Author response to Reviewer #2

The authors thank the reviewers and editors for beneficial and helpful suggestions for this manuscript. We have carefully revised the manuscript according to the suggestions. According to the reviewer's comments, the following replies have been made in blue.

General Comments: In this article the authors investigated the simulated changes in the mid-Pliocene Precipitation-Evaporation (P-E) pattern relative to the PI simulation. In addition, the authors also attempted to attribute these hydrological cycle changes to its dynamic and thermodynamic component, which is partially influenced by Seager et al. (2010). The results in this article could be useful for a detailed understanding of the mid-Pliocene hydro-climate but in its current form it is lacking some clarifications (listed below) that must be addressed before the publication.

Specific comments:

#1. Equation (1) only deals with the thermodynamic and mean circulation dynamics contribution. The transient eddy contribution and the surface quantities are included in the residual (R) term. It will be nice to see how different is the MMM PmE from the sum of TH and MCD component. This is since the poleward moistening is believed to be a result from the transient eddies and the difference might show this feature. I would also suggest to extend the meridional domain from 60° to 90°.

Response: Thanks for the comments. In fact, one of our main points in this paper is to distinguish the relative contribution of changes in Hadley circulation and Walker circulation to changes of PmE during the mid-Pliocene. Since these circulation anomalies mainly happen at the low latitudes, thus the transient eddies at mid-to-high latitudes are not discussed in this paper. And we have highlighted this point in the paper. For example, in the abstract, we have indicated that "Here, we apply a moisture budget analysis to investigate the response of the large-scale hydrological cycle **at low latitudes** within a 13-model ensemble from the Pliocene Model Intercomparison Project Phase 2 (PlioMIP2)." In the introduction, we have shown "However, it is difficult to distinguish the relative impact of the Hadley circulation and Walker circulation on Pliocene hydrological cycling **at low latitudes**. Fortunately, the three-pattern decomposition of global atmospheric circulation (3P-DGAC; Hu et al., 2017, 2018b, c) method can help us to decompose atmospheric circulation into zonal (i.e., local Walker circulation) and meridional (i.e., local Hadley circulation) circulation **at low latitudes.**"

Indeed, the review's comments are right, the contribution of transient eddies is quite important for poleward moisture. Previous studies indicate that the storm track (transient eddy component) may play a key role in changes in PmE for mid- to high latitudes (Seager et al., 2010; Han et al., 2019a; Han et al., 2019b). In addition, the residual term includes transient eddy contribution, the surface quantities, the nonlinear term and model biases. In the Section 6 "Conclusion and discussion" we have mentioned this, that is "Due to the lack of hourly model data, we mainly discuss the relative contributions from moisture budget components to changes in PmE at low latitudes in this paper. Much more work should be conducted to study the impact of storm tracks on changes in PmE during the mid-Pliocene using hourly data in the future at mid-to-high latitudes."

Therefore, since discussion of transient eddies at mid-high latitudes are not our main point in this paper and there still remain difficulties to distinguish this term from the residual term, and we decide to not discuss this topic in this paper, but in the future studies.

#2. Line 58: The wet-region-getting-wetter and dry-regions-getting drier phenomenon is primarily valid over the ocean. Over the landmass this characteristic is not always true. A study by Greve et al. (2014) reported that only 10.8% of the global land area shows dry gets drier and wet gets wetter pattern.

Response: Thanks for the comments. We have updated the descrption of changes over the ocean and land in the new version as follows:

"Note that this phenomenon is primarily focus on the ocean. A study by Greve et al. (2014) report that only 10.8% of the global land area shows dry gets drier and wet gets wetter pattern." (See Line 62-63)

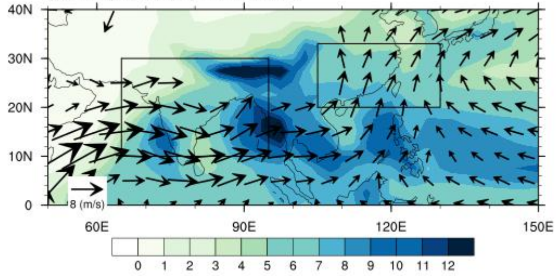
Reference:

Greve, P., Orlowsky, B., Mueller, B., Sheffield, J., Reichstein, M., and Seneviratne, S.I. 2014. Global assessment of trends in wetting and drying over land. Nature geoscience, 7(10), 716-721.

