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LETTER

Projected changes in tropical cyclones over the South West Indian Ocean under different extents of global warming

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Abstract

The Paris Agreement achieved in December 2015 established that the signatory countries should pursue to hold the increase in global average temperature to below 2 °C relative to the preindustrial period and to strive to limit the temperature increase to 1.5 °C below the preindustrial period. The potential changes in tropical cyclones over the basin making landfall over southern Africa under the key global temperature goals have not been thoroughly investigated. Using the Coordinated Regional Downscaling Experiment-Africa regional climate models, we downscale six global climate models of the Coupled Model Inter-comparison Project Phase 5 to high resolution. This serves towards studying changes in tropical cyclone tracks over the South West Indian Ocean under different extents of global warming (1.5 °C, 2 °C and 3 °C of warming with respect to pre-industrial conditions). It is projected that the number of tropical cyclones making landfalls over southern Africa under global warming will decrease, with 2 °C being a critical threshold, after which the rate of cyclone frequency with further temperature increases no longer has a diminishing effect. Fewer cyclones may bring benefits and reduce damage to the southern African region. Although a decrease in damages associated with flood events is desirable, general decreases in tropical cyclone and tropical lows may also be associated with decreased rainfall over the Limpopo River basin and southern, central and northern Mozambique (with negative impacts on dryland agriculture).

1. Introduction

On average, the South West Indian Ocean basin experiences nine tropical cyclones annually. If less intense tropical storms are also considered, the average number of tropical storm systems reaches eleven (Jury 1993). Out of the total number of tropical cyclones that form over the South West Indian Ocean, only 5% reach landfall over southern Africa (Reason 2007, Mavume *et al* 2009, Fitchett and Grab 2014). Such tropical cyclones making landfall along the eastern coast of southern Africa are typically associated with flooding in Mozambique, Zimbabwe and South Africa (Crimp and Mason 1999, Reason and Keibel 2004). For example, tropical cyclone Eline (a super-cyclone) brought devastating flooding to Mozambique in February 2000, then tracked across the southern African region for 2000 km towards the Atlantic Ocean. It was the longest lived tropical cyclone to have ever occurred in the South West Indian Ocean (Reason and Keibel 2004). While the system resulted in severe flooding in Mozambique, Zimbabwe and South Africa, it also contributed to 25% of the semi-arid Namibian rainfall during that summer season. Overall, tropical cyclones and weaker tropical systems from the South West Indian Ocean contribute significant amounts of rainfall over the semi-arid Limpopo River basin and are associated with the most significant rainfall events within the basin (Malherbe *et al* 2012). These systems, therefore, are both sources of damage, especially along the coast, and of much needed rainfall over large parts of the interior.

Previous research has indicated a projected decrease in the number of tropical cyclone-like vortices under the A2 (low mitigation) emission scenario over the South West Indian Ocean, as well as for land-impacting systems along the southeastern African Coast (Malherbe *et al* 2013). In the current study, a new set of latest available simulations are provided and the occurrence of tropical cyclone-like vortices analysed for 1.5 °C, 2 °C and 3 °C of global warming. We select model simulated years corresponding to the key global temperature goals under the RCP 8.5 scenario (a low mitigation future). An important aim of the investigation is to identify the benefits of limiting warming to 1.5 °C, against more drastic levels of global warming.

2. Methods

2.1. Model description and experiment

An ensemble of very high resolution climate model simulations of present-day climate, and projections of future climate change over southern Africa, has been analysed as part of the current project. The regional climate model used is the conformal-cubic atmospheric model (CCAM), a variable-resolution global climate model (GCM) developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) (McGregor 2005, McGregor and Dix 2001, 2008, Thatcher and McGregor 2009, Thatcher and McGregor 2010). CCAM runs coupled to a dynamic land-surface model CABLE (CSIRO Atmosphere Biosphere Land Exchange model). Six GCM simulations of the Coupled Model Intercomparison Project Phase Five (CMIP5) and Assessment Report Five (AR5) of the Intergovernmental Panel on Climate Change (IPCC), obtained for the emission scenarios described by Representative Concentration Pathway 8.5 (RCP 8.5), were first downscaled to 50 km resolution globally. The simulations span the period 1960–2100. RCP8.5 is a low mitigation scenario. The GCMs downscaled include the Australian Community Climate and Earth System Simulator (ACCESS1-0); the Geophysical Fluid Dynamics Laboratory Coupled Model (GFDL-CM3); the National Centre for Meteorological Research Coupled Global Climate Model, version 5 (CNRM-CM5); the Max Planck Institute Coupled Earth System Model (MPI-ESM-LR); the Norwegian Earth System Model (NorESM1-M), and the Community Climate System Model (CCSM4). The simulations are performed on supercomputers at the Centre for High Performance Computing (CHPC) of the Meraka Institute, CSIR,South Africa. In these simulations CCAM was forced with the bias-corrected daily sea-surface temperatures (SSTs) and sea-ice concentrations of each host model, and with CO_2, sulphate and ozone forcing consistent with the RCP8.5 scenario. The model's ability to realistically simulate present-day southern African climate has been extensively demonstrated (e.g. Engelbrecht *et al* 2009, Engelbrecht *et al* 2011, Malherbe *et al* 2013, Winsemius *et al* 2014, Engelbrecht *et al* 2015). Most current coupled GCMs do not employ flux corrections between atmosphere and ocean, which contributes to the existence of biases in their simulations of present-day SSTs—more than 2 °C along the West African coast. An important feature of the downscalings performed here, is that the model was forced with the bias-corrected SSTs and sea-ice fields of the GCMs. The bias is computed by subtracting for each month the Reynolds (1988) SST climatology (for 1961–2000) from the corresponding CGCM climatology. The bias-correction is applied consistently throughout the simulation. Through this procedure the climatology of the SSTs applied as lower boundary forcing, is the same as that of the Reynolds SSTs. However, the intra-annual variability and climate-change signal of the CGCM SSTs are preserved (Katzfey *et al* 2009).

2.2. Tropical cyclone tracking technique

An automated tropical cyclone tracking technique is used to objectively identify tropical-cyclone like vortices in the South West Indian Ocean. The procedure followed is after (Engelbrecht *et al* 2013 and Malherbe *et al* 2012). In order for the automated tracking technique to have consistency, the simulated and observed data (used for model verification) need to be of similar resolutions, both in time and space (Blender and Schubert 2000). In order to achieve this, the CCAM simulations and reanalysis data were interpolated to a 2° × 2° horizontal grid using bicubic interpolation. The NCEP/NCAR reanalysis data (Kalnay *et al* 1996) were analysed at six hourly intervals corresponding to the temporal resolution of CCAM output.

