Dear Prof. Dr. Fischer,

Thank you very much for handling the review process for our manuscript.

You can find below our responses to the reviewers' comments and the changes we applied in the revised version of the manuscript.

The original comments by the reviewers are written in italics.

**Reviewer #1:**

*It is missing some useful references:*
*2015, Passive suppression of South African rainfall by the Agulhas Current, Earth Interactions, 19, 1-14*
*2019, South Africa's future climate: trends and projections, in The Geography of South Africa, eds. J. Knight and C.M. Rogerson, Springer Nature, Switzerland, 305-313.*
*2020, Marine climate change over the eastern Agulhas Bank of South Africa, Ocean Science, 16, 1529-1544.*

We added the first suggested reference to the following sentence in line 23-25:

The Agulhas Current System impacts the precipitation in southern Africa (Imbol Nkwinkwa et al., 2021; Nkwinkwa Njouodo et al., 2018; Cheng et al., 2018; Jury, 2015; Reason, 2001).

and added this sentence in lines 27-28:

The sea surface temperature (SST) of the Agulhas Current also impacts South African precipitation indirectly via El Niño-Southern Oscillation (ENSO) (Jury, 2015)

We added the second suggested reference to the following sentence in lines 353-354:

A decrease in future rainfall has also been found by e.g. Dosio et al. (2019), Rojas et al. (2019), Jury (2019), Seager et al. (2019), and Polade et al. (2017).

We added the third suggested reference in lines 354-355:

Jury (2020) found that precipitation over the Agulhas Current is simulated to
355 decrease too.

*in Fig 4a, 5a the observed GPCP rain trend is given 1997-2018, this period is too short. With trends over the sea masked, why not use the Chirps2 or ERA5 rainfall trend? these cover a longer time period*

As CHIRPS covers a relative short period too (1981 onwards), we added three more data sets to the validation analysis: ERA5 (as suggested by the reviewer) and additionally GPCC (available 1891 onwards) and CRU (available 1901-2020). We added a short description of these data sets in section 2 (lines 96-108):

As observational data sets we use the Global Precipitation Climatology Project (GPCP, version v01r03,(Adler et al., 2003)), the Global Precipitation Climatology Centre (GPCC, version v.2020, (Schneider et al., 2016)) and precipitation data from the Climate Research Unit (CRU, version ts4.05, (Harris et al., 2020)). GPCP is a combination observations with satellite measurements of precipitation in 1 degree horizontal resolution and covers the period from October 1996 to the present. GPCC is based on in situ raingauge data, has 0.25 degree horizontal resolution, is available from 1981 onwards, and is the observational part of GPCP. CRU is also based on station data, has 0.5 degree horizontal resolution, and covers the period 1901 to today.

The Japanese reanalysis JRA-55 (Kobayashi et al., 2015) serves for the model validation as its the driving data of the regional model CCLM (COSMO model in CLimate Mode, https : ==www:clm?community:eu=), as described in the following section. It covers the period 1958 until April 2019 with a spatial horizontal resolution of 0.56 degree. Additionally, we use the reanalysis data set ERA5 (Hersbach et al., 2020) for validation of the precipitation trend. ERA5 data starts in 1978 with a horizontal resolution of 31 km.

We changed the introductory lines at the beginning of chapter 4 (lines 169-171) by adding the additional data sets:

In this section, we compare past precipitation trends in CCLM to the observational data sets CRU, GPCC, and GPCP and to the reanalysis data sets JRA-55 and ERA5 and we investigate the future precipitation changes under the SSP5-8.5 emission scenario.

and changed the description of the trend to the following (lines 175-200):