#3. Line 210-211: Did not understood properly the meaning of strengthened East Asian summer monsoon circulation (is it more rainfall or strong winds?) and how it affects the MMM PmE changes over Southeast Asia.

Response: Thanks for the comments. Here the strengthened East Asian summer monsoon *circulation* means strong winds, and subsequent more rainfall as explained in the following. Abundant studies have indicated that the monsoon rainfall changes are highly related to the large-scale circulation anomalies. To examine the changes in monsoon circulation and precipitation, we further show the climate mean and changes in precipitation and 850hPa wind field in Figure S1. Compared to the PI simulation (Figure S1a), there is a robust increased South Asian summer (SAS) rainfall revealed by PlioMIP2 ensembles, with precipitation maxima over north-eastern part of Indian subcontinent and south of Western Ghats region (Figure S1b). These changes in SAS rainfall are consistent with proxy indicators of precipitation over northern ISM region (Feng et al., 2021). Concurrently, the change in 850-hPa wind shows pronounced westerly winds anomalies over SAS region (Figure S1b), indicating strengthened ISM circulation. The similar results can also been seen over East Asian summer (EAS) monsoon region. There is a remarkably strengthened southerly winds anomalies over EAS region (Figure S1b), favoring to increase rainfall there. Therefore, this increased precipitation in monsoon regions result in the positive precipitation minus evaporation (PmE) there.

(a) Precipitation (PI),850hPa wind



(b) Change in Precipitation (Plio-PI),850hPa wind

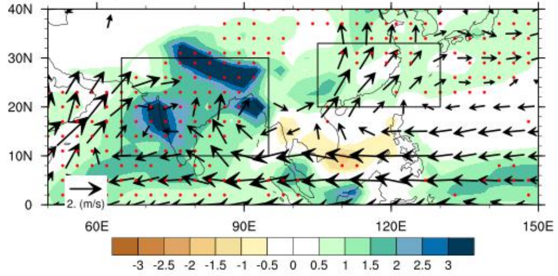


Figure S1. Ensemble (a) climatologies and (b) changes of precipitation (shading, mm/day) and 850 hPa wind (vector, m/s) during boreal summer season (June to September), simulated in the 13 PlioMIP2 models. The solid box marks the region (65°-95°E; 10°-30°N) and (105°-130°E; 20°-33°N) in which denote the South Asian summer monsoon and East Asian summer monsoon region, respectively. The red stippling in (b) indicates regions where at least 10 simulations show the same sign.

#4. Line 253-254: “mid-high latitudes" is a very broad region. You might specify the areas dominated by the climate mean horizontal circulation e.g. Western coast of South America, Southern tip of South Africa, a region extending from the Southern tip of South America to the Central tropical Pacific Ocean.

Response: The reviewer’s comments are right. We have specified the areas dominated by the climate mean horizontal circulation in the new version as follows:

“At mid-high latitudes, the δTH induced by climate mean horizontal circulation is caused by changes in moisture advection at mid-high latitudes (Fig. 3(k)), e.g., Western coast of North America, a region extending from the Southern tip of South America to the Central tropical Pacific Ocean, and Southern tip of South Africa.” (See Line 282-285)

#5. Line 274: What does it mean by Southern part and Northern part of the deep tropics? Is it Southern and Northern hemispheric part of the deep tropics or something else?

Response: Thanks for you comments. We have changed the confusion sentence in the new version as follows:

“... appears to dry the deep tropics but moisten its Northern hemispheric part of the deep tropics...” (See Line 305)

#6. Line 275: It is not clear to me how one can infer from Fig. 4(f) that ITCZ has shifted northward.

Response: Thanks for your comments. In Figure 8c, our studies indicate the northward shift of ITCZ, which could reorganize the atmospheric circulation (i.e., Hadley circulation). From the perspective of decomposition of moisture budget equation, the δMCD_{D_M} term reflect the changes in local Hadley circulation. As shown in Figure 4f, this term appears to dry the deep tropics but moisten its Northern hemispheric part of the deep tropics. We further calculate the relationship between the precipitation averaged over the Northern hemispheric part of the deep tropics (10°N-15°N, 180°E-180°W) in Figure S2. Indeed, the change in precipitation over the Northern hemispheric part of the deep tropics is related to the shift of ITCZ. Models with a northward shift of ITCZ tend to produce more rainfall over the Northern hemispheric part of the deep tropics, with the inter-model correlations of 0.7. Statistically, the inter-model correlation coefficients exceed the 0.01 significance level according to the t test.

