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Report describing regional climate extremes

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Summary

Key to FOCUS-Africa?s aim to improve user-centric climate services in southern Africa, is understanding and projecting future changes in the occurrence of extreme weather events. Building on deliverables submitted earlier, such as D3.3 (Extreme events identification and their variability) and D4.1 (Seasonal forecast quality assessment), this report (D2.2) further explores extremes with a focus on generating a variety of extreme event indices that are relevant to food security in southern Africa. The analysis is undertaken across southern Africa, and an assessment of risks and uncertainties are undertaken at regional and sub-regional levels. D2.2 proceeds to demonstrate how climate change indices may be used to make assessments of climate change impacting on agriculture and food security. In this way, the data and indices generated by D2.2 can inform all FOCUS-Africa case studies concerned with agriculture and food security. Note that this report does not aim to fully elaborate the risks to food security but identifies and characterises climate extremes under a changing climate that would be relevant for food security. Moreover, this report with its relevance to food security may be regarded as an input to D2.3, dealing with the understanding of the climate risks relevant to the water-energy-food (WEF) nexus. The report identifies and describes a number of climatic impact drivers relevant to food security in a changing climate. These include annual rainfall, extreme precipitation events, heatwaves, fire and droughts. At a regional level, D2.2. points out that southern Africa is a climate change hotspot with projected warming and drying trends amplifying stresses in a naturally warm, dry, and water stressed region. Despite model-projected uncertainty in projected rainfall changes at sub-regional scales, particularly over the eastern escarpment of South Africa (a region critical to water security), strong model agreement in projections indicate that the larger southern African region is likely to become generally drier in a warmer world. Sharply increased regional warming, associated strong reductions in soil moisture availability, and increases in heatwaves and high fire-danger days are virtually certain under low mitigation futures (that is, under high levels of global warming). These changes can already be detected in observed climate trends for the last few decades, including regional warming and drying in both the summer and winter rainfall regions. ...

Approval

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2023-02-22 10:26:21	Dr. Asmerom BERAKI (CSIR)
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Regional climate extremes relevant to food security in southern Africa

Deliverable D2.2

Lead Beneficiary: Global Change Institute, University of the Witwatersrand
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FOCUS-Africa – Full-value chain Optimised Climate User-centric Services for Southern Africa – is developing sustainable tailored climate services in the Southern African Development Community (SADC) region for four sectors: agriculture and food security, water, energy and infrastructure.

It will pilot eight case studies in six countries involving a wide range of end-uses to illustrate how the application of new climate forecasts, projections, resources from Copernicus, GFCS and other relevant products can maximise socio-economic benefits in the Southern Africa region and potentially in the whole of Africa.

Led by WMO, it gathers 14 partners across Africa and Europe jointly committed to addressing the recurring sustainability and exploitation challenge of climate services in Africa over a period of 48 months.

For more information visit: www.focus-africaproject.eu

About FOCUS-Africa

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Executive Summary

Key to FOCUS-Africa's aim to improve user-centric climate services in southern Africa, is understanding and projecting future changes in the occurrence of extreme weather events. Building on deliverables submitted earlier, such as D3.3 (Extreme events identification and their variability) and D4.1 (Seasonal forecast quality assessment), this report (D2.2) further explores extremes with a focus on generating a variety of extreme event indices that are relevant to food security in southern Africa. The analysis is undertaken across southern Africa, and an assessment of risks and uncertainties are undertaken at regional and sub-regional levels. D2.2 proceeds to demonstrate how climate change indices may be used to make assessments of climate change impacting on agriculture and food security. In this way, the data and indices generated by D2.2 can inform all FOCUS-Africa case studies concerned with agriculture and food security. Note that this report does not aim to fully elaborate the risks to food security but identifies and characterises climate extremes under a changing climate that would be relevant for food security. Moreover, this report with its relevance to food security may be regarded as an input to D2.3, dealing with the understanding of the climate risks relevant to the water-energy-food (WEF) nexus.

The report identifies and describes a number of climatic impact drivers relevant to food security in a changing climate. These include annual rainfall, extreme precipitation events, heatwaves, fire and droughts. At a regional level, D2.2. points out that southern Africa is a climate change hotspot with projected warming and drying trends amplifying stresses in a naturally warm, dry, and water stressed region. Despite model-projected uncertainty in projected rainfall changes at sub-regional scales, particularly over the eastern escarpment of South Africa (a region critical to water security), strong model agreement in projections indicate that the larger southern African region is likely to become generally drier in a warmer world. Sharply increased regional warming, associated strong reductions in soil moisture availability, and increases in heatwaves and high fire-danger days are virtually certain under low mitigation futures (that is, under high levels of global warming). These changes can already be detected in observed climate trends for the last few decades, including regional warming and drying in both the summer and winter rainfall regions. Moreover, an increase in intense rainfall events can be detected in eastern southern Africa. This signal of change is projected to further amplify under 1.5 °C level of global warming, which according to the IPCC AR6 will under low mitigation futures be reached as early as the early 2030s (that is, in the near term). Under higher levels of global warming, further substantial increases in climate extremes, as assessed by D2.2, will translate into increasing impacts on the agricultural sector and potentially on food security. As a demonstration of how the extreme event indices generated can be used, D2.2 shows in particular that the area suitable for maize production, the staple food in southern Africa, is projected to decrease substantially in western and central southern Africa, and over parts of eastern southern Africa. This occurs in response to general reductions in rainfall and increases in the occurrence of hot extremes. However, in other parts of the region climate change may bring opportunities, for example over Lesotho in South Africa, where reductions in cold extremes are projected to result in increasing climatic suitability for maize. Finally, the report highlights that the projected generally warmer and drier climate with associated reduced soil moisture availability, in combination with increases in the number of heatwaves and high fire-danger days, may trigger the occurrence of regional tipping points in southern Africa. Examples include the collapse of the maize crop in marginal regions, and of the cattle industry across southern Africa.

Keywords

Climate change, extreme weather events, climate indices, regional impacts, food security, agriculture.

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1 Introduction

Southern Africa (here defined as Africa south of 10 °S) was classified as a climate change hotspot by the Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5 °C (SR1.5; Hoegh-Guldberg et al., 2018). It is a region with a warm climate and pronounced wet-dry seasonality, which is acknowledged to be water-stressed in the context of naturally occurring droughts, a growing population, and the agricultural and industrial ambitions of a developing region. Under low mitigation emission scenarios southern Africa is certain to become substantively warmer and likely drier (Engelbrecht et al., 2009; Engelbrecht et al., 2015; Engelbrecht and Engelbrecht, 2015; Hoegh-Gulberg et al., 2018; Lee et al., 2021), justifying its classification as a climate change hotspot, as under such scenarios, the options for adaptation are limited. While drying is a general projection for the region, climate models also project likely sub-regional increases in intense rainfall events in eastern southern Africa, including the eastern escarpment region of South Africa and Mozambique, reflecting longer dry spells between more intense downpours (Ranasinghe et al., 2021).

The IPCC has recently assessed that general trends of drying and substantial warming can already be detected across this region (Ranasinghe et al., 2021). Moreover, the signal of increasing intense rainfall events in eastern southern Africa can also be detected in observed statistics over the last few decades (Ranasinghe et al., 2021). In Mozambique, increases either in the number of intense tropical cyclones (Fitchett, 2018), or in the rainfall amount that they produce, likely contribute to the upward trend in the number of recorded intense rainfall events. A recent climate change attribution study has assessed that climate change has likely resulted in an increase in precipitation associated with the series of tropical cyclones that made landfall in Mozambique in 2022 (Otto et al., 2022).

Over the last six decades, average temperatures have been increasing at a surprising rate over southern African, at 2-4 °C/century over large inland regions (Engelbrecht et al., 2015; Kruger and Nxumalo et al., 2016), with the highest warming rates recorded over northern Botswana and southern Zambia (Engelbrecht et al., 2015). Extreme temperature events such as very hot days, heatwave days and high fire-danger days have correspondingly increased sharply in frequency over the last several decades (Kruger and Sekele, 2013). It is certain that further increases in oppressive temperature events will occur in the region for as long as global warming continues (Engelbrecht et al., 2015; Garland et al., 2015), even under 1.5 °C of global warming (Seneviratne et al. 2021).

Generally, across most of southern Africa, inter-model agreement is strong across the ensembles of the Coupled Model Intercomparison Project Phase Six (CMIP6), Coordinated Regional Downscaling Experiment (CORDEX) and CORDEX-core ensembles, in terms of the general pattern of projected decreases in rainfall (Dosio et al., 2021). These changes are projected to further amplify even under 1.5 C of global warming, a level that will likely be reached as early as the early 2030s under low mitigation futures (Lee et al., 2021). However, there is less agreement over the eastern escarpment areas of South Africa, where some models do not project general reductions in rainfall totals, but rather rainfall total increases (Lee et al., 2021).

Confidence in the projections of a general drying in southern Africa in a warmer world follows not only from model agreement, but also from the understanding of the dynamic circulation of the region in a warmer climate. The poleward displacement of the westerlies in a warmer world, one of the best document changes in circulation that can already be detected in the Southern Hemisphere, is associated with a reduction in frontal rainfall over South Africa's winter and all-year rainfall regions (the southwestern Cape, and the Cape south coast; Engelbrecht et al., 2009; Engelbrecht et al., 2015b). The southward displacement of the rain-bearing frontal systems of southern Africa occurs in association with the strengthening of the subtropical high-pressure belt over southern Africa

(Engelbrecht et al., 2009), a mechanism directly linked to the now infamous 2015-2017 Cape Town 'day-zero' drought (Burls et al., 2019). A recent attribution study found that the likelihood of droughts of this magnitude occurring in South Africa's winter rainfall region has already increased by a factor of three as a consequence of anthropogenic climate change (Otto et al., 2018). During summer, the increase in the intensity and frequency of occurrence of the subtropical highs manifest in the mid-levels (Engelbrecht et al., 2009), including via the Kalahari high-pressure system. The more frequent occurrence of mid-level subsidence in mid-summer relate to longer dry spells, reduced precipitation and more sunlight reaching the surface, thereby contributing to sharply increased surface warming (Engelbrecht et al., 2009; Engelbrecht et al., 2015).

In this report, our focus is on exploring in more detail the main climate change signal projected for southern Africa, namely that of a strongly warmer and generally drier climate, through the application of the CMIP6 ensemble (e.g. Fan et al., 2020) – the largest ensemble of global climate model (GCM) projections obtained to date. This includes an analysis of projected changes in weather extremes associated with a drastically warmer and generally drier climate, building on the analysis in other FOCUS-Africa reports, particularly D3.3 (Extreme events identification and their variability) and D4.1 (Seasonal forecast quality assessment). Increases in the number of heatwaves and high fire-danger days, for example, which may occur in conjunction with a general trend of drying, may have potentially devastating impacts on agriculture, water security, human and animal health, and biodiversity under low mitigation climate change futures. We proceed to generate a range of climate indices and demonstrate how these can be used in the assessment of risks to food security in southern Africa. In this way, the report is designed to serve as an input into the next deliverable in Work Package 2, and the indices generated may also support FOCUS-Africa case studies concerned with climate change impacts on agriculture and food security.

