The impact of the Agulhas Current System on precipitation in southern Africa in regional climate simulations covering the recent past and future

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Abstract. Southern African climate is strongly impacted by climate change. Precipitation is a key variable in this region as it is linked to agriculture and water supply. An analysis of simulations with a regional atmospheric model over the last decades and the 21st century shows that in the past precipitation has decreased in some coastal areas of South Africa and increased in the rest of southern Africa. However, it is projected to decrease over the whole southern part of the domain in the future. The

5   Agulhas Current System, including the current and the leakage, surrounds the continent in the east and south and it is found to impact precipitation. The reduction in the strength of the Agulhas Current is linked to a reduction in precipitation along the southeast coast. The Agulhas leakage, the part of the Agulhas Current that leaves the system and flows into the South Atlantic, impacts the precipitation in the southwest of the continent, located in the winter rainfall zone. A more intense Agulhas leakage is linked to a reduction in precipitation in this region.

10   ## 1   Introduction

Precipitation is an important factor for the southern African climate. It defines the seasons and it directly impacts one of the principal sources of income, agriculture. Southern Africa is located between tropical and temperate systems. Hence, the latitudinal shift in the position of the Intertropical Convergence Zone and the westerlies south of the continent, as well as the location of the anticyclones over the South Atlantic and western Indian Ocean, impact rainfall over southern Africa (Reason, 2017).

15   Most of southern Africa receives most of the rainfall in austral summer (Reason, 2017). This Summer Rainfall Zone (SRZ) extents from the tropics to the Southern Hemisphere midlatitudes (Chevalier and Chase, 2016). Only the uttermost southwest of the continent receives its rainfall in the winter season (Chevalier and Chase, 2016). In this Winter Rainfall Zone (WRZ) rainfall is caused by frontal systems moving with the westerlies (Reason, 2017).

Southern Africa is surrounded by the Indian and the South Atlantic Ocean. Along its east and south coasts flows the Agulhas

20   Current. This warm water current flows through the Madagascar Street southeastward along the coast, overshoots when reaching the southernmost tip of the continent, the Cape Agulhas, and turns back into the Indian Ocean in the Retroflection area southwest of the continent as the Agulhas Return Current (Beal et al., 2011). A small fraction of the Agulhas Current leaves the

Cape Basin and continues into the South Atlantic (Tim et al., 2018). This proportion is called Agulhas leakage. The Agulhas Current System impacts the precipitation in southern Africa (Imbol Nkwinkwa et al., 2021; Nkwinkwa Njouodo et al., 2018;

25 Cheng et al., 2018; Reason, 2001). Especially for the southeast coast, the air masses that reach the continent accumulate heat and moisture by traveling from the Indian Ocean over the warm Agulhas Current towards the continent, favoring precipitation in that region (Imbol Nkwinkwa et al., 2021). The Benguela Upwelling System, one of the four Eastern Boundary Upwelling Systems, is located along the southwest coast. Its cold surface water impacts the moisture and heat content of the air masses above, leading to foggy conditions along the shore line and desert conditions further inland (Reason, 2017).

30 Due to its unique location between the trades and westerlies and the currents along its coast in the adjacent oceans, climatic changes in this region are linked to changes of these various drivers. Precipitation over the past decades displays long-term changes. Station data shows that precipitation in the WRZ has decreased (Roffe et al., 2021; Wolski et al., 2021) whereas gridded observational data sets and reanalysis data indicate an increase (Onyutha, 2018; MacKellar et al., 2014). By contrast, precipitation in the SRZ in austral summer (December-January-February, DJF) has increased or no trend has been detected in

35 both data types of datasets(Onyutha, 2018; MacKellar et al., 2014; Kruger and Nxumalo, 2017).

The prevailing wind systems, the trade winds and westerlies, have also shifted in the past and are projected to further shift poleward (Tim et al., 2019). This may not only cause changes in precipitation directly but probably also via changes in the Agulhas Current System. The Agulhas Current has weakened (Schwarzkopf et al., 2019) and shifted poleward (Yang et al., 2016), the Agulhas leakage has intensified (Tim et al., 2018) and both are projected to continue to do so in the 21st century

40 (Ivanciu et al., 2022).

As southern Africa is prone to changes via anthropogenic climate change due to changes in the wind systems, in the ocean currents and in air and ocean temperatures, we investigate here the current state of precipitation, past and future precipitation trends and the impact of the Agulhas Current System on precipitation.

45 For these purposes we analyse several simulations with a high-resolution (16 km horizontally) regional atmospheric model. This high resolution allows to more faithfully represent the processes leading to precipitation than the coarser resolution of global climate models (typically 100 km) and of regional climate models (about 50 km) that participate in the Coupled Model Intercomparison Project (CMIP6) used by the IPCC in their climate assessment reports (Lee et al., 2021). Our model set-up includes, in addition to the regional atmospheric model, a global coupled climate model that provides the boundary conditions

50 for the regional simulation. The resolution of the ocean component is also refined in the region surrounding southern Africa in comparison with usual global simulations, so that it allows for a better representation of the Agulhas Current and the Agulhas leakage (Schwarzkopf et al., 2019). This model set-up, therefore, allows to estimate the strength of the Agulhas Current and of the Agulhas leakage and to statistically analyse the connections between the Agulhas Current System and the sea surface temperature (SST), sea level pressure (SLP) and precipitation in this region.

55

The results of the Coupled Model Intercomparison Project (CMIP6) as summarised in the Sixth Assessment Report by the IPCC indicates that precipitation in this region will tend to decrease in the future, especially in the WRZ (see Figure 4.32 in

the full report by Working Group 1 (Lee et al., 2021)). The projected reduction in precipitation is robust across the ensemble of climate models and it also becomes more intense with increasing concentrations of greenhouse gases in the future. In fact, southern Africa and the Mediterranean countries are the two land regions that are projected to suffer from the strongest precipitation reductions in the future. Figure 4.4 in the Sixth Assessment Report (Lee et al., 2021) clearly shows that the southern hemisphere land areas where annual precipitation is projected to decrease are located in the subtropical western continental regions: western Australia, Chile and western southern Africa. In other land areas in the southern hemisphere the projected precipitation changes are small. Therefore, there is probably a large-scale common mechanism related to the increased radiative forcing that is behind this large-scale spatial pattern of precipitation reduction, and which is independent of changes in the Agulhas Current System. However, in addition to that large-scale mechanism, the regional ocean circulation patterns may also modulate the projected precipitation trends, and these regional mechanisms should also be considered and analysed with higher resolution models. Since the resolution of the global climate models, including the ocean component, might not be totally adequate to resolve important processes for southern African precipitation (Jury, 2012; Munday and Washington, 2018), as indicated above, a study with higher resolution models is important to confirm this future reduction in precipitation and to assess the contribution of regional ocean processes.

As far as we know, up to now there has been only one study by Cheng et al. (2018) investigating the impact of the strength of the Agulhas leakage on the regional climate in the past decades. This study was mostly focused on the impact of the Agulhas leakage on the interannual regional patterns of sea-surface temperature and precipitation over the ocean and adjacent land masses. These authors also analysed a coupled ocean-atmosphere simulation with a high resolution eddy-resolving ocean component. They found that a stronger leakage causes warmer surface water temperatures in the retroflection zone and colder water temperatures in the Indian Ocean further east. The impact of these temperature patterns is felt in stronger convective precipitation over the warmer ocean (and weaker over colder ocean regions). On the adjacent land, a stronger leakage causes weaker convective precipitation in the SRZ.

The present study has a broader scope. We also consider herein the future impact of the Agulhas Current, not only at interannual (or multi-annual) time scales in the historical period but also at the longer term centennial scales under increasing concentrations of greenhouse gases.

