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Stratospheric Aerosol Geoengineering could lower future risk of 'Day Zero' level droughts in Cape Town

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Abstract

Anthropogenic forcing of the climate is estimated to have increased the likelihood of the 2015–2017 Western Cape drought, also called 'Day Zero' drought, by a factor of three, with a projected additional threefold increase of risk in a world with 2 °C warming. Here, we assess the potential for geoengineering using stratospheric aerosols injection (SAI) to offset the risk of 'Day Zero' level droughts in a high emission future climate using climate model simulations from the Stratospheric Aerosol Geoengineering Large Ensemble Project. Our findings suggest that keeping the global mean temperature at 2020 levels through SAI would offset the projected end century risk of 'Day Zero' level droughts by approximately 90%, keeping the risk of such droughts similar to today's level. Precipitation is maintained at present-day levels in the simulations analysed here, because SAI (i) keeps westerlies near the South Western Cape in the future, as in the present-day, and (ii) induces the reduction or reversal of the upward trend in southern annular mode. These results are, however, specific to the SAI design considered here because using different model, different SAI deployment experiments, or analysing a different location might lead to different conclusions.

1. Introduction

Extreme weather and climate events are pathways through which climate change impacts are, and will continue to be, felt (Lavell *et al* 2012). In Africa, with the high level of vulnerability of many people, extreme weather and climate events often lead to differentially more severe social and economic impacts. The Western Cape Province in South Africa experienced an extreme multi-year drought spanning 2015–2017, causing the most severe water shortage experienced by the province in more than a century (Botai *et al* 2017). The City of Cape Town and its surrounds, a region with a population of about 3.7 million people, was severely affected to the point that 'Day Zero' became an iconic term representing the day at which the water supply system would

fail. While 'Day Zero' was avoided through a mix of drastic reductions in water usage (by nearly 50%) and short term supply augmentation (Wolski 2018), the drought was termed the 'New Normal', implying that climate change was acting to move the region towards semi-permanent drought-like conditions. The Cape Town drought motivated a number of studies to understand the atmospheric mechanisms and drivers behind it (Sousa *et al* 2018, Mahlalela *et al* 2019, Burls *et al* 2019, Abba Omar and Abiodun 2020, Odoulami *et al* 2020), as well as the role of anthropogenic climate change in increasing its likelihood (Otto *et al* 2018). Human-induced climate change was indeed found to have raised the likelihood of the drought by a factor of three; and that this would increase by a further factor of three at a global warming of 2 °C above preindustrial (Otto *et al* 2018).

Solar radiation management (SRM) is one class of geoengineering—a family of approaches proposed to deliberately intervene in the climate system to counteract anthropogenic global warming (Robock 2015, Kravitz *et al* 2016). One proposed method involves the injection of aerosol precursors into the stratosphere to reflect a small amount of incoming solar radiation into the troposphere and onto the Earth's surface to reduce the rate of global warming (Crutzen 2006, Robock 2015, Macmartin *et al* 2016). Decisions on the implementation of SRM or any other geoengineering technique require a full understanding of its potential side-effects on the climate system across a range of scales and contexts (NAS (National Academy of Sciences, Engineering and Medicine) 1992). To date, studies on the impacts of SRM through stratospheric aerosols injection (SAI) have focused on regional (Robock *et al* 2008, Pinto *et al* 2020) and global (Aswathy *et al* 2015, Dagon and Schrag 2016, Salzmann 2016) outcomes, showing that maintaining global mean temperatures at a given level through SAI results in regionally diverse climate outcomes. Over Africa, while SAI might induce a decrease in summer rainfall with negative implications for food and water security (Robock *et al* 2008); it might, however, stabilize increases in rainfall in various parts of Africa and also exacerbate decreases in parts of Southern and West Africa (Pinto *et al* 2020). The type of SAI considered can influence the impact as reported by (Cheng *et al* 2019), who showed using the same model that changes in the location of sulphur dioxide (SO₂) injection might influence annual rainfall over the Southern African region in different ways. These results show that there are still uncertainties associated with the impacts of SAI on droughts in Africa. This study is an attempt to address some of the uncertainties related to the impact of SAI on drought and water availability at the local scale through the lens of the Cape Town 'Day Zero' drought.