Therefore, we highlight that the positive contribution of δMCD_{D_M} term over the Northern hemispheric part of the deep tropics reflect the impact of shift of ITCZ.

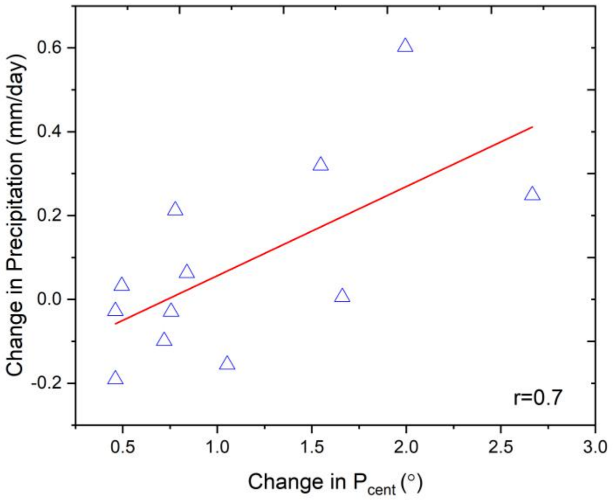


Figure S2. Changes in the latitudes of the center of annual mean precipitation between 20°S and 20°N (reflecting the shift of ITCZ; unit: °) versus changes in precipitation (units: mm/day) averaged over the Northern hemispheric part of the deep tropics (10°N-15°N).

#7. Line 277-278: Did not understand the meaning of the sentence starting with “There is a tendency...”.

Response: Thanks for the comments. We have revised the confusion sentence in the new version as follows:

“ δMCD_{D_M} term contributes to reduce PmE over SPCZ region, but this term increase PmE over the southern part of SPCZ in the tropical southern Pacific.” (See Line 308-309)

#8. Line 327-328: Unable to agree with this statement. The changes in the MMM SST (Fig. 6a) and specific humidity (Fig. 6b) does not seem to be in agreement. The MMM SST changes are largest over the higher latitudes and in contrary the largest changes in the specific humidity occurs over the tropics. Also you need to change the figure reference (it is not 5b, it should be 6b).

Response: Thanks for the comments. To avoid the confusion, we have changed the statement in the new version as follows:

"As expected, the specific humidity is increased in the low-level troposphere in a warmer climate (Fig. 7(b)) (Murray, 1966; Held and Soden, 2006)" (See Line 370-371)

Actually, the specific humidity anomalies are related to the changes in SST. To explain why the SST warming is larger at high latitudes than the low latitudes (Figure 7a) but with much less specific humidity increase there (Figure 7b), we further discuss the relationship between SST and specific humidity as follows.

Starting from the Clausius-Clapeyron (C-C) equation derived from thermodynamic theories, we can get the relationship between saturated vapor pressure (e_s) and temperature (t) as follows:

$$\frac{de_s}{dT} = \frac{L_v e_s}{R_v T^2} \qquad (1)$$

Here, T is temperature, e_s is the saturated vapor pressure with respect to a flat liquid surface. R_v is the specific gas constant. L_v is the latent heat of vaporization (assuming L_v is constant). We can get the simple Tetens's empirical formula (Murray et al., 1966) to calculate the e_s.

$$e_s = 6.1078 exp[\frac{17.2693882(T-273.16)}{T-35.86}] \qquad (2)$$

Based on the equation (2), we calculate the changes in es follows the response of t in Figure S2. Obviously, the changes in e_s is the function of T with logarithm to base e. Note that the tropical SST is more than 20℃, however, SST is reduced rapidly less than 10℃ on average at high latitudes. If we assume the SST change is Δt both at low latitudes and high latitudes, the change in e_s is Δe_{s2} and Δe_{s1} (as shown in Figure S3), respectively. **Noticeably, the Δe_{s2} is much larger than Δe_{s1}, indicating the e_s anomaly is more sensitive to the SST changes at the low latitudes (pronounced warm region) than the high latitudes (relative cooler region).**

Additionally, the relationship between relative humidity (U_w) and specific humidity (q) can be write as follow:

$$U_w \approx \frac{q}{q_s} \qquad (3)$$

Then, we can get the relationship between q and e_s:

$$q \approx U_w q_s \approx \frac{U_w \varepsilon}{p} e_s(T) \approx A e_s(T) \qquad (4)$$

Here, U_w is relative humidity, ε is 0.622, p is air pressure. Thus, the results of q are similar to $e_s(T)$ as mentioned above. That is, the specific humidity anomaly is much more sensitive to the SST changes at the low latitudes than the high latitudes.

