Interactive comment on "The response of tropical precipitation to Earth's precession: The role of fluxes and vertical stability", *reply to referee 2*

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1. **General Comments:** The authors thank you for your time and inputs.

2. ***Comment*:** *The structure of the text seems casual. I recommend that the authors put all the methods (including the ITCZ model, equation and decomposition) together. In the result section, it is better to merely show the figure and descriptions. That would help the paper to be easily read.*

   ***Reply*:** Thank you for the suggestion. We will re-organize the manuscript.

3. ***Comment*:** *Introduction: there are a lot of modeling studies in this field; however, the authors did not mention them in the introduction. For example,*

   Global:

   Kutzbach, J., Liu, X., Liu, Z., Chen, G., 2008. Simulation of theevolutionary response of global summer monsoons to orbital forcing over the past 280,000 years. Clim. Dyn. 30, 567-579.

   Asia and Africa:

   Tuenter, E., Weber, S., Hilgen, F., Lourens, L., Ganopolski, A., 2005. Simulation of climate phase lags in response to precession and obliquity forcing and the role of vegetation. Clim. Dynam. 24, 279-295

   Weber, S., Tuenter, E., 2011. The impact of varying ice sheets and greenhouse gases on the intensity and timing of boreal summer monsoons. Quat. Sci. Rev. 30, 469-479.

   Shi, Z., Liu, X., Cheng, X., 2012. Anti-phased response of northern and southern East Asian summer precipitation to ENSO modulation of orbital forcing. Quat. Sci. Rev. 40, 30-38.

Caley, T., Roche, D.M., Renssen, H., 2014. Orbital Asian summer monsoon dynamics revealed using an isotope-enabled global climate model. Nat. Commun. 5, 5371.http://dx.doi.org/10.1038/ncomms6371.

Shi, Z., 2016. Response of Asian summer monsoon duration to orbital forcing under glacial and interglacial conditions: implication for precipitation variability in geological records. Quat. Sci. Rev. 139, 30-42

***Reply*:** Thank you for these references. We will include them in the introduction.

4. ***Comment*:** *Experiments: Only two sensitivity runs are conducted in this study. The authors said the differences between Pmax and Pmin scenarios "has a similar spatial precipitation response as observed in MidHolocene, but with higher amplitude". In actual, there is certain contribution from obliquity in the MH-PI difference. I know in Bosmans et al (2015), there are already obliquity-linked experiments. Why do the authors not give results for the obliquity in this study? In my opinion, it is also important.*

***Reply*:** It is true that the Mid-Holocene response will have contributions from obliquity. However, the obliquity in Mid-Holocene is only 0.66° higher than PI. Hence, its contribution is much less in comparison to that of precession.

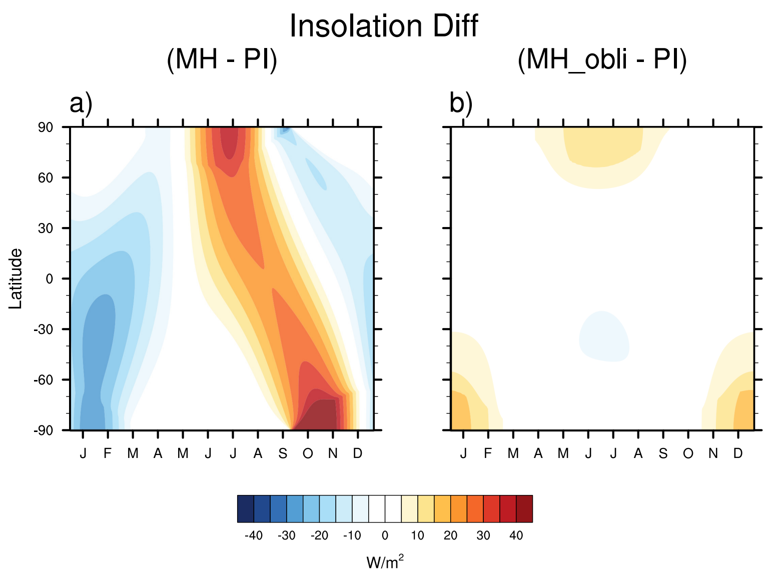


Figure 1. This figure shows that the contribution from tilt to the total insolation change is much smaller in comparison to that from precession. The difference in insolation between, **a)** MH and PI, **b)** MH (obliquity only) and PI.