2 Data and methods

The data used for this analysis encompasses regional atmospheric model simulations, gridded observational data sets, atmospheric reanalysis data and global coupled ocean-atmosphere simulations. As observational data set of precipitation we use the Global Precipitation Climatology Project (GPCP) precipitation dataset from October 1996 until March 2019 (Adler et al., 2003). It combines observations with satellite measurements of precipitation in 1 degree horizontal resolution.

The Japanese reanalysis JRA-55 (Kobayashi et al., 2015) serves for the model validation as its the driving data of the regional model CCLM, as described in the following section. It covers the period 1958 until April 2019 with a spatial horizontal reso-
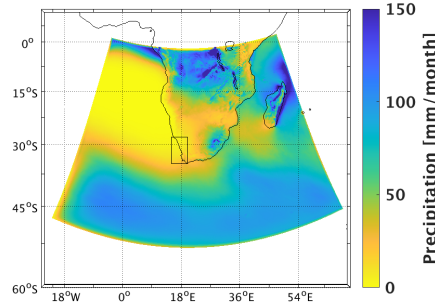
Figure 1. The CCLM domain of this study shown as the climatology of rainfall over the hindcast period 01/1958-04/2019.

lution of 0.56 degree.

In context of the CASISAC project (Changes in the Agulhas System and its Impact on southern African Coasts, funded by the German Federal Ministry of Education and Research BMBF), we performed three regional atmospheric simulations over southern Africa (covering the region 10 °W - 55 °E, 0 °S - 55 °S, fig. 1) with the CCLM model (COSMO model in CLimate
95 Mode, $https://www.clm-community.eu/$). We set up one hindcast simulation where the reanalysis JRA-55 (Kobayashi et al., 2015) is driving the simulation at the initial and lateral boundaries. This simulation spans the period January 1958-April 2019. The other two CCLM simulations are driven by the coupled climate model FOCI (Matthes et al., 2020) with interactive ozone chemistry, and high, mesoscale-resolving, ocean resolution around South Africa, ran by our project partners at the research centre GEOMAR (Germany). These encompass a historical simulation (1951-2013) and a scenario simulation with
100 increasing greenhouse gas concentrations (2014-2099, SSP5-8.5 (Lee et al., 2021)). These CCLM simulations have a horizontal resolution of about 16 km and an hourly output. We used spectral nudging (von Storch et al., 2000) for all three simulations. Thus, the large-scale pattern of the driving data sets are nudged over the whole model domain. This method is beneficial as small scale features are developing freely and large-scale features are kept tight to the driving data not only at the boundaries. Time series of the Agulhas Current and Agulhas leakage transport were obtained from the coupled climate model FOCI using
105 Lagrangian particle tracking technique, as described by Ivanciu et al. (2022).

To analyse the changes in precipitation over the past decades and the 21st century, we calculated the linear trend. For the statistical significance of these trends a significance level of p=0.05 was adopted using the method f-test.

To estimate the impact of the Agulhas Current and Agulhas leakage on SST and precipitation in the CCLM simulations, a
110 simple linear regression model was assumed:

$$Prec(t) = Prec_{mean} + aAL(t) + b(t) \tag{1}$$

where Prec (t) is the precipitation in a model grid-cell over the 5-year period starting in year t, $Prec_{mean}$ is the climatological mean precipitation in that model grid-cell, $AL(t)$ is the transport of the Agulhas leakage in the 5-year period starting in year t. The parameter a is the regression slope and $b(t)$ is the part of the precipitation in the 5-year period that is not related to the

115 Agulhas leakage. The regression parameters (for each grid-cell) can be estimated from the simulated values of the precipitation and the Agulhas leakage by ordinary least-squares regression. The portion of the variability in precipitation that can then be linearly attributed to the Agulhas leakage, $Prec_{AL}$, is

$$Prec_{AL}(t) = aAL(t) \tag{2}$$

and its long-term trend is simply the linear trends of $Prec_{AL}$. The same equations apply for the SSTs by replacing Prec with

120 SST and replacing the Agulhas leakage (AL) by the Agulhas Current. For the Agulhas Current, no 5-year period was used but the strength for each individual year.

3 Mean precipitation and validation of CCLM simulations

In this section we validate the precipitation simulated by the hindcast CCLM simulation over our model domain with the observational data set GPCP and the JRA-55 reanalysis data set and provide a general overview of the rainfall over southern

125 Africa.

The climatology of simulated precipitation represents well the different climatic regions in southern Africa (Fig. 2). Regions of higher rainfall amounts are located in the tropics, over Madagascar and along the southeast coast of South Africa. Dryer regions are the Namib and Kalahari deserts and the Western Cape region, the WRZ. South Africa is divided into 8 rainfall zones: the North-Western Cape and the South-Western Cape constitute the WRZ, the South Coast, which has similar rainfall

130 amounts during all months of the year (all-year rainfall region) and the SRZs Southern Interior, the Western Interior, the Central Interior, KwaZulu-Nata and the North-Eastern Interior (Rouault and Richard, 2003).

Comparing CCLM to GPCP shows that CCLM generally underestimates precipitation amounts (e.g. over Madagascar) except for the Drakensberg region in eastern South Africa and the large lakes in the northeast of our domain (Fig. 2c). Deviations of CCLM from the observations of GPCP are generally small in the southern part of the model domain and along the coasts, along

135 which the Agulhas Current flows. Differences are larger over Madagascar and the Congo basin and over the coasts north of 20 °S probably due to a misrepresentation of the African monsoon system. Thus, larger biases are mainly out of our focus region, as we are interested in southern African precipitation and whether and how it is impacted by the Agulhas Current System.

This general underestimation of rainfall amounts in CCLM can also be seen in the annual cycle (Fig. 3). CCLM represents well the annual cycle of both rainfall regions SRZ and WRZ. Rainfall peaks in December and January in the SRZ and in June in the

140 WRZ. But comparing the hindcast to its driving data set JRA-55 and to the observations GPCP shows that CCLM simulates generally lower rainfall amounts than the other two data sets. JRA-55 underestimates already slightly the observations and these too low rainfall amounts continues and intensifies in CCLM.

Thus, the simulated precipitation of CCLM represents well the rainfall zones of southern Africa covered by the model domain. It slightly underestimates the precipitation amount compared to the driving reanalysis data set and observations in most of the

