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Climate of the Past Discussions

Interactive comment on "Regional climate model experiments to investigate the Asian monsoon in the Late Miocene" *by* H. Tang et al.

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We thank referee #1 for the thorough and helpful comments. All the suggested modifications will be carefully addressed in the revised version of the manuscript. Here is our response to the comments as follows.

General comments:

a) "Sometimes it is not clear which region is meant by terms such as N-China, E-Asia, S-China, C-Asia, etc. I would suggest to provide an additional figure (or table) in which you define all regions you want to use."

We agree with the referee and have added the definition of different regions in a Figure of the revised manuscript.

b) “I suggest adding a map showing the present-day summer and winter circulation (850hPa wind, 500hPa) in the Asian monsoon region, e.g. derived from your CTRL simulation. It would also facilitate the assessment of the circulation anomaly figures you showed.”

We also agree with the referee. The present-day summer and winter circulation has been added in the revised manuscript.

c) “In the discussion chapter, you use a lot of different indices describing the changes in monsoon circulation. Please explain in the text or at least in the caption of Table 3, why you use other regions for averaging than defined for the original indices. It would also be helpful to keep the abbreviations of the indices used in Wang et al. 2008a, so that the reader can easily identify the indices you refer to.”

“Tab.3: It is not clear, which indices are used (see above) and I wonder if it is appropriate to use these indices at all. Have you adjusted the indices to your model output? The regions of averaging are derived from EOFs or climatological data, one can not simply modify them.”

“p.854, l.10: Just using two points for representing the pressure gradient in TORT and GTORT is probably insufficient. You should average over a few grid-boxes or, at least, use the centre of the pressure systems in each simulation. I guess, the lowest pressure in TORT is not located at the same coordinates as in GTORT.”

We agree that the different monsoon indices lacked of detailed descriptions in the manuscript. More detailed descriptions and discussions of these indices have been added in the revised version of our manuscript.

We think it is important to use these indices to depict the strength of the monsoon system, because they can capture different dynamical aspects of the monsoon system in a very concise and straightforward way. In addition, all these indices are derived from the modern monsoon studies. The application of them to the palaeo-monsoon study, will be useful to connect our definitions of the monsoon strength in these two fields together, therefore, provide a more coherent view on the features of the Asian monsoon climate in the past.

The referee doubts the validity of the indices that we adjusted to use and argues that those indices might be very sensitive to the regions of averaging. In fact, the advances of these indices are all based on the understanding of the modern monsoon dynamics. Their validity in characterizing the monsoon strength is tested by EOFs or the modern climatological data. So far, none of these indices have been reported to be highly sensitive to the regions of averaging. We tried to follow the original definitions of the monsoon indices as much as possible. However, owing to the restriction of our regional model domain, some of them had to be adapted. Here are the detailed descriptions of the 6 indices we employed, which have been largely included in the revised version of our manuscript as the footnote of Table 3.

MO: We follow the same definition as the original literature (Sakai & Kawamura 2009). This index was introduced to characterize the pressure gradient between the Siberian high and the Aleutian low, which is responsible for the northwesterly winter monsoon wind in E-Asia. Although only two points of the sea-level pressure are used, they are shown to be well representative of the large scale sea-level pressure anomaly between the Asian continent and N-Pacific (see Fig 2a in Sakai & Kawamura (2009)).

There are similar winter monsoon indices which average the sea-level pressure over certain regions to characterize the pressure gradient between the Asian continent and N-Pacific. However, their region of averaging over N-Pacific is normally around 160_E (e.g. Kuang et al 2008). This is beyond our regional model domain, making it impossible to use the index as suggested by the referee.

WJ: This index describes the low-level northwesterly wind over E-China and E-China

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Sea, which is an important feature of the E-Asian winter monsoon. We modify the region of averaging from (115-145_E, 25 -50_N) in the original paper (Wang & Jiang 2004) to (115-130_E, 25-50_N) to calculate this index. Our region of averaging is smaller than the original one, but is still sufficient to capture the same feature of the E-Asian winter monsoon.