2 Data and methods

For projections in mean rainfall and temperature, a large CMIP6 ensemble of 30 GCMs was used to derive average changes relative to a baseline period of 1850-1900 (i.e. a preindustrial baseline), under the Shared Socioeconomic Pathway 5-8.5 (SSP5-8.5) scenario (a largely unmitigated fossil fuel scenario). The projections were used to obtain changes in regional climate as a function of different levels of global warming, namely 1.5°C and 2°C (i.e. the end members of the global goal as defined by the Paris Agreement), and 3°C and 4°C of global warming (being representative of lesser levels of mitigation resulting in failure to meet the Paris Agreement targets). Twenty-year moving averages are used to define periods representative of the above levels of global warming, separately for each GCM in the ensemble, as per the methodology of Lee et al. (2021).

For extreme event analysis, daily rainfall, average temperature, minimum and maximum temperature, relative humidity, and surface wind speed data were obtained for the CMIP6 ensemble (Tebaldi et al., 2021) of GCM simulations. These six surface variables are essential for the calculation of the drought and fire indices that are key to the analysis undertaken here. Six CMIP6 models had available the mentioned six surface variables under the low mitigation scenario SSP5-8.5 (Socio-economic Pathway 5-8.5).

The relatively low resolution CMIP6 GCM data were interpolated to a common 1° latitude-longitude grid, towards a model-intercomparison of the projected climate change futures being undertaken. Since the extreme weather events of interest in this analysis that focuses on the major drivers of changing food security, namely heatwaves in the presence of drought or reduced rainfall totals are synoptic-scale features, their main characteristics are well-represented at 1° resolution. All changes

are shown for a specific level of global warming relative to the preindustrial baseline period (1850-1990), which enables an assessment of the strengthening climate change signal as a function of the level of global warming.

Three extreme weather-event definitions were employed in the analysis. The first is the World Meteorological Organization (WMO) definition for heatwaves, as events when the maximum temperature at a specific location exceeds the average maximum temperature of the warmest month of the year by 5°C, for a period of at least 3 days (Engelbrecht et al., 2015). The second is the Keetch-Byram drought index, D, which is defined in terms of a daily drought factor, dQ:

$$dQ = \frac{(203.2-Q)[0.968 \times e^{(0.0875T+1.5552)}-8.30]}{[1+10.88 \times e^{(-0.001736R)}]}. \quad (1)$$

Here R is the mean annual precipitation (mm) and Q (mm) is the soil moisture deficiency that results from the interaction between rainfall and evaporation. Once Q has been updated by dQ, the drought index is calculated from the equation

$$D = \frac{10Q}{203.2}. \quad (2)$$

Note that D ranges from 0 to 10, where D=10 indicates completely dried out soil and vegetation (Keetch and Byram, 1968, Engelbrecht et al., 2015).

We employed the McArthur forest fire index (FFDI) (Dowdy et al., 2009) to quantify fire-danger risks:

$$FFDI = 2e^{(-0.45+0.987lnD+0.0338T-0.0345H+0.0234U)} \quad (3)$$

Here T is maximum temperature (°C), H is relative humidity and U is average wind speed (measured at a height of 10 m in ms^{-1}).

In order to demonstrate how regional climate extremes in a changing climate may impact on food security in southern Africa, we make use of a simple yet robust index of maize suitability, which explains the current distribution of maize production in southern Africa. Maize is selected because it is the region's staple crop and because of its perceived vulnerability to climate change, particularly in the context of increasing extreme temperature events and reduced precipitation (Sanchez et al., 2014). The index adopts the structure of the widely used mechanistic species distribution model CLIMEX (Ramirez-Cabral et al., 2017):

$$MI = F(T,P) * \left[\frac{1-CS}{100}\right] * \left[\frac{1-HS}{100}\right]. \quad (4)$$

The above is an expression for the climatic suitability of maize (MI), assuming that moisture availability, determined by the balance between precipitation (P) and evaporation, which in turn depends on temperature (T), is the main control of suitability. This suitability is further modified by the probability of occurrence of cold extremes (CS, expressed as a percentage) and hot extremes (HS, expressed as a percentage). The index is scaled to range between 0 and 3, with 0, 1, 2 and 3

being thresholds that denote climatic unsuitability, marginal suitability, moderate suitability, and optimal suitability for maize. The Keetch-Byram drought index D, scaled to range between 0 and 3, is used to describe F(T,P) in equation (3). The Keetch-Byram index is ideal to use for this purpose, since it essentially describes moisture availability. A predictive species modelling approach is followed to apply the index to southern Africa (the CLIMEX approach). As a first step, the known distribution of maize in southern Africa (Ramirez-Cabral et al., 2017) was used to determine the relevant thresholds of moisture availability F(T, P) in southern Africa, to define regions of unsuitability, and marginal, medium and optimal suitability. Regions that were deemed to have some degree of suitability in terms of moisture availability, but are currently not maize production regions, were subsequently assumed to be unsuitable due to a high frequency of occurrence of temperature extremes. The probability of occurrence of hot and cold extremes were subsequently applied to refine MI towards it explaining the current distribution of maize in southern Africa.

3 Projected changes in regional climate and its extremes

3.1 Projected changes in annual rainfall totals

Changes are calculated with respect to the pre-industrial baseline period of 1850-1900, with the pattern of change scaling in a remarkably stable way across increasingly higher levels of global warming. A generally drier future is projected for southern Africa by the CMIP6 SSP5-8.5 ensemble average, a signal that is expected to manifest even under 1.5 °C of global warming and strengthening in amplitude at higher levels of global warming (Figure 1). Overall, this analysis provides a clear picture of the potential to avoid adverse impacts if future warming scenarios encompass the global goal according to the Paris Agreement (top two panels), as opposed to failure to meet the global goal (bottom two panels).

There are three regions where increases in rainfall are projected by the ensemble average: South Africa's KwaZulu Natal Province, east of the country's eastern escarpment; the most northern parts of the southern African domain, the subtropical Atlantic Ocean along the coast of Angola and parts of southwestern Madagascar. There is some variation across the ensemble members in terms of the projected pattern of rainfall change across southern Africa (see the next section, also see Dosio et al., 2021), but only two regions where model agreement is weak (that is, where conflicting signals of change are projected across the ensemble members). These regions are the KwaZulu-Natal Province of South Africa and the subtropical Atlantic Ocean west of Angola (Lee et al., 2021). Since model disagreement over these regions persist at high levels of global warming, the uncertainty is likely structural, rather than being caused by model internal variability. In the case of the KwaZulu-Natal province, this structural uncertainty may relate to the parameterisation of convection over South Africa's steep eastern escarpment, and area long known to be associated with substantial model rainfall biases (Engelbrecht et al., 2002; Dedekind et al., 2016).

The pattern of general drying projected across the southern African domain has previously been linked to general increases in subtropical subsidence over southern Africa and the poleward displacement of frontal systems in winter (Engelbrecht et al., 2009; Engelbrecht et al., 2015). This pattern of change is remarkably robust (in terms of the ensemble average, at least) across the CMIP6, CMIP5, CORDEX and CORDEX-core ensembles (Dosio et al., 2021). Moreover, the IPCC in Assessment Report Four (Christensen et al., 2007), Assessment Report Five (Niang et al., 2014), SR1.5 (Hoegh-Guldberg et al., 2018) and Assessment Report Six (Lee et al., 2021; Ranasinghe et al., 2021), made the assessment of the southern African region becoming generally drier, and/or to become more drought-prone in a warmer world.

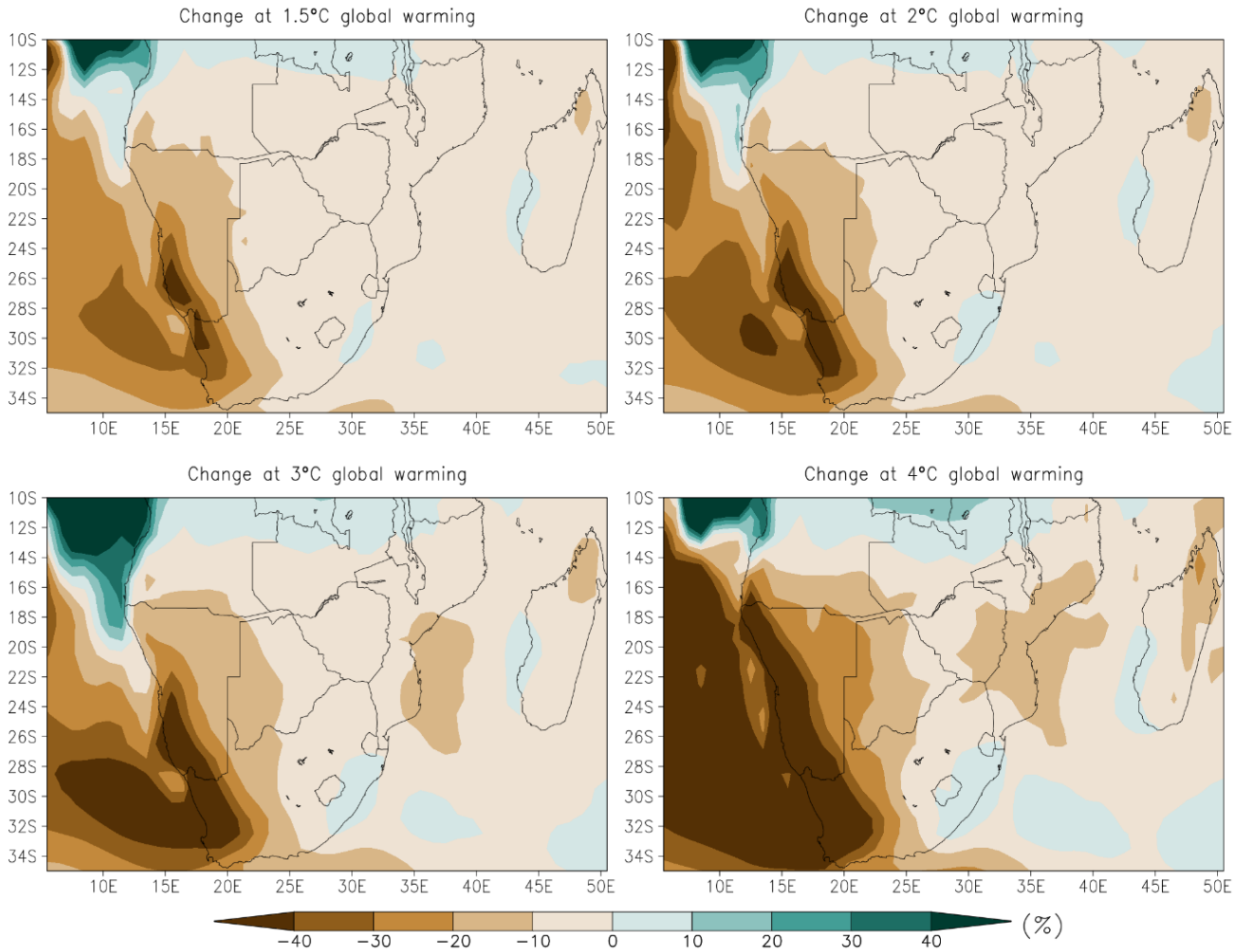

Figure 1: Changes in annual rainfall totals (% change) over southern Africa projected by the CMIP6 SSP5-8.5 ensemble-average, across various levels of global warming reached with respect to the 1850-1900 baseline period, with the upper two panels directly representing the end members of the global mitigation goal expressed in the Paris Agreement.

