Responses to Anonymous Reviewer 2

General Comment:

This paper evaluates the representation of the southern African rainfall in the GCMs and RCMs compared to a set of observational data. The rainfall climatology, annual cycle, trends and a couple of ETCCDI indices are analyzed along with the representation of the Angola Low, which is one of the important driving circulations that affect the rainfall in the area. The paper is of high importance for model improvement. However, I suggest the following comments to be addressed before the paper is published in GMD.

RESPONSE: We would like to thank the Anonymous Reviewer #2 for the positive interpretation of the manuscript. Based on the suggestions and comments, we provide the following replies.

Major comments:

1st Comment:

Page 8, 235-240, an evaluation of the moisture transported through the north-easterly monsoon should be performed here to support the hypothesis that the improved representation of the topography led to a lower bias in the CORDEX models.

RESPONSE: Thank you very much for this comment. We now include the following figure in the main manuscript, displaying the moisture flux and moisture flux divergence at 850 hPa during each month of the rainy season, for the period 1986-2005. More specifically, the moisture flux divergence was calculated using the product of specific humidity and wind at 850 hPa, following the equation below (the vertical component ($\frac{\partial qw}{\partial z}$) is considered negligible).

$$\nabla \cdot q\vec{u} = \frac{\partial qu}{\partial x} + \frac{\partial qv}{\partial y}$$

With this plot we aim to contribute to the discussion developed in Figure 11 in Munday and Washington, (2017). More specifically, one of the reasons responsible for the wet bias of CMIP5 models over southern Africa (SAF), was that mountainous regions over the northeast part of SAF were underrepresented, due to the spatial resolution of the CMIP5 models Munday and Washington, (2018). The high elevation areas over Malawi and Tanzania were not represented accurately in CMIP5 GCMs, which allowed moisture transport entering SAF from the northeast to penetrate central SAF, rather than to recurve around the high mountains and result to large precipitation amounts over northern Madagascar. Since the underrepresentation of topography in GCMs is a matter of spatial resolution, we make the hypothesis that in high resolution RCMs this issue is resolved, since moisture entering SAF from the northeast is blocked by the adequately high elevation over the Tanzania and Malawi region.

As seen in the Figure 1 below, during all months the moisture flux field is very spatially inhomogeneous in ERA5 and in both CORDEX ensembles, while in CMIP5/6 the field is considerably smoother, indicating that in low resolution GCMs the surface characteristics are not detailed enough, so as to allow for adequate friction and cause the moisture fluxes to recurve around mountainous areas. Particularly during December and January when the north-easterly monsoon is intensified, the moisture flux at the northeast of SAF is intercepted in both CORDEX ensembles, however not in CMIP5/6. After February the atmospheric flow from the northeast is weakened and it is strengthened at the southeastern part, entering SAF through Mozambique. This moisture transport originates from the Mascarene High that has developed over the South Indian Ocean. The recurvature of moisture seen at the south-eastern part of Mozambique is caused by the Mozambique Channel Trough (Barimala et al., 2018).

In the manuscript we comment concerning the moisture transport entering SAF from the northeastern part, by adding the following text as the last sentence of paragraph 3 in Section 3.2: “The improvement of orography has a further effect in blocking moisture transport entering SAF from the northeast, especially during Dec-Jan, as seen in Fig. 5.”

