

Author response to Reviewer #1

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.

Reviewer's Comments to Authors:

This paper evaluates the contribution of thermodynamical and dynamical effects to changes in P minus E in the simulated Pliocene warming. It decomposes the moisture budget into thermodynamical and dynamical contribution, which are further decomposed by applying the 3-pattern decomposition of the atmospheric circulation. The authors find that both mechanisms have significant contributions in explaining changes in PmE. In general, they find that thermodynamical effect can explain the wetter tropics and drier subtropics, however, when looking to more regional changes within the tropics and subtropics, dynamical effects have an important contribution. The paper goes on to explore possible reasons for the changes in the moisture budget components.

I think that the methods applied to achieve the main objective are appropriate and that the paper shows an interesting contribution to the research in the field. Therefore, I recommend the publication of this manuscript by the journal *Climate of the Past*, but I see some major issues that need to be addressed before publication.

General comments:

1. The main objective of the study is to evaluate the relative contribution of thermodynamical and dynamical effects in the PlioMIP models. However, the paper does not compare the relative contributions of the two. The authors correctly applied the moisture budget decomposition, but they do not quantitatively compare how much of each of the components contributes to the total PmE pattern. I think this analysis is crucial to this evaluation and would greatly improve the manuscript.

Response: Thanks for the comments. To quantitatively compare the contribution of the dynamic and thermodynamic components to the total PmE change, we firstly calculate the zonal mean of moisture budget components as shown in supplement Figure 1a. The changes in PmE generally show a wet-regions-getting-wetter and dry-regions-getting-drier pattern during the mid-Pliocene, and this is mainly contributed by the thermodynamic term. Furthermore, the thermodynamic term leads to increase in PmE by ~58.6% over tropic region, and decrease in PmE by ~84.6% over subtropics, respectively. The dynamic effect has relative smaller contribution, with increase in PmE by ~7.9% in tropic and ~10.5% in subtropics. In fact, the δTH component does not describe the full contribution of the changes in PmE everywhere. For example, over the North Indian Ocean, the δMCD_{D_z} (decomposed by the δMCD term) is the first-order contribution to strengthen the dynamic effect (by ~45%) and hence enhance the PmE over north Indian ocean (Figure 4g), which is caused by the shift of Walker circulation (Figure 10), the contribution of thermodynamic is negligible. We show the contribution of each moisture budget components over north Indian ocean in supplementary Figure 2.

We have added related sentences in the new version as follows:

“In general, the thermodynamic term increases PmE by ~58.6% over tropic region, and decrease in PmE by ~84.6% over subtropics (not shown), respectively.” (See Line 264-265)

“..., the convergence of zonal circulation anomalies (δMCD_{D_z}) is the first-order contribution to strengthen the dynamic effect (by ~45%) and hence enhance the PmE (Fig.4(g)).” (See Line 312-313)

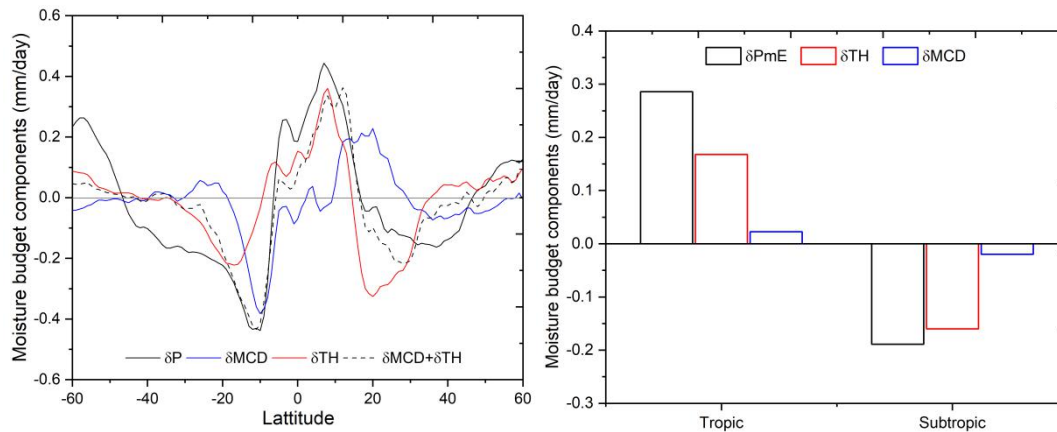


Figure S1. (a) The zonal average of the moisture budget components changes for PlioMIP2 models. (b) The average of moisture budget components in tropics (5°S-15°N) and subtropics (30°-5°S and 15°-30°N). Units: mm/day.

