Dear Editor,

Thank you very much for gathering the reviewers' comments and questions regarding our manuscript. We extend our gratitude to the three reviewers for their insightful comments, which have significantly contributed to the improvement of our paper.

We have carefully revised the manuscript and clarified certain points in accordance with the feedback and suggestions provided by the reviewers. The major modifications include: 1) adding the evolution history of the IP's built-up; 2) significantly extending the discussions on the uncertainties of paleogeography and the limitation of experimental design. We highlight the crucial role of IP evolution, an aspect that remains characterized by substantial uncertainty.

Below are our point-by-point responses. Texts in black are excerpts from the reviewers' comments. Texts in blue are our responses. We have endeavored to ensure that the revised manuscript aligns with the reviewers' feedback and hope that it meets the criteria for publication in "The climate of the Past".

Yours Sincerely,

Yan ZHAO on behalf of the co-authors

Referee#1:

This manuscript is well written and tires to clarify the role of the Himalaya uplift, Iranian Plateau (IP) uplift and atmospheric CO2 on SASM evolution in the mid-Miocene. They suggest IP uplift to be the main factor causing enhancement of SASM. Overall, I do recommend this study for publication after some revisions. Some suggestions and comments are listed below.

Response: We appreciate this suggestion very positive, below we account for all the comments from the referee.

1. There are several uncertainties in the Middle Miocene paleogeographic boundary conditions (Frigola et al., 2018) used in the simulation, such as the eastern Tethys seaway and Greenland-Scotland Ridge are deep water gateways, and the Bohai Bay and Yellow Sea basins in East Asia are shallow sea environments, which are inconsistent with many geological records (e.g., Sun J.M. et al., 2021, Paleo-3; Tan M.X. et al., 2020, Marine and Petroleum Geology; Stoker M.S. et al., 2005, Marine and Petroleum Geology). Some uncertainties of the boundary conditions are discussed in Section 5.3.

   Response: Thanks for this constructive suggestion. We agree that it is important to conduct paleoclimate modeling with "realistic" paleogeographic boundary conditions to improve our understanding of Miocene climate changes and narrow down model-data discrepancies. When we decided to perform Miocene simulations in early 2020, a few paleogeographic reconstructions were available, but they presented many differences and uncertainties. We chose the one produced by Frigola et al. (2018; henceforth F18) because it is based on the widely accepted Middle Miocene reconstruction (Herold et al., 2008) and is relatively state-of-the-art. However, as the referee pointed out, in F18 there are some uncertainties that should be addressed. Following your suggestion, in Section 5.3 we have added and extended the discussion regarding the uncertainties in the IP uplift, the above-mentioned settings inconsistent with geological records, the Tethys/Paratethys configuration and the surrounding topographies. Please see the following:

   "Geography, particularly the land-sea distribution, is another important driver for Asian monsoon development (Ramstein et al., 1997; Farnsworth et al., 2019; Sarr et al., 2022; Tardif et al., 2023). The land-sea distribution used in our Miocene simulations, like other reconstructions (Herold et al., 2008; He et al., 2021, and references therein) inevitably contain uncertainties. For instance, the Bohai Bay and Yellow Sea basins in East Asia are open in the F18, contrary to regional stratigraphy and lithofacies records (Tan et al., 2020). The Greenland-Scotland Ridge in F18 is set as ~4000 m, significantly deeper than a middle bathyal environment (<1000-m deep) indicated by geological evidence (Stocker et al., 2005). Large uncertainties also present in the Tethys/Paratethys configuration. The Tethyan Seaway is open with a depth of over 3000 m in F18, in contrast to geological evidence suggesting intermittent openings during ~15-12.8 Ma (Sun et al., 2021). The Paratethys was intermittently connected and disconnected from the global ocean during the Middle Miocene according to geological studies (Rögl, 1997). It is assigned to connect to the global ocean in F18 and Herold et al. (2008) while it retreats to the Carpathian-Black Sea-Caspian Sea region and is connected with the Mediterranean in He et al. (2021). In short, the Tethys/Paratethys configuration in F18 reflects more the feature of early Middle Miocene geography, with an open Tethyan Seaway and a smaller IP. However, given that most reconstruction records focus on the late Middle Miocene period (14-12 Ma), our Middle Miocene simulations may not adequately capture the IP's effects and may be less suitable for comparison with proxy data. Nonetheless, a previous study (Sarr et al., 2022) utilizing a late Miocene (10 Ma) configuration also emphasized the significant role of the Anatolia–Iran uplift on enhanced SASM. Their experiments showed that this uplift deepened the low-pressure area over the Arabian Peninsula, intensifying low-level wind and moisture transport from the Arabian Sea towards South Asia, a process consistent with our simulations (Fig. 4a). We thus emphasize that constraining the exact timing of IP uplift is crucial to improve our understanding of the evolution of the Asian monsoon."

2. In this study, authors lumped together all the mountain ranges west of the Himalayan, including the Hindu Kush and Pamir as the IP. The uplift history of the Iranian plateau, Hindu Kush, Pamir and East Africa remains controversial. Some studies suggested that the IP and East Africa began to uplift in the late Oligocene–early Miocene and rapidly uplifted in the middle–late Miocene (e.g., Macgregor, 2015, Journal of African Earth Sciences; Mouthereau et al., 2012). Uncertainties of topographic uplift can be appropriately added to the discussion.

Response: Thanks for this valuable input. We have inserted the development history of the East Africa in the texted in Section 5.1, Line 475-477, aligning with previous modeling studies and our simulation results:

"This aligns with geological evidence indicating that the East Africa began to uplift in the late Oligocene–early Miocene and rapidly uplifted in the middle–late Miocene (Macgregor, 2015)."

We've also added text regarding the evolution history of the IP in Line 64-73 as the follow:

"The evolution history of the IP uplift remains hotly debated (Agard et al., 2011; McQuarrie et al., 2003; Mouthereau, 2011; Ballato et al., 2017). Nevertheless, most studies suggest a Miocene age for the uplift of most landforms. Geological evidence indicates that in the northern sectors of the IP, the uplift likely occurred between 16.5-10.7 Ma (Ballato et al., 2016), particularly accelerated after 12.4 Ma (Mothereau, 2011) while in regions bordering the IP to the south between 15 and 5 Ma (Mouthereau, 2011). The Zagros orogen, a significant part of the IP, developed in three distinct pulses within the last ~20 Ma (Agard et al., 2011; Mouthereau, 2011). "

The relevant discussion on the uncertainty of IP's buildup is added in Section 5.3 (particularly Line 556-566).

3. Table 2: there are some errors and inappropriate references. For example, Zhuang et al. (2017) interpreted the late Miocene (11–10 Ma) ocean cooling as representing the establishment of monsoonal upwelling in the western Arabian Sea, which may not be suitable as evidence for the enhancement of SASM in the Middle Miocene. Betzler et al. (2016): "deposit" changes to "sedimentary and geochemical record". Bialik et al. (2020): "Precip" changes to "wind"; Ai et al. (2021): "Precip" changes to "wind". In these papers, authors mainly talked about wind/monsoonal upwelling, not precipitation.

