



Set-up and preliminary results of mid-Pliocene climate simulations

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Set-up and preliminary results of mid-Pliocene climate simulations with CAM3.1

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Abstract

The mid-Pliocene warm period (~ 3.3 to 3.0 Ma BP) is a potential analogue for future climate under global warming. In this study, we use an atmospheric general circulation model (AGCM) called CAM3.1 to simulate the mid-Pliocene climate with the PRISM3D boundary conditions. The simulations show that the global annual mean surface air temperature (SAT) increases by 2.0°C in the mid-Pliocene compared with the pre-industrial temperature. The greatest warming mainly occurs in the high latitudes of both hemispheres, with little change in SAT at low latitudes. The equator-to-pole SAT gradient is reduced in the mid-Pliocene simulation. The annual mean precipitation is enhanced by 3.6% of the pre-industrial value. However, the changes in precipitation are greater in low latitudes than high latitudes.

1 Introduction

The mid-Pliocene warm epoch, spanning from 3.29 to 2.97 Ma BP, was the most recent period with sustained warmth during Earth's history. This period has been a focus of data synthesis and paleoclimate modeling efforts for the last several decades. The period has been characterized as having an increased sea surface temperature (SST) in mid-high latitudes resulting in seasonally ice-free conditions, greatly reduced ice sheets leading to a sea level rise of 25 m, and an obvious expansion of warmth/moisture loving vegetation in the northern high latitudes (Dowsett et al., 2010). The mid-Pliocene warm period is considered the most accessible example of a world analogous to the predicted warming at the end of this century, as the mean global temperatures are estimated to be 2 ~ 3°C above pre-industrial temperatures (Jansen et al., 2007). The epoch also provides a chance to assess the reliability of climate models for projecting future climates. Understanding the climate of the mid-Pliocene has the potential to better understand the future climate change.

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Data synthesis and modeling studies for the mid-Pliocene started in the 1990s. The first reconstruction work, PRISM0 (Pliocene Research Interpretation and Synoptic Mapping, version 0) (Dowsett et al., 1994), was completed in 1994. Then, the PRISM1 (Dowsett et al., 1996) and PRISM2 (Dowsett et al., 1999) datasets were published in 1996 and 1999, respectively. Based on these reconstructions, the mid-Pliocene climate has been widely simulated using climate models (e.g. Chandler et al., 1994; Sloan et al., 1996; Haywood et al., 2000; Haywood and Valdes, 2004; Jiang et al., 2005; Yan et al., 2011).

After the PRISM3D reconstruction (Dowsett et al., 2010) was released, the Pliocene Paleoclimate Modeling Intercomparison Project (PlioMIP) started in 2010. Using the PRISM3D data, which represent the latest global paleoclimate reconstruction for the mid-Pliocene, PlioMIP aims to systematically study the climate features and mechanisms of the mid-Pliocene with model-data and model-model comparisons. Thus, PlioMIP provides an opportunity to better understand the past warm climate and to reduce uncertainties in interpreting the mid-Pliocene climate.

Here, we report our simulations on mid-Pliocene climate following the PlioMIP guidelines for Experiment I (Haywood et al., 2010). We carry out the simulations with an Atmospheric General Circulation Model (AGCM) CAM3.1 (Community Atmosphere Model version 3.1) based on the latest PRISM3D reconstruction. We organize the paper as follows: we give a detailed description of the CAM3.1 model and the experimental set-up in Sects. 2 and 3, respectively. In Sect. 4, we present the preliminary results, which are followed by a discussion on the Hadley circulation in Sect. 5. We summarize this study in Sect. 6.

2 Model description

We use the Community Atmosphere Model version 3.1 (CAM 3.1) in this study to simulate the mid-Pliocene climate. CAM3.1 was developed by the National Center for Atmosphere Research in collaboration with the climate modeling community, and it

is integrated with the Community Land Model version 3 (CLM3; Bonan et al., 2002a, b), a thermodynamic sea ice model and a data ocean. The thermodynamic sea ice model for CAM3.1, derived from the Community Sea Ice Model version 5 (Briegleb et al., 2004), is used to calculate energy fluxes between the ice and the overlying atmosphere.