The algorithm applied made use of the following parameters and threshold criteria.

- Identification of all the closed lows at 700 hpa; every six hour interval throughout the entire study period.
- There should be a temperature maximum at 250 hpa overlaying the low pressure identified at 700 hpa.
- At level 500 hpa there should be a reflection of the pressure minimum as that of 700 hpa low pressure minimum.
- For each closed low system identified at 700 hpa, the vorticity should be less than $-3.5 \times 10^{-5}\ s^{-1}$.

As recommended by Walsh *et al* (2007), the maximum wind speed at 10 m should be greater than $13\ m\ s^{-1}$. It should be noted that through the use of an iterative procedure, a low track is only constructed if a closed minimum can be tracked for at least 24 hours.

2.3. Transient definition of different degrees of global warming

The projected changes in regional climate over Africa, and associated changes in climate costs, are presented under different global temperature goals. It is important to consider how the 1.5 °C, 2 °C and 3 °C global worlds may be defined. A definition that is important in terms of the Paris Agreement (reference) is to consider so-called 'stabilisation' scenarios. For example, one may consider a future world where temperatures have stabilised at 3 °C with respect to a pre-industrial baseline, and proceed to study climate change impacts in such a world. Although global 1.5 °C and 2 °C stabilisation worlds can be similarly defined, it seems unlikely that these global temperature goals can be achieved without a scenario of 'overshoot', that is, temperatures are likely to first increase to above the 1.5 °C and 2 °C, where after future (yet to be developed) technologies enabling atmospheric carbon dioxide removal may be applied to eventually achieve 1.5 °C or 2 °C worlds. Climate change impacts are likely to be rather different in a scenario where overshoot occurs before stabilisation, compared to where the particular global temperature threshold is never exceeded (stabilisation without overshoot). Pragmatic reasons also complicate studying climate change impacts under scenarios of stabilisation at different global temperature goals. Only a few global climate change projection studies have to date been performed for mitigation forcings designed to generate stabilisation scenarios. In fact, the vast majority of projections considered in AR5 of the IPCC, have been performed for 'transient' scenarios, where greenhouse gas concentrations continue to increase during the 21st century with associated continued increases in the global average surface temperature. For example, under the RCP8.5 of AR5, the global average temperature in a typical GCM projection systematically increases during the 21st century to reach and then exceed the 1.5 °C, 2 °C and 3 °C thresholds, and from there continues to increase further.

It therefore makes sense to, from a data availability point of view, define global temperature worlds using the transient definition. The 1.5 °C world, for example, may be defined as the ten years before and after the year during which the 1.5 °C threshold is first exceeded in a particular global simulation. Another important consideration for studying climate change impacts under the transient definition is that the 'transient world' is likely to represent reality during the 21st century. It is likely that both the 1.5 °C and 2 °C thresholds will be exceeded during the 21st century, even under modest to high mitigation. Studying climate change impacts under the transient 1.5 °C definition is therefore very much a pragmatic choice and important towards the formulation of suitable adaptation strategies.

Consequently, this paper defines the 1.5 °C, 2 °C and 3 °C global worlds under the transient definition, and for each identifies the relevant 21 year period under RCP8.5 and for the particular GCM considered. A further consideration is that for the regional climate models participating in CORDEX, the simulations typically start in 1971 (i.e. the pre-industrial period is not simulated). Regional climate change is therefore calculated with respect to the 1971–2005 baseline (the same baseline used in AR5). Also following AR5, it is assumed that the 1971–2005 baseline already represents 0.6 °C of global warming with respect to the pre-industrial baseline. The global average surface temperature anomalies are therefore calculated with respect to the 1971–2005 baseline in the global CCAM simulations, to which a further 0.6 °C is added towards identifying the years during which the 1.5 °C, 2 °C and 3 °C thresholds are first exceeded.

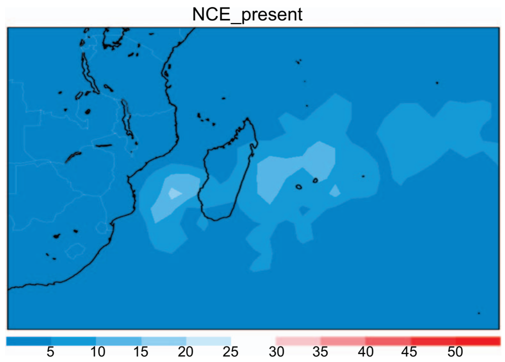


Figure 1. Frequency of tropical cyclone-like vortice centres at a 2° spatial resolution and six hourly temporal resolution under present-day climate (1971–2000); as simulated by NCEP/NCAR reanalysis.

3. Results and discussion

3.1. Climatology of tropical cyclones over the South West Indian Ocean basin

Figures 1–2 indicates the frequency of downscaled simulations for present-day (1971–2000) tracked tropical cyclone-like vortice centres. These are presented as occurring at each grid point (at 2° spatial resolution) across the domain of the South West Indian Ocean.

The simulated cyclone frequencies and tracks (figure 2) are in spatial agreement, with the occurrence of tropical cyclone-like vortices as simulated by six downscaled Assessment Report 4 models using CCAM (Malherbe *et al* 2013). It should be noted that the simulated present day number of tropical cyclones are slightly higher than the present day cyclones as simulate by NCEP reanalysis dataset (figure 1–2). This can be ascribed to the reason that most models that use prescribed climatological sea surface temperatures tend to simulate tropical cyclones that are higher in both intensity and numbers e.g. Li and Sriver (2018) studied the impact of ocean coupling and found that compared to mixed layer coupling and dynamic ocean coupling, prescribed sea surface temperature coupling results in high intensity and number of cyclones. There is also an agreement with observations as per International Best Track Archive for Climate Stewardship (IBTrACS—Knapp *et al* 2010) for the 1961–1990 period (Malherbe *et al* 2013). The highest frequency of cyclone-like vortices is simulated

