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Climate of the Past Discussions

Interactive comment on "Understanding the Australian Monsoon change during the Last Glacial Maximum with multi-model ensemble" *by* Mi Yan et al.

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General Comments This paper presents a multi-model study of changes in the Australian monsoon at the Last Glacial Maximum based on PMIP3 simulations. The topic is an important one, and the study presents interesting results showing a change in seasonality of rainfall, with increased seasonal cycle due to winter drying and early summer rainfall increases. The mechanisms producing this change are also explored, and the role of local circulation changes due to altered land configuration is identified as a major contribution to the changes. The study fails to adequately introduce the climate models used, or to deal with the uncertainty due to model biases or model disagreement on the sign of rainfall changes. The study also employs an overly simplistic method to decompose quantitative changes in rainfall due to dynamic and thermodynamic factors, relying entirely on multi-model mean changes and using a Clausius-Clapeyron scaling that is too large for the thermodynamic component. Despite these limitations, I believe the study could make a valuable contribution to our understanding of Australian monsoon rainfall changes under LGM conditions. Major revisions are recommended, as outlined below in my comments.

Reply to General Comments: Thank you very much for the comments on the models' uncertainties and on the method of attribution of the changes in precipitation to dynamic and thermodynamic factors. In the revised version, we implemented a brief discussion of the models' uncertainties along with the possible factors leading to the model biases, see Lines 383-405 in the revised text. We have also added a short description of the decomposition method in the revised version. Please find the details in the Reply to Specific Comment 8. We acknowledge your valuable comments and suggestions to improve our work.

Specific Comments 1. Line 69: The Australian monsoon is not defined clearly here or elsewhere, and the definition is not consistent throughout the paper or with other studies. Which domain is used? Does it include the Maritime Continent? Are land and ocean model grid points used? Is the domain the same in all models? How is the area shown in red in Figure 1a defined, and why does it include parts of the South Pacific Convergence Zone? Note that the largest rainfall changes (Fig 1a) are over ocean to the north of Australia. If the results in this study are the area average over the grid points enclosed by the red line, then they represent mainly changes over PNG and the Maritime Continent, which makes it difficult to compare with proxy records or model studies focused on Northern Australian land areas. I suggest to re-calculate rainfall changes over Northern Australian land areas only (e.g. to 20S or 25S) and discuss and consider whether the results are consistent with those for the larger Australia-Maritime Continent domain. Also, monsoon strength or intensity is defined in several different ways. Here (line 70) it is stated that a strong monsoon means wet conditions, whereas elsewhere a strong or intense monsoon means a large seasonal difference in rainfall between wet and dry seasons. Please clarify: What is the monsoon domain used? Does it include both land and ocean? How is monsoon strength and intensity defined?

Reply: The monsoon domain is defined following hydroclimate definition, i.e., a contrast between wet summer and dry winter (Wang and Ding 2008). The monsoon domain is defined by the area where the annual range (local summer minus local winter) exceeds 2.0 mm/day, and the local summer precipitation exceeds 55% of the annual total precipitation. Here in the southern hemisphere, summer means November to March and winter means May to September. Since the domains derived from different models are different, and the changes of domain are also different, we use the fixed domain derived from the merged CMAP-GPCP precipitation data. The domain includes both land and ocean areas. A brief statement has been added as the Sec. 2.3 in the revised version, Lines 173-184. Note that the monsoon domain is shown only to give a general view of precipitation change, but not the main focus of this study. The seasonal distribution of the area averaged precipitation (Fig. 1b) is not based on the monsoon domain, but on the area where the annual range is increased, which is (20°S-EQ, 115°E-145°E) (as seen in Fig. 1a). To make it easier to compare with proxy records, the rainfall changes are re-calculated over Northern Australian land areas (20°S-5°S, 120°E-145°E) as suggested. The monsoon intensity in this study is represented by the annual range or the seasonality, i.e., the local summer minus the local winter. This has been clarified throughout the revised version.

2. Lines 72-75: Several of these records are not from the monsoon region, so are not relevant here.

Reply: Those unrelated papers (Treble et al. 2017; Bowler et al. 2012) are removed from the revised version.

3. Line 94: Multi-model ensembles can also provide a clearer perspective on model uncertainty (when all models agree, the result may be more robust – although not always, as models may share systematic biases).

