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The El Niño–Southern Oscillation teleconnection to southern
Africa in a changing climate

Jessica Steinkopf* and Francois Engelbrecht

Global Change Institute, University of the Witwatersrand, Johannesburg, South Africa

* Author to whom any correspondence should be addressed.

E-mail: jessica.steinkopf@wits.ac.za**Keywords:** ENSO, El Niño, La Niña, teleconnection, southern Africa, climate changeSupplementary material for this article is available [online](#)

Abstract

Understanding how El Niño Southern Oscillation (ENSO) influences African rainfall is critical for water and food security planning. However, how this teleconnection may change in a warmer world remains unclear. Coupled Model Intercomparison Project Phase Six (CMIP6) models simulate the observed ENSO-rainfall teleconnection well, with southern Africa dry (wet) and East Africa wet (dry) during El Niño (La Niña) austral summers. This dipole pattern remains remarkably stable in a warmer world, with strong model agreement. This suggests that the global and southern African circulation responses to ENSO (the teleconnection) remain robust under warming. However, parts of eastern southern Africa, including the water-critical Integrated Vaal River System catchment, the ENSO signal weakens or even reverses in CMIP6 model projections. This likely reflects a general wetting of eastern escarpment regions, especially during El Niños, which may be linked to mesoscale and oceanic processes associated with relatively warm El Niño events under future climate conditions.

1. Introduction

El Niño Southern Oscillation (ENSO) associated changes in tropical-Pacific sea-surface temperatures (SSTs) result in climatic fluctuations in both tropical and extratropical regions around the world via atmospheric teleconnections (Taschetto *et al* 2020). Over southern and East Africa, ENSO typically results in a dipole pattern of rainfall anomalies, with El Niño (La Niña) events in southern Africa characterized by dry (wet) conditions during the austral summer, while East Africa typically experiences the opposite (Lindesay 1988, Taschetto *et al* 2020, Hoell *et al* 2021). The super El Niño of 2015/16 brought devastating impacts to southern Africa. The 2015/16 drought occurred at the end of a 5 year period during which multiple summers were dry. Botswana recorded very high cattle mortality during 2015 and 2016 (Anon 2018), and South Africa had to import maize for the first time in a decade in 2016 (Esterhuizen and Torry 2016), following the driest recorded summer in the maize-producing provinces (Engelbrecht and Monteiro 2021, Engelbrecht *et al* 2024). Moreover, the level of the Vaal Dam in South Africa fell to less

than 26% in October 2016 (Mthethwa 2020), the lowest level since Lesotho's Katse Dam started to provide water to the Integrated Vaal River System (IVRS) in 2004. The water supply of the economic heartland of South Africa, the Gauteng Province, was seriously threatened before the La Niña event of 2016/17 brought widespread rainfall and recovered dam levels. La Niña events are important for southern Africa's water security and agriculture, but also bring pronounced flood risk (Ward *et al* 2014, Rapolaki *et al* 2019, Mazibuko *et al* 2021). For example, the Durban floods of April 2022, which claimed 544 lives (EM-DAT database *n.d.*), occurred during the 2021/22 La Niña event (Thoithi *et al* 2022, Grab and Nash 2023).

Recently, ENSO has had devastating impacts on East Africa. The period 2020–2023 is noted as the most prolonged drought on record for the East African region and was strongly driven by La Niña conditions (Button 2023). This drought threatened millions of people in the Horn of Africa with starvation, as food prices increased, livestock died and crops failed (Cassidy, *n.d.*). Across Ethiopia, Kenya, Djibouti and Somalia the drought displaced approximately 2.4 million people, with millions more living

in drought-affected areas (DTM 2022). This severe La Niña-induced drought was broken by the recent 2023/24 El Niño, which caused major flood impacts in East Africa, including loss of lives, at least 2 million people displaced across the region, and livelihoods disrupted or lost (OCHA 2023). The flood risks were further exacerbated by the spread of disease and damage to critical infrastructure such as hospitals, schools, homes and roads (OCHA 2023).

Given the importance of ENSO in rainfall variability over Africa and Africa's well-known vulnerability to climate change (Engelbrecht and Monteiro 2021, Intergovernmental Panel On Climate Change 2023), it is critical to investigate and understand how the ENSO-rainfall teleconnection is projected to change in a warmer world. Specifically, southern Africa is a region that is naturally dry and warm and is projected to become drastically warmer and likely drier under low-mitigation futures (Engelbrecht *et al* 2015, Engelbrecht and Monteiro 2021, Intergovernmental Panel On Climate Change 2023, Ranasinghe *et al* 2023), rendering the region a climate change hotspot (Hoegh-Guldberg *et al* 2018). It is important to understand whether specifically summer rainfall in southern Africa will continue to exhibit pronounced interannual variability in a warmer world, and to understand whether changes in the teleconnection are contributing to the region being assessed to likely become drier.

The Intergovernmental Panel on Climate Change (IPCC) in its Assessment Report Six (AR6) assessed that it is 'virtually certain' that ENSO will persist through the 21st century and remain the dominant mode of interannual climate variability (Lee *et al* 2023). However, the IPCC AR6 also determined that there is no consensus across the Coupled Model Intercomparison Project Phase Six (CMIP6) models in terms of changes in ENSO amplitude or the frequency of El Niño or La Niña events, using the Niño 3.4 index as metric (Trenberth 1997). Recent work also highlights that while ENSO may persist as the dominant mode of variability, its teleconnections—including rainfall responses—are projected to change regionally in a warming climate (Cai *et al* 2021). Furthermore, AR6 did not make any detailed assessment about potential changes in the ENSO teleconnection to specifically southern Africa. In terms of the CMIP6 models' ability to represent the ENSO teleconnection to southern African rainfall under present-day climate, it was demonstrated that most models correctly portray the correlation between rainfall and Niño 3.4 SSTs to be negative, however, most models underestimated the strength of the correlation, and a minority of models incorrectly portray the correlation as positive (Eyring *et al* 2023).

Here we investigate how well models in CMIP6 represent the ENSO teleconnection to rainfall in

Africa, and examine how this teleconnection might change under future climate change, with a focus on southern Africa.