Here, we assess how the deployment of SRM using stratospheric SO₂ injection could impact the projected frequency of events such as the Cape Town 'Day Zero' drought using the Stratospheric Aerosol Geoengineering Large Ensemble (GLENS) Project dataset (Tilmes *et al* 2018). Probabilistic event attribution methods are used to assess the difference in the likelihood of such a drought under a high emissions scenario with and without the implementation of a hypothetical SAI intervention. Although hydrological drought is a multi-factor phenomenon, this study only examines drought from a rainfall deficit perspective. This is motivated by the fact that the 'Day Zero' drought has been shown to be driven predominantly by rainfall (e.g. Otto *et al* 2018) and rainfall deficit remains the focal narrative of climate change impacts on water resources in this region. Stratospheric SO₂ injection does, however, affect evapotranspiration and soil moisture (see e.g. Cheng *et al*

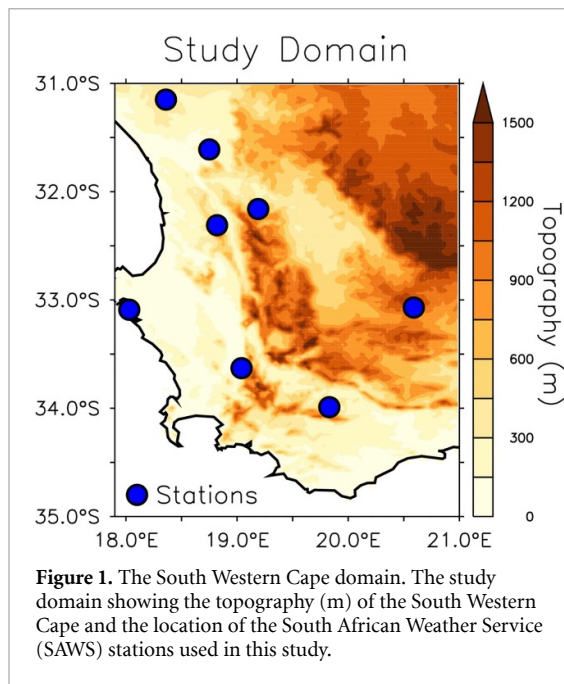
2019 and Simpson *et al* 2019), but to follow Otto *et al* (2018), we keep the scope to precipitation component of drought.

2. Data and methods

This study uses a probabilistic event attribution (Stott *et al* 2016, Otto 2017) approach to assess changes in the likelihood of 'Day Zero' level droughts in Cape Town in the future under an SRM experiment that used stratospheric SO₂ injection. First, it used a number of observation and reanalysis rainfall datasets to define the range of possible return periods for a 'Day Zero' level drought, after which a representative return period was chosen for use in subsequent analysis. Second, the study assessed and compared the likelihood—in the form of probability ratio and fraction of attributable risk—of 'Day Zero' level droughts in the present-day and the future climates with and without SAI. Further description of the data and approach used in this study is provided in this section.

To estimate the return period of the Cape Town 'Day Zero' drought, we analysed six rainfall datasets that have coverage over the water resource area that supplies water to the City of Cape Town and surrounds: (i) eight South African Weather Service (SAWS) meteorological stations, each containing fewer than 60 missing days between 1997 and 2017 and no more than 10 missing days during the drought period (2015–2017), (ii) the Climatic Research Unit (CRU-TS4.03) gridded monthly rainfall product at 0.5° spatial resolution (Harris *et al* 2014), (iii) the Global Precipitation Climatology Project (GPCP) gridded daily satellite-based rainfall at 1° spatial resolution (Huffman *et al* 2001), (iv) the Global Precipitation Climatology Centre monitoring analysis dataset (GPCC) with monthly rainfall at 1° spatial resolution (Schneider *et al* 2014), (v) the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 monthly rainfall reanalysis datasets at 0.25° resolution (Hersbach *et al* 2019), and (vi) the Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) blended satellite-station dataset at 0.05° resolution (Funk *et al* 2014, 2015). We used these data to define the drought event in section 3.