EIMR: This index represents the convective heating fluctuation associated with the Indian monsoon. We use the same region of averaging (70-110_E, 10-30_N) as the original literature (Goswami et al 1999) to calculate this index.

WY: This index depicts the vertical zonal wind shear over S-Asia controlled by the thermal contrast between the Indian/Indochina subcontinent and the tropical ocean. We change the region of averaging from (40-110_E, 0-20_N) in the original literature (Webster & Yang 1992) to (60-110_E, 5-20_N) in our manuscript. This index has also been widely applied and adapted in other studies, e.g. in Dobler & Ahrens (2010), the region of averaging is (45-80_E, 5- 20_N).

WN and WYF: The two indices both belong to the "southwest monsoon indices" in Wang et al. (2008), which directly measure the strength of the low-level E-Asian summer monsoon wind, i.e. southerly at 850 hPa. The area where the winds are averaged basically covers the E-Asian monsoon region, but with various latitudinal and longitudinal extents in different studies (Wang et al 2008). WN is adapted from IWN in Wang et al. (2008). The region of averaging is modified from (110-130_E, 20-30_N) to (110-125_E, 20-40_N) to measure the strength of the southerly wind over the whole E-China. WYF is adapted from IWWO in Wang et al. (2008) to demonstrate the regional difference in the strength of the southerly wind between S-China and N-China. This index is particularly useful to reflect the prevailing position of the E-Asian summer monsoon system (Wang et al 2001). The region of averaging is modified from (110-140_E, 20-30_N and 110-140_E, 30-40_N) in Wang et al. (2008) to (110-125_E, 20-30_N and 110-125_E, 30-40_N), which is smaller in longitudinal extent, but still sufficient to represent the basic feature of the original regions.

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d) “In the last part of your manuscript you use the term GTORT as name for a forcing, in the first part as name for the simulation. Please rename one, it is confusing.”

This is true. We have separated the notation for the simulation (referred to as GTORT) and the forcing (referred to as TORT-GF) in the revised manuscript.

e) “You sometimes show the land-sea mask of the model in the figures, sometimes not. You also use different projections. It would be much easier to compare the figures if only one standard format is used.”

We have added the land-sea mask to all the figures in the revised manuscript. As to the projection, we prefer to use the rotated coordinates for the configuration of the orography and vegetation of our regional model (i.e. Fig. 3 in the manuscript), because it is important to display the original boundary set up of our regional model. Using other projections will require interpolation and distort the original data to some extent. For the other figures, we interpolated the regional model results to the normal lon-lat-coordinates to facilitate the comparison with the global model results.

Specific comments

“p.842, l.6: I guess, you have not simulate the entire Tortonian period from 11-7Ma. Be more precise which years you analyse.”

We aim at simulating the average state of the climate in the Tortonian (11-7 Ma) rather than a specific short time interval or the entire period of the Tortonian. We have made it clearer in the revised manuscript.

“p.842, l.18: What do you mean by the term ’other forcings’? please give examples.”

“p.849 l.11-18: To better understand your experimental setup, you could further describe/ repeat what you mean by regional boundary conditions (orography or vegetation,...) and what you mean by global boundary conditions (SST or sea-ice,...)”

We agree with the reviewer that our text was unfortunately unclear. The ‘regional

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boundary conditions' and 'global boundary conditions' have been more specifically described in the revised manuscript.

"p.846, Say some words on the orbital configuration you used and the spin-up"

We use the modern orbital configuration, which is a good average for the 4 million years of the Tortonian. The global model was integrated 2500 years for reaching dynamic equilibrium. This is mentioned now in the revised version.

"p.846, l.12: It is not clear if you reduce orography globally or regionally."

We have added details on this point in the revised version. In the AOGCM, Micheels et al. (2011) reduced the orography with regional differences, not by simply using a global multiplication factor. The most pronounced changes were made for Greenland and Tibet, but Micheels et al. (2011) also adapted other mountain ranges such as the Alps.

"p.846, l.14-18: Say a few more words on how you prescribed vegetation. Is it based on proxies? Is it consistent to the vegetation prescribed in the regional model?"

