Climate change in Madagascar; recent past and future

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This report provides background information on changes in historical climate observed at sites within Madagascar and the changes, due to anthropogenic climate change, expected towards the middle of the 21st century. As such it draws on observations, downscaled climate change projections, reviewed literature and the 4th Intergovernmental Panel on Climate Change (IPCC) report (AR4).

1 Background

Madagascar's climate is highly varied, largely due to its geographical position in the Indian Ocean, its wide range of altitudes and different microclimates. Most rain falls during summer (November – April) with rainfall during winter (May – October) restricted to the southern and eastern coasts. Rainfall over the east coast is largely a product of easterly trade winds that bring moisture to its shores during much of the year. The steep topography causes the warm and moist air masses to rise, producing rainfall and leaving less moisture for rainfall further west. The central uplands and drier western regions receive rainfall during summer, mostly through convective activity and thunderstorms linked to the Inter-Tropical Convergence Zone (ITCZ), which lies across the northern parts of Madagascar during this time of year. During winter mid-latitude storms pass to the south of Madagascar which, when in a northerly position, can bring lower temperatures and rain to the southern parts of the country. This rainfall may be enhanced in regions of steep topography but remains small with much of the region receiving on average less than 800 mm each year. This contrasts sharply with regions in the northeast of the country which on average receive more than 3500 mm of annual rainfall

Mean annual temperatures are greatest along the dry west coast and coolest over the central upland plateaux. Temperature variations depend on location and altitude with minimum temperatures in winter on average less than 5 °C during June and July in the highlands (though some days reach below freezing). Maximum temperatures are highest in spring (October and November) over the west coast, on average greater than 36 °C in some regions, though some days are significantly hotter.

Tropical cyclones are a prominent feature of the Madagascan climate often leading to heavy rainfall and strong winds, which can cause significant damage and loss of life. The cyclone season is generally from November to May, with the peak of the season in January and February often extending into March. Cyclones form over warm waters (> 28 °C) in the South Indian Ocean to the east of Madagascar and move west and south. Depending on environmental factors these cyclones may pass to the north of Madagascar and head south through the Mozambique Channel (where they may be further fuelled by warm sea temperatures) or they may remain offshore and pass along the east coast. Greatest damages are caused if a cyclone makes landfall, sometimes passing directly across the island.

2 Global and regional climate trends

It is widely recognized that there has been a detectable rise in global temperature during the last 40 years and that this rise cannot be explained unless human activities are accounted for (IPCC, 2001; Solomon *et al.*, 2007). The regional distribution of temperature increases is not however uniform and some regions have experienced greater change than others, especially the interior of continental regions such as southern Africa (see figure 1). This is consistent with detected increases in annual temperatures found over southern Africa since 1900 (Hulme *et al.*, 2001). Additionally these changes in temperature are associated with decreases in cold extremes accompanied by increases in hot extremes (New *et al.*, 2006). Furthermore, the global average temperature indicates an increasing rate of change, such that temperature is rising quicker during the latter half of the 20th century (see figure 1). Importantly, this increase in the rate of change is expected to continue, potentially resulting in more rapid changes of climate in the future.

Changes in rainfall are typically harder to detect due to its greater variability, both in time and space. Even so, changing rainfall patterns have been detected for many parts of the globe, including moderate decreases in annual rainfall over southern Africa. Where records are of sufficient length there have been detectable increases in the number of heavy rainfall events (Solomon *et al.*, 2007) and within the southern hemisphere there is evidence for a moistening of the tropics and subtropics (Zhang *et al.*, 2007). This is consistent with regional studies over continental southern Africa which have shown trends for an increasing length of the dry season and increases in average rainfall intensity (New *et al.*, 2006). This has important implications for the seasonality of regional rainfall and together suggests a shorter but more intense rainfall season.

Besides changes in temperature and rainfall, other aspects of global change are notable (IPCC, 2007):

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

There is therefore compelling evidence for climate change at the global level, attribution to human activities, as well as its effects on continental southern Africa. However, understanding how global climate change may affect individual countries and small regions within a country is still a matter of research and is inherently linked to issues of uncertainty (see box 1). So whilst the observed global level changes serve to highlight that climate change is a reality and that we have confidence in continuing and potentially accelerating change, it is necessary to explore how local climates may already be changing as well as how they are expected to change in the future.

Box 1: Understanding uncertainty and risk

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

To be able to assess risk, one needs to consider all sources of information. It is therefore imperative that a probabilistic framework is used in developing projections which, at a minimum, should be an interpretive statement that draws on the diverse sources of information that are available. In this context and recognised within the IPCC process, one should recognize that four sources of uncertainty currently limit the detail of the regional projections:

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

3 Recent historical changes in the climate of Madagascar

Studies of recent historical changes in climate within Madagascar are limited and complicated by the significant regional variations in climate mentioned earlier, as well as natural variability on time scales of 10 years or longer. However, there is clear evidence that temperatures have increased, following the global trend and that the character of rainfall has changed appreciably. Whilst past trends are no guarantee of future change, especially in the context of uncertainty (box 1), they are the foundation from which to assess current adaptation strategies to climate change and how they may be appropriate given future expected change.

3.1 Historical changes of air temperature in Madagascar

Figure 2 indicates surface air temperature observed over southern (figure 2a) and northern (figure 2b) Madagascar. Over southern Madagascar temperature has been steadily climbing since the 1950's and though it was also significantly warmer in the early part of the century, temperatures in the year 2000 are approximately 0.2 °C warmer. Over northern Madagascar temperatures started rising since the early 1970's, but have yet to reach temperatures seen in the first half of the century, being approximately 0.1 °C colder at the end of the century

Similar to the global record, temperatures in both regions started cooling during the 1940's, reaching a minimum in the period 1950-1970. Global cooling during this period is mostly attributable to increases in volcanic and sulphate aerosols, after which the impact of anthropogenic emissions dominate the global temperature signal (IPCC, 2007). In this regard it is important to recognize that the anthropogenic signal in the global temperature record is expected to increase and that past changes are no guide to how the future will develop. This is evident in figure 2 as a rapid increase in temperature between 1975 and 2000, more so in the south of the country. Superposed on the positive temperature changes are decadal-scale fluctuations that suggest climate variability acting at these timescales, which are also seen in the rainfall record (see later).