We use the Stratospheric Aerosol Geoengineering Large Ensemble (GLENS) Project dataset (Tilmes *et al* 2018) to estimate the impact of SAI on drought risk over the study region. GLENS provides SAI simulations with the Community Earth System Model using the Whole Atmosphere Community Climate Model for the atmospheric component (CESM1(WACCM)) (Mills *et al* 2017). This state-of-the-art model uses the Modal Aerosol Module (MAM3), which is coupled interactively to the radiation and chemistry components of the model



and includes prognostic stratospheric aerosols (Mills *et al* 2016, Tilmes *et al* 2018); it has a horizontal grid resolution of 0.9° latitude \times 1.25° longitude, with 70 vertical levels from the surface up to 140 km (Tilmes *et al* 2018). We used the control and feedback simulations of the GLENS dataset under a high emission scenario (RCP8.5). The control simulations are forced with the concentrations of greenhouse gases and tropospheric aerosols as specified for RCP8.5 by the Coupled Model Intercomparison Project 5 (CMIP5) protocol (Meinshausen *et al* 2011, van Vuuren *et al* 2011). In the feedback simulations (SAI), SO_2 is injected into the tropical stratosphere at about 5 km above the tropopause at four locations (at 30°N , 30°S , 15°N , and 15°S) with the aim of keeping the mean global warming, inter-hemispheric and equator-to-pole near-surface air temperatures at the 2020 level until the end of the century, while the remaining anthropogenic forcings follow RCP8.5. For more on the amount of SO_2 injected at each location for each simulation, one should refer to Tilmes *et al* (2018). Two periods were analysed in this study: 2010–2030 for the control, referred to as the present-day climate (PRST) and 2070–2090 under RCP8.5 forcing for both control (FUTR) and feedback (FSRM) simulations. We used all available ensemble members for each experiment: 20 for PRST and FSRM, and 3 for FUTR. Total annual rainfall is calculated for each data and then averaged over a domain for the southwest of South Africa that encompasses the Cape Town region, extending from 18°E to 21°E longitude and 31°S to 35°S latitude (figure 1), corresponding to that analysed in a previous study by Otto *et al* (2018).

We also use the GLENS zonal (u) and meridional (v) wind components, specific humidity (q) at all available pressure levels, and mean sea level

pressure (MSLP). We used MSLP data to compute the southern annular mode (SAM) at seasonal scale (Gong and Wang 1999, Meneghini *et al* 2007), while q, u, and v are used to compute moisture flux. The seasonal SAM is then used to calculate the Sen's slope for the linear rate of change for each simulation with the 95% confidence interval. The Sen's slope is a non-parametric approach to estimate linear trends in a dataset. Unlike the least squares regression estimator, the Sen's slope does not make assumptions about the shape of the distribution of the data (Sen 1968).

We use a set of 30 CMIP5 models with a total of 74 individual simulations (supplementary table 1 (available online at stacks.iop.org/ERL/15/124007/mmedia) to see how CESM1(WACCM) PRST and FUTR results compare with other global Earth system models. We analysed all CMIP5 models with at least one simulation forced by the RCP8.5 scenario for the periods 2010–2030 (PRST) and 2070–2090 (FUTR). Importantly, the CESM1(WACCM) model reproduced well the seasonal cycle and spatial distribution of rainfall over Southern Africa compared to observations (Pinto *et al* 2020).

We use the probability ratio (PR) and the fraction of attributable risk (FAR) to assess the potential influence of SAI on the likelihood of 'Day Zero' droughts over the Western Cape in the future. PR is the ratio of the probabilities of occurrence of drought of a given magnitude in any pair of experiments. We define two versions of FAR (Wolski *et al* 2014): the fraction of attributable increased risk (FAIR) due to increased radiative forcing under RCP8.5 relative to the present; and the fraction of attributable decreased risk (FADR) when SAI is applied in combination with RCP8.5 forcing.

As the 'Day Zero' drought was characterised by persistent rainfall deficit over three consecutive years, we define the magnitude of the drought event as the 2015–2017 mean annual rainfall. To determine the probability of occurrence of such an event, we first calculated, for each dataset, a 3 year running mean of annual rainfall using the area average rainfall (supplementary figure 1). Next, we used the Kolmogorov–Smirnov goodness of fit test (Kolmogoroff 1933, Smirnov 1948) to verify whether the 3 year running means in each dataset can be described by a normal distribution and then we fitted a normal distribution to the data. Finally, we derived the probability of non-exceedance of the event from that fitted distribution and expressed this likelihood as a return period in each of the observational datasets. Uncertainty of the event probability was estimated through bootstrapping (with 1000 replicates) the series of 3 year running means. Due to model biases, observation-derived event magnitude cannot be used directly to derive its probability under modelled climate, and we used the following procedure instead. We used the return period calculated from the observational data and the normal distribution