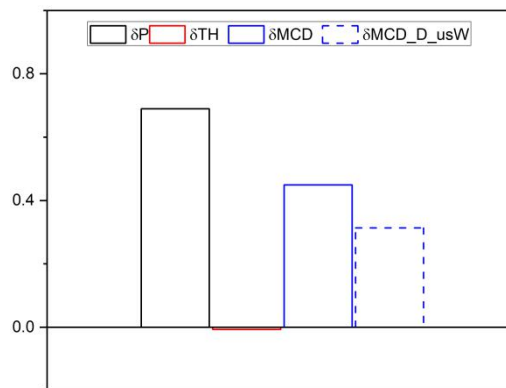


Figure S2. The average of moisture budget components over north Indian ocean (0-20°N, 40°-100°E). unit: mm/day.

2. The authors have produced interesting results that should be introduced more carefully. There is a contradiction in the abstract. The authors initially exemplify the changes in PmE over the Pacific ITCZ as a result of the thermodynamical effect. And a few lines below, they evaluate that the ITCZ shifts 1° northward (which is a result of dynamical changes). To me, the results show that in a very general (large-scale) manner the thermodynamical effects explain the wetter deep tropics and drier subtropics. But when looking to regional changes within the tropics and subtropics the

dynamical effect plays an important role (i.e. northward ITCZ shift, southward SPCZ shift, wetter north Indian ocean).

Response: The reviewer's suggestions are very beneficial. The reviewer's opinion is right. Indeed, our results indicate that the thermodynamical effects explain the wetter deep tropics and drier subtropics in a large-scale manner. These results can also be found in Figure S1 (see comment 1). Although the dynamic term is relative smaller than thermodynamic term in a general manner (Figure S1), the dynamic effects can not be neglect when looking to regional changes in the low latitudes. **To avoid the confusion in abstract, we have revised and added the related sentences as follows:**

“Note that the dynamic effect play a more important role in regional PmE changes (i.e., northward ITCZ shift and wetter in north Indian ocean).” (See Line 44-45).

3. It was not clear to me what boundary conditions the PlioMIP2 models have applied. For example, did they apply 400 ppm CO₂? Are there changes in the extension of the ice sheets in both hemispheres? Vegetation? Changes in the configuration of the continents? Also, I think there should have a final discussion as how these boundary conditions could have affected the simulated PmE changes.

Response: Thanks for the comments. We use a suite of model simulations from 13 the Pliocene Model Intercomparison Project Phase 2 (PlioMIP2) participating the Coupled Model Intercomparison Project phase 6 (CMIP6) (Haywood et al., 2016). Boundary conditions for mid-Pliocene simulations are derived from the latest iteration of the U.S. Geological Survey PRISM data set (PRISM4) (Dowsett et al., 2016), including land versus sea, vegetation, soils, lakes, land ice cover, topography and bathymetry. The concentration of atmospheric CO₂ level for mid-Pliocene and PI simulations are prescribed at 400ppm and 280ppm, respectively. Other solar output, trace gases and orbital parameters for mid-Pliocene simulations are set to be consistent with each model's PI simulation. Modeling groups are given the option to either prescribe vegetation changes or simulate vegetation changes using a dynamic global vegetation model. And only one modeling group (COSMOS) in the suite of simulations we analyzed opted to use a dynamic configuration for vegetation.

We agree with the reviewer that it is important to discuss the impact of boundary conditions on changes in PmE during mid-Pliocene. Note that the large-scale atmospheric circulation changes are related to the temperature pattern anomalies. Earlier studies demonstrate that the temperature changes during mid-Pliocene are controlled by the combined effects of external forcings, including the atmospheric CO₂ concentration, land cover (surface vegetation and land ice cover), and topography (Haywood et al., 2016). Any changes in each boundary conditions could lead to changes in PmE through dynamic (i.e., atmospheric circulation changes) or thermodynamic (i.e., atmospheric moisture changes) effects. For example, several studies highlight the role of remote biophysical effects in the northern mid-high latitudes in driving the variation of monsoon rainfall in low latitudes, which could lead to land surface characteristics changes (i.e., evapotranspiration and albedo),

altering shifts of ITCZ due to the imbalance of atmospheric energy budget and hence changing monsoon rainfall (Swann et al., 2014; Chase et al., 2000; Mahmood et al., 2014). Proxy and simulations suggest that the needleleaf tree shifts greatly and expands northward in eastern Eurasia during mid-Pliocene (Zhang and Jiang, 2017; Feng et al., 2021). These changes in land cover during mid-Pliocene may alter PmE in the low latitudes as well, especially in monsoon regions. In addition, some studies indicate that there exist uncertainties of boundary conditions of changing South Asian summer monsoon hydrological cycling. Sarathchandraprasad et al. (2017) indicate the tectonically induced reorganization of the Indonesian Throughflow can strengthen the South Asian summer monsoon (SASM) during mid-Pliocene due to the increased cross-equatorial pressure gradient. Recent study by Prescott et al., (2019) highlight the substantially influence of orbital forcing on the changes in SASM during mid-Pliocene. The simulations suggest that tectonic uplifts in South African Plateaus can strengthen the SASM as well (Zhang and Liu, et al., 2013). Based on these studies, the boundary conditions applied by the PlioMIP2 models are important to hydrological cycling during mid-Pliocene in low latitudes. However, since not all models carry out the sensitivity experiments designed in PlioMIP2, it remains difficult to distinguish which change in boundary conditions is more dominant for the PmE changes in low latitudes.

