Heat budget analysis in three typical warm periods simulated by FGOALS-s2

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ABSTRACT
This study compared basic warming patterns among three typical warm periods — the mid-Holocene (MH), Medieval Warm Period (MWP), and the twentieth century warming (20CW) — and carried out a comprehensive heat budget analysis using four experiments simulated by the Flexible Global Ocean–Atmosphere–Land System model, Spectral Version 2 (FGOALS-s2). The model simulates similar spatial warming patterns in all three warm periods, e.g. stronger warming appears in the high latitudes. However, changes in surface air temperature (SAT) over the tropical regions are different: a significant warming occurs in the 20CW and MWP but a significant cooling in the MH. The heat budget analysis suggested that SAT changes are mainly induced by the heat flux. In the MH, the insolation and positive snow and ice feedback are responsible for the warming in the Southern Ocean but the wind anomalies and decreased downward longwave radiation (DLR) induce the cooling in the tropics. In the 20CW, the decreased shortwave radiation and increased sea surface temperature dependency of evaporation dampen the warming in the tropics. In the MWP, the shortwave radiation induces the Southern Ocean warming, but the DLR and wind anomalies warm the SAT in the tropics. The simulated ocean temperature and ocean heat content anomalies are different in the upper ocean (above 1500 m), which are mainly induced by the wind stress changes, but similar in the deep ocean in all three warm periods.

1. Introduction

Against the global warming background, the climate system (e.g. atmospheric and oceanic circulation) has undergone significant changes. To better understand the global warming since the preindustrial (PI) era, it is important to extend our scope of investigation to the paleoclimate. The mid-Holocene (MH, 6 ka BP), MWP (around AD 900–1300), and the twentieth century warming (20CW) are three important and typical warm periods in the Quaternary since the start of the Holocene. These three typical warm periods were driven by different external forcings (Solomon et al. 2007; Stocker et al. 2013). In the MH, the most important external forcing was the seasonal changes of insolation induced by the changes in orbital parameters. The external forcing for the MWP was changes in solar radiance and volcanic eruptions, in which there were fewer volcanic eruptions but greater solar radiation input. And the 20CW is mainly being driven by anthropogenic greenhouse gas (GHG) emissions.

Previous studies have investigated the past climate changes in specific periods such as the MH and MWP relied on proxy data (Marcott et al. 2013; Wang et al. 2002) or climate models (Wang, Wang, and Jiang 2010; Zhou et al. 2011). Marcott et al. (2013) indicated that the global mean annual temperatures around the MH were about 0.7 °C higher, and extratropical Northern Hemisphere (NH) temperatures were about 1 °C higher, than under PI conditions. Numerical simulations show broad agreement with reconstructions (Braconnot et al. 2007), albeit with some mismatch in annual and winter temperatures.
The climate of the MWP was warmer than that in the past millennium (Wang et al. 2002), but the warming magnitude was weaker than that in the twentieth century (Zhou et al. 2011).

A number of studies have shown that the changes in ocean heat content (OHC) played an important role in the changes of Earth’s heat balance in the late twentieth century, demonstrating that OHC more reliably represents the response of Earth’s energy budget to radiative perturbations than do surface temperatures (Hansen et al. 2005; Levitus et al. 2000, 2001, 2012). Rosenthal, Linsley, and Oppo (2013) used high-resolution proxy records to show that the changes in OHC were also larger than those in surface temperature during the MH and MWP.

However, the above-mentioned studies only focused on one specific period; understanding the similarities and differences among the characteristics and mechanisms of warming in the aforementioned three warm periods (MH, WMP, 20CW) is very important for projecting future climate change. The Flexible Global Ocean–Atmosphere–Land System model, Spectral Version 2 (FGOALS-s2) has carried out most of the Coupled Model Intercomparison Project, Phase 5 (CMIP5) experiments — including simulation of the MH, the last-millennium (LM) climate simulation, and the historical simulation — providing an excellent opportunity to better understand the warming mechanisms in those three periods. Based on these simulations with FGOALS-s2, the objectives of the present study were to compare the spatial patterns of atmosphere and ocean warming in the three warm periods and explore the possible causes using heat budget analysis.

The rest of the paper is organized as follows: Section 2 describes the model data used in the study. Section 3 reports the results from the model’s simulations. And finally, a summary and discussion are provided in Section 4.