Response: Thanks for these notices and suggestions. We have corrected Table 2 as suggested (See below). We've also removed the reference Zhuang et al. (2017) as the evidence of SASM intensification during the Middle Miocene, which has no essential impact on our conclusions and discussions.

Table 2. Evidence of modern SAM in middle Miocene from recently published studies.

No	station	Location (lat/lon)	Proxies	Intensification age (Ma)	Trend*	variable	references
1	Well Indus Marine A-1	24/66	weathering	15~12	decreasing	Precip	Clift et al., 2008
2	ODP 359	5/73	Sedimentary& geochemical record	12.9	increasing	wind	Betzler et al., 2016
3	ODP 722B	16.6/59.8	Bio-marker	12.9	increasing	wind	Gupta et al., 2015
	ODP 722B	16.6/59.8	Bio-marker	14	increasing	wind	Bialik et al., 2020
4	NGHP-01-01A	15/71	Bio-marker	14	increasing	Precip	Yang et al., 2020
5	Varkala	8.7/76.7	Pollen fossil	17-15	No change	Precip.	Reuter et al., 2013
6	ODP 758	5.4/90.4	weathering	13.9	increasing	wind	Ali et al., 2021
7	Surai Khola	27.8/83	Leaf Fossil	13	increasing	Precip.	Srivastava et al., 2018 Bhatia et al., 2021
8	Darjeeling	27/88.5	Leaf Fossil	13	increasing	Precip.	Khan et al., 2014
9	Arunachal Pradesh	27/93.5	Leaf Fossil	13	No change	Precip.	Khan et al., 2014
	Arunachal Pradesh	26/93.5	weathering	13	No change	Precip.	Vogeli et al., 2017

* Trend of monsoon index change from middle to late Miocene.

4. Table 2: “sample” changes to “proxies”.

   Response: Thanks for your correction. It is done.

5. Lines 507 and 523: “geography” changes to “land-sea distribution”.

   Response: Thanks for this suggestion. While we indeed emphasized the importance of land-sea distribution as demonstrated by the following cited studies, we have added a discussion on the uncertainties in Greenland-Scotland Ridge which is bathymetry rather than land-sea distribution. Therefore, we maintain the term “Geography” but append a half sentence “particularly the land-sea distribution” to underline this aspect.

References:

Agard, P., Omrani, J., Jolivet, L., Whitechurch, H., Vrielynck, B., Spakman, W., Monié, P., Meyer, B., Wortel, R., 2011. Zagros orogeny: a subduction-dominated process. Geological Magazine 148, 692–725. https://doi.org/10.1017/S001675681100046X

He, Z., Zhang, Z., Guo, Z., Scotese, C.R., Deng, C., 2021. Middle Miocene (~14 Ma) and Late Miocene (~6 Ma) Paleogeographic Boundary Conditions. Paleoceanography and Paleoclimatology 36, e2021PA004298. https://doi.org/10.1029/2021PA004298

McQuarrie, N., Stock, J.M., Verdel, C., Wernicke, B.P., 2003. Cenozoic evolution of Neotethys and implications for the causes of plate motions. Geophysical Research Letters 30. https://doi.org/10.1029/2003GL017992

Mouthereau, F., 2011. Timing of uplift in the Zagros belt/Iranian plateau and accommodation of late Cenozoic Arabia–Eurasia convergence. Geological Magazine 148, 726–738. https://doi.org/10.1017/S0016756811000306

Referee#2:

This manuscript discusses the enhancement of the South Asian summer monsoon during the Miocene and explores the drivers of that change. By using an ocean-atmosphere global climate model, the response of the South Asian summer monsoon to the uplift of the Iranian Plateau coincides with observed precipitation and wind speeds compared to reconstructions. The uplift of the Iranian Plateau is found to play a dominant role in the enhancement of the South Asian summer monsoon, especially in north-west India. The research work carries out a large number of simulation experiments, a large amount of analysis and simulation, the article is readable, and the findings are important for understanding the long-term evolution of the South Asian monsoon since the Miocene. It is recommended for publication after detailed revision of the following comments.

Thanks for your recommendation and comments. We agree with you that some unclear information exists in the manuscript. We have revised the manuscript according to your comments.

General:

1. The authors have emphasised that the time period of the study is MMIO, 17-12 Ma, and from the authors' very limited collection of record sites, it appears that the age of all the records is concentrated in the 14-12 Ma range, and the trend of the state of the South Asian monsoon indicated by these sites is "increasing".

Here, the authors need to be more explicit about the motivation for the Iranian Plateau, Himalayan and CO_2 modelling. The reasons are as follows. Firstly, according to the general concept, the atmospheric CO_2 concentration peaked around 15 Ma in the Miocene and then declined (e.g., Toward a Cenozoic history of atmospheric CO2, THE CENOZOIC CO_2 PROXY INTEGRATION PROJECT (CENCO2PIP) CONSORTIUM 2023). Therefore, it is unlikely that CO_2 is responsible for the intensification of the monsoon during this period from 14 to 12 Ma. Secondly, the authors have cited and elaborated that the Himalayas have reached their present height at 15 Ma, which also seems unlikely to be a factor in the 14~12 Ma monsoon intensification, and thus seems to be excluded. Finally, the authors mention that the Iranian Plateau uplifted at 15~12 Ma, but do not give clearer paleo-height constraints, and there is a lack of geographically reconstructed paleo-height evidence for the study.

The authors need to explicitly give the above information. This relates to the design rationale for the height of the Iranian Plateau in the authors' experimental design, as well as the attribution of monsoon intensification in the geological record.

Response: Thanks for these valuable inputs. We overall agree with your comments and have reworded the introduction as suggested. The following information is included:

- Considering that CO2 levels in atmosphere peaked around 15 Ma, it is unlikely that CO2 variations alone were responsible for the SASM intensification between

14 and 12 Ma. However, CO2 levels may have been a contributing factor to the peak SASM intensity around 15 Ma inferred from weathering proxies (Clift et al., 2008). Considering that the uplift of HM and IP predominantly occurred after 15 Ma, roughly coinciding with pronounced CO_2 variations during 17-14 Ma, we conduct two sets of sensitivity experiments based on the possible range of the CO2 variation.

- While the Himalayas (HM) started rising above the Tibetan Plateau (TP) around 15 Ma, it seems unlikely that this uplift significantly influenced the intensification of the SASM between 14 and 12 Ma. Nevertheless, there are augments suggesting that the ongoing uplift of the Himalayas above the TP contributes to the intensified SASM (Khan et al., 2014; Bhatia et al., 2021).

- We incorporate the evolutionary history of the IP uplift to limit its paleo-height, although there remains considerable uncertainty regarding the process of its elevation. The respective contributions of the IP and HM to intensified SASM during the Middle Miocene remain unclear.

Therefore, the effect of the IP and HM uplift, and the variation of CO2 during Middle Miocene are needed to be investigated.

1. The authors excessively cite previous research findings in the experimental analysis section, e.g., P9L227~L228, P11L256~L257, and P14L318~319. which tends to confuse the reader: is this the result of your experiment or the result of previous work? It may even lead to the misunderstanding: your experiment is exactly the same model and experimental design as the previous work? It needs to be revised.

Response: Thanks for these comments. We acknowledge that these citations may lead to confusion. We rephrase these sentences accordingly.