The prescribed global vegetation is based on palaeobotanical evidences. We adapted the surface parameters in the regional model consistent to the global model, but with more regional details. For each vegetation type a set of surface parameters is taken from a look-up-table. Some words about this aspect have been added in the revised manuscript.

"p.846, l.24-26: According to Fig.3, the strongest warming occurs in the Sahara and on the Tibetan Plateau which are located in the low-latitudes. Therefore, the meridional T-gradient is probably not weaker in GTORT."

There is a reduction of the meridional temperature gradient, although not as pronounced as the older time intervals such as the Eocene. For more details we would like to refer to Micheels et al. (2011).

“p.846, l.26-30: You mention the heat transport in the ocean, are these explanations results of other studies? then: please cite them. Perhaps, there are also other explanations for the cooling in Europe, have you analysed e.g. cloud cover? I guess, the westerlies also intensify due to the temperature change.”

The results of the ocean heat transport are from Micheels et al. (2011) and results are consistent with other studies. Concerning the cloud cover, it does increase. Nevertheless, the most important mechanism is the ocean. For instance, Steppuhn et al. (2006) focused on the role of a weak ocean heat transport. They found that a weaker ocean heat transport caused a strong cooling in the European region. We have modified our manuscript to make this clear.

“p.847, l.1: The strongest westerly wind anomalies are located south of the strongest precipitation anomalies. Please check the moisture flux and the moisture flux convergence to prove if the increased westerlies are really responsible for the increase in precipitation.”

In our model (GTORT), the intensification of the westerlies is associated with a strengthening of the storm tracks (see figure 6 in Micheels et al. (2011), which slightly shift northward. This explains why there is a difference in the position of the precipitation and wind field anomalies. The moisture flux for the North Atlantic and European region has been shown in figure 8 in Micheels et al. (2011). It is mainly enhanced in southern Europe (40-50_N) due to the strengthened westerlies. The pronounced increase of precipitation in northern Europe (50-60_N), therefore, is due to the enhanced moisture flux convergence. For details of the experiment GTORT, we would like to refer to Micheels et al. (2011).

“p.847, l.3-5: I think, a large part of the precipitation increase in North Africa is related to a strengthening of the summer monsoon, please check.”

The African summer monsoon is stronger in the Tortonian experiment, whereas precipitation doesn’t change so much during the winter season. This is explained by the

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dense vegetation cover in the Miocene. A “green North Africa” including the absence of the Sahara desert enhances precipitation because of a stronger evapotranspiration (Micheels et al 2009). This effect is most pronounced in the summer monsoon season. We have added more words on this aspect in the revised manuscript.

“p.847, l.11-13: Figure 2d shows hardly no changes in summer wind field in East China. Thus, a weaker summer monsoon is probably not responsible for the strong reduction in precipitation. Please check if other mechanisms lead to the precipitation anomaly.”

How the summer monsoon changes in GTORT can be clearly seen from WN and WYF indices in Table 3. Although there is no pronounced change, or even slightly enhancement of the summer monsoon wind at 850 hPa on the regional average of the whole E-China (see WN index in Table 3), the prevailing position of the E-Asian monsoon system moves southward in GTORT (see WYF index in Table 3). This is similar to that in our regional model and suggests a weak summer monsoon circulation in E-Asia. The weakened E-Asian summer monsoon is largely responsible for the decrease of the annual precipitation in E-China. In addition, the decrease of precipitation in other seasons also contributes to the reduced annual precipitation shown in Fig. 2b of our manuscript, but this is of minor relevance. The global model results are just summarized in section 2.2, but we address this pattern later on when presenting and discussing the results of the regional model.

“p.850, l.4-7: This suggests a reduced thermal contrast between land and oceans’ – In my opinion, this sentence seems not to be correct, at least not for the summer season. Large parts of the South and Central Asian continent warm more than the ocean. This increases the temperature gradient, please check.”

We agree that this sentence is inaccurate. What we want to emphasize is that the change of summer temperature in the N-Asian continent is less pronounced than that in the other regions. We have removed this statement from the revised manuscript.