CAM3.1 uses the spectral Eulerian dynamical core and employs a T42 spectral truncation with 26 vertical levels, which corresponds to a horizontal resolution of approximately 2.8° latitude \times 2.8° longitude. Compared with the earlier version of CAM2.0, CAM3.1 employs the prognostic cloud water parameterization. The radiative parameterizations include new treatments of the interactions of shortwave and longwave radiation with cloud geometry and with water vapor. In addition, the uniform background aerosol is replaced by a present-day climatology in calculating shortwave fluxes and the heating rate. Furthermore, a careful formulation of the vertical diffusion of dry static energy and a clean separation between the physics and dynamics are implemented into CAM3.1. A more complete description of the physical basis and numerical implementation is given in Collins et al. (2004).

CAM3.1 reasonably simulates the present climate and captures major features of the observed climatology (Collins et al., 2006), and it has been widely used in paleoclimate studies (e.g. Diffenbaugh and Ashfaq, 2007; Donohoe and Battisti, 2009; Jochum et al., 2009; Caballero and Huber, 2010).

3 Experimental design

3.1 Pre-industrial experiment

3.1.1 Ocean conditions

In the pre-industrial run, we use the default SST and sea ice concentrations in CAM3.1 (Collins et al., 2006). In details, the SST and sea ice concentrations are the monthly

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climatology for the period 1950 through 2001 calculated from the datasets which combine the global Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) dataset (Rayner et al., 2003) for years up to 1981 and the Reynolds et al. (2002) dataset after 1981. We set the sea ice thicknesses to 2 m in the Northern Hemisphere and 0.5 m in the Southern Hemisphere according to Collins et al. (2006).

3.1.2 Geographic boundary conditions

We convert the GTOPO30 dataset, which is a global digital elevation model with a resolution of 30 arcsec, to a 10-min grid. Then we use the interpolated data to create the surface topography and the standard deviation of the surface topography with a resolution of T42. The land-sea mask is derived from the same data. In the model configuration, the Central American Seaway (Panama Gateway) remains closed while the Bering Strait, Madagascar Strait, Drake Passage, Tasman Gateway, Gibraltar Strait and Indonesian Gateway remain open.

We create the land surface information for the pre-industrial experiment based on the methods/tools provided by the CESM (Community Earth System Model) paleoclimate working group. First, we construct the Land Surface Model (LSM) land cover types from modern biome types (Matthews, 1985) provided by PRISM3D for each grid (<https://wiki.ucar.edu/display/paleo/Biome4+conversion+to+LSM>). Because CLM3 represents vegetation in a grid cell as mixtures of up to 16 plant functional types (PFTs; Bonan et al., 2002a, b), whereas LSM uses an integer value to represent land cover at each grid point, we convert the LSM vegetation types to CLM3 PFTs (<http://www.cgd.ucar.edu/ccr/paleo/Notes/lsm2clm.txt>). Meanwhile, according to the constructed CLM3 PFTs, we calculate the corresponding leaf/stem areas and heights for each PFT using the physiological parameters obtained from Bonan (1996). Lakes, urban areas and wetlands are specified as being absent. Subsequently, we construct the soil texture by interpolating the modern soil texture (percent sand, silt, and clay) profiles (Global Soil Data Task, 2000) from a 10-min grid to a resolution of $2^\circ \times 2^\circ$.

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Finally, a land surface file, eventually recognized by CLM3, is created and converted to the resolution of T42 at the model runtime using the above-created land surface files.

3.1.3 Other boundary conditions

For greenhouse gases, we set the atmospheric CO₂ concentration to 280 ppmv, N₂O concentration to 270 ppbv and CH₄ concentration to 760 ppbv. The SUNYA ozone data climatology (Liang et al., 1997) is adopted in the pre-industrial run.

We set the orbital parameters to the values for the year 1950 and the solar constant to 1365 W m⁻². The aerosol dataset is derived from a chemical transport model constrained by the assimilation of satellite retrievals of aerosol depth for the period 1995–2000.

