The role of Central Asian uplift in East Asian Monsoon circulation and its palaeoclimate implication

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Abstract

It has been clearly established that the climate of Asia is significantly affected by high-elevation orogens such as the Tibetan Plateau, Mongolian Plateau and Tian-Shan. The East Asian Monsoon (EAM), one of the most prominent features of Asian climate, has been well studied in a modern context and its dynamics are generally well understood. However, specific features of the EAM are less studied and understood in a palaeoclimate context, largely because of associated uncertainties in palaeotopography for the Cenozoic era. Here, we investigate changes in the individual stages of the EAM in response to increasing topography over Central Asia. We perform a series of sensitivity experiments with different palaeogeographic elevations using a coupled ocean-atmosphere General Circulation Model (HadCM3), to investigate seasonal variability of the EAM, and investigate the emergent critical threshold in elevation where the patterns of atmospheric circulation and climate over Asia attains the characteristics observed in the modern climate system. Our results indicate that above an elevation threshold of 3000 m, EAM circulation follows the modern pattern, but below that threshold, EAM circulation and precipitation follow a distinctly different pattern, where the westerly jet does not propagate into the higher latitudes and monsoonal precipitation is limited to June and July. This shift in circulation pattern has important implications for the successful interpretation of proxy-based palaeoclimate and environmental reconstructions. In addition, our results emphasize the

importance of the latitudinal position of high-elevation on the EAM circulation, by showing that low-elevation can produce modern-like EAM conditions, if located at different latitudes than modern.

Keywords: East Asian Monsoon, uplift, climate, monsoonal precipitation

1. Introduction

The uplift of the Tibetan Plateau (TP) was the most dramatic tectonic event in recent geological history (X. D. Liu and Dong 2013), and is one of the suggested factors that drove climatic change in Asia during the Cenozoic (Wu et al. 2007). Geological evidence links TP uplift with the development of the Asian monsoon and inland aridification (An et al. 2001; Guo et al. 2002). Despite decades of study, controversy remains over the tectonic history of the continent since the Palaeogene. Although most studies concur on the existence of an early proto-plateau in the southern margin of Asia, the palaeolatitude of this feature during the Cenozoic remains unclear (Lippert et al., 2014). Southern Tibet has remained approximately at its present height for 35 ±5 Ma (Rowley and Currie 2006), yet the elevation history of northern Tibet remains only partially constrained (Molnar et al., 2010). Additionally, geological evidence indicates that the Tian-Shan (TS) orogen and the Mongolian Plateau (MP) experienced significant uplift since the late Miocene (R. Zhang et al. 2017), and in turn this uplift caused a decrease in annual precipitation over inland Asia (Liu et al. 2015). The effects of the uplift of the whole TP have been explored in a number of numerical climate modelling studies since the 1970's (e.g. Manabe and Terpstra 1974). For example, An et al. (2001) used an Atmospheric General Circulation Model (AGCM within CCM3) to perform experiments with idealized stages of elevation for the TP. Liu and Yin (2002) also used an AGCM with more intermediate uplift stages to investigate the effect of uplift in the evolution of the East Asian Monsoon (EAM). However, it was not until recently that studies focused on the latitudinal distribution of the TP and not simply its elevation (e.g. Zhang et al. 2018). The tectonic evolution and uplift of the Tian Shan orogen is not as well studied and constraint as the Tibetan Plateau. Studies in the past indicate that the uplift of Tian Shan orogen began in the Late Oligocene to Early Miocene (Sobel and Dumitru 1997; Yin et al. 1998). Middle Miocene is the period that researchers have pointed out as the onset of rapid growth and its being ongoing ever since (Aitken 2011). However, parts of the Tian Shan comprise of marine sediments and ophiolites that date back to Cambrian (Brunet et al. 2017).

The formation of the Mongolian Plateau has been attributed by some researchers to the collision between India and Eurasia (i.e. De Grave et al. 2007) while other studies propose that it is a product of the interaction between a mantle plume and continental lithosphere (i.e. Windley and Allen 1993). Additionally, Jolivet et al. (2007), showed that the plateau has been uplifted since the Jurassic but did not attain its current elevation until the Late Miocene.

Recent modelling studies using higher resolution GCMs have shown that the uplift of TP, TS and MP all played an important role for East Asian climate, causing a decrease in precipitation and changes to low-level and middle-tropospheric winds due to changes in the thermal structure of the atmosphere (R. Zhang et al. 2017). Modern East Asian climate has been studied extensively, as it influences over 1 billion people and is of particular interest due to its unique characteristics that do not conform with the behaviour of typical monsoons (Chiang et al. 2014), as the monsoonal precipitation and winds are associated with frontal systems and the jet stream (Molnar et al., 2010), rather than the tropical monsoon circulation in which precipitation is primarily linked with the Intertropical Convergence Zone (ITCZ). Additionally, the south to north migration of the westerly jet during boreal summer over East Asia plays an important role in driving seasonality and transitions of monsoonal precipitation (Chiang et al. 2014). The initiation of the EAM has been attributed to a change from a zonal to a non-zonal monsoon climate pattern (Li et al. 2018), however the timing of the onset and the abrupt changes of the EAM during past climates, and in turn the mechanisms controlling it, are still under investigation.

