Responses to Anonymous Reviewer 1

General Comment:

The paper presents an analysis of precipitation in Southern Africa from RCMs, CMIP5 and 6, GCMs and observational data during a historical period from 1986-2005. The authors make use of several groupings of RCMs, GCMs and observational data into ensembles for a more thorough analysis. The focus of the paper is on the differences in annual and monthly rainfall in the southern Africa region between the different sets of ensembles and in terms of various metrics of rainfall. The paper also compares the trend in rainfall over this historical period between the RCMs, GCMs, and observational ensembles to understand the fidelity of the models compared to observed datasets in this region. In general, I find the paper well sourced and written however there are some instances where I find the wording confusing. I find the scientific analysis of the paper quite sound and thorough. My main concerns with the paper are that the novelty of the paper within the context of model development is not clearly defined. I also find the analysis and conclusions quite general and I think the focus of the paper could be improved.

RESPONSE: We thank very much Anonymous Reviewer #1 for this comment! We have followed closely their corrections and recommendations and we have addressed all points stated.

Major comments:

1st Comment:

I recommend more clearly laying out what the novelty or newness is of this work. Based on previous work it seems that precipitation in this region has been studied in similar ways before. Why is the method/results/approach in this work an improvement on those studies?

RESPONSE: Thank you very much for this comment. Indeed, precipitation over southern Africa has been studied before. More specifically, Nikulin et al. (2012) was the first to present an overview of the CORDEX-Africa ensemble and to analyze the spatiotemporal patterns of precipitation. They showed that during the rainy season (Jan-Mar as used in Nikulin et al. (2012)) there is a weak wet bias over southern Africa, and that the use of the ensemble mean was able to outperform individual models, highlighting the importance of ensemble-based approaches. The Nikulin et al. (2012) analysis was conducted on a pan-African scale. Similarly, Kalognomou et al., (2013) analyzed the same ensemble of CORDEX-Africa simulations, focusing over southern Africa and reported similar findings to Nikulin et al., (2012). In Shongwe et al. (2014) a particular emphasis was put on the onset and retreat of the rainy season, especially over the eastern part of southern Africa. Nonetheless, as stated in Shongwe et al. (2014) "No attempt is made in this paper to identify the model physics and dynamics responsible for the differences in RCM performance." All the aforementioned studies employed the evaluation (hindcast) simulations performed within CORDEX-Africa, driven by ERA-Interim; the analyzed ensemble was comprised of 10 RCMs. It is also worth mentioning that the regional climate model (RCM) versions used in the studies listed above, refer to previous versions of the respective RCMs, which have now been replaced by newer versions in more recent studies.

In Meque and Abiodun (2015) the same ensemble of 10 hindcast simulations was again used, but it was also compared with a set of CMIP5 GCM simulations, with the purpose to identify a causal association between ENSO and drought events over southern Africa. In Meque and Abiodun (2015) it was stated for the first time that RCMs were able to provide added value, compared to their driving GCMs. The issue of the added value of the CORDEX-Africa ensemble was clearly stated in Dosio et al. (2015), where 1 RCM participating in CORDEX-Africa (CCLM) was compared against 4 different driving GCMs. In Favre et al. (2016) a special focus was given on the annual cycle of precipitation over South Africa, using the same ensemble of 10 CORDEX-Africa hindcast simulations and in Abba Omar and Abiodun (2017), although the same hindcast ensemble was used, there was an effort to associate extreme precipitation events with dynamical processes such as the Tropical Temperate Troughs.

A comprehensive assessment of the added value between historical CORDEX-Africa RCMs simulations and of their driving CMIP5 GCMs on a seasonal timescale over the whole of Africa, was performed in Dosio et al. (2019). The first time the CORDEX-Africa

ensemble over southern Africa was compared with a plethora of observational and satellite products was presented in Abiodun et al., (2020), while the first time that CORDEX Africa at 0.44^o and at 0.22^o was analyzed compared to both CMIP5 and CMIP6 ensembles is presented in Dosio et al. (2021). More specifically, in Dosio et al. (2021) the analysis is performed on a seasonal timestep and on pan-African scale and its particular emphasis is placed on the projected changes of future precipitation, although a part of the analysis is dedicated to the period 1981-2010.