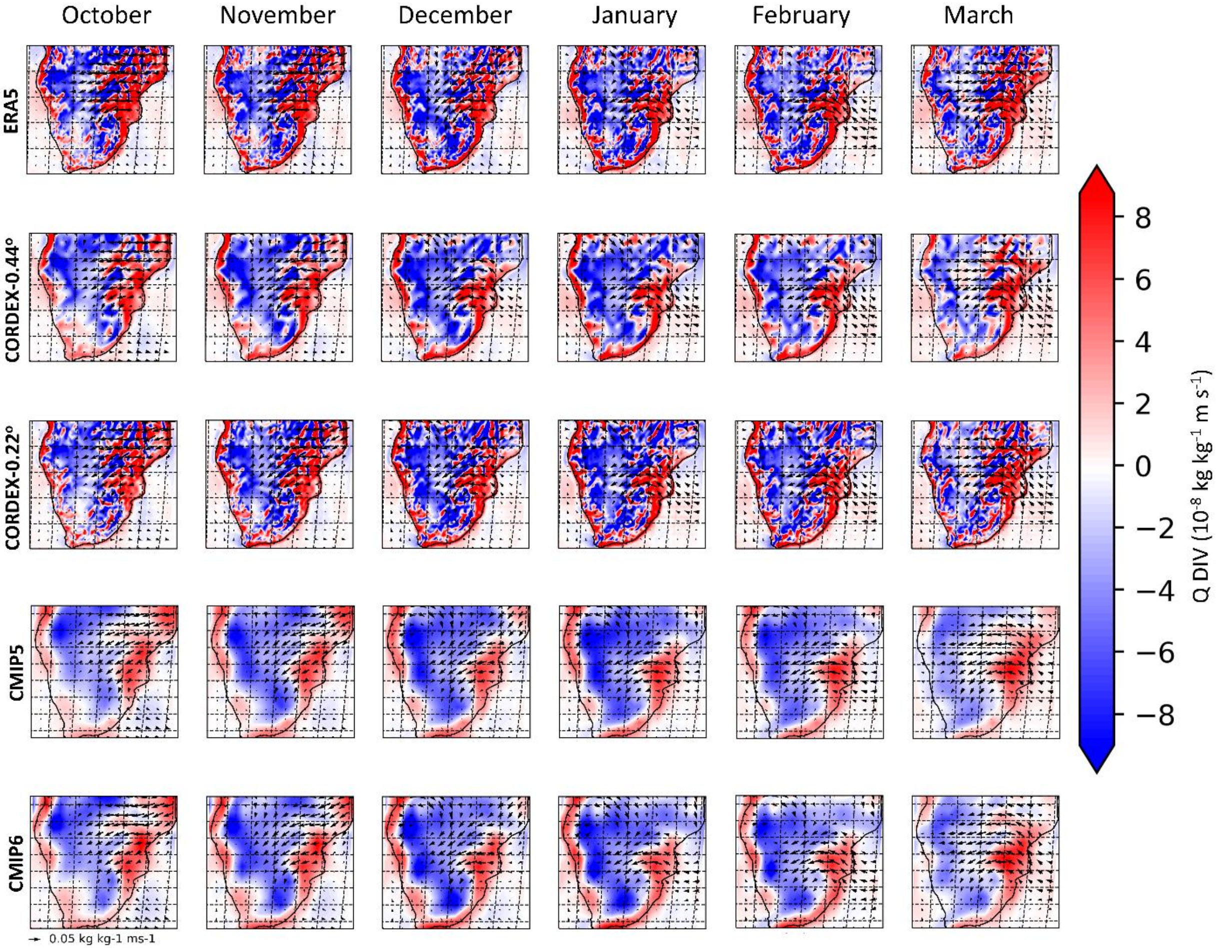

Figure 1: Moisture flux and divergence at 850 hPa.

2nd Comment:

Page 9, section 3.3. It should be made clear why there is a special focus on the Angola low given the different processes that significantly affect the rainfall in the area. For example, the cloudband or tropical temperate trough is one of the major processes that drive rainfall in SAF but is never mentioned here. I would even suggest including the cloudbands in the analyzes.

RESPONSE: Thank you very much for this comment. Indeed, not mentioning the Tropical Temperate Troughs (TTTs) in the manuscript is a significant lack, since TTTs are one of the main mechanisms producing precipitation over southern Africa. We now refer to the role they play for precipitation over southern Africa in the introduction, and also in the results section (section 3.3), where findings about the Angola Low have further implications for the formation of TTTs.

More specifically, the reason why we chose to put an emphasis on the Angola Low pressure system is that usually Angola Low events precede the formation of TTTs and hence, they can be considered as their precursor in the "climate process chain" controlling precipitation over southern Africa (Daron et al., 2019). As stated in Howard et al., 2018, it is common that Angola Low events precede TTT events, since the Angola Low pressure system functions as a key process necessary for the transport of water vapor from the tropics towards the extratropics (Hart et al., 2010).

In addition, based on a Scopus query investigating the number of documents with the keywords "Angola Low" and "Tropical Temperate Troughs" in the Title-Abstract-Keywords, we saw that TTTs have received almost the double attention in the literature (47 published papers), relative to the Angola Low (23 published papers). Hence, our work is, in part, an attempt to address this gap, considering the limitations set by the availability of variables in all the ensembles that are currently examined (CORDEX-Africa 0.22°/0.44° and CMIP5/6). For this reason, we did not include an analysis of the TTTs, since it is beyond of the scope of the current study, but it is imperative that a comparative analysis of how TTTs are simulated in CORDEX-Africa 0.22°/0.44° and CMIP5/6 is performed.

3rd Comment:

Page 9, section 3.3. I wonder why theta850 is used to calculate the Angola low instead of the geopotential height (as in Munday et al., 2017) or the vorticity (as in Howard et al., 2018). The CMIP6 models do have these variables available and should be used for a fair comparison.