In this study, we use a fully coupled GCM (HadCM3) to carry out simulations with different topographic configurations for high-elevation Central Asia. Specifically, starting with the pre-industrial topography, we decrease the elevation over the area covering the TP, MP and TS in regular stages, resulting in five different intermediate elevation experiments (see section 2.2 for details). We also carry out two additional simulations with this region set to sea-level and a simulation with Oligocene-like topography over Asia (after Markwick 2007), in order to assess the climatic response to the latitudinal distribution of high elevation areas. Focusing on the East Asian monsoon, we explore: a) the seasonal variability of the westerly jet and associated precipitation over East Asia, b) the elevation threshold for changes in the climate patterns over Asia and c) the westerly jet latitudinal position in relation to the uplift to determine the role of high elevation as a palaeoclimate forcing altering the jet.

2. Methods

2.1 Model description and experimental design

For this study, we use the UK Met Office coupled atmosphere-ocean HadCM3 General Circulation Model (GCM), with the MOSES 1 land-surface scheme (Cox et al. 1999). HadCM3 consists of a dynamically coupled atmosphere, ocean and sea-ice model (see Gordon et al. 2000 for further details). The horizontal resolution of the model is 3.75^{o} x 2.5^{o} for the atmosphere which corresponds to 278 km x 295 km at 45^{o} latitude and 278 x 417 km at the equator and 1.25^{o} x 1.25^{o} for the ocean, producing a global grid of 96 x 73 grid cells. The vertical layers for the atmosphere and ocean are 19 and 20 respectively. The orography and gravity wave parameterization include the effects of flow blocking, trapped lee waves, and high drag states (Gregory et al. 1998; Pope et al. 2000). Precipitation is produced by the convection scheme and the large-scale precipitation scheme. The large-scale precipitation and cloud scheme is produced as described in Smith (1990) regarding an explicit cloud water variable. The majority of the 19 atmospheric layers are distributed in less than 10 km altitude (13 layers in total), whereas 9 of them are distributed between 0 and 5 km (Pope et al. 2001).

HadCM3 has been used successfully in the representation of modern Asian climate (Jiang et al., 2005) and can reproduce with success seasonal and annual precipitation.

In contrast to previous climate modelling studies that have examined the effect only uplifting the TP, in this study we uplift all major Central Asian orogens (namely the TP, TS and MP). Specifically, we decrease elevations from modern by 96%, 77%, 58%, 38% and 19% (hereafter referred to as TP5000, TP4000, TP3000, TP2000 and T1000 respectively). The number following "TP" in the experiment name denotes the maximum elevation of the TP in each experiment in metres (Table 1). Additionally, we carried out a simulation with no orogens in Central Asia where TP, TS and MP were set to sea-level (hereafter referred to as FlatTP). Finally, a simulation with Oligocene-like elevation (OligTP) in Central Asia (after Markwick 2007) was completed, where the TS and MP were at elevations lower than 1000 m (see Fig 1a), and the TP was at approximately 2300 m elevation but was located at a lower latitude (Fig.1b). The changing elevation in the model is implemented over the area between 62.5^{o}E and 125^{o}E and 20^{o}N – 52.5^{o}N (Fig.1b). All other boundary conditions for each experiment were kept constant and specified as pre-industrial (PreInd). Specifically, atmospheric CO_2 was set to 280 ppmv, vegetation type and distribution was specified as being modern, as was the land-sea distribution, ice-sheet coverage and topography for the rest of the globe, outside of the geographical domain specified above. The experiments were not designed to represent a specific geological period of the past, but since the influence of the TP, TS and MP are considered predominant for the evolution of East Asian climate during the Cenozoic (Zoura et al. 2019), our experimental design represents an appropriate methodology to better understand regional uplift and how uplift controlled the way that the East Asian climate regime developed. Each simulation was performed for 500 simulated years with the final 100 years used to derive the required climatological means for subsequent analysis.

Experiment name	**Maximum TP elevation**	**Maximum MP elevation**	**Maximum TS elevation**
PreInd	5351	2425	4100
FlatTP	sea level	sea level	sea level
TP1000	1016.69	460.75	779

TP2000	2033.38	921.5	1558
TP3000	3103.58	1406.5	2378
TP4000	4120.27	1867.25	3157
TP5000	5136.96	2328	3936
OligTP	2364	900	1100

Table 1: List of experiments with maximum elevation (metres above sea level) for the Tibetan Plateau (TP), Mongolian Plateau (MP) and Tianshan (TS) orogen respectively.