“p.850, l.18-19: Most of the Tibetan Plateau receives more precipitation. There is no

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distinctive north-south difference."

The precipitation does decrease over the "northern Tibetan Plateau". Here, the "northern (or southern) Tibetan Plateau" refers to that of the present day. The referee may consider it as the Tortonian Tibetan Plateau, thus had the impression that most of the (Tortonian) Tibetan Plateau receives more precipitation. We have clarified this in the revised manuscript.

"p.851, l.5-7: At least according to reanalyses data, N-India is affected by westerly winds (850hpa), S-India by easterlies. Thus, the Indian winter monsoon is not intensified in TORT."

The referee is right that N-India (north to 20_N) is affected by westerly wind at 850 hPa. We have removed this statement from our manuscript.

"p.851, l.10-11: 'The Asian trough is a little shallower resulting...' - I'm not sure, do you mean 'ridge' and not 'trough' ? Please add the atmospheric level: the ridge/trough in 500hPa ... ."

We have added the atmospheric level (500 hPa) and revised our description to make it clearer. The sentence now reads: "In northern Eurasia, the isolines of the geopotential field at 500 hPa shift slightly southward. The trough at 500 hPa to the northeast of the TP is, therefore, less pronounced. As a result, the northerly wind component in the vicinity of the trough is weakened, leading to a significant southerly wind anomaly over NE-Asia."

"p.852, l.25-26: One of your key results is the confirmation of the existence of monsoonal influenced climate in large parts of South and Central Asia during the Tortonian. It would be interesting to further examine the extent of the monsoon region. You could use modern definitions like described in Wang and Linho, J. Climate, 2001."

Following the suggestion of the referee, we tried the method described in Wang & LinHo (2002), which primarily use the annual range of the pentad mean precipitation

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(>5 mm/day) to depict the distribution of monsoonal climate. The result is shown in Fig. 1 of this reply. This method depicts the present-day distribution of the monsoonal climate in CTRL quite well. Compared to CTRL, the extent of the monsoon region in TORT shrinks in N-China and the NW-Indian subcontinent, while the “atypical monsoonal climate” in S-China (i.e. the white area) in CTRL, which is similar to that in Wang & LinHo (2002), becomes typical monsoonal climate in TORT. These trends agree with that revealed by the Köppen classification and further confirm our results. However, the changes in the monsoon extent of TORT shown by this method are relatively small compared to those shown by the Köppen classification. This can be attributed to the fact that the method of Wang & LinHo (2002) only considers the precipitation, while the Köppen classification takes the effects of both the temperature and precipitation into account. As is well-known, the temperature increases significantly in the Tortonian in most of the Asian monsoon region. Such increase of temperature will probably raise the threshold value of precipitation for separating the monsoonal and dry-continental climate in the Tortonian. Therefore, using the same present-day threshold value (5mm/day) to quantify the monsoon region in the Tortonian, may bias the result.

“p.853, l.15-19: According to Fig.7, you average over longitudes between 80_ and 95_E. This region does not represent the Indian subcontinent. It covers rather the Bay of Bengal region. Better use longitudes between 70_ or 75_ and 85_E.”

We use the zonal average between 80_ and 95_ E to show the vertical motion, because this region is the center of the Tibetan Plateau. The effect of the surface height of the Tibetan Plateau on vertical motion can be best manifested in this region.

We have made it clearer in the revised manuscript that the region of averaging represents the Bay of Bengal. Nevertheless, the Bay of Bengal is an essential part of the Indian summer monsoon system. The summer monsoon over the Indian subcontinent is closely associated with that over the Bay of Bengal. Therefore, the changes of the vertical motions over the Bay of Bengal can be a good representation of that over the

Indian subcontinent. We have checked the vertical motion averaged over 70-85_E, 75-80_E, or 75-90_E. The changes to the south of the Tibetan Plateau are in concert with that averaged over 80-95_E. This confirms that the vertical motion averaged over 80-95_E is representative of that over the Indian subcontinent.