RESPONSE: Indeed, Munday and Washington, (2017) use the lowest 5% of mean DJF geopotential height at 850 hPa (zg850) over southern Africa. The reason why we were not able to use the same index in order to identify the Angola Low, was that within the context of CORDEX-Africa simulations, geopotential height at 850hPa is not available. Two of our ensembles (CORDEX-Africa 0.44° and CORDEX-Africa 0.22°) come from the CORDEX family and are lacking this variable. Hence, based on the variables that are already available within both CORDEX and CMIP5, we used potential temperature at 850 hPa (theta850) as an alternative “proxy” variable that provides thermodynamical information. In order to ensure that theta850 could be used instead of zg850, we examined the relationship between theta850 and zg850 over the study region in ERA5, for each month of the rainy season (Oct-Mar), using the climatological mean monthly values for the period 1986-2005. The comparison is depicted below as a series of maps and scatterplots. Each point in the scatterplots represents a pixel in the ERA5 dataset.

More specifically, in Figure 1 the mean monthly zg850 values for the period 1986-2005 are shown. During October, over the south-eastern part of Angola there is a region of low pressures. Moving towards the core of the rainy season, the low-pressure system deepens, while there seems to be a very weak extension of low pressures towards the south. In Figure 2 the mean monthly theta850 values for the period 1986-2005 are shown. As it is depicted, during October there is an array of high theta values located over south-eastern Angola, coinciding with the region of low zg850 values. As stated in Munday and Washington, (2017), this is indicative of the dry convection processes that are at play during the beginning of the rainy season over the region. Moving towards DJF, the high theta850 values move southwards, indicating that in the core of the rainy season, convection over the greater Angola region is not thermally induced, but there is a rather dynamical large-scale driver. Through Figure 1 and Figure 2 we concluded that although theta850 is not a perfect proxy for zg850, it can be used to identify certain aspects of the Angola low pressure system, such as its strength and location during the rainy season.

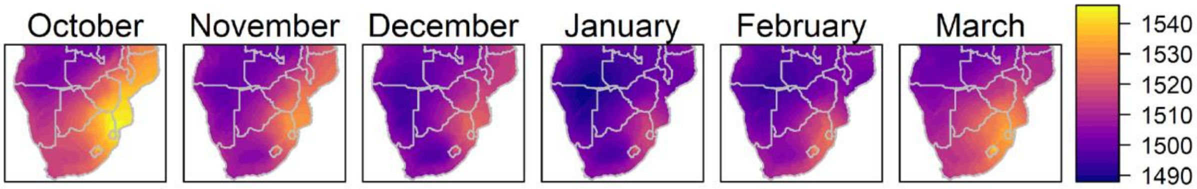

Figure 2: Mean monthly geopotential height at 850 hPa in ERA5 for the period 1986-2005.

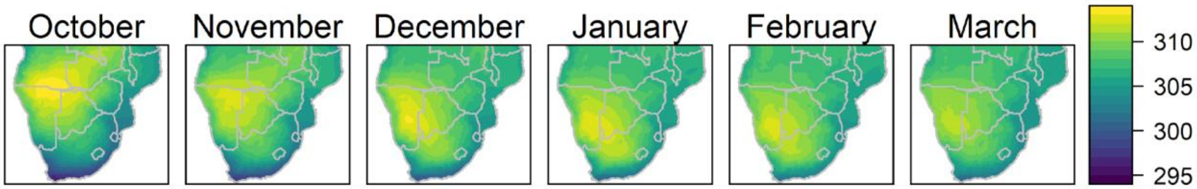

Figure 3: Mean monthly potential temperature at 850 hPa in ERA5 for the period 1986-2005.

In addition, in Figure 3 the scatterplots between zg850 (x-axis) and theta850 (y-axis) for each month of the rainy season for the period 1986-2005 are shown, over the whole southern Africa (land pixels only). The same plot, but with pixels only from the greater Angola region (14 °E to 25 °E and from 11 °S to 19 °S) is displayed in Figure 4. Although the relationship between the two variables is not perfectly linear, they display a considerable association, especially over the greater Angola region (Figure 4).