145 domain. Nevertheless, precipitation is generally realistically represented in the southern part of our domain with the exception of mountainous regions Drakensberg and Madagascar.
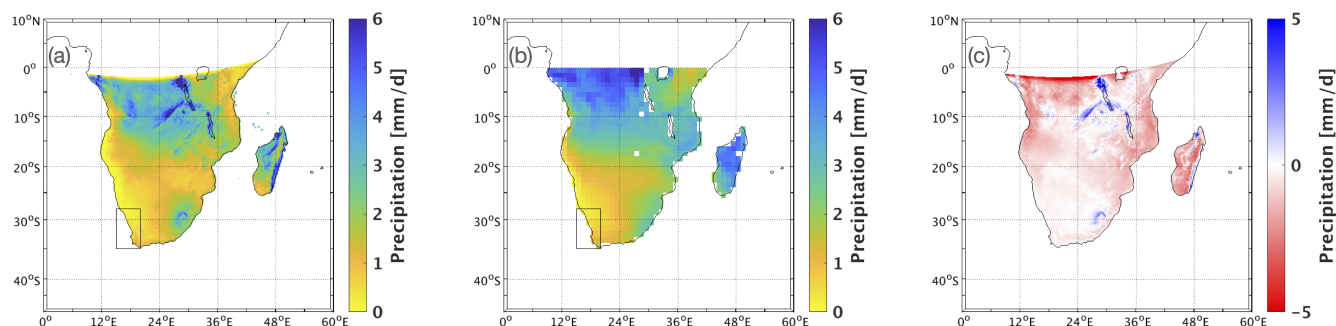
Figure 2. Comparison of modelled and observed rainfall from CCLM and GPCP, repectively for the overlapping period 1997-2018. (a) shows the climatology of CCLM, (b) the climatology of GPCP and (c) the difference between both data sets (CCLM-GPCP). The black box indicates the Winter Rainfall Zone (WRZ).
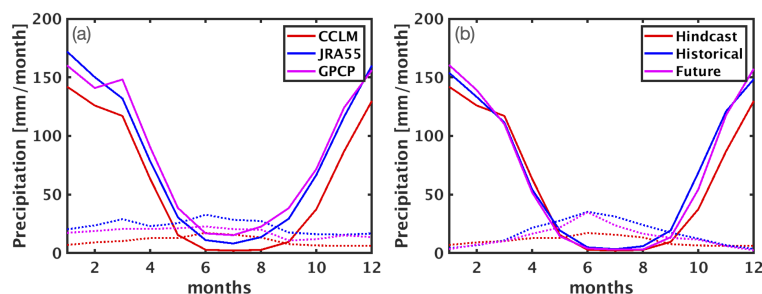
Figure 3. Annual cycle of rainfall over the Summer Rainfall Zone (SRZ) and the Winter Rainfall Zone (WRZ) for (a) the hindcast CCLM simulation, the GPCP observational data set and the reanaylsis data set JRA-55 and for (b) the three CCLM simulations hindcast, historical, and future. Solid lines represent the rainfall for the SRZ, dashed lines represent the WRZ.

4 Trends in precipitation

In this section, we compare past precipitation trends in CCLM to JRA-55 and GPCP and we investigate the future precipitation changes under the SSP5-8.5 emission scenario. We aim to answer the following questions: How has precipitation changed over
150   the past over the WRZ and SRZ? Are there regional differences? And how is the rainfall projected to change until the end of the 21st century?

Precipitation trends are shown for austral summer in figure 4 and for austral winter in 5.
Regarding austral summer, changes in precipitation over southern Africa look quite different between the observational data set
155   GPCP and the reanalysis data set JRA-55. GPCP shows more a reduction in precipitation, especially over Madagascar and the east coast (Fig. 4a), whereas JRA-55 indicates an increase in precipitation over Madagascar and western southern Africa (Fig. 4b). CCLM generally simulates trends of reduced strength. The hindcast simulation shows a extenuated but similar pattern than
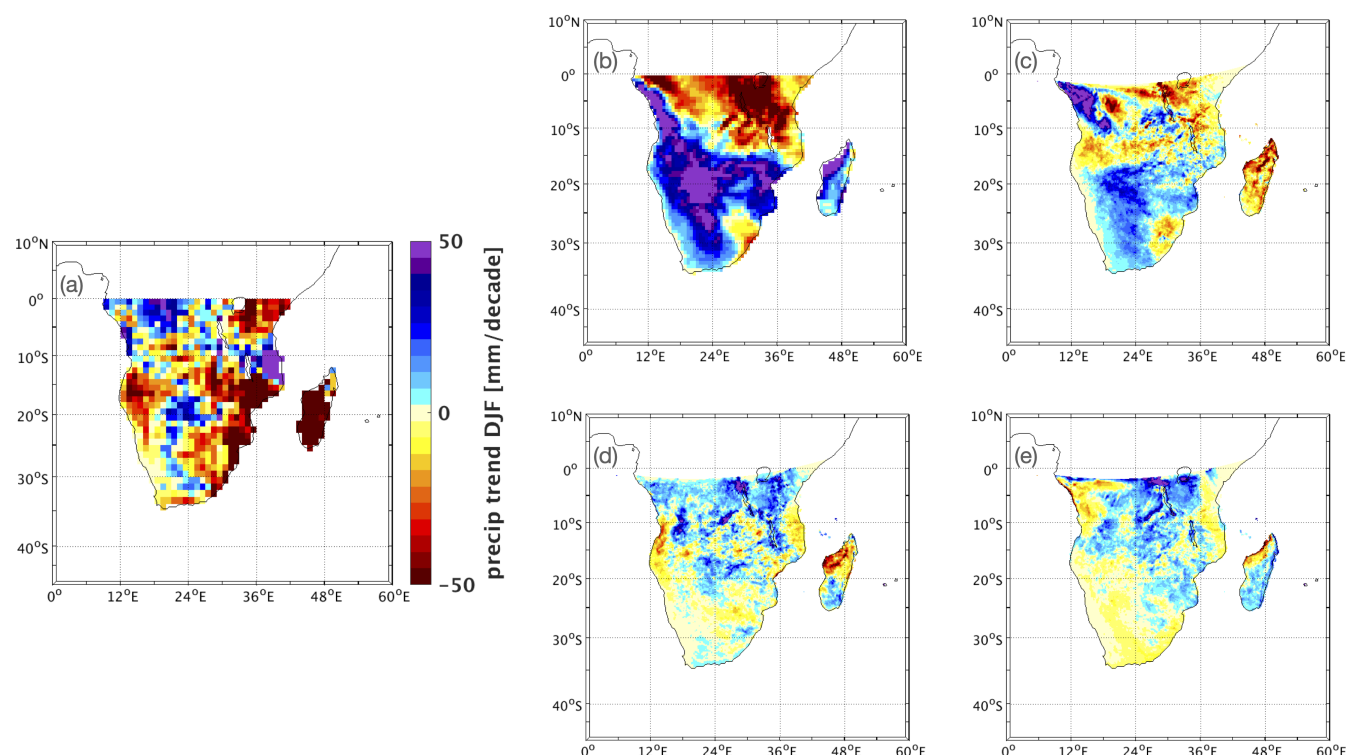
Figure 4. Precipitation trends for austral summer (December-February) for the Summer Rainfall Zone (whole area except for the WRZ in the south west) for (a) the observational data set GPCP (1997-2018, year dates of January and February of the seasons), (b) the reanalysis data set JRA-55 (1958-2019), (c) the hindcast simulation of CCLM (1958-2019), (d) the historical simulation of CCLM (1951-2013), and (e) the scenario simulation of CCLM (2014-2099). Trends are in mm/decade.

JRA-55 (Fig 4c). The FOCI driven simulation over the historical period (Fig. 4d) provides a somewhat similar precipitation trend for the southern part of the domain but with even smaller regions of intensification than the hindcast and JRA-55. It has to be kept in mind that GPCP covers only the recent past from October 1996 onward, whereas JRA-55 and thus the hindcast run covers the period starting in 1958. Nevertheless, CCLM simulates weaker trends but the pattern agrees between hindcast, historical run and JRA-55 for the coastal southern Africa.

Overall, since 1958, the model and JRA-55 show a drying over parts of the southeast coast and a wettening over the west coast, south coast, and central southern Africa for austral summer. Trends in the future simulation (Fig. 4e) are weak too. Precipitation is projected to decrease in the southern part of the domain, also along the coast. An intensification is simulated for Madagascar and the east coast of the African continent along the Mozambique channel.