### Table 1. Annual mean, boreal summer and boreal winter changes of global mean net radiative flux at the top of the atmosphere (Net), SAT, SST, OHC in the upper 700 m of the ocean and OHC in the whole ocean in the MH, 20CW, and MWP.

|                  | MH–PI | 20CW–PI | MWP–LM |
|------------------|-------|---------|--------|
| **Annual mean**  |       |         |        |
| Net (Units: W m⁻²) | −0.18 | 0.50    | 0.02   |
| SAT (Units: °C)  | −0.14 | 1.23    | 0.16   |
| SST (Units: °C)  | −0.16 | 0.82    | 0.11   |
| OHC (700 m) (Units: 10⁸ J m⁻²) | −2.4 | 10      | 1.6    |
| OHC (whole) (Units: 10⁸ J m⁻²) | 22.4 | 35.1    | 14.2   |
| **Boreal summer** |       |         |        |
| Net (Units: W m⁻²) | 9.69  | 0.55    | 0.04   |
| SAT (Units: °C)  | 0.05  | 1.16    | 0.17   |
| SST (Units: °C)  | 0.23  | 0.81    | 0.11   |
| OHC (700 m) (Units: 10⁸ J m⁻²) | −2.7 | 10      | 1.6    |
| OHC (whole) (Units: 10⁸ J m⁻²) | 22.1 | 35.1    | 14.2   |
| **Boreal winter** |       |         |        |
| Net (Units: W m⁻²) | −10.13| 0.40    | 0.02   |
| SAT (Units: °C)  | −0.28 | 1.32    | 0.17   |
| SST (Units: °C)  | −0.09 | 0.84    | 0.12   |
| OHC (700 m) (Units: 10⁸ J m⁻²) | −2.1 | 10      | 1.7    |
| OHC (whole) (Units: 10⁸ J m⁻²) | 22.8 | 35.1    | 14.2   |

### 2. Model data

The datasets used in the present study were from four groups of experiments — the PI simulation, historical simulation, LM simulation, and MH simulation — simulated by FGOALS-s2 (see Bao et al. 2013) for more details). The simulations have several experiment members, but one member (r1i1p1) in each simulation was used in this study.

### 3. Results

Previous studies have suggested that FGOALS-s2 is able to capture the major characteristics of modern and paleo climate changes, especially the large-scale features of the atmospheric and oceanic circulations (Bao et al. 2013; Zheng and Yu 2013). Compared to the PI, the major forcing in the MH was the changes in the seasonal cycle of insolation. The MH was characterized by an enhanced seasonality of insolation in the NH and a reduced seasonal cycle of insolation in the Southern Hemisphere (SH) (Berger 1978; Luan et al. 2012). In boreal summer (June–August), more net radiative flux at the top of the atmosphere (TOA) was received in the MH than that in the PI (Table 1), accompanied by a warming over the mid and high latitudes but cooling over the tropical regions...
In the 20CW period, the net radiative flux at TOA has not changed much, not only in boreal summer but also in boreal winter (December–February) (Table 1). The warming has mainly arisen from increased anthropogenic GHG emissions. The MWP climate was characterized mainly by natural variability due to changes in solar variability and volcanic eruptions. The global averaged surface air temperature (SAT) anomalies were positive during boreal summer and winter in the MWP, compared with the LM (Table 1).

The spatial patterns of the annual mean changes in SAT and wind stress in the three warm periods are illustrated in Figure 1. In the MH, FGOALS-s2 simulates warming in Northern Eurasia, the Arctic, Antarctic, and Southern Ocean around 60°S. Significant cold anomalies are found in the tropical regions and middle latitudes (Figure 1a). In the 20CW, significant warming occurs at the global scale. However, the SAT warming over the tropics is weaker than that in the high latitudes (Figure 1b). In the MWP, the changes of SAT are smaller than those in the MH and

Figure 1. Annual mean changes of SAT (contour lines; units: °C) and wind stress (arrows; units: N m⁻²) in the (a) MH, (b) 20CW, and (c) MWP. Color shading indicates statistically significant SAT changes at the 95% confidence level using the t-test.
FGOALS-s2 simulates a weaker global warming in the MWP compared with the LM, especially in the tropical regions (Figure 1c). It is notable that in all three warm periods the warmer SATs appear in the high latitudes, particularly in the Southern Ocean around 60°S. However, the SAT changes over the tropical regions are different in the three warm periods. FGOALS-s2 simulates significant annual cooling in the MH, but annual warming in the 20CW and MWP.

To understand the changes in heat budget in various regions, we divided the globe into five bands: 45°S–90°S, 15°S–45°S, 15°S–15°N, 15°N–45°N, and 45°N–90°N. Figure 2 shows the changes in the regional and annual mean TOA radiative flux, including net heat flux (Net), SR, DLR, LHF, and SHF, in the (a, b) MH, (c, d) 20CW, and (e, f) MWP. Downward is positive; units: W m⁻².

