Quantifying Effects of Earth Orbital Parameters and Greenhouse Gases on Mid-Holocene Climate

Yibo Kang and Haijun Yang*

Department of Atmospheric and Oceanic Sciences and Institute of Atmospheric Science and CMA-FDU Joint Laboratory of Marine Meteorology, Fudan University, Shanghai, 200438, China.

Shanghai Scientific Frontier Base for Ocean-Atmosphere Interaction Studies, Fudan University, Shanghai 200438, China.

Correspondence to: Haijun Yang (yanghj@fudan.edu.cn)

Abstract. The mid-Holocene (MH) is the most recent typical climate period and a hot topic for global paleocultural research. Following the latest Paleoclimate Modelling Intercomparison Project (PMIP) protocol and using a fully coupled climate model, we simulated the climate difference between the MH and the pre-industrial (PI) periods, and quantified the effects of Earth orbital parameters (ORB) and greenhouse gases (GHG) on climate difference. More attention was paid to the simulated differences in the Atlantic meridional overturning circulation (AMOC) between these two periods. Compared to the PI conditions, the ORB effect in the MH simulation led to the seasonal enhancement of temperature, consistent with previous findings. For the MH simulation, the ORB effect led to a remarkably warmer climate in the mid-high latitudes and increased precipitation in the Northern Hemisphere, which were partially offset by the cooling effect of the lower GHG. The AMOC in the MH simulation was about 4% stronger than that in the PI conditions. The ORB effect led to 6% enhancement of the AMOC in the MH simulation, which was, however, partly neutralized by the GHG effect. The simulated stronger AMOC in the MH was mainly due to the thinner sea ice in the polar oceans caused by the ORB effect, which reduced the freshwater flux export to the subpolar Atlantic and resulted in a more saline North Atlantic. This study may help us quantitatively understand the role of different external forcing factors in the Earth's climate evolution since the MH.

Keywords: mid-Holocene, Earth orbital parameters, Greenhouse gases, AMOC

1. Introduction

The mid-Holocene (MH, 6000 years before the present) is a period of profound cultural transition worldwide, particularly in the arid-semi-arid belt (~30°N) (Sandweiss et al., 1999; Moss et al., 2007; Roberts et al., 2011; Warden et al., 2017). The MH climate, which belongs to the Holocene climatic optimum (Rossignol-Strick, 1999; Chen et al.,...
2003; Zhang et al., 2020), is significant different from the subsequent period. Many studies have shown that the development of human civilization during this period was influenced by the climate, which was closely related to external factors such as the Earth's orbital parameters (ORB), greenhouse gases (GHG) and solar constants (Jin, 2002; Wanner et al., 2008; Warden et al., 2017). Therefore, it is of great interest to study the MH climate, for a better understanding of the influence of external forcing factors on human civilization.

As the key benchmark period of the Paleoclimate Modeling Intercomparison Project (PMIP) program, starting with the earliest PMIP program (Joussaume and Taylor, 1995; Kageyama et al., 2018), the MH experiment was designed to examine the climate response to a change in the seasonal and latitudinal distribution of incoming solar radiation caused by known changes in Earth orbital forcing. As the program evolved, the GHG concentrations used in the MH experiments are closer to the true values (Monnin et al., 2001, 2004). However, most studies focused on the general climate differences between the MH and pre-industrial (PI) periods; the individual effects of the ORB and GHG on the climate are not isolated. Some studies examined the role of GHG by comparing the PMIP programs. Otto-Bliesner et al. (2017) found that the change in the experimental protocol between PMIP4 and PMIP3, with a reduction in CO₂ concentration from 280 to 264.4 ppm, would reduce GHG forcing by about 0.3 W/m². This change can produce an estimated global mean cooling in surface air temperature (SAT) of about 0.28°C based on the climate sensitivity of each model in PMIP4 (Brierley et al., 2020). Note that the differences in the MH experiments between PMIP4 and PMIP3 include only the GHG effect: the GHG contribution to temperature change is not negligible although it is small. Quantifying the effects of ORB and GHG on the difference between the MH and PI is much needed. Explaining this issue clearly has important implications for a deeper understanding of the role played by external forcing factors in the past climate.