This indicates that even SST warming is larger at high latitudes than the low latitudes, however, much less specific humidity increase for the former than the latter. **These results suggest the SST changes (Figure 7a) and specific humidity (Figure 7b) are reasonable.**

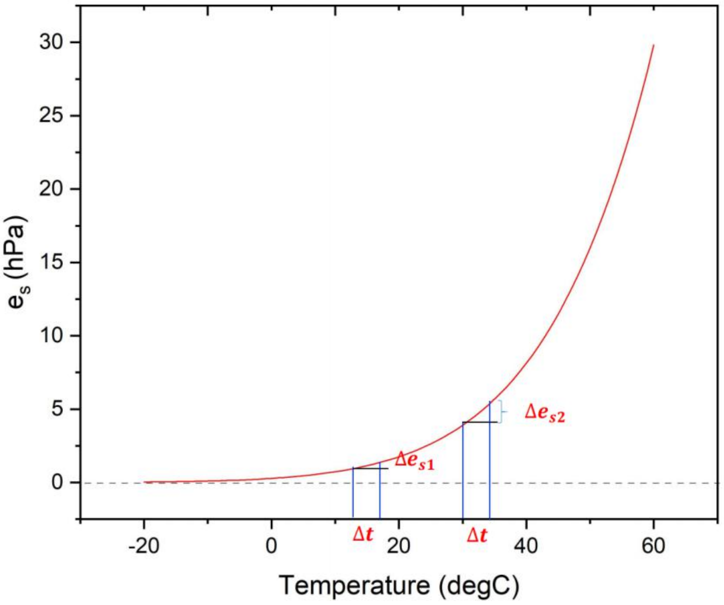


Figure S3. The changes in saturated vapor pressure (e_s; hPa) follows the response of temperature changes (t; ℃).

Reference:

Murray, F. W.. On the computation of saturation vapor pressure. Rand Corp Santa Monica Calif. 1966.

Held, I. M. and Soden, B. J.: Robust responses of the hydrological cycle to global warming, J. Clim., 19, 5686–5699, https://doi.org/10.1175/JCLI3990.1, 2006.

Technical corrections:

#9. Line 68: remove enhance or increase. Both have the same meaning.

Response: Thanks for your carefully reading. We have removed the word "enhance the" in this sentence (See Line 68).

#10. Line 214: I think the figure referencing is wrong here. It should be Fig. 6b.

Response: Thanks for your comment. We have changed this figure referencing in the new version.

#11. Line 220: It would be nice to add one more plot here which will represent the changes in the MMM PmE due to the combined TH and MCD component.

Response: Thanks for your comment. We have added one more plot as Figure 5 to present the changes the MMM PmE due to the combined δTH and δMCD component. We have added the related sentence in the new version as follows:

"In summary, the dynamic and thermodynamic can explain the largest changes in

PmE at low latitudes (Figs. 5 vs 1)" (See Line 325)

"Even the dynamic term overwhelmingly contributes to the increased changes in PmE over North African and Southeast Asian monsoon regions and the North Indian Ocean (Fig. 4 vs 5)." (See Line 329-330)

