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The southern African climate under 1.5 °C and 2 °C of global warming as simulated by CORDEX regional climate models

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Abstract

Results from an 25 regional climate model simulations from the Coordinated Regional Downscaling Experiment Africa initiative are used to assess the projected changes in temperature and precipitation over southern Africa at two global warming levels (GWLs), namely 1.5 °C and 2.0 °C, relative to pre-industrial values, under the Representative Concentration Pathway 8.5. The results show a robust increase in temperature compared to the control period (1971–2000) ranging from 0.5 °C–1.5 °C for the 1.5 °C GWL and from 1.5 °C–2.5 °C, for the 2.0 °C GWL. Areas in the south-western region of the subcontinent, covering South Africa and parts of Namibia and Botswana are projected to experience the largest increase in temperature, which are greater than the global mean warming, particularly during the September–October–November season. On the other hand, under 1.5 °C GWL, models exhibit a robust reduction in precipitation of up to 0.4 mm day^{-1} (roughly 20% of the climatological values) over the Limpopo Basin and smaller areas of the Zambezi Basin in Zambia, and also parts of Western Cape, South Africa. Models project precipitation increase of up to 0.1 mm day^{-1} over central and western South Africa and in southern Namibia. Under 2.0 °C GWL, a larger fraction of land is projected to face robust decreases between 0.2 and 0.4 mm day^{-1} (around 10%–20% of the climatological values) over most of the central subcontinent and parts of western South Africa and northern Mozambique. Decreases in precipitation are accompanied by increases in the number of consecutive dry days and decreases in consecutive wet days over the region. The importance of achieving the Paris Agreement is imperative for southern Africa as the projected changes under both the 1.5 °C, and more so, 2.0 °C GWL imply significant potential risks to agricultural and economic productivity, human and ecological systems health and water resources with implied increase in regional water stresses.

Introduction

The Paris Agreement which was achieved in December 2015 holds signatory countries responsible for keeping the increase in global average temperatures well below 2.0 °C and particularly under 1.5 °C below the preindustrial period recognizing that 'this would significantly reduce the risks and impacts of climate change'. Parties to the Agreement are subject to achieving this limit in warming by reducing greenhouse emissions accordingly as directed by National Climate Action Plans. Given this impetus at global level, it is of paramount importance to consider the implications of the 1.5 and 2.0 °C thresholds in the average global temperature for the southern African region which already has a projected strong signal of warming.

Significant upward trends of mean annual temperature have been reported for southern Africa with higher increased rates recorded in Namibia and Angola for the period of 1979–2007 (Morishima and Akasaka 2010). Engelbrecht *et al* (2015) reported that temperatures within most of the southern African region are projected to increase between 4 °C and 6 °C by the end of the century under the A2 (a low mitigation) scenario of the Special Report on Emission Scenarios. Using a Coordinated Regional Downscaling Experiment (CORDEX) ensemble of regional climate models (RCMs) and the R package RClimDex for calculating precipitation indices, studies show that the western part of southern Africa is projected to become drier with drought frequency and number of heat waves increasing towards the end of the 21st century under the A2 scenario (Engelbrecht and Engelbrecht 2016) and under both Representative Climate Pathway (RCP) 4.5 and RCP 8.5 (Dosio 2017). Such strong signals of warming and drying have been shown to be consistent with most of the Coupled Model Intercomparison Project Phase 3 (CMIP3) and Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor *et al* 2012) Global Climate Models (GCMs) and are attributed to the projected future strengthening of the subtropical highs and the mid-level anticyclonic circulation under low mitigation scenarios (Christensen *et al* 2007, Engelbrecht *et al* 2009, Engelbrecht *et al* 2015, Déqué *et al* 2017).