P9L227~L228, the domain of the SAM extends westward both in land and over the Arabian Sea where it nearly connects the African monsoon (Fig. 3c), a feature also presented in the study of Fluteau et al. (1999)".

This sentence is modified in Line 240-243 as:

"The domain of the SAM extends westward both in land and over the Arabian Sea where it nearly connects the African monsoon (Fig. 3c). This characteristic is also noted in the Miocene study of Fluteau et al. (1999), despite significant differences in the climate model and paleogeography employed in the two studies."

P11L256~L257: This anomaly regarded as the deepening of thermal low is also shown in previous study (Sarr et al., 2022).

This sentence has been revised and moved to Section 5.3 (Line 560-565) as discussion:

"Nonetheless, a previous study (Sarr et al., 2022) utilizing a late Miocene (10 Ma) configuration also emphasized the significant role of the Anatolia–Iran uplift on enhanced SASM. Their experiments showed that this uplift deepened the low-pressure area over the Arabian Peninsula, intensifying low-level wind and moisture transport from the Arabian Sea towards South Asia, a process consistent with our simulations (Fig. 4a)."

P14L318~319: Similar conclusion is also reported in projecting future climate change facing the rising CO_2 (Endo and Kitoh, 2014).

Response: We have moved this sentence to the end of Section 3.3 (Line 370-372) as a second example to prove that the SASM response to CO2 forcing in the Middle Miocene is very similar to that of projecting future climate change.

"Endo and Kitoh (2014), drawing from analysis across 20 climate models, demonstrate that in a warmer climate, enhanced SASM precipitation is primarily driven by thermodynamic processes, consistent with our findings from the MBA results shown in Figure 5."

Specific issues:

P4L79~82 Therefore, it is worthy to revisit the response of the SASM to the IP and HM uplift under Miocene boundary conditions with a fully coupled Ocean-Atmosphere Global Climate Model (OAGCM) and investigate the underlying physical processes.

The authors emphasize the coupled experiments in the introduction, but they do not mention the advantages of the coupled ocean-air experiments throughout the analysis and discussion. In addition, considering that each experiment only runs for 200 years and that thousands of years of credits are generally required to carry out a coupled experiment simulation, 200 years is too short a credit for a coupled experiment simulation. Considering the high horizontal resolution used in all experiments, 200 years seems to be acceptable. However, whether the authors have considered biases due to SST disequilibrium or uncertainties in the conclusions of the study due to additional feedbacks would be best discussed briefly in the Discussion section.

Response: Thanks for these excellent comments concerning two aspects. We have slightly modified the sentence (Line 86-89) to explain why OAGCM is chosen in our study. The added values of running OAGCM compared to AGCP are briefly discussed in Section 5.2 (Line 518-524). The uncertainties in the conclusions of this study due to disequilibrium has been added in the discussion Section 5.3 (Line 611-615).

Line 86-89:

"Therefore, we opt to use a fully coupled OAGCM to revisit the response of the SASM to the IP and HM uplift under Miocene boundary conditions, although it needs more computer resources and longer integrations to reach equilibrium."

Line 518-525

"While the effects of IP uplift from our AOCGM simulations qualitatively agree with previous studies using AGCMs (Wu et al., 2012; Liu et al., 2017; Zhang et al., 2015; Acosta and Huber, 2020), additional analysis (not shown) reveals notable impacts on ocean circulations. These impacts are evidenced by changes in SSTs and precipitation in tropical oceans, potentially influencing SASM intensity through teleconnection. However, further discussion on the added value of OAGCM extends beyond the scope of our current study."

Line 611-615:

"We also acknowledge that running OAGCMs necessitates an extended period to achieve equilibrium. Particularly with significant modifications to topography or CO_2 levels, integrations spanning 200/500 years may carry the risk of non-equilibrium, potentially affecting the quantitative estimation of their effects, but not essentially change the results."

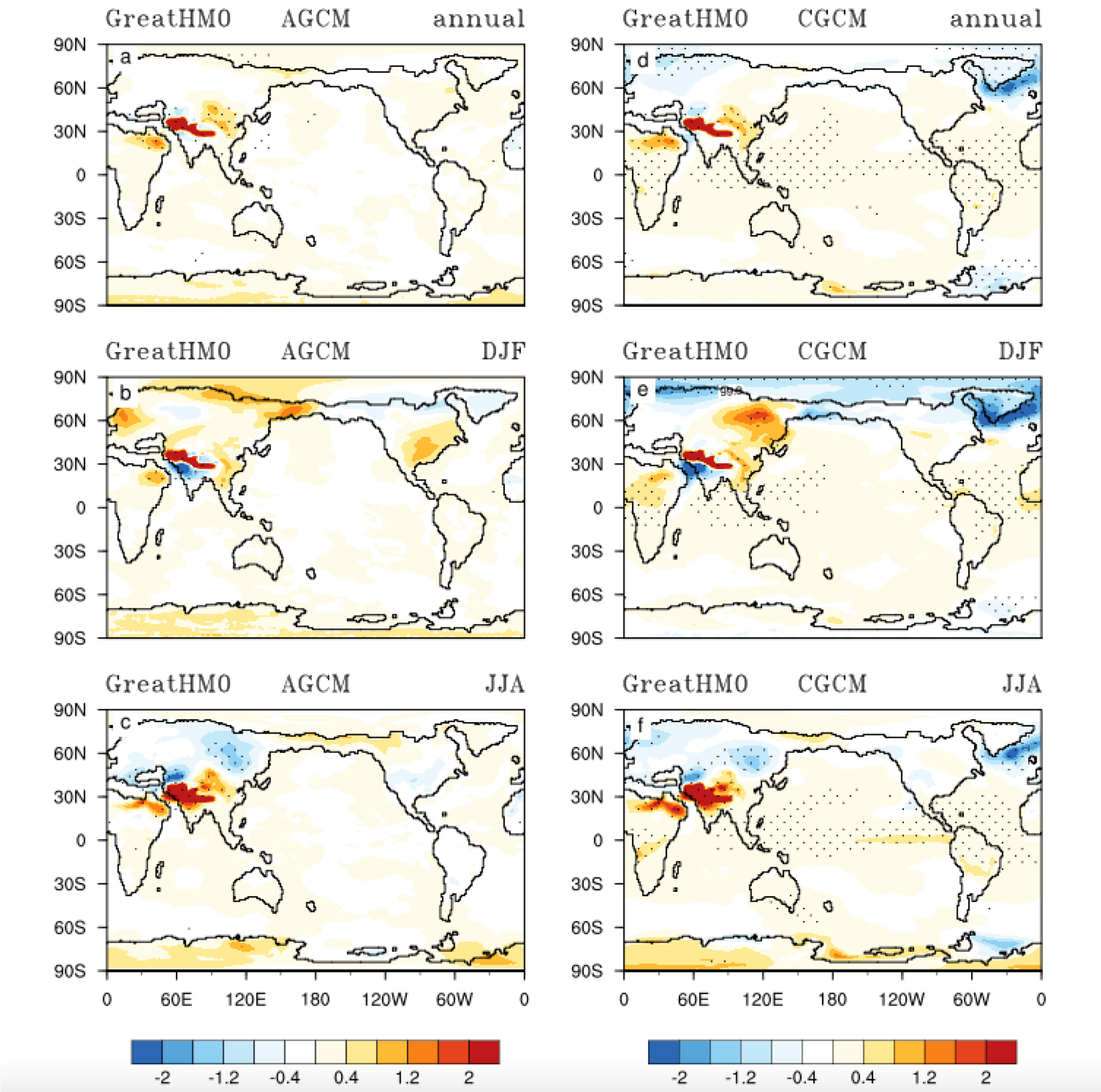
For more information about (1) the added value of running OAGCM vs AGCM, and (2) the quasi-equilibrium simulations, we provide in the following to reinforce our experimental design and conclusions.