For the austral winter, GPCP in figure 5a indicates a slight drying in the north of the WRZ and a wettening in the south of the WRZ. The hindcast simulation and JRA-55 agree that precipitation in the WRZ has increased in the past. Here the
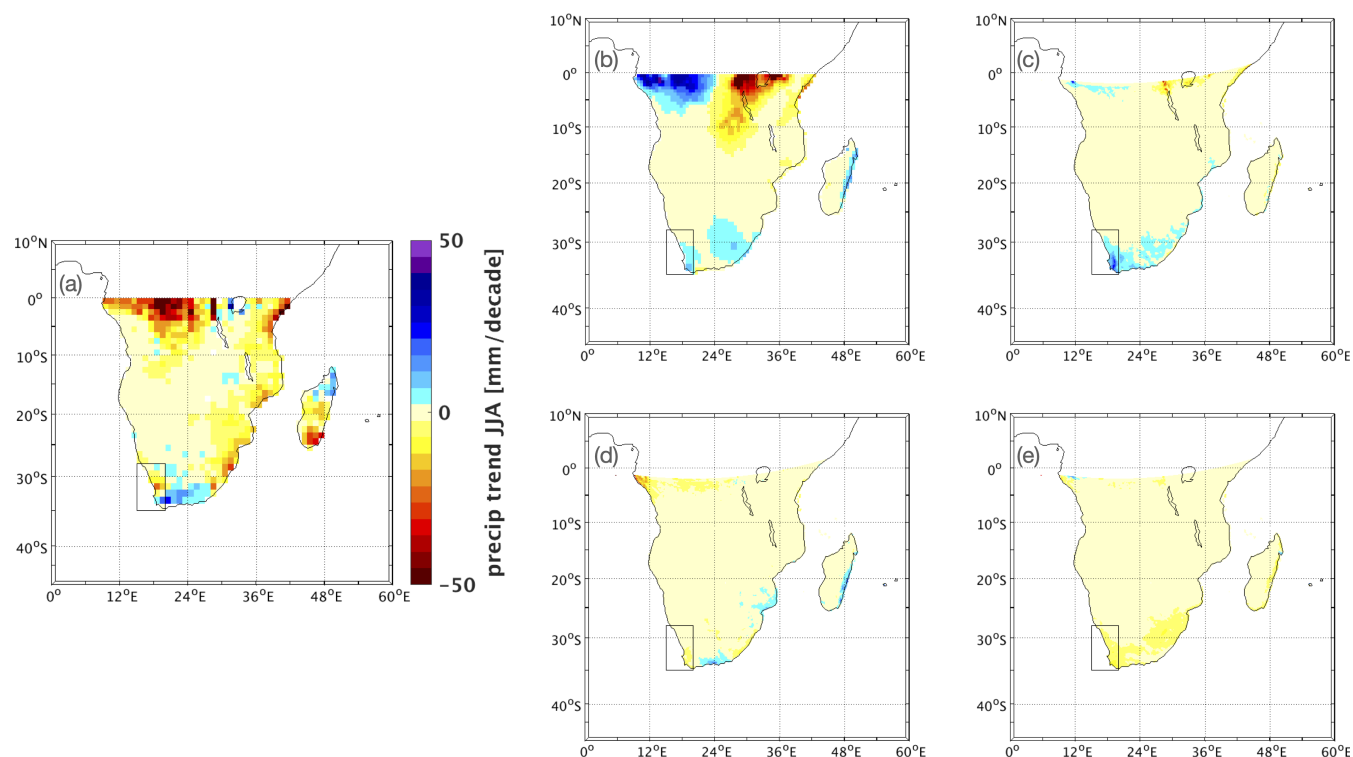
Figure 5. Precipitation trends of the winter rainfall season (June-August) for the Winter Rainfall Zone (marked by the box) for (a) the observational data set GPCP (1997-2018), (b) the reanalysis data set JRA-55 (1958-2019), (c) the hindcast simulation of CCLM (1958-2019), (d) the historical simulation of CCLM (1951-2013), and (e) the scenario simulation of CCLM (2014-2099). Trends are in mm/decade.

170   hindcast simulation (Fig. 5c) shows a stronger trend than JRA-55 (Fig. 5b). The historical and future simulations (Fig. 5d and 5e) show drying in the whole WRZ. Averaged over the WRZ, the past trends are positive, except for GPCP but non significant except for the hindcast (4.9 mm/decade). The future simulation exhibits a significant decrease in precipitation of -3.4 mm/decade.

Thus, precipitation in the SRZ and WRZ have mainly increased in the past in the respective season and decreased in some
175   coastal areas, while precipitation trends are negative for South Africa in the future for both regions and seasons. This projection agrees with the IPCC assessment of future precipitation based on the CMIP6 model ensemble.

The agreement with the IPCC projections is reflected in the simulated trends of the large-scale atmospheric circulation. The SLP patterns of the 1950s (Fig. 6b, 6c) compared to the ones of the 2090s (Fig. 6d, 6e) show that changes in austral summer
180   of the subtropical highs in the South Atlantic and the western Indian Ocean are small, decreasing slightly close the the South African coast. The continental heat low over the Kalahari has intensified. SLP is lower over the Agulhas Current which may hinder the inflow of moist warm air from the Indian Ocean and the development of tropical temperate troughs, responsible for
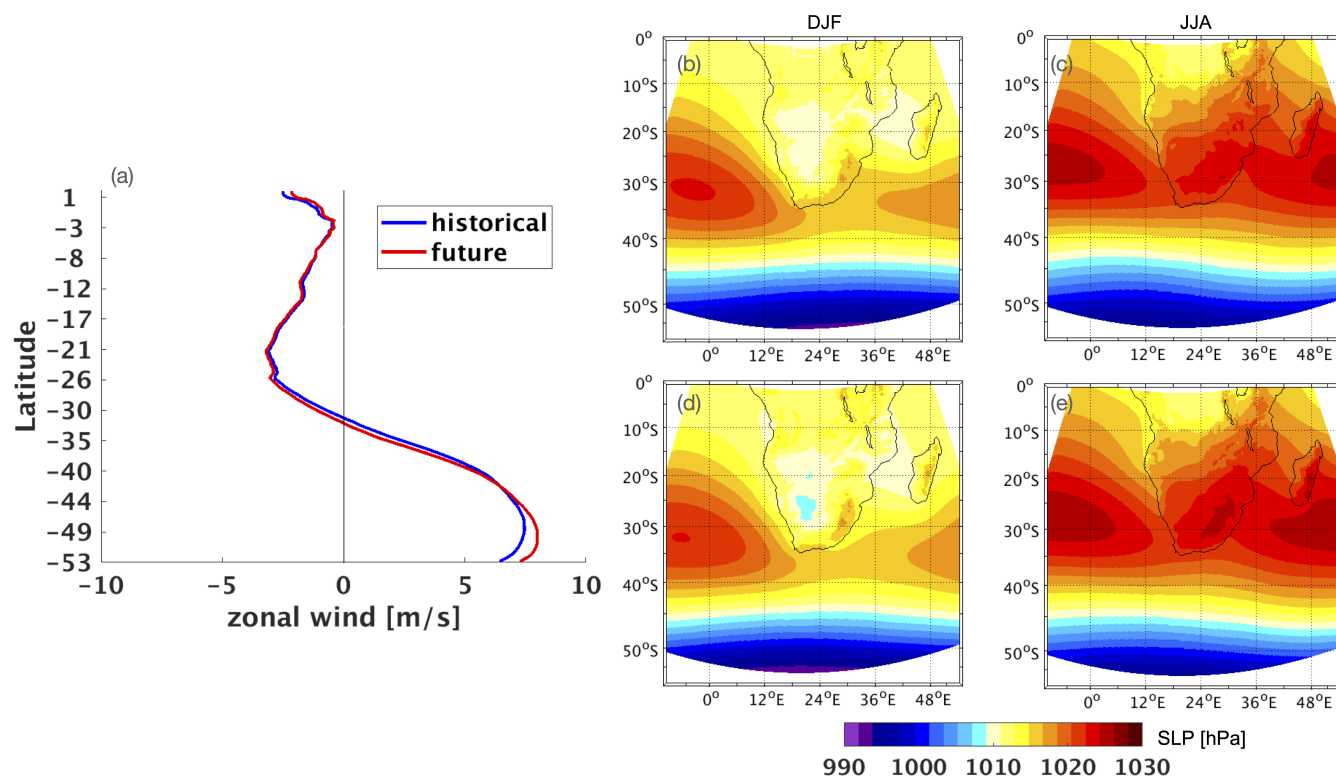
Figure 6. (a) The position and strength of the surface westerlies in the historical and scenario simulation as latitudinal plots (meridionally averaged over the model domain) of zonal wind strength. The SLP pattern for both rainfall seasons, (b) DJF, (c) JJA of the first 10 years of the historical simulation, (1951-1960) (d) DJF, and (e) JJA of the last 10 years of scenario simulation (2090-2099), in hPa.

summer rainfall. This is linked to the decrease in precipitation over the southeast coast in austral summer. In austral winter, the SLP has increased over the oceans and the continent. Both subtropical highs have not only intensified but also shifted poleward.