“p.853, l.20-21: In my opinion, one can not see an ITCZ shift in Fig.7a,b. In TORT, there is still a strong upward motion at 20_N, south of it (between 15 and 18_N) downward motion appears. Maybe the upward motion at ca. 12_N is induced by a change in upper-tropospheric wind divergence. The upward motion at ca.12_N does not start at the surface as it should do in the ITCZ.”

We agree with the referee that the upward motion at ca. 12_N may be induced by a change in upper-tropospheric wind divergence. Saying that the tropical convergence zone (TCZ) shift southward was inaccurate and we have removed this statement from the revised manuscript. The annual evolution of the vertical motion over the same region (Figure not shown) reveals that the strengthening of the ascending motion at ca. 12_N in summer (JJA) in TORT can be explained by two facts: (1) In CTRL, there is a sudden northward shift of the TCZ from S-India and the southern Bay of Bengal (10-15_N) to N-India and the northern Bay of Bengal (i.e. 20-25_N) in early June. Such northward displacement of the TCZ is delayed in TORT, and as a result, the TCZ stays at 10-15_N for most of June. (2) In July and August, the upward motion over S-India and the southern Bay of Bengal (10-15_N) is generally strengthened in TORT. The upward motion over N-India and the northern Bay of Bengal is weakened, but still the strongest in the whole Indian monsoon region. This indicates that the TCZ may still reside in N-India and the northern Bay of Bengal in TORT for most of the summer. That the upward motion at ca. 12_N does start at the surface, was not clearly seen in Fig. 7 of our manuscript, probably because of the colour scheme of this figure, which has been modified in the revised manuscript.

“p.853, l.23: The sinking motion in TORT is enhanced only south of TP. North of TP, the descending motion is extended to the upper troposphere. Descending motion also

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occur in the upper troposphere above the northern TP. Be more precise.”

We have modified the sentence accordingly, and it now reads: “. . ., while a strengthened rising motion over the southern TP is found in TORT, with a sinking motion enhanced immediately to the south of it and appearing in the upper troposphere over the northern TP as an offset. . ..”

“p.855, l.3-12: ODP site 885/886 is located far in the north. It is possible that the westerly wind belt is shifted southward in the Tortonian, and that this site is not located downstream of the Loess Plateau any more.”

According to the study by Pettke et al. (2000), the dust source for ODP site 885/886 is mainly from the basins north of the Tibetan Plateau, the Gobi Desert and the Loess Plateau and the regions of dust source have not changed during the last 11 Ma. This evidence may not favor the explanation suggested by the referee, which implies a change in the dust source region.

“p.856,l.13-18: I suggest rewriting this section. It would be useful to add a sentence on the problem of different definition of the monsoon strength in literature (instead of referring to other papers), and that nowadays the term ’weak East Asian Monsoon’ is commonly used for describing an anomaly with little precipitation in N-China and more precipitation in South China. Afterwards you could go on with the following issues: - your results show this anomaly pattern - conclusion: the East Asian summer monsoon was weaker in the Tortonian.”

We have modified the text accordingly, it now reads: “. . .However, as illustrated in TORT, the precipitation changes in S-China and N-China can be out of phase. In such a case, a strong (weak) E-Asian summer monsoon is commonly characterized by the increased (decreased) precipitation in N-China but decreased (increased) precipitation in S-China (Wang et al 2008). Therefore, the seemingly contradictory records from S-China and N-China in the Tortonian may actually be concordant with each other, and both point to a weak E-Asian summer monsoon at that time.”

“p.859, l.16: Have you prescribed an open Indonesian seaway? In this case I suggest mentioning this fact in your model setup section.”

We did not prescribe an open Indonesian seaway in our regional model, because the regional model domain does not cover the region where the Indonesian seaway opens. The opening of the Indonesian seaway is, however, prescribed in our global model, which climatic effect may propagate from our global forcing to the regional model. We have mentioned this fact in the revised manuscript.

“Fig.5: You plot sea level pressure anomalies to the domain average, did you use the entire domain for calculating the reference value? In general, the centre of the winter high-pressure system is located further to the west.”