The climate of the southern African region defined here as a region of Africa bounded in the north by latitude 10°S and in the south by 38°S (see Pinto *et al* 2016), is influenced by tropical, subtropical and mid-latitude dynamics with most of the region's rainfall occurring during the austral summer period. The most important rainfall bearing systems are the Tropical Temperate Troughs (TTTs) which account for about 60% of the summer rainfall (Harrison 1984). Other systems are the Intertropical Convergence Zone (ITCZ) which brings most of the rainfall in the northern parts of Madagascar and South Africa (Waliser and Gautier 1993) and the Cut-off Low (COL) which occurs during the spring and autumn seasons (Singleton and Reason 2007). Dry austral summers which are resultant from warming in the Indian Ocean, have been reported for the region (Hoerling *et al* 2006). This is corroborated by New *et al* (2006) who reported decreased total precipitation (regionally averaged) for southern Africa although the decrease was non-significant. In addition, GCMs have projected unusually dry austral summers implying decreased wet austral summers over southern Africa (Tennant 2003, Bellprat *et al* 2015). On the other hand, Regional Climate Models (RCMs) have projected increase in summer rainfall over the eastern escarpment of southern Africa, with its attribution to increase in convective rainfall and changes in the synoptic scale circulations (Fauchereau *et al* 2003, Engelbrecht *et al* 2009, Pinto *et al* 2016). Given the signals of warmer and more arid conditions that have been noted over the past few decades and across most parts of southern Africa (Morishima and Akasaka 2010), this paper examines the potential impacts of climate change on temperature and precipitation under 1.5 °C and 2.0 °C global warming levels over southern Africa using a large ensemble of RCMs from the CORDEX. This is important as it informs climate adaptation and mitigation policy, planning as well as implementation for the countries within the southern African region, and in consideration of the Paris Agreement. The study is part of a series of papers generated within the CORDEX Africa analysis activities (www.csag.uct.ac.za/cordex-africa/) which focus on West (Klutse *et al* 2018), East (Osima *et al* 2018), Central (Pokam *et al* 2018) and pan Africa (Nikulin *et al* 2018).

Methods

Simulated daily temperature and rainfall data from the CORDEX simulation dataset were analysed for the study. The simulations were produced by 25 CORDEX RCM runs (a combination of 10 RCMs and 10 CMIP5 GCMs- listed in Nikulin *et al* (2018); the detailed reference of which will be inserted at the time of the final publication of this paper) used in downscaling GCMs participating in the CMIP5 over a numerical domain covering the entire African continent at a resolution of 0.44° for past (1950–2005) and future climate (2006–2100) under Representative Concentration Pathway RCP8.5. The CORDEX RCMs have been found to be able to simulate monthly rainfall variation, the timing of the rainy season and the relative frequencies of rainfall events of varying intensities over southern Africa quite well (Shongwe *et al* 2014, Pinto *et al* 2016, Dosio *et al* 2015, Dosio and Panitz 2016). For detailed information on the models and their configuration for the CORDEX experiment, readers are referred to Nikulin *et al* (2012). Climate simulations for the high emission scenario, i.e. RCP 8.5 are analysed, as it comprises the largest ensemble (25 runs) and may be considered as the most realistic business-as-usual scenario given the current trajectory of greenhouse gases emissions. Precipitation and mean temperature in the CORDEX models are extracted for a 30 year period identified by the driving GCM and compared to those of the control period of 1971–2000. The methodology for determining the timing when global warming levels (GWL) are reached and the quantification of the robustness of the climate change signals are are described in Nikulin *et al* (2018) of this focus collection. We summarise these methodologies very briefly below and refer the reader to Nikulin *et al* (2018).

We define the GWLs as the average GWL that is above any baseline period (of e.g. 1.5 and 2 °C). Although different definitions of GWLs exist in the literature, all generally start with some pre-industrial (PI) baseline and use an averaged window period, e.g. 15, 20 or 30 years to compute departure from the baseline and determine when the GWL of interest is reached. We used the 1861–1890 to define the PI period as it is available across all CMIP5 historical simulations. Then, for each GCM downscaled, the timing of the relevant GWL is defined as the first time the 30 year moving average (centre year) and the global mean temperature is above 1.5 or 2 °C compared to the PI mean. The corresponding 30 year period is then extracted from the downscaling RCM for analysis using 1971–2000 as a control period.

There are also many methodologies used to determine the robustness of a climate change signal (see Collins *et al* 2013). We consider a climate change signal robust if the following two conditions are fulfilled:

1. the model agreement, i.e. more than 20 (80%) of model simulations agree on the sign of the change;
2. the signal-to-noise ratio (SNR), i.e. when the ratio of the mean to the standard deviation of the ensemble of climate change signals, is equal to or larger than one.

The first criterion considers model agreement and the second is a measure of the strength of the climate change signal (with respect to the inter-model variability in that signal). We use both in defining robustness because the first criterion may be fulfilled even in the case of a very small, close to zero change.

Simulated temperature and precipitation for the control period and projected changes under the 1.5 °C and 2.0 °C GWLs with respect to the control period are presented in seasonal and annual maps. Differences between projections of both variables under 2.0 °C and 1.5 °C are also shown as well as extreme indices, namely consecutive dry days (CDD) and consecutive wet days (CWD). The CDD (CWD) is defined as largest number of consecutive days when precipitation is less (greater) than 1 mm. A full descriptive list of the indices can be found on the ETCCDI website http://etccdi.pacificclimate.org/list_27_indices.shtml.