185 This, together with the poleward shift of the westerlies (Fig. 6a), leads to a more southward position of the frontal systems causing drying in the winter rainfall zone as we have seen in the precipitation trend analysis.

There are two additional considerations. One is that the relatively weak trend in the future projected with the CCLM model might be an underestimation as this model produces weaker precipitation trends than observations and reanalysis in the present period. The second is that the historical and projected trends do not have the same sign in some regions, and thus the mecha-

190 nism behind the observed historical trends may be partly unrelated to the increase of greenhouse gases.

5   The Agulhas Current System as a driver of precipitation

As we have seen in the previous section, precipitation trends are different on the coasts of southern Africa than inland. The nearby warm Agulhas Current System and its changes might have an influence on these spatial patterns of the trend. Therefore,

195   in this section we investigate the relationship between the Agulhas Current System and the trends in precipitation over southern Africa.

The Agulhas leakage exhibits a significant positive trend and the Agulhas Current exhibits a significant negative trend in both FOCI simulations, the historical simulation covering the past and the scenario simulation covering the 21st century. The trend in the Agulhas leakage has been further proven by using a proxy based on the SST of the CCLM simulation: The SST

200   difference between the southwest Indian Ocean (36-40 °S, 25-35 °E) and the southwest Atlantic (34-40 °S,10-20 °E). The SST difference was proven to be a good indicator for the Agulhas leakage intensity (Biastoch et al., 2015). Trends are significant for the hindcast simulation and for the past and future FOCI-driven simulations. Thus, the leakage has intensified whereas the Agulhas Current has reduced in strength and these trends are predicted to continue during the twenty-first century.

To detect the impact of the Agulhas Current System and its changes in strength on the precipitation over South Africa and on

205   the neighbouring SST, we applied a linear regression model.

5.1   Attributing SST and precipitation to the strength of the Agulhas Current and Agulhas leakage

In this section, we look specifically at the impact of the strength of the Agulhas Current and Agulhas leakage on SST around and precipitation over southern Africa. The Agulhas Current is expected to impact precipitation of coastal southern Africa due to its closeness to the shore. The Agulhas Current is a region of high moisture and heat fluxes into the atmosphere (Lee-Thorp

210   et al., 1999). And since the Agulhas leakage determines the volume of warm and saline water masses from the Indian Ocean flowing into the South Atlantic, it can impact the SSTs, the atmospheric circulation and precipitation over southern Africa. The transport of the Agulhas Current and leakage is calculated from FOCI, the driving data set of the historical and scenario simulation of CCLM. The high resolution of FOCI around southern Africa enables the simulations of the mesoscale features, important for the Agulhas Current System. The purpose of analysing both periods is to identify the impact of the Agulhas

215   Current System on regional climate trends in the current climate on the one hand, and to estimate the contribution of changes in the Agulhas Current System on future climate change on the other hand.

The Agulhas Current is defined as the volume transport at a transect at 32 °S. The Agulhas leakage is defined as the amount of waters originating in the Agulhas Current at 32 °S and crossing the Good Hope Line (Ansorge et al., 2005) within a 5 year window, thus leaving the Cape Basin and entering the South Atlantic (as described in Tim et al. (2018)). We set up a simple

220   linear regression model as described in the data section.

Figure 7 shows the impact of the Agulhas Current and Agulhas leakage on the SST in the historical simulation. The SST trend shows a warming especially in the Retroflection area of around 0.03 degree Celsius per year (Fig. 7a). Around 1/6 of this SST trend can be attributed to the Agulhas leakage (Fig. 7b). The Agulhas leakage and SST exhibit a positively correlated of 0.4
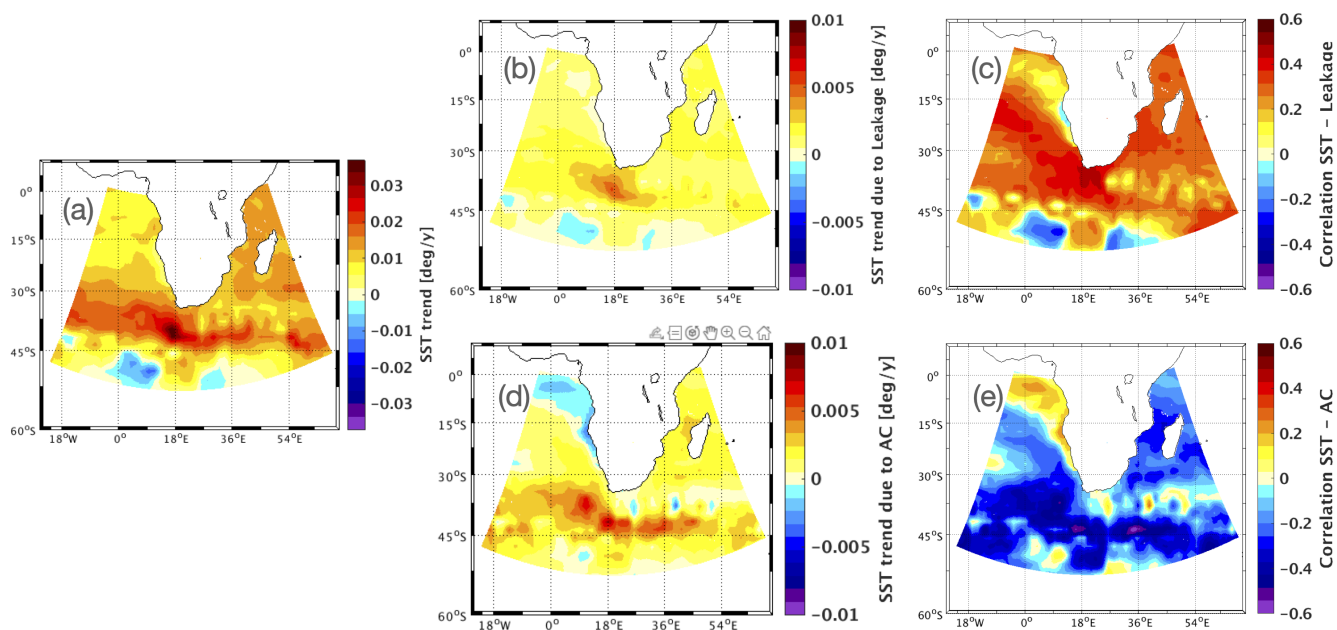
Figure 7. Impact of the Agulhas leakage and Agulhas Current on SST in the historical simulation. (a) Trend in SST, (b) the portion of the SST trend attributed to the Agulhas leakage, (c) correlation pattern of SST and the strength of the Agulhas leakage, (d) the portion of the SST trend attributed to the Agulhas Current, and (e) correlation pattern of SST and of the strength of the Agulhas Current.