Our work aims to provide a comprehensive overview of the observed precipitation climatology particularly focusing over southern Africa, in all tools that are currently available in the climate community. For this reason, we employ all four ensembles used in Dosio et al. (2021) for the period 1986-2005 and we additionally employ a set of 12 observational (satellite, gridded and reanalysis) products. By doing so, we aim to highlight the precipitation uncertainty that exists even among different observational products, which is inherent in the methods used for their production. In addition, we attempt to make a connection between monthly precipitation climatology over southern Africa and a particularly important atmospheric feature, the Angola Low pressure system. To our knowledge, the Angola Low pressure system has not been studied yet within the context of CORDEX-Africa simulations. Although there has been an ample work of evaluating CORDEX-Africa simulations, we think that in order to better understand the reasons why RCM simulations do, or do not, display an improvement relative to their driving GCMs, there must be a shift towards process-based evaluations that examine particular (thermo)dynamic atmospheric processes over specific regions and specific time periods. For this reason, we also chose to perform our analysis on a monthly timescale during the rainy season (Oct-Mar). Often, seasonal means are conveniently used, however, seasonal averages might obscure spatio-temporal patterns that can only be identified on a finer temporal resolution. One of the main hindrances that often limits the ability to perform dynamic analysis in CORDEX-Africa (and CORDEX in general) simulations is the lack of available variables at different pressure levels. This was a shortcoming in our analysis also. In addition, we discuss the results with respect to monthly precipitation trends, as seen in all observational and modeling ensembles we use.

We agree that we need to present more clearly in the manuscript what the novelty and the newness of this work is. For this reason, we made the following changes in the Introduction:

Section to last paragraph: “Therefore, in this paper we expand on previous research to investigate how monthly precipitation during the rainy season over southern Africa is simulated by different modelling systems, by analyzing the monthly precipitation climatologies, the interannual variability, specific precipitation indices and monthly precipitation trends during the period 1986-2005, in four different modeling systems (CORDEX 0.22^o/0.44^o, CMIP5/6) and observational ensembles (satellite, reanalysis and gridded datasets). Our main goal is to provide a comprehensive overview with regards to precipitation climatology over SAF as simulated by the state-of-the-art tools used by

climate scientists. In addition, we investigate whether higher resolution models are able to provide an improved representation of precipitation over southern Africa and we investigated how a particularly important atmospheric feature, the Angola Low pressure system, is simulated in the RCM and GCM ensembles."

References:

Abba Omar, S., Abiodun, B.J., 2017. How well do CORDEX models simulate extreme rainfall events over the East Coast of South Africa? Theor. Appl. Climatol. 128, 453–464. https://doi.org/10.1007/s00704-015-1714-5

Abiodun, B.J., Mogebisa, T.O., Petja, B., Abatan, A.A., Roland, T.R., 2020. Potential impacts of specific global warming levels on extreme rainfall events over southern Africa in CORDEX and NEX-GDDP ensembles. Int. J. Climatol. 40, 3118–3141. https://doi.org/10.1002/joc.6386

Dosio, A., Jones, R.G., Jack, C., Lennard, C., Nikulin, G., Hewitson, B., 2019. What can we know about future precipitation in Africa? Robustness, significance and added value of projections from a large ensemble of regional climate models. Clim. Dyn. 53, 5833–5858. https://doi.org/10.1007/s00382-019-04900-3

Dosio, A., Jury, M.W., Almazroui, M., Ashfaq, M., Diallo, I., Engelbrecht, F.A., Klutse, N.A.B., Lennard, C., Pinto, I., Sylla, M.B., Tamoffo, A.T., 2021. Projected future daily characteristics of African precipitation based on global (CMIP5, CMIP6) and regional (CORDEX, CORDEX-CORE) climate models. Clim. Dyn. 57, 3135–3158. https://doi.org/10.1007/s00382-021-05859-w

Dosio, A., Panitz, H.-J., Schubert-Frisius, M., Lüthi, D., 2015. Dynamical downscaling of CMIP5 global circulation models over CORDEX-Africa with COSMO-CLM: evaluation over the present climate and analysis of the added value. Clim. Dyn. 44, 2637–2661. https://doi.org/10.1007/s00382-014-2262-x

Favre, A., Philippon, N., Pohl, B., Kalognomou, E.-A., Lennard, C., Hewitson, B., Nikulin, G., Dosio, A., Panitz, H.-J., Cerezo-Mota, R., 2016. Spatial distribution of precipitation annual cycles over South Africa in 10 CORDEX regional climate model present-day simulations. Clim. Dyn. 46, 1799–1818. https://doi.org/10.1007/s00382-015-2677-z

Kalognomou, E.-A., Lennard, C., Shongwe, M., Pinto, I., Favre, A., Kent, M., Hewitson, B., Dosio, A., Nikulin, G., Panitz, H.-J., Büchner, M., 2013. A Diagnostic Evaluation of Precipitation in CORDEX Models over Southern Africa. J. Clim. 26, 9477–9506. https://doi.org/10.1175/JCLI-D-12-00703.1