3.2 Mid-Pliocene experiment

3.2.1 Ocean conditions

Using the anomaly method, we first calculate the SST anomalies between the PRISM3D mid-Pliocene (Dowsett, 2007; Robinson et al., 2008; Dowsett et al., 2009) and the PRISM3D present SST (Reynolds and Smith, 1995; Schweitzer and Survey, 1995), and we interpolate the derived SST anomalies to the resolution of CAM3.1 (T42). Then, we add the interpolated anomalies to the HadISST fields, which are the climatological monthly mean SST used in the pre-industrial experiment, to create the SST for the mid-Pliocene experiment. We set the sea ice coverage conditions based on the rebuilt SST in the mid-Pliocene. If the SST in the mid-Pliocene is higher than -1.8 °C, we set the sea ice coverage to 0. The reconstructed sea ice coverage shows an ice-free condition in the Arctic in boreal summer.

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3.2.2 Geographic boundary conditions

To create the surface topography for the mid-Pliocene experiment, we first calculate the topography anomalies between the PRISM3D mid-Pliocene (Sohl et al., 2009) and PRISM3D present topography (Amante and Eakins, 2009). Then, we interpolate the anomalies to the T42 resolution and add them to the present topography in the pre-industrial experiment. Note that the land-sea mask remains as the same as in the pre-industrial experiment.

For the land cover in the mid-Pliocene, the same methods as in the pre-industrial experiment are adopted. First, we convert the reconstructed mid-Pliocene land cover (Hill et al., 2007; Salzmann et al., 2008) to LSM land cover types for each grid. Then, the LSM land cover types are converted to the CLM3 PFT types. Subsequently, according to the constructed CLM3 PFTs, we calculate the corresponding leaf/stem areas and heights for each PFT still using modern physiological parameters. We set the percentages of lakes, urban areas and wetlands to zero. Soil color and soil texture are specified as the same as in the pre-industrial run. Finally, a land surface file is created and tailored to the land and ocean grids (T42) at the model runtime using the above-created land surface files. The rebuilt mid-Pliocene land cover shows greatly reduced ice volume and ice area in Greenland and Antarctic, an obvious expansion of warmth/moisture-loving vegetation in the northern high latitudes and much smaller deserts in Africa, Australia and Central Asia.

3.2.3 Other boundary conditions

For the greenhouse gases, the atmospheric CO₂ concentration increases to 405 ppmv, with the N₂O concentration, CH₄ concentration and ozone unchanged compared with the pre-industrial run. The orbital parameters, solar constant and aerosol datasets are all kept as the same as in the pre-industrial run.

The two experiments have been integrated for 50 yr. A detailed experimental design is summarized in Table 1.

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4 Results

Both time series of the surface air temperature (SAT) and deepest soil temperature (DST) indicate that the model has reached equilibrium (Fig. 1). Here, we calculate the climatological means from the last 30-yr results in each experiment. The results show that the annual mean net energy at the top of the atmosphere is -0.7 W m^{-2} and 2.2 W m^{-2} in the pre-industrial and mid-Pliocene experiments, respectively. The global annual mean SAT increases by 2.0°C in the mid-Pliocene compared with the pre-industrial run. The global annual mean precipitation increases by 3.6% of the pre-industrial value (Table 2).

4.1 Surface air temperature

For the zonal mean SAT, the CAM3.1 model simulates a distinct pattern of mid to high latitude warming over oceans and continents in the mid-Pliocene (Fig. 2). The maximum warming in the zonal mean SAT is located in the high latitudes, where the SAT increases by approximately 10°C (at approximately 80°N) and 8°C (at approximately 70°S). However, the SAT remains nearly unchanged in the low latitudes. The equator-to-pole SAT gradient, defined as the SAT differences between $0 \sim 30^\circ\text{N(S)}$ and $60 \sim 90^\circ\text{N(S)}$, decreases by 7.3°C and 4.1°C in the Northern Hemisphere and Southern Hemisphere, respectively.