- **Added value of OAGCM vs AGCM**

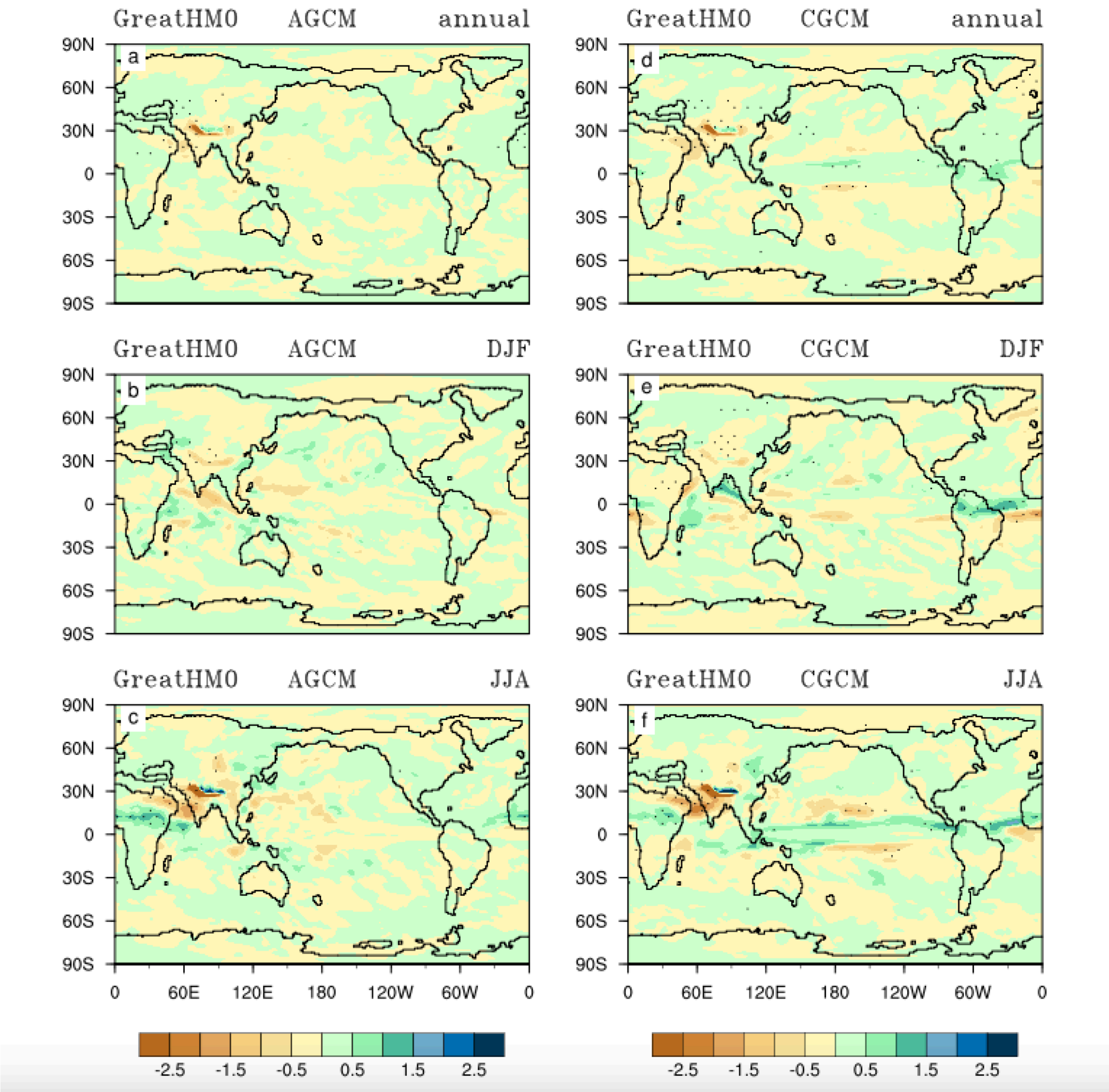
To evaluate the added-value by performing simulations with AOGCM, we've made two paired experiments of MMIO and IP0HM0 with AGCM-only. That is, after 2700-year running with OAGCM for the MMIO experiment, we continued the simulations with AGCM-only for another 150 years (named as MMIO_agcm and IP0HM0_agcm) with the last 100 years for analyses. We compared the responses of surface temperature and precipitation to IP-HM change, that is, differences between (IP0HM0 - MMIO) and (IP0HM0_agcm - MMIO_agcm). From the attached figures (FigS1 and FigS2), we can find that:

1. In AGCM simulations, temperature responses to IP-HM topographic changes are primarily seen in the extended South Asian Monsoon region from northeastern Africa to East Asia, extending to northeast Asia in boreal summer. In OAGCM simulations, along with local responses, temperature differences are also observed in tropical Africa and the Norwegian Sea Basin.
2. Likewise, AGCM simulations indicate local precipitation responses, while OAGCM simulations show broader effects in the tropical Atlantic and Pacific.

While results from OAGCM compared to AGCM are not significant different for the SASM, they do reveal notable impacts on ocean circulations, evidenced by changes in SSTs and precipitation in tropical oceans and the Norwegian Sea Basin, possibly impacting the SASM. Hence, we opt to employ OAGCM for our topographic sensitivity experiments to better capture the underlying dynamical processes related to the SASM. However, further discussion on the added value of OAGCM extends beyond the scope of our current study



FigS1: surface temperature (K) response to IP-HM change from AGCM simulations (Left column) and OAGCM (Right column). (a, d) annual mean; (b, e) DJF mean and (c, f) JJA mean. The black dots in each panel indicate values >99% confidence level based on the *Student's t* test. GreatHM0 indicates (IP0HM0_agcm - MMIO_agcm) or (IP0HM0 - MMIO). We note that MMIO(_agcm) is equal to IP100HM80(_agcm).



FigS2: Precipitation (mm day^{-1}) response to IP-HM change from AGCM simulations (Left column) and OAGCM (Right column). (a, d) annual mean; (b, e) DJF mean and (c, f) JJA mean. The black dots in each panel indicate values >99% confidence level based on the *Student's t* test. GreatHM0 indicates (IP0HM0_agcm - MMIO_agcm) or (IP0HM0 - MMIO). We note that MMIO(_agcm) is equal to IP100HM80(_agcm).