Our analysis is still valid for MH. It is discussed in detail in the section **Results and Discussion-1.1** of this document. The asymmetric precipitation response over India and Bay of Bengal is driven by the same mechanism, in MH and P_{min}.

Obliquity has a much smaller forcing than precession. The land-ocean asymmetric response in tropical precipitation still exists, albeit much weaker at the regional scale. The mechanisms governing these changes are different and hence were not included in the manuscript. **Results and Discussion section 1.2** here, has the relevant discussion.

5. ***Comment:*** *Results: From figure 5 and 6, I can see the distinct response of land and ocean precipitation, but it is also significantly negative over northwestern Pacific besides the Bay of Bengal. This indicates that the East Asian/Northwestern Pacific summer precipitation is also typical for the proposal of this paper. I recommend the authors to add additional analyses on this region and compare the results to those over the Bay of Bengal.*

***Reply*:** The response of East Asian/Northwestern Pacific precipitation is shown in the following figure. It will be included in the revised manuscript.

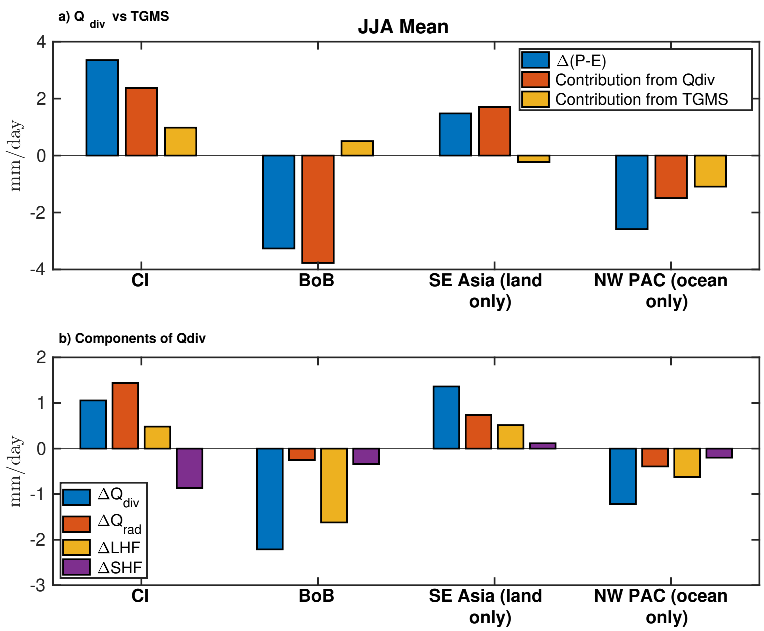


Figure 2. For the extreme precession experiments (.viz. P_{min} and P_{max}), the bar chart shows, **a)** the relative contribution of Q_{div} and TGMS to the changes in (P-E) and, **b)** the changes in the various fluxes contributing to Q_{div}. Here Q_{div} is the sum of all the fluxes at the surface and top of atmosphere, Q_{rad} is the sum of all the radiation fluxes (top and bottom of atmosphere), LHF and SHF are the latent and sensible heat fluxes. (Q_{div} = Q_{rad} + LHF + SHF). **CI:** Central India (15°, 25°N; 73°, 83°E) **BoB:** Bay of Bengal (10°, 20°N; 85°, 95°E) **SE Asia:** South East Asia (0°, 25°N; 100°, 125°E)