fitted to individual models' series of 3 year rainfall means in PRST simulations (the distributions of the observed and simulated datasets are shown in supplementary figures 2 and 3, respectively) to determine the model-specific rainfall amount associated with the 'Day Zero' event. Subsequently, the probabilities of rainfall deficits of this magnitude in the FUTR and FSRM simulations were determined from normal distributions fitted to 3 year means of rainfall from these simulations. PR and FAR were then calculated from these probabilities. We determine the 95% confidence interval (CI) of each of the calculated variables (PR, FAR) using a bootstrapping procedure, simultaneously drawing from the distributions of the 3 year running mean rainfall in PRST, FUTR, and FSRM simulations and repeating distribution fitting and calculations. In the above process, we kept the return period of the event derived from observations constant. To assess the sensitivity of our results to the uncertainty in the return period determination (due to both the short duration of the time series compared to the rarity of the event, and the differences across the observational datasets), we repeated our attribution calculations for the minimum and maximum value of the return periods estimated from six observational data sources.

3. Defining the event and its probability

Drought is a multi-factor process, but here, similarly to Otto *et al* (2018), we focus on rainfall deficit only to analyse drought. Using different observation and reanalysis datasets covering the period 1997–2017, we determined the return period of the 'Day Zero' drought as defined as the 2015–2017 3 year rainfall deficit over the spatial domain extending from 18°E to 21°E longitude and 31°S to 35°S latitude (figure 1). We use the most recent 21 years in these datasets to represent as closely as possible the response of the observed climate system to the current levels of global warming. There is a large divergence in the return periods of the drought across the datasets used: from 40 years for the selected SAWS station datasets to 380 years for the CRU-TS4.03 data (figure 2). The large spread among the observation and reanalysis datasets may arise from the superposition of spatial differences in the magnitude of rainfall anomaly (Wolski *et al* 2020) with differences in data aggregation procedures in each of the analysed datasets, making the return period sensitive to the resolution of gridded data, the number and location of stations, the domain size, or even the approach used to estimate rainfall in the gridded data. To define a 'Day Zero' level drought in this study, we, therefore, used the median value of the six return periods calculated using these observation and reanalysis datasets, which is 131.9 years. Then, using that value rounded to 100 years, we define the 'Day Zero' level drought as a period of three consecutive years with a severe

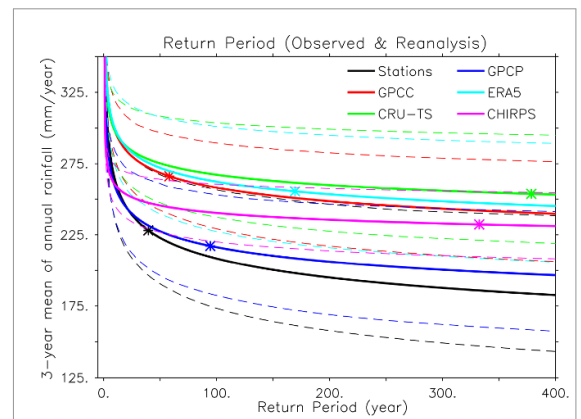


Figure 2. Estimated likelihood of the Cape Town 'Day Zero' drought. The return period of 3 year running mean of total annual rainfall in observation and reanalysis datasets in the present climate (1997–2017). The data used are: SAWS rainfall stations data, CRU-TS4.02, GPCC, GPCP, ERA5, and CHIRPS. The asterisk (*) symbols represent the 2015–2017 mean rainfall (y-axis) and the associated return period (x-axis) for each dataset. The dash lines represent the 95% confidence interval for each dataset.