Results

Modelled temperature and precipitation for the control period (first column of figure 1) during the December–January–February (DJF) season, and their projected changes for 1.5 °C and 2.0 °C GWLs with respect to control period (second and third columns) are shown in figure 1. Differences between projections of both variables under 2.0 °C and 1.5 °C are also shown (rightmost column). For precipitation maps, we use positively sloped hatching to show areas where the criterion of model agreement is met and negatively sloped backward hatching to show areas where the SNR criterion is met. An overlapping of the hatchings imply the robustness of the signal of the change. We decided not to show hatching for temperature in all figures presenting this variable as all models exhibit a robust signal throughout the region. Under both 1.5 °C and 2.0 °C GWLs, models show a robust change in temperature, ranging from 0.5 °C–1.0 °C over coastal areas to 1.0°–1.5 °C elsewhere in the southern African subcontinent for 1.5 °C GWL and from 1.5 °C–2.0 °C to 2.0 °C–2.5 °C over the same areas under the 2.0 °C GWL (figure 1). Under the latter GWL, regional temperatures are projected to be increase up to 0.8 °C more than under the 1.5 °C GWL, more over the south-western region of the subcontinent, covering South Africa and parts of Namibia and Botswana (figure 1).

Projected changes in precipitation are much more varied than temperature; however, during the DJF season the spatial patterns of precipitation changes under the 1.5 °C and 2.0 °C GWLs look almost the same, with areas covering central and southern Mozambique, southern Zimbabwe, eastern and western parts of South Africa, most of Namibia and southern Angola showing decreases in precipitation of up to 0.4 mm day^{-1} (around 10% of the climatological values) (figure 1). In contrast, the remaining regions show an increase in precipitation of up to 0.4 mm day^{-1} undseasoner the two GWLs. Comparison of the two GWLs shows that under the 2.0 °C, the southern African region may exhibit precipitation decreases between 0.2 and 0.3 mm day^{-1} (around 10%–15% of the climatological values), mainly over South Africa, Namibia and parts of Botswana, while the region may experience approximately the same magnitude but opposite sign in projected daily precipitation change (figure 1). However, it is important to note that models' uncertainty on precipitation change is large, as less than 80% of the models agree on the sign of change and the intermodel variability is greater than the climate change signal.

During the September–October–November (SON) season, the early rainfall season, the CORDEX models show a robust change in temperature (top row), similar to that of the DJF season, ranging from 0.5 °C–1.0 °C over coastal areas to 1.0 °C–1.5 °C in a large part of the inland, including a patch located across the borders of Namibia, Angola and Botswana that shows an increase of 1.5 °C–2.0 °C under the

