

Numerical Experiments with Multi-Models for Paleo-Environmental Problems

Project Representative

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The MIROC4m AOGCM was used for several paleoclimate simulations of the mid-Pliocene Warm Period (mPWP, 3.3-3.0 million years ago), stadial states (millennial-scale cold period during the last glacial cycle), and the last millennium (850-2000 C.E.). MIROC4m mPWP simulations resemble the multi-model means, created from 8 other models, in terms of warming and changes in precipitation. Sensitivity experiments show that changes in ice sheets and vegetation are largely responsible for the spatial patterns in warming. Further experiments highlight the importance of reduced ice sheets in high CO₂ scenarios. A higher resolution AGCM is used to simulate freshwater hosing to investigate stadial climate states. Initial analysis suggests that monsoonal changes indicated by proxy data are well-represented. Several sensitivity experiments are conducted under time-varying forcing of the last millennium. The use of different forcing reconstructions and isolated forcing experiments, such as a solar-forcing-only experiment, depicts the effect of forcing and its uncertainty on the simulations. The use of different initial conditions also depicts the effect of internal variability. The preliminary investigation with respect to the carbon cycle during this period is also conducted inserting the output of the simulated climate into an offline terrestrial vegetation and carbon cycle model.

Keywords: atmosphere-ocean GCM MIROC, paleoclimate modeling, mid-Pliocene, last millennium

1. Introduction

The mid-Pliocene warm period (mPWP), defined as the interval between 3.3-3.0 million years ago, was the most recent period with sustained warmth during the earth's history. Global mean temperatures were comparable to those predicted for the latter half of the 21st century [1], leading to the mPWP as being thought of as an analog for future climate conditions [2]. This particular interval was chosen for paleoclimate reconstruction for a variety of reasons [3], not least because there are multiple temperature proxies from extant fauna and flora and continental distribution was not unlike that of present day [4]. The mPWP has thus become a period of particular interest within the paleoclimate community and includes potential targets, such as climate sensitivity and vegetation, for reducing uncertainties in future projections [5]. The last millennium (LM) simulation (850 – 2000 C.E.), designed under the Paleoclimate Modelling Intercomparison Project phase 3 (PMIP3, [6]) and included in a suite of tier 2 experiments in the Coupled Model Intercomparison Project phase 5, is now being carried out by

multiple climate modeling centers over the world and archived.

In the current study, we aim to conduct not only a basic millennium simulation but also several sensitivity experiments in order to evaluate a model, investigate the uncertainty in the simulations, and pin down the cause of the simulated changes.

2. Modeling the climate of the mid-Pliocene Warm Period (mPWP) and related experiments

The Pliocene Model Intercomparison Project (PlioMIP) was established to allow a systematic comparison of climate models used to simulate the climate of the mid-Pliocene Warm Period (mPWP). Experimental design and datasets for monthly sea surface temperatures, vegetation and topography were specified as part of the first phase [3,7]. MIROC4m [8], a coupled atmosphere-ocean general circulation model (AOGCM) developed at CCSR/NIES/FRCGC, was used to simulate the mPWP climate under PlioMIP protocols [9] and to run related sensitivity experiments. In addition to boundary conditions specified in the above datasets, atmospheric CO₂ concentration

is set to 405ppm, while levels of other greenhouse gases and orbital parameters are kept at their pre-industrial values. The individual contributions from each factor are also investigated with sensitivity experiments, results of which are compared with those of a control experiment based on pre-industrial conditions.

Figure 1 shows a comparison between some MIROC4m model results and a multi-model mean (MMM) which was calculated by using the results of 8 AOGCMs from international research groups participating in PlioMIP. For the surface air temperature (SAT) (Fig. 1a), MIROC4m simulates an increase from pre-industrial values over most areas, with largest increases at high latitudes, in particular over Greenland and parts of the Antarctic where ice sheet has been reduced. This polar amplification leads to a reduced meridional gradient in the temperature. SAT increases are smaller over the oceans, with the largest increases located in the northwest of the Pacific and Atlantic Oceans. The results show general agreement with the MMM: although the warming seen in MIROC4m results is