225 in the Agulhas Retroflection region, southwest of it and in the corridor where Agulhas rings transport Indian Ocean water into the South Atlantic (Fig. 7c). This reflects the transport of warm Indian Ocean water by the Agulhas Current and the further pathway of this warm water into the South Atlantic due the Agulhas leakage (Gordon, 1986). The increase in Agulhas leakage over the last decades (Schwarzkopf et al., 2019; Tim et al., 2018; Durgadoo et al., 2013; Biastoch et al., 2009) and the warming of the Agulhas Current System (Rouault et al., 2009, 2010) lead to a positive SST trend southwest of the Cape region. About

230 1/6 of this warming can be attributed to the Agulhas leakage.

The Agulhas Current contributes as well around 1/6 of the SST trend (Fig. 7d), in the Retroflection area and in the region of the Agulhas Return Current. Correlations are mainly negative, indicating a warming when the strength of the Agulhas Current is reduced. This opposite relationship between the strength of the Agulhas Current and the Agulhas leakage has been found previously by van Sebille et al. (2009).

235 In the scenario simulation, the SST trend is similar to the trend in the past with a maximum of 0.04 degree Celsius per year (Fig. 8a). The Agulhas leakage contributes again around 1/6 of this SST trend southwest of the Cape region, in the Agulhas Retroflection, and at the coast of northern Namibia and Angola (North Benguela Upwelling region) (Fig. 8b). The impact of the Agulhas leakage on the North Benguella Upwelling region is known to exhibit a lag of several years (Tim et al., 2018). The strong positive trends in the Cape region and North Benguela Upwelling region are interlinked in another way. The poleward

240 shift and intensification of westerlies and trades impact both oceanic regions: an intensification of the Agulhas leakage causes
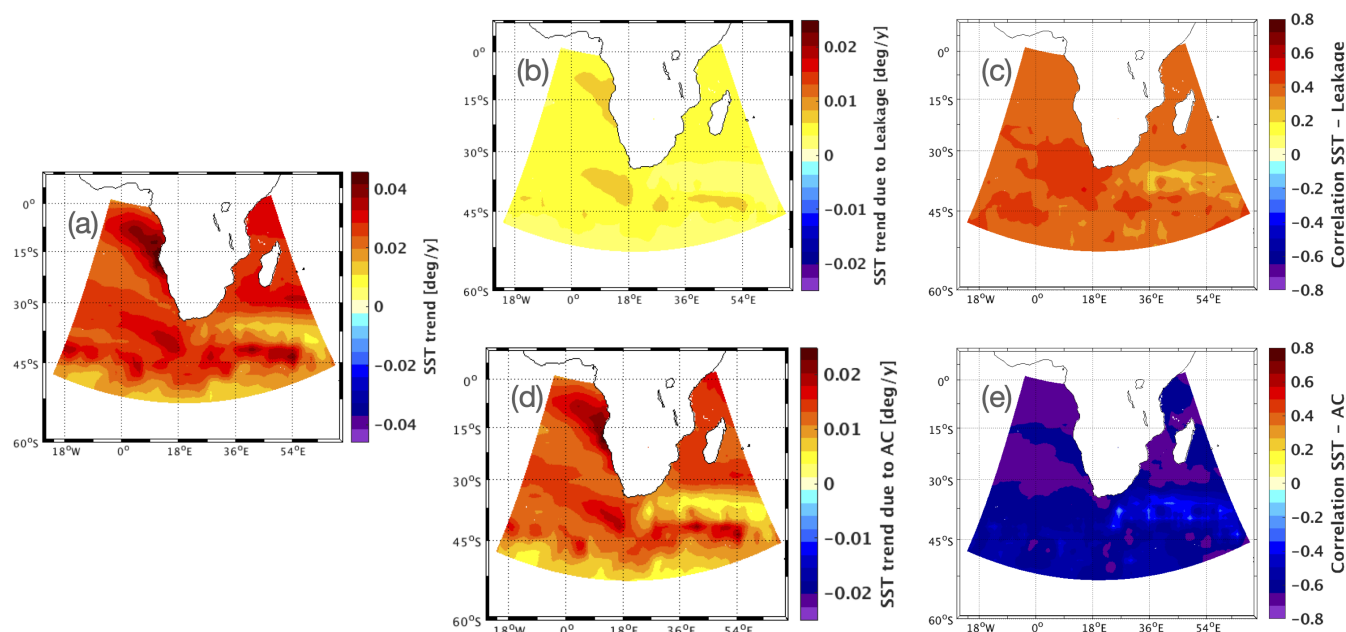
Figure 8. Impact of the Agulhas leakage and Agulhas Current on SST in the scenario simulation. (a) Trend in SST, (b) the portion of the SST trend attributed to the Agulhas leakage, (c) correlation pattern of SST and the strength of the Agulhas leakage, (d) the portion of the SST trend attributed to the Agulhas Current, and (e) correlation pattern of SST and of the strength of the Agulhas Current.

a warming in that area (Biastoch and Böning, 2013) and a poleward shift in the upwelling region leads to reduced upwelling and consequently warmer temperatures off the coasts of Angola and northern Namibia (Rykaczewski et al., 2015).

In the scenario simulation, as for the historical period, the Agulhas leakage and SSTs are positively correlated up to 0.5 in the Southeast Atlantic Ocean (Fig. 8c). Again as in the historical simulation, SSTs are rising as the leakage is projected to increase
245 under global warming (Biastoch and Böning, 2013; Ivanciu et al., 2022).

The Agulhas Current is also contributing to the warming in the Retroflection area (Fig. 8d) and correlations show, as for the historical period, that SSTs are rising when the strength of the Agulhas Current is reduced (Fig. 8e). Nevertheless, the strong SST trend in the Cape basin is possibly more linked to the Agulhas leakage. As well as the SST trends in the North Benguela Upwelling System are probably not directly impacted by the Agulhas Current, but rather climate change impacts both the
250 Agulhas Current and the SSTs.

Thus, the Agulhas Current and the Agulhas leakage contribute to the warming trend of SSTs adjacent to southern Africa. The ocean surface has warmed and this trend is projected to continue. The decrease in the Agulhas Current and the increase in the Agulhas leakage contribute to this warming for both past and future periods.