2. Methods

2.1. Rainfall and Niño 3.4 anomaly calculations

Monthly precipitation and SST data were downloaded for 42 CMIP6 models available for the historical period (1850–2014) and under shared socioeconomic pathway (SSP) 5–8.5 (Eyring *et al* 2016) for the period 2015–2100. A single ensemble member was used in the analysis for each of the GCMs. SSP5–8.5 was selected since it is the highest emission scenario in CMIP6, with likely the strongest climate change signal in terms of the potentially changing ENSO teleconnection to Africa. All selected models were interpolated onto the same global 1° longitude-latitude grid. For observations, to evaluate the CMIP6 models, we use the station-based gridded dataset, Climatic Research Unit (CRU) TS v. 4.05, available for 1901–2023, at a 0.5° resolution, at a monthly time-increment (Harris *et al* 2020). Southern Africa displays a sharp west-east rainfall gradient (Steinkopf and Engelbrecht 2022), and this is well-captured in the CMIP6 models (see figure S1 in the supplementary data). The ENSO teleconnection to southern and East Africa is evident in the CRU data (Steinkopf and Engelbrecht 2022). The Niño 3.4 index, as calculated by the National Oceanic and Atmospheric Administration (NOAA) (NOAA Climate indices database [n.d.](#)), is used to measure ENSO states because this SST region is strongly coupled with the overlying atmosphere and the Southern Oscillation (Reason *et al* 2000).

The austral summer December to February (DJF) total precipitation for each summer season 1954/55–2013/4 was calculated for each CRU/GCM gridpoint. This period represents the last 60 years of the historical simulation period in CMIP6 (Eyring *et al* 2016). This period's ENSO signal was compared to the period that runs to the end of the century, 2040/41–2099/2100, under SSP5–8.5. DJF rainfall totals for all summers in this period were calculated. We assume 60 year long periods are sufficient to distinguish potential trends in the teleconnection from its natural variability (Eyring *et al* 2023). Note that three of the GCMs end in 2099 and therefore have a 59 year time series to represent their climate change signal. However, we consistently refer to the general 60 year period ending in 2099/2100 in the paper. Our focus is on DJF given that El Niño and La Niña events tend to peak in amplitude during this season (Ropelewski and Halpert 1987, Lindesay 1988, Reason *et al* 2000, Blamey and Reason 2023), with the ENSO teleconnection to Africa then also best established (Steinkopf and Engelbrecht 2022). Moreover, DJF is the season

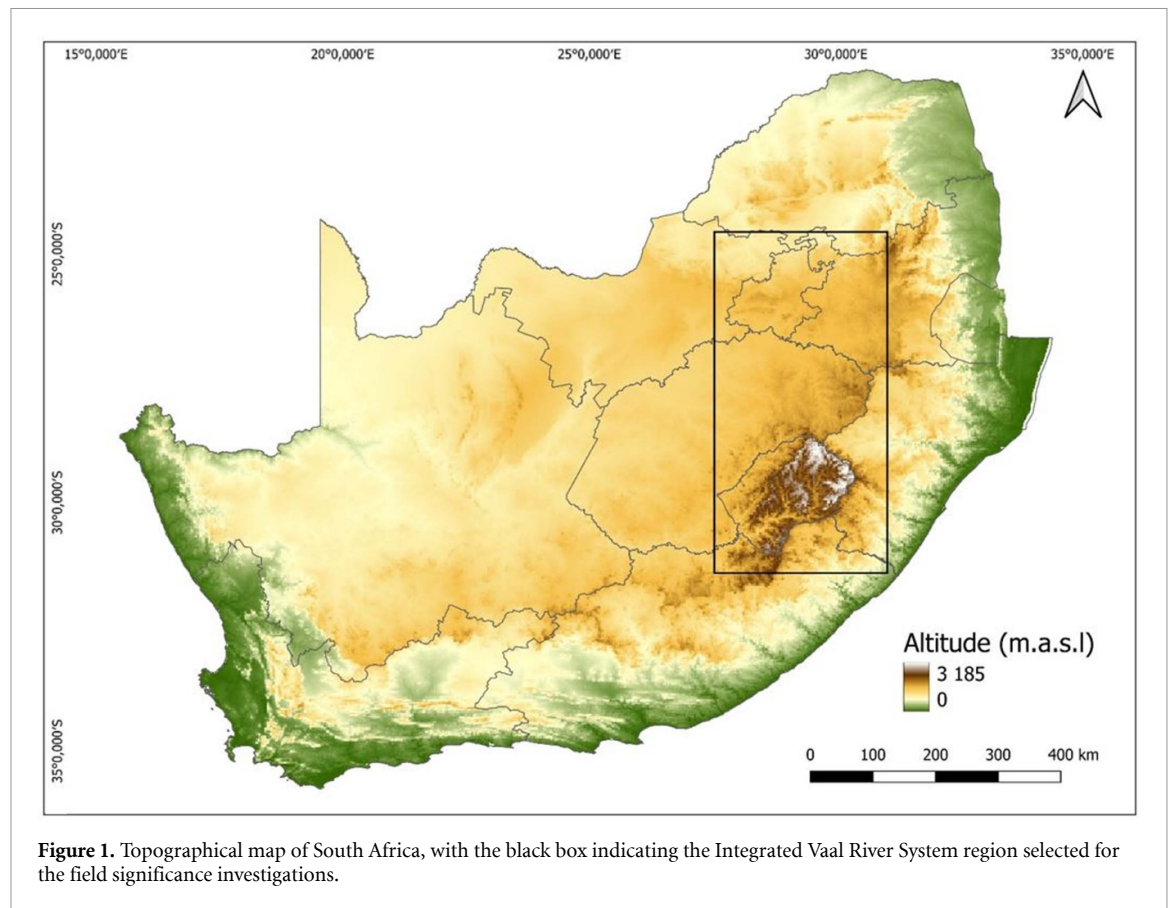


Figure 1. Topographical map of South Africa, with the black box indicating the Integrated Vaal River System region selected for the field significance investigations.

of highest rainfall totals over the summer rainfall region of southern Africa (Engelbrecht *et al* 2009). Spearman's rank correlations were calculated between DJF precipitation and Niño 3.4 SST anomalies, for each of the periods 1954/55–2013/14 and 2040/41–2099/2100, to explore the ENSO-rainfall teleconnection. For each CMIP6 model, Niño 3.4 SST anomalies were calculated separately for the present-day and future periods, with respect to the climatology of each period (1954/55–2013/14 and 2040/41–2099/2100). These anomalies were averaged over the Niño 3.4 region (5° N– 5° S, 120° W– 170° W), to form the Niño 3.4 index and correlated to the CRU/GCM rainfall at gridpoint level. Note that CRU has a constant rainfall series over the Sahara (Steinkopf and Engelbrecht 2022), resulting in no correlation calculated in this region (see white regions in figure 2(a)). In this paper, 'model agreement' or 'most' models means 2/3rds or more of the models.