The strong high latitude warming can also be observed in the spatial distribution of SAT anomalies between the mid-Pliocene and pre-industrial experiments (Fig. 3). Between 40°N and 90°N , the annual mean SAT is approximately $2 \sim 16^\circ\text{C}$ higher in the mid-Pliocene than in pre-industrial. The greatest warming appears in Greenland and the sub-polar North Atlantic with a rise of $8 \sim 16^\circ\text{C}$. Between 40°S and 40°N , the SAT increases by $0 \sim 2^\circ\text{C}$ in most regions. Between 40°S and 80°S , the SAT rises by approximately $4 \sim 18^\circ\text{C}$. The greatest warming compared with pre-industrial occurs in the margins of the East Antarctic and West Antarctic, where the SAT is $8 \sim 18^\circ\text{C}$ and $6 \sim 12^\circ\text{C}$ higher, respectively.

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However, cooling is still apparent in some local regions in the mid-Pliocene. The SAT decreases by $0 \sim 2^\circ\text{C}$ over the East African rift zone and the western tropical Pacific. The SAT remains nearly unchanged or exhibits slight cooling at $80^\circ\text{S} - 90^\circ\text{S}$ in the East Antarctic.

During boreal winter (Fig. 3), the globally averaged SAT compared with the pre-industrial rises on average by 2.0°C . The extreme warming over the high latitudes of the Northern Hemisphere becomes stronger in comparison with the changes in annual mean SAT, with a maximum warming of $\sim 20^\circ\text{C}$ over the sub-polar North Atlantic. The warming areas also expand. In low latitudes, the magnitude of warming is unchanged. In contrast, the magnitude of warming in the Southern Hemisphere between 60°S and 90°S decreases by about $2 \sim 3^\circ\text{C}$.

During boreal summer, the averaged SAT increases by 1.9°C compared with the pre-industrial (Fig. 3). Compared to the annual mean SAT anomalies, the summer warming is weaker in the northern high latitudes, especially over the Arctic. In contrast, the warming magnitude over the Antarctic increases dramatically ($10 \sim 18^\circ\text{C}$), together with the expansion of warming areas. It is noted that the annual, winter and summer mean surface warming are generally consistent in the low latitudes, and the discrepancies are mainly found in the high latitudes.

4.2 Precipitation

Compared with pre-industrial, annual mean precipitation is enhanced over the continents in the mid-Pliocene, with great increases ($0.8 \sim 1.6 \text{ mm day}^{-1}$) over South Greenland, Africa, the Middle-East region, Australia and the west coast of South America (Fig. 4). Over the oceans, the precipitation is greatly enhanced ($\sim 3.0 \text{ mm day}^{-1}$) over the sub-polar North Atlantic and the cold tongue in the eastern tropical Pacific. In contrast, the precipitation decreases significantly by $0.8 - 3 \text{ mm day}^{-1}$ and $0.2 - 2.6 \text{ mm day}^{-1}$ over the North Indian Ocean and the InterTropical Convergence Zone (ITCZ), respectively. Decreased precipitation is also simulated in the tropical Atlantic. Generally, the changes in precipitation are greater in low latitudes than high latitudes.

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During boreal winter (Fig. 4), the spatial distribution and magnitude of precipitation anomalies are nearly unchanged compared with the anomalies of the annual mean precipitation. During boreal summer (Fig. 4), the precipitation decreases much more ($> 3.2 \text{ mm day}^{-1}$) over the North Indian Ocean and the ITCZ compared with the changes in annual mean precipitation. Inversely, the precipitation is enhanced over North Africa, the Middle-East region and Indonesia together with the nearby oceans. The area of enhanced precipitation over the sub-polar Atlantic becomes smaller. However, the global mean summer precipitation remains unchanged compared with the pre-industrial.

5 Discussion

As the reconstruction and our simulation illustrate, substantial warming ($8 \sim 16^\circ\text{C}$) is located in the high latitudes in the mid-Pliocene, with slight warming ($0 \sim 2^\circ\text{C}$) in low latitudes. So the equator-to-pole temperature gradient is reduced.