The Atlantic meridional overturning circulation (AMOC) is considered an important heat transmitter of the Earth's climate system, which affects global climate on multiple timescales (Rahmstorf, 2006). Paleoclimate studies showed that the weakening or stopping of the AMOC will lead to a large-scale drastic cooling in the Northern Hemisphere (NH) (Brown and Galbraith, 2016; Yan and Liu, 2019). Therefore, studying past AMOC changes will help us understand the nature of climate change in the past and better predict future climate. In the previous MH simulations of the PMIP, the AMOC is generally stronger than that of the PI (Gâinuşă-Bogdan et al., 2020), but these simulation results may be slightly different due to model or resolution differences (Shi and Lohmann, 2016; Shi et al., 2022). Recent studies suggested that the difference of the AMOC between the MH and PI periods is not significant (Brierley et al., 2020). By comparing the strength of the AMOC during the interglacial period, it was found that the
variation range of the AMOC in the MH is within the internal variability range of all models; and the ORB does not seem to have played a role (Jiang et al., 2023).

In this paper, we further study the mechanism of weak difference of the AMOC between the MH and PI periods. The effects of different external forcing factors on the AMOC will be quantified. This paper is organized as follows.

An introduction to the fully coupled climate model is given in section 2, along with the experiments design. The effects of ORB and GHG on the MH climate, the AMOC, and Hadley cell are shown in section 3. The changes of North Atlantic Ocean buoyancy are described in section 4. Summary and discussion are given in section 5.

2. Model and experiments

The National Centre for Atmospheric Research’s Community Earth System Model version 1.0 (CESM1.0) is used in this study. The coupled model includes atmospheric, oceanic, sea-ice, and land model components. The atmospheric model has 26 vertical levels and T31 horizontal resolution. The land model has the same horizontal resolution as the atmospheric model. The ocean model has 60 vertical levels and gx3v7 horizontal resolution. The sea-ice model has the same horizontal resolution as the ocean model. More details on these model components can be found in a number of studies (Smith and Gregory, 2009; Hunke and Lipscomb, 2010; Lawrence et al., 2012; Park et al., 2014).

To quantify the effects of ORB and GHG on climate differences between the MH and PI periods, we designed three experiments following the PMIP4 protocol (Table 1). Experiment MH uses the ORB and GHG in the MH period. Experiment MH_ORB uses the ORB in the MH period and the GHG in the PI period. Experiment PI uses the ORB and GHG in the PI period. Specific values of the Earth orbital parameters are listed in Table 1 (Berger and Loutre, 1991). The vernal equinox is set to noon on 21 March, and the solar constant is set to 1360.75 W/m² in all three simulations. The GHG data comes from the ice-core records of the Antarctica and Greenland (Otto-Bliesner et al., 2017). The three experiments are all integrated for 2000 years, with MH and MH_ORB starting from the PI condition. In this paper, we use the monthly mean data of the last 500 years of each model simulation. The effect of ORB is obtained by subtracting the Exp PI from the Exp MH_ORB, and the effect of GHG is obtained by subtracting the Exp MH_ORB from the Exp MH. The combined effect of ORB and GHG is obtained by subtracting the Exp PI from the Exp MH.
Table 1. Forcing and boundary conditions. More details can be found in Otto-Bliesner et al. (2017)