Regarding austral summer, changes in precipitation over southern Africa look quite similar for CRU and GPCC but different from GPCP and the reanalysis data sets JRA-55 and ERA5. For the southern part of the domain, CRU and GPCC show weak trends of both wetting and drying (Fig. 3a, b). GPCP shows stronger trends and rather a reduction in precipitation, especially over Madagascar and the east coast (Fig. 3c), whereas JRA-55 and ERA5 indicate an increase in precipitation over Madagascar and western southern Africa (Fig. 3d, e). The results from CRU, GPCC, and JRA-55 are plotted here for the same period 1958-2019. The deviations of GPCP might be due to the shorter period covered by this data set (1997-2018). The reanalysis data set ERA5 starts in 1979, later than JRA-55. This might lead to the weaker wetting trends in the southern part of the domain.
CCLM generally simulates trends of reduced strength compared to its driving data set JRA-55. The hindcast simulation shows an attenuated but generally similar pattern to JRA-55 (Fig 3f). The FOCI driven simulation over the historical period (Fig. 3g) 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, similar to CRU and GPCC.
Overall, since 1958, the hindcast and reanalysis data sets show stronger trends with drying over parts of the southeast coast and wettening over the west coast, south coast (the YRZ), and central southern Africa for austral summer. CRU indicates a wettening in the east (including the YRZ-part of the SRZ) and drying in the west; the historical simulation agrees well with
GPCC showing weak trends of both, drying and wetting.
Trends in the future climate simulation (Fig. 3e) 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 (Fig. 4), GPCC, GPCP, JRA-55, ERA5, and the hindcast simulation show a wettening in the south of the WRZ and a drying in the north. Here the hindcast simulation (Fig. 4f) shows a stronger trend than the other data sets. CRU, the historical and future simulations (Fig. 4a, g, and h) show drying in the whole WRZ.
Thus, precipitation in the SRZ and WRZ have mainly increased in the past in the respective season and decreased in some coastal areas, while for the future precipitation trends are negative for South Africa for both regions and seasons. This projection agrees with the IPCC assessment of future precipitation based on the CMIP6 model ensemble.

*in Fig 7a the (Hadley) observed SST trend should be compared with model trend*

We add the observed trend to the figure and compared it to the simulated SST trend (lines 247-250):
Compared to the observed SST trend (Fig. 7b), the simulated trend does not show a cooling in the Benguela Upwelling System either in west of the retroflection or between the Agulhas Current and the Return Current south of it. Nevertheless, both data sets, HadISST1 and CCLM, show a warming of the Agulhas Current and in the area of retroflection.

*in Fig 8a there is a SST warming in the Angola Dome in the tropical E. Atlantic which is said to be related to the Agulhas leakage, however this zone is where most models fail to correctly simulate the shift of anticyclonic winds and tropical rainfall. Thus changes in SST due to Agulhas leakage could be linked to a poleward shift in the subtropical ridge? or* *inability of model to reflect the teleconnections? A useful reference on this subject: 2013, Climate trends in southern Africa, S. Afr. J. Science, 109, 53-63 - although using CMIP3 their Fig 1 shows the model bias that continues (with lesser values) in CMIP6.*

In our interpretation, the reviewer is suggesting that the deficiency of coarse resolution global models to replicate the shift of the anticyclone and tropical rain band could be due to the unrepresented effect of the Agulhas leakage in those models. This is an interesting hypothesis. We have investigated a bit further to what extent the variations of the Agulhas leakage impacts rainfall in the Eastern Tropical Atlantic. Usually, the bias of coarse resolution global climate models in the EBUS, in particular SSTs, has been attributed to an incorrect cloud parametrization or to a poorly resolved upwelling dynamics (see e.g doi: 10.1002/wcc.338), but the role of the Agulhas system is an interesting alternative, at least in the Benguela EBUS. We discussed this in view of the suggested reference. Essentially, we now show the expansion to ocean precipitation of the analysis presented in Figure 9:
Precipitation trends in the tropical east Atlantic are negative (also in the Angola Dome but much weaker) and so is the contribution of the Agulhas leakage and of the Agulhas Current. Correlations are negative with the Agulhas leakage and positive with the Agulhas Current. Thus, the strengthening of the Agulhas leakage and the weakening of the Agulhas Current seem to be linked to this reduction in precipitation. Therefore, we conclude that the SST trend in the Angola Dome in figure 8 may really be related to the Agulhas leakage and that the CCLM model is able to realistically simulate tropical rainfall.