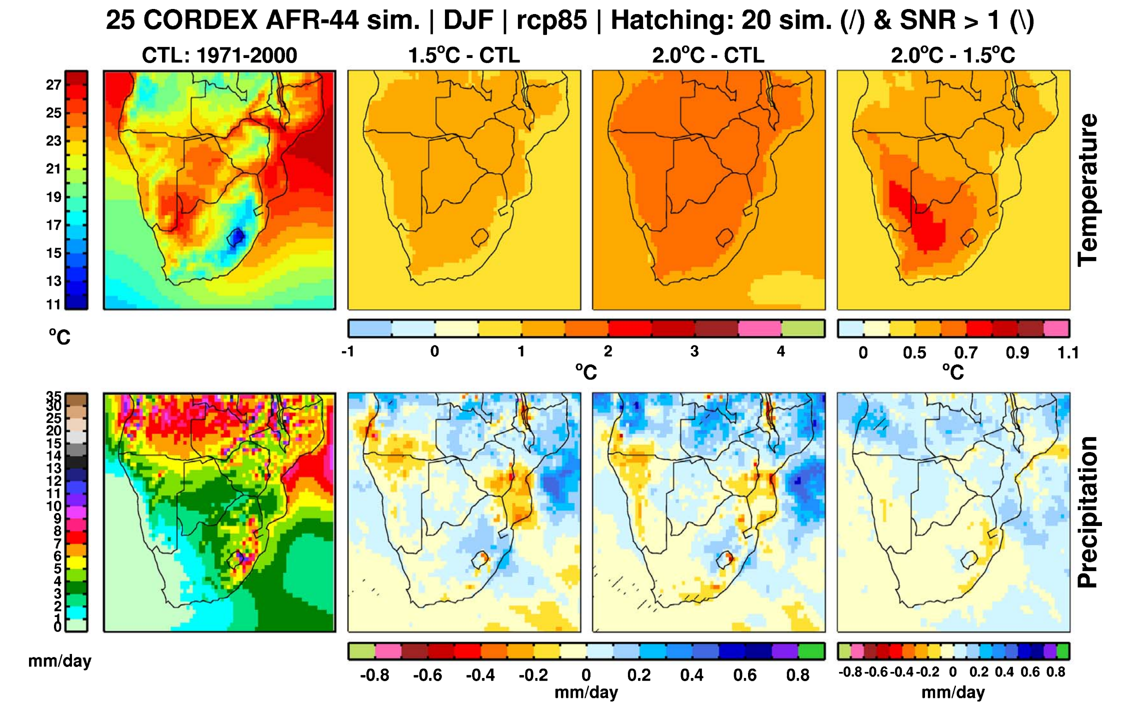

Figure 1. The CORDEX Africa ensemble average December–January–February (DJF) mean temperature and precipitation for 1971–2000 (CTL, left column), the projected changes at the 1.5 and 2° GWLs with respect to 1971–2000 (middle columns) and difference between the changes at 2 and 1.5° GWLs (rightmost column). Areas where at least 80% of the simulations (20 of 25) agree on the sign of the change are marked by positively sloped hatching. Areas where the signal to noise ratio is equal or more than 1 are marked by negatively sloped hatching. For temperature all grid boxes satisfy the two criteria (the agreement and signal to noise ratio) and the hatching is not shown. Note that colour scales for the 2 °C–1.5 °C plots are different from the 1.5 °C–CTL and 2 °C–CTL ones.

1.5 °C GWL (figure 2). For the 2.0 °C GWL case, regional temperatures increases have a magnitude and spatial pattern close to that of DJF; however, with a patch covering large parts of the interior of the subregion where increases with respect to the control period reach up to 2.0 °C and 2.5 °C. Temperature projections under 2.0 °C GWL are 0.5 °C–0.7 °C degrees higher than those of 1.5 °C GWL near coastal regions. The difference is higher–up to 0.8 °C–over the central parts of the region (figure 2).

In relation to precipitation, the model ensemble under 1.5 °C GWL shows a robust reduction (of up to 0.3–0.4 mm day^{-1}) over the Limpopo Basin and smaller areas of the Zambezi Basin, in Zambia, as well as in parts of Western Cape, in South Africa, while an increase (although not robust) of up to 0.1 mm day^{-1} in precipitation is projected over central and western South Africa as well as in southern Namibia (figure 2). Under 2.0 °C GWL a larger fraction of land is projected to face a robust decrease in precipitation ranging from 0.2 to 0.4 mm day^{-1}, (i.e. around 10%–20% of the climatological values), over a diagonal area covering most of the central subcontinent and parts of western South Africa and northern Mozambique (figure 2). Nevertheless, there is no robustness in the differences between the changes under the 2.0 °C and 1.5 °C GWL.

A consistent signal of annual mean temperature is seen in figure 3, with positive changes ranging from 0.5 °C–1.0 °C over coastal regions to 1.0 °C–1.5 °C throughout the continent, under the 1.5 °C GWL. The pattern on the 2.0 °C GWL does not differ much from the 1.5 °C one in terms of spatial pattern; however, changes can amount to 1.5 °C–2.0 °C. In addition, a patch covering large parts of northern and eastern Namibia and areas of neighbouring countries bordering thereto show an increase of up to 2.0 °C–2.5 °C with respect to the control period. Differences of projected temperature changes between these two GWLs show a signal of increased temperatures for the region, with the highest values of 0.7 °C–0.8 °C over the bordering region of Namibia, Botswana and South Africa, lowering to up to 0.25 °C–0.5 °C towards the coastal regions (figure 3).