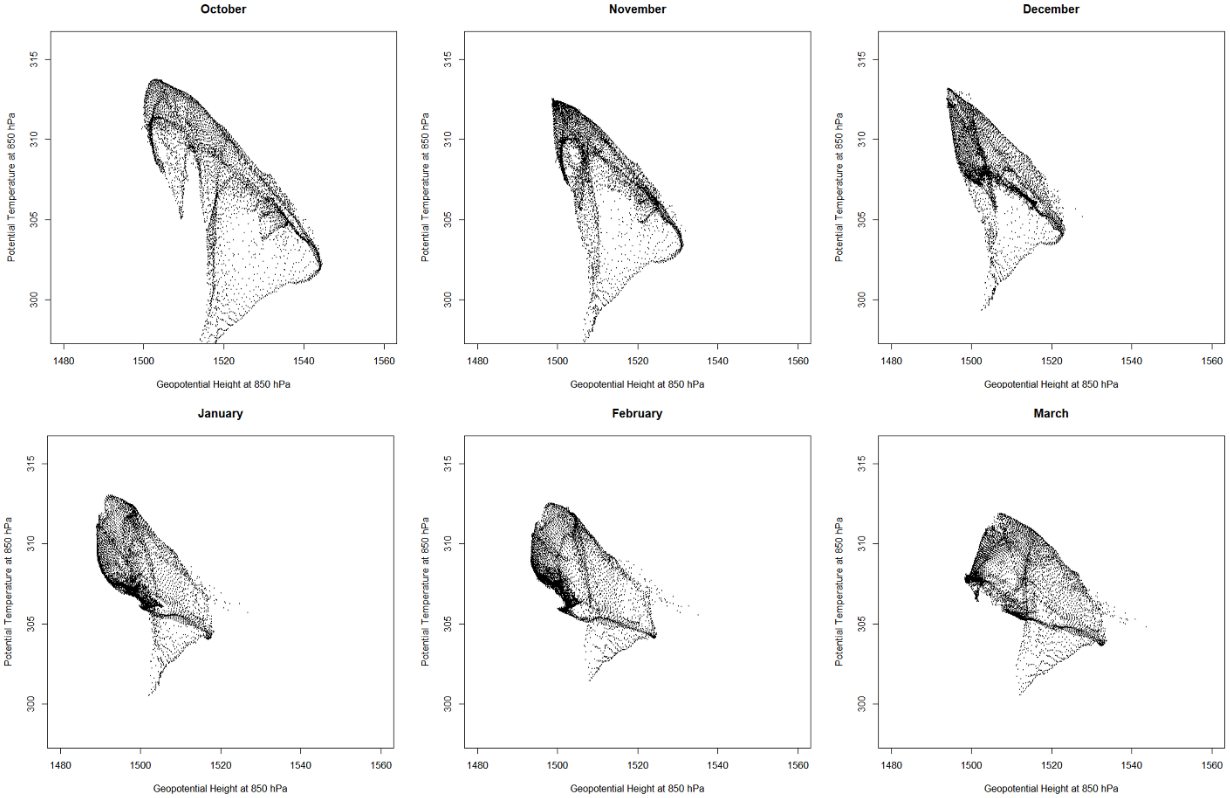

Figure 4: Geopotential height at 850 hPa (x-axis) plotted against Potential temperature at 850 hPa (y-axis). Values refer to climatological monthly means for the period 1986-2005. Each dot in the scatterplot represents a pixel of the ERA5 dataset over the whole southern Africa region 10 °E to 42 °E and from 10 °S to 35 °S.