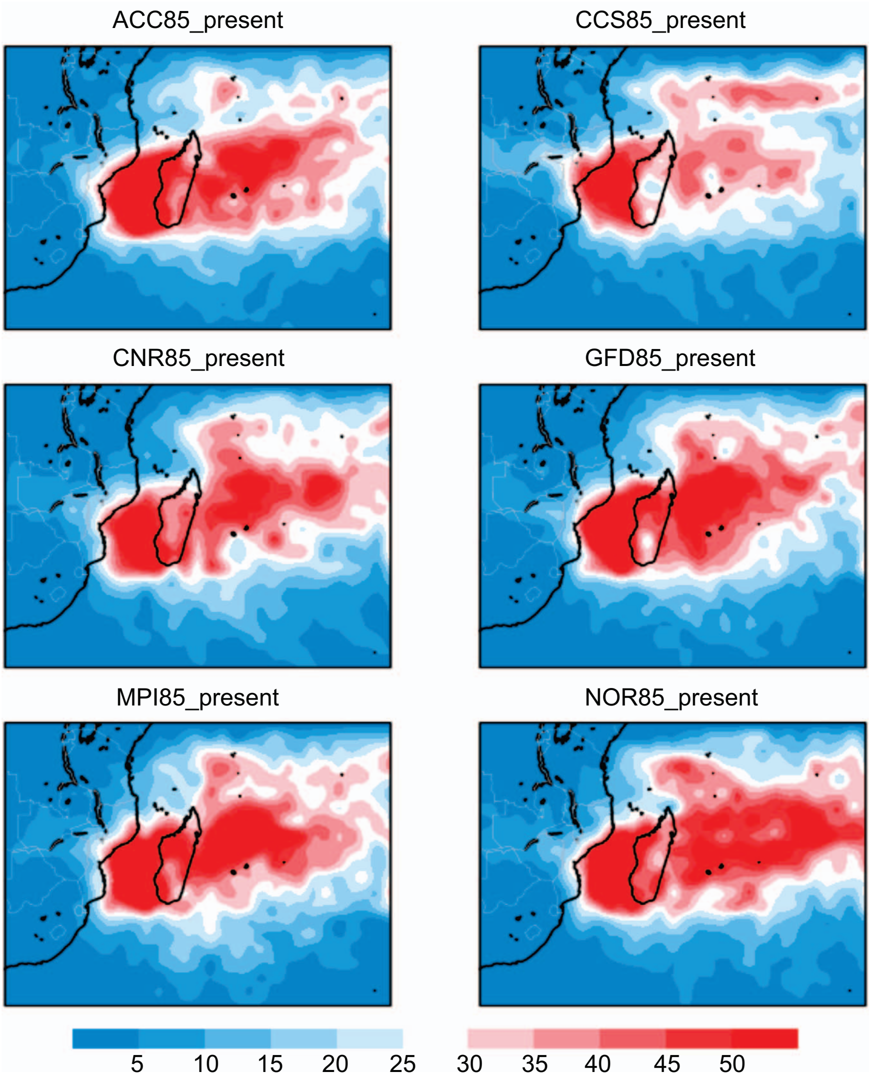


Figure 2. Modelled frequency of tropical cyclone-like vortice centres at a 2° spatial resolution and six hourly temporal resolution under present-day climate (1971–2000); obtained from six different CCAM downscalings under RCP8.5.

consistently by all models over the central Mozambique Channel, around 18°S. Another maximum is simulated towards the north or northeast of Mauritius, along 16°S. Landfall and westward penetration are simulated by all models, with the preferred westward track towards the north of Botswana along 16°S.

Figures 3–5 show the projected change, as simulated by each downscaling under 1.5 °C, 2 °C and 3 °C of global warming (see section 2.4 for details on how these periods were calculated) relative to the present-day baseline period of 1971–2000. With increasing global warming, there is a tendency for all downscalings to simulate lower tropical cyclone frequencies across the main tropical cyclone formation region of the South West Indian Ocean. This is demonstrated by larger and more intense negative anomalies associated with stronger global warming, in particular over the Mozambique Channel. Another region of large reductions is visible to the north and northeast of Mauritius. While the downward trend in simulated tropical cyclone-like vortices is consistent, there is some spread among the models in their magnitude of projected change. The largest reduction in numbers of simulated tropical cyclone-like vortices is noticed in the projections of ACCESS1-0, while CNRM-CM5 clearly simulates comparatively smaller reductions.

These simulated results are in agreement with earlier findings based on a set of AR4 models (Malherbe *et al* 2013). The lower projected frequency of occurrence, especially over the southern parts of the domain, is associated with a simulated increase in vertical wind shear. Over most of the domain, however, the decrease is associated with increases in static stability as well as a change in large-scale vorticity in the region. Moreover, the findings are largely consistent with the global observation of a general decrease in tropical cyclone frequencies, which are occurring in association with general increases in cyclone intensities (Elsner *et al* 2008, Holland and Bruyère 2014, Strazzo *et al* 2015). Most climate models are indicative of this pattern which is intensifying under enhanced global warming; our results indicate that the same pattern