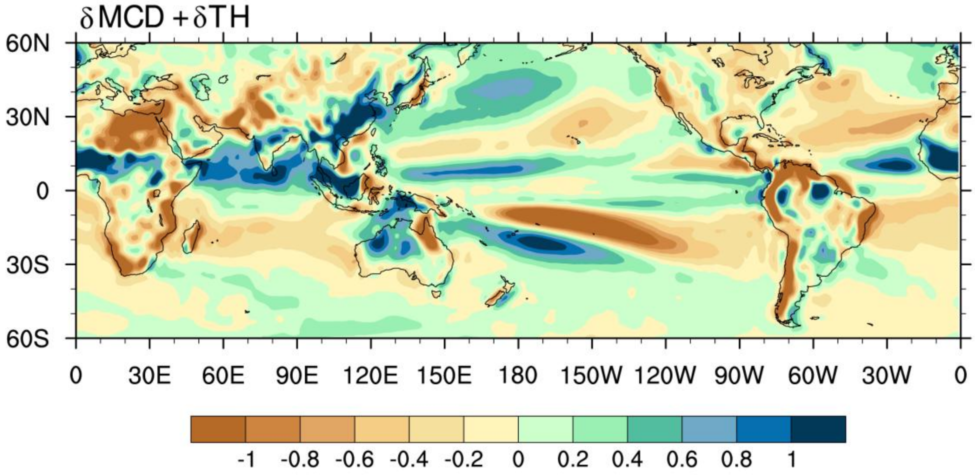


Figure 5. The estimated annual mean changes in the PmE (calculated by the sum of the dynamic term and thermodynamic term) of the mid-Pliocene minus PI control of the PlioMIP2 multimodel mean. Unit: mm day^{-1}.

#12. Line 253: "... unaltered divergence of the mean zonal circulation.." puzzled a bit with the usage of "unaltered" and "mean". I believe you can remove the "unaltered".
Response: Thanks for your comment. We have removed "unaltered" in this sentence.

#13. Line 269: "Overwhelming" is not the correct word in this context. Probably one can use "dominating".
Response: Thanks for your comment. We have changed the word "overwhelming" to "dominating" in new version.

#14. Line 317-318: In Figure 5 caption the orange band marking is wrong and I don't see any green band.
Response: Thanks for your comment. We have changed the wrong Figure 5 caption in the new version as follows:

"Here, the tropical region is defined as the region between 10°S and 10°N (marked as an orange band), while the subtropical region refers to 10-30° N and 10-30° S (marked as an cyan band)." (See Line 351-353)

#15. Please make the contour intervals in such a way that it removes the zero contour lines. Applicable to all the figures. Often inclusion of the zero contours lead to misinterpretation of the results.
Response: Thanks for your comment. We have added the Figures' labels of contour lines in the new version.

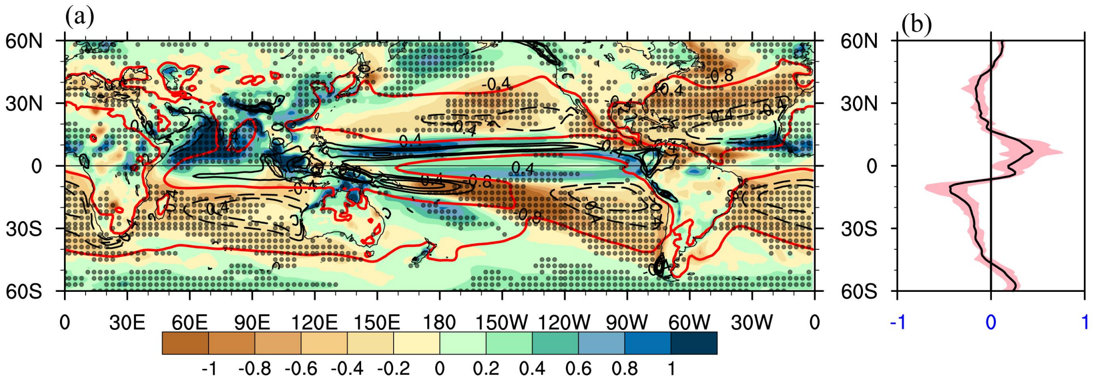


Figure 1: (a) Changes in multimodel mean (MMM) PmE for the mid-Pliocene compared with the PI simulation (shading), overlaid by the climatological MMM PmE of the PI simulation (for the contours, a solid line indicates positive values and a dashed line indicates negative values). The red solid curves represent the zero value. (b) The zonal average of the change in PmE, where the shading indicates the interquatile range among models. Stippling (left) indicates regions where at least 10 of 12 simulations in the model group agree on the sign of the ensemble mean. Units: mm·day^{-1}.