Projected precipitation changes, in turn, show a similar spatial pattern for both the 1.5 °C and 2.0 °C GWLs throughout the region, though significant changes occur more over the 2.0 °C GWL, particularly over the western coasts of South Africa and southern Namibia and parts of the Limpopo Basin in Zimbabwe and eastern Botswana, where reductions in daily precipitation can amount to 0.3 mm day^{-1}. Projected changes in annually averaged daily precipitation under the 2.0 °C are generally 0.1 mm larger than under 1.5 °C GWLs, especially over the western region of South Africa near the Atlantic coast (hatched region, bottom right of figure 3). In general, under the two GLWs, annual mean changes of temperature seem to be dominated by the DJF season (top row of figure 2), while annual mean changes of precipitation

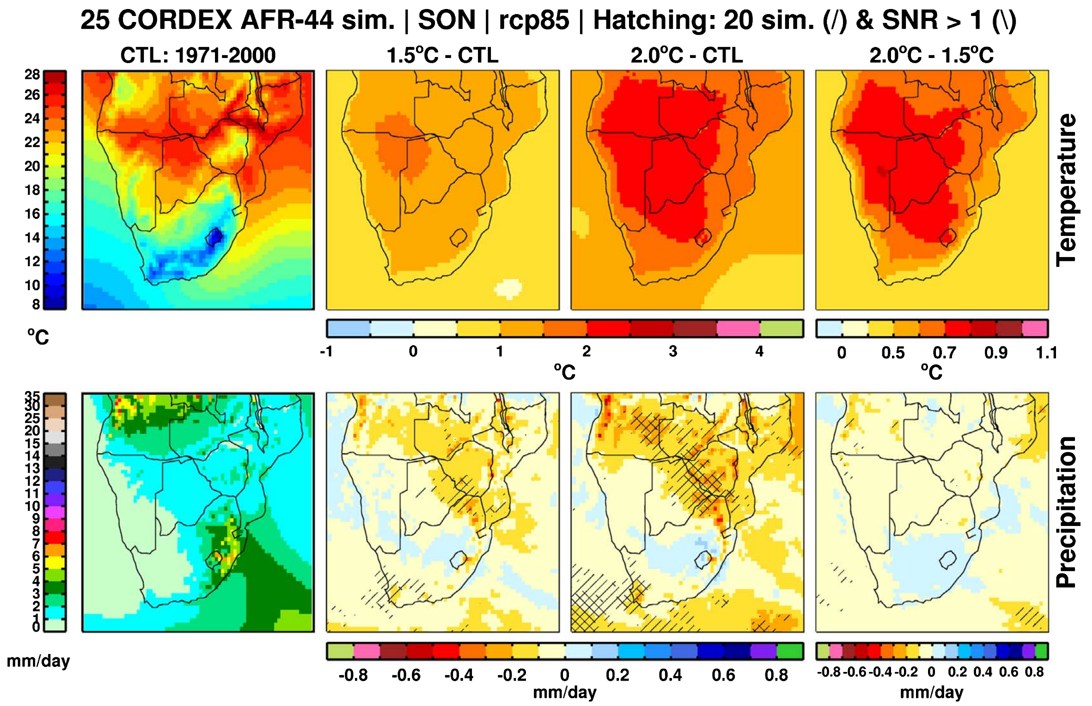

Figure 2. Same as figure 1, but representing the September–October–November (SON) season. Areas where at least 80% of the simulations (20 of 25) agree on the sign of the change are marked by positively sloped hatching. Areas where the signal-to-noise ratio is equal or more than 1 are marked by negatively sloped hatching. For temperature all grid boxes satisfy the two criteria (the agreement and signal to noise ratio) and the hatching is not shown. Note that colour scales for the 2 °C–1.5 °C plots are different from the 1.5 °C–CTL and 2 °C–CTL ones.