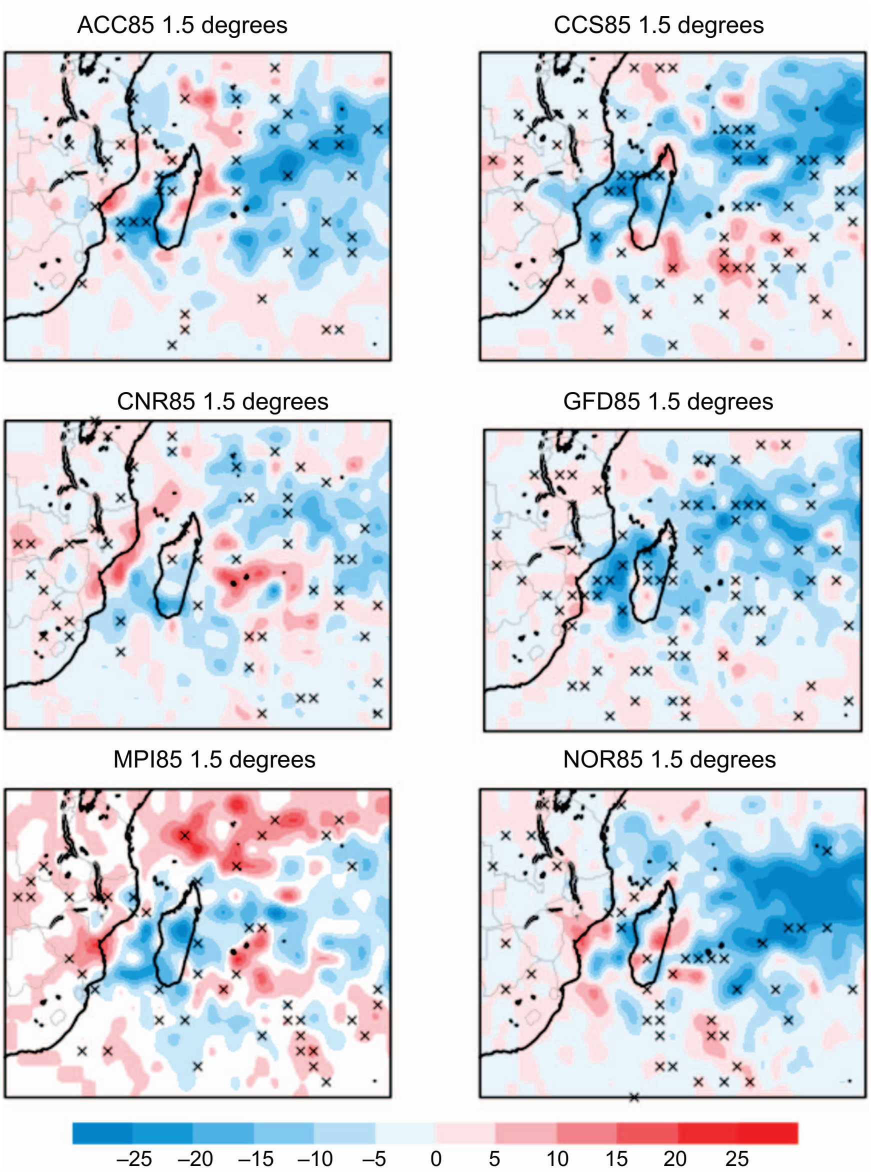


Figure 3. Simulated change in the frequency of tropical cyclone-like vortices per 2° grid point across six downscalings under 1.5 °C of global warming. The area were the changes are significant are indicated by crosses.

our results indicate that the same pattern of decreasing number of systems holds for the South West Indian Ocean. A general theoretical framework for tropical cyclone formation has in fact recently developed, which postulates that under global warming, enhanced subsidence develops in the upper troposphere in the tropics, which functions to suppress tropical cyclone formation. However, the lower troposphere contains more water vapour and latent heat in response to enhanced surface warming, and consequently the smaller number of tropical cyclones that form in such an environment are more intense (Kang and Elsner 2015). Contrary to findings of increases in intensity of tropical cyclones with global warming, the current set of projections indicate that when considering the maximum wind speed at the surface over the South West Indian Ocean, there is a projected decrease in maximum intensity of tropical cyclones with increasing temperature (figure 6). Such results should however be treated with caution, even though downscaling has been performed e.g. Strazzo *et al* (2013, 2015) has indicate the most global climate model are unable to realistically simulate maximum wind speeds and other key tropical cyclone features.

The decrease in the simulated number of tropical cyclone-like vortices is accompanied by a simulated decrease in the maximum wind speed per latitude across those latitudes most frequented by tropical cyclones over the South West Indian Ocean (figure 6). Decreases ranging between 1 and 2 m s^{-1} are simulated from 18°S to 10°S, which are currently the latitudes with the highest numbers of simulated systems. Simulated changes in the large scale environment over the South West Indian Ocean with warming may play a more important role in tropical cyclogenesis and intensification than the increase in potential