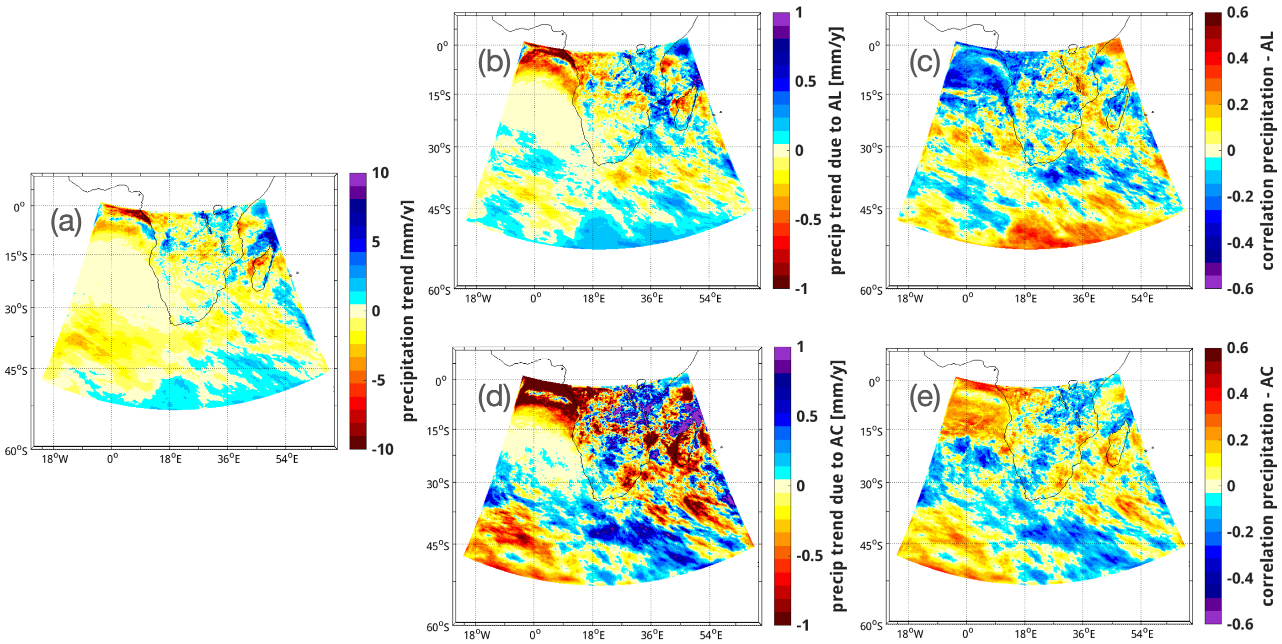


Figure: Impact of the Agulhas leakage and Agulhas Current on precipitation over southern Africa in the historical simulation. (a) Trend in precipitation, (b) the portion of the precipitation trend attributed to the Agulhas leakage, (c) correlation pattern of precipitation and the strength of the Agulhas 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. Colorbars of the correlation patterns (c, e) are reversed compared to the colobars of the other subplots.

*in Fig 9c,e, 10c,e the color bars are reversed, which may correctly be interpreted, but the caption needs to provide a note on this.*

We now indicate the reversed colourbars in the figure caption.

Colorbars of the correlation patterns (c, e) are reversed compared to the colorbars of the other subplots.

**Reviewer #2:**

*L133: generally, in regional climate models, precipitation is overestimated over the Drakensberg region. E.g: the weather research forecast model (WRF, see Koseki et al. 2018). How about the CCLM? Why does your model have more inland precipitation?*

CCLM also overestimates precipitation over the Drakensberg region and the large lakes in the northeast of our domain (Fig. 2c). In the rest of the domain, precipitation is underestimated.

*L320: you state that "trends over the past are spatially heterogeneous and strongly depend on the analysed time period as well as on the used data set." How does your chosen period and your data influence your analysis?*

The heterogeneity of precipitation trends over the past in different data sets may impact our analysis. We included more observational and reanalysis data sets to compare to CCLM. Nevertheless, most data sets agree upon a wetting over most parts of the SRZ. Precipitation trends in the future are more robust, with projected drying of the whole region.

For the section on the impact of the Agulhas Current System on precipitation, results are robust as they show a stationary relation between both variables. The strengthening of the Agulhas leakage leads to drying in the WRZ and the weakening of the Agulhas Current leads to a drying over the south and southeast coast of South Africa. The stronger trends of both, the Agulhas Current and the Agulhas leakage, in the future compared to the past, may contribute to a homogeneous drying of the region in the future. We added a figure of the trend of Agulhas Current and leakage in a revised version.

*There is a whole system for the formation of winter and summer precipitation (see the introduction of Imbol Nkwinkwa et al. 2021). What is the percentage of the contribution of the Agulhas leakage to winter precipitation?*

Our analysis of the contribution of the Agulhas Current System on precipitation is not done for each season separately. Nevertheless, precipitation in the WRZ is typically strongest in winter. Therefore, we assume that the contribution of the Agulhas leakage is of the same range for winter precipitation only as for the annual precipitation, namely 1/10. We analyzed the contribution for the winter season separately and included it in the appendix. The following sentence has been added at lines 303-305:

An analysis of impact of the Agulhas Current System on the winter rainfall (shown in the appendix), indicates that the decline in austral winter rainfall in the past is driven by the Agulhas leakage and in the future by both Agulhas leakage and Agulhas Current.