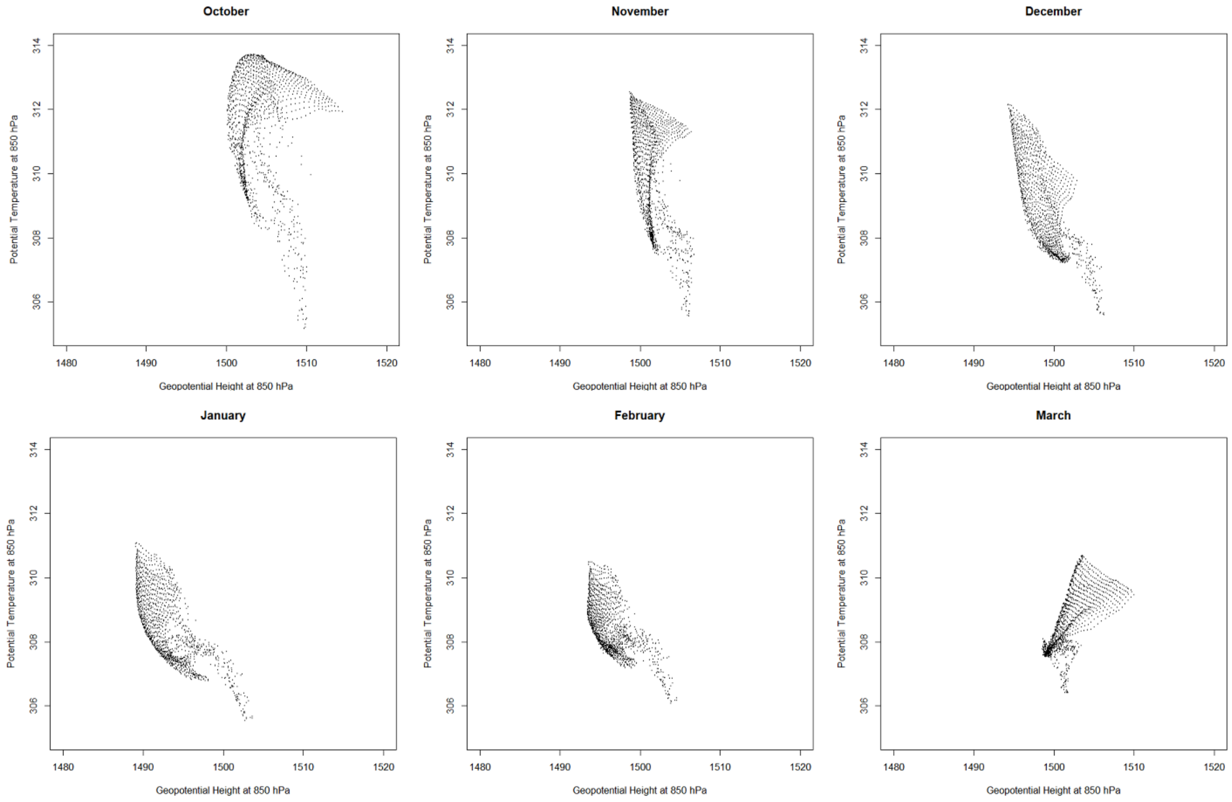

Figure 5: Geopotential height at 850 hPa (x-axis) plotted against Potential temperature at 850 hPa (y-axis). Values refer to climatological monthly means for the period 1986-2005. Each dot in the scatterplot represents a pixel of the ERA5 dataset over the whole southern Africa region 14 ^{o}E to 25 ^{o}E and from 11 ^{o}S to 19 ^{o}S.

Concerning relative vorticity (ζ) as used in Howard et al., 2018 we had to investigate the following issues: In Howard et al., 2018, they identify Angola Low events by using daily relative vorticity at 800 hPa. Although u and v wind components are available at 800 hPa in CMIP5/6, they are not available in CORDEX simulations. More specifically, in CORDEX-Africa, u and v wind components are only available at 850, 500 and 200 hPa. Hence, we had to investigate if we could use the 850 hPa pressure level (instead of 800) and if we did so, should we apply the same ζ threshold? In Howard et al., 2018, Angola Low events are identified within the region 14 ^{o}E to 25 ^{o}E and from 11 ^{o}S to 19 ^{o}S for mean daily ζ values $< -4 \times 10^{-5}$ s^{-1}. An additional issue that we took into account, is that u and v wind components at 850 hPa were not available on a daily timestep in CMIP6, but only on a monthly timestep. Hence, for consistency reasons we had to work with monthly files in all ensembles (both CMIP, CORDEX) and in ERA5. Lastly, some files from the CORDEX-Africa ensembles did not have complete timeseries (from 1986-2005), so they were not included in the calculation of the ensemble mean that eventually were used for the calculation of monthly relative vorticity. For CORDEX-Africa 0.22^{o} these files were:

*850_AFR-22_MOHC-HadGEM2-ES_historical_r1i1p1_ICTP-RegCM4-7_v0.nc

*850_AFR-22_MPI-M-MPI-ESM-MR_historical_r1i1p1_ICTP-RegCM4-7_v0.nc

*850_AFR-22_NCC-NorESM1-M_historical_r1i1p1_ICTP-RegCM4-7_v0.nc

With regards to the fact that u and v wind components were available only on a monthly timestep in CMIP6, we compared the daily and monthly relative vorticity values at 800 hPa in ERA5 for all the months of the rainy season (Oct-Mar). The histograms are displayed below in Figure 5, with the daily ζ values as in Howard et al., 2018 on the left panel and the monthly values on the right. The difference in the y-axis results from the fact that when ζ is calculated using a daily timestep, the histogram is drawn using 5.421.825 values, while when the ζ is calculated using monthly u and v values, it is drawn using 178.200 values (for the period 1986-2005). The histograms display only cyclonic vorticities. Green lines display the threshold set by Howard et al., 2018 (ζ values $< -4 \times 10^{-5}$ s^{-1}), while red values display the threshold set by Desbiolles et al., 2020 (ζ values $< -1.5 \times 10^{-5}$ s^{-1}). As it is shown, using the distribution of the monthly values has a much shorter tail and the Howard et al., 2018 threshold appears to be very strict, as a criterion for the identification of Angola Low events.