Kim, Y.-H., Min, S.-K., Zhang, X., Sillmann, J., Sandstad, M., 2020. Evaluation of the CMIP6 multi-model ensemble for climate extreme indices. Weather Clim. Extrem. 29, 100269. https://doi.org/10.1016/j.wace.2020.100269

Meque, A., Abiodun, B.J., 2015. Simulating the link between ENSO and summer drought in Southern Africa using regional climate models. Clim. Dyn. 44, 1881–1900. https://doi.org/10.1007/s00382-014-2143-3

Nikulin, G., Jones, C., Giorgi, F., Asrar, G., Büchner, M., Cerezo-Mota, R., Christensen, O.B., Déqué, M., Fernandez, J., Hänsler, A., Meijgaard, E. van, Samuelsson, P., Sylla, M.B., Sushama, L., 2012. Precipitation Climatology in an Ensemble of CORDEX-Africa Regional Climate Simulations. J. Clim. 25, 6057–6078. https://doi.org/10.1175/JCLI-D-11-00375.1

Shongwe, M.E., Lennard, C., Liebmann, B., Kalognomou, E.-A., Ntsangwane, L., Pinto, I., 2014. An evaluation of CORDEX regional climate models in simulating precipitation over Southern Africa. Atmospheric Sci. Lett. 16, 199–207. https://doi.org/10.1002/asl2.538

Wyser, K., van Noije, T., Yang, S., von Hardenberg, J., O'Donnell, D., Döscher, R., 2020. On the increased climate sensitivity in the EC-Earth model from CMIP5 to CMIP6. Geosci. Model Dev. 13, 3465–3474. https://doi.org/10.5194/gmd-13-3465-2020

2nd Comment:

In the second to last paragraph of the introduction the purpose and goals of the paper are given but there are several different statements of goals which I find somewhat unfocused. Is there a main goal that can be defined? It seems that the main focus of the paper is on how the RCM ensemble can be shown to be more useful for precipitation projections over this region compared to the GCMs but this is not clear. From the abstract it is also not very clear what are the main results the reader should see.

RESPONSE: Thank you very much for this comment and correction. Our analysis has two main goals: The first goal is to provide an intercomparison of how monthly precipitation during the rainy season over southern Africa is simulated by different modelling systems (CORDEX 0.22º/0. 44º, CMIP5/6) and to also provide an overview of the spread that is seen even among the so called "observational products", highlighting the need for improved modeling and monitoring efforts over the region. Our second goal is indeed, to highlight how RCMs are able to address certain deficiencies identified in GCMs. The second to last paragraph of the introduction has now changed to the following:

"Therefore, in this paper we expand on previous research to investigate how monthly precipitation during the rainy season over southern Africa is simulated by different modelling systems, by analyzing the monthly precipitation climatologies, the interannual variability, specific precipitation indices and monthly precipitation trends during the period 1986-2005, in four different modeling systems (CORDEX 0.22º/0.44º, CMIP5/6) and observational ensembles (satellite, reanalysis and gridded datasets). Our main goal is to provide a comprehensive overview with regards to precipitation climatology over SAF as simulated by the state-of-the-art tools used by climate scientists. In addition, we investigate whether higher resolution models are able to provide an improved representation of precipitation over southern Africa and we investigated how a particularly important atmospheric feature, the Angola Low pressure system, is simulated in the RCM and GCM ensembles."

3rd Comment:

My understanding is that the CORDEX-Africa 0.22º data are available. If so, why was the older 50km dataset used when a newer one was available?

RESPONSE: Thank you for this comment. We have now included all the CORDEX-Africa 0.22º simulations available in the analysis. The CORDEX-Africa 0.22º simulations added, are listed in the table below. We have kept, however, all CORDEX-Africa 0.44º simulations, since they constitute a larger ensemble (26 ensemble members used).

Driving GCMs	RCMs	Realisations	Variables
CanESM2	CanRCM4	r1i1p1	Pr,
HadGEM2-ES	CCLM5-0-15	r1i1p1	Pr, hus850, ua850, va850, ta850
	REMO2015	r1i1p1	Pr, hus850, ua850, va850, ta850
	RegCM4-7	r1i1p1	Pr, hus850, ua850, va850, ta850
MPI-ESM-LR	CCLM5-0-15	r1i1p1	Pr, hus850, ua850, va850, ta850
	REMO2015	r1i1p1	Pr, hus850, ua850, va850, ta850
	RegCM4-7	r1i1p1	Pr, hus850, ua850, va850, ta850
NorESM1-M	CCLM5-0-15	r1i1p1	Pr, hus850, ua850, va850, ta850
	REMO2015	r1i1p1	Pr, hus850, ua850, va850, ta850
	RegCM4-7	r1i1p1	Pr, hus850, ua850, va850, ta850

Minor Comment:

1st Comment:

Line 17: SAF hasn't been defined yet, it should be defined here.