And this appendix:

Appendix B: Attributing precipitation in the WRZ to the strength of the Agulhas Current and Agulhas leakage

The impact of the Agulhas Current and the Agulhas leakage on precipitation in the WRZ looks very similar for austral winter precipitation in the WRZ (Fig. B1) as for the whole year (Fig. 9). Precipitation decreases and Agulhas leakage and Agulhas Current both impact this negative trend. The increase in Agulhas leakage strength contributes to the drying, as the precipitation trend induced by the leakage is negative and the leakage is negatively correlated to precipitation. The Agulhas Current is also negatively correlated with

precipitation, so that its negative trend would contribute to an increase in precipitation. However, as the total precipitation trend is negative, Agulhas leakage should dominate here over the Agulhas Current. This is more pronounced here than in figure 9 where the precipitation trend due to Agulhas Current is negative and correlations with the Agulhas Current are positive in the southwestern most part of the WRZ.
Regarding the precipitation trend over the WRZ in austral winter in the future and the impact of the Agulhas Current System (Fig. B2), again, the relation looks similar to the analysis of the whole year (Fig. 10). Precipitation decreases and both Agulhas leakage and Agulhas Current contribute to this decline. The Agulhas leakage is negatively correlated with precipitation, and as its strength increases it causes a precipitation decrease. The Agulhas Current is positively correlated with precipitation and as its strength weakens it causes a decrease of precipitation.
Thus, in the past, the impact of the Agulhas leakage seems to dominate over the Agulhas Current on winter rainfall. In the future, both drivers contribute to the reduction of precipitation.

*The south coast of South Africa receives precipitation all year long (Engelbrecht et al. 2015; Engelbrecht and Landman, 2016). Could you tell from your analysis whether this phenomenon is due to the Agulhas Current or the Agulhas leakage?*

Unfortunately, we cannot disentangle this from our analysis. Nevertheless, regarding future precipitation, in figure 10d, it looks as if rainfall trends in the YRZ are impacted by the Agulhas Current and not that much by the Agulhas leakage (Fig. 10b).

Minor corrections:

*Line 90: define CCLM because it is the first use.*

Changed as suggested

*Line 97: define FOCI.*

Definition added (lines 113-116):
The other two CCLM simulations are driven by the coupled climate model FOCI (Flexible Ocean and Climate Infrastructure, 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).

*Line 107: explain or give a reference for the method f-test.*

Added an explanation in lines 124-126:
For the statistical significance of these trends a significance level of p=0.05 was adopted using the method f-test, a test for the null hypothesis that the variance of two normal populations is the same.

*Figure 2 is the annual mean or the climatology?*

It is the climatology. It is the mean over the whole overlapping period 1997-2018. We changed this plot in the revised version and included more observational and reanalysis data sets.

*Caption figure 3, replace reanaylsis by reanalysis*

Changed as suggested.

*L157 replace a extenuated by an extenuated*

Changed as suggested.

*L180 replace “decreasing slightly close the the South African coast” by “decreasing slightly close to the South African coast*

Changed as suggested.

*L197-L203: precise the figures you are referring to*

We added a figure of the trends of the Agulhas Current and Agulhas leakage strength.

*L227: “to” is missing*

Changed as suggested.

**Revisions addressing the community comment that have not been already addressed are included here:**

*1. I would argue that the claims regarding recent WRZ rainfall trends made in the introduction (lines 31–33) are unclear, misleading and not well substantiated. Since this relates to relatively central conclusions of the study, a correction is required.*

We rewrote this part of the introduction in line 34-45:

Precipitation trends in the WRZ based on observations depend on the time period and on whether annual means or the actual rainfall season is analysed. A drying is detected for the winter rainfall season over the recent past (1987-2016) (Roffe et al., 2021) whereas a wettening was found over longer periods (1960-2010) for the winter rainfall season alone and for annual precipitation (MacKellar et al., 2014). Wolski et al. (2021) found negative trends of annual means for the long period 1900-2017 and for the recent past 1981-2017, positive trends for the period 1933-2014, and mixed trends for the periods 1981-2014 and 1933-2017. This shows that trends over periods including the drought 2015-2017 are generally negative. Ndebele et al. (2020) analysed the observed rainfall of one station in Cape Town and found again that trends depend on the considered period. Rainfall increased over the periods 1841-1900 and 1930-1970 but decreased when the long period from 1900 to 2016 is analysed. Gridded observational data indicate mostly an increase in the winter rainfall season for several time periods (Onyutha, 2018). Precipitation in the SRZ in austral summer (December-January-February, DJF) has either increased or no trend has been detected. This happens in both types of datasets, station observations and gridded fields (Onyutha, 2018; Kruger and Nxumalo, 2017; MacKellar et al., 2014).