- **Short simulations for orography sensitivity experiments**

The global averaged annual mean SST and Rnet (net radiation flux at the Top of the Atmosphere) in the experiments of MMIO, IP0HM0, IP50HM50 and IP100HM100 are displayed in the attached figure (FigS3). Based on the outputs of the last 100-year of each simulation, the Mann-Kendall trend analysis confirms that there are no statistically obvious trends of SST and Rnet for these experiments despite that the Rnet stays at ca 3.10 W/m2, thus these experiments reach quasi-equilibrium.

Why can the three sensitivity experiments reach quasi-equilibrium after a short simulation period of 200 year? There are two possible reasons: 1) these simulations start from a state of quasi-equilibrium (MMIO); 2) the orographic changes are relatively small leading to weak impacts on global mean ocean circulations.

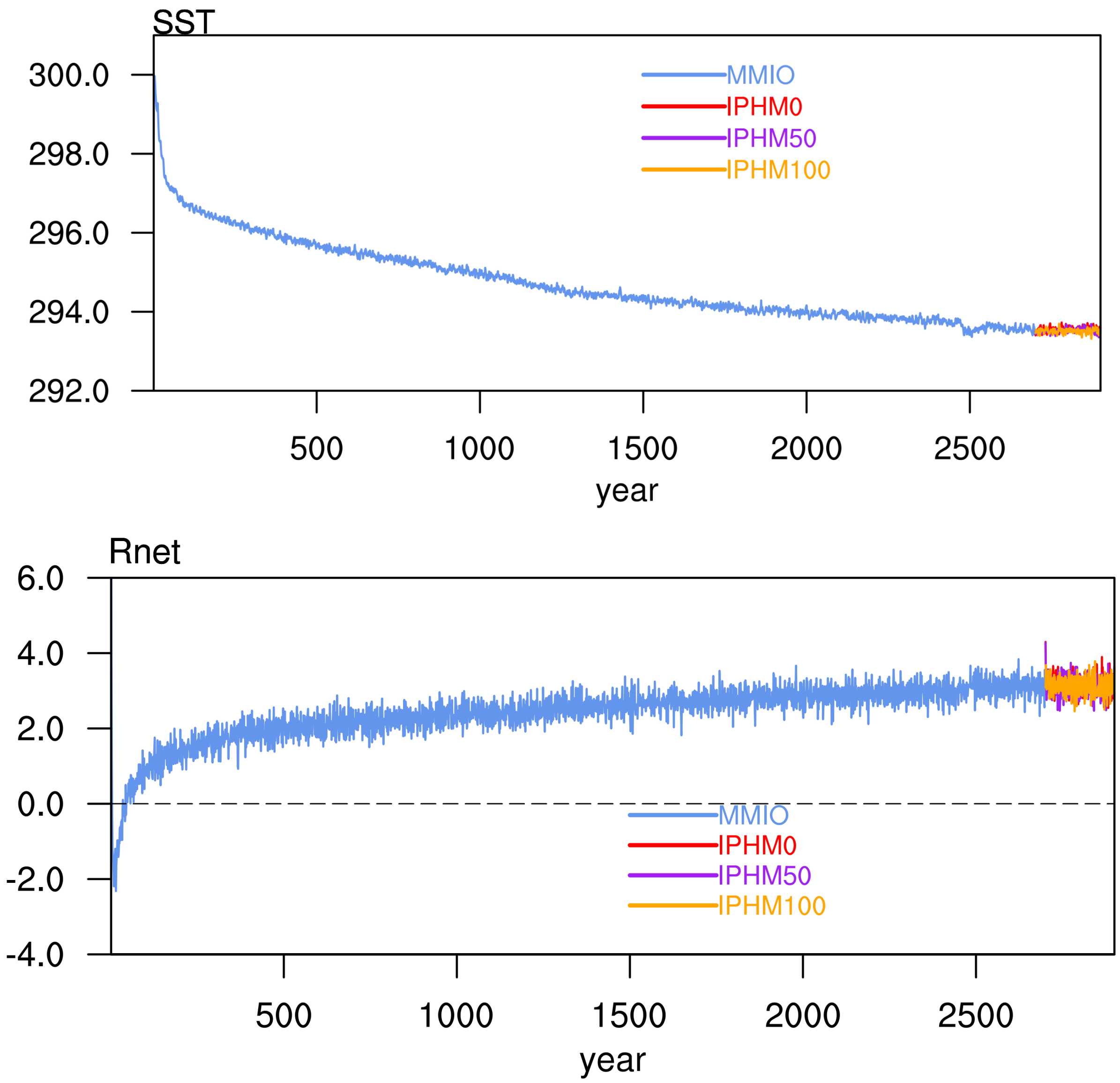


Fig. S2. The global averaged annual mean (a) sea surface temperature (SST; K) and net radiation flux (Rnet; W/ m^2, downwards is positive) at TOA (top of atmosphere) for the 2700-year MMIO (blue curves) and 200-year IP0HM0 (red curves), IP50HM50 (violotta curves) and IP100HM100 (orange curves) runs.

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P6L136~138 Is the topographic palaeoheight design of the Iranian Plateau supported by relevant cited literature?

Response: This palaeoheight of the IP comes from the reconstruction of Frigola et al. (2018, F18 henceforth). We've added this reference here (Line 149) and added a discussion regarding the uncertainties of F18 in Section 5.3 (particularly Line 556-566).

P7L182~183 (2) Webster-Yang Index (WYI; Webster and Yang, et al., 1992): meridional wind stress 183 shear between 850 hPa and 200 hPa averaged over 40-110°E, 0-20°N during June-August.

Did the authors use the WY index with the same selected area as in the original work? Did you take into account the uncertainty associated with the index's indication of monsoon circulation due to the inconsistency of the land and sea distribution in the Middle Miocene with the modern era, and did you correct the computed area? Please provide a brief description.

Response: Thanks for this suggestion. In the manuscript, we use the WY index with the same selected area in the original work. We re-calculate this index by shifting the longitude 4 degrees westward and find that the variations/trends are the same although the values are ca 0.7 m/s uniformly higher in the shifted one. Thus, we confirm that our conclusions are insensitive to the selected area given the inconsistency of the land-sea distribution between the Middle Miocene and the modern era.