2.2. Statistical investigations

The IVRS of South Africa, key to the country's water security, lies between 25° S– 31° S and 27° E– 30° E (figure 1). The IVRS contains much of South Africa's eastern escarpment and is vulnerable to El Niño-induced droughts (Taylor *et al* 2016). The region is characterized by varied orography, with elevations ranging from 1100 to over 3000 m a.s.l. (figure 1). Although observed rainfall across this region is negatively correlated to Niño 3.4 SSTs in

a spatially coherent way, the correlations are generally not locally statistically significant (figure 2(a)). Therefore, field significance of correlations in the IVRS was explored. For each model, a bootstrap resampling technique was applied to each gridpoint in the IVRS, generating 1000 random resamplings of rainfall values, which were correlated to Niño 3.4 index values. For each of the 1000 samples of correlation values, the number of gridpoints with the same sign (positive or negative) of correlation was counted and the 95th percentile of these gridpoint counts was calculated. The number of same-sign correlation points was counted in the observed correlations and compared to the 95th percentile threshold, and if higher than this threshold, the spatial correlations were statistically significant at 5% level of field significance.

The models' representation of the ENSO-rainfall teleconnection was further investigated through composite anomaly maps. CRU composite maps were based on ENSO events classified using the NOAA Niño 3.4 anomalies, and the CMIP6 models' composite maps were based on ENSO events classified by each model's derived Niño 3.4 anomalies. The ENSO events were classified as follows: Niño3.4 > 0.5 an El Niño event, Niño3.4 < −0.5 a La Niña event and $-0.5 < \text{Niño3.4} < 0.5$ a neutral event (Steinkopf and Engelbrecht 2022).

The model correlation results were further explored using daily precipitation extremes. Out of

the 42 CMIP6 models, only 33 had sufficient daily precipitation data (data for both the historical and future periods) for further analysis. For each CMIP6 model, the 90th percentile in the daily precipitation values for the DJF season was calculated for each grid-point over Africa, for the historical and future periods, respectively. Furthermore, for each identified ENSO event, the number of days with daily rainfall totals above the historical 90th percentile threshold was calculated.

3. Results

3.1. Present-day and future ENSO teleconnection to austral summer rainfall in Africa

The correlations between observed Niño 3.4 SSTs and rainfall in Africa for DJF are shown in figure 2(a), for the period 1954/55–2013/14. The dipole of the ENSO teleconnection to austral summer rainfall response over southern and East Africa can be seen; there is spatial coherency of negative correlations across southern Africa and of positive correlations across East Africa. Local statistical significance occurs over larger regions in southern Africa compared to East Africa (figure 2(a)), noting that such relationships at the point-scale are quite remarkable given the pronounced inter-annual variability of rainfall in Africa (Janowiak 1988, Nicholson and Kim 1997, Steinkopf and Engelbrecht 2022). For southern Africa, local statistical significance of the teleconnection is widespread over most countries in the region, with a small subregion in the southwestern Cape of South Africa displaying a non-significant positive correlation (Dinku 2019) (figure 2(a)). In East Africa, local statistical significance is present over northern Tanzania, Kenya, Uganda, southern Somalia and most of Ethiopia. In West and North Africa there is spatial coherency in a generally negative correlation between DJF rainfall and Niño 3.4 SSTs (figure 2(a)). Statistical significance is limited, noting that this is a data-sparse region, particularly so in the Sahel and Saharrah desert (Dai *et al* 2004, Dinku 2019, Harris *et al* 2020).

Considering the ensemble mean of model correlations and comparing these to observations, CMIP6 historical simulations for 1954/55–2013/14 realistically portray the dipole in the ENSO teleconnection to austral summer rainfall over southern and East Africa (figure 2(b)). Compared to observations, most CMIP6 models overestimate the spatial extent of positive correlations, extending this from East Africa westwards across subtropical Africa north of the equator into West Africa (figure 2(b), dots). The CMIP6 average correlation also shows spatial coherency in southern African rainfall being negatively correlated to Niño 3.4 SSTs. The southern African regions of model agreement of a negative correlation (figure 2(b), crosses) correspond to those where observations show local statistical significance of the correlation. There are small regions in northeast

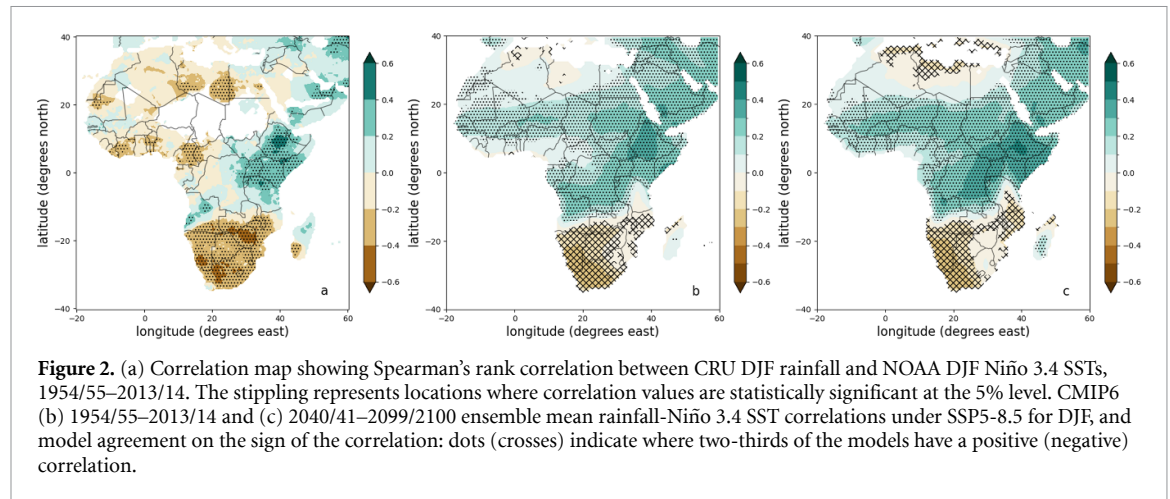
South Africa, southern Mozambique and southern Tanzania where less than two-thirds of the models agree on the correlation to be negative (figure 2(b)).