We have added the related description of boundary conditions and discussion of the possible effects in the new version as follows:

“..., including soils, lakes, land ice cover, vegetation, topography, bathymetry. The CO₂ level for mid-Pliocene and PI simulations are set at 400ppm and 280ppm, respectively.” (See line 104-106)

“Zhang et al. (2016) indicate that the combined influence of SST and CO₂ level, as well as the vegetation changes, play very important role in changing the atmospheric circulation over North Africa during mid-Pliocene, owing to the increased net atmospheric energy there.” (See line 214-216)

“Note that the global temperature during mid-Pliocene is controlled by the combined effects of boundary conditions (e.g., CO₂ level, vegetation and topography) (Haywood et al., 2016). Any changes in each boundary condition could induce large-scale hydrological cycling changes. For example, the role of remote biophysical effects in the northern mid-high latitudes is highlighted in driving the variation of monsoon rainfall in low latitudes and shift of ITCZ, since the needleleaf tree expands greatly northward in eastern Eurasia during mid-Pliocene (Chase et al., 2000; Swann et al., 2014; Mahmood et al., 2014; Zhang and Jiang, 2014; Burls and Fedorov, 2017). In addition, some studies indicate that there exist uncertainties of boundary conditions of changing South Asian summer monsoon hydrological cycling. Sarathchandraprasad et al. (2017) indicate the tectonically induced reorganization of the Indonesian Throughflow can strengthen the SASM during mid-Pliocene due to the increased cross-equatorial pressure gradient. Recent study by Prescott et al. (2019) highlight the substantially influence of orbital forcing on the changes in SASM during mid-Pliocene. The simulations suggest that tectonic uplifts in South African Plateaus can strengthen the SASM as well (Zhang and Liu, 2013). Based on these studies, the

boundary conditions applied by the PlioMIP2 models are important to hydrological cycling during mid-Pliocene in low latitudes. However, the relative impact of boundary conditions on hydrological cycling still remains uncertainties. In addition, not all models carry out the sensitivity experiments designed in PlioMIP2, increasing the difficulty of exploring their relative contributions to PmE changes, and these questions need to be further explored in the future.” (See Line 529-543)

References:

Haywood, A. M., Dowsett, H. J., Dolan, A. M., Rowley, D., Abe-Ouchi, A., Otto-Bliesner, B., Chandler, M. A., Hunter, S. J., Lunt, D. J., Pound, M., and Salzmann, U.: The Pliocene Model Intercomparison Project (PlioMIP) phase 2: scientific objectives and experimental design, *Clim. Past*, 12, 663-675, <https://doi.org/10.5194/cp-12-663-2016>, 2016.

Zhang R. and Jiang D.. 2014. Impact of vegetation feedback on the mid-Pliocene warm climate. *Advances in Atmospheric Sciences*, 31: 1407-1416.

Swann, A.L., Fung, I.Y., Liu, Y. and Chiang, J.C., 2014. Remote vegetation feedbacks and the mid-Holocene green Sahara. *Journal of climate*, 27(13), pp.4857-4870.

Chase, T.N., Pielke Sr, R.A., Kittel, T.G.F., Nemani, R.R. and Running, S.W., 2000. Simulated impacts of historical land cover changes on global climate in northern winter. *Climate dynamics*, 16(2), pp.93-105.

Mahmood, R., Pielke Sr, R.A., Hubbard, K.G., Niyogi, D., Dirmeyer, P.A., McAlpine, C., Carleton, A.M., Hale, R., Gameda, S., Beltrán-Przekurat, A. and Baker, B., 2014. Land cover changes and their biogeophysical effects on climate. *International journal of climatology*, 34(4), pp.929-953.

Burls, N. J. and Fedorov, A. V.: Wetter subtropics in a warmer world: contrasting past and future hydrological cycles, *Proc. Natl. Acad. Sci. U. S. A.*, 114, 12888, <https://doi.org/10.1073/pnas.1703421114>, 2017.

Sarathchandraprasad, T., Tiwari, M. and Behera, P., 2021. South Asian Summer Monsoon precipitation variability during late Pliocene: Role of Indonesian Throughflow. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 574, p.110447.

Zhang R. and Liu X.D., 2010. The effects of tectonic uplift on the evolution of Asian summer monsoon climate since Pliocene. *Chinese Journal of Geophysics*, 53(6), pp.948-960.

4. Section 3 is an important section of paper that introduces the simulated PmE changes that will be further explored in the next sections and should be carefully revised. To me the key message of section 3 is that, in a first look to changes in PmE, there seem to have important contributions from both TH and MCD, but the authors mainly discuss TH (see comment 2 and detailed comments below).