<table>
<thead>
<tr>
<th></th>
<th>Exp MH</th>
<th>Exp PI</th>
<th>Exp MH_ORB</th>
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<tbody>
<tr>
<td>Orbital parameters</td>
<td></td>
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<tr>
<td>Eccentricity</td>
<td>0.018682</td>
<td>0.016764</td>
<td>0.018682</td>
</tr>
<tr>
<td>Obliquity (degrees)</td>
<td>24.105</td>
<td>23.459</td>
<td>24.105</td>
</tr>
<tr>
<td>Perihelion – 180</td>
<td>0.87</td>
<td>100.33</td>
<td>0.87</td>
</tr>
<tr>
<td>Greenhouse gases</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>CO₂ (ppm)</td>
<td>264.4</td>
<td>284.3</td>
<td>284.3</td>
</tr>
<tr>
<td>CH₄ (ppb)</td>
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<td>808.2</td>
<td>808.2</td>
</tr>
<tr>
<td>N₂O (ppb)</td>
<td>262</td>
<td>273.0</td>
<td>273.0</td>
</tr>
</tbody>
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ORB includes eccentricity, precession, and obliquity. In the past six millennia, the eccentricity and obliquity did not change much. The main change came from precession, which is influenced by eccentricity and the longitude of perihelion. As a result, perihelion is close to the NH autumn equinox in the MH period and close to the NH winter solstice in the PI period. Therefore, with respect to Exp PI, the solar energy received at the top of the atmosphere (TOA) in Exp MH changed seasonally and latitudinally, as shown in Fig. 1a. Compared to Exp PI, Exp MH had higher NH summer radiation and lower winter radiation, and the difference during June–August (JJA) reached 30 W/m² in the high latitudes. Smaller precession led to more radiation received in the NH summer in the MH period. Figure 1b shows the meridional variation of annual mean shortwave radiation at the TOA, which is greater than 4 W/m² poleward of 45°N(S), but negative and smaller than 1 W/m² between 45°S and 45°N. This situation is associated with the larger obliquity in the MH (Otto-Bliesner et al., 2006; Williams et al., 2020). In addition, the difference of GHG between the MH and PI periods can lead to an effective radiative forcing of 0.3 W/m² (Otto-Bliesner et al., 2017).

Figure 1 (a) Latitude-month distribution of solar radiation change at the TOA in Exp MH, and (b) annual mean solar radiation change, with respect to Exp PI. Units: W/m².
3. Results

3.1 Surface air temperature and precipitation

Compared to Exp PI, Exp MH has warmer annual mean temperatures in the NH high latitudes and cooler temperatures in the rest of the globe (Fig. 2a), while Exp MH_ORB has a warmer surface at mid–high latitudes in both the NH and SH, with a greater range and magnitude than Exp MH (Fig. 2b). Figure 2b shows the direct response to the meridional change of annual mean solar radiation. The lower GHG in the MH contributed to a lower global surface temperature, which is clear in the mid–high latitudes (Fig. 2c). In the NH summer (June–August, or JJA), Exp MH shows a general warming of more than 1°C north of 30°N, which is more significant in Greenland and Euro-Asian continent, and a cooling belt in northern India and central Africa (Fig. 2d), which is associated with increased rainfall due to the enhanced monsoon (Fig. 3d). The magnitude and extent of warming due to the ORB effect are apparently greater, with warming of up to 3°C in central Asia (Fig. 2e). The GHG cooling is more pronounced over the Southern Ocean (Fig. 2f). In the NH winter (December–February, or DJF), only the NH polar latitudes remain the warming. There is strong cooling (up to 3°C) in the African and Euro-Asian continents (Fig. 2g). The patterns under the ORB and GHG forcing are similar to their annual mean situations, except for the enhanced cooling in South Asia and central Africa (Fig. 2h) and over the subpolar Atlantic (Fig. 2i). Most figures are featured with a polar amplification, which may be related to the change of sea ice (Otto-Bliesner et al., 2017; Williams et al., 2020).

