Point by Point Response for Reviewer 1

General Comment:

This paper "High-resolution downscaled CMIP6 drought projections for Australia" is well written, with a clear structure, well-chosen illustrations and well explained results to address their research question: representing the characteristics of meteorological droughts in Australia at high-resolution.

I particularly commend the introduction and the discussion, giving a very good perspective on the study and its results.

I feel the comments from the previous reviewers have been well addressed, with pertinent elements added to the article and comprehensive answers written.

I recommend this article for publication and only have a few minor comments, notably to improve the presentation of the methodology and the choices made in the downscaling part of the study.

Response:

Thank you for the time spent reviewing the article and for the positive and constructive feedback. Our comments below indicate where we have made changes to the manuscript to address these concerns.

Minor Comment:

My main issue in the paper is related to the section "2.2 Data", which I feel could be made clearer. It would be helpful to better present the project for which the downscaling was done, to explain some of the choices made. Why "some model variants were downscaled multiple times" (l.114) ? This sentence seems to come too early, and corresponds to the explanation given l. 124 and Table 1? How did the authors select their model ensemble? Why are some CMIP6 models downscaled with different set-ups and not others? This needs to be better explained, especially since in the later sections, we need to understand when it is pertinent to analyse the 15-model ensemble, or rather consider an 11-model average. It would made the section 2.4 clearer (l. 196 to 204).

Response:

We have revised our 'Data' Section to make the downscaling approach clearer by including additional information on the downscaling methodology and the model selection process. The model selection process was based on a combination of data availability, model performance, model independence, and the climate change signal. Both atmosphere only and ocean-coupled simulations were considered to test improvements from new ocean coupling modelling techniques. These choices were made with all climate hazards in mind and not just droughts. We have explained the downscaling and model selection approach in our manuscript (refer to lines 115-143 of our revised manuscript for implementation of these changes):

'We used the CCAM model developed by CSIRO (McGregor & Dix, 2008) to dynamically downscale 15 CMIP6 GCMs. Typically, dynamical downscaling involves running an RCM over a limited domain, with the host GCM forcing the lateral boundaries. CCAM differs as it is a global stretched grid model and so is run for the entire globe, with the domain of interest run at a higher resolution. Here, instead of providing lateral boundaries, the regional atmosphere in CCAM is influenced by large scale climate simulated from the host GCM, while at a small scale

the atmosphere is allowed to evolve freely (Thatcher & McGregor, 2009). CCAM was run using a stretched C288 grid in both atmospheric and ocean-coupled versions, which consists of a model resolution of approximately 10 km. In total, 35 vertical layers in the atmosphere and 30 layers in the ocean for the ocean-coupled models were applied (Thatcher et al., 2015). A downscaling approach outlined by Hoffman et al. (2016) was used, which involved bias correcting the sea surface temperatures and sea ice from the host GCMs prior to downscaling. This approach has been found to improve the simulations of climate from CCAM and other regional climate models (Hoffmann et al., 2016; Kim et al., 2020; Lim et al., 2019).

*We used an ensemble of 60 downscaled climate model simulations derived from 11 different CMIP6 GCMs (Table 1). The ensemble consists of 15 runs for historical simulations and three sets of 15 runs for future simulations under three Shared Socioeconomic Pathways (SSP126, SSP245 and SSP370), representing low, moderate, and high-emissions pathways, respectively. The ensemble of GCMs used in this study was selected in order to best represent the future spread in the climate change signal from the ensemble of global CMIP6 models, while prioritising models which were better able to represent the Australian climate (Trancoso et al., 2023). For instance, we selected several GCMs spread across the distribution of projected temperature and precipitation changes, but also outlier models representing the driest (ACCESS-ESM1.5) and wettest (EC-Earth3) GCMs (Chapman et al., 2023). All the GCMs were assessed based on their ability to represent Australia's precipitation and temperature compared to Australian Gridded Climate Data Project (AGCD; Evans et al., 2020) observational data between 1995 and 2014 using the Kling-Gupta Efficiency (KGE). The climate change signal at the mid and end of the century was evaluated and combined with the KGE score from the historical simulations to select the best performing ensemble runs from the different GCMs through a Skill-Spread-Selection algorithm (Trancoso et al., 2023). Five of the CCAM simulations were run using dynamic atmosphere-ocean coupling as presented in **Error! Reference source not found.** in order to better understand the influence of ocean coupling on model outputs. Additionally, three variants including the best performing, the wettest, and the driest ensemble member from the large ensemble (40 members) of ACCESS-ESM1.5 simulations were considered, to facilitate assessments of intra-model variability and the influence of initial conditions. This represents the largest downscaled ensemble of projections in Australia ran at the highest resolution.'*

<u>*Minor Comment:*</u>

Also, the authors mention that the downscaling approach significantly improve the performance on temperature and precipitation than using the coarse scale GCMs. Against which observation data? Since we are in the data section and that observation data are directly mentioned in the following paragraph, I feel this information could be added.

