Non-uniform spatial difference in the South Asian summer monsoon during the mid-Piacenzian

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ABSTRACT

The South Asian summer monsoon (SASM) during the mid-Piacenzian is analyzed through climate modelling with CAM4. The model results reveal a non-uniform spatial difference in the SASM during the mid-Piacenzian compared to the pre-industrial era, with the SASM being more intense north of ~20°N but weaker south of ~20°N. In particular, summer precipitation is higher in South Asia north of ~20°N, accompanied by anomalous low-level southwesterlies from the Arabian Sea, whereas the precipitation is lower in South Asia south of ~20°N, with anomalous low-level easterlies. These differences in the SASM are related to changes in sea level pressure (SLP) due to the different boundary conditions between the two periods. Further analysis isolates the climate effects of the different boundary conditions and indicates the combined difference in atmospheric carbon dioxide concentration and SST to be the most important factor in this difference in the SASM through the changes in SLP. By comparison, the differences in vegetation and topography have limited effects. The availability of geological evidence is relative greater in northern India than in southern India, and comparison with this geological evidence shows the simulated monsoon climate to be qualitatively consistent with it, particularly for the wetter climate in northern India.

1. Introduction

The mid-Piacenzian (3.264–3.025 Ma) was a relatively warm period in geological time (Haywood et al. 2013), and this warm climate is in some respects comparable to the expected climate of the near future (Sun et al. 2013). Many climate modelling studies over the past 20 years or so have therefore investigated the climate of this period (e.g. Chandler, Rind, and Thompson 1994; Jiang et al. 2005). In particular, phase one of the Pliocene Model Intercomparison Project (PlioMIP) has recently been launched, involving a large number of model–model comparisons (Haywood et al. 2010), with a focus on large–scale features, high-latitude warming, Atlantic meridional overturning circulation, El Niño–Southern Oscillation, monsoon climate, and so on (e.g. Zhang, Nisancioglu, et al. 2013; Zhang, Yan, et al. 2013; Hill et al. 2014; Brierley 2015).

To date, several studies have focused on the monsoon climate of the mid-Pliocene (e.g. Jiang et al. 2005; Zhang, Yan, et al. 2013). However, the South Asian summer monsoon (SASM), a major component of the Asian summer monsoon, still remains to be investigated. In the mid-Piacenzian, compared to the pre-industrial period, several of the boundary conditions would have been different—mainly, the orography, land cover (vegetation and ice sheet), atmospheric CO₂ concentration (405 ppmv compared to 280 ppmv), and also the sea surface temperature (SST). Here, we investigate which of these boundary conditions’ differences are more responsible for the difference in the SASM during the mid-Piacenzian, as compared to the pre-industrial period.
We do not use the model results from phase one of the PlioMIP in this study, because these model results only include one pre-industrial and one mid-Pliocene experiment, and thus lack the sensitivity experiments necessary to investigate the different boundary conditions during the mid-Piacenzian. Additionally, we do not use an AOGCM simulation, because the SST in the tropics is usually overestimated in models of this type (Haywood et al. 2013). Instead, we use an AGCM, accompanied by the reconstructed boundary conditions, including SST, from PRISM3 (Pliocene Research, Interpretation and Synoptic Mapping) data, to investigate the effects of the different boundary conditions on the SASM in the mid-Piacenzian.

2. Model and experimental design

We use the same experimental design and CAM4 model results in this study as those used in Zhang et al. (2016). In CAM4, we adopt a high horizontal resolution of F09, which is roughly equivalent to 0.9° latitude × 1.25° longitude, and 26 layers in the vertical direction (Neale et al. 2013).

The results from four experiments with CAM4 are used. First, the pre-industrial (PI) experiment, which has an atmospheric CO₂ concentration of 280 ppmv and modern-day averaged SSTs (Neale et al. 2010). Then, based on PI, three more experiments, in which the boundary conditions of the mid-Piacenzian are altered one-by-one according to PRISM3, including different topography in experiment PI_t (Figure 1(a)), land cover in experiment PI_tv (Figure 1(b)), and atmospheric CO₂ concentration (altered to 405 ppmv) and SST (CO2SST) in experiment MP (Figure 1(c) and (d)). For a more detailed description of the experimental design and boundary conditions, please refer to Haywood et al. (2010) and Zhang et al. (2016).