Due to the reduced temperature gradient, the Hadley circulation slows down in the mid-Pliocene compared with the pre-industrial circulation. Both the ascending branches of the Hadley cell near $10^\circ\text{S} \sim 15^\circ\text{N}$ and the descending branches at approximately $15^\circ\text{N} \sim 25^\circ\text{N}$ and $10^\circ\text{S} \sim 20^\circ\text{S}$ are weakened (Fig. 5). The weakened descending branches of the Hadley cell enhance precipitation in the subtropics. The weakened ascending branches of the Hadley cell (approximately $10^\circ\text{S} \sim 15^\circ\text{N}$) lead to weakened deep convection over ITCZ, which in turn causes decreased precipitation over ITCZ. In addition, the slow-down of the Hadley cell leads to weakened surface winds, namely trade winds, in the tropics. However, it should be noted that the sinking motion at the poleward edge of the Hadley cell (approximately 30°N and 30°S) is strengthened (Fig. 5), which may indicate the poleward expansion of the Hadley cell.

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To quantify the expansion of the Hadley cell, we utilize two methods to define the Hadley cell edges. The first is to find the latitudes where the mass stream function of the Mean Meridional Circulation (MMC) in the troposphere (at 500 hPa) becomes zero poleward of the subtropical maxima (Lu et al., 2007; Johanson and Fu, 2009). The other method is to find the latitudes where the outgoing longwave radiation reaches 250 W m^{-2} in each hemisphere's subtropical transition zone (Lu et al., 2007; Johanson and Fu, 2009). The results show that based on calculated mass stream function, the descending branches of the Hadley cell in the mid-Pliocene expand poleward by 0.4° and 1.0° in the Northern and Southern Hemispheres, respectively, while expand poleward by 0.6° and 0.2° based on the simulated outgoing longwave radiation (Fig. 6).

The poleward expansion of the Hadley cell is potentially important for understanding future climate under global warming (Seidel et al., 2008; Johanson and Fu, 2009). However, it should be noted that the simulation for the Hadley circulation here is mainly controlled by the prescribed PRISM3D SST fields. Due to the uncertainties in the reconstruction of the PRISM3D SST, it remains a task to compare our simulation with other coupled simulations.

6 Conclusions

In this study, using AGCM CAM3.1, we simulate the mid-Pliocene climate with the prescribed PRISM3D boundary conditions. Our simulations illustrate that the global annual mean SAT in the mid-Pliocene is approximately 2.0°C higher than the pre-industrial value. The warming is stronger in the mid and high latitudes than in the low latitudes, which leads to a reduced equator-to-pole SAT gradient. The annual mean precipitation increases by 3.6% of the pre-industrial value. However, the changes in precipitation are much greater in the low latitudes than the high latitudes.

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Table 1. Summary of the experimental design.

Boundary conditions	pre-industrial	mid-Pliocene
SST	local modern	PRISM3_SST_v1.3.nc
Land-sea mask	local modern	local modern
Topography	local modern	topo_v1.4
Ice sheets and vegetation	BAS_Observ_BIOME	biome_veg_v1.2
Greenhouse gases	CO ₂ = 280 ppm, N ₂ O = 270 ppb, CH ₄ = 760 ppb, CFCs = 0, O ₃ = local modern	CO ₂ = 405 ppm, N ₂ O = 270 ppb, CH ₄ = 760 ppb, CFCs = 0, O ₃ = local modern
Solar constant	1365 W m ⁻²	1365 W m ⁻²
Aerosols	local modern	local modern
Orbital Parameters	ecc = 0.016724, obl = 23.446°, peri – 180° = 102.04°	ecc = 0.016724, obl = 23.446°, peri – 180° = 102.04°