Besides these general long-term changes in temperature an analysis of 21 observing stations with daily records since 1961 (covering the period when anthropogenic influences on the global climate are detectable) indicates that there have been consistent increases in daily minimum temperatures, averaged for the whole year across all stations (Figure 3a), with increases at 17 stations statistically significant. These increases in minimum temperature are consistent across all seasons throughout the year. Daily maximum temperatures increased at most stations during summer with less consistent changes during winter, resulting in mostly positive changes (except towards the northwest) when averaged over the year (Figure 3b).

Table 1 presents the trends for maximum and minimum daily temperatures between 1961 and 2005, for each season and the annual average. Most trends are significant at the 99% level or higher (indicated by '**'), most notably in minimum temperatures across all seasons (67% of all trends). Maximum temperatures indicate significant (>95% level) positive trends in 63% of all calculations with only one station demonstrating significant negative trends (Maevatanana). It is therefore clear from these data that Madagascar has been warming significantly since 1961, especially minimum temperatures, which is consistent with global observations.

Station	*Maximum daily temperatures*					*Minimum daily temperatures*				
	DJF	*MAM*	*JJA*	*SON*	*ANN*	*DJF*	*MAM*	*JJA*	*SON*	*ANN*
Antsirabe	0.025**	0.040**	0.056**	0.051**	0.043**	0.028**	0.035**	0.026	0.032**	0.031**
Vohemar	0.031**	0.021**	0.015*	0.011*	0.016**	0.029**	0.024**	0.018**	0.014*	0.021**
Tulear	0.039**	0.044**	0.038**	0.038**	0.040**	0.023**	0.030**	0.020**	0.033**	0.027**
Morondava	0.008	0.024**	0.024*	0.016*	0.019**	0.025**	0.037**	0.040**	0.036**	0.035**
Ranohira	-0.002	-0.003	-0.003	0.014	0.002	0.030**	0.038**	0.026**	0.047**	0.033**
Sainte-Marie	0.009	0.008*	-0.003	0.005	0.004	0.030**	0.036**	0.027**	0.026**	0.030**
Sambava	-0.003	-0.003	-0.003	-0.009	-0.006	0.042**	0.039**	0.030**	0.034**	0.037**
Taolagnaro	0.031**	0.039**	0.034**	0.037**	0.033**	0.021**	0.033**	0.027**	0.032**	0.026**
Toamasina	0.024**	0.029**	0.022**	0.015**	0.021**	0.007	0.010*	0.001	0.003	0.005
Fianarantsoa	0.031**	0.023*	0.029**	0.032**	0.027**	0.034**	0.035**	0.027**	0.038**	0.033**
Maevatanana	-0.040	-0.057**	-0.084**	-0.099**	-0.069**	0.030	0.020*	-0.024	-0.020	0.006
Mahajanga	0.037**	0.037**	0.028**	0.035**	0.033**	0.008	0.008	0.004	0.011*	0.001*
Mahanoro	0.016*	0.012*	0.011*	0.017**	0.013**	0.027**	0.028*	0.017	0.023**	0.022**
Mananjary	0.005	0.014*	0.013	0.015	0.008	0.029**	0.030**	0.032**	0.033**	0.031**
Morombe	0.013	0.023	0.001	0.001	0.01	0.017	0.050**	0.019	0.034*	0.040**
Ambohitsilaozana	0.017	0.017**	0.01	0.014	0.013*	0.019**	0.022**	0.018**	0.019**	0.020**
Analalava	0.031**	0.037**	0.026*	0.014	0.025**	0.009	0.008	0.007	0.01	0.005
Antananarivo	0.034**	0.034**	0.030**	0.038**	0.032**	0.028**	0.032**	0.027**	0.035**	0.029**
Antsiranana	0.034**	0.027**	0.019**	0.021**	0.024**	0.012*	0.005	0.001	0.001	0.004
Besalampy	0.006	0.006	-0.002	0.001	0.003	0.015	0.026**	0.022*	0.031**	0.026**
Farafangana	0.004	-0.001	0.003	0.002	0.001	0.023**	0.037**	0.035**	0.034**	0.037**

Table 1: Trends (°C yr^{-1}) in daily maximum temperatures (left of divide) and daily minimum temperatures (right of the divide) for 21 observing stations during the 1961-2005 period. Trends are presented for each season (DJF, December-February; MAM, March-May; JJA, June-August; SON, September-November) and annual average (*ANN*). Trends significant at the 95%(99%) confidence level are noted with a *(**).

3.2 Historical changes of rainfall in Madagascar

Detecting consistent changes in rainfall is typically more difficult than detecting changes in temperature, especially in highly variable arid climates such as can be found in the western and southern regions of Madagascar. This is largely because a single extreme rainfall event can contribute a significant proportion of the annual rainfall, leading to the spatial pattern of rainfall being more discontinuous than that of temperature. Figure 4 shows how rainfall has varied between 1901 and 2000 in both southern (figure 4a) and northern (figure 4b) Madagascar. During the 100-year period there are no obvious trends in either region, though comparison with the temperatures since 1950 (Figure 2) suggests that over northern Madagascar the temperature record goes up when the rainfall record goes down, and vice versa. Over southern Madagascar the relationship is the opposite with rainfall increasing when temperature increases. Figure 5 indicates the average monthly rainfall distribution between 1901 and 2000, demonstrating that most of the western regions are dry (less than 40mm of rainfall) between May and October, with the onset of rainfall in the north typically occurring in November, spreading southward through December and peaking in January/February. During March and April average rainfall retreats northward, with the east coast receiving moderate amounts (> 80 mm month^{-1}) of rain during the winter months.