3. Model results

The model results show that, in the mid-Piacenzian, compared to the pre-industrial period, the SASM intensifies in South Asia north of ~20°N but weakens south of ~20°N. Summer precipitation is enhanced in South Asia north of

![Figure 1](image-url). The different boundary conditions between the mid-Piacenzian and the pre-industrial period based on PRISM3 data: (a) topography (units: m); (b) summer surface albedo; (c, d) summer and winter SST (units: °C).
near 20°N, accompanied by anomalous low-level southwest-erlies, while precipitation is reduced, mainly over ocean south of ~20°N, with anomalous low-level easterlies (Figure 2(a)). Owing to the enhanced summer precipitation and, further, the intensified seasonality of precipitation, the monsoon domain (Wang et al. 2012) expands northwards in South Asia, north of ~20°N, especially in the region west of ~80°E, whereas the monsoon domain retreats northwards in South Asia, south of ~20°N, due to the reduced summer precipitation and weakened precipitation seasonality in that region.

Meanwhile, the surface air temperature (SAT) differences are also not uniform. The SAT is higher in regions over the Tibetan Plateau and central Asia, but lower in northern India and the south side of the Tibetan Plateau (Figure 3(a)). These differences in SAT over land are largely related with the differences in regional topography due to the effects of the temperature lapse rate (Figure 1(a)), with elevated topography resulting in lower SAT and depressed topography resulting in higher SAT.

Overall, the difference in the SASM can be explained by the different sea level pressure (SLP). The SLP is reduced north of ~30°N, and there is an anomalous area of high pressure over ~15°–25°N. Thus, the merid-ional pressure gradient is reinforced north of ~20°N and weakened south of ~20°N (Figure 3(a)). Under these differences in SLP in the mid-Piacenzian, the flow of moist air into northern India from the Arabian Sea north of ~20°N becomes stronger, whereas monsoon winds are weaker south of ~20°N (Figure 2(a)). Meanwhile, upward movement intensifies north of ~20°N but weakens south of ~20°N (Figure 4(a)). Thus, ultimately, precipitation increases north of ~20°N but decreases south of ~20°N (Figure 2(a)).

Figure 2. The differences in summer precipitation (shaded; units: mm d⁻¹) and 850-hPa wind (vectors; units: m s⁻¹) at the 95% confidence level, with the red and blue contours indicating the monsoon domains of the two experiments being compared: (a) experiment MP (red) minus experiment PI (blue); (b) experiment MP (red) minus experiment PI_tv (blue); (c) experiment PI_tv (red) minus experiment PI_t (blue); (d) experiment PI_t (red) minus experiment PI (blue).
of ~20°N (Figure 4(b)), these combined differences act to markedly enhance the onshore flow from the Arabian Sea and increase the precipitation north of ~20°N, as well as weaken the monsoon winds and reduce the precipitation south of ~20°N (Figure 2(b)). Furthermore, the monsoon domain expands further northwards in South Asia in the area north of ~20°N and west of ~80°E, but retreats northwards in South Asia in the area south of ~20°N (Figure 2(b)), due to the difference in precipitation. On the whole, the contribution of the difference in CO2SST to the difference in the SASM in the mid-Piacenzian, as compared to the pre-industrial period, is greater than that of the other boundary conditions.

The CO2SST difference, i.e. the combined CO₂ concentration and SST differences, is the most important factor in the difference of the SASM in the mid-Piacenzian compared to the pre-industrial period. This combination leads to the marked warming north of ~30°N, but slight warming and cooling south of ~30°N (Figure 3(b)). As a result, the surface pressure decreases in the area north of ~30°N due to the marked increase in SAT, and increases in the area south of ~30°N due to the weaker increase in, or decrease in, SAT, with the increased pressure center located over the middle of the Indian subcontinent at ~20°N (Figure 3(b)). Accompanied by the intensified vertical movement north of ~20°N but weakened vertical movement south of ~20°N (Figure 4(b)), these combined differences act to markedly enhance the onshore flow from the Arabian Sea and increase the precipitation north of ~20°N, as well as weaken the monsoon winds and reduce the precipitation south of ~20°N (Figure 2(b)). Furthermore, the monsoon domain expands further northwards in South Asia in the area north of ~20°N and west of ~80°E, but retreats northwards in South Asia in the area south of ~20°N (Figure 2(b)), due to the difference in precipitation. On the whole, the contribution of the difference in CO2SST to the difference in the SASM in the mid-Piacenzian, as compared to the pre-industrial period, is greater than that of the other boundary conditions.

Figure 3. The differences in summer SAT (shaded; units: °C) and SLP (contours; units: hPa): (a) experiment MP minus experiment PI; (b) experiment MP minus experiment PI_tv; (c) experiment PI_tv minus experiment PI_t; (d) experiment PI_t minus experiment PI. For SAT, only the differences significant at the 95% confidence level are illustrated. For SLP, only certain levels (−1, 0, 1, and 2) are shown, with negative values shown with dashed lines.
corresponding precipitation and winds also differ only slightly (Figure 2 (d)).