Response: Thanks for the comments. We have added a few sentences to try to avoid this confusion as follows:

“Note that there is moistening signal in SPCZ’s southern part in the tropical southern Pacific.” (See line 207-208)

“Earlier studies indicate these features of changes in PmE at low latitudes are linked to the increased specific humidity (i.e., changes in thermodynamic effect). However, there are some opposite phenomenon as well, when looking to the regional changes in PmE (i.e., north Indian Ocean, North Africa and SPCZ). These may suggest that another factor, such as atmospheric circulation anomalies (i.e., changes in dynamic effect), may play an important role in changing regional PmE pattern at low latitudes.” (See Line 229-233)

5. Section 5.1: it is interesting to examine the global pattern in wind divergence and humidity. But SST pattern must be analysed more thoroughly, especially in the tropics where local SST will probably help to explain the thermodynamical effect.

Xie, S.-P., C. Deser, G. A. Vecchi, J. Ma, H. Teng, and A. T. Wittenberg, 2010: Global warming pattern formation: Sea surface temperature and rainfall. *J. Climate*, 23, 966–986, <https://doi.org/10.1175/2009jcli3329.1>.

Response: The reviewer’s suggestions are very beneficial. Figure S3 shows the changes in annual mean SST and wind at 850 hPa. The SST warming is amplified in the northwest tropical Indian Ocean, whereas it is reduced off the Indonesian coast, showing tropical Indian Ocean dipole (IOD)-like pattern. The sharp SST gradients drive strong southeasterly wind anomalies (Figure S3) over the equator. Figure S4 show the changes in annual mean of zonal wind (U) versus changes in SST for 13 PlioMIP2 models. These results can also be seen in Figure S4. As expected, the models with an enhanced zonal SST gradient across the equatorial Indian Ocean tend to produce increased easterly wind anomalies, with the inter-model correlations of -0.9. Xie et al. (2010) suggest that this easterly wind anomalies may shoal the thermocline in the east, helping cool SST there via upwelling. This indicates that this SST anomalies over tropical Indian Ocean may be related to the Bjerknes feedback. Studies indicate that the simulated North Atlantic warming is related to an intensified mid-Pliocene AMOC (Li et al., 2020). However, Zhang et al. (2021) suggest that the increased background ocean vertical mixing parameters can be also responsible for the warm SSTs there. Note that the relative cool SST in Southeast Pacific and Atlantic, which is collocated with the intensified southeast trades, suggesting the role of WES feedback (Xie et al., 2010).

According to the comments, we have added more discussion of the SST pattern as follows:

“Note that the SST warming is amplified in the northwest tropical Indian Ocean, whereas it is reduced off the Indonesian coast, showing tropical Indian Ocean dipole (IOD)-like pattern. The sharp SST gradients drive strong southeasterly wind anomalies on the equator (not shown). Xie et al. (2010) suggest that this easterly wind anomaly may shoal the thermocline in the east, helping cool SST there via upwelling, and indicating this SST anomaly over tropical Indian Ocean may be related to the Bjerknes feedback. The simulated North Atlantic warming might be related to an intensified mid-Pliocene AMOC (Li et al., 2020). However, Zhang et al. (2021) suggest that the increased background ocean vertical mixing parameters could also contribute to the warm SSTs there. In addition, the relative smaller SST warming in

Southeast Pacific and Atlantic, which is collocated with the intensified southeast trades, suggests the role of wind-evaporation-SST feedback (Xie et al., 2010). These SST warming patterns are consistent with current studies (Haywood et al., 2020; Williams et al., 2021).” (See line 360-371)

References:

Xie, S.-P., C. Deser, G. A. Vecchi, J. Ma, H. Teng, and A. T. Wittenberg, 2010: Global warming pattern formation: Sea surface temperature and rainfall. *J. Climate*, 23, 966–986, <https://doi.org/10.1175/2009jcli3329.1>.

Li, X., Guo, C., Zhang, Z., Otterå, O.H. and Zhang, R., 2020. PlioMIP2 simulations with NorESM-L and NorESM1-F. *Climate of the Past*, 16(1), pp.183-197.

Zhang, Z., Li, X., Guo, C., Otterå, O.H., Nisancioglu, K.H., Tan, N., Contoux, C., Ramstein, G., Feng, R., Otto-Bliesner, B.L. and Brady, E., 2021. Mid-Pliocene Atlantic Meridional Overturning Circulation simulated in PlioMIP2. *Climate of the Past*, 17(1), pp.529-543.