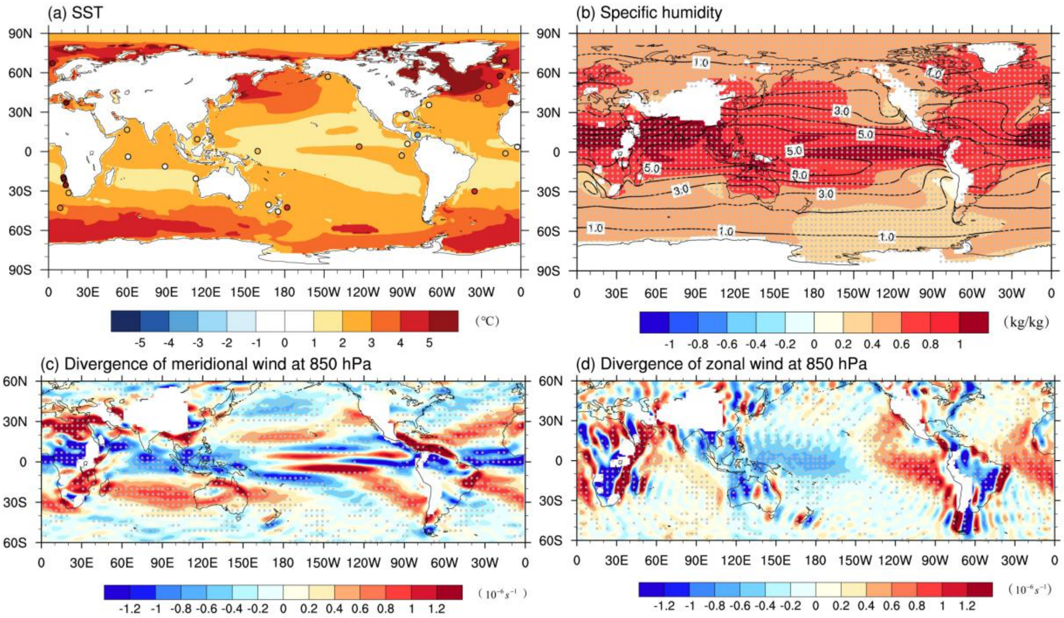


Figure 7: Change in (a) MMM SST (shading, unit: ℃), (b) specific humidity (shading, unit: kg·kg^{-1}) overlaid by its climate mean for PI simulation. (c) and (d) show the MMM divergence of meridional $\vec{V}_M$ and zonal wind $\vec{V}_Z$ fields decomposed from the 3P-DGAC method at the 850 hPa level for PI simulation (unit: 10^{-6} s^{-1}). The circles in (a) are the anomalies of reconstructed SST from the alkenone-derived $U_{37}^{K'}$ index (Prahl and Wakeham, 1987) and foraminifera calcite Mg/Ca (Delaney et al., 1985). Stippling in (b-d) indicates regions where at least 10 of 13 simulations in the model group agree on the sign of the ensemble mean.