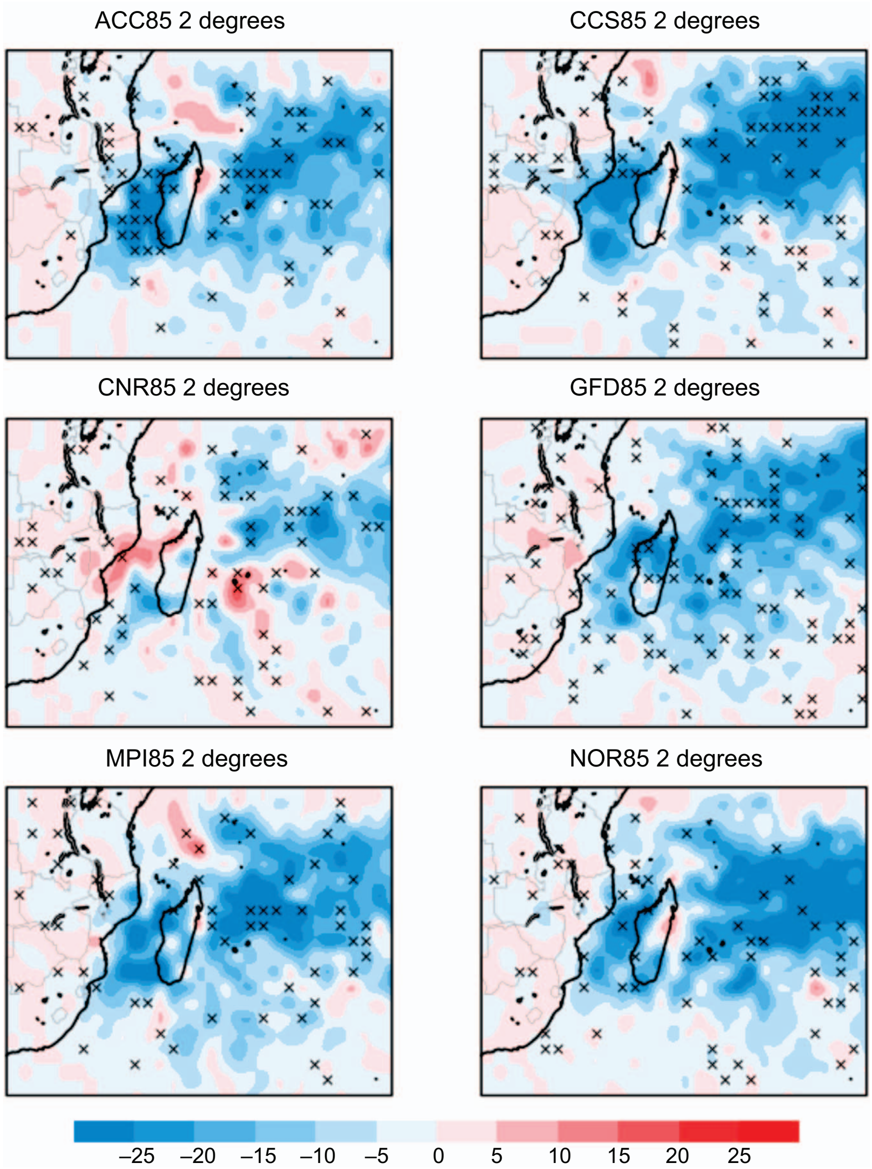


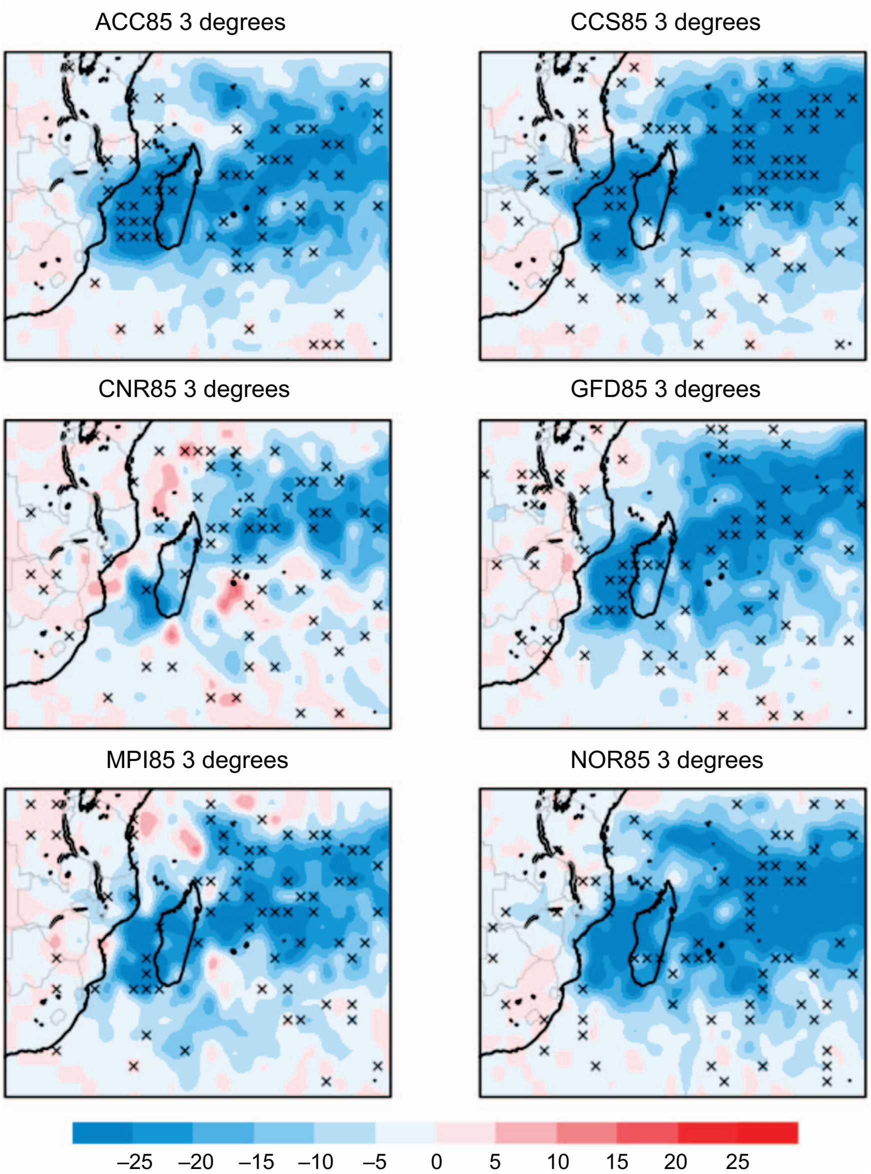
Figure 4. Simulated change in the frequency of tropical cyclone-like vortices per 2° grid point across six downscalings under 2 °C of global warming. The area were the changes are significant are indicated by crosses.

for intense systems related to the energy budget from the ocean.

The change in tropical cyclone frequencies, as indicated in figures 3–5, also has implications for the frequency of storm landfalls over eastern southern Africa. While coastal flooding and damage are the main phenomena associated with landfall, further westward penetration into the subcontinent is responsible for widespread rain, especially over the Limpopo River Basin. Figure 6 shows the median (calculated across the ensemble of downscalings) of the simulated number of six hourly time-steps during which a tropical cyclone centre is located on the coast (as a proxy for the tendency of these systems to make landfall) under different global warming scenarios.

The latitude of maximum landfall (16°S) is slightly north of the observed latitude (18°S) of maximum number of landfalls, similar to what was detected in the case of six AR4 models downscaled by Malherbe *et al* (2013). Unlike the previous study, the simulated favoured landfall latitudes are expected to remain similar with warming, even up to 3 °C. There is, however, a large decreasing tendency for landfalls (25%–50%) according to these simulations. Largest reductions in landfalls are expected along the main landfall latitudes (16°S–18°S), observed between the present climate and 1.5 °C–2 °C warming, but with little change simulated towards a warming of 3 °C.

The present day annual rainfall of the region is indicated by figures 8–9. The observed gridded rainfall dataset was obtained from the Climatic Research unit (CRU) at a resolution of 0.5 × 0.5 (Harris *et al* 2014). All the downscalings do capture the spatial patterns of rainfall on the land with the Eastern escarpment of the area being much wetter than the other areas. The dry area around the Limpopo basin (parts of Limpopo and



ACC85 3 degrees

CCS85 3 degrees

CNR85 3 degrees

GFD85 3 degrees

MPI85 3 degrees

NOR85 3 degrees

Figure 5. Simulated change in the frequency of tropical cyclone-like vortices per 2° grid point across downscalings under 3 °C of global warming. The area were the changes are significant are indicated by crosses.

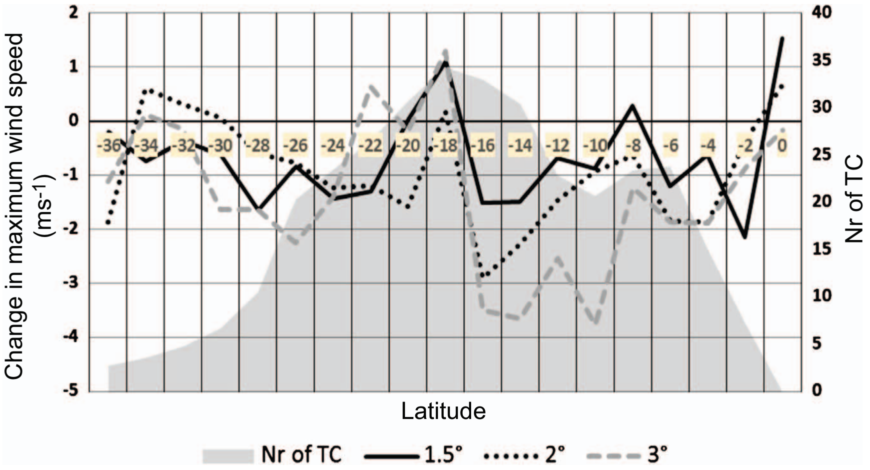


Figure 6. Median of simulated maximum wind speed per latitude (as indicated) over the South West Indian Ocean (35°E–80°E) relative to present simulated maximum, for 1.5 °C warming (solid black line), 2 °C warming (broken black line) and 3 °C warming (broken grey line).