Figure (2a), shows that the dominant reason for the changes in (P-E) between P_{min} and P_{max}, is Q_{div} for all the four regions chosen. The land regions (Central India and South East Asia) show an increase in Q_{div} (and hence in (P-E)), while over the oceanic regions (BoB and NW Pacific) Q_{div} (and hence (P-E)) decreases. The increased insolation drives the positive changes in Q_{div} over land regions, whereas the decrease in LHF is the main cause of decrease in Q_{div} over oceanic regions (Figure 2b). This decrease in the surface latent heat fluxes over the North-West Pacific is due to the reduction in wind speeds. This in turn, is a response to the convective heating of atmosphere over the West Equatorial Indian ocean and the Red Sea. This is the same reason why wind speed over the Bay of Bengal reduces (discussed in detail in the discussion paper).

1 Results and Discussions

1.1 (P_{min}-P_{max}) vs (MH-PI):

In this section, we have discussed the similarities between the sets of experiments (P_{min}, P_{max}) and (MH, PI). All four of these experiments used the model EC-Earth. The details of the experiments can be found in (Bosmans et al., 2012, 2015). Both the sets of simulations exhibit a land-ocean asymmetry in the response of precipitation to orbital foricngs. The amplitude of the response is nearly a third in the (MH-PI) in comparison to that of (P_{min}-P_{max}) (Figure 3). Figure 4 shows the spatial response of (P-E) and Q_{div}. For MH, the response is quite similar in pattern to P_{min}, but of a smaller amplitude. There are some differences at the regional scale. This could be due to the effect of obliquity. However, the analysis that we have used in the discussion paper can still be used. The India-Bay of Bengal land-ocean asymmetry is due to the same mechanism in both MH and P_{min}.

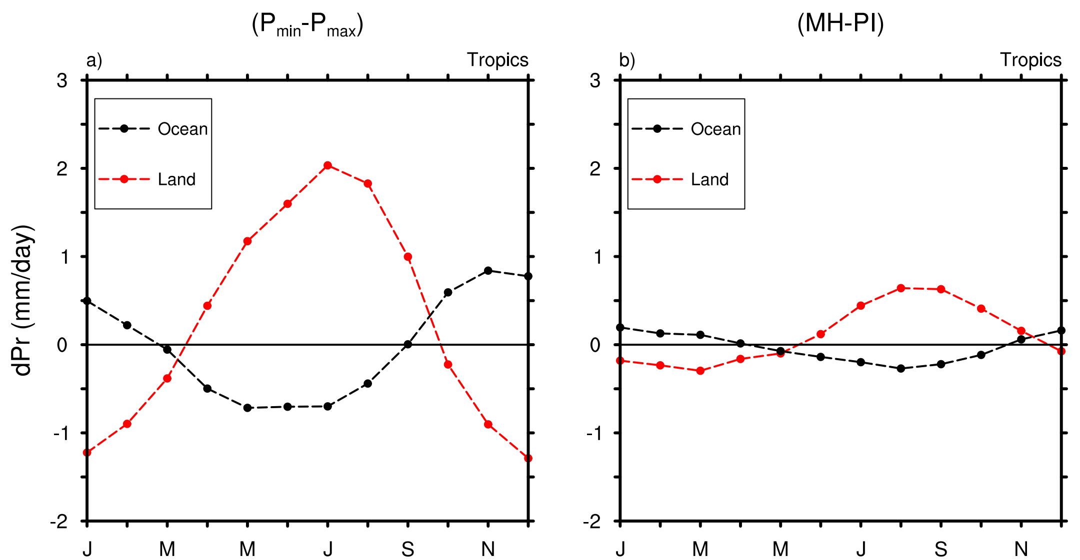


Figure 3. Seasonal cycle of the change in precipitation over all the tropical land and ocean taken separately, for **a)** (P_{min}-P_{max}) and, **b)** (MH-PI).