The pattern of drying is particularly strong for the winter rainfall region of the southwestern Cape in South Africa, across all the ensemble members. The strong climate change signal over this region may be linked to a reduction in frontal rainfall linked to the poleward displacement of the westerlies, an already detectable change in the Southern Hemisphere (Goyal et al. 2021) that has been linked to an increased likelihood for multi-year droughts to occur. The increase in precipitation over the northern part of the domain is consistent with general increases in precipitation in tropical Africa in a warmer world (Lee et al., 2021), and the expansion of the tropical belt. When considering the implications of projected changes in extreme temperature and rainfall events in southern Africa, as in the following sections, it is important to frame these changes in the context of strong regional warming, and a likely general decline in rainfall.

3.2 Projected changes in annual average near-surface temperature

The CMIP6 SSP5-8.5 ensemble average projected changes in annual average near-surface temperature are shown in Figure 2, across different levels of global warming. As with the rainfall projections, this analysis provides a clear picture of the potential to avoid adverse impacts under mitigation scenarios that encompass achievement of the global goal according under the Paris

Agreement (top two panels), and the virtually certain adverse impacts in the case of failure to meet the global goal (bottom two panels).

Consistent with trends that can already be detected (Engelbrecht et al., 2015), the strongest warming is centered over Botswana, extending across the western and central interior regions of southern Africa. The interior regions of southern Africa are projected to warm at a higher rate than tropical Africa, whilst the moderating effect of the ocean also tempers the rate of warming over coastal areas. The relatively high rate of warming over subtropical interior southern Africa has been attributed to a strengthening of mid-level anti-cyclonic circulation and subsidence, which suppresses cloud formation and rainfall, resulting in more solar radiation reaching the surface, thereby driving the relatively high rate of temperature increase (Engelbrecht et al., 2009; Engelbrecht et al., 2015).

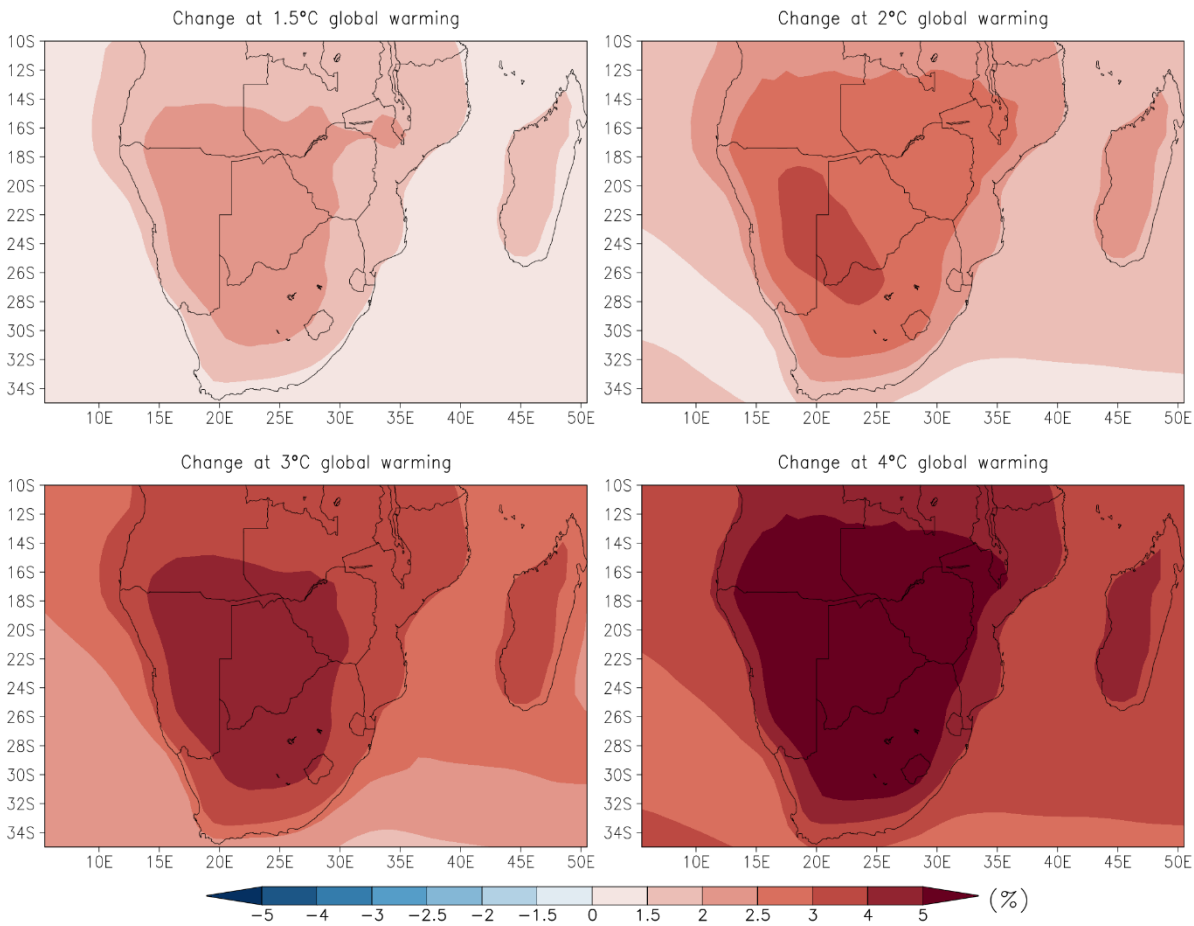

Figure 2: Changes in near surface mean annual temperature (□C) over southern Africa projected by the CMIP6 SSP5-8.5 ensemble-average, across various levels of global warming reached with respect to the 1850-1900 baseline period, with the upper two panels directly representing the end members of the global mitigation goal expressed in the Paris Agreement.

3.3 Projected changes in regional extremes

With a view to gaining insight into weather extremes in southern Africa in a warmer world, projections of six CMIP6 GCMs are considered for which daily data are available for the variables of precipitation, minimum and maximum temperature, relative humidity and surface wind speed (allowing for the calculation of fire-danger indices). To facilitate comparison with Figures 1 and 2 above, projected changes in annual rainfall totals (Figure 3) and annual average surface temperature

(Figure 4) are plotted for each of the six GCMs under 3 °C of global warming. This level of global warming is selected for extreme event analysis since it is likely to be associated with a clear climate change signal (as opposed to the relatively larger role that climate/internal variability may play under 1.5°C, and possibly 2°C, of global warming). Moreover, under current international commitments to greenhouse gas reductions (as per the Nationally Determined Contributions), the exceedance of the 3°C threshold of global warming remains entirely possible.

The rainfall projections indicate variation in rainfall spatial patterns of change across the ensemble (Figure 3). For example, three of the six projections indicate slight rainfall increases over South Africa's KwaZulu-Natal Province, whilst all six indicate pronounced drying over the winter rainfall region of the southwestern Cape. Three of the six projections also indicate slightly wetter conditions over all or parts of western Botswana (the larger CMIP6 ensemble shows model agreement in this region, in terms of a general signal of drying). All the simulations are indicative of pronounced warming over southern Africa, peaking over the western interior at levels of 4-6 °C (Figure 4).

The projected changes in the Keetch-Byram drought index (Figure 5) are indicative of general reductions in soil moisture availability across southern Africa under 3 °C of global warming. This is an important finding: although there is variation in the pattern of rainfall change in the 6-member model ensemble considered here, with conflicting signals in some regions, all projections are in agreement of general reductions in soil moisture availability, even in the areas of projected increases in rainfall. These reductions are the consequence of enhanced evaporation in a substantially warmer region. Thus, it is possible to conclude with some certainty that southern Africa is likely to become generally drier in terms of rainfall totals, but is virtually certain to become generally drier in terms of soil moisture availability, a crucial element for crop production in the region. This finding is consistent with strong model agreement in terms of projected decreases in soil moisture as parameterised in CMIP6 GCMs (Wang et al., 2022, Zhai et al., 2020). Moreover, earlier work has indicated that such general reductions in soil moisture in southern Africa translate to a shortening in the growing season in the summer rainfall region. That is, the amount of soil moisture needed for crops to be planted is reached later in the season in a warmer world compared to a cooler world; moreover, soil moisture peaks at lower values at the end of the rainy season in a warmer compared to a cooler world (Engelbrecht et al., 2015).

Consistent with the sharp increases in temperature, the six GCMs considered here also project substantial increases in the number of heatwave days over southern Africa (Figure 6). These increases range from 20-60 days per year over much of the western and central interior regions, implying that heatwaves, compared to the pre-industrial threshold, will become a common and in some regions a semi-permanent feature of summer climate. The geographical 'centre' of heatwave increases is over Botswana in all the projections considered. This pattern of change likely relates to increases in mid-level highs and associated subsidence (Engelbrecht et al., 2009), specifically through the intensification and more frequent occurrence of the Botswana high. Indeed, over northern Botswana and southern Zambia, the observed rate of increase in average temperature in decades has been about 4 °C per century (Engelbrecht et al., 2015). Implications of heatwaves on agriculture and food security are not only on the food crops (for example, reduced yield and harvest delays), but also on farmer and farmworker health and wellbeing (Garland et al., 2015).