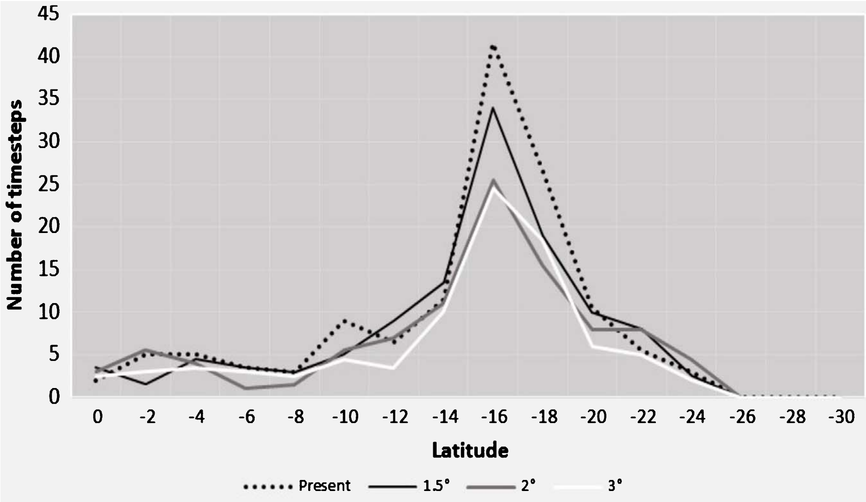


Figure 7. Simulated median number of time steps with tropical cyclone-like vortices making landfall per 2° grid point along the southeastern African coastline. These are for the present climate (broken black line), 1.5 °C warming (solid black line), 2 °C warming (solid grey line) and 3 °C warming (solid white line).

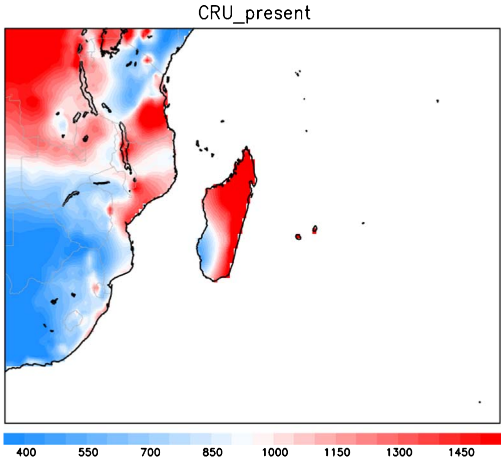


Figure 8. Annual average rainfall in mm day^{-1} at a 0.5° spatial resolution under present-day climate (1971–2000) as shown by CRU TS3.10 data set.

Zimbabwe) are indicated as dry in all the simulations which indicates that the model realistically captures the rainfall distribution in the area. While initially there seems to be a decrease in rainfall over much subtropical southern Africa under future scenarios, especially near the Limpopo River Basin (e.g. Malherbe *et al* 2013), further increases in temperatures seem to be associated with a general increase in precipitation over large parts of the eastern southern African subcontinent (figures 10–12). This increase is simulated in while precipitation is expected to decrease over much of the South West Indian Ocean, where less tropical cyclones are simulated. It is typical for subsidence to occur over the subcontinent when tropical cyclones are active over the South West Indian Ocean, and the general increase in rainfall while the numbers of tropical cyclones over the South West Indian Ocean decrease is a realistic scenario.

While the simulated changes in rainfall under different extent of global warming seem to be a realistic scenario, significance test was conducted using the variant of the Mann-Whitney nonparametric procedures that accounts for variance caused by incidents of ties (Mason and Graham 2002, Beraki *et al* 2015). The results is significant is mostly in areas close to the Limpopo River Basin, the Mozambique Channel and Mozambique which are the areas where a reduction in rainfall is simulated.

4. Conclusion

The six GCM simulations of the CMIP5 and AR5 of the IPCC, after being downscaled to 50 km resolution globally using the regional climate model CCAM, show a realistic representation of current tropical cyclone occurrence over the South West Indian Ocean. Moreover, preferred latitude of tropical storms landfalls over the southeastern African coast is simulated within 2° of the observed. Projections based on a low mitigation scenario were evaluated to investigate projected change in tropical cyclone occurrence in the region for 1.5 °C, 2 °C and 3 °C change relative to the present (1971–2000) baseline climate.

Projected changes in tropical cyclone climatology with increasing temperatures show strong agreement between the six models evaluated. Most noteworthy is an agreement in the general downward trend in tropical cyclone frequencies for the region. The downward trend is apparent right through the time series, and is noted between all the time slabs considered from the present climate, through each of the