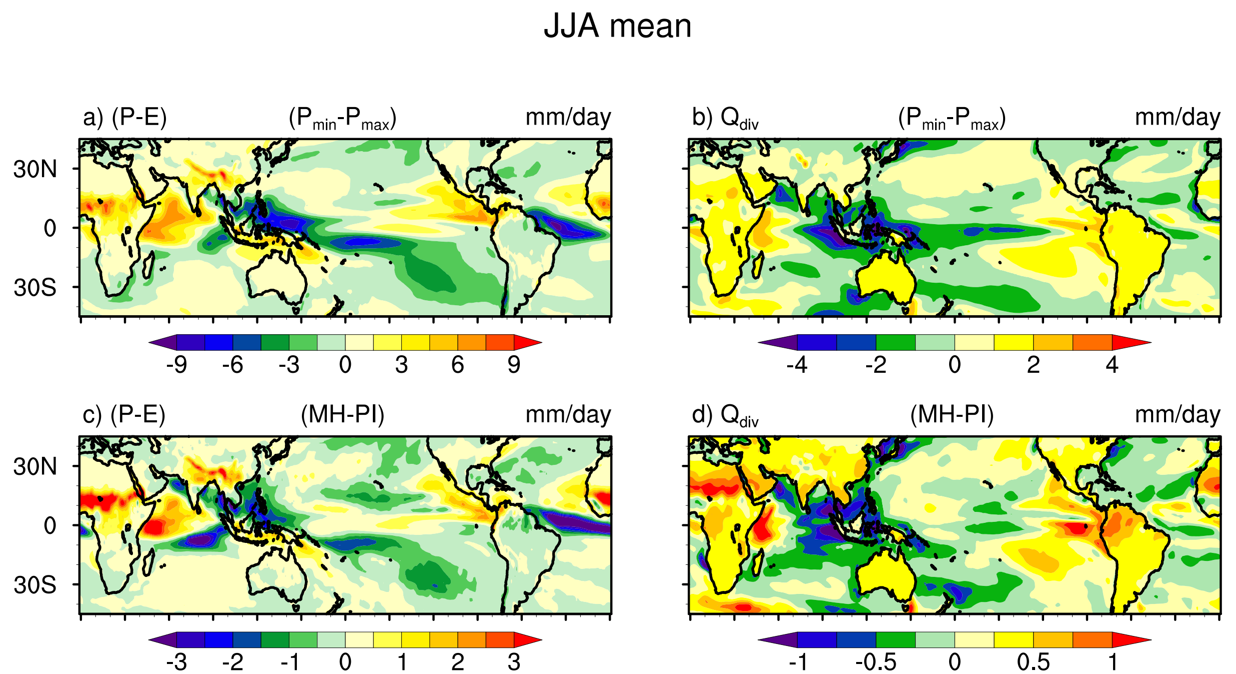
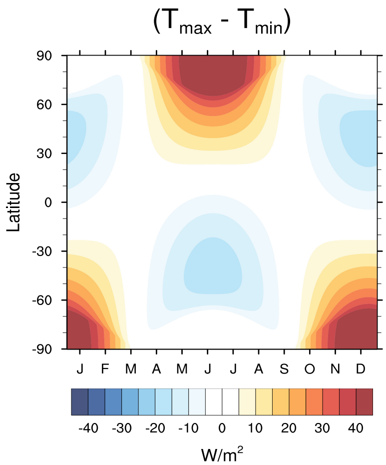


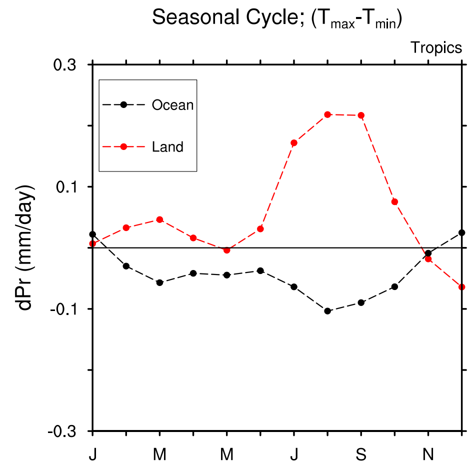
Figure 4. Spatial patterns of the changes in (P-E) (left panel) and Q_{div} (right panel), averaged over JJA. The top panel is for (P_{min}-P_{max}) and the bottom panel is for (MH-PI). There is a remarkable spatial coherence, but with a different magnitude.