Changes are often hard to detect in annual rainfall where different changes may counteract each other e.g. increases in summer rainfall may offset decreases in winter rainfall. Therefore rainfall changes on shorter timescales, such as during particular seasons or for attributes such as daily rainfall intensity, may be easier to detect. This may be particularly important when trying to detect changes due to anthropogenic climate change, which may be more easily seen in changes in seasonality and increases in rainfall intensity. Subjecting the same observing stations in table 1 to tests for trends (1961-2005) in some of these attributes indicated that there have been changes, though not at all times of the year. The most consistent changes in the record (in terms of statistical significance and spatial coherence) were found during the winter (June-August) and spring (September-November) seasons over the central and east coastal regions (see Figure 6). Total rainfall in both seasons over these regions has been steadily decreasing between 1961 and 2005 (Figure 6, left panels), and this has been accompanied by similar increases in the length of dry spells (Figure 6, middle panels), which indicates that rain has been falling less frequently. Some of these decreases in total rainfall are also because there have been less heavy rainfall episodes, as indicated by decreases in the number of days with rainfall greater than 10 mm (Figure 6, right panels). These reductions in winter and spring rainfall have also contributed to an increase in the maximum number of consecutive dry days over much of the country, especially the central and eastern regions (Figure 7). The maximum number of consecutive dry days often relates to the length of the dry season in regions which experience one single dry and wet season each year (e.g. the western regions). Over the east coast these changes are more consistently associated with the reduced frequency of rainfall in winter and spring.

3.3 Historical changes in atmospheric pressure

Whilst there have been few studies of trends in the atmospheric circulation over Madagascar, Hewitson *et al.*, 2006 note a trend for increases in the daily frequency of higher pressures (usually associated with reduced rainfall) over southern Africa during the December – February period. Over this region these changes may be related to reductions in the frequency of rainy days (Tadross *et al.*, 2007) and a later onset of the rainy season during spring (Tadross *et al.*, 2005). A similar mechanism may explain some of the reductions in the frequency of rain noted in Madagascar though changes over Madagascar are more prominent during winter and spring.

Changes in atmospheric circulation have been noted in the Southern Annular Mode (SAM), which is the dominant mode of atmospheric circulation in the southern hemisphere (Marshall *et al.*, 2004; Solomon *et al.*, 2007). Since 1979 the SAM has tended towards a positive polarity, a consequence of lower pressures over the Antarctic and higher pressures further north between 40°S and 50°S.

This change is consistent with that expected due to increases in greenhouse gases (Arblaster and Meehl, 2006) and therefore may continue in the future. The promotion of higher pressures in the mid-latitiudes can enhance the likelihood of dry days over southern Madagascar in several ways, e.g. by suppressing convective rainfall during summer or by reducing the incidence of storms during winter. It is, however, beyond the scope of this report to identify the mechanism responsible for the changes in rainfall noted previously, except to say that the changes are not inconsistent with changes noted over southern Africa and the southern hemisphere in general.

4 Climate projections

General Circulation models (GCMs) are the fundamental tool used for assessing the causes of past change and projecting change in the future. They are complex computer models, which represent interactions between the different components of the climate system such as the land surface, the atmosphere and the oceans. In making projections of climate change, several GCMs and scenarios of future emissions of greenhouse gasses are used to predict the future (see box 2). This leads to a suite of possible futures, each of which is a valid representation of what the future climate may be. That there is a range of future possibilities is an important concept to understand clearly as it means that we can only suggest futures that may be more *likely* than others.

Box 2: Is one GCM better than another at projecting future change ?

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

GCMs typically work at a spatial scale of 200-300km, with the scales at which they have skill, i.e. at which they can usefully project the future, typically greater. Whilst this problem is greatest for projections of rainfall, it limits the application of GCM projections for assessments of change at the local scale. Therefore, the technique of ‘downscaling’ is typically used to produce projections at a finer spatial scale. Downscaling works because the GCMs are generally good at projecting changes in atmospheric circulation (high and low pressure) but do a poor job of translating that information into changes in rainfall. The projected changes in rainfall presented here are therefore taken from the statistical downscaling of 6 GCMs, three of which were used in the IPCC 3rd assessment report (HadCM3, CSIRO MK II, ECHAM 4.5) and three used in the AR4 (GFDL, MIROC, MRI CGCM). These downscaled projections of changes in rainfall are explained in Hewitson and Crane, 2006 and presented in Christensen *et al.*, 2007. The range of future changes in temperature have been calculated using a combination of a regional climate model and 13 GCMs taken from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset[1].

All future scenarios are for the IPCC A2 SRES scenario (which assumes that society will continue to use fossil fuels at a moderate growth rate, there will be less economic integration and populations will continue to expand) for the period 2046-2065. The rainfall data was linearly scaled to this period from projections for the period 2081-2100.

[1] http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php

4.1 Future regional climate scenarios: Rainfall

Figure 8 indicates the median value of change in total monthly rainfall from the 6 statistically downscaled GCM rainfall estimates, for all months of the year. Whilst the median value is presented here, this is simply one of many values that could be taken for the future and in reality there is an envelope (range) of future projections from the 6 models; the median rather than the mean is shown as this better represents any potentially skewed distributions. The figure is derived from projections downscaled to 23 stations most of which were used in the earlier section looking at trends in the observations. As there are 6 projected futures (from each GCM) for each station, those stations indicating 3 positive and 3 negative changes are masked out as this indicates the 6 downscaled GCMs do not converge on whether the climate is going to become wetter or drier at such a station.

The projected median changes in rainfall in figure 8 suggest that rainfall will increase throughout the summer months of January to April, though the projections are inconsistent and therefore inconclusive over the northwestern regions; one station suggests (4 out of 6 models) a drying in March. Starting in May for the most southerly station, rainfall is projected to decrease, with the affected area spreading along the east coast through June and July. Throughout July, August and September the southern half of the east coast is projected to be drier by 2050, whilst the rest of the country is projected to be wetter. In October the dry region is only indicated for the most southerly station with the rest of the country becoming progressively wetter, especially in the north, passing through November and December (again the projections are inconsistent in the northwestern regions during this month).

These projected changes are consistent with the process-based understanding of how climate change will manifest itself over the southern African region i.e.

1. That winter storms will retreat southward, reducing winter rainfall to the southern extremes;
2. Increases in thermal heating, coupled with increases in atmospheric moisture, especially during mid to late summer, are expected to increase convective rainfall over much of the region.