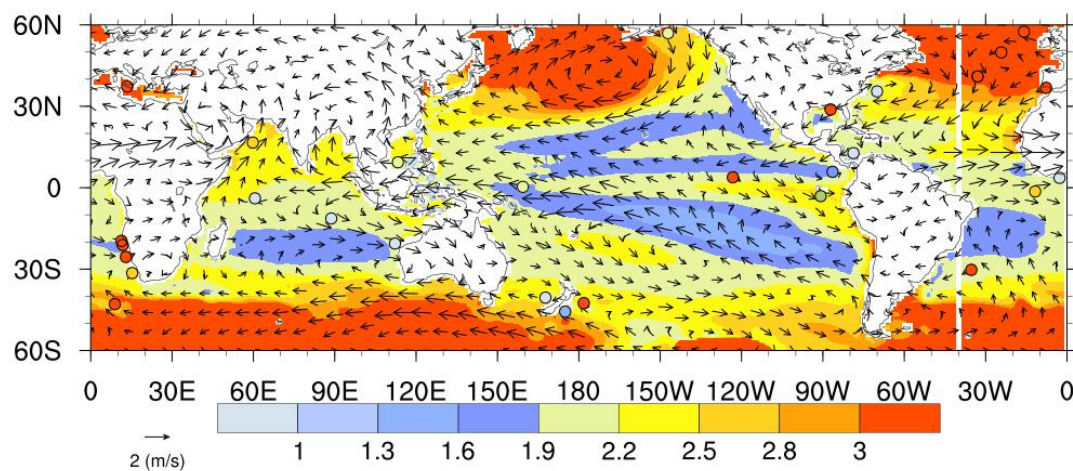


Figure S3. Change in multimodel mean SST (shading, unit: °C) and wind at 850hPa (vectors, unit: m/s).

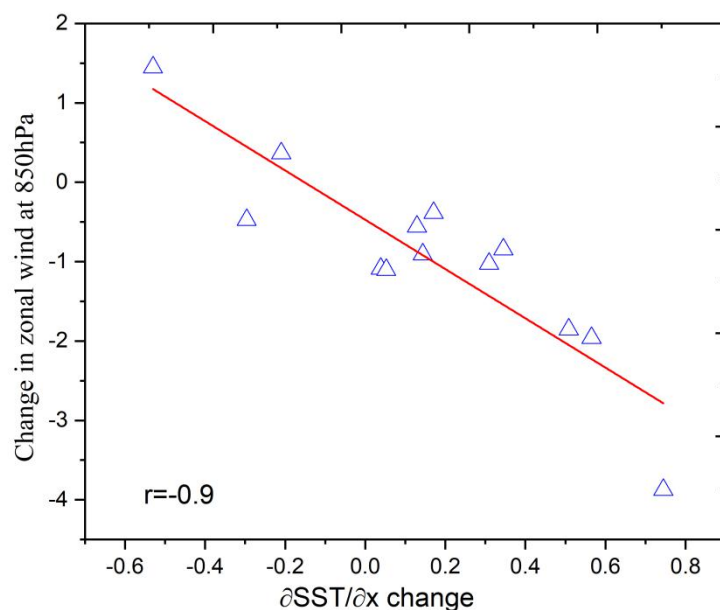


Figure S4. Intermodel scatterplots of changes in west-minus-east SST difference (west box: 10°S-10°N, 50°-70°E; east box: 0°-10°S, 90°-110°E) vs surface zonal wind in central equatorial Indian Ocean (CEIO; 70°-90°E).

Specific comments:

6. Line 54: Changes in the hydrological cycle are a response to regional and global climate anomalies. I would rephrase to “Global warming can induce regional and global anomalies in the Earth’s hydrological cycle...” or similar.

Response: Thanks for the comments. We have changed this sentence as “Global warming can induce regional and global anomalies in the Earth’s hydrological cycle...”. (See Line 55)

7. Line 203: Figure 1a indicates that changes over the Maritime Continent are not consistent across models. I suggest removing mentions to Maritime Continent and rather focus on the North Indian Ocean, where changes are significant.

Response: Thanks for the comments. We have removed the “Maritime Continent”. (See Line 206)

8. Line 207: When discussing changes in Southeast Asia and Sahel the authors must discuss the effect of vegetation. Do the PlioMIP models apply changes in vegetation?

Response: Thanks for the comments. As we discussed in comment 3, boundary conditions for MP simulations are derived from the latest iteration of the U.S. the vegetation is from Geological Survey PRISM data set (PRISM4) (Dowsett et al., 2016). Modeling groups were given the option to either prescribe vegetation changes or simulate vegetation changes using a dynamic global vegetation model. For the latter experiment, model simulations were started with pre-industrial vegetation and the model was allowed to spin up until a new equilibrium distribution of vegetation was achieved. Note that only one modeling group (COSMOS) in the suite of simulations we analyzed opted to use a dynamic configuration for vegetation.