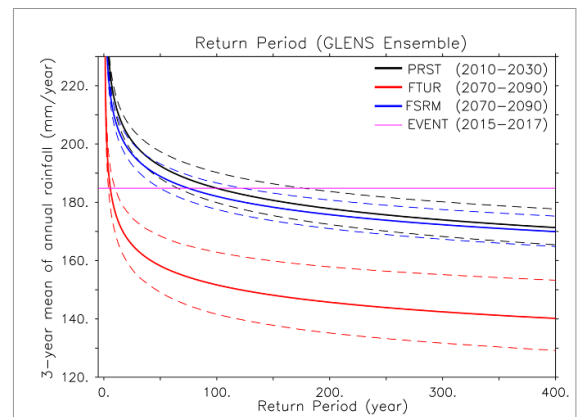


Figure 3. Changes in the likelihood of 'Day Zero' level droughts in Cape Town. Changes in the return period of 'Day Zero' level droughts in the future (2070–2090) under RCP8.5 emission scenario with (FSRM) and without (FUTR) solar radiation management (SRM) as simulated by CESM1(WACCM) model of the GLENS project. PRST is the present-day (2010–2030) climate and EVENT is the 'Day Zero' droughts as simulated by the CESM1(WACCM). The dash lines represent the 95% confidence intervals.

rainfall deficit with an occurrence probability of 1 in 100 years over the South Western Cape domain (figure 1) similar to Otto *et al* (2018).

4. Projected changes in the likelihood of 'Day Zero' droughts

Analyses of the GLENS ensemble for the PRST and future (FUTR) climates, showed that a rainfall deficit severe enough to cause a 'Day Zero' drought with a likelihood of 1 in 100 years in PRST would become as frequent as 1 in about 6 years [95% CI 4–10 years] in the future under RCP8.5 (figure 3). These results are consistent with those from CMIP5 simulations, where all simulations show an increased frequency of 'Day Zero' level droughts under RCP8.5 in

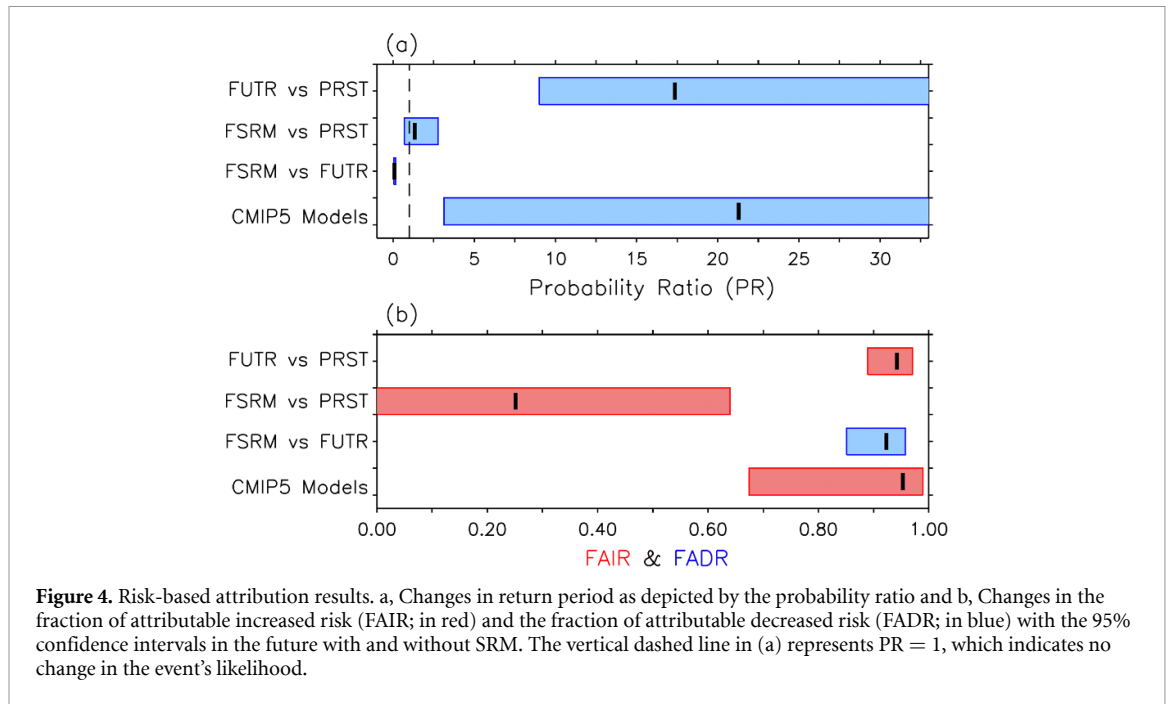


Figure 4. Risk-based attribution results. a, Changes in return period as depicted by the probability ratio and b, Changes in the fraction of attributable increased risk (FAIR; in red) and the fraction of attributable decreased risk (FADR; in blue) with the 95% confidence intervals in the future with and without SRM. The vertical dashed line in (a) represents PR = 1, which indicates no change in the event's likelihood.