In a generally drier regional world (Figure 3), that is also warming at an almost unprecedented rapid rate, meteorological fire-danger may also be expected to increase. This is illustrated by Figure 7, which shows the projected change in the number of high fire-danger days, as defined by the McArthur Fire Danger Index (eq 3). Substantial increases in the number of high fire- danger days, of between 20 and 80 days per year, are projected for extensive parts of the western and central interior, in some projections extending into the Limpopo River Valley. In relation to generally drier conditions, these

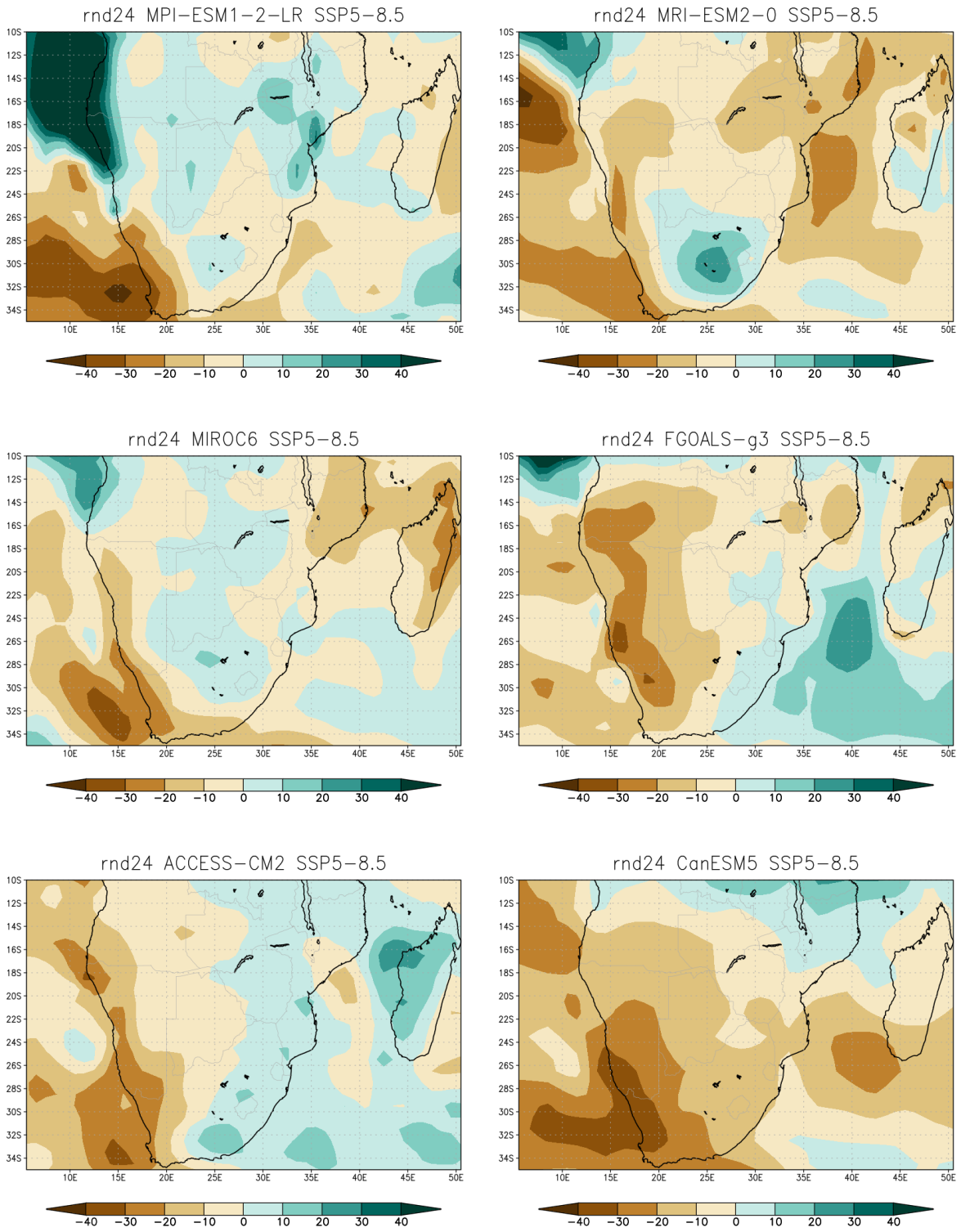

Figure 3: Projected changes in annual rainfall totals (% change) over southern Africa under 3 °C of global warming relative to pre-industrial climate, as per an ensemble of six CMIP6 GCMs.

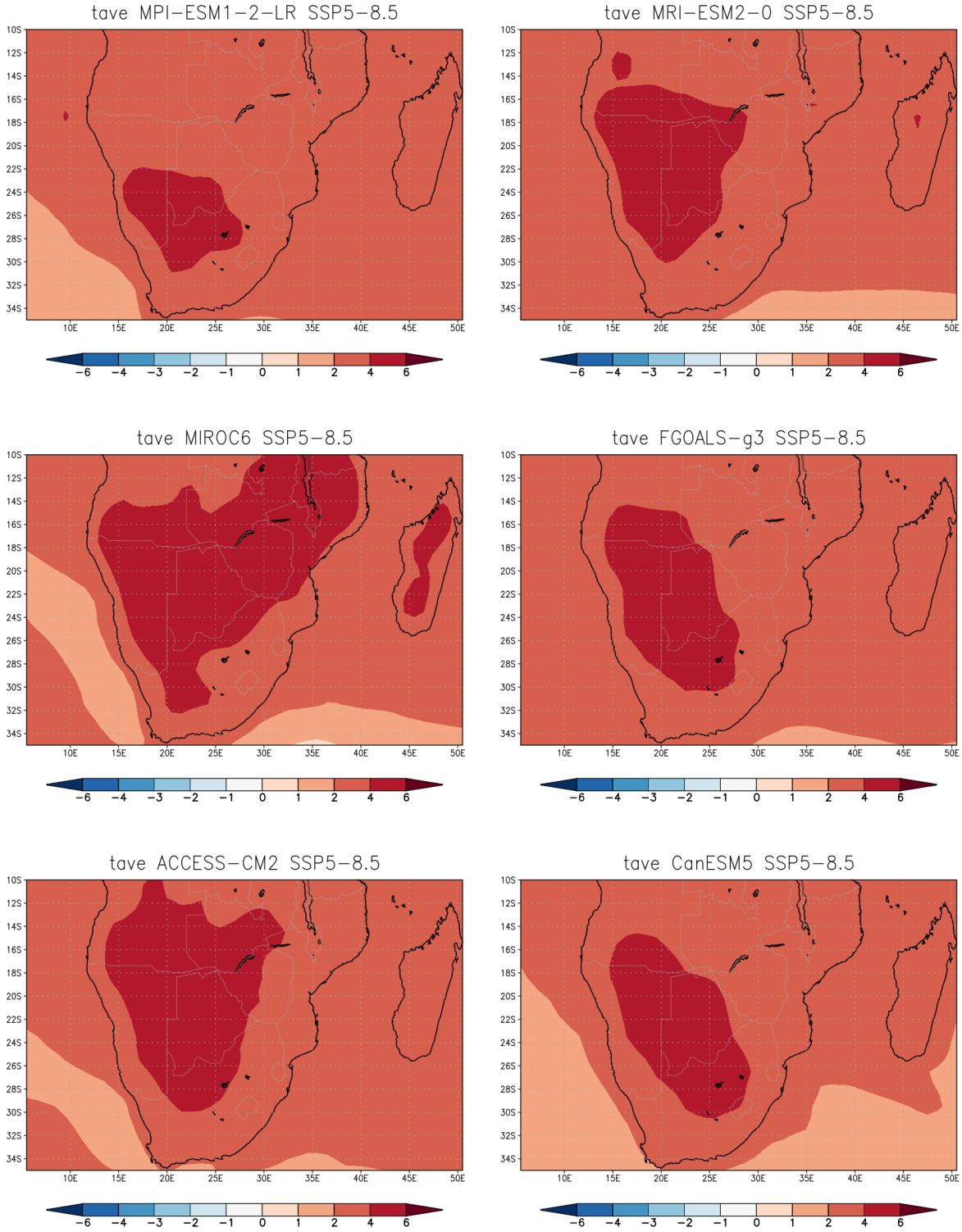

Figure 4: Projected changes in annual average temperature (°C) over southern Africa under 3 °C of global warming relative to pre-industrial climate, as per an ensemble of six CMIP6 GCMs**.**

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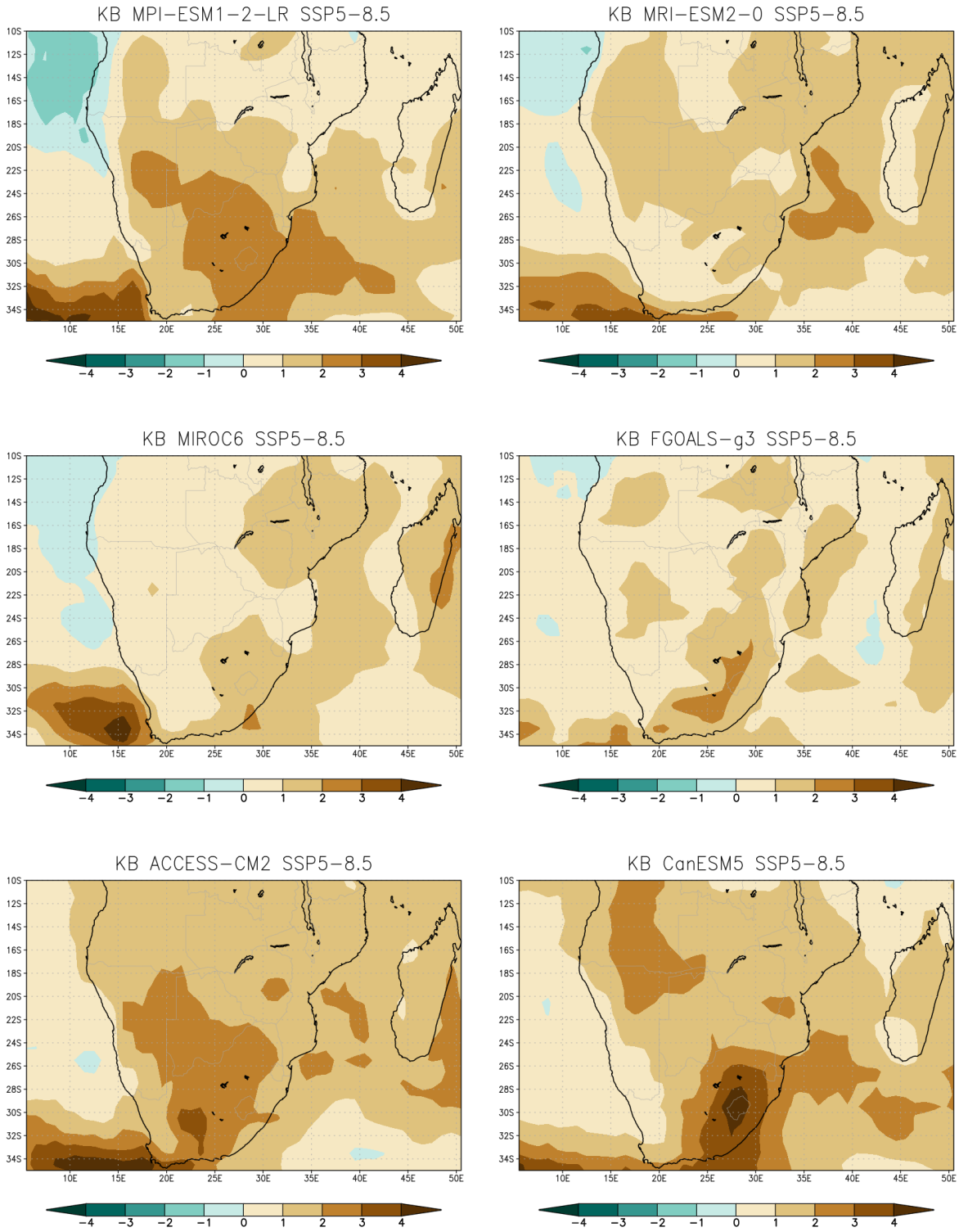

Figure 5: Projected changes in the Keetch-Byram drought index over southern Africa under 3 °C of global warming relative to pre-industrial climate, as per an ensemble of six CMIP6 GCMs.