*3. The WRZ is mischaracterised in section 3, specifically in lines 126–129 and 138–140 and Figures 2 and 3.*

The WRZ region in this study covers the domain 15°E - 20°E and 28°S - 35°S. This WRZ spans the region west of Cape Agulhas (20°E and 35°S) up to the South-African - Namibian border at the west coast (as indicated in the blue line in Figure1 Roffe et al. (2021)). The choice of a rectangular domain lead to the inclusion of a small part of the YRZ and, yes, the WRZ includes regions of very little rainfall. The WRZ region is, of course, the same for all data sets. We added the geographic coordinates to the manuscript (lines 158-159):

The WRZ region in this study covers the domain 15 E - 20 E and 28 S - 35 S.

*In the text the WRZ is equated to the “Western Cape region”, despite the WRZ covering less than half the Western Cape provincial area and extending beyond its borders. Without a specific definition, the “Western Cape region” is likely to be assumed by readers to correspond approximately to the South African province by that name. Furthermore, the WRZ is described as a “dryer region”. Whereas some of the driest recording gauges in*

*South Africa are located in the WRZ, the wettest recording gauge in the country is also situated in the WRZ and there are multiple gauges in the domain recording in excess of 1500mm per annum on average (Lynch, 2004; Slingsby et al., 2021). The South-Western Cape, as generally conceived, is certainly not a uniformly dry area, as appears to be suggested.*

We changed the wording in the revised version from:

Dryer regions are the Namib and Kalahari deserts and the Western Cape region, the WRZ

to:

Dryer regions are the Namib and Kalahari deserts in the WRZ.

*Furthermore, the relatively coarse resolution GPCP data do not adequately capture the regions of high (> 3mm/day from other datasets) rainfall in the south-west, the Drakensberg or eastern Madagascar (Fig. 2 and 3). CCLM appears to do better over the Maloti-Drakensberg of Lesotho than the reference data. The fact that absolute scales are used in all panels of Fig. 2 and that the area on which most of the paper focuses on is dry relative to the Congo Basin and northern Madagascar means that the relative amplitude of the CCLM biases relative to GPCP are difficult to ascertain. In understanding trend and variability influence, relative bias is at least as important to assess as absolute biases.*

We added additional observational data sets not only for the trend validation but also for the bias of mean precipitation. We added the bias as percentages of the total precipitation in an appendix. Comparing to other observational data sets will improve the validation section. The following sentences regarding figure 2 were added (line 152-157):

Comparing CCLM to other observational data sets that cover a longer period but are available at monthly resolution, like GPCC and CRU, provides a very similar picture (see Fig. A1). The relative bias of CCLM to all three observational data sets (GPCP, GPCC, and CRU)(Fig. A2) is again of similar magnitude. But considering the relative bias reveals that deviations of simulated precipitation from observed ones are noticeable in the whole domain, also in our focus region, the southern part of the model domain and along the coasts, along which the Agulhas Current flows.

4. Whereas it is noted in the work that the YRZ occurs along the South Coast, it is not clear why in the analysis only the WRZ is distinguished from the rest of the domain, which appears to be collectively considered as the SRZ. In addition, very wet areas near the Equator apparently included in the SRZ have a very different precipitation seasonality to those areas south of roughly 15◦S. Whereas the text notes that these areas are not the focus of the study, why are these regions then used as part of the aggregation domain in Fig. 3? Or if they aren’t, what domain bounds are applied for Fig. 3?

Figure 3 is applied over the whole domain. As the YRZ is the transition zone between WRZ and SRZ and represents a small region, it is not separated from the large SRZ. Trends are given here anyway as spatially resolved plots and as a spatially averaged timeseries. We added a sentence to address the differences in precipitation trends in the YRZ-part from the rest of the SRZ in the revised version (lines 162-164).

Both the WRZ and the SRZ in this study include parts of the YRZ (all-year rainfall zone). This relatively small transition zone between the WRZ and SRZ is not analysed separately here. This may contribute to the relative flat annual cycle of the WRZ.