![Figure 2](https://doi.org/10.5194/egusphere-2023-380)

Figure 2 (Left column) Changes in SAT in the Exp MH, with respect to the PI, and the contributions from (central column) the ORB effect and (right column) the GHG effect. (a)–(c) are for annual mean; (d)–(f), for the NH JJA; and (g)–(i), for the NH DJF. Stippling shows significance over the 90% level calculated by Student t-test. Units: °C.
Differences in precipitation between the MH and PI simulations are shown in Fig. 3. Consistent with the latitudinal and seasonal differences of insolation (Fig. 1), the largest difference in precipitation between the two periods also occurs in the NH summer, with significantly more precipitation in northern India and in the equatorial African monsoon region, and drier in the equatorial Atlantic and Pacific in Exp MH (Fig. 3d). The difference between Exps MH and PI is mainly in the global tropics and is contributed predominantly by the ORB effect (Figs. 3e, h), as the GHG effect is very weak (Figs. 3f, i).

Although the numerical values may be slightly different due to different models or resolutions, in general the annual and seasonal climatology differences of temperature and precipitation between Exps MH and PI are in good agreement in some recent studies (Williams et al., 2020; Zhang et al., 2021b). The ORB effect dominates the changes in global surface temperature and precipitation. Exp MH has a warmer climate than Exp PI, particularly in the NH high latitudes.

3.2 Meridional atmospheric circulation

The meridional atmospheric circulation, namely, the Hadley cell in Exp MH is about 10% weaker than that in Exp PI (Fig. 4a), consistent with the weaker meridional atmospheric temperature gradient in Exp MH than in Exp PI. The weaker Hadley cell in Exp MH is mainly due to the ORB effect (Figs. 4b, e, h). The GHG effect can be neglected (Figs. 4c, f, i). The Hadley cell is weaker due to the strong warming of the high-latitude temperatures in the NH.
summer (Fig. 4d). The strengthening of the Hadley cell in the NH winter (Fig. 4g) corresponds to an increasing temperature gradient between the tropics and mid latitudes (Fig. 2g). The weaker Hadley cell also leads to a weaker meridional atmospheric heat transport from low to high latitudes, which will be discussed in section 3.4.

**Figure 4** Same as Fig. 2, but for the mean Hadley cell in Exp PI (contour) and its changes (shading) in Exp MH. Units: $10^9$ kg/s.

### 3.3 AMOC

The AMOC strength, defined as the maximum streamfunction between 0–2000 m and 20°–70°N in the North Atlantic, are 19.4 and 18.3 Sv in Exps MH and PI, respectively. The depth of the maximum AMOC in all experiments occurs near 1000 m. The AMOC patterns in Exps MH and PI are similar (Figs. 4a, c), which suggests that the combined effect of the ORB and GHG on the AMOC is small (Fig. 4d). However, individual effects of the ORB and GHG are not negligible (Figs. 4e, f). In fact, the ORB effect leads to 6% stronger AMOC in Exp MH than in Exp PI (Fig. 5e). The deep overturning is significantly enhanced south of 45°N, but slightly weakened north of 45°N. However, at the same time the GHG effect leads to a slight decline in AMOC strength in Exp MH, especially above 1500 m south of 45°N (Fig. 5f). The ORB and GHG have the opposite effects on the AMOC, which make the AMOC in Exp MH roughly the same as that in Exp PI. This is different from most previous findings (Otto-Bliesner et al., 2017).
In section 4, we will explain the mechanism of weak enhancement of the AMOC by presenting the changes in the North Atlantic.

3.4 Meridional heat transport

Meridional heat transport (MHT) plays an important role in maintaining energy balance of the Earth climate system. Figure 6a shows the annual MHTs in different experiments, which are nearly identical. The climate differences between Exps MH and PI hardly change the integrated heat transport in both the atmosphere and ocean. Consistent with previous studies (Trenberth and Caron, 2001), the annual mean MHT shows an antisymmetric structure about the equator, with the peak value of about 5.5 PW (1 PW=10^{15}W) at 40°N/S. Compared with ocean heat transport (OHT), the atmosphere heat transport (AHT) dominates at most latitudes, which is also consistent with most studies (Held, 2001; Wunsch, 2005; Czaja and Marshall, 2006).