Figure 2. Changes in regional and annual mean (a, c, e) TOA radiative flux, including net heat flux (Net) and SR, and (b, d, f) surface heat flux, including net heat flux (Net), SR, DLR, LHF, and SHF, in the (a, b) MH, (c, d) 20CW, and (e, f) MWP. Downward is positive; units: W m⁻².

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Figure 3. Changes in regional and annual mean LHF, the oceanic response of LHF (LHF_OcF), and the atmospheric forcing of LHF (LHF_AtF), in the (a) MH, (b) 20CW, and (c) MWP. Downward is positive; units: W m⁻².
noteworthy that because the LHF over the ocean surface is larger than that over the land surface, the discussion below focuses only on the ocean surface LHF. The atmospheric forcing of LHF (LHF\textsubscript{AtF}) is due mostly to atmospheric adjustments in wind speed, surface relative humidity, and the sea minus air surface temperature difference (\(\Delta T\)). The oceanic response of LHF (LHF\textsubscript{OcF}) arises from the sea surface temperature (SST) dependence of evaporation and may approximately act as a Newtonian cooling term. In the MH, the two components of LHF act to slightly dampen the SST warming in the Southern Ocean by about \(-0.5\) W m\(^{-2}\).

In the middle latitudes and tropical regions, LHF\textsubscript{OcF} acts to warm the ocean, but LHF\textsubscript{AtF} acts to cool the ocean (Figure 3a). In the 20CW, the atmospheric forcing of LHF acts to warm the ocean in the global region; however, LHF\textsubscript{OcF} balances the atmospheric forcing (Figure 3b). In the MWP, the roles of the two components are similar with those in the MH and 20CW. In the 20CW, the TOA SR increases in the mid and high latitudes but decreases in the tropics (Figure 2d). At the surface, increased GHG concentrations enhance DLR from 1.5 to 5.5 W m\(^{-2}\) in the global region (Figure 2d), warming the global SAT. Whereas, in the tropical region, the decreased SR offsets the GHG effect (Figure 2d), damping the SAT warming. In the MWP, the insolation increases almost globally (Figure 2e), but the surface heat fluxes are smaller than those in the MH and 20CW. In the high latitudes of the SH, the SR at the surface warms the SAT, whereas the surface DLR warms the SAT in the middle latitudes and tropics. The LHF acts to cool the surface air by about \(-0.3\) W m\(^{-2}\) (Figure 2f).

As shown in Figure 2, the contributions of the LHF to the SAT changes are very important in the three warm periods. We decomposed the LHF into the atmospheric forcing and oceanic response, following Du and Xie (2008). It is noteworthy that because the LHF over the ocean surface is larger than that over the land surface, the discussion below focuses only on the ocean surface LHF. The atmospheric forcing of LHF (LHF\textsubscript{AtF}) is due mostly to atmospheric adjustments in wind speed, surface relative humidity, and the sea minus air surface temperature difference (\(\Delta T\)). The oceanic response of LHF (LHF\textsubscript{OcF}) arises from the sea surface temperature (SST) dependence of evaporation and may approximately act as a Newtonian cooling term. In the MH, the two components of LHF act to slightly dampen the SST warming in the Southern Ocean by about \(-0.5\) W m\(^{-2}\). In the middle latitudes and tropical regions, LHF\textsubscript{OcF} acts to warm the ocean, but LHF\textsubscript{AtF} acts to cool the ocean (Figure 3a). In the 20CW, the atmospheric forcing of LHF acts to warm the ocean in the global region; however, LHF\textsubscript{OcF} balances the atmospheric forcing (Figure 3b). In the MWP, the roles of the two components are similar with

**Figure 4.** Annual mean changes in the vertical profile of (a–c) air temperature and (d–f) ocean temperature in the (a, d) MH, (b, e) 20CW, and (c, f) MWP. Units: °C.
those in the 20CW but with smaller magnitude (Figure 3c). The atmospheric forcing via LHF is mainly due to changes in wind speed in the MH and 20CW (Figure 1). But the LHF_ATF due to changes in surface relative humidity and \( \Delta T \) may not be negligible in the ocean heat budget (Du and Xie 2008).