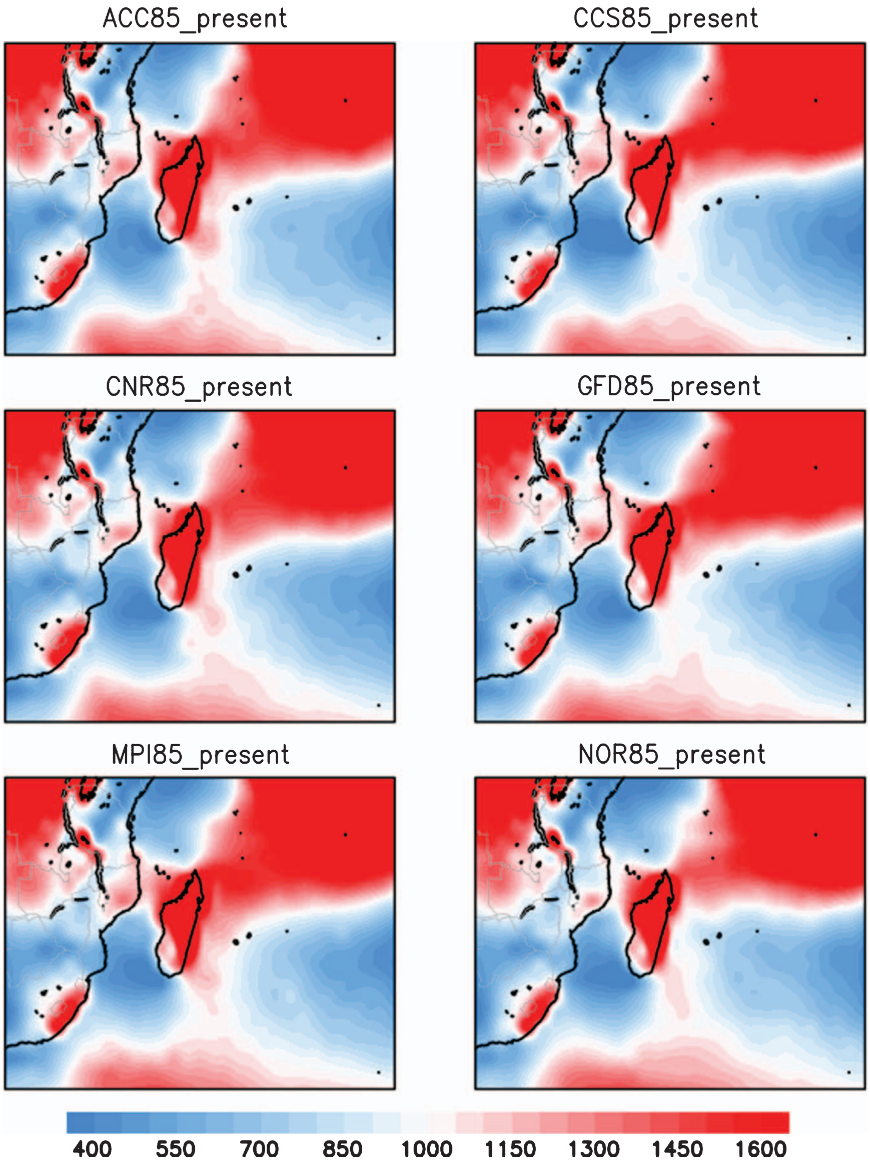


Figure 9. Annual average rainfall in mm at a 0.5° spatial resolution under present-day climate (1971–2000), as shown by different downscalings.

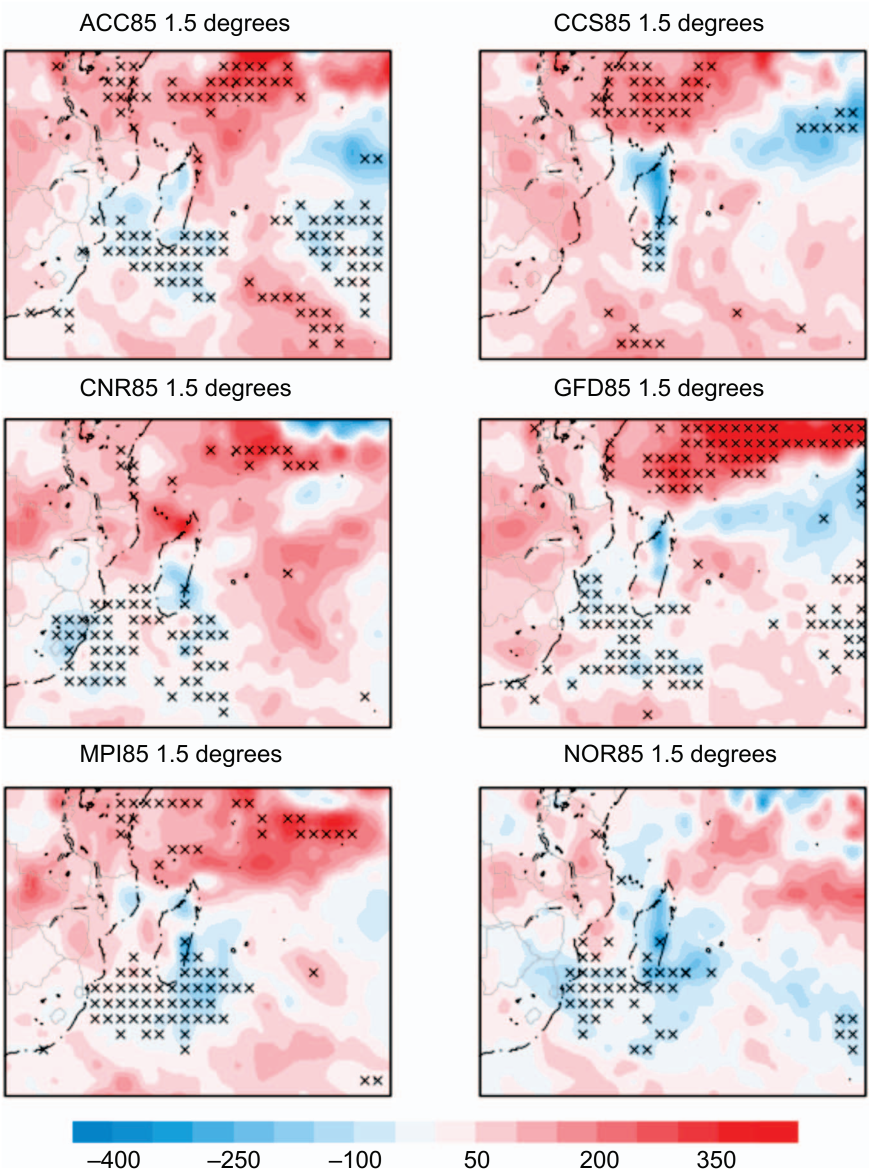


Figure 10. Simulated change in precipitation (mm) with a 1.5° increase in global average temperature. The areas where the changes are significant are indicated by crosses.