However, the MHT changes caused by the ORB and GHG effects appear to be nonnegligible. The ORB causes an increase in OHT in the NH, with the maximum change of about 0.10 PW near the equator, roughly 10% of the mean OHT there. This is due to the enhanced AMOC and is the main cause of temperature increase in the NH high latitudes (Fig. 2b). The northward AHT is reduced, with the maximum change of about 0.10 PW. This is due to the weakend Hadley cell. The AHT change compensates the OHT change very well in the deep tropics, while the former overcompensates the latter in the NH off-equatorial regions (Fig. 6b). The GHG effect on the MHT is very weak, with
the maximum MHT change of no more than 0.04 PW near 5°N, which is just one third of the ORB-induced MHT change (Fig. 6c).

Figure 6 (a) Annual mean meridional heat transport (MHT). Black, red, and blue for the total MHT, AHT, and OHT, respectively. Solid, dashed, and dotted for Exps MH, MH_ORB, and PI, respectively. (b) and (c) show changes in the total MHT, AHT, and OHT due to ORB and GHG effects, respectively. Units: PW (1 PW = 10¹⁵ W).

4. Changes in the North Atlantic Ocean

4.1 Changes in sea-surface temperature, salinity, and density

The strength of the AMOC is largely determined by the North Atlantic deep-water formation, which is in turn determined by upper-ocean density. Figure 7 shows the differences of sea-surface temperature (SST), salinity (SSS), and density (SSD) in the North Atlantic between Exps MH and PI. The SST difference is characterized by a warming up to 1.6°C in the subpolar Atlantic and a cooling of about 1°C near the Nordic Seas and Gulf Stream extension region (Fig. 7a). The surface ocean warming in the North Atlantic is due to the ORB effect (Fig. 7b), which causes a strong and extensive warming in the North Atlantic, with the maximum warming in the subpolar Atlantic. The GHG effect causes a general cooling in the North Atlantic (Fig. 7c), offsetting partially the ORB-induced warming, leaving a cooling in the Nordic Seas and Gulf Stream extension (Fig. 7a).

The patterns of SSS difference between Exps MH and PI are similar to those of SST difference. In general, the North Atlantic is more saline in Exp MH than in Exp PI (Fig. 7d), mainly due to stronger evaporation over precipitation in Exp MH than in Exp PI (Fig. 9d), which is in turn due to the warmer SST forced by the ORB effect (Fig. 7e). The polar oceans are fresher in Exp MH than in Exp PI (Figs. 7d, e), mainly, due to more freshwater flux coming from the sea ice in Exp MH (Figs. 9a, b), consistent with the warmer climate in the MH due to the ORB effect. The SSS difference caused by the GHG effect is roughly opposite to that caused by the ORB effect, but with much weaker magnitude (Fig. 7f), because the cooling effect of the GHG makes less evaporation in the subtropical to subpolar Atlantic and more sea ice in the polar oceans (Fig. 9c).
The patterns of SSD difference (Figs. 7g–i) resemble those of both SSS and SST differences, while its polarity is determined by SSS difference. The higher SSD in the North Atlantic is favorable to stronger deep-water formation and thus a stronger AMOC in Exp MH. Forced by the ORB effect, the North Atlantic surface ocean can be 0.5 kg/m³ denser in Exp MH than in Exp PI (Fig. 7h), which could have resulted in 1.2-Sv stronger AMOC in Exp MH than in Exp PI (Fig. 5e). However, the GHG effect, although weak, has an opposite effect on SSD and thus the AMOC (Fig. 7i), and eventually mitigates the ocean change in Exp MH.