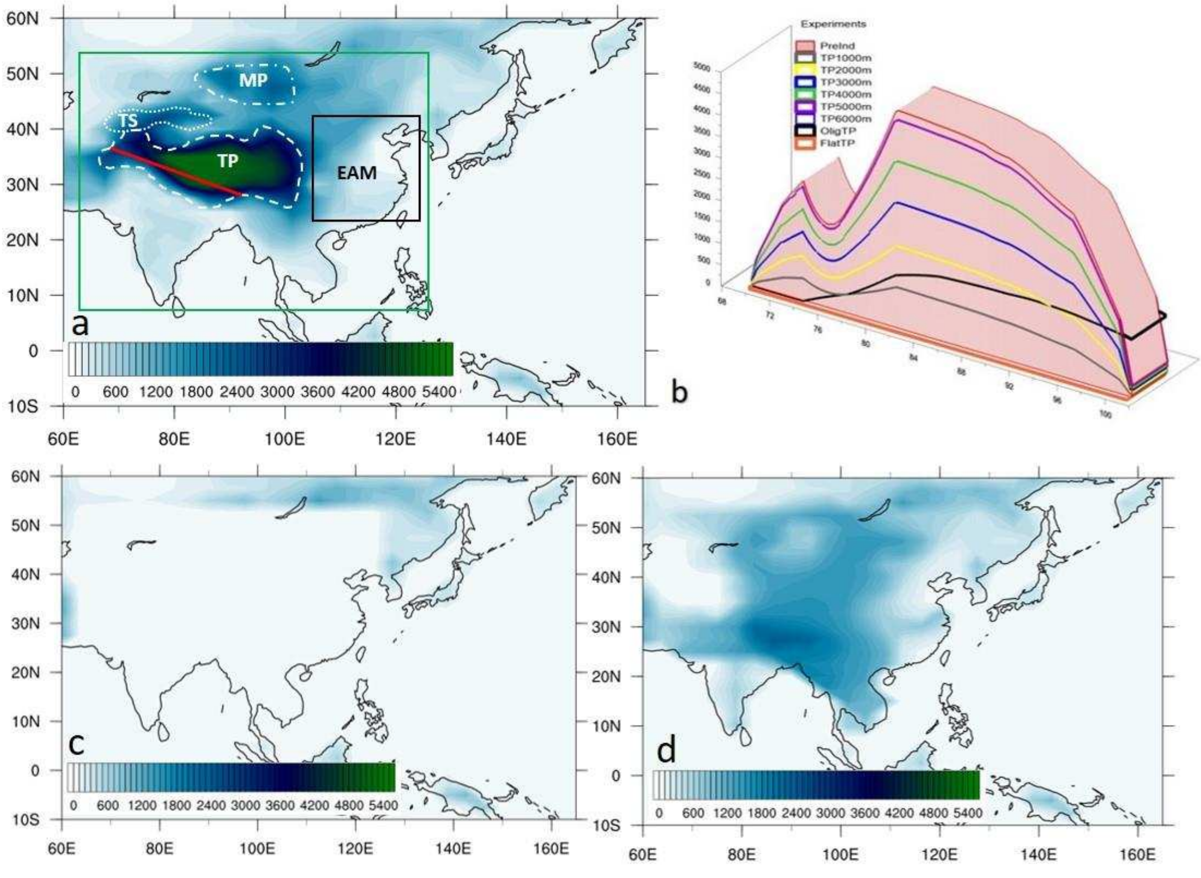

Fig. 1: a) Pre-industrial (PreInd) elevation. The dashed line shows the Tibetan Plateau (TP), dotted line the Tian-Shan (TS), dash/dot line the Mongolian Plateau (MP), black box shows the region used to analyse the East Asian Monsoon (EAM) patterns, and the green box the area over which the elevation is decreased for all the experiments (see section 2.2 for details); the red line shows the axis along which elevation profiles are shown in b. b) Elevation profiles for the simulations carried out by this study along the (red) axis shown in a). c) flattened TP, TS and MP topography d) Oligocene-like elevation (after Markwick, 2007).

3. Results

3.1 East Asian Monsoon precipitation

The rainfall pattern from April to July over East Asia can be divided in the following four stages: 1) persistent rainfall in April over the South EAM region, 2) Pre-Meiyu phase in May, 3) Meiyu rainfall in June where rainfall shifts northward and 4) second northward jump of the rainfall that marks the end of the Meiyu stage (Chiang et al. 2014; Molnar et al. 2010). The term Meiyu is associated with the subtropical front that brings summer rainfall over the EAM region and is one of its most prominent features. For the purpose of this paper, we are studying the East Asian Monsoon from a frontal system perspective. We include the April rainfall that occurs in the Southern part of the EAM region as it is associated with convergent frontal circulation (Zhou et al., 2004) and we do not include August as the Meiyu front is reaching maturity in mid-July and the northward jump during this month is marking the end of the Meiyu front, making August a post-Meiyu season (Chen and Bordoni, 2014).