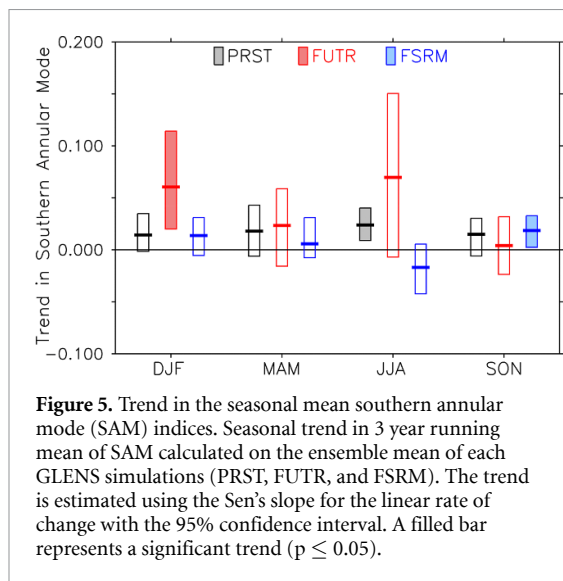


Figure 5. Trend in the seasonal mean southern annular mode (SAM) indices. Seasonal trend in 3 year running mean of SAM calculated on the ensemble mean of each GLENS simulations (PRST, FUTR, and FSRM). The trend is estimated using the Sen's slope for the linear rate of change with the 95% confidence interval. A filled bar represents a significant trend ($p \leq 0.05$).

the future (supplementary figure 4), as well as previous work showing projected drying over the Western Cape region as the climate is continuously impacted by anthropogenic forcings (Moise and Hudson 2008, Shongwe *et al* 2009, DEA (Department of Environmental Affairs) 2013). These future return periods translate into large increases in probability ratios (figure 4(a) and supplementary figure 5(a)). For GLENS the PR for FUTR versus PRST is 17.35 [95% CI 9.01–34.03], while for the overall CMIP5 ensemble, the PR is 21.3 [95% CI 3.1–95.8] (figure 4(a)). These PR translate into a fraction of attributable increased risk (FAIR) of 94.2% [95% CI 88.9%–97.1%] and 95.3% [95% CI 67.4–98.9] for GLENS and CMIP5 (figure 4(b)), respectively. This increased risk, although higher, is in agreement with a previous finding on the influence of anthropogenic climate

change on the 'Day Zero' drought (Otto *et al* 2018), which highlighted that the risk of the 'Day Zero' level droughts will continue to increase in the future as the warming level increases.

Under the specific SAI application used here, there is a large reduction in the likelihood of 'Day Zero' droughts in the future period (2070–2090) considered (figure 3). The return period shifts from 1 in 6 years to 1 in 75 years, moving it much closer to the present-day return period of 1 in 100 years. The PR shifted to 1.3 (95% CI of 0.7–2.8) for FSRM against PRST (figure 4(a)). Similarly, the FAIR decreases to 25.1% [95% CI of –44.9–64.0%] (note that negative values of FAIR is not directly interpretable, but indicates a decrease in risk) (figure 4(b)). When PR and FADR for the future are calculated, it can be seen that the simulated climate with SAI results in a very low PR of 0.08 (95% CI 0.04–0.15) and a reduction in risk of 92.3% (95% CI of 85.1%–95.7%) (figure 4(b)). These results suggest that SAI would significantly contribute to reducing the likelihood of 'Day Zero' level droughts, caused by human-induced climate change over the South Western Cape, by keeping its likelihood in the future in the range of the present-day climate (figure 3). These results are robust for the datasets used as they are not sensitive to the threshold used to define the drought (supplementary figures 6 and 7).