4. Model–data comparison

The climate in northern India was likely wetter in the mid-Piacenzian compared to the Late Quaternary. In terms of humidity, the $\delta^{18}O$ values of pedogenic carbonates and the hydrogen isotope ratio of pedogenic clay in the Himalayan foreland basins have been found to be generally lower in the mid-Piacenzian, revealing that conditions were probably wetter (Quade, Cerling, and Bowman 1989; Sanyal et al. 2010; Singh et al. 2012) in that period compared to the Late Quaternary. In addition, palynological studies at the Surai

By comparison, the changes in vegetation and topography have limited effects on the intensified SASM. The difference in vegetation lowers the SAT slightly over the Indian subcontinent, and there is no obvious increase in SLP anomalies in the Indian subcontinent (Figure 3(c)); thus, the summer winds and precipitation differ only slightly (Figure 2(c)). In contrast, due to the effects of the temperature lapse rate, elevated topography causes the SAT to decrease, and depressed topography causes it to increase (Figure 3(d)). However, the difference in topography only affects the SLP in the Indian subcontinent, and there is also no obvious increase in SLP anomalies over the middle of the Indian subcontinent (Figure 3(d)). Thus, the corresponding precipitation and winds also differ only slightly (Figure 2(d)).
Khola Section in central Nepal have yielded information regarding changes in moisture, via the percentages of tropical forest and grassland taxa. The slightly lower proportion of tropical forest and higher proportion of grassland in the mid-Piacenzian compared to the Late Quaternary (Hoorn, Ohja, and Quade 2000) is again a likely indicator that the climate was wetter, with enhanced monsoon conditions in the former period. Furthermore, based on fossilized murine rodents, there is also an indication that the climate in the northwestern part of the Indian subcontinent was wetter in the mid-Piacenzian (Patnaik 2011). By comparison, there have been relatively fewer reconstructions of humidity for southern India.

The simulated wetter climate in northern India agrees with the geological evidence (Hoorn, Ohja, and Quade 2000; Patnaik 2011; Singh et al. 2012), likely indicating that the monsoon winds were stronger in this region, as shown in model results. Besides, the simulated weakened SASM south of ~20°N is also a reasonable result (Clift et al. 2008). The weakened Indian summer monsoon indicates that the climate was probably drier in southern India, which was also shown in the simulations. On the whole, for South Asia, the simulated strengthened monsoon winds in northern India and weakened monsoon winds in southern India qualitatively agree with the available geological evidence, together implying a spatial difference in the intensity of the SASM in the mid-Piacenzian compared to the Late Quaternary.

5. Summary

The present study has investigated the climate impacts of different boundary conditions on the nature of the SASM in the mid-Piacenzian compared to the pre-industrial period. The model results suggest a non-uniform spatial difference of the SASM in the mid-Piacenzian, compared to the pre-industrial period, with the SASM being more intense north of ~20°N but weaker south of ~20°N, which can be explained by the different SLP. Moreover, the combined CO2SST difference appears to be the most important factor responsible for the difference in the SASM during the mid-Piacenzian. A qualitative model–data comparison is also provided.

Our model results indicate that the different SST in the mid-Piacenzian, compared to that in the pre-industrial period, was an important factor responsible for the different SASM. In the AOGCM, the simulated difference in the SST derives from the difference in topography, land cover, and also the atmospheric CO2 concentration. However, AOGCMs often overestimate the SST in the tropical oceans, as compared to the SST determined from reconstructions. The inconsistency between the simulated and reconstructed SST in the tropical oceans may derive from the uncertainties in the reconstructed boundary conditions or the potential absence of some key parameterizations in the AOGCM. Regardless of the reason, or reasons, finding a solution to this problem will certainly improve our understanding of how the SASM differed in the mid-Piacenzian compared to today. Besides, another consideration is that orbital forcing may markedly affect SAT, precipitation, and thus the SASM. In this respect, more studies are needed in the future.

Disclosure statement

No potential conflict of interest was reported by the authors.

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References

Brierley, C. M. 2015. “Interannual Climate Variability Seen in the Pliocene Model Intercomparison Project.” *Climate of the Past* 11: 605–618.

Chandler, M., D. Rind, and R. Thompson. 1994. “Joint Investigations of the Middle Pliocene Climate II: GISS GCM Northern Hemisphere Results.” *Global and Planetary Change* 9: 197–219.

Clift, P. D., K. V. Hodges, D. Heslop, R. Hannigan, H. Van Long, and G. Calves. 2008. “Correlation of Himalayan Exhumation Rates and Asian Monsoon Intensity.” *Nature Geoscience* 1: 875–880.