With boundary conditions set to PreInd and TP5000, simulated precipitation from April to July follows the modern-like seasonal variability and spatial extent described above (Fig. 2, S1). Furthermore, our experiments show that spring rainfall over East Asia is absent with topography set to less than TP2000, indicating dry conditions during spring (Fig. 2). Greater elevation produces an increase in spring rainfall South of the Yangtze river (approx. 31°N), characteristic of the first stage of the EAM (Fig. 2). The tipping point from the dry conditions to the persistent spring rainfall, and thus the formation of stage 1 of the modern EAM, is seen in experiment TP3000. In TP3000, spring precipitation is significantly decreased in terms of extent and intensity than experiment PreInd, and conditions resemble the PreInd pattern when elevation surpasses that of TP4000. In the OligTP experiment, spring rainfall over the south part of the EAM region is close to PreInd in terms of intensity but is more limited spatially and mainly affecting the southeast EAM (Fig. 2). Interestingly, even though in terms of "absolute" elevation the OligTP is set to less than that of TP3000, stage 1 of the EAM is not absent.

The FlatTP to TP2000 experiments produce dry conditions during the second stage of the EAM (Fig. 2, S1), and again TP3000 is the threshold elevation for a shift to wetter conditions that can be characterized as the pre-Meiyu phase, even though limited to the southeast of the region. The OligTP simulation shows the precipitation zone extending to the west and north, indicative of stage 2 EAM circulation (Fig. 2).

During the Meiyu phase, all experiments show a precipitation increase and northward propagation (Fig. 2). Lower elevation produces weakened and spatially limited precipitation (i.e. FlatTP), but as we move to the higher elevation experiments the pattern becomes increasingly similar to the PreInd.

Finally, in July rainfall propagation into the higher latitudes is evident in experiments TP3000 or above even though weaker compared to the PreInd (Fig. 2). This is not the case for the FlatTP simulation where precipitation is spatially confined to the lower latitudes. The OligTP experiment shows a relatively dry zone over the central EAM region, however the South and North are significantly wetter (Fig. 2).

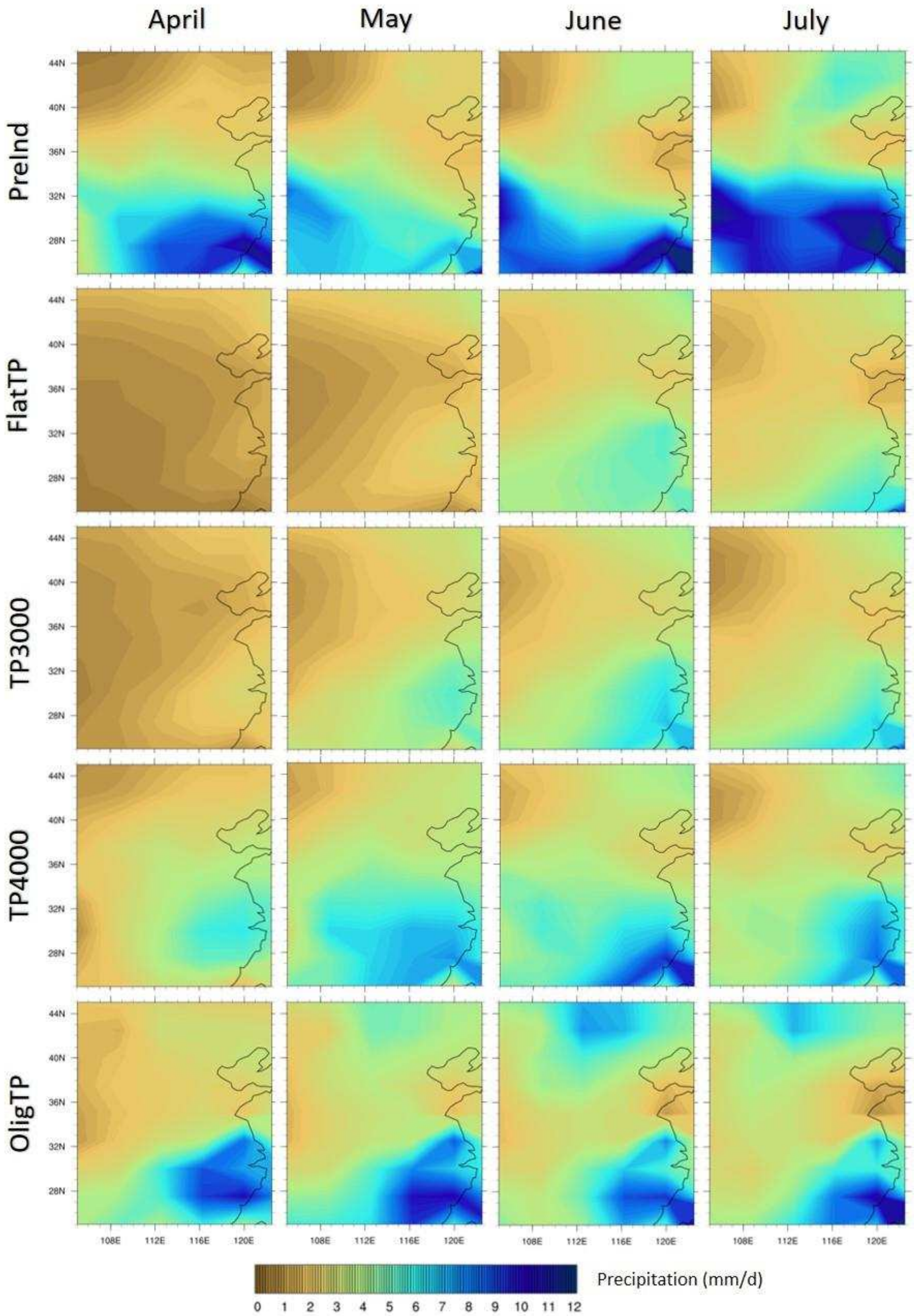

Fig. 2: April to July monthly total precipitation rate (mm/day). Experiments TP1000, TP2000 and TP5000 are shown in the Supplementary.