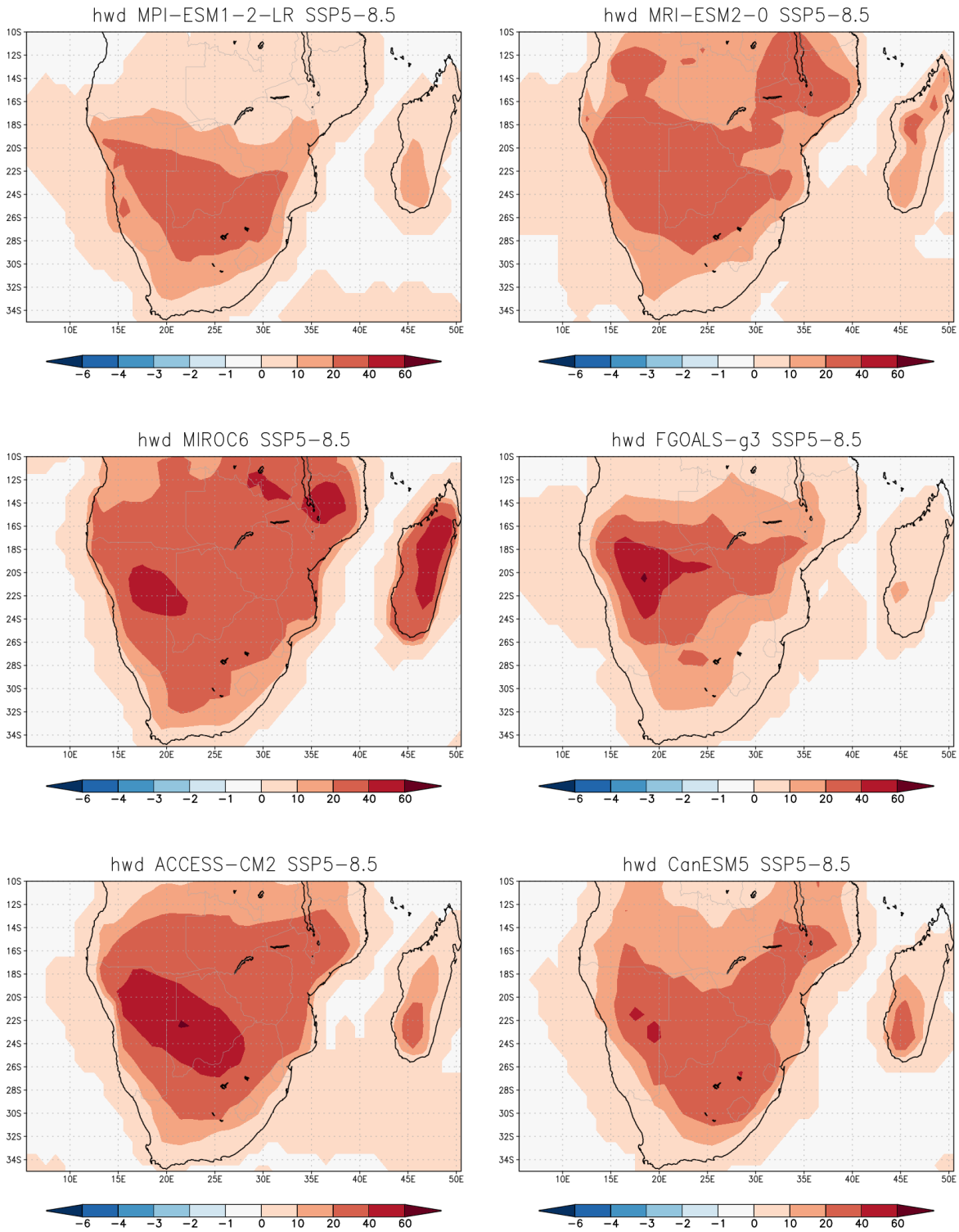

Figure 6: Projected changes in the number of heatwave days over southern Africa under 3 °C of global warming relative to pre-industrial climate, as per an ensemble of six CMIP6 GCMs.

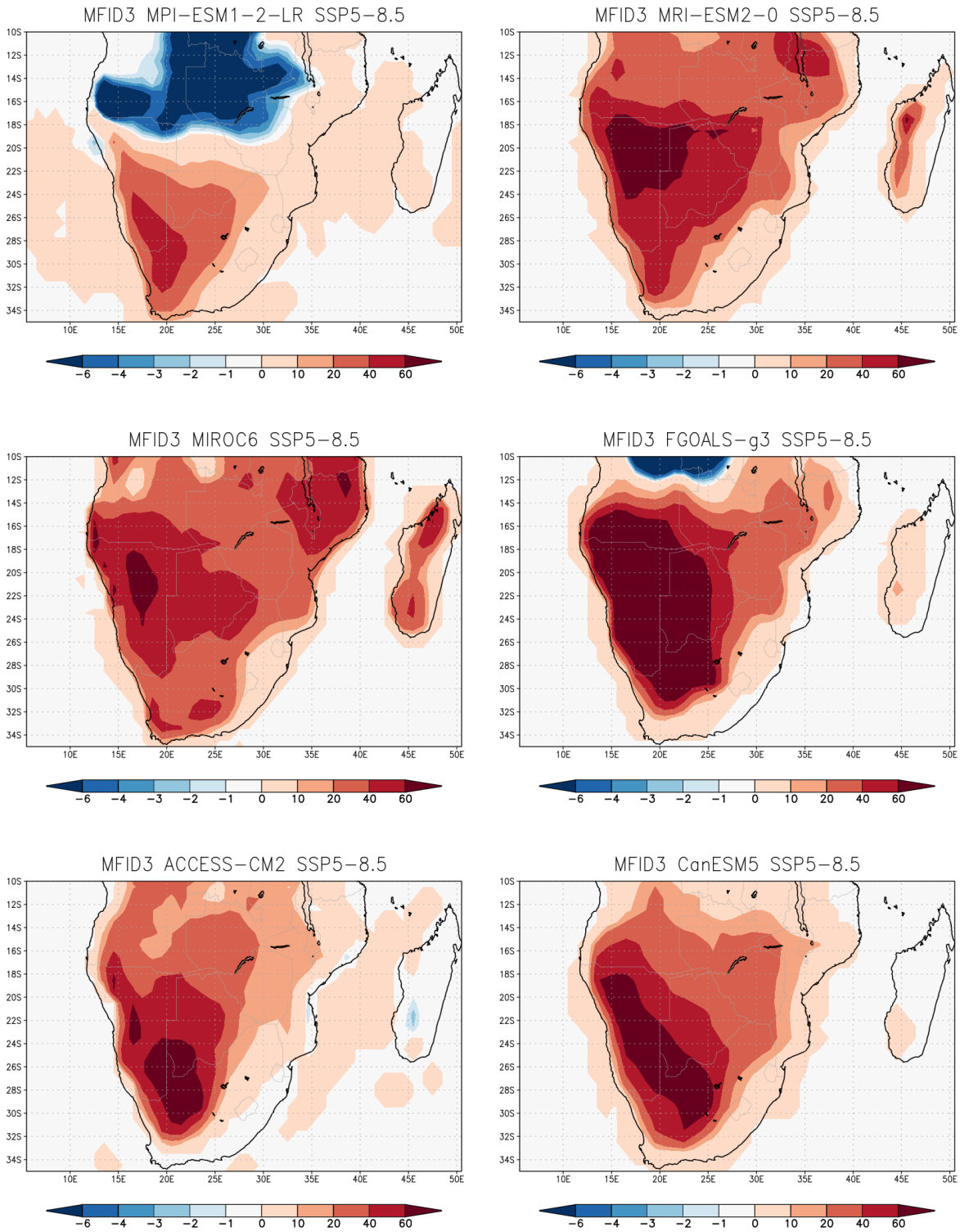

Figure 7: Projected changes in the number of high fire-danger days per year over southern Africa under 3 °C of global warming relative to pre-industrial climate, as per an ensemble of six CMIP6 GCMs**.**