Haywood, A. M., H. J. Dowsett, B. Otto-Bliesner, M. A. Chandler, A. M. Dolan, D. J. Hill, D. J. Lunt, et al. 2010. “Pliocene Model Intercomparison Project (PlioMIP): Experimental Design and Boundary Conditions (Experiment 1).” *Geoscientific Model Development* 3: 227–242.

Haywood, A. M., D. J. Hill, A. M. Dolan, B. L. Otto-Bliesner, F. Bragg, W.-L. Chan, M. A. Chandler, et al. 2013. “Large-scale Features of Pliocene Climate: Results from the Pliocene Model Intercomparison Project.” *Climate of the Past* 9: 191–209.

Hill, D. J., A. M. Haywood, D. J. Lunt, S. J. Hunter, F. J. Bragg, C. Contoux, C. Stepanek, et al. 2014. “Evaluating the Dominant Components of Warming in Pliocene Climate Simulations.” *Climate of the past* 10: 79–90.

Hoorn, C., T. Ohja, and J. Quade. 2000. “Palynological Evidence for Vegetation Development and Climatic Change in the Sub-Himalayan Zone (Neogene, Central Nepal).” *Palaeogeography Palaeoclimatology Palaeoecology* 163: 133–161.

Jiang, D., H. J. Wang, Z. L. Ding, X. M. Lang, and H. Drange. 2005. “Modeling the Middle Pliocene Climate with a Global Atmospheric General Circulation Model.” *Journal of Geophysical Research* 110: D14107. doi:10.1029/2004JD005639.

Neale, R. B., J. H. Richter, A. J. Conley, S. Park, P. H. Lauritzen, A. Gettelman, D. L. Williamson, et al. 2010. “Description of the NCAR Community Atmosphere Model (CAM4).” *Tech. Rep. NCAR/TN-485+STR. National Center for Atmospheric Research.* 212 pp.
Neale, R. B., J. Richter, S. Park, P. H. Lauritzen, S. J. Vavrus, P. J. Rasch, and M. Zhang. 2013. “The Mean Climate of the Community Atmosphere Model (CAM4) in Forced SST and Fully Coupled Experiments.” *Journal of Climate* 26: 5150–5168.

Patnaik, R. 2011. “Fossil Murine Rodents as Ancient Monsoon Indicators of the Indian Subcontinent.” *Quaternary International* 229: 94–104.

Quade, J., T. E. Cerling, and J. R. Bowman. 1989. “Development of Asian Monsoon Revealed by Marked Ecological Shift during the Latest Miocene in Northern Pakistan.” *Nature* 342: 163–166.

Sanyal, P., A. Sarkar, S. K. Bhattacharya, R. Kumar, S. K. Ghosh, and S. Agrawal. 2010. “Intensification of Monsoon, Microclimate and Asynchronous $C_4$ Appearance: Isotopic Evidence from the Indian Siwalik Sediments.” *Palaeogeography Palaeoclimatology Palaeoecology* 296: 165–173.

Singh, S., B. Parkash, A. K. Awasthi, and T. Singh. 2012. “Palaeoprecipitation Record Using O-isotope Studies of the Himalayan Foreland Basin Sediments, NW India.” *Palaeogeography Palaeoclimatology Palaeoecology* 331: 39–49.

Sun, Y., G. Ramstein, C. Contoux, and T. Zhou. 2013. “A Comparative Study of Large-scale Atmospheric Circulation in the Context of Future Scenario (RCP4.5) and past Warmth (mid-Pliocene).” *Climate of the Past* 9: 1613–1627.

Wang, B., J. Liu, H. J. Kim, P. J. Webster, and S. Y. Yim. 2012. “Recent Change of the Global Monsoon Precipitation (1979–2008).” *Climate Dynamics* 39: 1123–1135.

Zhang, Z. S., K. H. Nisancioglu, M. A. Chandler, A. M. Haywood, B. L. Otto-Bliesner, G. Ramstein, C. Stepanek, et al. 2013. “Mid-Pliocene Atlantic Meridional Overturning Circulation Not unlike Modern.” *Climate of the Past* 9: 1495–1504.

Zhang, R., Q. Yan, Z. S. Zhang, D. Jiang, B. L. Otto-Bliesner, A. M. Haywood, D. J. Hill, et al. 2013. “Mid-Pliocene East Asian Monsoon Climate Simulated in the PlioMIP.” *Climate of the Past* 9: 2085–2099.

Zhang, R., Z. Zhang, D. Jiang, Q. Yan, X. Zhou, and Z. G. Cheng. 2016. “Strengthened African Summer Monsoon in the mid-Piacenzian.” *Advances in Atmospheric Sciences* 33: 1061–1070.