4.2 Future regional climate scenarios: Temperature

Figure 9 indicates the multi-model (13 GCMs) minimum and maximum expected change in surface temperature for the period 2046-2065. These changes are produced using the change predicted by a regional climate model (which better represents the local topography and therefore the spatial distribution of change, see Tadross *et al.*, 2005), which is then scaled by the minimum and maximum change from the 13 GCMs. Together the minimum and maximum represent the envelope of expected change given many model simulations and an A2 emissions scenario. The lowest expected changes are in the north of the country and along the coastal regions (increases in excess of 1.1 °C). This is largely due to increased moisture, clouds and rainfall in the north can moderate temperature increases and because temperatures in coastal regions are strongly regulated by the temperature of the nearby ocean. The minimum expected temperature increases away from the coast and especially towards the south where it is in excess of 1.5 °C. The maximum expected change from all 13 models (Figure 9 right panel) indicates a similar spatial pattern to the minimum expected change for the same reasons mentioned above. Around the coast the maximum expected change is in excess of 1.8 °C, which rises to more than 2.6 °C in the south of the country, indicating that the maximum expected change varies more depending on the spatial location than does the minimum expected change. It is also apparent that the range of projected temperature changes from the different GCMs is greatest and hence less constrained for southern Madagascar.

Whilst the range of annual mean projected change presented here is a reasonable guide to change on an annual timescale, it should be remembered that it does not represent the range of change expected for individual seasons, months and days. These shorter timescales are characterised by greater variability, a greater dependency on the simulated changes in rainfall and often a wider range of projected change.

4.3 Future climate scenarios: Cyclones

Data from 4 GCMs were used to calculate the projected change in Genesis Potential (GP, an approximate measure of the potential frequency of cyclone formation) and maximum Potential Intensity (PI, an approximate measure of the potential destructive power of a cyclone as measured by its potential maximum sustained wind speed). Both GP and PI were averaged over the southwest Indian Ocean (SWIO, 30°-100°E, 0°-30°S, not including land areas) and Figure 10 indicates the monthly projected changes for the 2060-2100 period. The projected change in GP (upper panel) indicates inconsistent changes (some GCMs increasing GP and others decreasing GP) between January and August. However, between September and December all 4 GCMs indicate a reduction in GP (of between 10% and 80%). The cyclone season currently starts in November and these data suggest that in the future there will be fewer cyclones over the SWIO during what is currently considered to be the early part of the cyclone season. Monthly changes in PI over the SWIO suggest a clearer picture; except for the months of July, August and September all 4 GCMs project an increase in PI, and hence destructive power, of between 2% and 17%. This has important implications for the risk of cyclone damages (to infrastructure, agriculture and lives) and development activities within vulnerable regions in the future. Therefore, whilst changes in GP indicate decreases in the frequency of cyclones during the early part of the main season, their intensity, associated winds and destructive power are all suggested to increase as we progress towards the end of the century.

5 Reconciling observed trends and future change

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

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

However, these changes in the physical system will interact and couple in a non-linear manner and individually manifest themselves at different periods in the future. The regional expression of change is therefore dependent on which mechanisms, which may compete with each other (e.g. increases in rainfall may offset decreases in rain days), are dominant at any particular time. Unlike the temperature signal due to climate change, which is currently observable, the rainfall signal (as estimated from low variability GCM data and therefore likely a conservative estimate) is not expected to be observable for several decades (Christensen *et al.*, 2007).

Given these caveats and the relatively coarse resolution of the source GCMs it is perhaps remarkable that the observed reductions in winter rainfall over the east coast are not radically dissimilar to those projected under climate change. These reductions may be tied to changes in the strength and positioning of easterly winds, which in turn may be linked to changes in the strength and positioning of the south Indian Ocean high-pressure system (noted previously) or the winter storm tracks. However, the differences between future projections of increased summer rainfall (due to increases in surface heating and moisture) and the observed record are greater, which suggests that this aspect of change is not yet well developed and can be expected to become more apparent in the future.