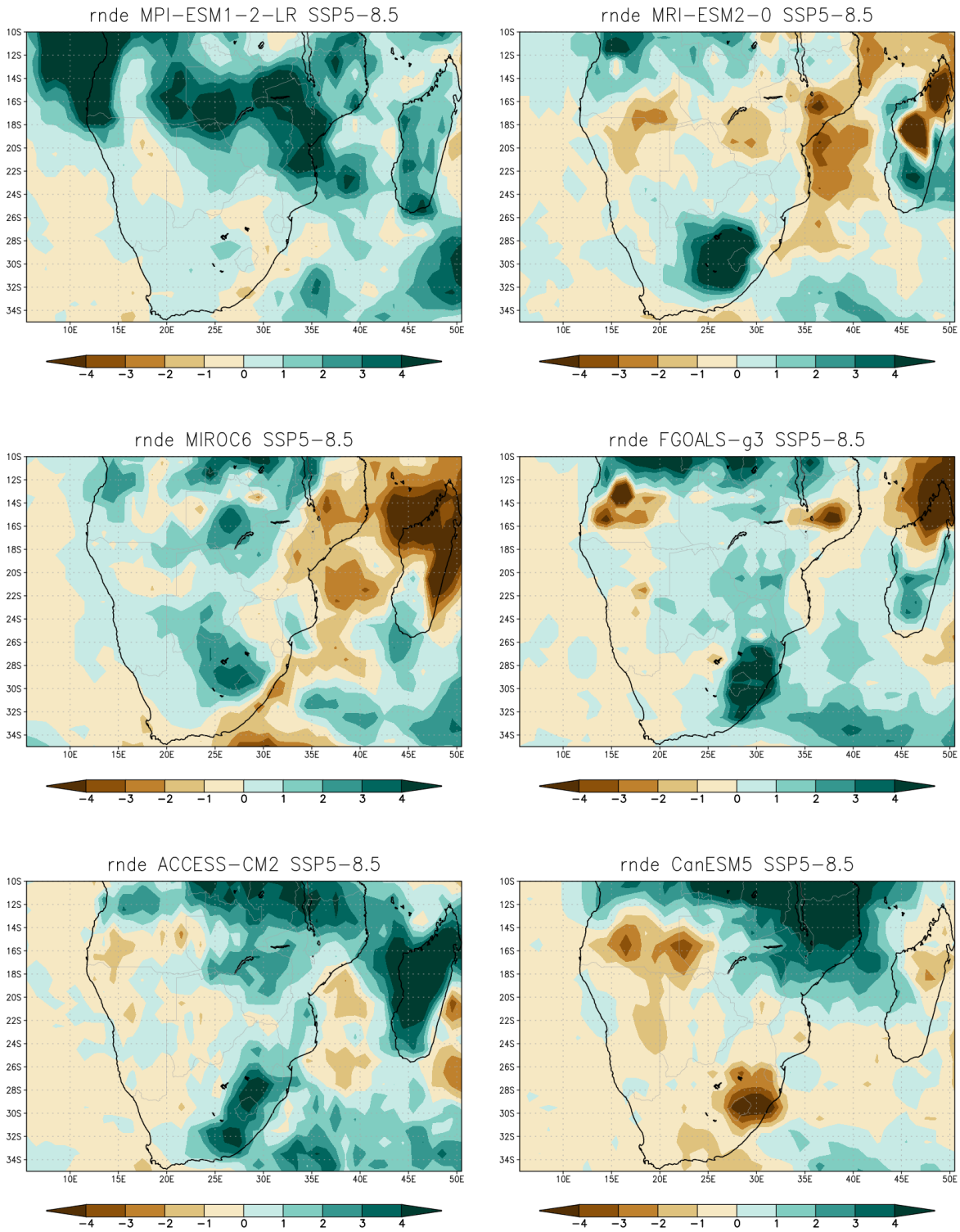

Figure 8: Projected changes in the number of intense rainfall events (more than 20 mm of rain falling over an area of 10 000 km2) over southern Africa under 3 °C of global warming relative to pre-industrial climate, as per an ensemble of six CMIP6 GCMs**.**

changes also translate to a lengthening of the fire season in southern Africa (Engelbrecht et al., 2015). It may be noted that one of the ensemble members analysed (MPI-ESM1-2) is indicative of pronounced decreases in high fire-danger days over Zambia. This change is underpinned by rainfall increases (Figure 3) and an increase in the number of rainfall days in this particular model projection. Although "controlled" fires are a feature of some small-scale agriculture in the region, where they are used as a means to clear the land after each cropping cycle (often called the slash-and-burn agriculture), the increasing probabilities of uncontrolled fires pose risks of substantial losses of crops, grazing and agricultural infrastructure.

Despite the likely wide-scale decreases in rainfall, including substantial decreases in rainfall in the west, and virtually certain increases in average temperatures, heatwave days and high fire-danger days, general increases in intense rainfall events are likely in a warmer world in eastern southern Africa, including eastern South Africa and Mozambique, a trend that can already be observed (Ranasinghe et al., 2021). The ensemble of six projections considered in Figure 8 are indicative of the spatial variability in the projections of changes in extreme events. All the projections are indicative of increases in intense rainfall events across the northern part of the domain, including Northern Mozambique, a more consistent change compared to the model projections of changing annual rainfall totals. Some of the projections are also indicative of the potential of pronounced increases in intense rainfall events over and to the east of the eastern escarpment.

4. Application of extreme weather indices: the maize crop in southern Africa

Extreme event indices are useful to assess the potential impacts of a changing climate on a variety of crops, the livestock sector and on food security in general. Typically, in order to obtain projections of changing crop yield under climate change, the indices or the daily values of variables such as temperature, rainfall, evaporation and radiation would be used to drive a mechanistic crop production model, for example as in Case Study 1 (CS1) of FOCUS-Africa, which explores changing maize crop yield in South Africa's North West Province. D2.2 and other deliverables in FOCUS Africa, through the data sets and indices it has generated, thus also serve to support the case studies directly focussing on estimating changes in crop yield, CS1 being the primary application in this regard.

Although mechanistic (physical) crop models (as applied in CS1) represent the most advanced methodologies to estimate future changes in crop yield, statistically derived indices are useful to provide qualitative insights into the changing suitability of a specific crop in a specific area under future climate change. For example, Moeletsi and Walker (2012), Ramirez-Cabral et al. (2017) and Chemura et al. (2022) developed crop suitability indices for maize, incorporating variables such as growing degree days, hot days, hot nights, growing season rainfall, dry-spell length and the occurrence of frost. Building on this existing body of literature, D2.2. uses a consolidating methodology that incorporates the Keetch-Byram drought index, in combination with extreme temperature events, to define maize suitability in southern Africa. First, from the existing spatial range of maize production in southern Africa, we identify the soil moisture content needed, as per the Keetch-Byram index, for the growing season of maize (stretching from October to April). This approach effectively describes the combined effects of rainfall and evapotranspiration (which in turn depends on temperature) on moisture availability, which is a critical determinant of maize crop suitability. The resulting range of suitability for maize production (as defined by moisture availability) is subsequently modified by the frequency of occurrence of damaging extreme temperature events, following Ramirez-Cabral et al. (2017) and using equation (4). The resulting suitability maps are shown in Figure 9 (present-day climate), Figure 10 (pre-industrial climate) and Figure 11 (3 °C of global warming).

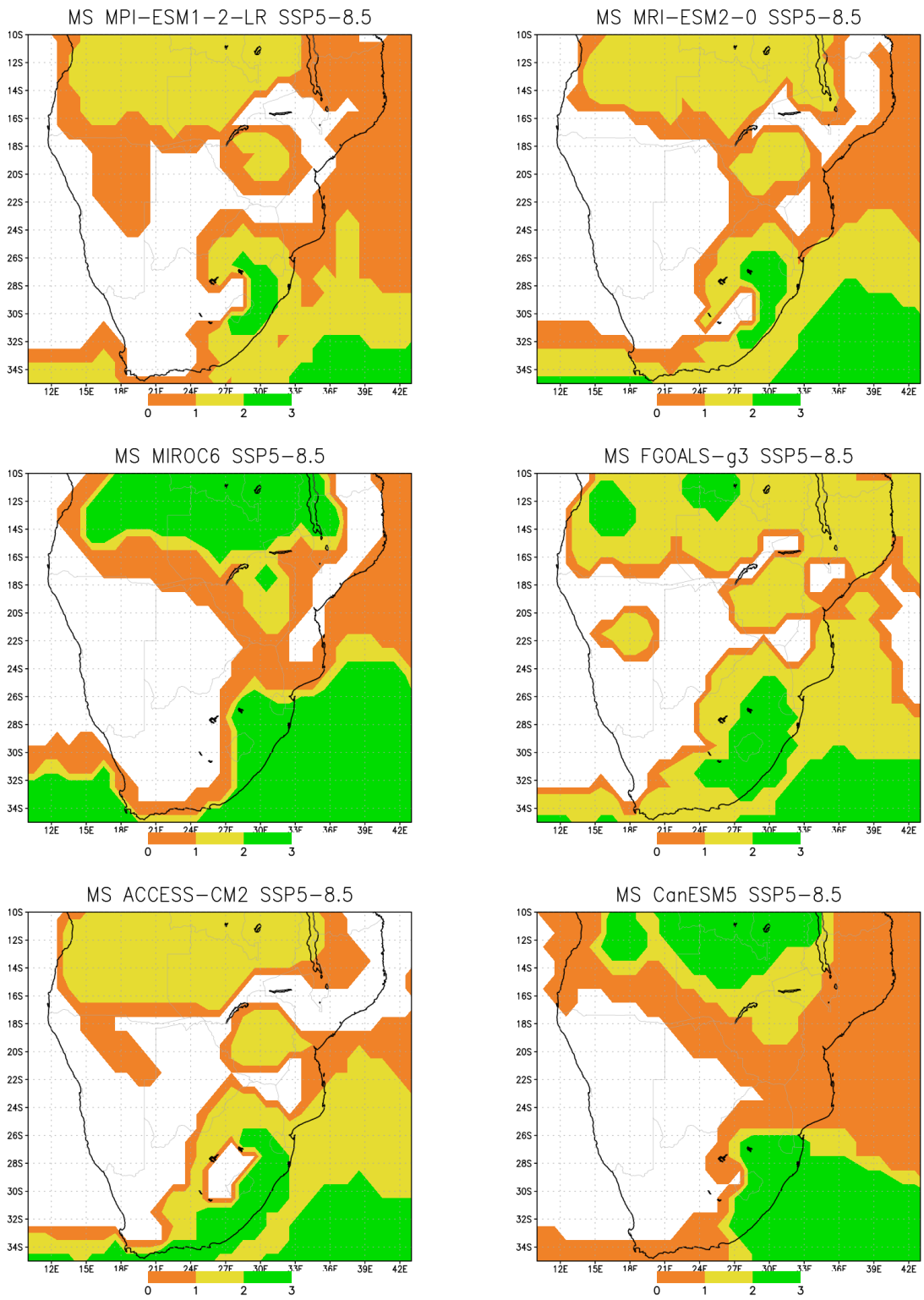

Figure 9: Maize suitability index for southern Africa based on moisture availability and the impact of extreme temperature events, here calculated for present-day (1961-1980) climate**.**