According to the reviewer’s suggestion, we have added the related discussion in the new version as follows:

“..., including soils, lakes, land ice cover, vegetation, topography, bathymetry. The CO₂ level for mid-Pliocene and PI simulations are set at 400ppm and 280ppm, respectively.” (See Line 104-105)

“Zhang et al. (2016) indicate that the combined influence of SST and CO₂ level, as well as the vegetation changes, play a very important role in changing the atmospheric circulation over North Africa during mid-Pliocene, owing to the increased net atmospheric energy there. Additionally, the expansion of vegetation into the Sahara region tend to decrease the surface albedo, which can enhance the Saharan Heat Low and hence impact rainfall over West Africa, reflecting the vegetation-albedo feedback (Charney, 1975). Recent studies indicate the enhanced vegetation in PlioMIP2 ensemble is likely to have contributed to the increasing of the mid-Pliocene West African summer rainfall (Haywood et al., 2020; Bertell et al., 2021).” (See Line 214-220)

“Note that the global temperature during mid-Pliocene is controlled by the combined effects of boundary conditions (e.g., CO₂ level, vegetation and topography) (Haywood et al., 2016). Any changes in each boundary condition could induce large-scale hydrological cycling changes. For example, the role of remote biophysical effects in the northern mid-high latitudes is highlighted in driving the variation of monsoon rainfall in low latitudes and shift of ITCZ, since the needleleaf tree expands greatly northward in eastern Eurasia during mid-Pliocene (Chase et al., 2000; Swann et al., 2014; Mahmood et al., 2014; Zhang and Jiang, 2014; Burls and Fedorov, 2017).” (See Line 529-534)

References:

- Zhang, R., Zhang, Z., D Jiang, Yan, Q., Zhou, X., and Cheng, Z.. 2016. Strengthened african summer monsoon in the mid-pliacenzian. *Advances in Atmospheric Sciences*.
- Swann, A.L., Fung, I.Y., Liu, Y. and Chiang, J.C., 2014. Remote vegetation feedbacks and the mid-Holocene green Sahara. *Journal of climate*, 27(13), pp.4857-4870.
- Chase, T.N., Pielke Sr, R.A., Kittel, T.G.F., Nemani, R.R. and Running, S.W., 2000. Simulated impacts of historical land cover changes on global climate in northern winter. *Climate dynamics*, 16(2), pp.93-105.
- Mahmood, R., Pielke Sr, R.A., Hubbard, K.G., Niyogi, D., Dirmeyer, P.A., McAlpine, C., Carleton, A.M., Hale, R., Gameda, S., Beltrán-Przekurat, A. and Baker, B., 2014. Land cover changes and their biogeophysical effects on climate. *International journal of climatology*, 34(4), pp.929-953.
- Zhang R. and Jiang D.. 2014. Impact of vegetation feedback on the mid-Pliocene warm climate. *Advances in Atmospheric Sciences*, 31: 1407-1416.
- Burls, N. J. and Fedorov, A. V.: Wetter subtropics in a warmer world: contrasting past and future hydrological cycles, *Proc. Natl. Acad. Sci. U. S. A.*, 114, 12888, <https://doi.org/10.1073/pnas.1703421114>, 2017.
- Berntell, E., Zhang, Q., Li, Q., Haywood, A.M., Tindall, J.C., Hunter, S.J., Zhang, Z., Li, X., Guo, C., Nisancioglu, K.H. and Stepanek, C., 2021. Mid-Pliocene West African Monsoon rainfall as simulated in the PlioMIP2 ensemble. *Climate of the Past*, 17(4), pp.1777-1794.
- Charney, J. G.: Dynamics of deserts and drought in the Sahel, *Q. J. Roy. Meteor. Soc.*, 101, 193–202, <https://doi.org/10.1002/qj.49710142802>, 1975.
- Haywood, A. M., Tindall, J. C., Dowsett, H. J., Dolan, A. M., Foley, K. M., Hunter, S. J., Hill, D. J., Chan, W. L., Abe-Ouchi, A., Stepanek, C., Lohmann, G., Chandan, D., Peltier, W. R., Tan, N., Contoux, C., Ramstein, G., Li, X., Zhang, Z., Guo, C., Nisancioglu, K. H., Zhang, Q., Li, Q., Kamae, Y., Chandler, M. A., Sohl, L. E., Otto-Bliesner, B. L., Feng, R., Brady, E. C., Von der Heydt, A. S., Baatsen, M. L. J., and Lunt, D. J.: The Pliocene model intercomparison project phase 2: large-scale climate features and climate sensitivity, *Clim. Past*, 16, 2095–2123, <https://doi.org/10.5194/cp-16-2095-2020>, 2020.

9. Line 213: It is not clear to me why a drier extratropical North Atlantic is related to increased SST. Wouldn't an increased SST drive increased precipitation (note increased humidity in the north Atlantic in Figure 6b)? Also, Figure 5a does not show SST. Do you mean Figure 6a? I suggest leaving this discussion to Section 5.1 to avoid referencing figure 5 without mentions to figure 3 and 4.

Response: The reviewer's comments are right. In fact, we have discussed the cause of drier extratropical North Atlantic in Section 5.1. According your comments, we remove the related misunderstanding description as follows:

We have removed "..., and this change might be caused by the simulated largely increased SST in the North Atlantic (Fig. 5(b))". (See in Line 222)

10. Line 215: I suggest a reformulation of this paragraph to include that both TH and MCD seems to be important for the PmE changes, as it shown later in the manuscript.