1.2 Obliquity experiments:

In this section, we have discussed the response of tropical precipitation to obliquity forcing. For these experiments eccentricity was set to zero (circular orbit). The maximum and minimum obliquity experiments (T_{max} and T_{min}) have a tilt of 24.45^{o} and 22.08^{o}, respectively. Further details of the experiments can be found in (Bosmans et al., 2015). Figure 5a shows the difference in insolation between the two obliquity experiments. The obliquity forcing is much smaller than the precessional forcing. However, there still exists a land-ocean asymmetry in the response of tropical precipitation, though of much smaller magnitude (Figure 5b).



(a) Difference in insolation for the two obliquity experiments, T_{max} and T_{min}.



(b) Seasonal cycle of the change in precipitation over all of tropical land and ocean taken separately.

Figure 5. Figures showing the obliquity forcing and the precipitation response.

The spatial patterns of the response of (P-E) are in general similar to that of precession (Figure 6). There are however, some regional differences. Using equation 13 of the discussion paper to identify the cause of these changes, reveals a much different mechanism than that for precession. For example, over Central India the changes in (P-E) is due to Q_{div} in the precession experiments (Figure 2a) and due to TGMS in the obliquity experiments (Figure 7a). Even though over BoB, Q_{div} causes a decrease in (P-E) for both precession and obliquity experiments, Q_{div} decreases for different reasons. Precessional forcing causes winds to decrease, which reduces latent heat fluxes. Winds (and hence latent heat flux) also decrease in the obliquity experiments, but the decrease is not large enough. Hence, the changes in net radiation fluxes (Q_{rad}) become equally important (Figure 8f).