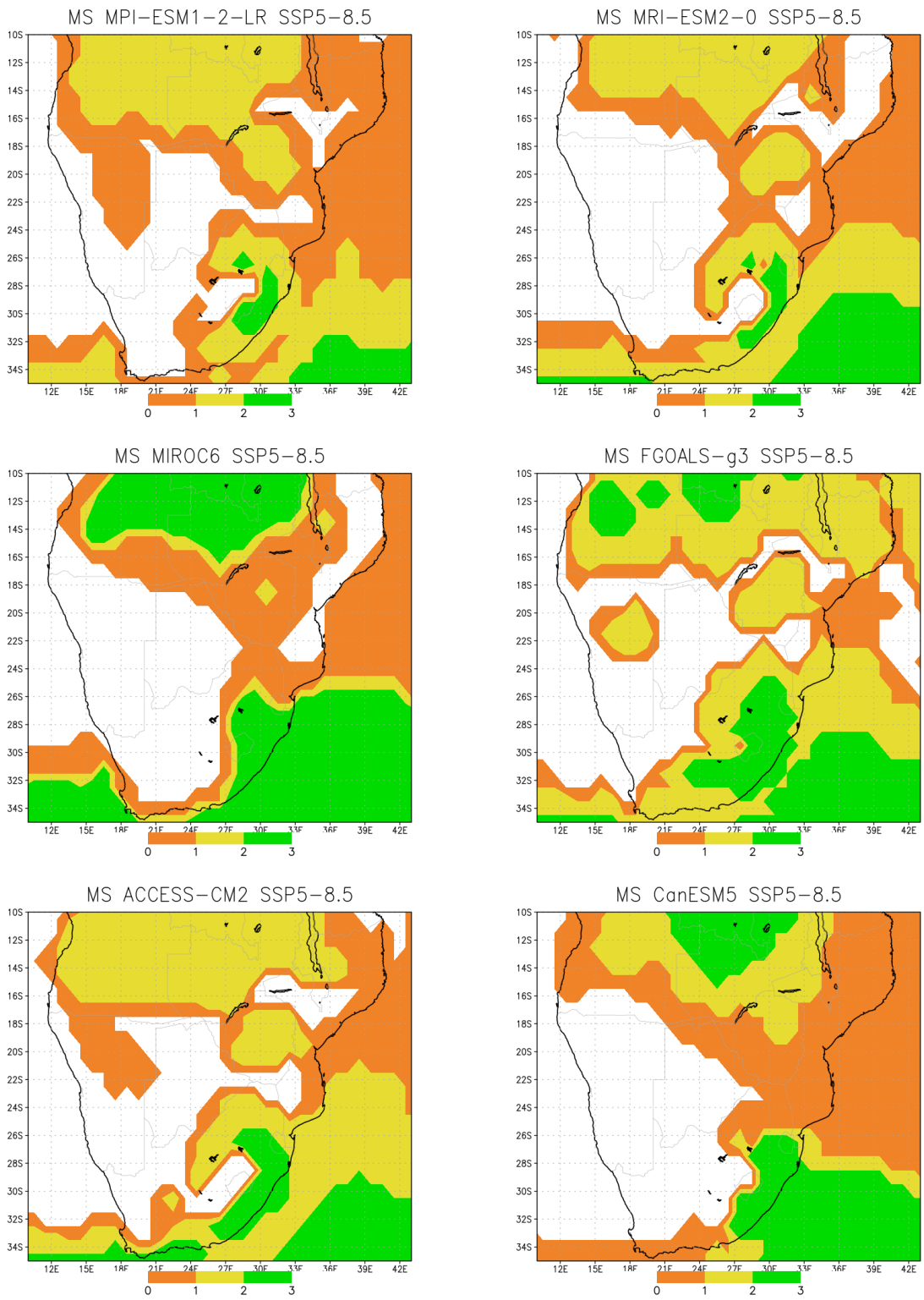

Figure 10: Maize suitability in southern Africa based on moisture availability and the impact of extreme temperature events, here calculated for pre-industrial (1850-1900) climate.

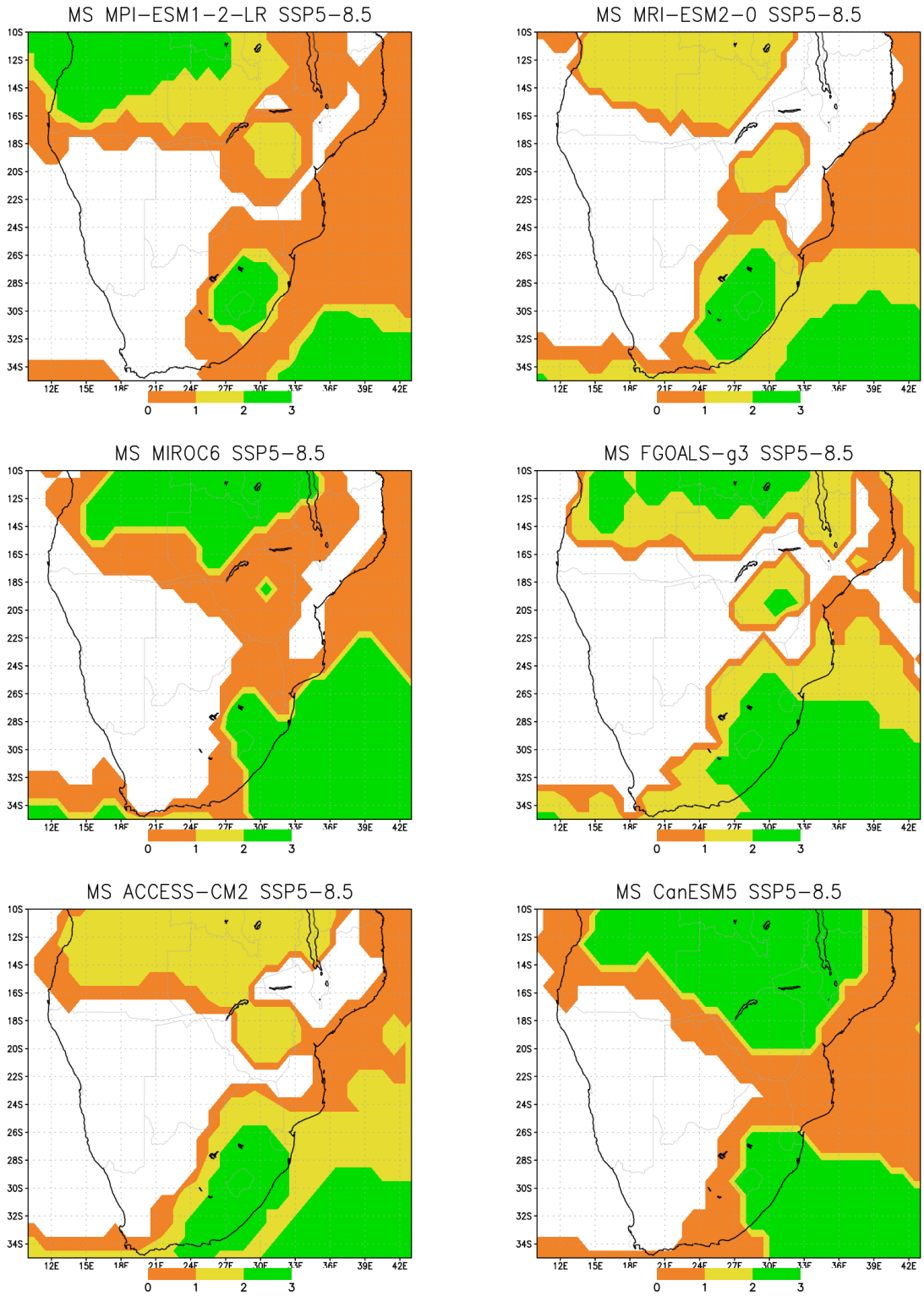

Figure 11: Maize suitability in southern Africa based on moisture availability and the impact of extreme temperature events, here calculated for climate corresponding to 3 °C of global warming.

It may first be noted that for present-day climate (1961-1980), the maize suitability index realistically portrays the current observed range of maize production in southern Africa (see Ramirez-Cabral et al., 2017). This characterisation is robust across the climatologies simulated by six different GCMs, since the modelled soil moisture availability is fitted to the observed occurrence of maize production across the region (following the CLIMEX predictive-species modelling approach of Ramirez-Cabral et al., 2017). This includes areas of medium to optimal climatic suitability over eastern South Africa, and the most northern parts of southern Africa, marginal suitability over the central interior of South Africa, and unsuitability over the dry western parts, stretching eastwards into the Limpopo River valley. All six model representations are also indicative of unsuitability in the Zambezi river valley, known for its hot extremes, and consistent with the analysis of Ramirez-Cabral et al. (2017). Some of the models are realistically indicating unsuitability over Lesotho under present-day climate, given that these models simulate a relatively high occurrence of cold extremes over this region.

Maize suitability for pre-industrial climate is shown in Figure 10, for the sake of using this as a baseline when assessing changes under future levels of global warming. The patterns of suitability are qualitatively similar compared to those for present-day climate. One important difference is that present-day climatic suitability is simulated to be higher over Lesotho and the surrounding eastern escarpment areas of South Africa. This is due to a decrease in the occurrence of cold extremes in the present-day climate of this sub-region – a consequence of the regional response to global warming. Under 3 °C of global warming, regions in western and central southern Africa currently assessed to be marginally suitable for maize production are projected to become unsuitable, due to reductions in rainfall and an increasing frequency of occurrence of hot extremes. Drastic increases projected in hot extremes in areas surrounding the Limpopo River valley and Zambezi river valley are similarly resulting in larger areas in eastern southern Africa becoming unsuitable for maize production. It is specifically the more frequent occurrence of days with maximum temperatures higher than 35 °C, during the flowering and anthesis stages of growth (Sanchez et al., 2014) , that are resulting in this projected expanding unsuitability. Increases in suitability are projected over Lesotho and the resulting eastern escarpment regions of South Africa, due to reductions in cold extremes and in particular, the occurrence of frost. Steep mountains slopes may however make it difficult to take advantage of enhanced climatic suitability of this sub-region, unfortunately. Finally, over northern southern Africa, where climate models project increases in rainfall, maize suitability is similarly projected to increase.

5. Regional extremes: the risk of regional tipping points

Regional tipping points refer to shifts in regional climate system that would establish a novel climate regime, where weather events unprecedented in the historical record have the potential to occur. Once a given threshold of global warming has been reached, these shifts are irreversible on the scale of human lifetimes. Tipping points in regional climate systems would, in all likelihood, induce ecological or socio-economic changes at regional scales that are similarly irreversible.

For southern Africa the almost certain reductions in soil moisture availability, increases in heatwave and fire-danger days, combined with a generally drier and warmer climate holds the risks of triggering a number of regional tipping points. Four examples of such potential tipping points are discussed below: the potential of a ‘day zero’ drought in South Africa’s Gauteng Province, the collapse of the maize crop in marginal regions, and of the cattle industry across southern Africa due to multi-year droughts, unprecedented heatwaves impacting on food production and human

mortality, and the risk of intense tropical cyclones making landfall further to the south than in the historical record (Engelbrecht and Monteiro, 2021).

In September 2016, at the end of four consecutive years of drought in South Africa's summer rainfall region, the level of the Vaal Dam fell to 25%. Water restrictions were in place in South Africa's Gauteng Province, which depends on about 50% of its water supply from the integrated Vaal River system. If the level of the Vaal Dam should fall to below 20%, the Gauteng water supply would be severely compromised for two reasons. The first relates to the engineering limitations of pumping water uphill to Johannesburg. The second relates to poor water quality at a dam level of 20% or lower, to the extent that the water would not be suitable for human consumption. It may be noted that the four-year-long period of below normal rainfall that resulted in dam levels being this low culminated in the occurrence of the 2015/16 El Niño and related drought in southern Africa. The 2015/16 El Niño was the strongest in recorded history, at least in terms of the magnitude of anomalies in the Niño 3.4 region, and there is evidence that climate change strengthened the event. Although the IPCC in AR6 did not make high confidence statements about changes in El Niño and La Niña amplitudes and frequencies in a warmer world, it did assess that impacts are likely to strengthen in amplitude in most regions of the world (Lee et al., 2021). This finding, in conjunction with projections of generally drier conditions in southern Africa, reduced soil moisture availability and increased temperatures and evaporation, suggest that the possibility exists that multi-year droughts in South Africa's eastern mega-dam region may occur more frequently, last longer and be more intense under higher levels of global warming. This in turn, suggests that the likelihood of the Vaal Dam's level falling below the critical threshold of 20% will increase in a warmer world, creating the possibility of a 'day zero' drought in the Gauteng Province. Such a drought is probably the largest climate change risk South Africa faces in the context of socio-economic impacts. The Gauteng Province is South Africa's industrial heartland, where 15 million people live. A 'day-zero' drought would imply extensive water restrictions and the reallocation of water between the sectors of agriculture (e.g. for irrigation), urban usage (household and industrial demand) and energy (the cooling towers of power plants).