Majority (about 80%) of the annual rainfall in the South Western Cape falls during the austral winter, linked to cold fronts associated with the anti-cyclonic circulation in the mid-latitude westerlies which expand equatorward and influence this region in that season (Reason and Jagadheesha 2005, Reason and Rouault 2005, Mahlalela *et al* 2019). Processes affecting cyclo- and fronto-genesis, their latitudinal

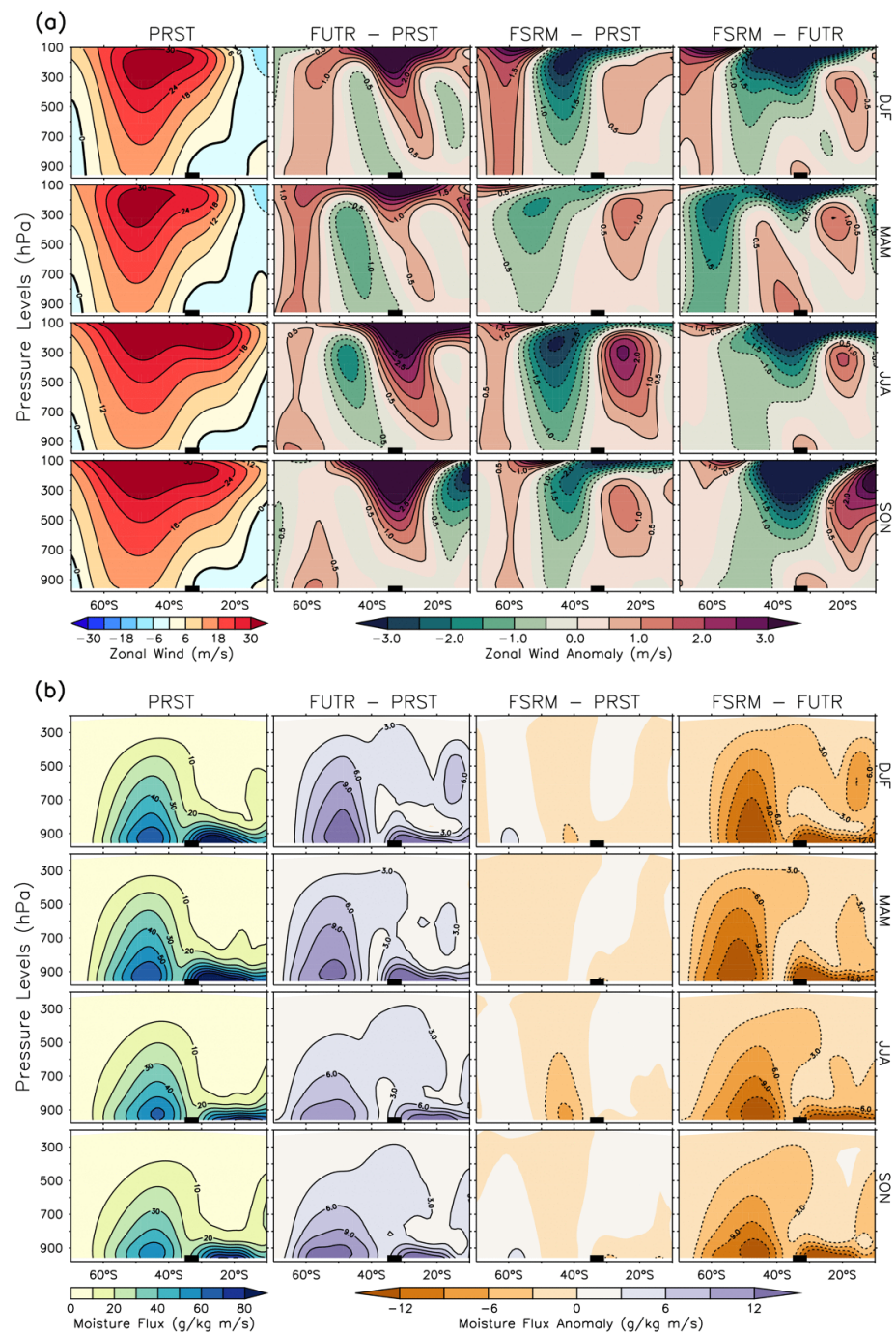


Figure 6. Latitude-height cross section of seasonal zonal wind and moisture flux at 10°E , upstream of the South Western Cape. a, Mean seasonal zonal wind in the PRST period (2010–2030; left-side column), seasonal zonal wind anomaly under FUTR (2070–2090; middle left-hand column) and under FSRM (2070–2090; middle right-hand column), seasonal difference in zonal wind between FSRM and FUTR is in the right-hand side column. b, same as in (a) but for moisture flux. The anomaly is calculated with reference to PRST period using the first three ensemble members of each simulation.