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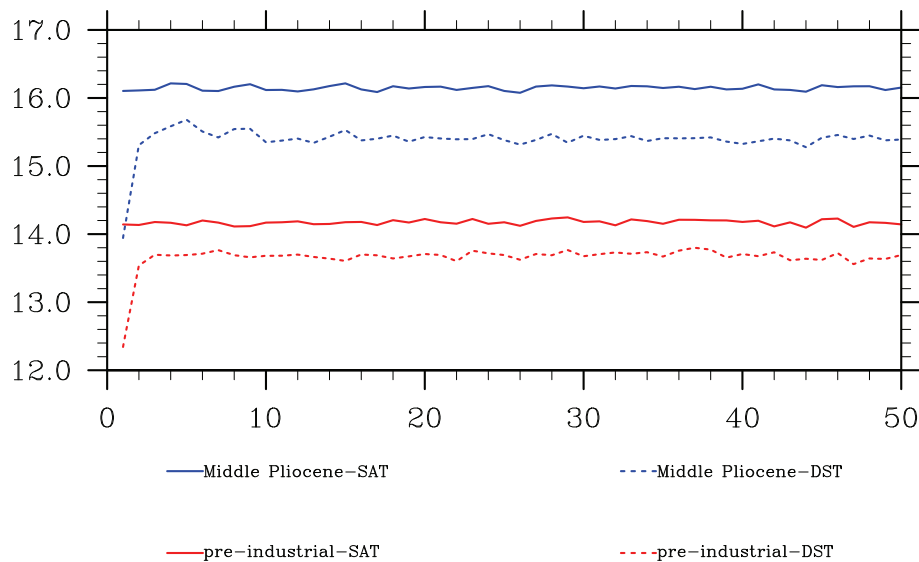


Fig. 1. Time series of global annual mean surface air temperature (°C) and the deepest soil temperature (DST, °C) in the pre-industrial and mid-Pliocene experiments.

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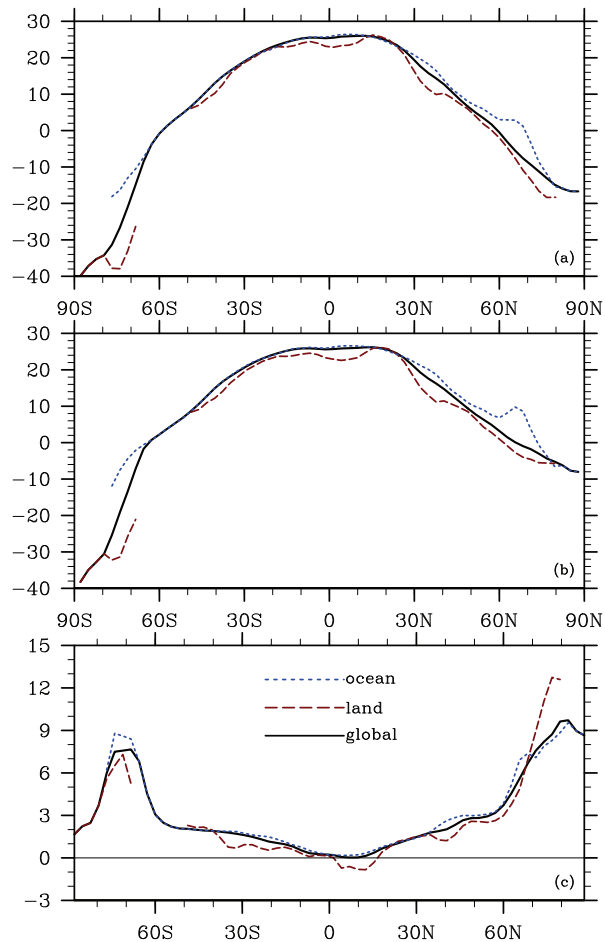


Fig. 2. Zonal mean surface air temperature (°C) in the pre-industrial experiment (a), the mid-Pliocene experiment (b) and the anomalies between the mid-Pliocene and pre-industrial (c).