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

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Figures

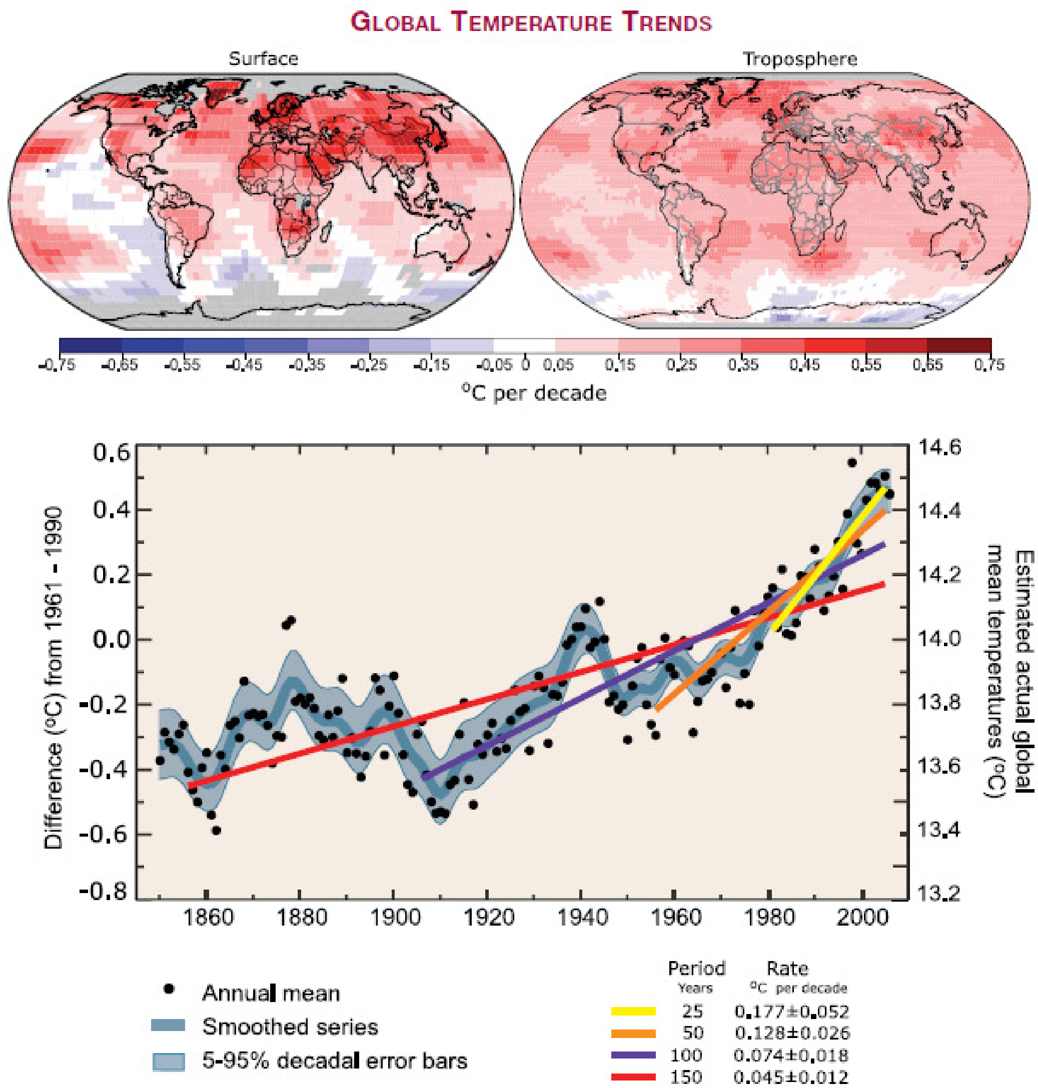
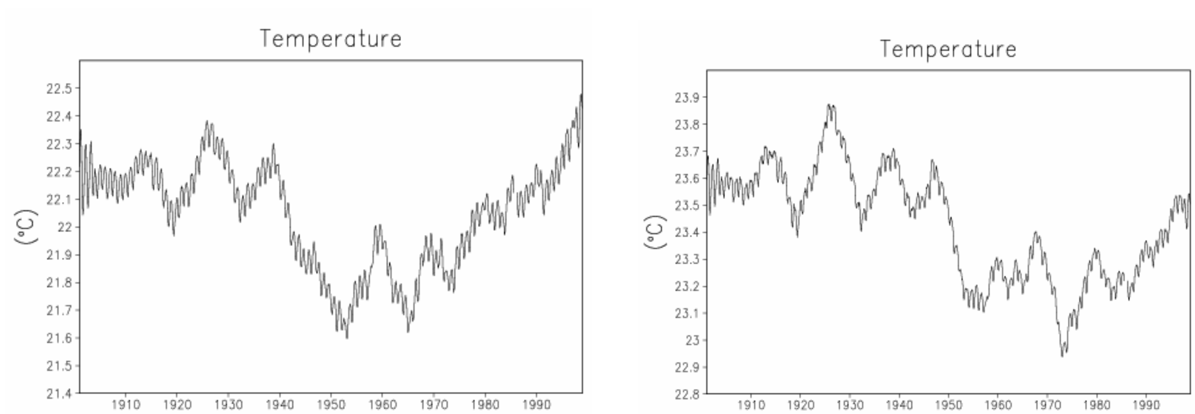
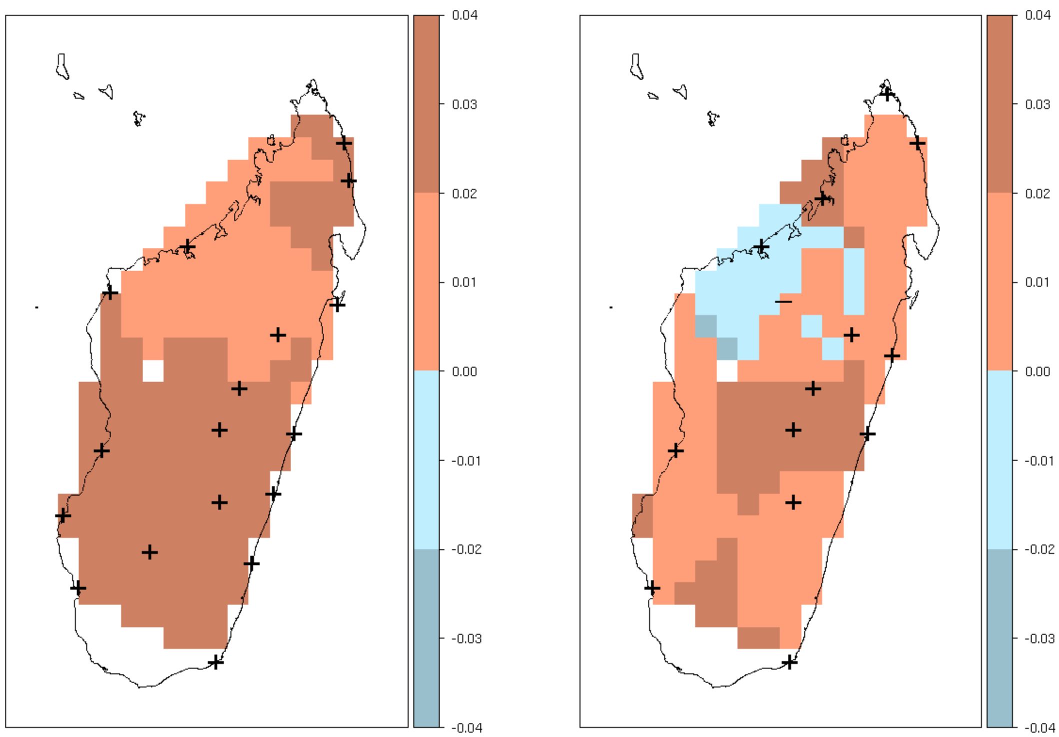


Figure 1: Distribution of global temperature trends (1979-2005) for the surface (left) and troposphere (right) from satellite records. Below: the average global temperature since 1850 indicating the increased rate of change during the later part of the 20th century. Source: Solomon *et al.*, 2007.