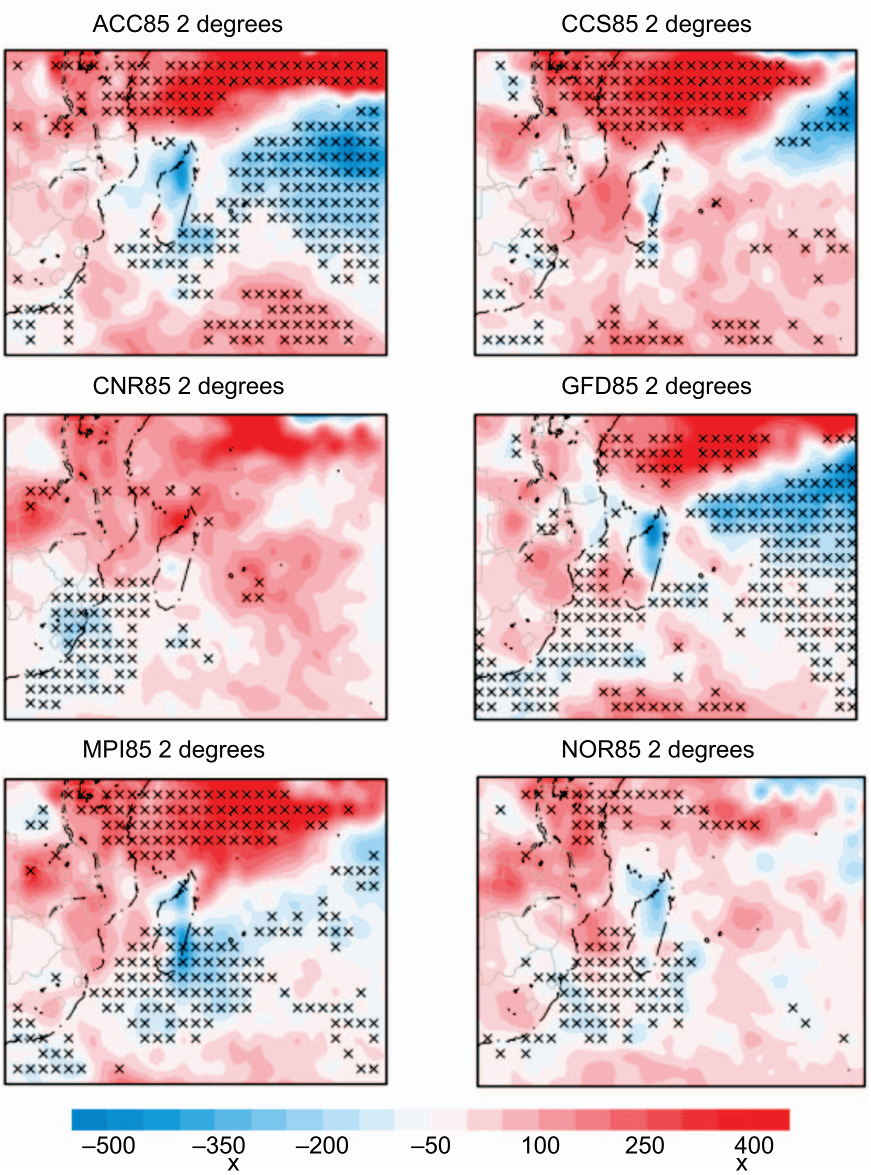


Figure 11. Simulated change in annual precipitation (mm) with a 2° increase in global average temperature. The areas where the changes are significant are indicated by crosses.

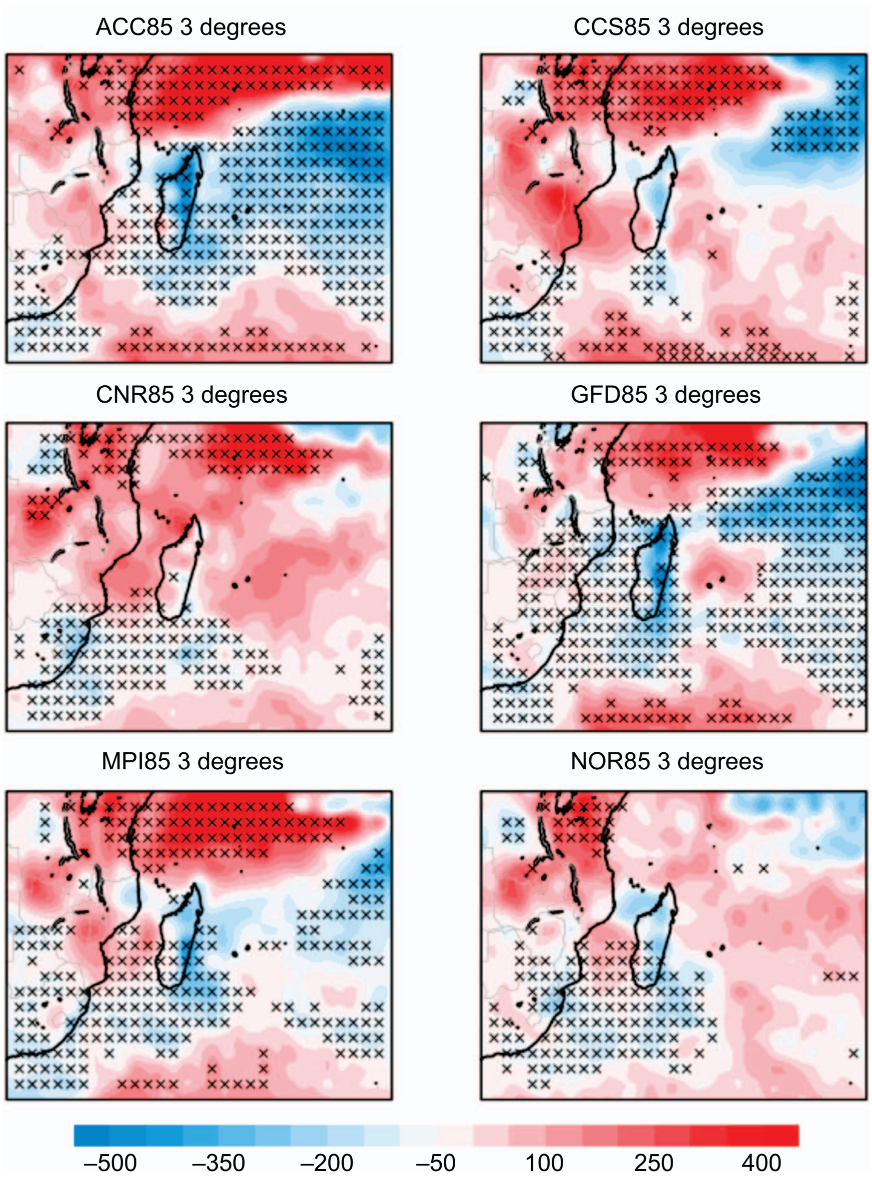


Figure 12. Simulated change in annual precipitation (mm) with a 3° increase in global average temperature. The areas where the changes are significant are indicated by crosses.

incremental changes in global average temperature. Associated with the lower frequency of tropical cyclones simulated, there is also a decrease ranging between 25% and 50% in landfalls simulated, particularly along the most favoured latitudes. The largest reduction in landfalls is indicated between the present climate and scenarios of a 1.5 °C–2 °C warming. No spatial shift in preferred latitude of tropical storm landfalls is simulated. The lower landfall frequency may be a driver of lower rainfall simulated over parts of subtropical southern Africa, associated with the strengthening of the mid-tropospheric high-pressure system over the region. More generally, the lower simulated tropical cyclone frequency over much of the South West Indian Ocean is related to changes in large-scale circulation, with consequential changes in vorticity and wind shear, as well as changes in static stability in the troposphere.

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