255 The impact of the Agulhas Current and Agulhas leakage on the precipitation over southern Africa in the past decades is shown in figure 9. Precipitation shows a weak negative trend in most of southern Africa, with some precipitation intensification along
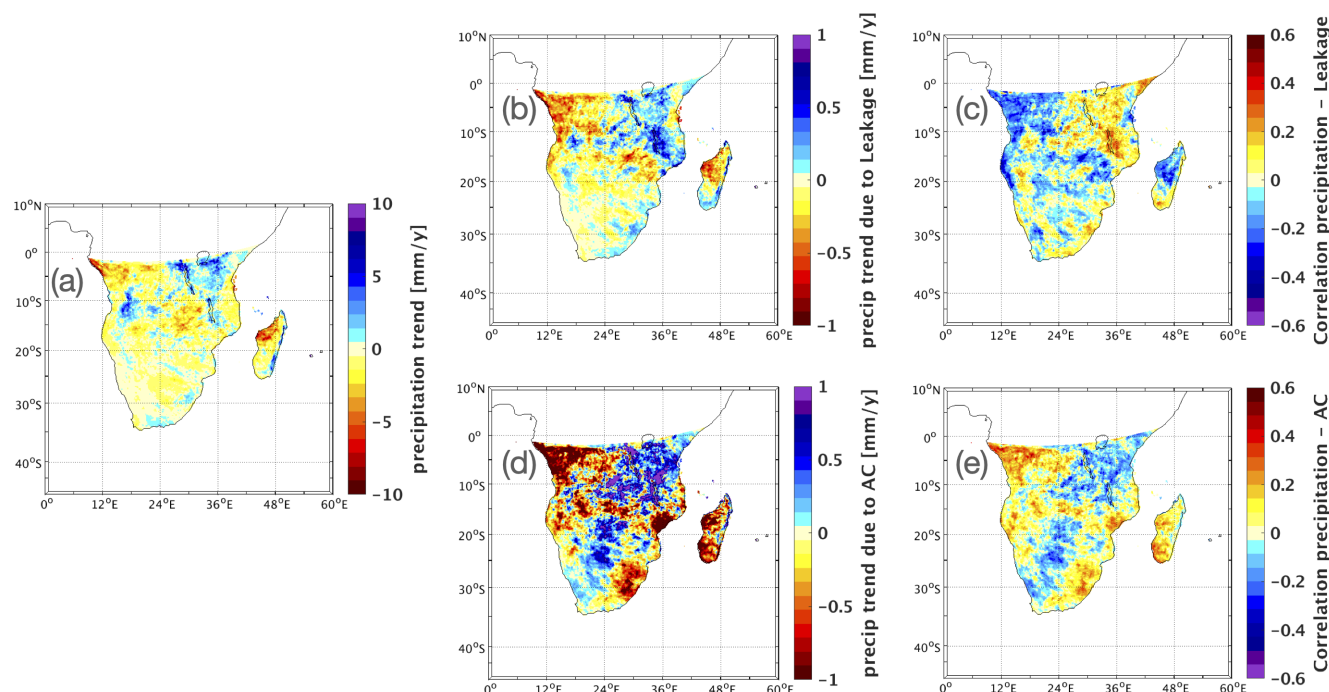
Figure 9. Impact of the Agulhas leakage and Agulhas Current on precipitation over southern Africa in the historical simulation. (a) Trend in precipitation, (b) the portion of the precipitation trend attributed to the Agulhas leakage, (c) correlation pattern of precipitation and the strength of the Agulhas leakage, (d) the portion of the precipitation trend attributed to the Agulhas Current, and (e) correlation pattern of precipitation and of the strength of the Agulhas Current.

the southeast coast (Fig. 9a) and around 1/10 of this trend is due to the Agulhas leakage (Fig. 9b). Agulhas leakage and precipitation are positively correlated along the southeast coast of South Africa (Fig. 9c). The Agulhas leakage impacts precipitation via the SST: SSTs in the Retroflection are positively correlated with precipitation at the southeast coast of South Africa (Cheng
260 et al., 2018) and SSTs west of the Retroflection with precipitation in the SRZ (Walker, 1990). Correlations with precipitation in the WRZ around the Cape of Good Hope are negative (Fig. 9c).

The Agulhas Current causes a precipitation trend of opposite sign along the South African coast (Fig. 9d). Correlations are positive for coastal South Africa (Fig. 9e). Thus, a strong Agulhas Current is linked to enhanced rainfall, but as the Agulhas Current has weakened, precipitation has decreased.

265 Regarding changes in precipitation in the future scenario, the Agulhas leakage and precipitation are negatively correlated over South Africa (Fig. 10c). Thus, as the leakage will intensify (Ivanciu et al., 2022) precipitation will diminish along the whole coast and the southern inland in the future. In the past, a decrease in precipitation due to increased leakage only occurred for the Cape region. This can be seen in figure 10a, which shows a projected weakening in precipitation in southern Africa. Again, around 1/10 of this trend is due to the Agulhas leakage (Fig. 10b).
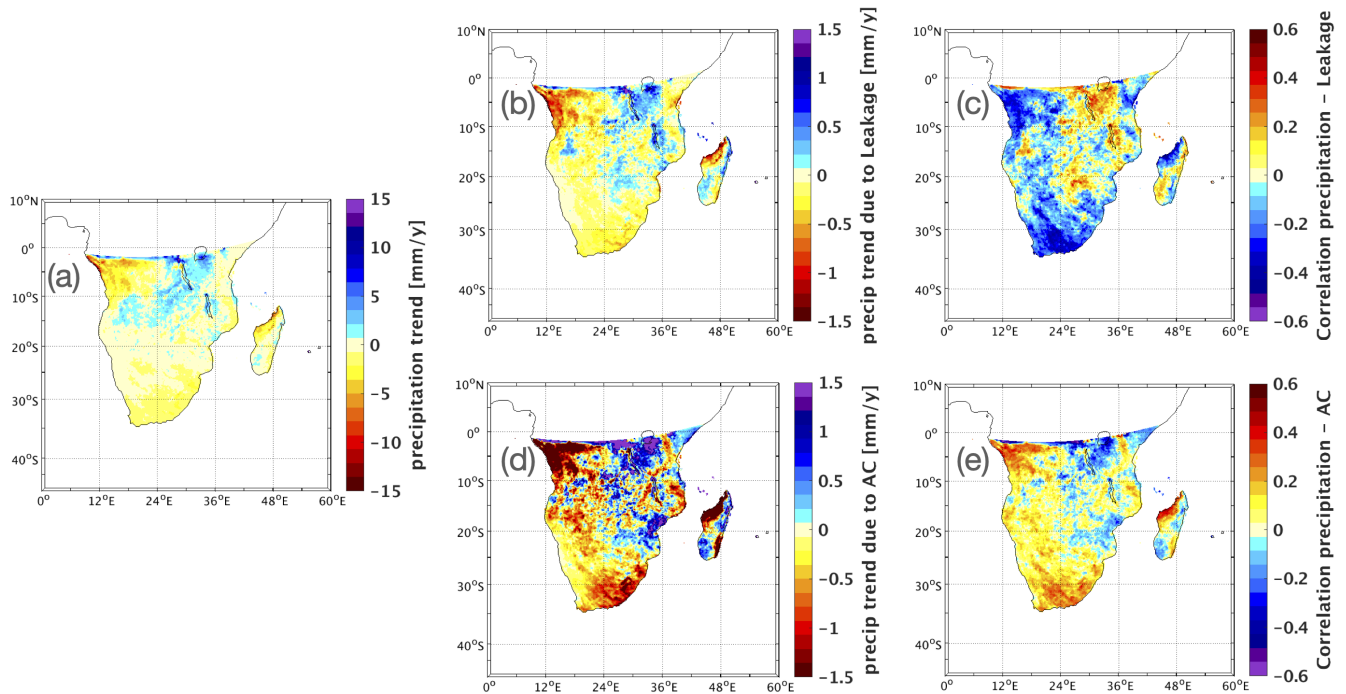
Figure 10. Impact of the Agulhas leakage and Agulhas Current on precipitation over southern Africa in the scenario simulation. (a) Trend in precipitation, (b) the portion of the precipitation trend attributed to the Agulhas leakage, (c) correlation pattern of precipitation and the strength of the Agulhas leakage, (d) the portion of the precipitation trend attributed to the Agulhas Current, and (e) correlation pattern of precipitation and of the strength of the Agulhas Current.

270   The analysis of the impact of the Agulhas Current on future precipitation indicates, like for the historical period, that the reduction of precipitation is partially caused by decrease in the strength of the Agulhas Current (Fig. 10d, 10e).