3.2 Westerly jet and meridional temperature gradient

In simulations with elevation higher than TP3000, the latitudinal position of the westerly jet follows the modern-day seasonal variation (Fig. 3). In April the jet over the EAM region is located at 34°N, during May it shifts northward by 2 degrees, in June the jet migrates to the north of the TP and finally, during July the jet acquires its northernmost latitudinal position further north from the TP. However, simulations with lower elevation show a different pattern. Specifically, in experiments FlatTP to experiment TP2000, the westerly jet latitudinal position shifts northwards by only 2° from April to July and does not propagate into the higher latitudes (Fig.3), as the westerlies are not impeded by the TP, and temperature gradient is not as strong with the absence of high elevation over Central Asia (Fig. 4, S2). The four jumps in the westerly jet latitudinal position are also evident in the OligTP experiment. However, due to the difference in the latitudinal distribution of the TP elevation the westerly jet does not reach as far north compared to the PreInd, with its northernmost position being at 40°N (Fig.3).

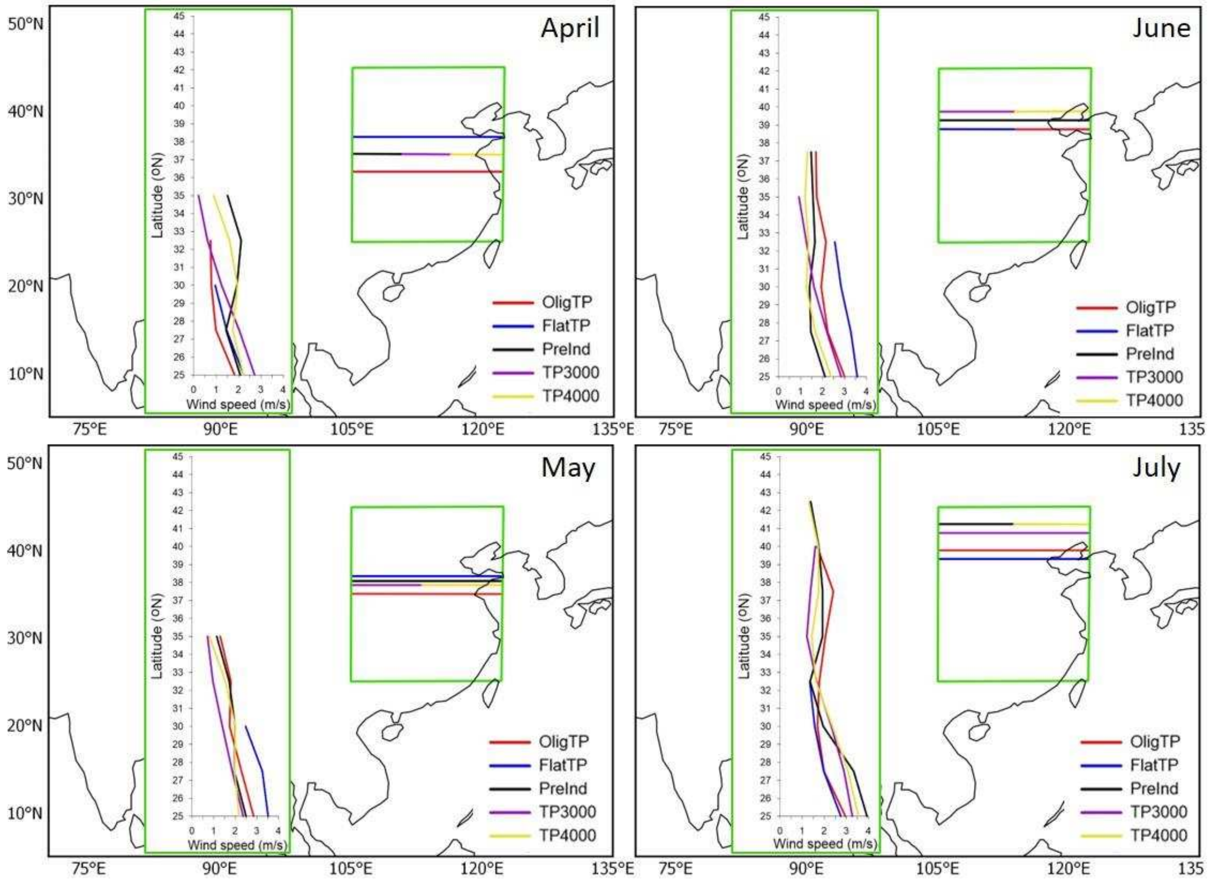