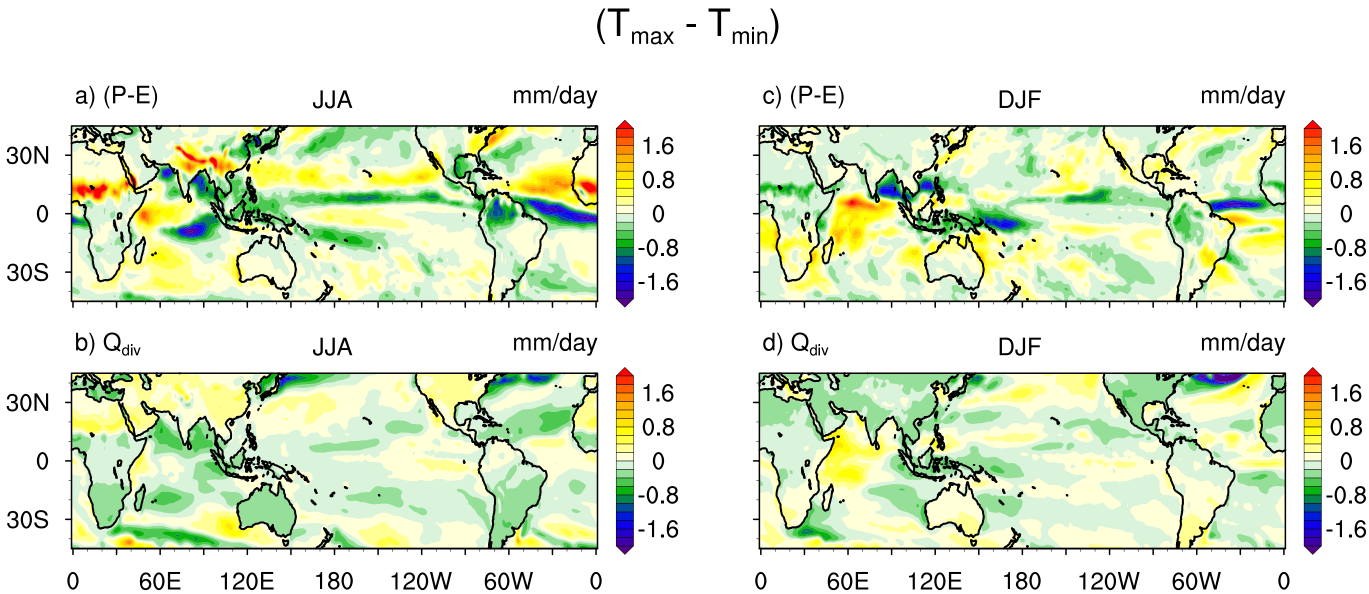


Figure 6. Spatial variation in (P-E) (top panel), and Q_{div} (bottom panel), averaged over the months JJA (left panel) and DJF (right panel).

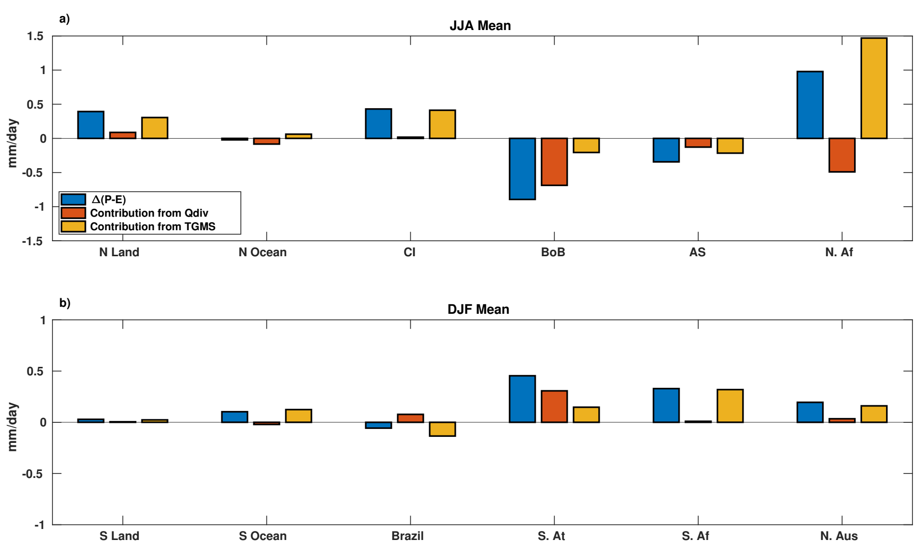


Figure 7. The bar chart shows the relative contribution of Q_{div} and TGMS to the changes in (P-E) for the, **(a)** northern summer, and **(b)** southern summer. **N. Land:** Northern Tropics (land only) (0^oN-30^oN; 0^oE-360^oE); **N. Ocean:** Northern Tropics (ocean only); **CI:** Central India (15^oN-25^oN; 73^oE- 83^oE); **BoB:** Bay of Bengal (10^oN-20^oN; 85^oE- 95^oE); **AS:** Arabian Sea (10^oN-20^oN; 60^oE- 70^oE); **N. Af:** North Africa (5^oN-15^oN; 20^oW- 0^oE); **S. Land:** Southern Tropics (Land only) (30^oS- 0^oN; 0^oE-360^oE); **S. Ocean:** Southern Tropics (Ocean only) (30^oS- 0^oN; 0^oE-360^oE); **Brazil:** (20^oS-10^oS; 70^oW- 50^oW); **S. At:** South Atlantic (20^oS-10^oS; 30^oW- 0^oE); **S. Af:** South Africa (20^oS-10^oS; 15^oE- 35^oE); **N. Aus:** North Australia (25^oS-15^oS; 130^oE-140^oE)