We use the entire domain to calculate the reference value. We have checked the absolute sea level pressure in both the regional model and the global model experiments. The locations of the winter high-pressure system depicted by the absolute values are concordant with Fig. 5 of our manuscript. Similar to our results, there are also studies showing that the center of the winter high-pressure system lies to the northeast of the Tibetan Plateau (e.g. Liu & Yin 2002).

“Fig. 9: What are the stars in your plot? I wonder, how good the hypsodonty is as proxy for the climate. Lower hypsodonty values are related to more precipitation. That means: in present-day, Eastern China receives much more precipitation than India. There are also other examples.”

The stars in Fig. 9 of our manuscript denote the fossil localities. The hypsodonty can depict the large-scale distribution of the present-day precipitation reasonably well over the Asian continent (Eronen et al 2010). The lower hypsodonty in E-China (particularly S-China) and higher hypsodonty in central India are in accordance with the present-day precipitation observation, which shows higher precipitation in S-China than that over most of India. Such difference in hypsodonty mainly results from the different ruminants in the two areas: while the semi-endemic high-crowned (high hypsodonty) ungulates, like four-horned Antelope (Tetracerus quadricornis), are widely distributed in the Indian subcontinent, the ungulates in E-China are mainly low-crowned (low hypsodonty), such as Chinese forest musk deer (Moschus berezovski). The hypsodonty might lead to a slight overestimation of the present-day precipitation in S-China. One possible reason for this is that the elephant (Elephas maximus), which has high hypsodont teeth and commonly exists in the tropical and subtropical monsoon climate (like India), is rare in S-China today. This is largely due to human influence.

Technical corrections:

All the technical corrections are accepted and have been taken into account in the revised manuscript.

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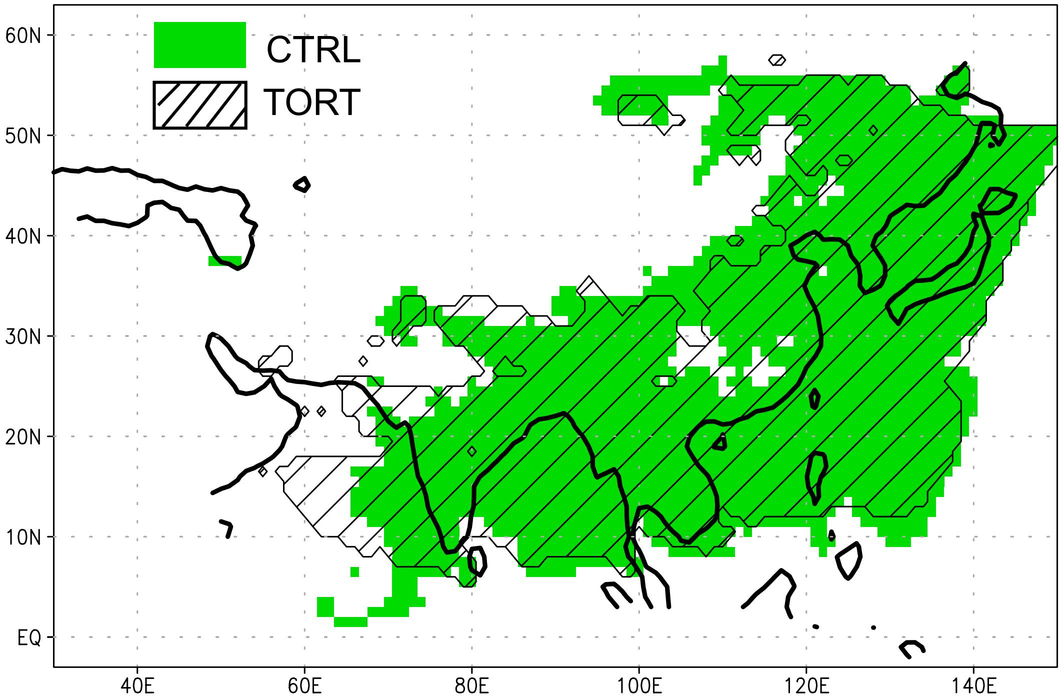

Fig. 1. Distribution of monsoonal climate in CTRL and TORT based on the method described by Wang & LinHo (2002).

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