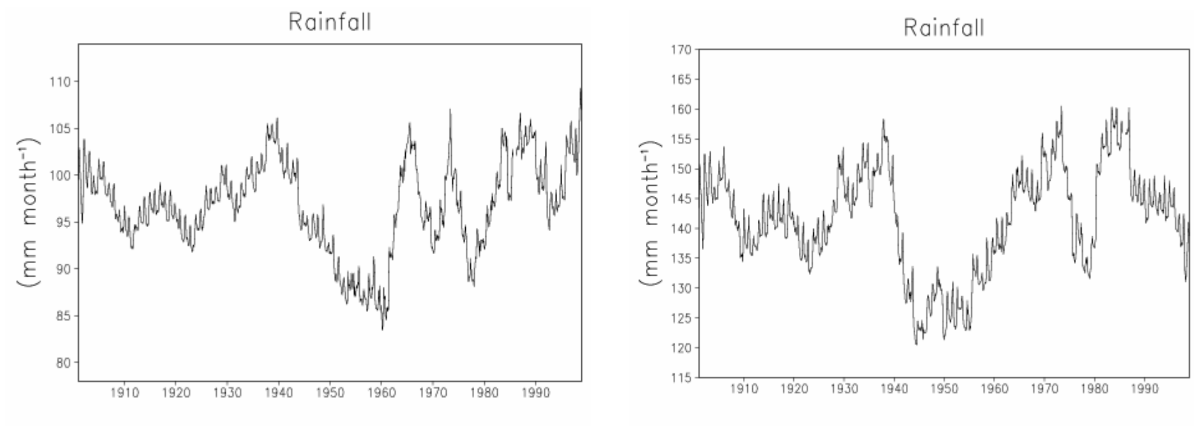
(a) **(b)**

Figure 2: Mean (6-year average) surface air temperature (°C) measurements 1901-2000: a) southern Madagascar (43-51°E, 27-20°S); b) northern Madagascar (43-51°E, 20-11°S). Source Climate Research Unit (Mitchell *et al.*, 2004).



(a) (b)

Figure 3: Trend in annual average minimum (a) and maximum (b) daily temperature 1961-2005. "+"/"-" indicates where observations show a positive/negative trend (getting warmer/colder) that is statistically significant at the 95% confidence level or higher.



(a) **(b)**

Figure 4: Mean (6-year average) rainfall (mm month^{-1}) measurements 1901-2000: a) southern Madagascar (43-51°E, 27-20°S); b) northern Madagascar (43-51°E, 20-11°S). Source Climate Research Unit (Mitchell *et al.*, 2004).

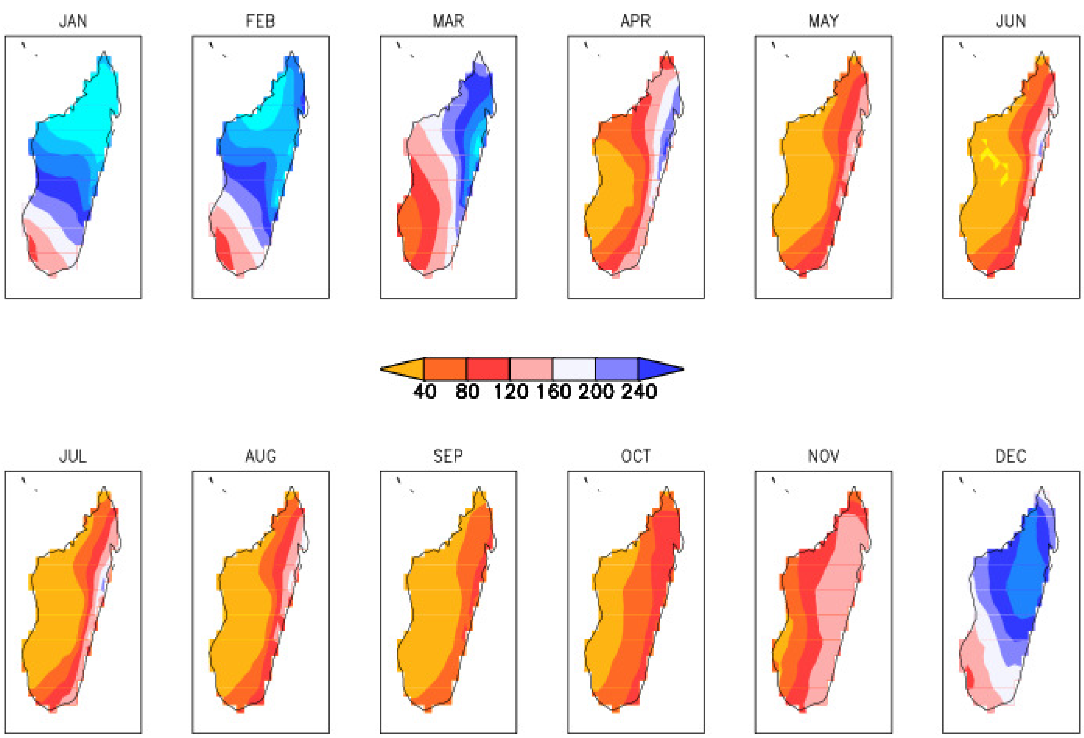


Figure 5: Monthly mean rainfall distribution (mm month^{-1}) 1901-2000. Source Climate Research Unit (Mitchell *et al.*, 2004).