Fig. 3: Map plots show a schematic of the latitudinal position of the westerly jet (horizontal lines) for months April – July, over the EAM region (green box) for each experiment. PreInd (black), FlatTP (blue), TP3000 (magenta), TP4000 (yellow), OligTP (red). The integrated graph plots show the latitudinal propagation and windspeed of the low-level southerlies/south-easterlies averaged over the EAM region. Notably, the northward propagation of the low-level southerlies/south-easterlies is controlled by the latitudinal position of the westerly jet. Experiments TP1000, TP2000 and TP5000 are not shown, as their results are similar to the FlatTP for the first two and the PreInd for the latter. The westerly jet position (or jet occurrence) is defined at a location where the wind speed is a local maximum (exceeding 30 m/s) between 100 and 500 hPa (Chiang et al. 2014; Schiemann et al. 2009). The propagation of the low-level winds is given by the position in which the directionality changes from south/south-east to westerlies

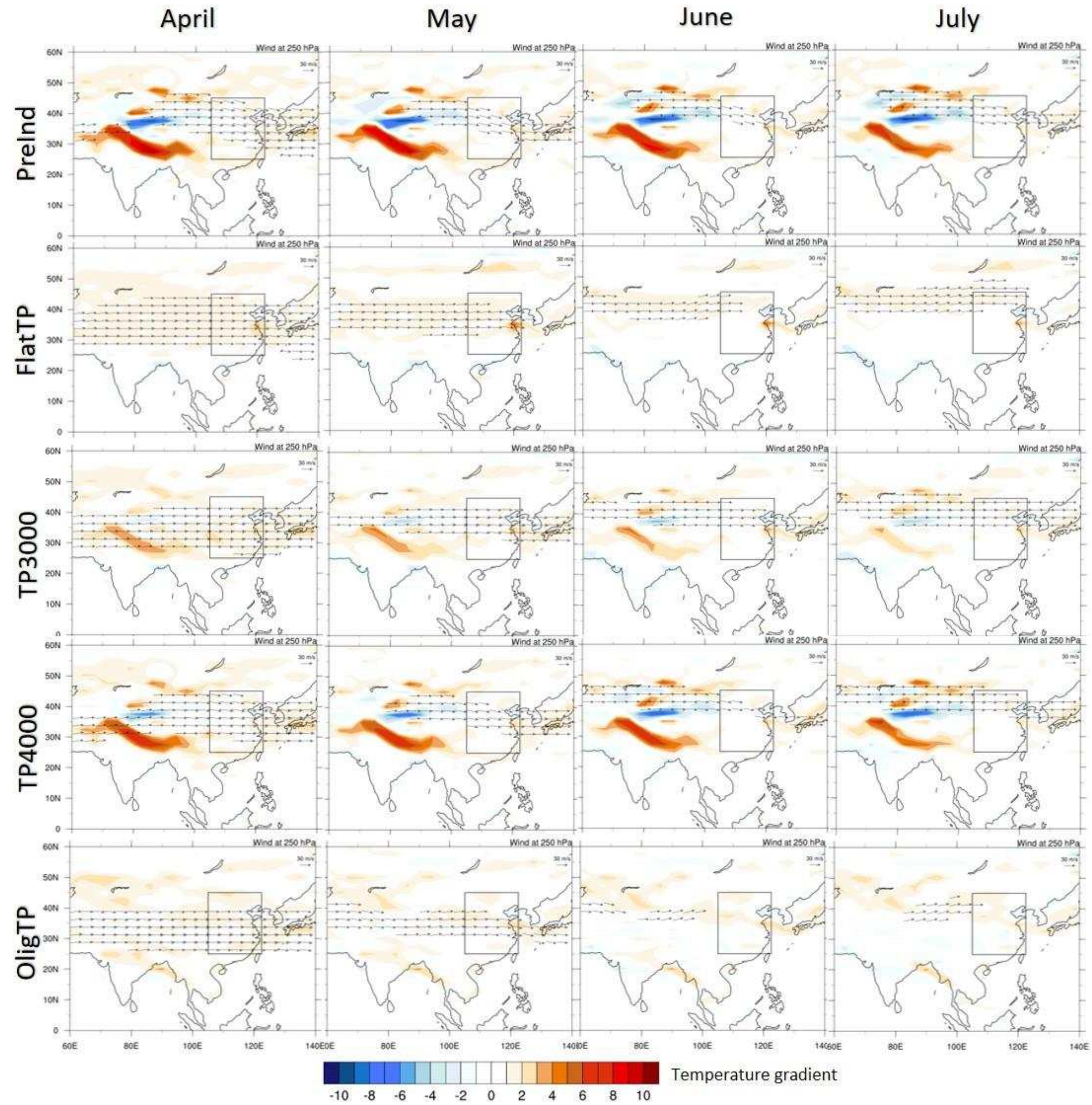

Fig. 4: Meridional surface temperature gradient (°C) April – July and 250hPa winds (m/s). Westerlies with speed less than 30 m/s, which is the lower threshold for a jet occurrence, are masked out. The meridional gradient is defined as dT/dLat.