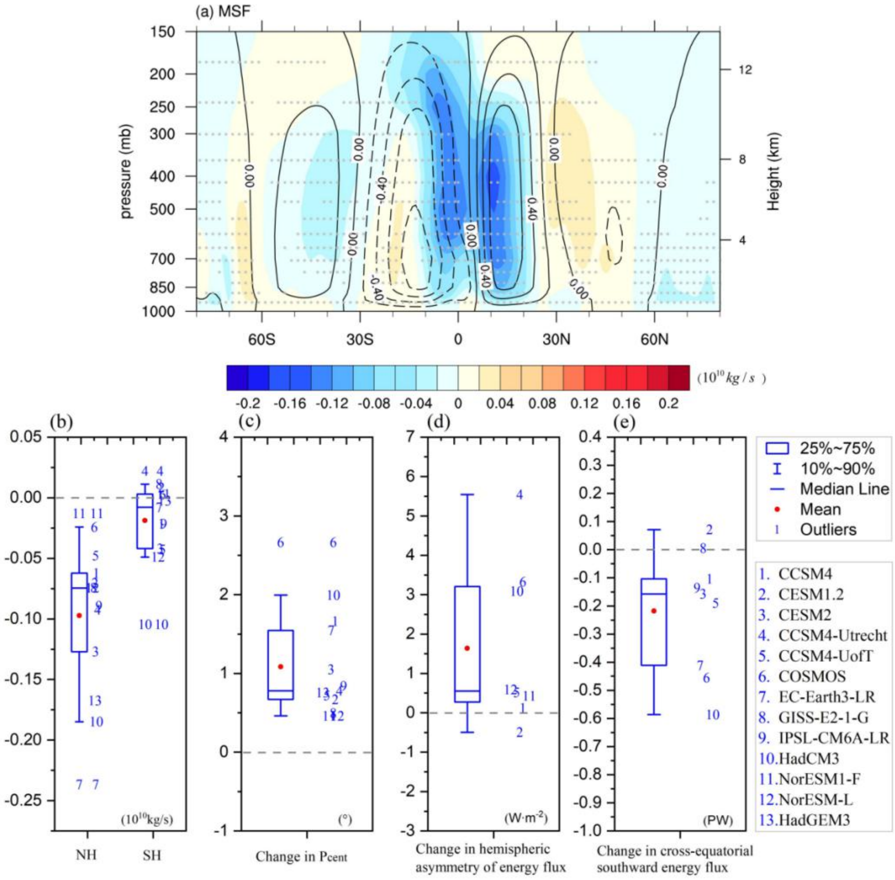


Figure 8: (a) Changes in annual mean MSF (shading; units: 10^{10} kg·s^{-1}) of meridional circulation for mid-Pliocene with respect to the PI simulation, overlaid by the climate mean MSF for the PI simulation (contours). The meridional wind $\vec{V}_M$ is decomposed from the 3P-DGAC method. Solid curves indicate positive values, and dashed curves indicate negative values. Stippling indicates regions where at least 10 of 13 simulations in the model group agree on the sign of the ensemble mean. (b) Changes in annual mean intensities (unit: 10^{10} kg/s) of meridional circulation in the NH and SH. (c) The latitudes of the center of annual mean precipitation between 20°S and 20°N (unit: °). (d) Hemispheric asymmetry (NH minus SH) of energy flux into the atmosphere (unit: W·m^{-2}). (e) Changes in the integrated atmospheric meridional heat transport across the equator (unit: PW).

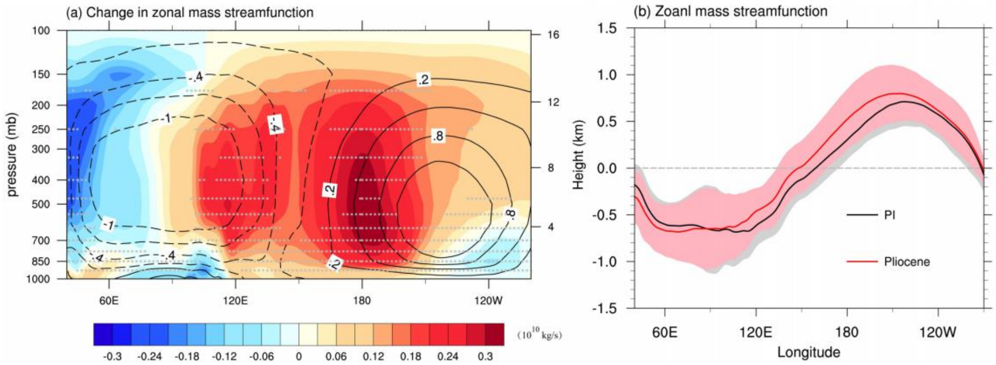


Figure 11: (a) Changes in ZMS (shading, unit: 10^{10} kg s^{-1}) averaged between 10°S/N for the mid-Pliocene with respect to the PI simulation, overlaid by the climate mean ZMS for the PI

simulation (contours). The zonal wind $\vec{V}_Z$ is used to calculate ZMS, which is decomposed from the 3P-DGAC method. The contours represent the climate mean ZMS for the PI simulation. Solid curves indicate a positive value, and dashed curves show a negative value. Stippling indicates regions where at least 10 of 13 simulations in the model group agree on the sign of the ensemble mean. (b) is the vertical integrated ZMS in (a). The gray and pink shading indicates 1 standard deviation of individual model departure from the MMM mean of MSF for the PI and mid-Pliocene simulations, respectively.

#16. I think stippling should be used on the non-significant regions so that we have a clear view of the significant results.
Response: Thanks for your comment. We have changed the stippling to be smaller in the significant regions to try to make it more clear in the new version.