Response: Thanks for you comments. We have added some sentences to highlight the importance of δ TH and δ MCD in this paragraph as follows:

"Earlier studies indicate these features of changes in PmE at low latitudes are linked to the increased specific humidity (i.e., changes in thermodynamic effect). However, there are some opposite phenomenon as well, when looking to the regional changes in PmE (i.e., north Indian Ocean, North Africa and SPCZ). These may suggest that another factor, such as atmospheric circulation anomalies (i.e., changes in dynamic effect), may play an important role in changing regional PmE pattern at low latitudes." (See Line 229-233)

11. Figure 1b: Why the authors choose to show the models' standard deviation? To be consistent with your choice of showing significance based on model agreement in Figure 1a, it would be more appropriate to show interquartile range (non-parametric statistics).

Response: Thanks for you comments. Following your suggestion, we have changed the model's standard deviation to its interquartile range in Figure 1b as follows.

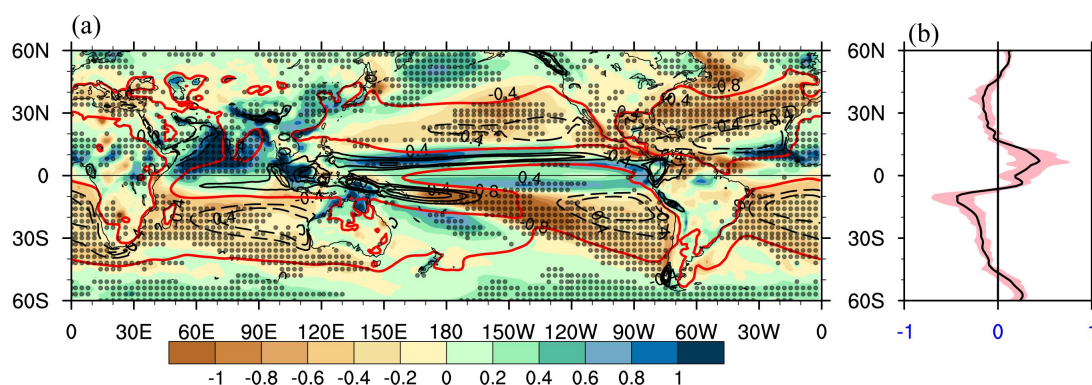


Figure 1: (a) Changes in multimodel mean (MMM) PmE for the mid-Pliocene compared with the PI simulation (shading), overlaid by the climatological MMM PmE of the PI simulation (for the contours, a solid line indicates positive values and a dashed line indicates negative values). The red solid curves represent the zero value. (b) The zonal average of the change in PmE, where the shading indicates the interquartile 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: $\text{mm}\cdot\text{day}^{-1}$.

12. Line 396: Figure 9a indicates that the intensification of the PWC is not significant. I wouldn't mention the value.

Response: Thanks for the comments. We have removed the sentence “with the mean PWC intensity strengthened by 1×10^{10} kg/m^2 compared with the PI simulation”. (See Line 430)

13. Lines 395-405: I think that the key message of this paragraph is that the change in the intensity of the PWC does not explain the change in PmE in the Indian Ocean. As such, here it should be clearer for the reader that the changes in PWC intensity, dSST and dSLP are not consistent (nor significant) across models. Nonetheless, changes in dSST and dSLP can explain changes in PWC intensity. This paragraph needs to be reformulated.

Response: Thanks for the comments. Figure S5 further examines the relationships between the change in dSST versus the changes in dSLP and PWC intensity among 13 PlioMIP2 models. Indeed, the change in PWC intensity is highly related to the changes in zonal SST and SLP gradient. Models with an enhanced zonal SST gradient across the equatorial Indo-Pacific tend to produce weaker zonal SLP gradient and decreased PWC, with the inter-model correlations of -0.95 and -0.75, respectively. We have added the related sentences to avoid the confusion as follows:

“As expected, the models with an enhanced zonal SST gradient across the equatorial Indo-Pacific tend to produce weaker zonal SLP gradient and decreased PWC (Figure not shown), with the inter-model correlations of -0.95 and -0.75, respectively. Note that, ...” (See Line 448-450)