*Furthermore, the statement in lines 247–248 that "the strong SST trend in the Cape basin is possibly more linked to the Agulhas leakage" needs to be substantiated.*

This conclusion is plausible, as the climate change signal would be of larger spatial scale, but the reviewer is right that it is not completely substantiated by our results. We rewrote this sentence (lines 274-275).

Nevertheless, the link between the strong SST trend in the Cape basin and the Agulhas Current occurs possibly via the Agulhas leakage.

*Lines 272–273: "The change in the dependency of Agulhas leakage strength on precipitation from the past to the future requires further investigation." Surely this is the incorrect direction of implied dependence?*

We of course meant the change of dependency of precipitation on the Agulhas leakage. We rephrased the sentence (299-300).

The change in the dependency of precipitation on Agulhas leakage strength from the past to the future requires further investigation.

*7. Parts of the discussion in the conclusion seem like they would be better suited to the introduction or results sections. The statement: "Dosio et al. (2021b) found a good agreement of JRA-55 to other observational data sets for precipitation (1979-2018) and show generally comparable precipitation seasonal means in observational data sets for southern Africa" should not be in the conclusion, but rather should inform assessment in section 3 of the implications of the comparisons conducted. At the scale that results are reported and conclusions drawn in this work (e.g. the south-east coast of South Africa, the South African South Coast or the WRZ), the cited paper does not appear to provide support for this claim, however.*

Section 6 is titled Conclusions *and* Discussion, but we agree with the reviewer that this section needs a better structure, separating more clearly the discussion and the conclusion parts. We included a short Conclusions section without reference to previous results (lines 325-326, 338-339, and 351-352).

– 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 underestimated in most of the domain.
– 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.
– Future precipitation is projected to decrease for South Africa in both seasons. Trends in the future

More minor concerns are:

*2. It should be clarified in lines 16–18 that the far south-west (the WRZ) is unique in that most of the annual precipitation here occurs during the winter season; the all-year or year-round rainfall zone (YRZ), as noted in line 130, also receives significant rainfall contributions during winter, as do some other parts of the east coast (see, for example, papers reviewed by Roffe et al. (2019)). Also, while frontal rainfall contributes ≈ 90% of winter rainfall in the core of the WRZ (Burls et al., 2019), it is not accurate to imply this is the only source of rainfall in the WRZ (see, e.g., Abba Omar and Abiodun (2020)).*

We clarified this in the revised version in lines 16-18.

Only the uttermost southwest of the continent receives most of its annual rainfall in the winter season (Chevalier and Chase, 2016). In this Winter Rainfall Zone (WRZ) rainfall is caused mainly by frontal systems moving with the westerlies (Reason, 2017).

*4. The motivating paragraph, lines 41–43, makes claims that probably require further substantiation and clarification.*

Changes in the winds, ocean currents and its link to anthropogenic change are the subject of the previous paragraph. This is just a summarizing sentence. To be more clear, we merged it to that previous paragraph.

*5. Line 65: "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." This mechanism has been widely studied by, for example, Seager et al. (2019) and Polade et al. (2017).*

We cited Seager et al. (2019) in lines 73-75. The mechanisms that these authors suggest for the Southern Hemisphere is essentially the expansion of the Hadley cell caused by increased atmospheric greenhouse gases. Surely, the Agulhas Current System is only one of the drivers of precipitation changes. Our results show that 1/10 of the drying can be attributed to the Agulhas Current System.

A common large-scale mechanism related to the increased radiative forcing and independent of changes in the Agulhas Current System is likely behind this large-scale spatial pattern of precipitation reduction. Previous studies have identified a diminished zonal moisture advection from the oceans located further west (Seager et al., 2019).

*7. Lines 128-131: The division of South Africa into 8 rainfall zones by the South African Weather Service in 1972 (Rouault and Richard, 2004) is only one of a range of subdivisions that have been proposed. The sentence should be rephrased to indicate this.*

We rephrased this sentence in lines 145-148:

South Africa can be divided into 8 rainfall zones: the North-Western Cape and the South-Western Cape constitute the WRZ, the South Coast, which has similar rainfall 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).

*11. Line 183: "is linked to" should perhaps be "may be linked to", unless the authors demonstrate the nature of the link.*

Changed as suggested.

*12. Line 288–289: Citation suggested.*

Reference has been added (Ivanciu et al., 2022b).