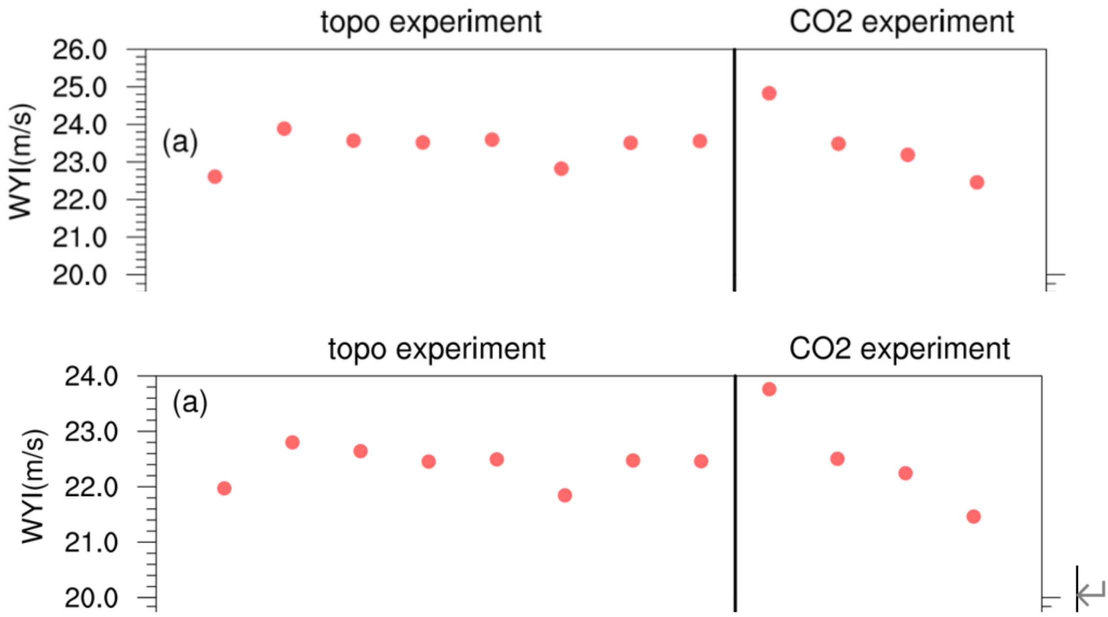


Fig. S3: Webster-Yang Index (meridional wind stress shear between 850 hPa and 200 hPa averaged over (top) 36-106°E, 0-20°N and (bottom) 40-110°E, 0-20°N during June-August).

P2L22: Global Climate Model 22 CESM1.2 through a series of 12 sensitivity experiments, the authors stated 12 sets of experiments, while in Table 1 (P32L845) only 10 sets are shown. Please change!

Response: Thanks for pointing out this mistake. We correct Table 1 by inserting another two sets of CO2 sensitivity experiments (MMIO560 and MMIO800) as described in the experimental design.

P17L367 Fig7 extra experiment 560ppm 800ppm, but the experiment description clearly states that.

Response: The two experiments are added in Table 1 as stated in the experimental description. Thanks for this reminder.

Table 1. Simulations performed with CESM1.2 in this study. See Fig.2 for modern and paleogeography maps.

experiment	Geolography	vegetation	CO2 (ppm)	IP	HM
piControl	Modern	Modern	280	Modern	Modern
MMIO (IP100HM80)	M.Miocene*	M.Miocene	400	M.Miocene	M.Miocene
IP0HM0	M.Miocene	M.Miocene	400	0	0
IP50HM0	M.Miocene	M.Miocene	400	50%	0
IP100HM0	M.Miocene	M. Miocene	400	100%	0
IP0HM100	M.Miocene	M.Miocene	400	0	100%**

IP50HM100	M.Miocene	M.Miocene	400	50%	100%
IP100HM100	M. Miocene	M. Miocene	400	100%	100%
MMIO280	M. Miocene	M.Miocene	280	M. Miocene	M.Miocene
MMIO560	M. Miocene	M.Miocene	560	M. Miocene	M.Miocene
MMIO800	M. Miocene	M.Miocene	800	M. Miocene	M.Miocene
MMIO1000	M.Miocene	M.Miocene	1000	M. Miocene	M.Miocene

*M.Miocen: Middle Miocene
** 100% of the height of modern HM.

P7L182: Webster and Yang, et al., 1992 is incorrectly cited; it should be Webster and Yang, 1992.

Response: Thanks for this correction.

P12L269: 722B, monsoonal signal is absent in IPHM0 (Fig.3d). What is IPHM0? Is it a writing error?

Response: It's a writing error, so it is corrected to "IP0HM0".

P16L6 The figure is labelled IPHM0 as well?

Response: Thanks for this careful check. We correct the Figure label as "Moisture budget (MMIO1000 – IP0HM0)".

P18L399~400 north Africa to North Africa

Response: Thanks for this correction that is done in the updated version.

P18L402 2 Medina et al., 2010? The literature is not cited.

Response: Thanks. The cited literature is added in the updated version.

"Medina, S., Houze Jr., R.A., Kumar, A., Niyogi, D., 2010. Summer monsoon convection in the Himalayan region: terrain and land cover effects. Quarterly Journal of the Royal Meteorological Society 136, 593–616. https://doi.org/10.1002/qj.601"

P19L414 Regarding to change to Regarding or Regard to.

Response: We correct this grammar error. Thanks.

P21L463 bewteen to between. Words are spelled incorrectly, please double-check the entire text

Response: Thank for this reminder. We correct this typo and double-check the entire text.

Referee#3

The manuscript uses climate modeling to compare the effect from the uplift of the Himalaya (HM) and Iranian Plateau (IP) and the increase of atmospheric CO2 to the intensified SASM during the Middle Miocene (17-12 Ma) with coupled atmosphere-ocean global climate model CESM. The results indicate the IP uplift plays a dominant role in the intensification of the SASM, and the effect of the HM uplift is confined to the range of the HM and its vicinity. In the case of extremely atmospheric CO2 variation, the effects of two factors are comparable in the SASM region. Although some results are similar to previse modeling studies, this study compares the effect from topographic forcing and atmospheric CO2 variation, which are also interesting and important. However, there are still several limitations. Particularly, because the main purpose of this study is to compare the effect from topographic forcing and atmospheric CO2 variation, the uncertainties in used topographic change and CO2 variation should be mentioned, these uncertainties may affect the main conclusions of this study.

Response: We thank you for summarizing and providing insightful comments on the issues addressed in our manuscript. These comments and valuable inputs help us to improve the quality of this paper. Recognizing the significant uncertainties inherent in reconstructing topography and CO2 variation during the Middle Miocene, we fully agree with your comments/suggestions regarding the uncertainties surrounding these factors and their potential impacts on our conclusions. We have incorporated a discussion addressing these uncertainties in the updated version of the manuscript.

Lines 60-67, Can you give an estimate of the raised height of the IP during the Middle Miocene?

Response: Thank for this reminder. We acknowledge that there are currently very few studies available for constraining the paleo-height of the IP. However, we extent this paragraph by providing the evolution history of the IP (Line 64-73).

"The evolution history of the IP uplift remains hotly debated (Agard et al., 2011; McQuarrie et al., 2003; Mouthereau, 2011; Ballato et al., 2017). Nevertheless, most studies suggest a Miocene age for the uplift of most landforms. Geological evidence indicates that in the northern sectors of the IP, the uplift likely occurred between 16.5-10.7 Ma (Ballato et al., 2016), particularly accelerated after 12.4 Ma (Mothereau, 2011), while in regions bordering the IP to the south between 15 and 5 Ma (Mouthereau, 2011). The Zagros orogen, a significant part of the IP, developed in three distinct pulses within the last ~20 Ma (Agard et al., 2011; Mouthereau, 2011). Our IP relevant sensitivity experiments reflect the possible range of IP uplift during the Middle Miocene. However, the configuration of Tethys/Paratethys in our simulations leads to small size of the IP."

Lines 85-87, during mid- to late Miocene, the CO2 decreases according to the reconstruction, why increased CO2 is considered here?

Response: Thanks for this comment. We've corrected the mis-description of the modeling results of a previous study (Thomson et al., 2021). It is corrected as follow (See Line 94):

"…even when the pCO_2 is set **from 560 ppm to 280 ppm** (Thomason et al., 2021)."