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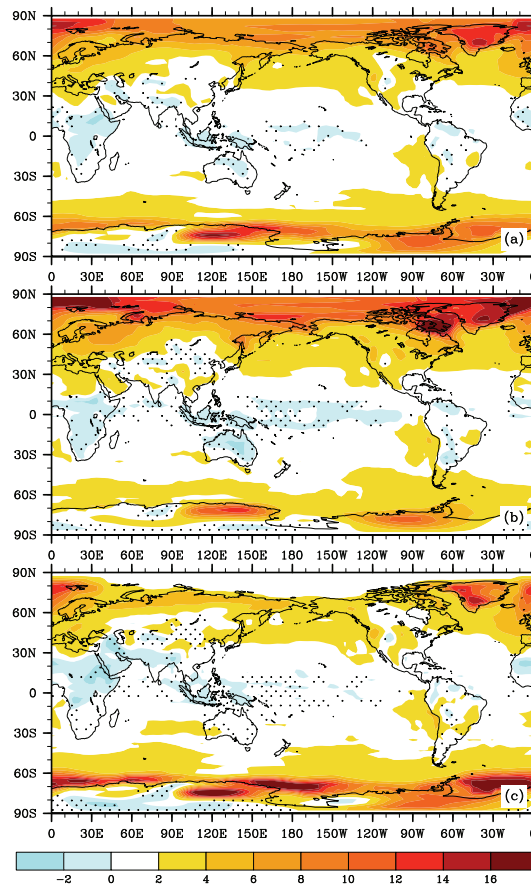
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Fig. 3. Surface air temperature anomaly ($^{\circ}\text{C}$) between the mid-Pliocene experiment and the pre-industrial experiment for the annual period (a), winter (b) and summer (c) seasons. Areas with a confidence level less than 95% are dotted.

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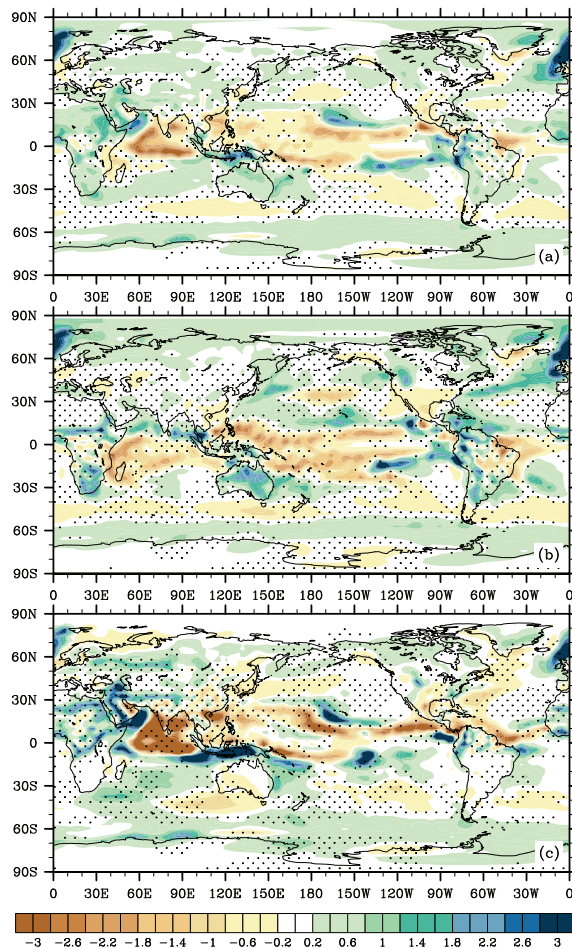


Fig. 4. Same as in Fig. 3 but for the precipitation anomaly (mm day^{-1}).