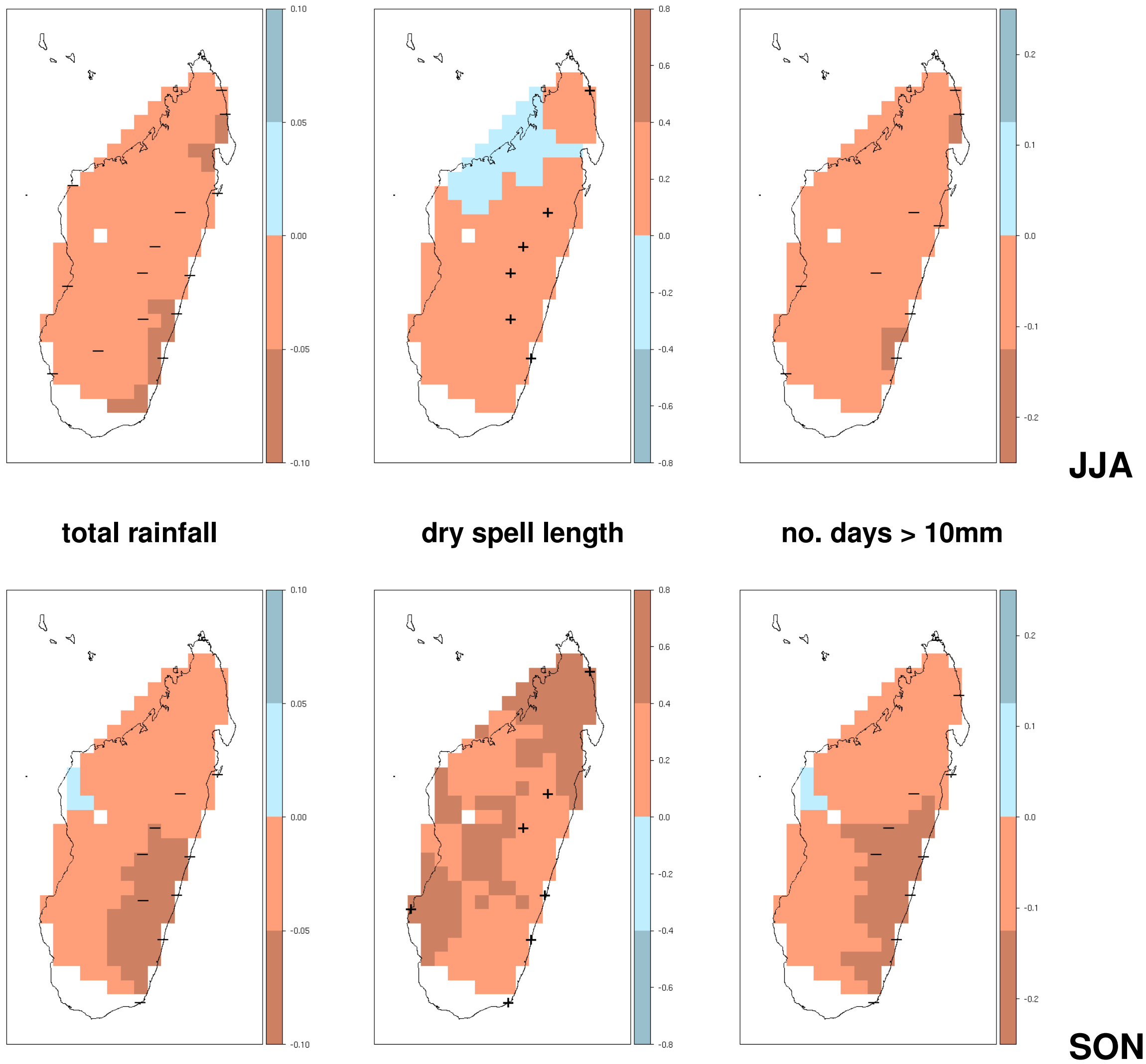


Figure 6: Trends in average rainfall (mm day^{-1} year^{-1}), mean dry spell length (days year^{-1}), number of days > 10 mm of rain (days year^{-1}) for the June-August (upper 3 panels) and September-November (lower 3 panels) periods. Statistically significant (>95% confidence level) positive/negative trends are indicated by "+"/"-".

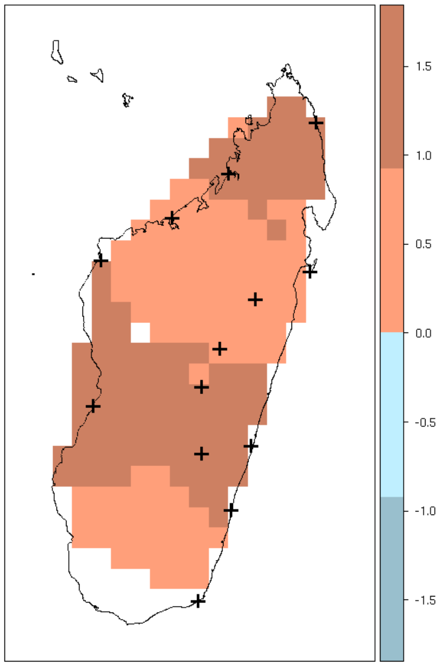


Figure 7: Trends in annual maximum number of consecutive dry days (days year^{-1}). Statistically significant (>95% confidence level) positive trends are indicated by "+".

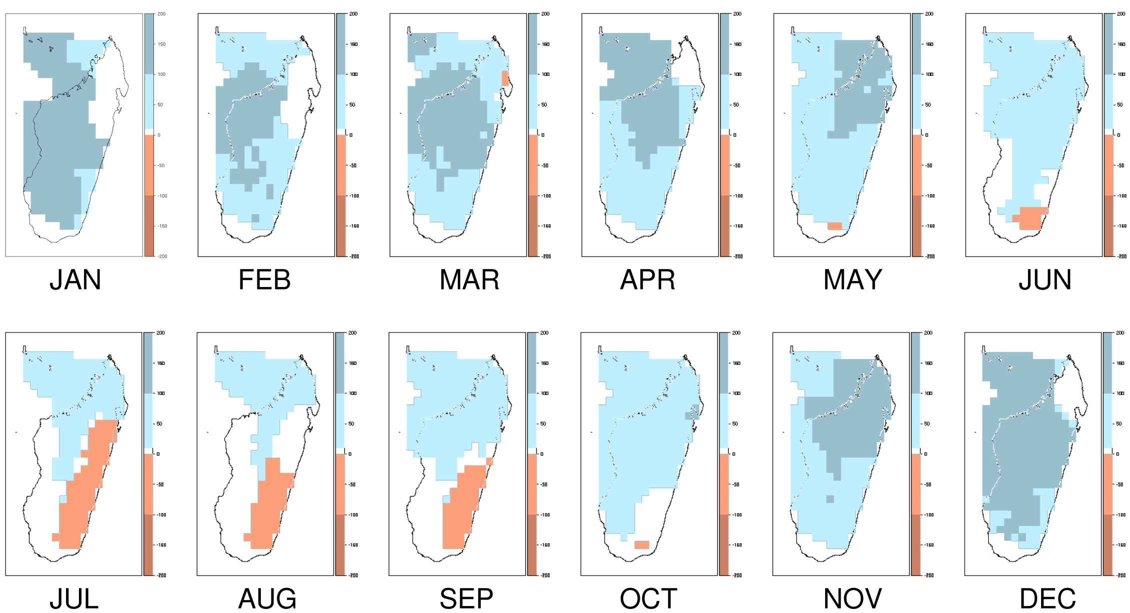


Figure 8: Median change in total monthly rainfall (mm month^{-1}) from 6 downscaled global models (for the period centred on 2055). Regions where 3 models give positive and 3 models negative changes are left blank – as are regions of increases < 10 mm month^{-1}, which will be offset by increases in potential evapotranspiration