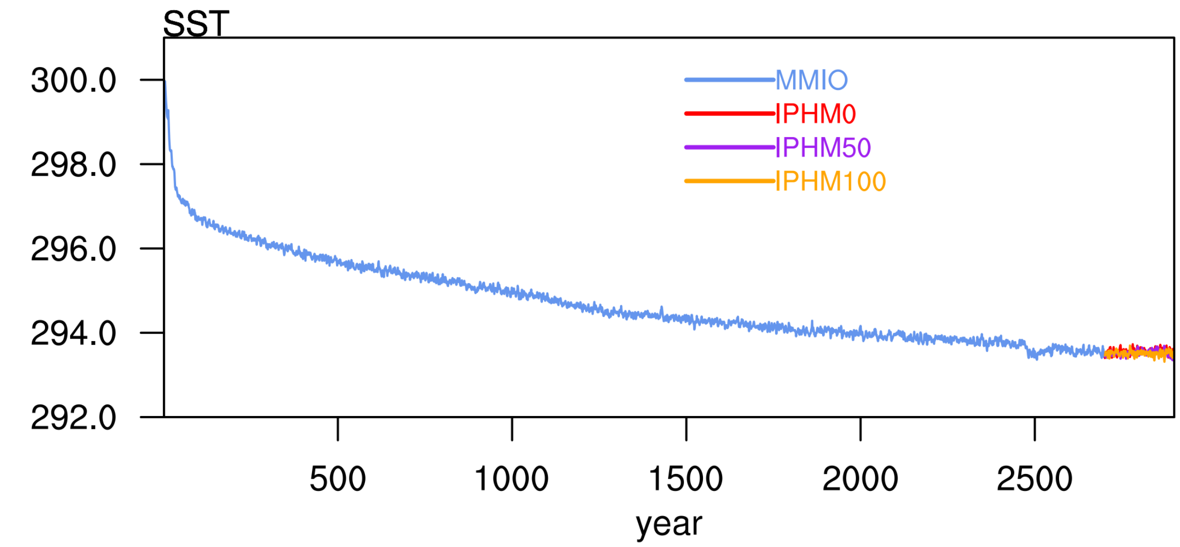
Line 111, is the ice sheet model active during the simulation?

Response: the ice-sheet model is inactive during the simulation. We've added this information in the updated version as follow:

"Both the Ice sheet Model and the dynamic vegetation module (Lawrence et al., 2011) incorporated in CLM4 are switched off in this study".

Lines 154 and 175, it's better to show the times series of the surface temperature and net top of the atmosphere radiation imbalance in these experiments.

Response: Thanks for this suggestion. The global averaged annual mean SST and Rnet (net radiation flux at the Top of the Atmosphere) in the experiments of MMIO, IP0HM0, IP50HM50 and IP100HM100 are displayed in the attached figure (FigS1). The SST and Rnet curves from other experiments generally lie between IP0HM0 and IP100HM100. Based on the outputs of the last 100-year of each simulation, the Mann-Kendall trend analysis confirms that there are no statistically obvious trends of SST and Rnet for these experiments despite that the Rnet stays at ca 3.10 W/m2, thus these experiments are regarded to reach quasi-equilibrium.



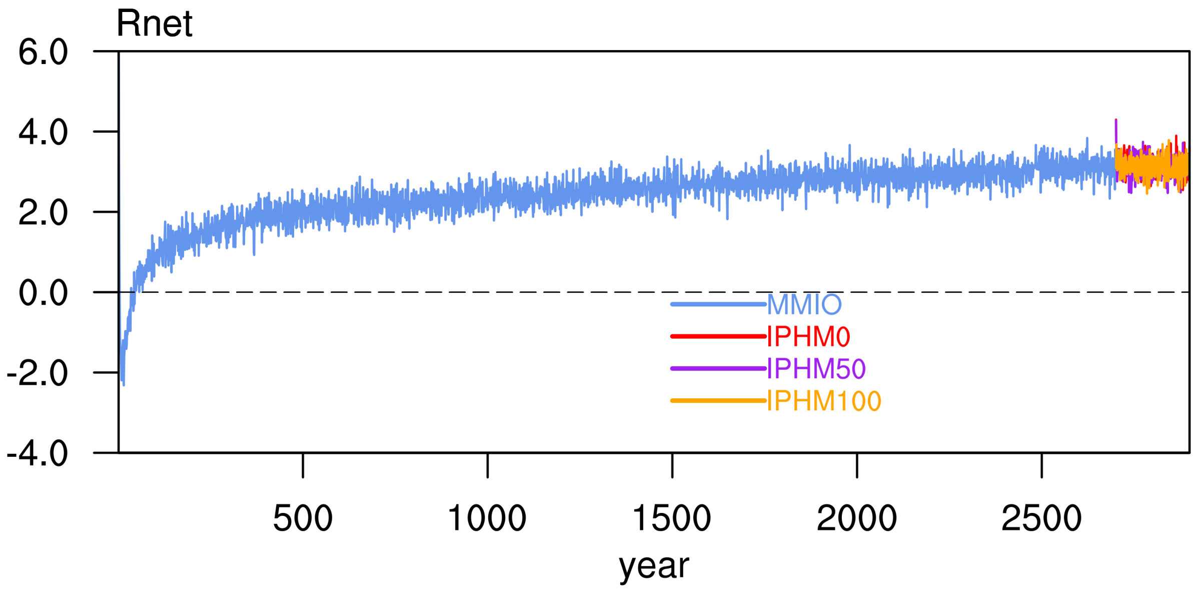


Fig. S1. The global averaged annual mean (a) sea surface temperature (SST; K) and net radiation flux (Rnet; W/ m^2, downwards is positive) at TOA (top of atmosphere) for the 2700-year MMIO (blue curves) and 200-year IP0HM0 (red curves), IP50HM50 (violotta curves) and IP100HM100 (orange curves) runs.

Lines 159-160, why the reference height is different between HM and IP?

Response: Thanks for this question. In the Middle Miocene, despite HM notable increase in height, its position remained relatively stable, making its modern height a suitable reference point. However, the evolution of the IP during this period is complex and largely uncertain, presenting challenges in using its modern height and size as a reference. Moreover, by comparing IP100HM100 and MMIO (IP100HM80), we can investigate whether the uplift of

HM above the Tibetan Plateau indeed leads to the intensification of the South Asian Summer Monsoon (SASM), as hypothesized by some researchers. Therefore, we've opted for different reference heights for the two mountains to address these considerations.

Lines160-164, the experimental design for the uplift of HM and IP from flat to 100% is too idealized compared to the geological evidence (Lines 53-56, 60-67) during the Middle Miocene.

Response: Thanks for this comment. Given the significant uncertainty regarding the growth of the IP and the coarse spatial resolution in our model, our experimental design necessitates idealization while incorporating the evolution of orogeny.

1）For instance, the experimental setups IP100HM100 and MMIO(that is, IP100HM80) reflect the uplift of HM above the TP after 15 Ma. Although the pattern of precipitation changes in (IP100HM100 – MMIO) closely resembles that of (IP100HM100 – IP0HM0), it exhibits a smaller intensity. We've added this information in Section 3.2 in the updated version as follow:

"Notably, the patterns of precipitation and low-level circulation changes between IP100HM100 and MMIO (not shown) closely resemble those illustrated in Fig. 4c, albeit with lesser intensity. This underscores that further uplift of HM above the TP does not lead to an intensified SASM."