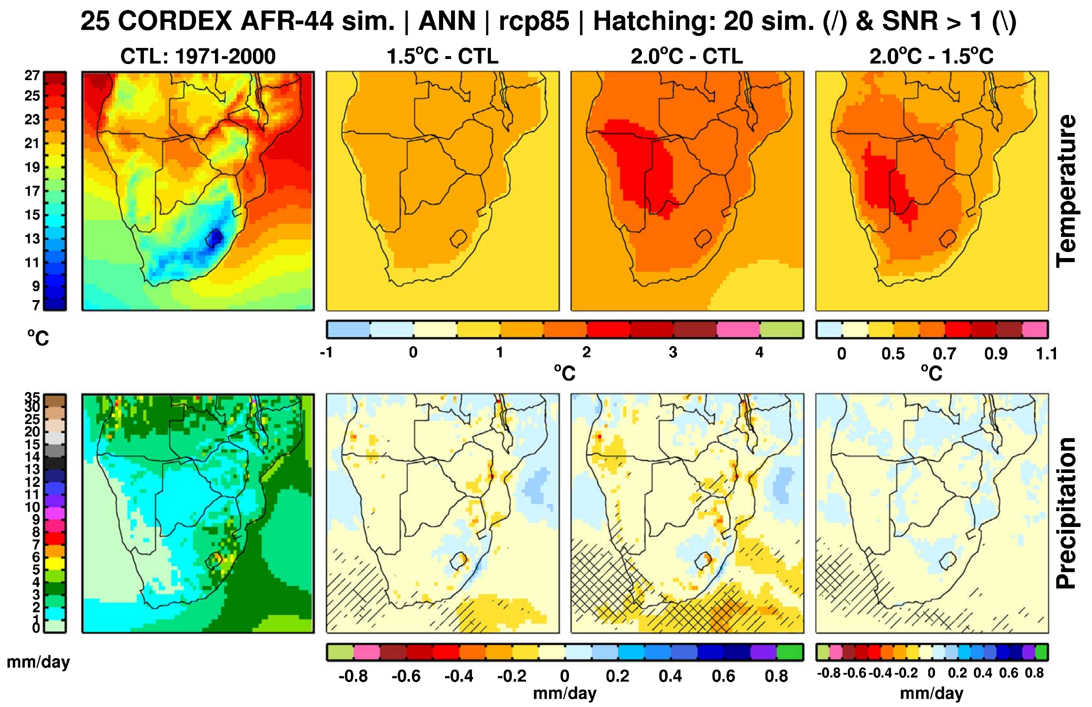

Figure 3. The same as figures 1 and 2, but for annual mean values.

seem to be dominated by the SON season (bottom row of figure 3).

We not only analyze mean climate but also two selected precipitation indices from the Expert Team on Climate Change Detection and Indices (ETCCDI) that are based on daily precipitation, since under the same warming, extremes can change differently than the mean climate. The maximum number of CDDs and maximum number of CWDs were chosen as they are commonly used

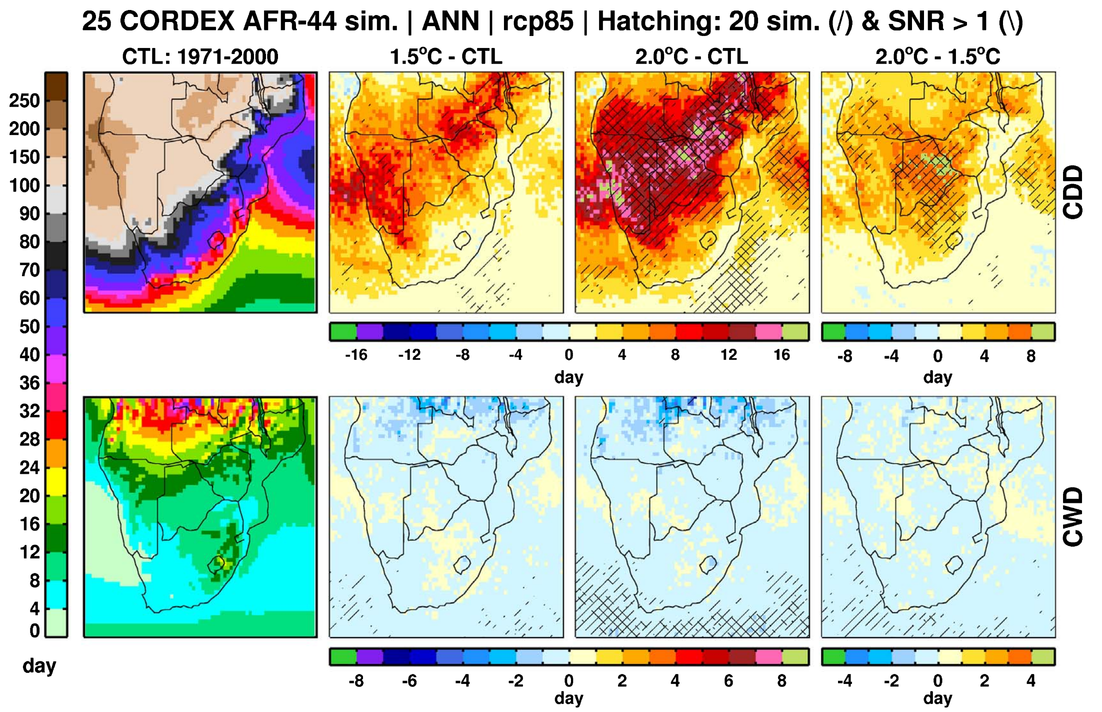

Figure 4. Annually grid averaged control period and projected changes of CDDs, on the top row, and CWDs, on the bottom row, under 1.5 and 2.0 °C GWLs. Positively sloped hatching to show areas where the criterion of model agreement is met and negatively sloped backward hatching to show areas where the SNR criterion is met.