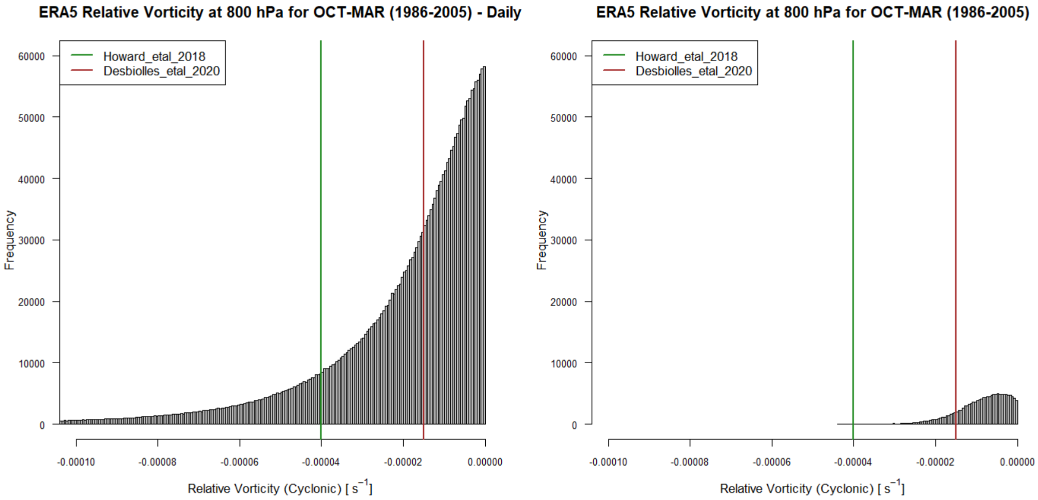

Figure 6: Histogram of relative vorticity for months Oct-Mar during 1986-2005 in ERA5 using daily u and v values (left) and using monthly u and v values (right). Pixels used are enclosed by the region from 14 ºE to 25 ºE and from 11 ºS to 19 ºS.

With regards to the question of whether the 850 pressure level can be used instead of 800 hPa as in Howard et al., 2018, we examine monthly relative vorticity in ERA5 in both pressure levels, within the region from 14 ºE to 25 ºE and from 11 ºS to 19 ºS. The results are displayed in Figure 6. Both distributions are very similar in shape, maxima and spread, although the distribution of ζ values at 800 hPa appear to have a shorter tail. On both panels, both the Howard et al., 2018 and Desbiolles et al., 2020 thresholds are indicated. We conclude that 850 pressure level can be used instead of 800 hPa.

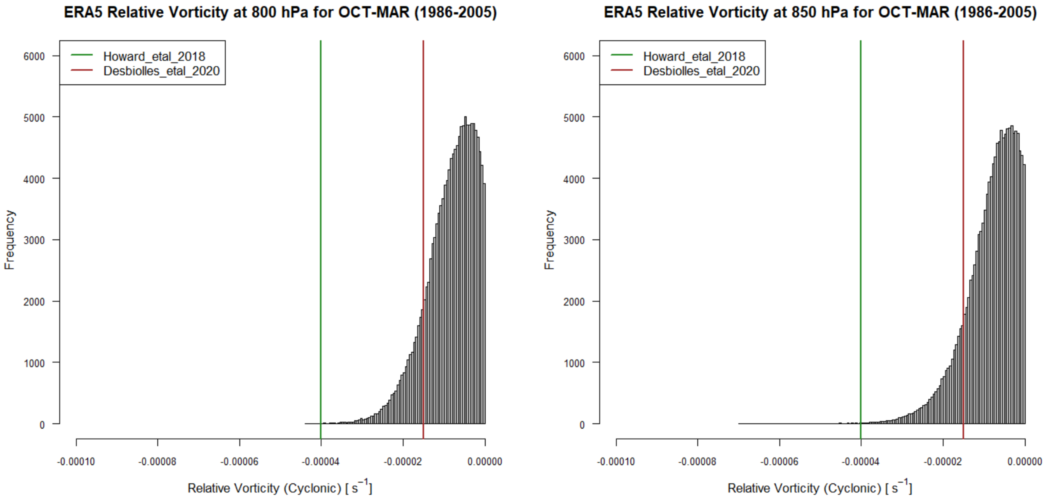

Figure 7: Histogram of relative vorticity for months Oct-Mar during 1986-2005 in ERA5 using u and v values at 800 hPa (left) and using u and v values at 850 hPa (right). Pixels used are enclosed by the region from 14 °E to 25 °E and from 11 °S to 19 °S. For both histograms mean monthly u and v values are used.