3.3 850 hPa winds and moisture availability

It has been well established by previous studies that changes in the elevation of the TP cause a change in wind circulation over Asia, not only in the upper troposphere but in the lower as well. In both PreInd and TP4000 experiments, easterlies and south-easterlies are dominating the South of the EAM region carrying moisture from the Pacific Ocean and South China Sea during April and May and reach higher latitudes during June and July (Fig.3, 5). Spatially, the change from moisture carrying easterlies to westerlies occurs in the latitude the westerly jet is positioned (Fig. 3).

Flattening of the TP, TS and MP, creates a dry zonal area over Asia stretching west to east during monsoonal months (Fig. 5, S3). In these scenarios the westerlies dominate more than 2/3 of the EAM region. With the orography flattened completely, the easterlies and south-easterlies do not propagate to the north, and thus do not contribute as a moisture source for spring precipitation over EAM (Fig.2). Increasing the elevation (TP1000 and TP2000 simulations), leads to a northward propagation of the westerly jet of about 2^{o}, and now the easterlies and south-easterlies propagate into higher latitudes, but with topography significantly lower than PreInd, moisture availability remains low over the whole EAM and thus not producing spring precipitation (Fig. 3, 5, S1-3). In TP3000, the westerly jet reaches its northernmost position, while easterlies and south-easterlies propagate into the EAM region providing enhanced moisture available in the South. With higher topography over Asia, the pattern of moisture availability changes from being zonal (running west to east) to a more complex pattern with the south EAM region's moisture availability increasing (Fig. 3, 5). In TP4000 the simulated wind, precipitation, humidity and moisture availability begin to display a pattern that is very similar to the PreInd, and when moving to TP5000 the pattern becomes almost identical to the PreInd (Fig, 2, 3, 5). In the OligTP experiment the TP is located further South, and the westerlies are significantly weaker than in any other experiment. However, there moisture is available in the north and northwest of the EAM to be carried by the westerlies to the north of the EAM. The underlying mechanisms that control the westerly jet's latitudinal position which in turn controls the EAM precipitation are analysed in detail by Chiang et al. (2014).

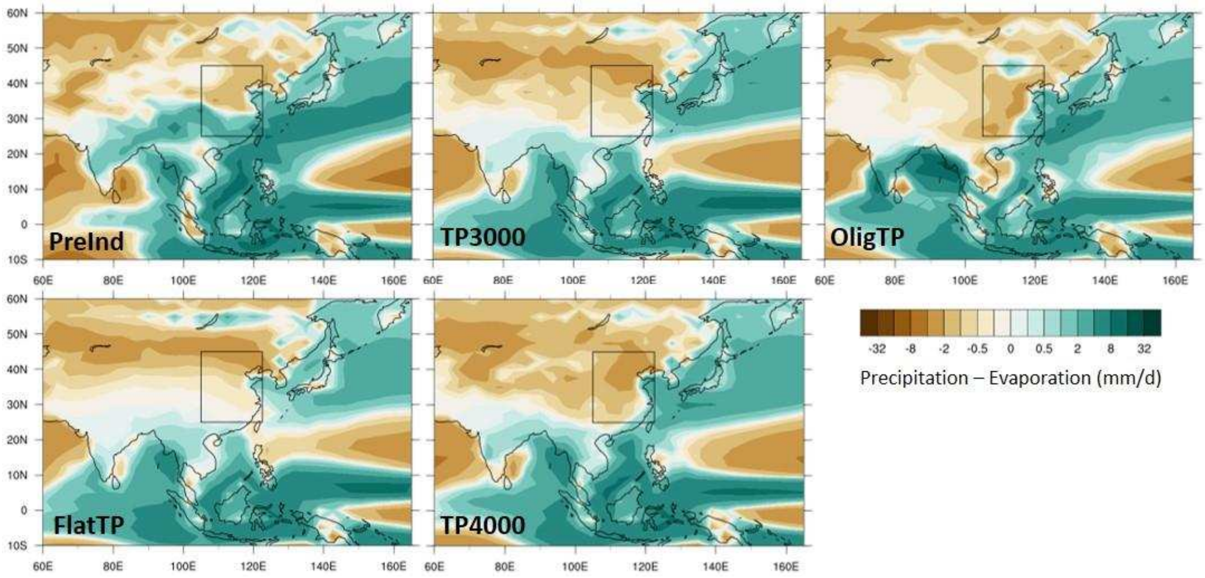

Fig. 5: Moisture availability (P – E: mm/day) averaged from April to July for different experiments. For elevations less than TP3000, broad arid belts are simulated in Asia from West to East, a pattern that changes with higher elevation (TP3000 and above).