in impact studies and are relevant under the current drought situation in southern Africa. The large scale pattern of CDD and CWD at annual time scale is shown in figure 4. The maximum number of CDD is projected to increase over the entire subcontinent with longer dry spells projected over Namibia, Botswana, northern Zimbabwe and southern Zambia under the 1.5 °C GWL. Under 2.0 °C GWL the CDD are projected to increase over the entire subcontinent. Conversely, the CWD is projected to decrease across the subcontinent with a non-robust signal throughout land areas (figure 4).

Discussion

The general pattern of temperature increases throughout the year is similar in both GWLs and consistent with results found by other researchers e.g. Engelbrecht *et al* (2015) and Déqué *et al* (2017) for parts of southern and tropical Africa. In some areas, projected increases in temperature are equal or even greater than the corresponding GWLs. A similar pattern was found by James *et al* (2013) using GCMs. This implies that those areas are projected to likely experience an increase in the magnitude and duration of heat-waves (e.g. Russo *et al* 2016, Dosio 2017, Déqué *et al* 2017) and fire-risk, as suggested by Weatherly and Rosenbaum (2017). Consequently, an increased evapotranspiration is expected as a result of rising temperatures, with consequent reduction of the amount of available soil moisture content (e.g. Harmsen *et al* 2009). This may result in possible increased aridity in already arid to semi arid areas. The implications are increased heat and extremes such as heat waves as well as intense storms which are already being observed across the region.

In comparison, our results under RCP 8.5 seem to compare well with EURO-CORDEX high resolution (12 km) models which have been used to evaluate how well they can simulate the region's climate. The EURO-CORDEX ensembles have been able to capture some features of Europe region climate well but not others (Kotlarski *et al* 2014). For instance, Vautard *et al* (2013) found that they simulated too frequent heat wave events with the ensembles exhibiting large spread simulations but projected similar patterns of precipitation and temperature following RCP 4.5 and RCP 8.5 pathways (Jacob *et al* 2014). When used to simulate precipitation indices across a large spatial coverage of Scottish Islands, no single model simulated all precipitation metrics well (Foley and Kelman 2017). This underscores the need to evaluate the models across multiple spatial scales. In addition, it is important to note that our work may have some caveats which have to be considered which include the fact that the GCM-RCM matrix we used is not complete, i.e, not all RCMs downscaled all the GCMs, with some GCMs being downscaled by one or few RCMs. Therefore, results may be clustered towards individual RCMs or GCMs (e.g. Dosio 2017). However, a detailed analysis of this issue is beyond the scope of this study. As shown by e.g. Dosio and Panitz (2016), RCMs and GCMs can project very different climate change signal;

for instance, over central Africa the climate change signal from the RCMs may be opposite in sign to that of driving GCMs, due to many causes including large scales forces and on the feedback between land and atmosphere. Detailed investigation between RCMs and GCMs will be a subject of subsequent work.

No significant or robust differences seem to exist on the projected precipitation changes under both GWLs as for both cases, seasonally and annually averaged reductions in daily precipitation of 10%–20% are suggested by the CORDEX models. Similar results were found by Haensler *et al* (2013) over Central Africa. Reductions in CWD which also manifest in reductions in rainfall together with increases in CDD have implications for seasonal precipitation onset in southern Africa (e.g. Tadross *et al* 2005) and are likely to have negative impacts in agriculture, particularly in the areas of traditional rain-fed agriculture and water resources. Increases in CDD over southern Africa were also found in Giorgi *et al* (2014) but for the period of 2071–2100 compared to 1976–2005. At a seasonal timescale (figure S4, in supplementary material available at stacks.iop.org/ERL/13/065002/mmedia) SON is the season with higher changes in CDD following MAM and DJF. Drier conditions during SON might be associated with increases in frequency of occurrence of high pressure circulation pattern (e.g. Engelbrecht *et al* 2009). This implies a need for corresponding changes in production sectors such as agriculture such as changing crop and livestock varieties accordingly and a need for agricultural diversification as mitigation measures to combat agricultural production decreases due to these projected changes. The projected changes are important considerations given that in southern Africa a significant portion (up to 60%) of the GDPs in the southern African region comes from agriculture and the majority of the agricultural production is rain-fed.

