable statistical trend. The apparent long-term decrease could easily be reversed by just one further data point.

Figure 82: Historic Seasonal Rainfall Distribution at Morogoro

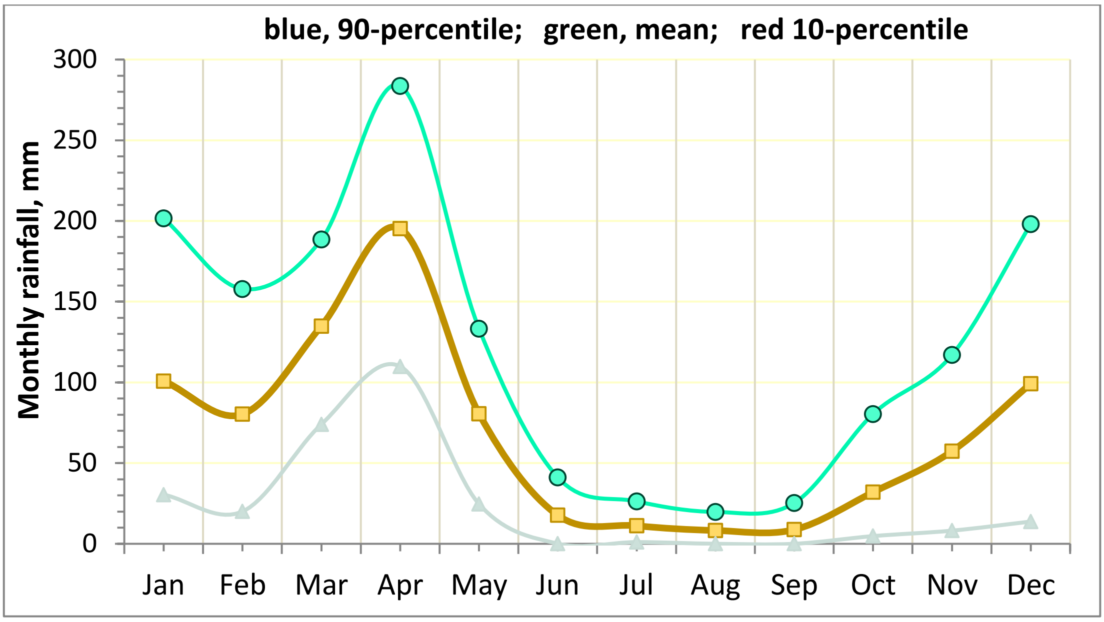
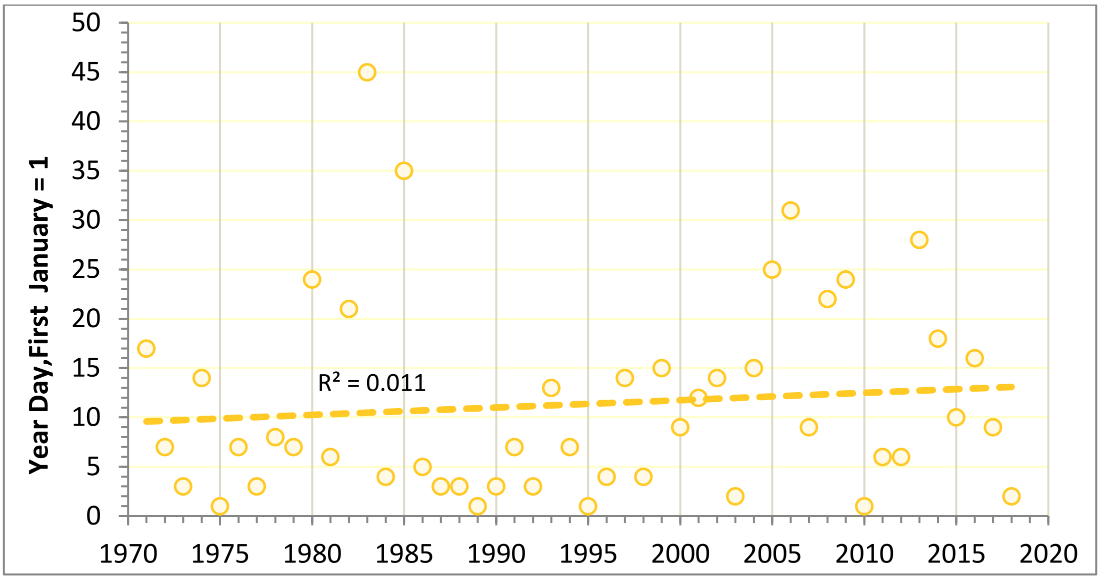
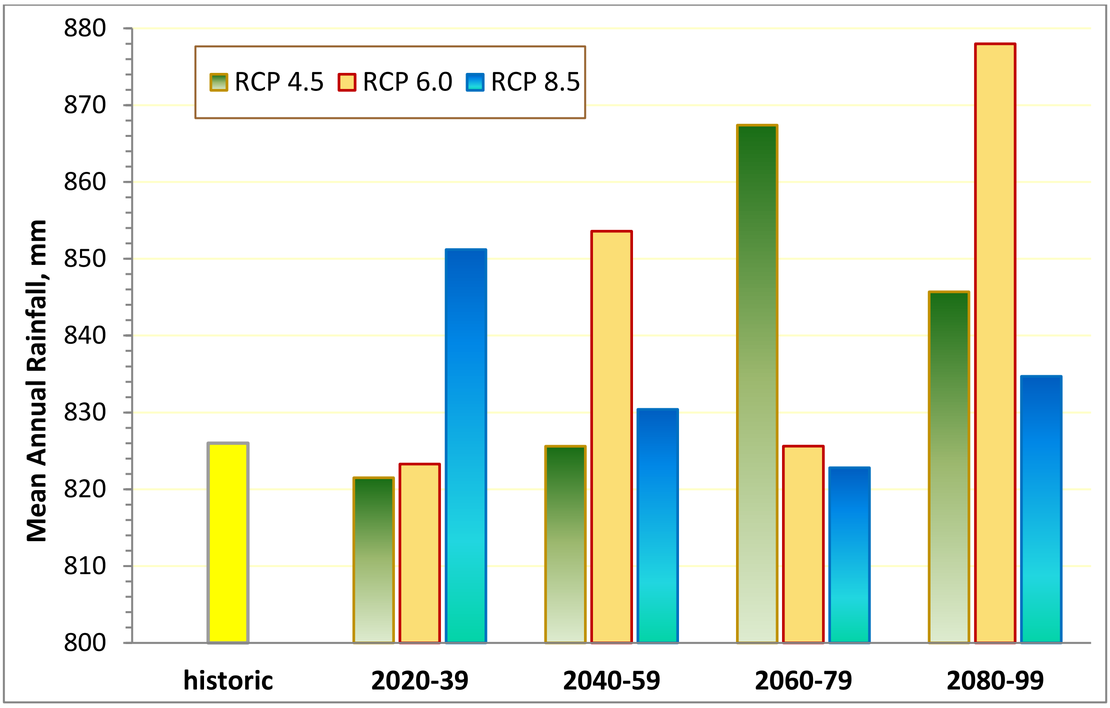