Under the low-mitigation future SSP5-8.5 the ENSO teleconnection to DJF rainfall for 2040/2041–2099/2100 in Africa is projected to remain remarkably similar to the signal for the historical period, with model agreement of southern African (East African) rainfall being negatively (positively) correlated to Niño 3.4 SSTs (figure 2(c)). Specifically, the ensemble-averages model correlation strengthens over East Africa, the Horn of Africa and westwards across tropical Africa and subtropical Africa north of the equator (figure 2(c)). Conversely, the ENSO signal as depicted by the ensemble average of the correlation is projected to weaken over eastern southern Africa; this may be the consequence of a weaker signal across individual models, and/or because of diminished model agreement on the sign of the correlation (figure 2(c)). This region includes southern Zimbabwe, northeastern South Africa, the eastern escarpment of South Africa and the catchment area of the IVRS, a critical water supply area for South Africa's Gauteng Province, the country's economic hub (Taylor *et al* 2016), and hence, we investigate this further here.

3.2. Composite rainfall anomaly investigation for southern Africa

Over the IVRS, negative correlations between Niño 3.4 SSTs and CRU DJF rainfall over the period 1984–2013 are statistically significant at 5% field significance level. This result is consistent with several other studies pointing out that eastern southern Africa, including the eastern escarpment region of South Africa with its relatively high annual rainfall totals, is drought-prone during El Niño events, and wetter than normal during La Niña events (Nicholson and Kim 1997, Steinkopf and Engelbrecht 2022, Blamey and Reason 2023). In the 42-model ensemble, 27 models correctly represent the negative correlation between Niño 3.4 SSTs and rainfall over the IVRS at 5% level of field significance in the historical simulations (1954/55–2013/14). The models that do not capture this key relationship are excluded in aspects of the analysis that follow. Of these 27 models, 15 project that the ENSO-DJF rainfall over the IVRS will persist at 5% field significance level for the future period (2040/41–2099/2100). Of the remaining 12 models, 7 project a reversal of the signal, that is, a change to a statistically significant positive correlation over this region, whilst 5 models project the signal to lose its field significance. We investigate further the 15 models that project the negative correlation persisting, versus the 7 models that project a reversal of the signal.

DJF rainfall composite anomaly plots are considered for El Niño, La Niña and neutral events for



1954/55–2013/14 and 2040/41–2099/2100 for observations and CMIP6 model simulations (figure 3). The composite maps for observations (figures 3(a)–(c)) are spatially consistent with the correlations in figure 2(a); southern Africa including the IVRS is typically dry (wet) during El Niño (La Niña) summers. Neutral years are on the average associated with weaker rainfall anomalies. These results have also been established for remotely-sensed precipitation datasets, such as CHIRPS (Steinkopf and Engelbrecht 2022). CMIP6 simulations (ensemble mean of all 42 models) for the historical period 1954/55–2013/14 exhibit similar composite maps (figures 3(d)–(f)) to observations, realistically representing the marked differences between rainfall anomalies in southern Africa for El Niño versus La Niña summers. Neutral conditions are simulated to, on average, be associated with rainfall anomalies of substantially weaker amplitudes, consistent with observations (figure 3(f)). Moreover, the CMIP6 ensemble mean overestimates the drying (wetting) over western to central southern Africa during El Niño (La Niña) events (figures 3(d) and (e)). The ENSO teleconnection to southern African DJF rainfall in the CMIP6 ensemble mean remains remarkably stable in a warmer world (figures 3(g) and (h)). The most notable change is that the signal of drying (wetting) weakens over eastern southern Africa during El Niño (La Niña) events (figures 3(g) and (h)), the same region for which negative correlations are projected to weaken in a warmer world, with diminished model agreement (figure 2(c)). For neutral years, most of southern Africa is projected to continue experiencing general weak rainfall anomalies (figures 3(f) and (i)).

For the 15 models with the correct present-day negative correlation over the IVRS, and that project this correlation will persist in a warmer world, the composite maps for 2040/41–2099/2100 (figures 3(m)–(o)) correspond closely to those for 1954/55–2013/14 (figures 3(j)–(l)). That is, the classical ENSO signal in southern Africa persists into

the future. Neutral events are simulated to be relatively wet over eastern South Africa, Zimbabwe and southern Mozambique (figure 3(l)) for the historical period, contradicting observations (figure 3(c)). Moreover, this subset of models project this relative wetness in the east to expand westwards over northern Botswana and northern Namibia in a warmer world (figure 3(o)). For the 7 models that correctly portray the present-day negative correlation but project it to reverse into a significant positive correlation over the IVRS, the classical ENSO signal for southern Africa present in the composite maps for 1954/55–2013/14 (figures 3(p) and (q)) is projected to no longer persist in eastern southern Africa in a warmer world (figures 3(s) and (t)). For these models, eastern southern Africa is projected to experience wet (dry) conditions in austral summer during El Niño (La Niña), whilst western southern Africa will remain relatively dry (wet) (consistent with the present-day ENSO signal). Also for this subset of models, neutral years are simulated to be wet over southern Mozambique, with this signal strengthening in a warmer world.