higher, the spatial patterns are similar. Areas where temperature increases are small or even negative in MIROC4m (resulting from, for example, lower topography) also appear in the MMM. The zonal means at high latitudes show large variations among the various models. For the precipitation (Fig. 1b), MIROC4m simulates large increases over the central Pacific Ocean, much of the Indian Ocean and central Africa. On the other hand, precipitation decreases over the subtropical Pacific, southern Africa, the tropical Atlantic and Brazil. The MMM precipitation anomalies show a similar pattern, although there is a large model variation in the tropics. The zonal bands indicate a northward shift in the Hadley circulation and an expansion in the ascending branch [10]. For the sea surface temperature (SST) (Fig. 1c), MIROC4m simulates smaller changes compared to the MMM, with both showing largest increases in the northwest Pacific. MMM zonal means show largest variability at mid to high latitudes, more specifically, in the Southern Ocean and, in particular, the northern North Atlantic where models

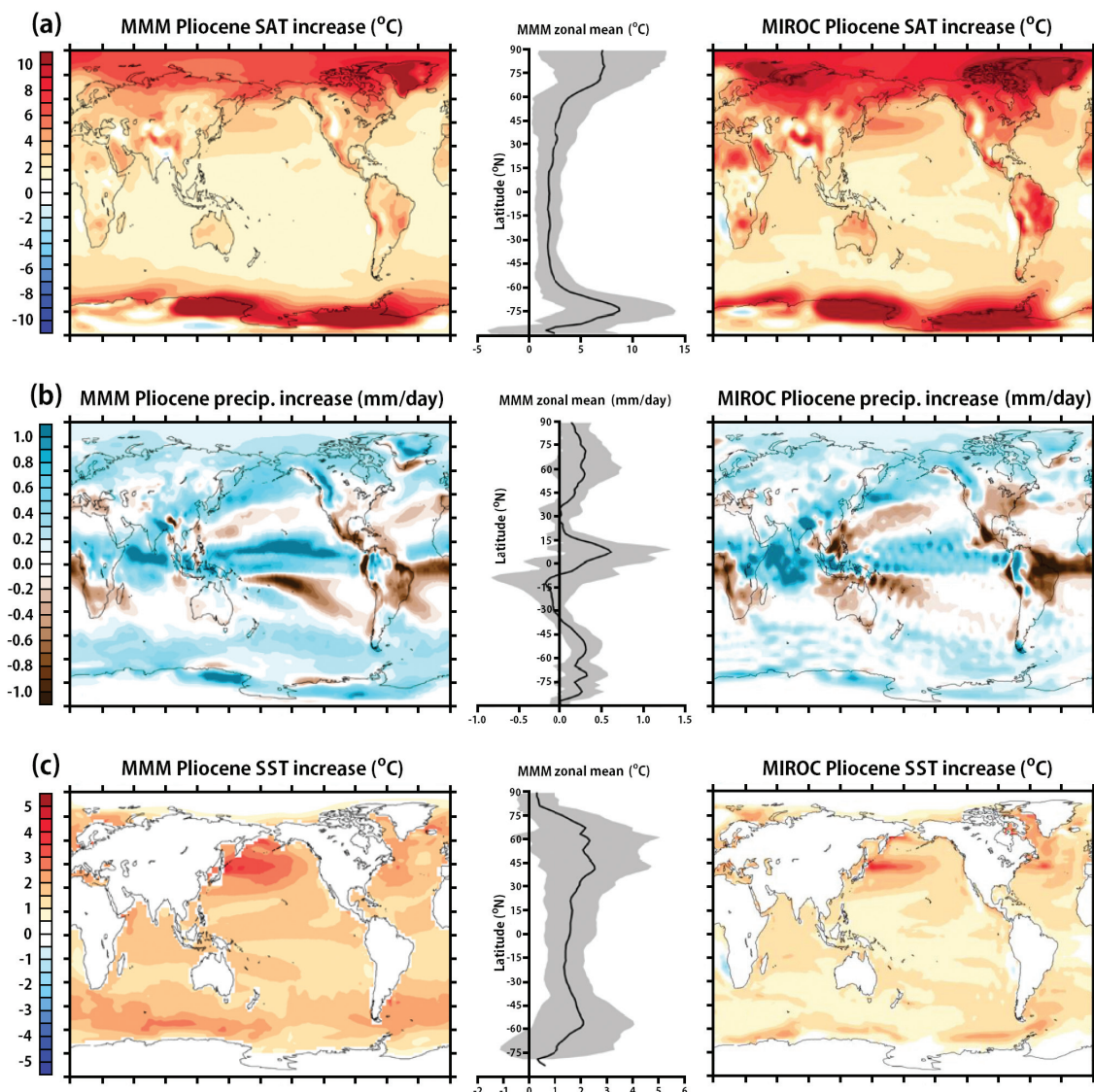


Fig. 1 Comparison of MIROC mPWP experimental results (right hand column) with their corresponding multi-model mean (MMM) values (left hand column) and the zonal mean of multi-model mean values (middle column – gray shading denotes the 2 σ range). The anomalies (mPWP minus pre-industrial) of the following variables are shown: (a) SAT, (b) precipitation, (c) SST. Original figures can be found in [12].

consistently fail to simulate temperature increases as high as those indicated by marine proxy data [e.g., 9,11,12]. In conclusion, the MIROC results seem to be representative of the MMM, although the MIROC climate sensitivity lies in the upper range of all models in PlioMIP [12].

SAT anomalies taken from sensitivity experiments related to the mPWP are shown in Fig. 2. The two main contributing factors to the warming seen in the mPWP experiment (Fig. 2a) are the vegetation/ice sheets and atmospheric CO₂ level. In the mPWP vegetation and ice sheet experiment (Fig. 2b), temperature changes are confined mostly to land, as expected. The changes in vegetation and ice sheet extent give rise to the spatial pattern seen in the mPWP experiment, especially in Antarctica, Greenland and northern Siberia where tundra is replaced by deciduous forest and woodland. These changes contribute one half of the total warming at high latitudes and one third globally. The effect of increase in atmospheric CO₂ level alone (Fig. 2c) is much more evenly distributed, with zonal mean increases at low to mid-latitudes of about 2°C, greater than those of the mPWP vegetation and ice sheet experiment, and reaching 3°C in the polar regions. The effect of complete removal of ice sheets is shown in Fig. 2d. The temperature increase exceeds 40°C in some parts of the Antarctic, and 20°C in central Greenland.