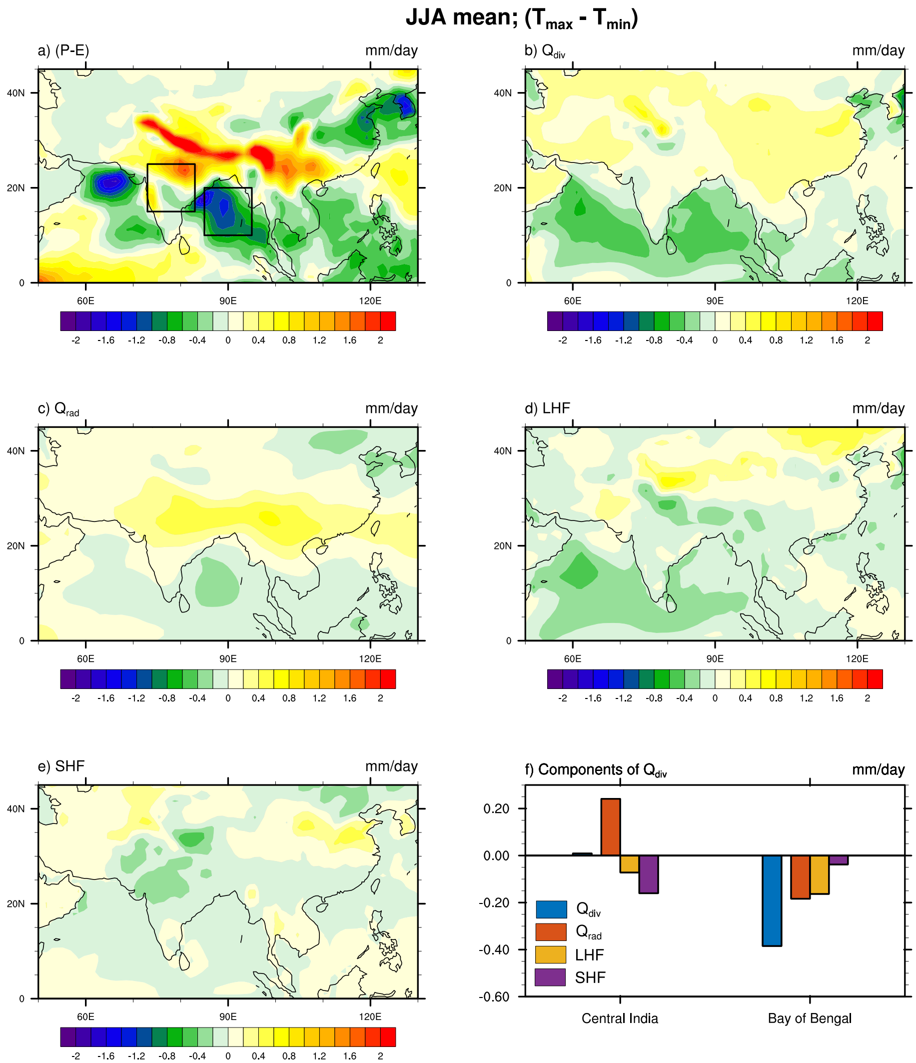


Figure 8. JJA mean difference between P_{min} and P_{max} for, **a)** (P-E), **b)** Q_{div}, **c)** Q_{rad} (sum of all radiation fluxes), **d)** Latent Heat Fluxes, **e)** Sensible Heat Fluxes, **f)** the components of Q_{div}.

References

Bosmans et al.: Monsoonal response to mid-holocene orbital forcing in a high resolution GCM, Climate of the Past, 8, 723, 2012.

Bosmans, J., Drijfhout, S., Tuenter, E., Hilgen, F., and Lourens, L.: Response of the North African summer monsoon to precession and obliquity forcings in the EC-Earth GCM, Climate dynamics, 44, 279–297, 2015.