The projected changes in figure 3 serve to explore future ENSO-driven variability in austral summer rainfall over southern Africa in a warmer world, relative to the climate of a warmer world. It is also illuminating to explore how climate is projected to change relative to its present-day baseline, as a function of ENSO phase (figure 4). The full ensemble mean shows general increases in DJF rainfall across the northern parts of southern Africa, north of 10° S, with several subregions in this area showing model agreement in projected rainfall increases for all ENSO phases (figures 4(a)–(c)). This is a well-described climate change signal for the southern African region, related to the southward expansion of the tropical rainfall belt in the austral summer in a warmer world (Seidel *et al* 2008, Engelbrecht *et al* 2009, 2024). The ensemble average is indicative of general rainfall increases over eastern southern

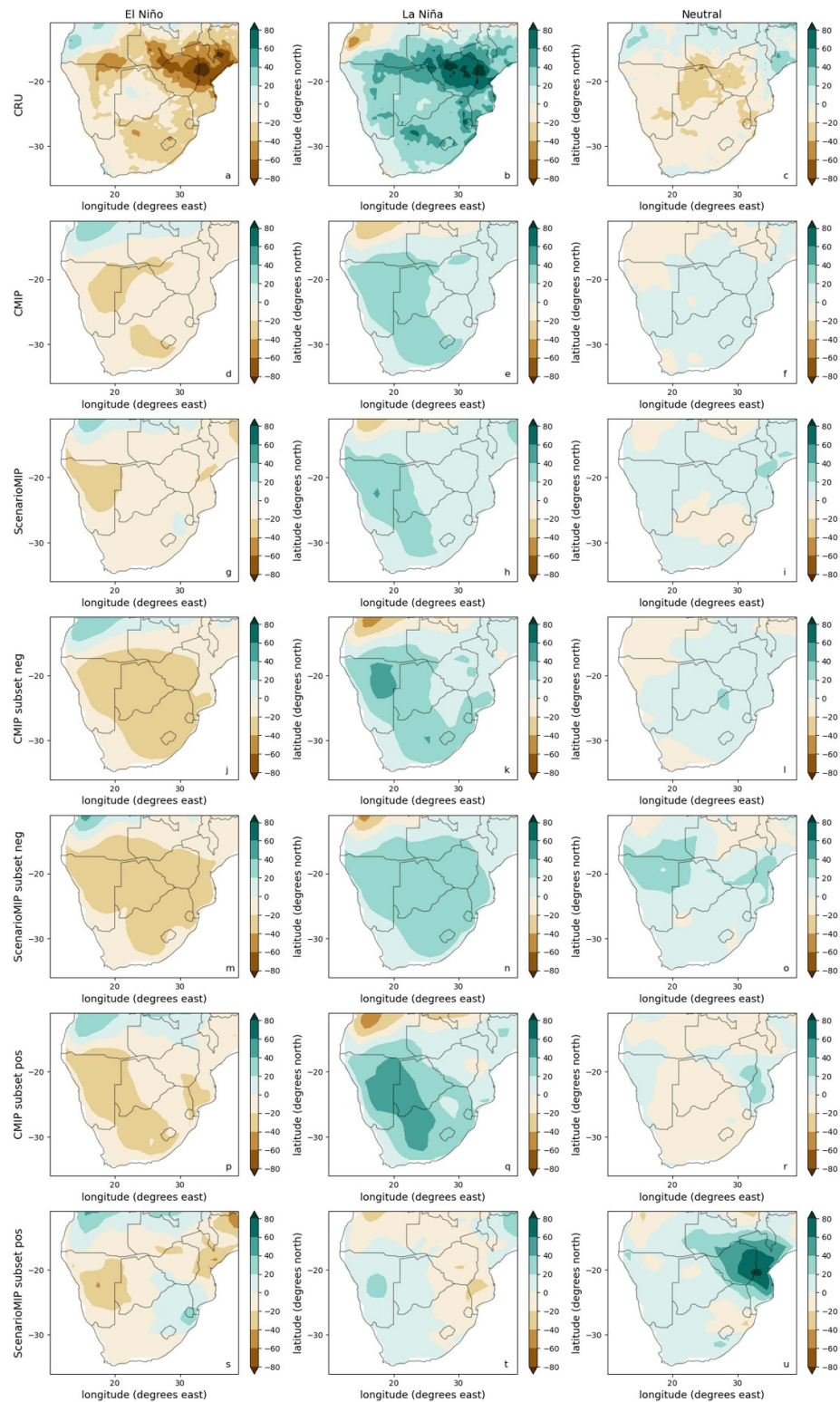
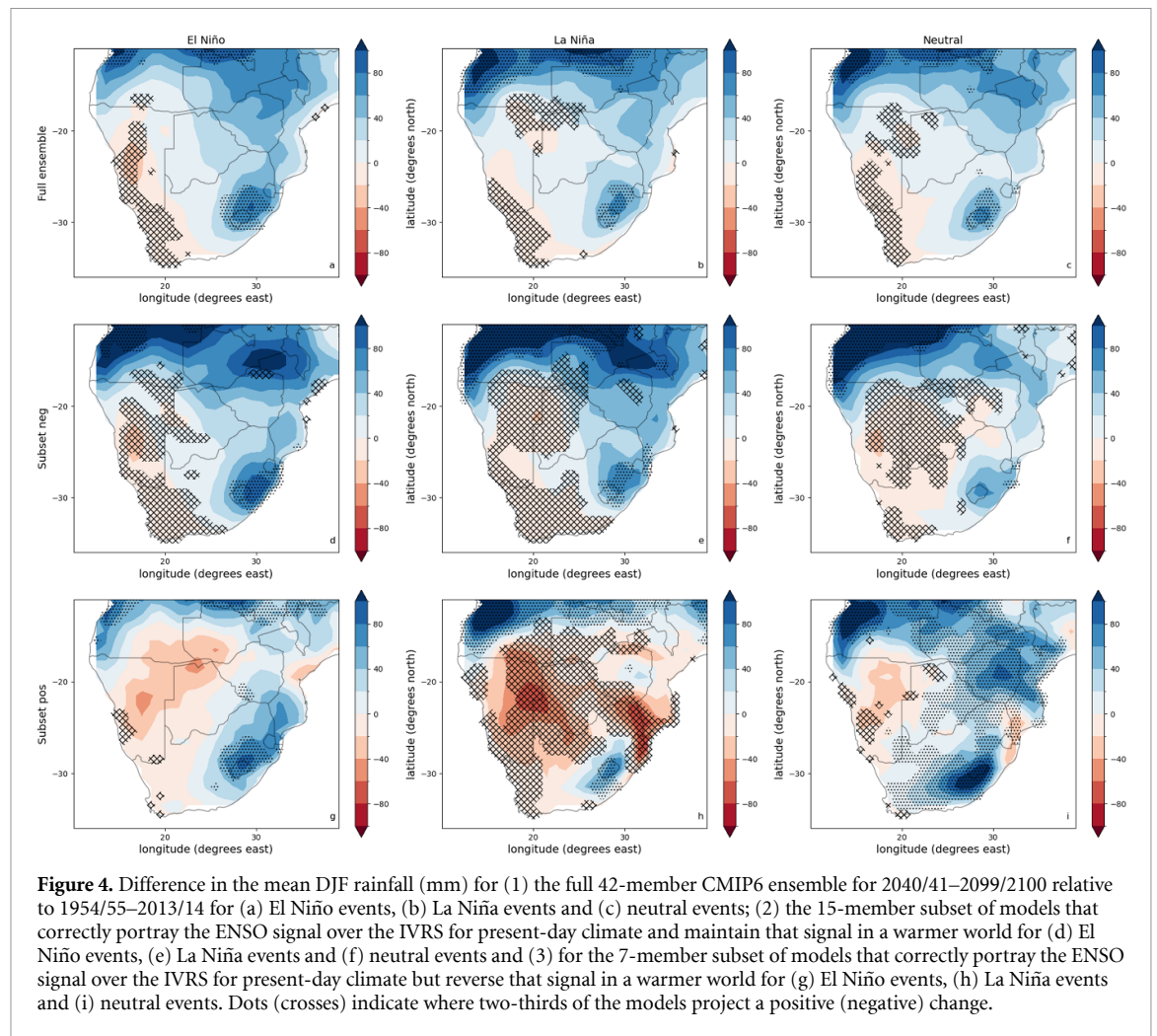