A drought of duration and intensity to severely compromise Gauteng's water supply from the integrated Vaal River system has never occurred in the historical record, and if materialised would represent a tipping point in the regional climate system. The four-year drought including the 2015/16 El Nino was broken by good falls of rain in October 2016, and thus represents a near-miss of a 'day-zero' drought. Quantifying the probability of a Gauteng day zero drought under different levels of global warming should thus be a research priority. Given the potentially severe impacts of such a drought, a disaster risk reduction plan needs to be in place for such an event, even if it is low-probability event.

The terminology of 'day zero' droughts had its origin in the 2015-2017 Cape Town drought, during which the city came close to running out of water. A controversial issue during the drought was the reallocation of water from the agricultural sector in the region to satisfy the household demand for water in the city. This multi-year drought brought substantially reduced rainfall totals in the Theewaterskloof catchment, which is key to the City's water security. Associated with the substantially reduced rainfall totals projected for the southwestern Cape (Figure 1), is the more frequent occurrence of multi-year droughts. A tipping point may be reached where multi-year droughts in the southwestern Cape will occur so frequently that it will impact on the City of Cape Town's sustainable growth, to the extent that it will require a new water resource. Desalination plants are often proposed as a solution in this regard, although the large electricity needs and excessive costs of the associate technologies renders its implementation non-trivial. The mechanism

underpinning day zero droughts in the southwestern Cape is the poleward displacement of the Southern Hemisphere westerlies, a fingerprint of climate change that can already be detected (Goyal et al. 2021). Observed trends in rainfall in the winter rainfall region over the last thirty years are consistently negative (Wolski et al., 2021). Moreover, an attribution study concluded that the risks of day zero type droughts occurring in the southwestern Cape is already three times as large as in pre-industrial times (Otto et al., 2018). The risk of day zero type droughts extends into the all-year rainfall region and South Africa's Eastern Cape Province (Archer et al., 2022).

Multi-year droughts occurring in association with intense and heatwaves pose risks to the agricultural sector, including the maize-crop (southern Africa's staple food) and the high commodity cattle industry. The 2015/2016 summer, experienced intense El Niño induced drought and heatwaves and was the driest in recorded history across South Africa's Free State and North West Provinces, which together produce more than 60% of South Africa's maize crop. The South African maize-crop was reduced by about 40% compared to yield of the previous summer. Botswana lost 40% of its cattle. The IPCC has warned that the collapse of both the maize crop and cattle industry are likely in southern Africa under 3 °C of global warming (IPCC 2017). This assessment is based purely on the biophysical effects of heat-stress on the maize plant and cattle in a southern African climate that is warming drastically compared to the global rate of temperature increase, and which is likely to also become generally drier (Hoegh-Guldberg et al., 2018). However, if one also considers the socio-economics of farming, including the ability of subsistence farmers and small commercial farmers to absorb the shocks of multi-year droughts becoming more intense, and occurring more frequently, the possibility exists that such droughts may occur more frequently. Generating probabilistic assessments of tipping points in these key commodities in southern Africa thus requires a combined approach that is informed by both the physical science base and the socio-economics of farming. To this end, more reliable seasonal forecasts would provide critical adaptation support as they could facilitate important decisions such as risk assessments relating to planting timing to minimize costly drought related crop failure. Cultivar or crop species selection matched to the projected climate conditions would also comprise a valuable potential adaptation option.

The 2015/16 El Niño brought heatwaves of unprecedented frequency and intensity to southern Africa, and there are clearly detectable upward trends in the frequency of occurrence of extreme (warm) temperature events in the region. Climate model projections indicate potentially devastating increases in heatwave occurrences across southern Africa under high levels of global warming (Figure 6; Seneviratne et al., 2022). It is also clear though, that heatwaves of unprecedented intensity will already occur in southern Africa in the near-term (the next twenty years). Millions of people live in informal housing in southern Africa, without air conditioning, and often without easy access to cool water. The elderly are particularly vulnerable to such heat related stresses. The possibility exists of regional climate change in the near-term reaching a tipping point where heatwaves of unprecedented intensity and duration may kill thousands of people (including farmworkers involved in tasks that expose them to this hazard) and livestock across southern Africa. Heat-adaptation plans in southern Africa will benefit from an enhanced understanding of the risk of heatwaves associated with high mortality occurring.

The fourth example of a tipping point worthy of highlighting is quite different from those related to oppressive temperatures and drought. It involves the potential landfall of intense tropical cyclones (that is, a category 4 or 5 hurricanes) at latitudes further to the south than ever recorded before in southern Africa. Global tropical cyclone statistics are indicative of the more frequent occurrence of intense systems as well as of landfall at more poleward locations. Warmer sea-surface temperatures in the southwest Indian Ocean, and in particular in the Mozambique Channel, may similarly allow for

the more southward landfall of intense tropical cyclones in a warmer world. Indeed, recent decades has brought an increase in the number of category 4 and 5 hurricanes in the southwest Indian Ocean (Fitchett, 2018), although actual landfall of a category 5 hurricane has never been recorded in Mozambique.

Intense tropical cyclone Idai reached category 4 status in the Mozambique Channel, before making landfall as category 3 hurricane at Beira around midnight on 14 March 2019 (Engelbrecht and Vogel, 2021). In the destructive winds, storm surge and pluvial and fluvial flooding that followed, hundreds of people lost their lives. The total death toll in tropical cyclone Idai's path across Malawi, Mozambique and Malawi is estimated to have been more than 1000. This makes Idai the worst flood disaster in the history of Africa south of the equator. In Beira, there is some experience in local populations and disaster management agencies in terms of dealing with the impacts of tropical lows and cyclones. Tropical cyclone Idai serves as a stark reminder of how severe the impacts of category 3 to 5 hurricanes in southern Africa can be. In Mozambique, the impacts of Cyclone Idai included devastation of over 700,000 hectares of agricultural land affecting over 500,000 families (WFP, 2019). These can have major impacts on crop and livestock production. The flooding that follows the cyclones often makes replanting impossible.

Further to the south, in cities such as Maputo and Richards Bay, or in the Limpopo River valley between South Africa and Zimbabwe, there is no community or governance experience in coping with the impacts of intense tropical cyclones as no such events have occurred in the historical record. Should the climate regime shift into a regime where such southern landfalls of intense tropical cyclones become possible, or where the landfall of category five cyclones start to occur in southern Africa, impacts may well be devastating, including on food security. The probability of such a tipping point being breached is not well understood, however, AR6 of the IPCC had to base its assessment on only two regional climate modelling studies focused on tropical cyclone landfall in southern Africa (Malherbe et al., 2013: Muthige et al., 2018). In addition to the observational increases in the occurrence of category 4 and 5 hurricanes in the southwest Indian ocean, a recent study confirms the high rainfall associated with tropical cyclones in Mozambique can be attributed to anthropogenic warming effects (Otto et al, 2022).

6. Conclusion

Southern Africa is classified as a climate change hotspot in the IPCC's SR1.5. This stems from the region being naturally warm, dry, and water stressed, with climate change projections indicating a substantially warmer and likely also generally drier future. Such changes will imply limited options for climate change adaptation. There is model uncertainty in terms of the signal of rainfall changes over South Africa's KwaZulu-Natal Province and the eastern escarpment, with some models indicative of general increases in rainfall. Over South Africa's eastern interior, and northwards over Mozambique, general increases in intense rainfall events are likely. The main patterns of projected change described above can already be detected in trends in observed data over the last few decades: substantial regional warming, negative trends in rainfall in both the summer and winter rainfall regions and increases in intense rainfall events across the eastern escarpment and northwards into Mozambique. These observed changes, consistent with the assessment of projections, indicate to us the most likely climate change future of southern Africa: a generally drier and substantially warmer regional climate system, with more intense rainfall events in the east. Climate change adaptation plans first and foremost need to prepare for such a future.

Additionally, the analysis we have presented point out that general reductions in soil moisture availability are virtually certain to occur across the region, even in regions where the model ensemble

average, or individual models, are indicative of increases in rainfall. This is a consequence of enhanced evaporation in the warmer regional climate, and implies a generally shorter growing season and longer wildfire season across the region. Moreover, substantial increases in the number of heatwave days and high fire-danger days are virtually certain to occur under high levels of global warming. Implications for the maize crop, southern Africa's staple food, may be profound under high levels of global warming. Reductions in the area suitable for maize production are projected under 3 °C of global warming, largely due to reduced moisture availability and the impact of extreme temperatures (very hot days) in western and central southern Africa, and in parts of eastern southern Africa.

Against this background it is clear that the potential exists for the regional climate system to tip into a new regime, where unprecedented climate change impacts may start to occur in southern Africa. Examples include the possibility of a day zero drought in Gauteng, the collapse of the maize crop and cattle industry in some regions, the occurrence of heatwaves of unprecedented intensity, and the landfall of tropical cyclones as far south as Maputo, the Limpopo River Valley, or Richards Bay. More research is urgently required to quantify the probabilities of these and additional tipping points being reached. This information is critical for the identification and implementation of climate change adaptation plans and actions, especially as any of these adaptation options are likely to be extensive, expensive and requiring of long lead time for implementation. It is clear though, that the risk exists of the southern African region to become less habitable under high levels of global warming. Imagine for example, a future South Africa where maize can no longer be produced in its North West Province, or a future Botswana where the cattle industry has collapsed. At the same time intense heatwaves may frequently impact on human health and mortality, with more frequent long-lasting droughts hampering industrial development and the sustainable growth of cities. It is clear that southern Africa as a region needs to advocate strongly for climate change mitigation, and contribute its fair share to this mitigation effort, with the aim of avoiding these tipping points being reached in the first place. At the same time, more research is needed to improve the probabilistic understanding of tipping points being reached in the southern African region. While this report identified and characterised some of the key regional climate extremes relevant to food security under a changing climate in southern Africa, a follow-up report of FOCUS-Africa (D2.3) will aim explore the specific risks and vulnerabilities to the food, water and energy nexus in southern Africa.

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