4. Discussion

The TP has a marked effect on the westerlies over Asia (Schiemann et al., 2009) and the seasonal migration of the westerly jet from South to North is vital to the East Asian rainfall climate (Liang and Wang 1998). The "Jet Transition Hypothesis" (Chiang et al. 2014) suggests that changes to the position of the westerlies relative to the TP, drive rainfall changes over East Asia over geological timescales. Our simulations provide further evidence that the westerly jet transition plays an important role for the dynamics of the EAM by controlling the associated monsoonal precipitation. The northward jumps of the westerly jet coincide with the stepwise northward propagation of the EAM rainfall during monsoonal months (April to July). The westerly jet latitudinal position controls the low-level inland flow of moisture-carrying southerlies and south-easterlies over East Asia that leads to precipitation where they converge. The lower-level southerly flow is an important factor in the spatial extent and seasonality of the EAM (Rodwell and Hoskins 2001). There have been numerous studies deciphering the dynamics of the westerly jet and its association to the EAM climate as well as the role of the thermal and mechanical forcings from the TP (i.e. Baker et al. 2015; Chiang et al. 2015; Zhang et al.

2017, 2018), and it has been established that the high elevation over Asia alters the westerly flow, which in turn alters the EAM circulation pattern.

For elevations greater than TP3000, the pattern of atmospheric circulation is similar to the modern, with spring precipitation in the southern part of the region controlled by the moisture-carrying southerlies from the South China Sea and Pacific Ocean. This is consistent with the moisture source analysis by Baker et al. (2015). However, the EAM does not display the same characteristics when elevation is less than in experiment TP3000. Notably, with lower elevation the model simulates a change in monsoonal pattern; specifically, the absence of the first two stages of the present-day monsoon. With the westerlies flowing zonally and dominating the mid-latitudes over Central Asia, rather than splitting in the Southern and Northern branch, there is no persistent spring precipitation (stage 1) and pre-Meiyu phase (stage 2), but there is summer precipitation over the EAM reaching to the Northern part of the region (albeit weaker and spatially constrained (stages 3 and 4)). In terms of general precipitation pattern, our simulations are consistent with earlier studies that show that the uplift of the TP enhances precipitation over East Asia (Jiang et al. 2008; Zhang et al. 2007). The tipping point for the development of a modern-like circulation is seen in TP3000. This threshold is also consistent with the simulated shift from zonal arid belts to a non-zonal pattern (Fig. 5), a shift that has been suggested as an indicator for the onset of the EAM (Li et al. 2018).

Even though the land-sea thermal contrast has been suggested in the past as the necessary condition for spring rainfall over the South EAM region (Tian and Yasunari 1998), Wu et al. (2007) showed that the spring rainfall is formed when westerlies are split by the TP into a southern and northern branch, and cold air from the North and warm moist air from the South converge over eastern China. As shown by our simulations, the deflection of the westerlies, and the subsequent precipitation, occurs when the TP topography reaches the elevation equivalent to that used within experiment TP3000, suggesting that with elevations lower than this the EAM misses one of its most characteristic features - the spring rainfall.

Furthermore, the latitudinal position of high elevation is also an important factor that should be taken into consideration. Our OligTP experiment shows that with elevation closer to the TP2000 but positioned further to the South, monsoonal circulation is more similar to the PreInd than in the TP2000 experiment, a fact that highlights the importance and necessity for enhanced constraints on the palaeogeographical history of the region to inform the boundary conditions used for climate modelling studies.

Moving forward, it will be important to study the EAM pattern in a fully palaeoclimate context, using fully realistic palaeogeographic boundary conditions that not only represent the bulk uplift that occurred in the region, but also the timing and magnitude of differential uplift of the individual regions that comprise the TP, TS and MP orogens. This is likely to provide a valuable dataset for proxy data interpretation. Insights from proxy data in the region are not limited to the intensity and/or the presence of monsoonal circulation, but also its spatial limits, seasonal variability and monsoonal phases, and fully realistic palaeo-simulations of the uplift history of the region would prove useful in terms of interpreting the palaeoclimate signals recorded in different proxy archives.

Further work using different climate models with and without realistic palaeogeographic reconstructions of the region will be necessary to evaluate the model dependency of the elevation threshold determined in this study for the onset of modern-like circulation in the region.

5. Conclusions

Using HadCM3, we attempt to determine the effect of the Central Asian orogens uplift to the East Asian Monsoon (EAM) circulation. Our simulations show that by uplifting the Tibetan Plateau, Tian-Shan and Mongolian Plateau, there is an evolution towards a modern-like circulation with an elevation threshold for that change at 3000 m. Lack of high-elevation leads to the westerlies flowing zonally over Central Asia producing monsoonal precipitation limited to the summer months, whereas when elevation is set to 3000 m and above, westerlies are deflected by the Tibetan Plateau, and the EAM circulation and associated precipitation follows the pattern seen in the present-day. Furthermore, we show that the latitudinal position of high elevation is an important factor for the EAM and we highlight the necessity for constraints on the palaeogeographical boundary conditions that will lead to a better understanding of the Asian paleoclimate and evolution. Our results show that the latitudinal distribution of the high elevation can be as important as the uplift in controlling the westerly jet, seasonal variability and monsoonal precipitation. This factor should be explored through a set of realistic palaeo-simulations as it has the potential to provide a highly valuable methodology for interpreting different proxy records.

Acknowledgments

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