Figure 3. Precipitation anomaly maps (mm) for DJF associated with the ENSO cycle (El Niño, La Niña and neutral) for CRU 1954/55–2013/14 (a)–(c), the 42-member CMIP6 ensemble for 1954/55–2013/14 (d)–(f) and 2040/41–2099/2100 (g)–(i), subset 15 models that realistically represent the negative correlation between Niño 3.4 SSTs and DJF rainfall over the IVRS for 1954/55–2013/14 (j)–(l) and maintain the negative correlation for 2040/41–2099/2100 (m)–(o), and subset of 7 models that realistically represent the negative correlation between Niño 3.4 SSTs and rainfall over the IVRS for 1954/55–2013/14 (p)–(r) but simulate a positive correlation for 2040/41–2099/2100 (s)–(u).

Africa for all ENSO phases, but with model agreement limited to Lesotho and South Africa's eastern escarpment area (figures 4(a)–(c)). Rainfall decreases are projected over western southern Africa across

all ENSO phases, with model agreement limited to western South Africa and parts of subtropical Africa centered around northern Botswana (figures 4(a)–(c)). Considering only the 15 models that project



the persistence of the present-day IVRS ENSO signal, their spatial patterns of change are similar to those of the full ensemble, across all ENSO phases (figures 4(d)–(f)). This indicates an even more pronounced increase in rainfall in the northern part of the domain, reaching 20 °S, with similar levels of model agreement as for the 42-member ensemble (figures 4(d)–(f)). Over Lesotho and South Africa's eastern escarpment, this ensemble average indicates DJF rainfall increases across all ENSO phases, but with model agreement limited to El Niño and La Niña. There are indications of the rainfall increases for El Niño being larger than for La Niña over eastern South Africa (figures 4(d) and (e)), but not to the extent that the ENSO teleconnection to the IVRS reverses (figures 3(m) and (n)). For these 15 models, there is stronger agreement of rainfall decreases across the western interior of South Africa, Namibia and Botswana, for all ENSO phases (figures 4(d)–(f)). For the subset of 7 models that project a reversal of the ENSO teleconnection to the IVRS (figures 3(s) and (t)), there is model agreement of La Niña events becoming generally drier across southern Africa in a warmer world. The exceptions are the northern parts of southern Africa, Lesotho and South Africa's

eastern escarpment, where rainfall increases are projected (figure 4(h)). The projected signal for El Niño summers (figure 4(g)) is similar, but with the wetting over eastern southern Africa being more pronounced, and the drying of western southern Africa non-coherent across the models. The increase in rainfall projected over Lesotho and South Africa's eastern escarpment is larger for El Niño (figure 3(g)) compared to La Niña (figure 3(h)) summers, thereby explaining the reversal of the ENSO signal in this subset of models. Moreover, for this group of models, neutral years are also projected to become substantially wetter over southern Africa (figure 3(i)).

3.3. Projected changes in daily rainfall extremes over southern Africa

To explore what could be driving the reversal of the ENSO signal over the IVRS, projected changes in daily rainfall extremes are considered. Over western southern Africa, most models project a decrease in the 90th percentile value of daily DJF rainfall totals for the period 2040/41–2099/2100 compared to the 1954/55–2013/14 period, while higher 90th percentile thresholds are projected for the northern and eastern regions of southern Africa in a warmer