2）Considering the significant uncertainty in the build-up of IP, we varied its height change from 0% to 100% to encompass the widest range of possibilities. While different height changes quantitatively impact the intensity of the South Asian Summer Monsoon (SASM), they do not alter the circulation pattern, suggesting a consistent underlying mechanism.

In the updated version, we have included a description of the evolution history of the IP (Line 64-73), we thus emphasize the importance of constraining the exact timing of IP uplift to improve our understanding of the evolution of the SAM; We have added a discussion on the uncertainty in the utilized topographic changes and their impact on the experimental design in Section 5.3, as we point out that the Tethys/Paratethys configuration used in our study, namely F18, reflects more the feature of early Middle Miocene geography, with an open Tethyan Seaway and a smaller IP. Thus, our topography sensitivity simulations may not adequately capture the IP's effects (Line 550-558). We also acknowledge that a better understanding of the impact of topographic change on the SASM and the underlying mechanism would benefit from additional simulations performed with increased spatial resolution (Line 589-606).

Lines 180-181, annual or seasonal precipitation?

Response: It is seasonal mean. We have corrected it:

"(1) All Indian rainfall (AIR): regional **summer** mean precipitation over the land points within the domain of 7-30°N, 65-95°E."

Figure 1, in the experimental design, how do the authors determine the extent of the HM and IP? The extent of the HM looks larger in Fig. S2.

Response: Thanks for these questions concerning technique treatment.

We determine the Miocene HM extent according its modern extend, but with 3-5 westward shift due to the TP is about 3-5 °C west than present day. We manually adjust the disconnected grids.

We first determine the extent of modern HM, then apply this mask to the Miocene orography but westward shift of 3-5 degree due to the Tibetan Plateau 3-5 °C west compared to its modern location. As for the IP, its orography at Miocene is considerable different from present-day, so "we lumped together all the mountain ranges west of the Himalayan, including the Hindu Kush region and Pamir as the IP. The northern part of the IP reached a near modern elevation as 1000-2000 m, but its southern part was lower than 1000 m (Please see Section 2.2)."

The extend of the HM looks larger in Fig. S2 than in Fig. 1 because their spatial resolutions are different. Fig. S2 is at 1.9x2.5 (lat x lon), which is the one actually used in our simulations. Conversely, Fig. 1 is at 0.5 x0.5, based on the boundary conditions from Frigola et al. (2018). This discrepancy is a common challenge in paleoclimate modeling when transforming the land-sea configuration and topography from high to low resolution.

Lines 228-229, it's better to point out the inconsistencies between model results and records. How about the ODP 359 and 758?

Response: Thanks for these suggestions. Here, we briefly provide the spatial distribution of the sites and the general picture of monsoon-like region. More detailed modelling and proxy data comparison regarding the two sites is given in Section 5.1 as the following:

"The two sites ODP 359 and 758, situated in the Inner Sea of the Maldives and the southern Bay of Bengal, respectively, indicate an abrupt strengthening of monsoonal circulations in the SASM regions at 12.9 Ma and 13.9 Ma, respectively. However, our modeling efforts cannot replicate these enhancements through either the uplift of the IP and HM or a reduction in CO_2 levels. Hence, it is likely that other factors exert a more significant influence on the reorganization of the SASM system. Examples include Antarctic glaciation, as suggested in Ali et al. (2021; Sarr et al., 2021), as well as the closure of the Tethys, as discussed in research by Betzler et al. (2016) and Bialik et al. (2019)."

Line 279, where is the 'core' region?

Response: It is the region (7-30°N, 65-95°E) where the AIR index is defined. We've added this information here.

Line 307, "to its west" should be "to its east"?

Response: Yes, it's "to its east". Thanks for this correction.

Line 399, "southeasterly" should be "southwesterly"?

Response: Yes, it's "southwestly". Thanks for this correction.

Line 404, from Figure 9d, LCL is increased over the IP.

Response: Please note the unit of LCL in hPa.

"(d) Lifting condensation level (LCL, unit: hPa, positive value represents lower LCL);"

Line 468, where is "American region"?

Response: Yes, it's American region. This sentence is to cite the teleconnection effect on precipitation change in the eastern HM from previous modeling studies (Chakraborty et al., 2006; Miao et al., 2022), possibly reconciling the model-proxies discrepancy. The removal of

American orography delays the onset of the SASM thus reduces its intensity via a shift in position of the Rossby wave pattern (Chakraborty et al., 2006).

Lines 484-486, the different used extent of the HM between these studies can explain the disagreement the author mentioned.

Response: Thanks for this suggestion. The primary reason for the discrepancy between our results and the one mentioned (Zhang et al., 2012) is that if the Tibetan Plateau exists before the uplift of the HM. Zhang et al. (2012) assumed first the uplift of HM, contrary to the current understanding of the evolution history of the HM-TP. Our findings aligh with other studies (Liu et al., 2017; Zhang et al., 2015; Acosta and Huber, 2020; Tardif et al., 2020, 2023) that considering the TP's existence prior to HM uplift even if the HM represented in these climate models are very different due to large differences in used geography (paleo or modern) and spatial resolution (from 0.23° × 0.31° to 3.75° × 0.1.9°).

Line 506, the uncertainties in used topographic change and CO2 variation should be discussed.

Response: Thanks for this valuable suggestion. We add a discussion on these aspects.

Line 539, Zhang et al., 2017 is not a modeling study.

Response: It is "Zhang et al., 2015". We've corrected it. Thanks.

Table 2 No 3, the change in ODP 722 at 11 Ma is out of the Middle Miocene (17-12 Ma).

Response: Thanks for this comment. This reference is removed from Table 2 as the evidence of SASM intensification during the Middle Miocene, which has no essential impact on our conclusions and discussions.

References:

Chakraborty, A., Nanjundiah, R.S., Srinivasan, J., 2006. Theoretical aspects of the onset of Indian summer monsoon from perturbed orography simulations in a GCM. Annales Geophysicae 24, 2075–2089.

Flower, B. P. & Kennett, J. P. The middle Miocene climatic transition: East Antarctic ice sheet development, deep ocean circulation and global carbon cycling. Palaeogeogr. Palaeoclimatol. Palaeoecol. 108, 537–555 (1994).

Miao, Y., Fang, X., Sun, J., Xiao, W., Yang, Y., Wang, X., Farnsworth, A., Huang, K., Ren, Y., Wu, F., Qiao, Q., Zhang, W., Meng, Q., Yan, X., Zheng, Z., Song, C., Utescher, T., 2022. A new biologic paleoaltimetry indicating Late Miocene rapid uplift of northern Tibet Plateau. Science 378, 1074–1079. https://doi.org/10.1126/science.abo2475

Zhang, R., Jiang, D., Zhang, Z., Yu, E., 2015. The impact of regional uplift of the Tibetan Plateau on the Asian monsoon climate. Palaeogeography, Palaeoclimatology, Palaeoecology 417, 137–150. https://doi.org/10.1016/j.palaeo.2014.10.030