Reply: Good point. It has been added to the revised version, Lines 94-95.

4. Lines 102-104: "This result... has not been proved yet" – it is not clear whether this discussion refers to models or proxy records. It is important to distinguish between these two sources of information, and to acknowledge that neither provides a "true" record of the LGM as proxy records require interpretation and calibration and may be spatially incomplete, while models contain biases.

Reply: Thanks for your suggestion. "This result" refers to the "simulated results", changed in the revision, Line 102. Also, "Neither model outputs nor proxy records provide a "true" record of the LGM, as proxy records require interpretation and calibration and may be spatially incomplete, while models contain biases" has been added in the revised text, Lines 104-106.

5. Line 104-107: Bayon et al. (2017) discussion of subtropics is not referring to the monsoon, which lies within the tropics. Remove or modify this sentence.

Reply: Modified, Lines 108-110.

6. Line 122: How many models were used? Comment on the model skill in simulating the Australian monsoon rainfall: the models used in PMIP3 are typically lower resolution CMIP5 models, and many do not have high skill in simulating regional rainfall. At least, cite some model evaluation studies of the Australian monsoon in CMIP5 models, e.g. Jourdain et al. (2013), Brown et al. (2016) and summarise model skill in this region.

Reply: Seven models are used in this study (Table 1), four of which have a higher resolution than 2 degrees in atmospheric component. For the oceanic component, the resolutions are even higher in six models (except IPSL). The resolutions of the oceanic components of each model have been added into Table 1 in the revised version. The suggested references have been added to illustrate the model performance. These models' performance in the Australian monsoon region has been summarized in the revised text, see Lines 129-132.

7. Line 166: According to Held and Soden (2006), who should be cited here, global precipitation would be expected to increase (or decrease) by around 2%/K. Previous studies have found a slightly higher scaling of around 3%/K for Asian monsoon rainfall (Endo and Kitoh, 2014).

Reply: Yes, you are right. Here the 7 % change per degree of temperature change comes from the Clausius-Clapeyron (CC) relation, which is also suggested by Held and Soden (2006).

8. Page 8, first paragraph: I am not comfortable with a quantitative decomposition based on the multi-model mean. The sign and magnitude of changes will be different in each model and the decomposition is only valid for individual models. Also, the scaling of precipitation with temperature is likely too strong (see point above). Further, can all these changes be considered linearly? A more robust decomposition of dynamic and thermodynamic changes in each model should be applied, e.g. Seager et al. (2010), Chadwick et al. (2013) or Endo and Kitoh (2014).

Reply: Yes, the changes are different in different models. However, we calculated the changes based on the areas where signal-to-noise ratio exceeds 1, which means this change is relatively robust among the models. Also, the 7 % /K ratio of global precipitation over temperature comes from the Clausius-Clapeyron (CC) relation, which is also suggested by Held and Soden (2006). The actual changes are nonlinear. But we have simplified the changes as linear. For attribution of precipitation changes, we use a simplified relation based on the linearized equation of moisture budget used in the previous works (Chou et al., 2003; Seager et al., 2010; Huang et al., 2013; Endo and Kitoh, 2014; Liu et al., 2016). Considering a quasi-equilibrium state, the vertical integrated moisture conservation can be approximately written as -∫_1000^0 ∇·(qv âČŚ)dpãĂŮ=P-E (1) where q is specific humidity, v âČŚ is horizontal velocity, p is pressure, P is precipitation, and E the surface evaporation. Since water vapor is concentrated in the lower troposphere, the vertical integrated total column moisture divergence can be approximately replaced by the integration from the surface to 500 hPa. Define the Δ (.) as the change from PI to the LGM, i.e.,

Δ(.)=(.)LGM-(.)PI (2)

Then the precipitation change ΔP can be approximately calculated as follows: ΔP=-∫_p1000^p500 Δ(q·âĹĞv âČŚ)dp- ∫_p1000^p500 Δ(v âČŚ·âĹĞq) dp+ΔE (3) To further simplify the equation, we use -ω_500 to represent vertical integrated âĹĞv âČŚ, and q at the surface to represent vertical integrated specific humidity (Huang et al., 2013). Thus, the precipitation change (ΔP) can be represented as