Figure 7 Changes in (a)–(c) sea-surface temperature (SST), (d)–(f) sea-surface salinity (SSS), and (g)–(i) sea-surface density (SSD) of the North Atlantic in Exp MH, with respect to the Exp PI. (a), (d), and (g) are for the total changes; (b), (e), and (h), for the changes due to ORB effect. (c), (f), and (i) are for changes due to GHG effect. Units are °C for SST, psu for SSS, and kg/m³ for SSD.

4.2 Change in surface freshwater flux

Sea-surface freshwater flux includes both sea-ice formation (melting) and net evaporation (i.e., evaporation minus precipitation, or EMP). Figure 8 shows the change of annual mean sea-ice thickness in the Arctic. The Arctic sea-ice thickness in Exp MH is about 1.0 m thinner than that in Exp PI (Fig. 8a). The largest sea-ice difference, which is about 3.0 m thinner in Exp MH, occurs in the Baffin Bay. Forced by the ORB effect only, the Arctic sea ice would be more than 1.5 m thinner (Fig. 8b), consistent with the stronger insolation and the warming in the NH high latitudes.
The GHG effect leads to a slight increase of sea ice in the Arctic (Fig. 8c) in Exp MH, which is less than 0.5 m in thickness. Changes in Arctic sea ice thickness can affect sea-ice transport to the subpolar Atlantic. The loss of sea ice in the central Arctic Ocean can reduce its export through the Fram Strait, which can lead to an increase in salinity in the associated sub-polar regions (Shi and Lohmann, 2016), as shown in Figs. 7d and e.

![Figure 8 Changes in the Arctic mean sea-ice thickness in Exp MH, with respect to Exp PI. Positive (negative) value represents sea-ice formation (melting). (a) for total change; (b) and (c) for changes due to ORB and GHG effects, respectively. Solid blue, black, and red curves show the sea-ice margin in Exps MH, MH_ORB and PI, respectively. The sea-ice margin is defined by the 15% sea-ice fraction. Units: m.](https://doi.org/10.5194/egusphere-2023-380)

The sea-ice margin in the North Atlantic in Exp MH is slightly more northward compared to that in Exp PI (solid blue curve, Fig. 8a). The curves in Fig. 8 show sea-ice margin in different experiments. The northward displacement of sea-ice margin and the decrease in ice volume in the Arctic favor the decrease in freshwater flux in the North Atlantic, helping a more saline North Atlantic, which contributes about 0.9 PSU 10 yr⁻¹ to the SSS tendency between 40° and 60°N (Fig. 9a). The EMP flux is small, and the upper ocean is refreshed at a steady rate of about 0.09 PSU 10 yr⁻¹ in the North Atlantic (Fig. 9d). Overall, for the North Atlantic the change of sea ice plays a dominant role; and its contribution to SSS tendency is about 10 times that of EMP.
Figure 9 Changes in (a)–(c) are virtual salt flux (VSF) due to sea ice, and in (d)–(f), VSF due to EMP in Exp MH, with respect to Exp PI. Positive (negative) value represents sea-ice formation (melting) or evaporation larger (smaller) than precipitation. (a) and (d) for total changes; (b) and (e) for changes due to ORB effect; (c) and (f) for GHG effect. The sea-ice margin in (a)–(b) are the same as those in Fig. 8. Units: psu yr\(^{-1}\).

The sea-ice margin in Exp MH is controlled by the ORB effect. In individual forcing experiment, the sea-ice margin forced by the ORB effect is almost the same as that in Exp MH (solid black curve, Fig. 9b). The contributions of ORB and GHG effects to changes in virtual salt flux (VSF) due to sea ice are 1.3 and -0.4 psu 10yr\(^{-1}\), respectively (Figs. 9b, c); and those due to the EMP flux are 0.06 and 0.03 psu 10yr\(^{-1}\), respectively (Figs. 9e, f). The sea-ice change caused by the ORB effect plays an important role in the enhancement of the AMOC in Exp MH.