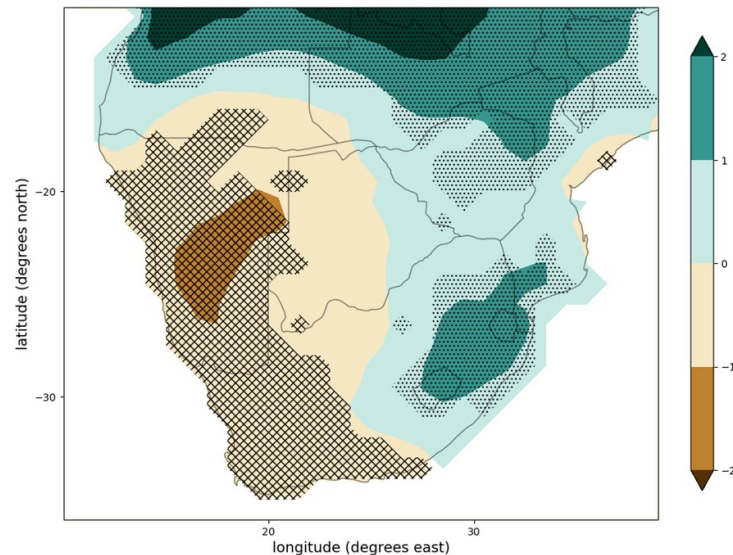


Figure 5. Ensemble average difference between the 90th percentile value of daily DJF rainfall for 2040/41–2099/2100 relative to 1954/55–2013/14 in CMIP6 models under SSP5-8.5. Dots (crosses) indicate model agreement, where two-thirds of the models have an increase (decrease) in the 90th percentile value.

world (figure 5). Notable is the model agreement of increases in daily extremes over the IVRS (figure 5), despite this being a region of model uncertainty in terms of the ENSO signal (figure 2(c)). We further investigate the differences in future and historical daily rainfall extremes for different ENSO phases, for the full ensemble and the ensembles of models that persist and reverse the historical ENSO signal. All three model ensembles project a decrease in the number of days with rainfall above the 1954/55–2013/14 90th percentile threshold over western and central southern Africa, for all ENSO phases (figures 6(a)–(c)). Additionally, over the northern and eastern regions of southern Africa, across all ENSO phases, the three model ensembles indicate an increase in the number of days above the simulated present-day 90th percentile (figures 6(a)–(c)). Notably, over the IVRS the number of days with rainfall above the present-day 90th percentile threshold is projected to increase, regardless of the ENSO phase, but more substantially so in the ensemble of models that project a reversal of the ENSO signal (figures 6(g)–(i)). Moreover, for the models that reverse the ENSO signal, the increases in the number of extreme rainfall days are more pronounced for El Niño than La Niña, likely contributing to a similar pattern of changes in rainfall totals seen for this region (figures 4(g) and (h)).

4. Discussion

Consistent with previous studies (Lee *et al* 2023), we have demonstrated that CMIP6 models realistically simulate the well-known dipole of austral summer rainfall anomalies observed over southern and East Africa during El Niño events, and the reversal of the dipole during La Niña events. However, compared to

observations, CMIP6 models spuriously extend the positive Niño 3.4 SST correlation to East African rainfall westwards, over subtropical Africa north of the equator. The ENSO teleconnection to Africa is projected to remain remarkably stable in a warmer world, with agreement in CMIP6 models that the southern Africa—East Africa rainfall dipole will persist, with southern Africa dry (wet) and East Africa wet (dry) during El Niño (La Niña) austral summers. The IPCC AR5 (Christensen *et al* 2014) and AR6 (Lee *et al* 2023) made the general assessment of an increase in the amplitude of the ENSO precipitation in various parts of the world. We did not find clear evidence of this for southern Africa. Rather, over eastern southern Africa our analysis is indicative of a weakening of the ENSO teleconnection. This result stems from general increases in austral summer rainfall projected for South Africa's eastern escarpment, with these increases being larger for El Niño than La Niña, thereby weakening the classical ENSO signal, or even reversing it.

The reduced model agreement of a negative correlation between Niño 3.4 SSTs and rainfall over eastern southern Africa in a warmer world, is important to the IVRS in South Africa, an area critical to the country's water security. We found that 27 out of 42 CMIP6 models correctly portray (in terms of field significance) the observed present-day ENSO-rainfall teleconnection over the IVRS. Of these 27 models, 15 project the ENSO signal to persist, whilst 7 project a reversal of the signal under low mitigation far-future climate change. That is, there is some uncertainty in future projections of the ENSO-rainfall teleconnection over this sub-region, despite model agreement of the larger pattern of the southern African—East African rainfall dipole persisting over time.