<u>*Response:*</u>

We have clarified which observational dataset was used to determine the improvements in downscaling which are detailed in (Chapman et al., 2023) (refer to lines 147-150 of our revised manuscript for implementation):

'The downscaling approach adopted has been shown to significantly improve the performance over the host GCMs for precipitation and temperature in all seasons when compared to gridded AGCD observational data, with the largest improvements noted for climate extremes, even when assessed across the four Australian IPCC regions (Chapman et al., 2023), which are similar

to the NRM super-clusters adopted in this study.'

Minor Comment:

Still in the methodological part, section 2.3, the authors mention a calibration on the historical period to fit the SPI and SPEI distribution in the future period.

I do not understand fully how this was conducted, and also how it fits with the analysis later on of the changes in the SPI and SPEI distributions and shifts in percentiles, if these distributions have been calibrated…

The paragraph from l. 174 to l. 180 needs to be made clearer, with more details given on the transfer function used for the calibration, if there was a calibration. The first section of the results (3.1) seems to imply that there was none, since you look at the biases between observation and simulation. Otherwise, how does the calibration changes the performances? I am confused.

Response:

The term calibration period relates to the period of data used to fit the Gamma and Log-Logistic distributions to derive SPI and SPEI, respectively. The fitted parameter values are then applied to estimate the SPI and SPEI values from the precipitation and potential-evapotranspiration data. There was no 'calibration' performed in our analysis. To avoid this confusion, we have changed all references from 'calibration period' to 'historical period' throughout the manuscript. Additionally, we have revised the description of text which was confusing (refer to lines 192-198 of our revised manuscript for implementation):

'However, when assessing changes to these indices as a result of climate change, a historical period is commonly adopted to fit the distribution. The fitted distribution parameter values are then applied to estimate the SPI and SPEI for the future period, allowing for a comparison of projected future dryness and wetness compared to the recent past. For our assessment, we have adopted a historical period from 1981-2010 to fit the Gamma and Log-Logistic distributions for SPI and SPEI, respectively. Fitted distribution values were then used to calculate SPI and SPEI over the full timeseries, containing both historical and future simulations (1981-2100).'

Specific Comment:

There is a redundant information in the introduction, with l.65 to 69 similar to l.84 to 86. Since the structure of your introduction shows: the use of GCM (l.54 to 64), their limits and the use of RCMs (l.65 to 70), but last studies used for CMIP5 (l.71 to 81), I feel you could reorganise slightly l81 to 86. It would avoid the redundancy and better highlight that you want to work with CMIP6, and it is the main novelty of your study.

Response:

Thank you for bringing this to our attention. We have revised the introduction by reworking what was said previously in lines 81-86 into the earlier paragraphs as suggested.

Specific Comment:

To help the method section of the article, I think you could mention the RCM you used in the end of your introduction and detail a bit more the Queensland Future Climate Science Program (QFCSP).

Response:

In accordance with the reviewer's recommendation we have revised the end of the introduction to provide some further details of the downscaling and of the QFSCP (refer to lines 84-93 of our revised manuscript for implementation):

'This study expands on the available body of knowledge for future meteorological droughts in Australia, employing an ensemble of 60 high-resolution dynamically downscaled CMIP6 simulations (15 historical and 45 future simulations). The downscaling was performed using dynamically downscaled using the Conformal Cubic Atmospheric Model (CCAM), and followed the CORDEX experimental protocol. These projections form part of the Queensland Future Climate Science Program (QFCSP) and are available at a 10 km resolution over the Australian continent as the QldFCP-2 data set (Queensland Future Climate Projections 2). The QldFCP-2 simulations were shown to lead to improvements in mean climate over the historical period, however, the largest improvements were noted for climate extremes, particularly over coastal and mountainous regions (Chapman et al., 2023). These projections form part of a national strategy for climate projections, contributing to a wider set of downscaled CORDEX compliant projections for Australia as part of the National Partnership for Climate Projections (Grose et al., 2023), which will underpin climate services and adaptation planning nationally.'

Specific Comment:

P.7: you use a notation SPI/SPEI. If I understood correctly, it means "SPI or SPEI". Be careful, it looks like a ratio. I feel this need to be changed.

Response:

As suggested, we have changed this to 'SPI or SPEI'

Specific Comment:

Section 3.2.2: how do you define the "area affected by droughts"? Is it all pixels for which there is at least one drought event (depending on the severity of the drought event defined)?

Response:

The area affected by drought, is the percentage of the area (i.e., number of grid cells affected by drought divided by total number of grid cells within a given region) at any given timestep, which are categorised as in drought (depending on the severity). This results in a timeseries of the percentage of area in drought for a given region. We have clarified this in the methods section (refer to lines 205-208 of our revised manuscript for implementation):

'Here, the frequency is defined as the total number of events recorded over a given time period, the duration is the average duration of recorded drought events (in months), the percent time in drought is the fraction of time droughts occur, and the spatial extent is the number of grid cells affected by each drought severity category divided by total number of grid cells within a given region for each timestep.'