The change in the dependency of Agulhas leakage strength on precipitation from the past to the future requires further investigation. A possible explanation could be that only the trend in precipitation in the WRZ is directly linked to the strength of the Agulhas leakage, whereas precipitation at the southeast coast is rather linked to the Agulhas Current. The signal of the
275   weakening Agulhas Current may dominate the signal of the strengthening Agulhas leakage for the precipitation in the South African SRZ and especially for precipitation over the southeast coast of South Africa. Another possible explanation might be that the Agulhas Current is only weakening at its current-day location (here measured at 32 °S) and is shifting southward, away from the coast. This has been stated by Yang et al. (2016). And as has been found by Jury et al. (1993), the precipitation at the southeast coast is linked to a Agulhas Current core located close to the coast. The strength of the Agulhas Current is linked
280   to the strength of the trade winds (Loveday et al., 2014) and the strength of the Agulhas leakage is linked to the position and strength of the westerlies (Beal et al., 2011; Durgadoo et al., 2013). The westerlies have intensified and shifted poleward from the historical simulation to the scenario simulation, as already shown in Fig. 6a.

Thus, a decrease in precipitation took place over some parts of southern Africa in the past and is projected to do so for a large part of southern Africa in the future. This is linked to changes in both oceanic and atmospheric circulation. We have shown
285 that the weakening of the Agulhas Current, both in the past and in the future, is associated with a reduction in precipitation, especially along the southeast coast, whereas the increase in Agulhas leakage is associated with a reduction of precipitation in the WRZ. At the same time, changes in the position and the strength of the westerlies and, related to that, changes in the SLP pattern, likely impact precipitation through other mechanisms not investigated here, such as changes in cut-off lows or in ridging highs.

290

6   Conclusions and discussion

In this paper, we analysed past and future precipitation trends as well as the impact of the Agulhas Current System on precipitation in southern Africa in the regional atmospheric model CCLM. Three simulations were used: a simulation driven by atmospheric reanalysis and two simulations driven by the global coupled climate model FOCI covering the past and future.

295

- CCLM is capable of a well representation of the rainfall zones of southern Africa when comparing the hindcast simulation to observations and the driving reanalysis. Precipitation is slightly underestimated in most of the domain, but southern coastal Africa is mainly well simulated except for mountainous regions and Madagascar. Dosio et al. (2021b) found a good agreement of JRA-55 to other observational data sets for precipitation (1979-2018) and show generally
300 comparable precipitation seasonal means in observational data sets for southern Africa. Gnitou et al. (2021) compared the annual cycle of a CCLM simulation to observations and a REMO simulation and found, like us, that CCLM is underestimating the monthly precipitation amounts. Nevertheless, CCLM preformed better than REMO for spatial added value coverage for all seasons (Gnitou et al., 2021). Munday and Washington (2018) found that CMIP5 models overestimate southern African rainfall (in austral summer) and underestimate rainfall over Madagascar due to the lower topography.
305 This is contrary to the performance of our CCLM simulation. Panitz et al. (2014) found that the underestimation of CCLM (CORDEX-Africa) simulated rainfall peaks in the regions affected by the passage of the monsoon and that this bias is a consequence of the wrong location of the monsoon center, and underestimation of its intensity. This might be an explanation for the underestimation of rainfall in our CCLM simulation in the southeast (Madagascar and adjacent mainland) and the tropical western area of our domain.

310

- Precipitation trends in both rainfall regions (SRZ and WRZ) are mostly positive in the past for the respective season but decreasing in some coastal areas of the SRZ, particularly the southeast coast. This agrees with the study of MacKellar et al. (2014) who analysed station data (1960-2010) and found an increase in rainfall over SRZ of South Africa for DJF and over WRZ in JJA and with Lim Kam Sian et al. (2021) who found mainly wettening over South Africa (1901-2014)

315   using CMIP6 simulations and gridded observations. Findings of Onyutha (2018) with CRU data agree with our results of mainly wettening, except for areas directly at the coast over the period 1901-2015 (annual precipitation) and more drying in coastal areas in austral summer. Analysis of station data for the WRZ showed a decrease for periods over the last 30 years (Roffe et al., 2021; Wolski et al., 2021). Also analysing precipitation trends over the last 30 years, Karypidou et al. (2022) found an underestimation of observed trends from CORDEX-Africa and CMIP5 models. Trends vary between

320   CORDEX-Africa RCMs and the GCMs of CMIP5 and CMIP6 (Karypidou et al., 2022). Thus, trends over the past are spatially heterogeneous and strongly depend on the analysed time period as well as on the used data set. Even station data, gridded observations and reanalysis data sets provide varying precipitation trends to some degree.

Future precipitation is projected to decrease for South Africa in both seasons (as also found by e.g. Dosio et al. (2019) and Rojas et al. (2019)).Trends in the future are relatively weak. This might be caused by the underestimation of precipitation

325   amounts and trends by CCLM. CMIP6 models project an initial increase in the near future and than a decrease in western and eastern southern Africa (Lim Kam Sian et al., 2021). Global CMIP5 and CMIP6 model project a wetter future compared to regional models (CORDEX, CORDEX-CORE), with a drying in western southern Africa and wettening in eastern southern Africa (Dosio et al., 2021a). Furthermore, Dosio et al. (2021a) found a decrease in precipitation frequency and an increase in dry spells over southern Africa. In a previous study Dosio et al. (2019) analysed RCMs and

330   got similar results, and a good agreement of these RCMs and their driving GCMs.

– We performed an analysis with a simple linear regression model to attribute the trends of SST and precipitation on the one hand to the strength of the Agulhas Current and on the other hand to the strength of the Agulhas leakage. Our results show that the Agulhas Current System is linked to the SST in southwest Indian Ocean and the South Atlantic and that it contributes to precipitation in South Africa. The reduction in the strength of the Agulhas Current is linked to

335   the reduction in precipitation along the southeast coast while the intensified Agulhas leakage is linked to the reduction in precipitation in the WRZ. Cheng et al. (2018) linked the reduction in rainfall over southeast Africa in summer to the strength of the Agulhas leakage. Our results indicate an impact of the Agulhas Current System dominated by the strength of the Agulhas Current leading to the drying in that region. Furthermore, they found a linkage of the strength of the Agulhas leakage to the meridional position and/or strength of the westerlies and the trade winds. This supports our

340   results that the future drying of southern Africa is also linked to the strength of the Agulhas Current and the Agulhas leakage, which in turn are associated with the poleward shift and/or strengthening of the westerlies, especially under the currently most realistic SSP5-8.5 scenario.

– In addition to the Agulhas Current System as oceanic driver, changes of the atmospheric circulation are leading to the drying in the southern parts of southern Africa. Westerlies are projected to shift southward and strengthen, as previously

345   found by e.g. Ivanciu et al. (2022) and Tim et al. (2019). This displacement and intensification is accompanied by a poleward shift and intensification of the high pressure systems of the oceans in austral winter. This implies a more southward passage of the frontal systems, responsible for rainfall in the WRZ, and thus can be linked to the drying in

this region. In austral summer changes in the SLP are smaller but may cause less moisture transport from the ocean to the southeast of our domain.

350   – Thus, our simulations are suitable to analyse southern African precipitation, its changes and the impact of the Agulhas Current System. Coastal South African precipitation will reduce and the strength Agulhas Current System is one of its drivers.

Data availability. CCLM and FOCI simulations are available upon request, JRA-55 and GPCP are freely available to download.

Author contributions. NT, EZ, and BH designed the study and analysed the results, NT and EZ set up and ran the CCLM simulations. NT
355 prepared the manuscript with contributions from EZ, BH and II.

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360 data set has been downloaded at the NCAR UCAR Research Data Archive. The GPCP data set has been downloaded at precip.gsfc.nasa.gov The project received funding by the German Federal Ministry of Education and Research (BMBF) of the SPACES-CASISAC project (grant 03F0796) and by the Helmholtz-Zentrum Hereon.

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