Figure 83: Onset of the 'Long-Rains' Season at Morogoro



Although the slight trend towards a later start to the 'long-rains' season is consistent with other stations (cf. Zanzibar, Figure 33 and Dodoma, Figure 69), all such trends are statistically very weak, unduly influenced by outliers and are considered too insufficient to extrapolate into the future.

Figure 84: Historic and Projected Mean Time-slice Rainfalls at Morogoro



Caution: Some of these changes only appear to be large because of the false origin of the rainfall scale.

Table 31: Median Ensemble Mean Time-slice Rainfall Projections for Morogoro, mm

CMIP-5 data for Morogoro (Bias Corrected)

Station	Historic mean, mm	RCP	Incremental Additions, mm			
			2020-39	2040-59	2060-79	2080-99
Morogoro	826	4.5	-5	0	41	20
		6.0	-3	28	0	52
		8.5	25	4	-3	9
			Projected Average Total Rainfalls			
		4.5	822	826	867	846
		6.0	823	854	826	878
		8.5	851	830	823	835

8.3 Rainfall Variability

As in Zanzibar, not far to the east, climate-change is expected to have a relatively minor impact upon the rainfall variation in Morogoro under any of the standard emissions scenario, or at any time-slice.

Figure 85: Historic Wet and Dry-Year Rainfall Variability at Morogoro

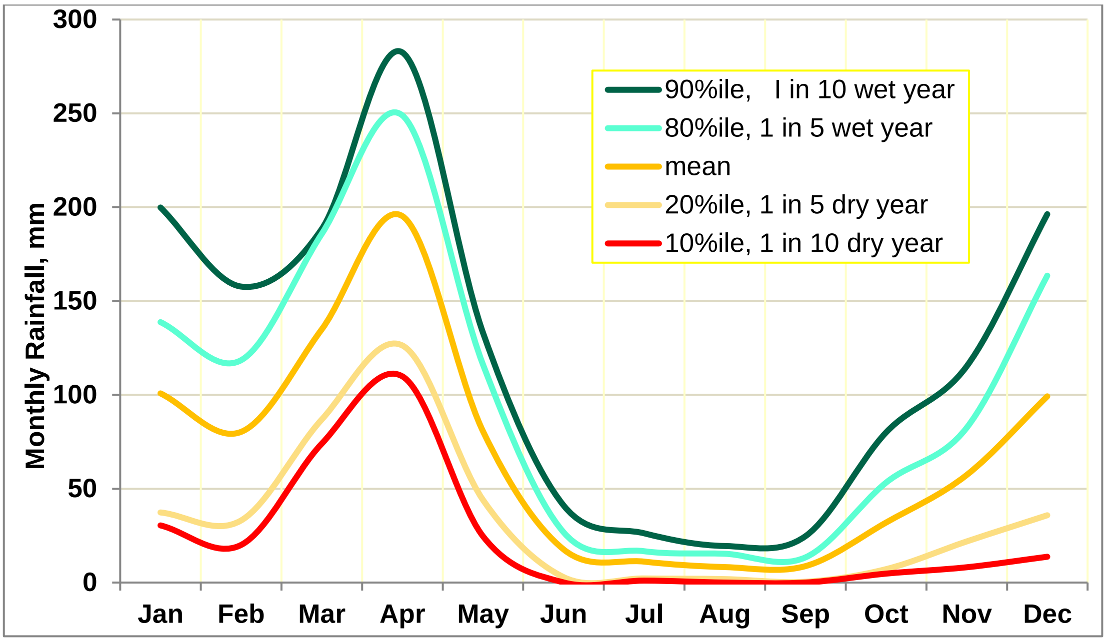


Table 32: Historic Wet and Dry-Year Contrasts in Rainfall for Morogoro, mm

MOROGORO	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
90%ile, I in 10 wet year	200	158	188	282	133	41	26	19	25	80	115	196	**1465**
80%ile, 1 in 5 wet year	139	118	186	249	116	27	17	15	13	53	82	164	**1180**
mean	101	80	135	195	81	18	11	8	9	32	57	99	**826**
20%ile, 1 in 5 dry year	37	33	87	126	44	3	2	2	0	7	22	36	**400**
10%ile, 1 in 10 dry year	30	20	74	110	25	0	1	0	0	5	8	14	**287**

9 CONCLUSION

An overall comparison of climate change parameters in the five EbARR sub-project areas is given in Table 25. These changes are small compared to the changes expected in more mountainous and higher latitude regions of the world. Nevertheless, there are five reasons why these data leave no scope for complacency.

1. These are annual averages. The critical condition for viability of agriculture, livestock farming, fishing, etc., is not *average* conditions, but short- or long-term *extremes*.
2. Extreme climate events will become much more frequent, albeit currently indeterminate, towards the end of this century.
3. Many small climate-change impacts are subtle, but have knock-on effects, such as small increases in temperature causing disproportionate increases in crop-water requirements, and decreases in soil moisture retention, groundwater infiltration, and available water resources (surface and sub-surface). In addition, small changes in water stress or temperature can have disproportionate effects upon crop germination, yield and quality.
4. Small changes in climate are coincident with high error bounds, and hence may prove to be worse than currently anticipated.
5. Some climatic changes will have consequences, which we cannot foresee, such as the rise of new or inadequately understood disease vectors.