ΔPâĹİω ÌĚ_500·Δq+q ÌĚ·Δω_500+ΔE-ΔT_adv (4)

where ω ÌĚ_500 is 500 hPa vertical velocity in PI, q ÌĚ is surface specific humidity in PI, ΔT_adv is the changes due to the moisture advection (∫_p0^p500 Δ(v âČŚ·âĹĞq) dp). The first term in the right-hand side of (4) (ω ÌĚ_500·Δq) represents thermodynamic effect (due to the change of q), and the second term (q ÌĚ·Δω_500) represents dynamic effect (due to the change of circulation). The above method has been added in the revised Sec. 2.2, Lines 151-172. The spatial distributions of each term in JJA and ND have been provided in the revised version as supplementary figures (Figure S3 and Figure S6). The descriptions are added in the revised text, Lines 226-229 and Lines 301-305. It is clear that the dynamic effect plays more important role than the thermodynamic effect in the precipitation change over Australia and Maritime Continent. But this is not always true for other regions, such as South Africa and South America, where the thermodynamic and dynamic effects have comparable contributions. Based on the new decomposition method, we modified the statements about the contributions of thermodynamic and dynamic effects.

9. Line 241: Where do the monsoon percentage changes come from? The rainfall changes in November-December shown in Figure 6 are in mm/day not %. The model spread (agreement) should also be discussed here and elsewhere: how many models simulate increased rainfall in the LGM and how many simulate decreased rainfall? How does this influence our confidence in the MMM changes?

Reply: The percentage of precipitation change is calculated by the difference between precipitation in LGME and in piControl divided by the climatology in piControl, i.e. (PLGME – P piContrl)/PpiControl *100. Five models simulate increased local summer rainfall and the other two simulate decreased rainfall, please refer to Fig. 13 in the revised version. We have added the area averaged results derived from each model in Table 3 in the revised version, including annual mean, local summer mean and annual range. A short summary has been added in the revised text, Lines 202-208. Since most models are in agreement, we can rely on the MME results.

10. Line 247: See point 1 above, please use a consistent definition of monsoon intensity. I suggest use “intensified seasonality” here for clarity. It is also necessary to describe in this paper how the average summer or wet season rainfall changes at the LGM, as this is the normal measure of the strength of the Australian summer monsoon. You should show (e.g. in a bar chart or table) annual mean and wet season (November to April) rainfall change for EACH model and for the MMM. This provides the context for the more detailed discussion of changes in seasonality and is more directly comparable with proxy reconstructions of annual or wet season rainfall and with studies of future monsoon (wet season) rainfall changes.

Reply: Thank you for the valuable suggestion. The seasonality is used in the revised version to represent the monsoon intensity. As we can see from the seasonal distribution of precipitation changes derived from each model (Fig. 1c) that the largest increasing occurs in the early austral summer (ND), the simulated wet season (November to April) mean precipitation is decreased in all the models. Therefore, we take local summer (DJF) as wet season. The annual mean, DJF mean and annual range of precipitation changes derived from each model are listed in Table 3 in the revised version.

11. Line 258-265: The discussion of Tharammal (2017) is confusing. Do your results agree with theirs? If so, then simply state this.

Reply: Yes, our results are in agreement with theirs. The confusing part has been deleted in the revised version.

12. Line 278: Why would the precipitation change lag the insolation change by two months? Provide a reference.

Reply: In the annual variation, precipitation responds to the lower tropospheric moisture convergence. The moisture change depends on temperature change while the circulation change depends on surface temperature gradients change. The change of the surface temperature lags insolation changes because of the ocean and land surfaces have heat capacity (thermal inertial). In other words, insolation is a heating rate which equals to temperature change (tendency) but not the temperature itself. This has been added into the revised version, see Lines 335-340.

13. Line 288: “Strong convergence rain belt”: Do you mean the ITCZ?

Reply: Yes, it is related to the ITCZ. “ITCZ” is added in the revised text, Line 350.

14. Line 291: A little more northerly? It is not clear what is being compared to what here.

Reply: It is compared to the position in our study. We have clarified in the revised text, Line 352.

15. Line 309 and line 314: See discussion under point 10. State that the monsoon seasonality is amplified or intensified (rather than the monsoon itself).

Reply: Thank you again for point out the misleading statement. All have been changed into “seasonality” in the revised version. For example, Line 410 and Line 416.