position, and moisture transport in the westerlies are therefore the main drivers of rainfall variability. Influence of climate change on this system is linked to hemispheric scale processes of increase in pressure gradient across high latitudes (SAM) and associated poleward shift and intensification of the westerlies, displacement of the mid-latitude jet and expansion of the tropics. The increase in SAM is in particular one of the more robustly attributed and projected impacts of increased greenhouse gas (GHG)

concentrations on atmospheric circulation (Lim *et al* 2016) even though it is influenced by GHG and ozone concentrations to a varying degree depending on the season. We, therefore, compare the trend in the SAM in the present and future simulations with and without SAI (figure 5). Across the three simulations, there is an upward trend in SAM in all seasons. This trend is, however, much higher for the FUTR than the FSRM simulations, indicating that SAI is, at least partially, moderating the impact of increased

GHG emissions on the SAM. That moderation may even reach the level of reversal—in the winter season (June–August), there is a downward, but not statistically significant, trend due to SAI. This could potentially contribute to increasing winter rainfall over the South Western Cape reducing the likelihood of ‘Day Zero’ level droughts over the region in the future.

In addition to SAM, we also evaluate zonal winds and moisture flux across sub-tropics and mid-latitudes along 10° East (just west of the analysed region). Projected future (2070–2090) changes in the zonal wind under RCP8.5 indicate a slight northward shift of the mid-latitude jet and strengthening of the upper level westerlies above the analysed region while over and south of the region they are projected to be weaker than in the present-day in all seasons (figure 6(a)). Such conditions may lead to fewer rain-bearing frontal systems reaching the South Western Cape, resulting in less rainfall over the region in the future. These results are concordant with the projected increase in risk of droughts as severe as the ‘Day Zero’ one and the projected upward trend in SAM in the future simulations without SAI (FUTR) reported earlier.

Under SAI, projected changes in the zonal wind indicate a strengthening of the subtropical jet (centred around 25° South) and a weakening of the mid-latitude jet further south (figure 6(a)). Over the South Western Cape, in contrast to the FUTR simulations, wind anomalies with respect to the present-day climate are minimal. SAI tends to keep westerly flow over the region similar to the PRST. Comparison of FSRM and FUTR anomalies reveals that under SAI, westerlies are stronger over the South Western Cape and to the north of it in all seasons, which is favourable to more rain in a future with SAI than in a future without SAI, reducing drought risk under the former compared to the later. A similar analysis of the moisture flux shows that SAI largely offsets the changes in FUTR so that the moisture flux in FSRM is similar to PRST (figure 6(b)).

5. Discussion and conclusion

Human-induced forcing of the climate has already increased the risk of severe drought in the South Western Cape of South Africa and, climate model projections consistently indicate this trend will continue with increasing greenhouse gas emissions in the future. Here we have used a probabilistic extreme event attribution approach to evaluate whether the implementation of SAI could offset future drought risk at a local scale, using the 2015–2017 Cape Town ‘Day Zero’ drought as an example. The GLENS experiment indicates that in the far future, SAI reduces the likelihood of ‘Day Zero’ level droughts in Cape Town to within the uncertainty range of the present-day climate (approximately 90% compared to the future

without SAI). The lowering of the trend rate of SAM in the model, especially the reversal in trend in the winter season with SAI and its influence in keep the westerly flow over the South Western Cape closer to the present day, contribute towards the decrease of such drought risk; this shift in SAM is similar to that seen in the CMIP5 climate models when forced with historic volcanic aerosols (Gillett and Fyfe 2013).

We caveat the findings of this study by noting they are specific to (a) the design of the SAI experiment considered here, namely the GLENS project and (b) to the Cape Town region. The results should therefore be interpreted within this context, especially with respect to possible different responses to SAI in other regional and local systems. We suggest further studies that consider (a) data from other geoengineering simulations, such as the Geoengineering Model Inter-comparison Project (GeoMIP) and/or further experiments using different SAI experiment designs and (b) other regions that have experienced multi-year droughts, such as Brazil, Australia, California, and Spain. Doing so will support more robust assessments of the impact of SAI on the risk of ‘Day Zero’-type droughts in the future, and increase our understanding about regional and local scale climate responses to SAI as well as the resultant socioeconomic and biophysical implications.

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Data availability statement

No new data were created or analysed in this study.

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