Table 33: Comparison of Key Climatic Changes at EbARR stations, RCP 6.0

Station	2040-59				2080-99			
	ΔMAT	ΔMAR	ΔET_0	DR	ΔMAT	ΔMAR	ΔET_0	DR
Zanzibar	+0.9	+21	+0.2	nc	+1.8	+49	+0.4	nc
Arusha	+1.2	+37	+0.1	+5	+2.1	+81	+0.2	+10
Shinyanga	+1.3	+38	+0.1	nc	+2.4	+92	+0.3	nc
Dodoma	+1.2	+20	+0.3	+10	+2.3	+32	+0.6	+13
Morogoro	+1.0	+32		+5	+2.3	+52		+13

Notes: ΔMAT= Change in Mean Annual Temperature, °C. ΔMAR= Change in Mean Annual Rainfall, mm. Change in Evapotranspiration, ΔET_0, in mm per day. DR= Estimated change in probability of annual severe drought, P(x) %. nc = no appreciable change.

10 REFERENCE LIST

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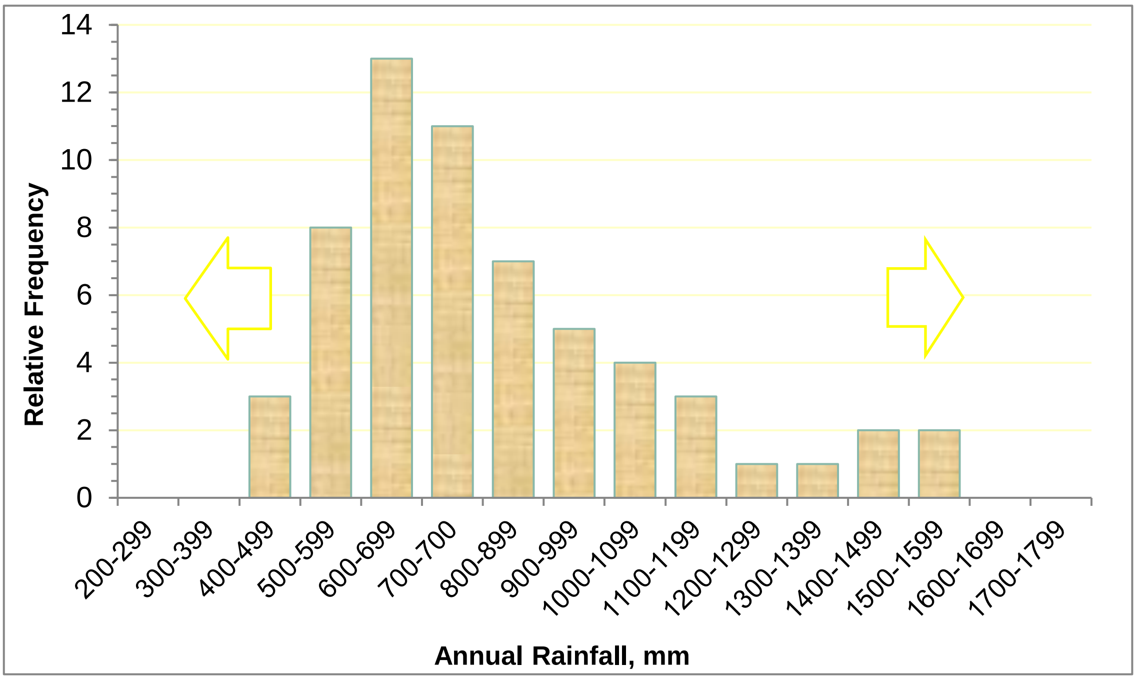
11 APPENDIX

An alternative way of indicating the Rainfall Probability Distribution is as a categorized histogram, as shown below. This example, from Arusha, shows that the historic rainfall occurs as a skewed normal distribution, but with some outlying heavy rain years. These anomalously heavy rains do not appear to belong to the main long- and short- rain distribution. They are most probably attributable to some other infrequent rain-forming mechanism.

Figure 86: The Historic Rainfall Distribution at Arusha



The arrows indicate the expected climate change trends, which are expected to stretch the distribution in both extreme tails

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