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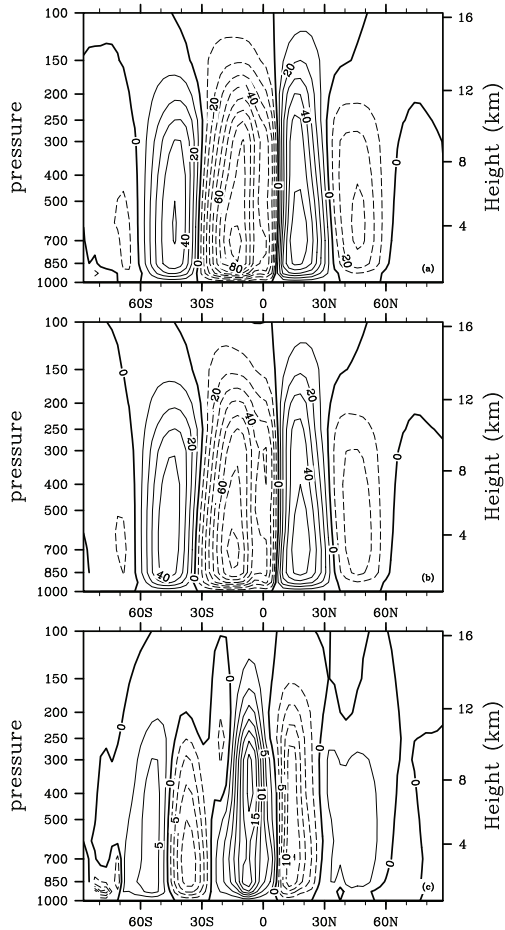


Fig. 5. Mass stream function ($\times 10^9 \text{ kg s}^{-1}$) of the annually averaged zonal mean meridional circulation in the pre-industrial (a), the mid-Pliocene (b) and the differences between the mid-Pliocene and pre-industrial (c).

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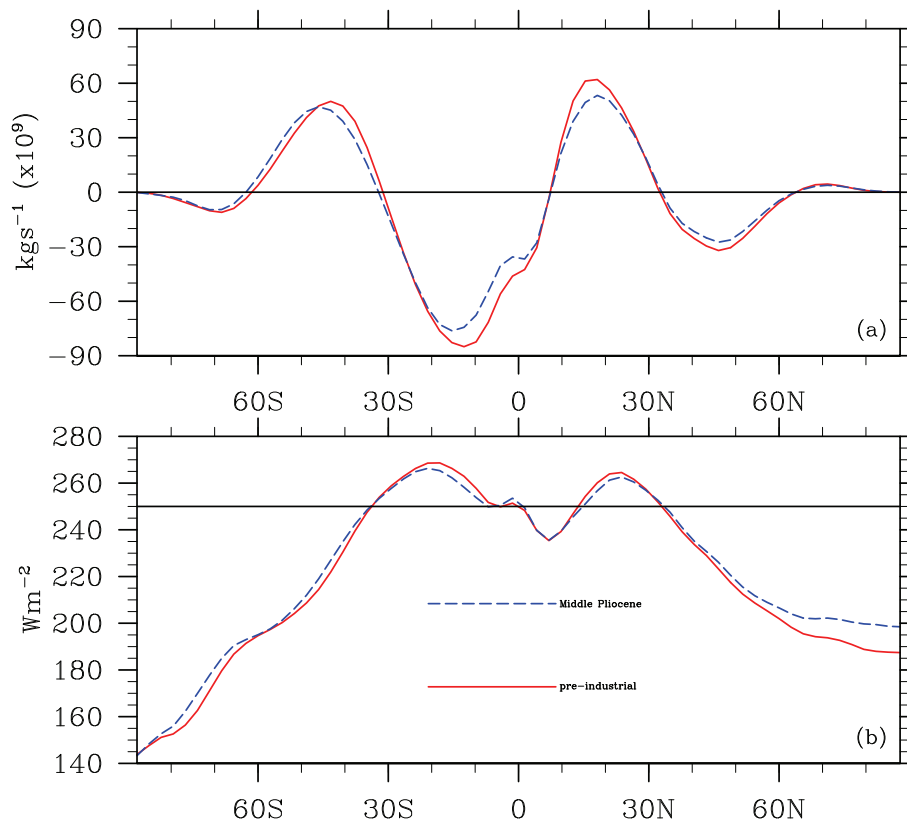


Fig. 6. (a): Latitudinal cross-section of the mass stream function at 500 hPa in the pre-industrial and mid-Pliocene experiments. (b): Zonal mean outgoing longwave radiation in the pre-industrial and mid-Pliocene experiments.

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