Lastly, with regards to the question of what the optimal threshold for the identification of Angola Low events in all datasets would be, we investigate the statistical distribution of mean monthly cyclonic vorticities in all ensembles used, for the 850 hPa pressure level. The results are displayed in Figure 7. In all histograms the Howard et al., 2018 and Desbiolles et al., 2020 thresholds are drawn. As it is indicated, the Howard et al., 2018 threshold is too strict and for 3 out of 4 ensembles it does not even correspond to existing ζ values. We conclude that the threshold used in Desbiolles et al., 2020 (ζ values $< -1.5 \times 10^{-5}$ s^{-1}) is reasonable, considering the shape of the distributions examined. However, when the Desbiolles et al., 2020 threshold was applied to the data, it was also found that it was too strict, especially for CMIP5/6. Hence, we now use monthly relative vorticity in order to identify Angola Low events, by employing the ζ values $< -1 \times 10^{-5}$ s^{-1} threshold.

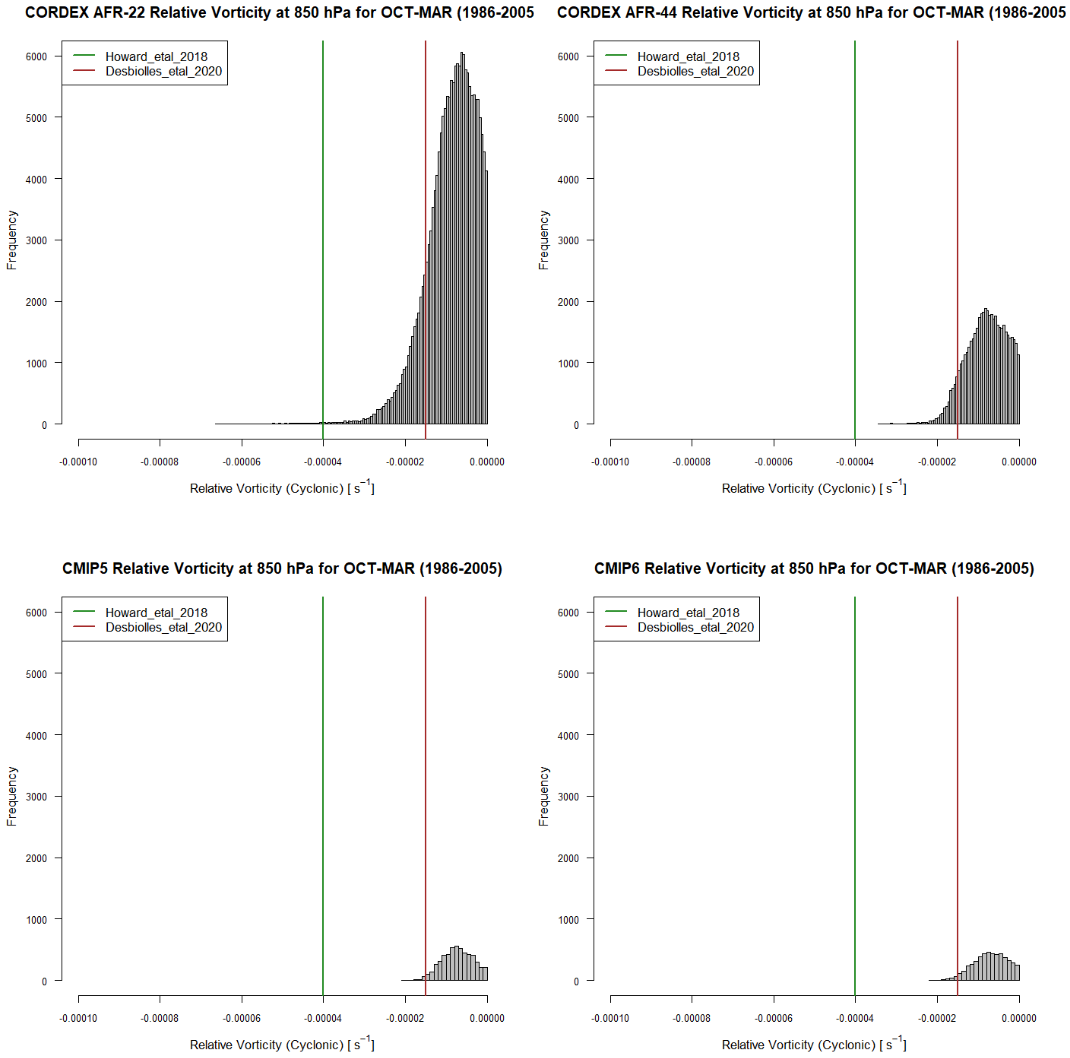

Figure 8: Histogram of relative vorticity for months Oct-Mar during 1986-2005 at 850 hPa for CORDEX-Africa at 0.22° (upper left), for CORDEX-Africa 0.44° (upper right), for CMIP5 (lower left), and for CMIP6 (lower right). Pixels used are enclosed by the region from 14 °E to 25 °E and from 11 °S to 19 °S. For all histograms mean monthly u and v values are used.