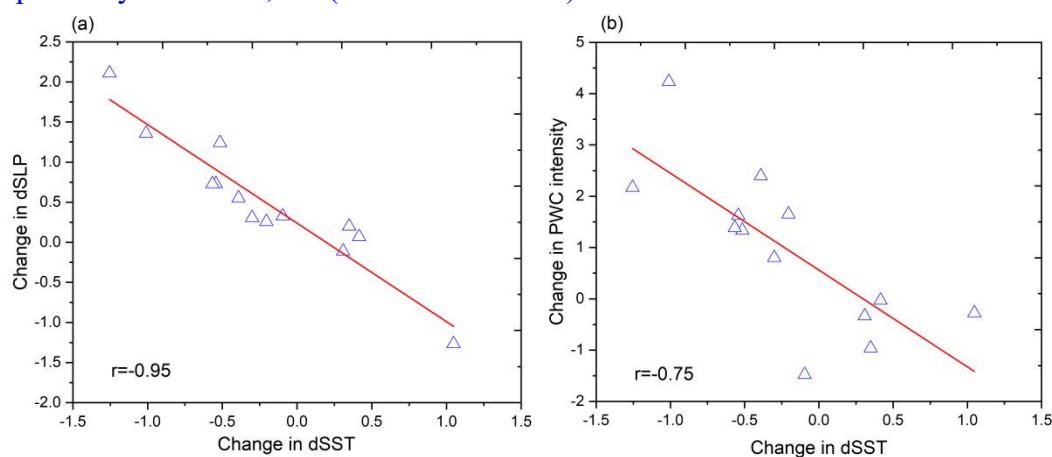


Figure S5. Changes in annual mean of the (a) intensities of Pacific Walker circulation (PWC; unit: 10^{10} kg/s) and (b) dSLP (units: hPa) versus changes in dSST (units: K) for 13 PlioMIP2 models. The inter-model correlation (r) is shown in each panel. Here, the PWC intensity is defined as the vertically integrated ZMS (Bayr et al., 2014; Schwendike et al., 2014) averaged in the equatorial Pacific (140°E - 120°W). The dSLP and dSST are defined as the difference in SLP and SST across the equatorial Indo-Pacific (160°W - 80°W , 5°S - 5°N minus 80°E - 160°E , 5°S - 5°N).

14. Figure 9: Panel 'b' seems lost in this Figure. I would consider moving it to Figure This way, all results explaining the shift in the zonal circulation would be clearly shown in one figure. There is no mention to Figure 9b in between lines 395-405.

References: Thanks for the comments. Actually, we mention the description of Figure 9b in between lines 449-457, and mainly discuss the movement of the Pacific Walker circulation. So we decide to keep it in Figure 9.

15. Line 422: Do you mean a westward expansion of the PWC and a westward displacement over the Indian Ocean?

References: The review's question is right. We have revised the confusion sentence as follows:

“..., indicating a westward expansion of the PWC (Fig. 11(b)).” (See Line 472)

16. Line 437: westward 'expansion' of the PWC?

References: The reviewer's question is right. We have revised the confusion sentence as follows:

“..., resulting from the westward expansion of the PWC” (See line 471)

17. Section 6: the authors must discuss the main results on the light of the boundary conditions applied by the PliomIP models and their uncertainties, to guide future research.

References: Thanks for your comment. We have discussed the impact of boundary conditions on hydrological cycling in section6 as mentioned above in comment 3.

Technical corrections:

18. Line 68: Redundance. “enhance the increase in atmospheric...”.

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

19. Figure 1a: I recommend changing the colour of the stiplings. It is hard to see even when zooming.

Response: Thanks for your comment. We have changed the color of the stiplings in the Figure 1a from gray to black. See comment 11.

20. Line 364: include a reference to Figure 8 for clarity.

Response: Thanks for your comment. We have added the “Fig. 9” after the sentence “... winds are located in the central Pacific”. (See line 392)

21. Figure 10a: indicate the intensity of the PI contours.

Response: Thanks for your comment. We have added the intensity of the PI contours in Figure 11 as follows:

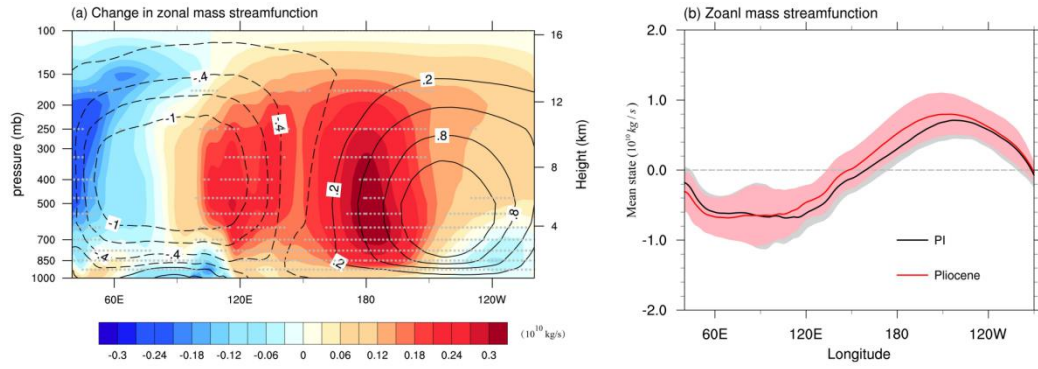


Figure 11: (a) Changes in ZMS (shading, unit: $10^{10} \text{ kg s}^{-1}$) averaged between 10°S/N for the mid-Pliocene with respect to the PI simulation, overlaid by the climate mean ZMS for the PI simulation (contours). The zonal wind \vec{V}_Z is used to calculate ZMS, which is decomposed from the 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 models departure from the MMM mean of MSF for the PI and mid-Pliocene simulations, respectively.