As shown above, the changes in SAT are mainly influenced by the radiative flux and wind anomalies. We further illustrate the vertical structure of the changes in the air and ocean temperatures during the three warm periods in Figure 4. The vertical pattern of the air temperature in the MH exhibits a cooling anomaly in the middle and low latitudes, with the cooling center of about −0.6 °C located at around 200–400 hPa and a warming anomaly in the high latitudes (Figure 4a). The 20CW and MWP simulations feature similar vertical patterns in the atmosphere, with the warming center located at around 200–400 hPa (Figure 4b and 4c). Nevertheless, the warming of the MWP is significantly weaker than that of the 20CW (0.2 vs. 1.8 °C). Zhou et al. (2011) suggested that the mid-tropospheric amplification of temperature is determined by the convective heating. In the ocean, the changes in simulated ocean temperature are different in the upper ocean (above 1500 m), but similar in the deep ocean, in the three warm periods (Figures 4d–f), and this is because the upper ocean temperature is mainly induced by the wind stress changes. In the MH, the upper ocean temperature is one of warming in the Southern Ocean but cooling in other regions (Figure 4d). In the 20CW, warming appears in the upper ocean above 500 m globally (Figure 4e). There are two cooling centers at around 1000 m in the 20CW (Figure 4e). In the MWP simulation, there is weak cooling in the tropics but warming in the middle and high latitudes in the upper ocean (Figure 4f). The annual mean OHC above 700 m decreases in the MH and increases in the 20CW and MWP (Table 1). The changes in annual mean OHC in the upper 700 m of the ocean are consistent with the SST changes in the three warm periods but with larger magnitude. The temperature anomalies in the deep ocean are warming anomalies, with the maximum located at around 3000 m and mainly induced by the thermohaline circulation. Furthermore, the annual mean changes in the whole ocean OHC of the three warm periods are positive (Table 1).

4. Summary and discussion

This study compared the spatial patterns of atmospheric and oceanic warming and analyzed the heat budget in three typical warm periods using FGOALS-s2. Because of the different external forcings, the responses of SAT are different in the three warm periods. In the MH, despite being referred to as a warm period, FGOALS-s2 simulates warming in northern Eurasia, the Arctic, Antarctic, and Southern Ocean around 60°S, but significant cooling in the tropics. In the 20CW and MWP, the model captures global-scale warming, with the warming being stronger over the land than over the ocean. Whereas, the SAT changes in the MWP are weaker than those in the 20CW due to the weaker surface radiative forcing.

Changes in SAT are mainly induced by the surface heat flux. In the MH, more net solar energy is received in the high latitudes, inducing the increased surface SR and warming the SAT. And the positive snow and ice feedback enhance the warming. However, in the tropics, the decreased DLR and atmospheric adjustments via LHF induce the SAT cooling. In the 20CW, increased GHG concentrations increase the DLR and warm the global SAT. However, the decreased SR and increased SST dependency of evaporation balances the positive forcing, damping the warming in the middle latitudes and tropics. In the MWP, solar radiation plays an important role in the Southern Ocean warming, but the DLR and atmospheric adjustments via LHF are more important in other regions.

The vertical structures of the changes in the air and ocean temperatures in the three warm periods were also compared. In the atmosphere, a similar pattern appears in the 20CW and MWP, with the warming center located at around 200–400 hPa. However, the warming of the MWP is significantly weaker than that in the 20CW. The air temperature anomalies are different in the MH and exhibit a cooling anomaly in the middle and low latitudes and a warming anomaly in the high latitudes. In the ocean, in addition to the Southern Ocean, the upper ocean temperature (above 1500 m) is one of cooling in the MH but warming in the 20CW and MWP, and this is because the wind stress changes are mainly responsible for the upper ocean temperature changes. There are two cooling centers at around 1000 m in the 20CW. The changes in annual mean upper OHC (700 m) are consistent with the SST changes in the three warm periods, but with larger magnitude. The temperature anomalies in the deep ocean are warming anomalies, with the maximum located at around 3000 m and mainly induced by the thermohaline circulation.

This study suggests that the warming mechanisms and patterns differ among the three warm periods. The SAT changes simulated by FGOALS-s2 are broadly consistent with other CMIP5 models, albeit with some non-significant mismatches in the Southern Ocean in the 20CW (figure not shown). Because of the uncertainty in the model simulations, a multi-model or model–data comparison would be needed to better understand the mechanisms of global warming. The study also indicates that the OHC in the deep ocean is more sensitive to the external forcing than the SST in these warm periods. With no observed OHC in the
deep ocean, it is difficult to assess the simulation ability of the model. In the future, it is necessary to strengthen the availability of observations and studies of OHC in the deep ocean.

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