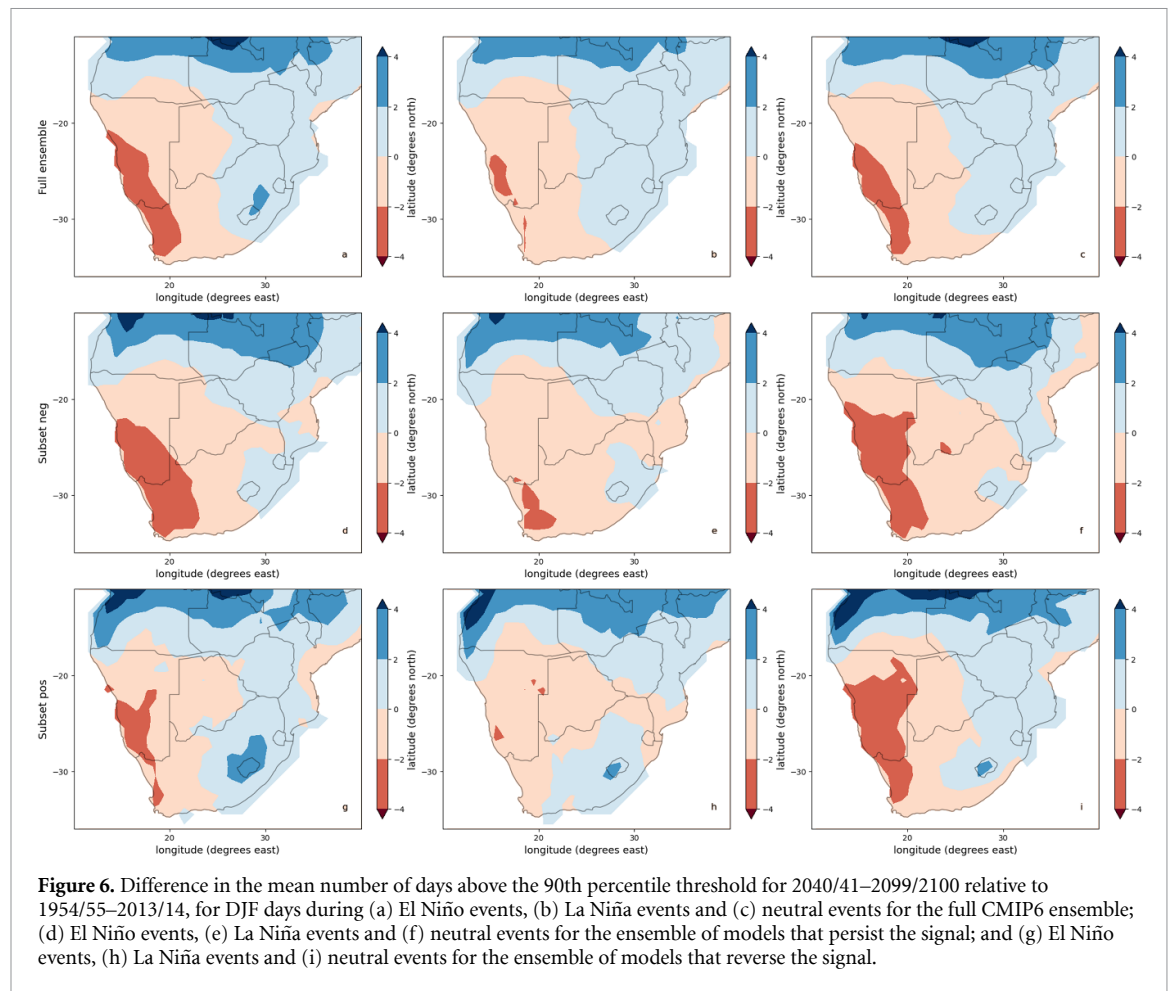


Figure 6. Difference in the mean number of days above the 90th percentile threshold for 2040/41–2099/2100 relative to 1954/55–2013/14, for DJF days during (a) El Niño events, (b) La Niña events and (c) neutral events for the full CMIP6 ensemble; (d) El Niño events, (e) La Niña events and (f) neutral events for the ensemble of models that persist the signal; and (g) El Niño events, (h) La Niña events and (i) neutral events for the ensemble of models that reverse the signal.

Most CMIP6 models project DJF rainfall increases over South Africa's eastern escarpment including the IVRS, regardless of ENSO phase. Additionally, there is model agreement of the number of extreme rainfall days being projected to increase over the eastern escarpment during all ENSO phases. This is supported by other studies which project heavier rainfall events over eastern parts of southern Africa, at least partially because of increased moisture in the atmosphere in a warmer regional world, noting the warming oceanic areas east of South Africa (Rouault *et al* 2009, Lenderink and Fowler 2017, Ranasinghe *et al* 2023). Moreover, projected rainfall increases over eastern southern Africa is more prominent for El Niño compared to La Niña events, which drives the teleconnection reversal in some models and subsequent reduced model agreement. The continental scale southern African—East African rainfall dipole remaining intact in a warmer world, suggests the ENSO teleconnection to Africa remains largely stable in a warmer world. This suggests changes in sub-regional or meso-scale processes driving the reversal in the teleconnection to the IVRS in a subset of GCMs, rather than larger-scale regional circulation changes driving the change. We have indeed explored projected changes in regional circulation in the low- and mid-levels of the troposphere for the subset

of models that reverse the ENSO signal, versus the subset of models that persist the signal, and could not find any systematic differences between the two ensembles.

When considering meso-scale processes, the weakening or reversal of the ENSO teleconnection to eastern southern Africa in most GCM projections may relate to how GCMs parameterize atmospheric convection over the escarpment regions. El Niño summers are generally warmer than La Niña summers across southern Africa, for both present-day climate and future warmer climates. Noting the warming of the Indian Ocean and Agulhas current east of South Africa under low-mitigation futures, our results indicate a coherent signal across GCMs, of more rainfall and extreme rainfall days occurring during summer over the eastern escarpment regions. These increases occur irrespective of the ENSO phase, but are more prominent for the relatively warm El Niño's, compared to the cooler La Niña's. In a subset of models this signal results in the ENSO teleconnection to the IVRS reversing in a warmer world, whilst in another subset there is only a weakening of the signal. This different response across the two ensembles may be a consequence of structural uncertainties in terms of how GCMs parameterize convection over eastern South Africa. A full dynamic circulation and

atmospheric thermodynamics investigation of the processes underpinning the reversal of the signal in the subset of models may potentially be undertaken at daily and sub-daily timescales but falls beyond the scope of this study, partially because of reduced data availability at finer temporal scales.

Model coherency of the persistence of the present-day teleconnection of ENSO to southern and East African rainfall patterns is important in the context of adaptation planning. Essentially, climate variability is projected to persist, but with dry and wet years occurring in a drastically warmer regional climate. Over eastern southern Africa, where the ENSO signal wanes in a warmer world, or even reverses, there may be implications for seasonal forecast skill (Landman *et al* 2001, Phakula *et al* 2020), which for present-day climate strongly depends on the ENSO signal. The general rainfall increases projected over the eastern escarpment regions for the austral summer may be seen as a benefit in terms of water security, but if associated with more extreme rainfall events, may also hold disadvantages, such as increased soil erosion and sedimentation in the mega dams of eastern South Africa.

Data availability statement

The CRU TS v4.05 dataset was downloaded from the University of East Anglia (<https://crudata.uea.ac.uk/cru/data/hrg/>). The monthly and daily outputs of CMIP6 models used in this study are available at the Earth System Grid Federation (<https://esgf-index1.ceda.ac.uk/search/cmip6-ceda/>).

All data that support the findings of this study are included within the article (and any supplementary files).

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Author contributions

Jessica Steinkopf drafted the initial manuscript and performed all data analysis. Francois Engelbrecht led the conceptualisation and guided the analysis. Both

Jessica Steinkopf and Francois Engelbrecht contributed to interpreting the results, discussion and subsequent versions of this paper.

Conflict of interest

The authors declare no competing interests.

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