16: Page 12, paragraphs 2 and 3: I repeat that I am not comfortable with a quantitative MMM decomposition. At least, you need to make it clear that your results are MMM values and state the model spread or uncertainty as well.

Reply: Changed in the revised version. The quantitative values have been removed. The model uncertainties have been concluded in Lines 443-445 in the revised text.

17. Figure 1: How is the monsoon domain defined? Why does it include the SPCZ region? Show some measure of model spread in Figure 1b, such as standard deviation of model range.

Reply: The monsoon domain is defined following Wang and Ding (2008), i.e., the areas where the annual range (local summer minus local winter) exceed 2.0 mm/day, and the ratio of local summer against annual mean precipitation exceeds 55 %. The definition has been added in the Sec. 2.3 in the revised version. The seasonal distribution derived from each model is added as Figure 1c in the revised version.

18. Figure 10: It may be more useful to show a smaller domain, excluding the North Pacific, with a smaller contour range. This would make the changes in Pacific and Indian Ocean tropical SSTs easier to see.

Reply: Actually, the SST change in a smaller domain was shown in Figure S4 in the original manuscript. SST change in a smaller domain has been used as Figure 10 in the revised version.

19. Figure 11: What is the “increased AR region” (11b)? What is the “central Australian monsoon region” referred to in the caption? Define the domain used.

Reply: The “increased AR region” is the “central Australian monsoon region”, as shown in Fig. 1a. The region used in the revised version has been changed into North Australian land area as suggested, which is (20°S-5°S, 120°E-145°E). The figure caption has been modified in the revised version.

20: Figure 12: I am not sure if this diagram is very useful. Also, arrows (if any) and linking lines are not clear in my print version.

Reply: In the revised version, we only show the local dynamic processes in the two seasons (JJA and ND), which we think is useful for understanding the mechanisms of precipitation change. We have used thick arrows to make it clearer. The modified figure is shown in Figure 16 in the revised version.

21: Table 1: Were all model run years used from each model? This should be mentioned in Section 2. It would be more consistent to use the same number of years from each model.

Reply: Yes, we have used the same number of years for each model to get the model climatology. It has been stated in Sec. 2.1 in the revised text, Lines 133-134.

Technical Corrections Line 85: Change wording: “The change in the Australian monsoon was inconclusive. . .”

Reply: Changed in the revised version, Line 84.

Line 94: Multi-model ensembles can reduce or cancel out the biases, not “delineate” (describe, define) them.

Reply: Modified in the revised version, Line 93.

Line 107: Remove “insight” before “studies”.

Reply: Removed in the revised version, Line 107.

Line 110: Here and elsewhere in the paper, use “thermodynamic” not “thermal dynamic”.

Reply: Yes, all have been fixed in the revised version.

Line 127: A simpler version of the PMIP3 website address is: https://pmip3.lsce.ipsl.fr/.

Reply: Yes, fixed, Line 138.

Line 151: Here and elsewhere, do not use the American term "Fall" to refer to Southern Hemisphere Autumn (use "Autumn").

Reply: All the "Fall" has been changed into "Autumn" in the revised version.

Line 159: Insert "global" before "temperature and humidity".

Reply: Yes, fixed. "global" has been added in the revised version, Line 211.

Line 205: Remove "We noticed that".

Reply: Yes, fixed, Line 230.

Line 256: It is not clear what the personal communication refers to here, I suggest remove it.

Reply: Removed in the revised version, Line 319.

Line 307: Insert "global mean" before "temperature and water vapor".

Reply: Yes, fixed. "global mean" has been added in the revision, Line 408.

Line 336: "Synthesized" does not make sense: should this be "simulated" (i.e. from models) or "multi-model mean" (i.e. averaged over many models)?

Reply: Deleted in the revised version, Line 448.

Line 469: Treble reference is incorrectly appended to Tharammal reference.

Reply: Thank you for pointing out this mistake. This redundant reference has been deleted in the revised version, Line 612.

Please refere to the Supplement File for convenience.

Please also note the supplement to this comment:
https://www.clim-past-discuss.net/cp-2018-24/cp-2018-24-AC1-supplement.pdf

Interactive comment on Clim. Past Discuss., https://doi.org/10.5194/cp-2018-24, 2018.

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Discussion paper