4th Comment:

Page 9, section 3.3. Apart from the strength of the Angola Low, its position also plays an important role, which I suggest being included.

RESPONSE: Thank you. We now include mean monthly maps of relative vorticity (applying the $\zeta < -1 \times 10^{-5}\ s^{-1}$ threshold for the identification of Angola Low events) (shaded) and the potential temperature at 850 hPa overlayed on them in the form of contours.

5th Comment:

Page 10, Section 3.5. It would be good to also see how many models agree on the sign of the trends in addition to the significance in Fig S5.

RESPONSE: Thank you for this suggestion. We now include the following figure in the supplementary material, displaying the number of models in each ensemble that display either increasing or decreasing trends.

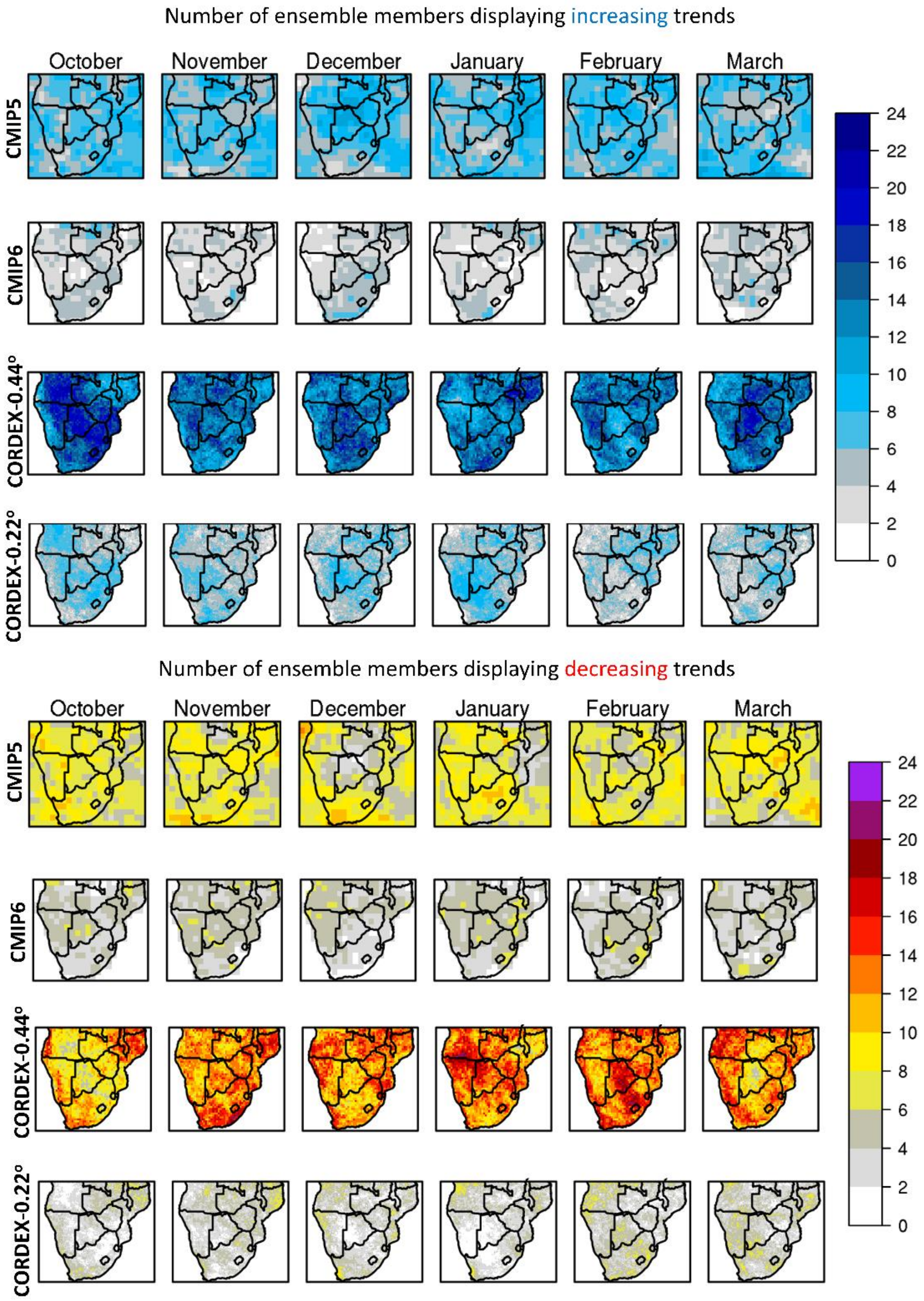

Figure 9: Number of ensemble members in each ensemble displaying increasing or decreasing trends.