Specific Comment:

L. 352-354: unclear : "differences between the 10th and 90th percentiles"?

Response:

We have revised this to make it clear we are referring to the range between the 10^{th} and 90^{th} percentiles (refer to lines 370-372 of our revised manuscript for implementation):

'There was a large range between the 10th and 90th percentile ensemble projections for both SPI and SPEI (Fig. S16 to Fig. S21), highlighting the uncertainty in these projections.'

Specific Comment:

Sentence l. 212-213 is not clear. A percentile can not be a shift. The sentence is not correct. Ta define a shift, you need a reference. So I think I understand what you mean. If the 50th percentile in the projected distribution matches the 40th percentile in the historical period, therefore there is a 10% shift towards dryness.

Response:

Your interpretation is correct. We have revised this sentence as suggested (refer to lines 229-230 of our revised manuscript for implementation):

'We therefore assessed when significant changes to the long-term average values occurred based on a 10% and 20% shift towards dryness compared to the historical period.'

Specific Comment:

L. 383: "time in" ?

Response:

We have clarified this in the text by changing 'time in' to "percentage of time spent in drought'.

Specific Comment:

L. 424: What does "this" refer to? The elevated PET?

Response:

We have clarified the text by changing 'this' to 'atmospheric water demand'.

Specific Comment:

L. 454: "may better" □ "would rather" ?

Response:

We have made this change.

References:

Chapman, S., Syktus, J., Trancoso, R., Thatcher, M., Toombs, N., Wong, K. K.-H., & Takbash, A. (2023). Evaluation of Dynamically Downscaled CMIP6-CCAM Models Over Australia. *Earth's Future*, *11*(11), e2023EF003548. https://doi.org/10.1029/2023EF003548

Evans, A., Jones, D., Smalley, R., & Lellyett, S. (2020). An enhanced gridded rainfall analysis scheme for Australia. *Australian Bureau of Meteorology: Melbourne, VIC, Australia*, *66*, 55–67.

Grose, M. R., Narsey, S., Trancoso, R., Mackallah, C., Delage, F., Dowdy, A., Di Virgilio, G., Watterson, I., Dobrohotoff, P., Rashid, H. A., Rauniyar, S., Henley, B., Thatcher, M., Syktus, J., Abramowitz, G., Evans, J. P., Su, C.-H., & Takbash, A. (2023). A CMIP6-based multi-model downscaling ensemble to underpin climate change services in Australia. *Climate Services*, *30*, 100368. https://doi.org/10.1016/j.cliser.2023.100368

Hoffmann, P., Katzfey, J. J., McGregor, J. L., & Thatcher, M. (2016). Bias and variance correction of sea surface temperatures used for dynamical downscaling. *Journal of Geophysical Research*, *121*(21), 12,877-12,890. https://doi.org/10.1002/2016JD025383

Kim, Y., Rocheta, E., Evans, J. P., & Sharma, A. (2020). Impact of bias correction of regional climate model boundary conditions on the simulation of precipitation extremes. *Climate Dynamics*, *55*(11–12), 3507–3526. https://doi.org/10.1007/S00382-020-05462-5/FIGURES/10

Lim, C. M., Yhang, Y. B., & Ham, S. (2019). Application of GCM Bias Correction to RCM Simulations of East Asian Winter Climate. *Atmosphere 2019, Vol. 10, Page 382*, *10*(7), 382. https://doi.org/10.3390/ATMOS10070382

McGregor, J. L., & Dix, M. R. (2008). An updated description of the conformal-cubic atmospheric model. In *High Resolution Numerical Modelling of the Atmosphere and Ocean* (pp. 51–75). Springer New York. https://link.springer.com/chapter/10.1007/978-0-387-49791-4_4

Thatcher, M., McGregor, J., Dix, M., & Katzfey, J. (2015). A new approach for coupled regional climate modeling using more than 10, 000 cores. *IFIP Advances in Information and Communication Technology*, *448*, 599–607. https://doi.org/10.1007/978-3-319-15994-2_61/COVER

Thatcher, M., & McGregor, J. L. (2009). Using a Scale-Selective Filter for Dynamical Downscaling with the Conformal Cubic Atmospheric Model. *Monthly Weather Review*, *137*(6), 1742–1752. https://doi.org/10.1175/2008MWR2599.1

Trancoso, R., Syktus, J., Toombs, N., & Chapman, S. (2023). *Assessing and selecting CMIP6 GCMs ensemble runs based on their ability to represent historical climate and future climate change signal* (Nos. EGU23-11412). EGU23. Copernicus Meetings. https://doi.org/10.5194/egusphere-egu23-11412