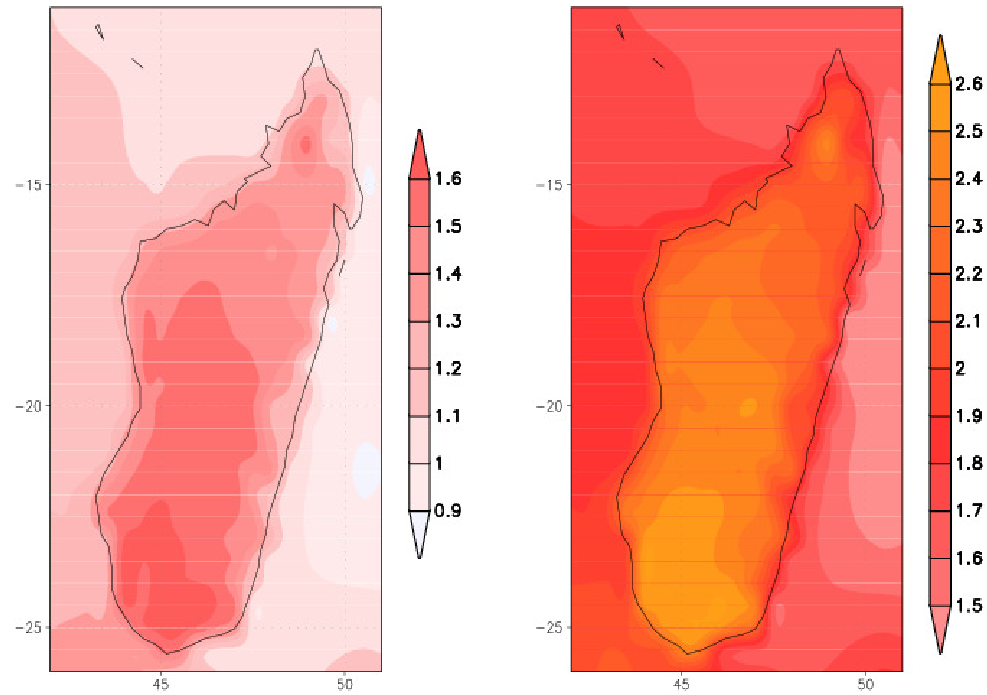
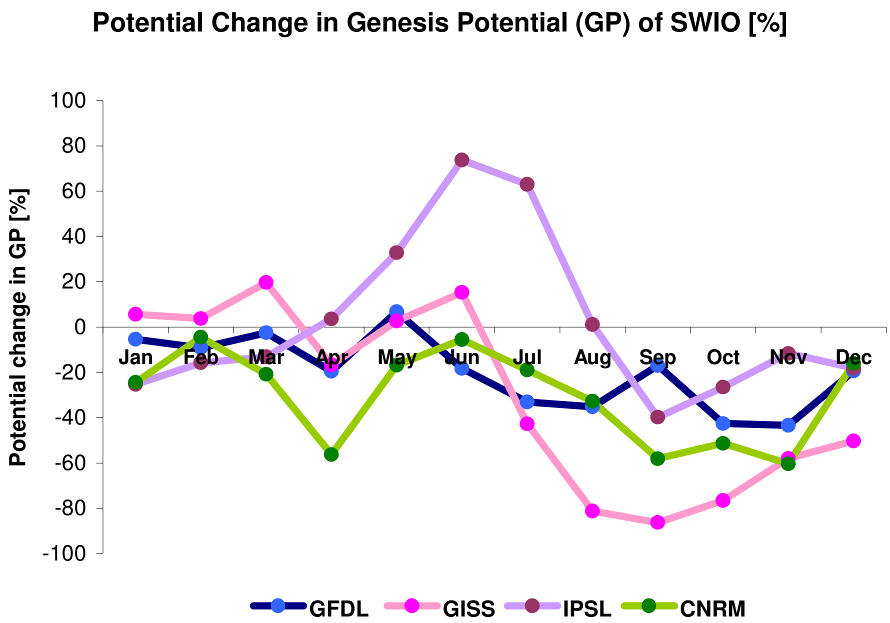


Figure 9: Multi-model (13 GCMs) minimum (left) and maximum (right) projected change in annual mean surface air temperature (°C) for the period centred on 2055.



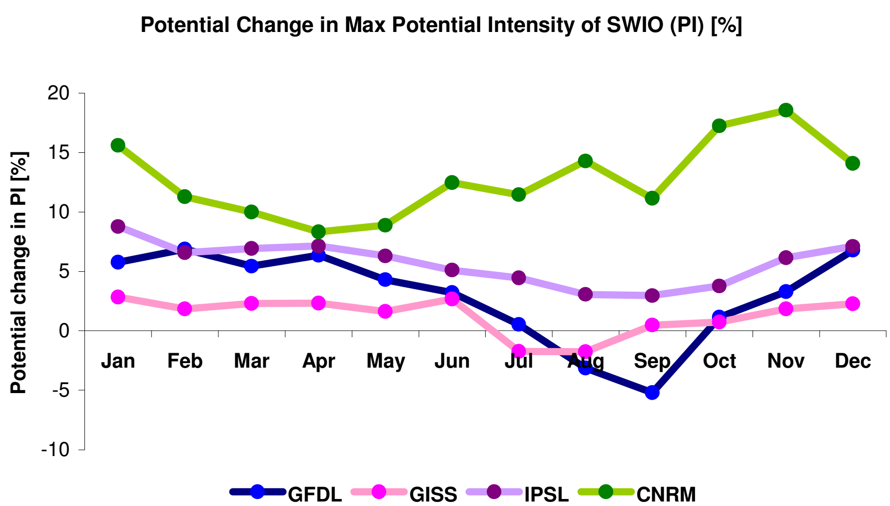


Figure 10: Projected change in Genesis Potential (top) and maximum Potential Intensity (bottom) from 4 GCMs for the southwest Indian Ocean (30°-100°E, 0°-30°S) for the period 2060-2100.