Increased aridity bears potential impacts on many sectors of productivity such as agriculture for both crops and livestock and ecosystem-based production such as wildlife utilisation, apiculture and fisheries as the optimal temperatures and thresholds for associated living organisms may be exceeded. Already, much of the planning around these sectors such as seasonal forecasts for planting dates, onset and cessation of the rainy season is based on archaic climate information which may not keep up with projected increases for future planning, adapting to, coping with and building resilience against climate change and variability. Again, the implications are worrying, given that the majority (up to 70%) of the region's (except for Botswana and South Africa) economies dependant on agriculture to a large extent, and more so, rain-fed agricultural production (Mapfumo *et al* 2014). A combination of high temperatures and low precipitation suggested by both GWLs will result in reduction of water availability for the rainfed agricultural sectors. As underscored earlier in this paper, this implies a need for corresponding changes in agricultural production in terms of planning for agriculture production through irrigation and floodplain agriculture.

In addition, the reductions in precipitation over the two major river basins of southern Africa (Limpopo and Zambezi) must be noted given the transboundary nature (and therefore potential water use conflicts) of these river basins and the significant services that they render which include the generation of hydropower (Zambezi) for the region, fisheries, tourism and agriculture production through irrigation and floodplain agriculture let alone the ecosystems they support. Projected decreases in these major river basins must be planned for in order to reduce water scarcity, conflicts and to allow the development of alternative forms of energy, livelihoods and appropriate policy interventions. The Zambezi River Basin for instance, experiences a high mean annual potential evapotranspiration of 1560 mm, which is above the mean annual precipitation (Beilfuss 2012). In comparison to our results of decreases in rainfall for parts of this basin, Arnell (2004) projected the basin's evaporation rates to likely increase up to 25% by 2100 using a macro-scale hydrological model and HadCM2 and HadCM3 scenarios, with much of the basin's surface becoming drier (Kling *et al* 2014, Pricope and Binford 2012, SARDC and HBS, 2010). Similarly, Desanker and Magadza (2001) projected that a 20% decrease in precipitation and a 25% increase in evaporation using CMIP GCMs combined with increased development and consequent water extraction across the Zambezi River Basin would result in a 26% to 40% decline in water runoff with consequent reductions in stream flow by 2100. Indeed, projected reductions in stream flow of between 5% and 10% (Kling *et al* 2014) have been associated with increased evaporation and transpiration rates resulting from a 1 °C rise in temperature across the Zambezi River Basin (Chenje 2000, Ndebele-Murisa *et al* 2011, Magadza 2010). These projections concurring with predicted 11%, 23% and 30% reductions in stream flow for 2 °C, 3 °C and 4 °C increases in temperature respectively in other hydrological systems (Henson 2011). Also, the current shortage of hydroelectric power across the southern African region has been attributed to reduced precipitation, leading to decreased stream flows and water levels resulting in an increased frequency of power rationing, particularly within the Zambezi Basin where some of the major hydroelectric plants (Kariba, Cabora Bassa, Kafue and Shire) supplying a fair amount of hydropower to the region (Botswana, Malawi, Mozambique, South Africa Zambia and Zimbabwe) are located.

Conclusion

This paper provides results of projections from an ensemble of 25 regional simulations out of the CORDEX suite of models analysed for the southern

Africa, as far as near surface temperature and precipitation are concerned. This is novel in that it is the first publication that speaks of possible scenarios under GWL of 1.5 and 2.0 degrees for the southern African region. Rather than the traditional 'future versus past' aggregation of the model statistics, we have considered two different time periods for the scenario, so that in each model simulation, the global warming level is 1.5 °C and 2.0 °C with respect to the 1971–2000 mean temperature. There are uncertainties on the projected changes in temperature and precipitation. However, the climate under 2.0 °C GWL is warmer than that under 1.5 °C GWL in many parts of the subcontinent while many parts of the subregion are projected to become drier. The implication of keeping the Paris Agreement for the region cannot be overemphasized as impacts on the region's agricultural systems and water resources can be substantially reduced by limiting the global average temperatures well below 2.0 °C and particularly under 1.5 °C GLW. In terms of precipitation the largest difference between the climate under 1.5 °C GWL and 2 °C GWL is seen during the SON season. This means that decreases in precipitation and increases in CDD might have shifted and cause delays in the onset of rainfall; this bearing potential negative impacts in the agriculture, energy, ecosystems and water sectors in particular. This calls for some attention to be focused on efforts of keeping the GWL under 1.5° as the 2.0 °C change in global temperatures may likely have serious implications for production, economies and development for the southern African region.

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