In general, the modelling results suggest that the stronger AMOC in Exp MH is resulted from more saline North Atlantic, which is contributed mainly by smaller freshwater flux coming from the Arctic. The contribution of EMP to salinity change is small, which is only one-tenth of sea-ice contribution. ORB and GHG consistently play opposite roles in the deep-water formation of the subpolar Atlantic. Their combined effect results in little change in the AMOC in Exp MH, with only about 0.8 Sv enhancement.

5. Summary and discussion

In this study, three experiments using the CESM1.0 were conducted to quantify the contributions of ORB and GHG effects to the MH climate. More attention was paid to the AMOC; and the mechanism to the insignificant difference of the AMOC between the MH and PI periods was explored. This study is the first attempt to separate the ORB and GHG effects on the MH climate. Simulations show that the NH climate exhibits much greater regional and seasonal variability due to the seasonal enhancement of insolation caused by changes in ORB; and these contrasting
seasonal responses lead to little change in annual mean climate (Fig. 2b). Lower GHG in Exp MH has a global cooling effect, with greater temperature decreases at higher latitudes associated with feedbacks from sea ice and snow cover (Fig. 2c). The combined effect of these two forcing factors leads to a weak warming at the NH high latitudes and cooling elsewhere (Fig. 2a), similar to the temperature changes in the PMIP4 ensemble (Brierley et al., 2020).

Weakening meridional atmospheric temperature gradient in Exp MH leads to the Hadley cell being weakened by about 10% in the NH (Fig. 4a). At the same time, due to the change of sea-surface buoyancy in the North Atlantic, the AMOC is slightly enhanced by about 4% (Fig. 5a). As far as the changes in MHT magnitude in the NH are concerned, the effect of ORB is about five times that of GHG (Figs. 6b, c). Our experiments also show that the change in AMOC is mostly determined by the freshwater flux change in the North Atlantic, which is in turn closely related to the Arctic sea-ice change related to the ORB effect. GHG has the opposite effect to ORB, which mitigates the enhancement of the AMOC (Figs. 9b, c).

The conclusions drawn in this paper may be model-dependent. Shi and Lohmann, (2016) simulated a stronger MH AMOC in the high-resolution version of the ECHAM, with a maximum change of more than 2 Sv. Most of the models in the CMIP5 ensemble reveal a positive AMOC change in the MH period. Some previous studies (Ganopolski et al., 1998; Otto-Bliesner et al., 2006) showed that the AMOC in the MH is weaker than that of the PI period. The main reason for the inconsistency is that the simulated ocean salinity in the North Atlantic is different. In addition to the model itself, whether the experimental setting includes the GHG is also an important factor. Our results on the AMOC in the MH are similar to those of (Jiang et al., 2023), but our focus is to find the mutual offsetting effect between external forcing factors. The experiments we conducted are time-slice experiments. And it is necessary to study whether the offsetting effects of the ORB and GHG exists in transient experiments.

Our experiments only consider the ORB and GHG effects; and the simulated cooler annual mean temperature over most areas of the NH differs from the warming record revealed by proxy data (Wanner et al., 2008; Liu et al., 2014), but is similar to the conclusions from the PMIP4 ensemble simulations. It is unclear whether these differences originate from the model, the data record, or a combination of both. Some proxy data suggested that the climate of North Africa was wetter in the MH period, which was known as the Green Sahara. (Jiang et al., 2012) analyzed six sets of PMIP2 coupled models’ results, and found that the dynamic vegetation has little impact on regional climate. Braconnot et al. (2021) and Zhang et al. (2021a) studied the effect of dust reduction on climate due to the greening of the Sahara desert, using the CESM and IPSL models, respectively, showing global mean surface temperature increased by about 0.1°C. Although there are other forcing factors in the MH period, such as vegetation, dust, and...
topography, overall our simulations are representative of the most important forcing factors and provide quantified estimates of the contributions of ORB and GHG effects to the MH climate.

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