RESPONSE: We have defined SAF in line 10 (beginning of the abstract).

2nd Comment:

Lines 22-23: "…a similar behavior to CMIP5, however reducing slightly the ensemble spread." I would replace 'however' here with 'but'.

RESPONSE: Thank you! We will make this change in the manuscript.

3rd Comment:

Line 61: Over what period is this trend seen? I assume it's a historical period but it would be good to explicitly say it here.

RESPONSE: Thank you! We will make this clarification in the manuscript. The trend is calculated over the period 1986-2005. The sentence in the manuscript will be changed to "During DJF, precipitation trends for the period 1986-2005 over SAF display…".

4th Comment:

Sentence starting at Line 71 "However,…": This sentence is a little bit confusing I would recommend removing 'still' and the comma between 'period' and 'persist'.

RESPONSE: Thank you! The sentence in the manuscript will be changed to "However, although the CMIP6 ensemble exhibits multiple improvements on various levels (Wyser et al., 2020), certain biases and challenges identified in CMIP5 during the historical period persist in CMIP6 (Kim et al., 2020)."

5th Comment:

Line 90: Provide more detail of what will be addressed in the results section (Section 3). For instance, describe the subsections of the results and what will be covered.

RESPONSE: Thank you very much for this comment! This sentence in the manuscript will be changed to: "In Section 3 the results are presented. More specifically, the results are analyzed based on the monthly climatology, the annual cycle of precipitation, the Angola Low pressure system, the ETCCDI precipitation indices and the monthly precipitation trends. Lastly, in Section 4 we provide the discussion of the analysis along with some concluding remarks."

6th Comment:

Line 107: Should this be "less **than** or equal to"?

RESPONSE: Thank you very much. We will change the sentence to "The gauge-based products were chosen so that they have a spatial resolution less than or equal to 0.5^o x 0.5^o…"

7th Comment:

Line 183: How was the calculation of standard deviation done to get the within-ensemble agreement? Was the monthly mean of over the 1986-2005 period calculated for each model first and then the SD of the ensemble taken?

RESPONSE: Yes, we first calculated the monthly means over the period 1986-2005 for each model (or observational dataset) separately, and then we calculate the standard deviation.

8th Comment:

Figures 1, 2 and 7: The alignment and spacing of the panels is not consistent. I recommend making sure the Figures have consistent spacing and are aligned to improve their visual aesthetic.

RESPONSE: Thank you! We will make this correction in all panel plots!

9th Comment:

Lines 355-356: Expand on what improvements can be made. This is an important statement for readers who may be interested in expanding on this work.

RESPONSE: Thank you very much for this comment. The paragraph in the manuscript has been changed to the following: “In conclusion, while CORDEX-Africa displays marked improvement over coarser resolution products, there are still further improvements to be made. More specifically, since the wet bias in RCM simulations persists (although considerably reduced relative to GCMs), it is necessary that precipitation over southern Africa is no longer assessed based on bulk descriptive statistics, but that there will be a shift towards process-based evaluation, where the dynamical and thermodynamical characteristics of specific atmospheric features are investigated more thoroughly in the CORDEX-Africa simulations. For this reason, it is imperative that all institutes submitting RCM simulations in data repositories such as the Earth System Grid Federation or the Copernicus Climate Data Store, provide model output data on multiple pressure levels, so that a fair comparison with the CMIP community would be possible. In addition, since the climate of southern Africa is highly coupled with the moisture transport coming from the adjacent oceans, it is necessary that the next generation of RCM simulations within CORDEX-Africa are performed coupled with ocean models. Lastly, since convection over southern Africa has a strong thermal component during specific months of the year, it is necessary that the land-atmosphere coupling processes within each RCM are examined in more detail, with coordinated efforts such as the LUCAS Flagship Pilot Study (https://ms.hereon.de/cordex_fps_lucas/index.php.en), as performed in the Euro-CORDEX domain. In the world of regional climate modelling community, the 0.44^{o} resolution of CORDEX-Africa is no longer state of the art and ensemble efforts are now approaching convection permitting grid-spacing (i.e., < 4 km) in some parts of the world (Ban et al., 2021; Pichelli et al., 2021). The next generation ensembles for Africa will hopefully provide insight and improvements to the challenges described here.”