Previous experiments have also looked at other scenarios with CO₂ levels higher than those of present day, for example, late 21st century projections and double CO₂ scenarios. The AOGCM used in the present study does not incorporate a dynamical ice sheet and so the additional response from ice sheet melting is not included. The effect of removing all ice sheets in a much warmer world with atmospheric CO₂ levels four times that of the pre-industrial, similar to parts of the Cretaceous period when the Antarctic ice sheet had yet to form, is investigated (Fig. 2f). Compared to just CO₂ quadrupling (Fig. 2e), removal of ice sheets contribute to an additional increase in temperature as seen before in Fig. 2d. Thus, CO₂ quadrupling can potentially result in a 40°C increase across most of eastern Antarctica and more than 20°C in the rest of the polar regions. [13] have stressed the importance of taking into account the more slowly adjusting components of the climate system, like ice sheets, in quantifying equilibrium responses of temperatures to CO₂ increase.

3. Using higher resolution models to model climate during the last glacial cycle

Previously, the mid-resolution MIROC4m model (both AOGCM and AGCM, the atmospheric component) was used extensively to simulate climates of the last glacial cycle. The AOGCM was also employed to run so-called ‘freshwater hosing’ experiments whereby freshwater is artificially introduced into the northern North Atlantic Ocean to simulate discharge of meltwater originating from the Laurentide ice

sheets during Heinrich events and to simulate climate of the cold North Atlantic stadials. A high resolution T106 AGCM (same version as the atmospheric component of MIROC4m) is currently being used to simulate climate in similar scenarios. Paleoclimate proxies, such as ice and sediment cores, can serve a useful purpose as one way of testing the robustness of climate model results. Climate reconstructed from proxies can be compared to model data to increase confidence in the model’s ability to represent past climate and constrain future climate projections. As part of the initial analysis, areas where there is better agreement with proxy data are identified.

As a simple approach to using AGCMs, we apply freshwater hosing monthly anomalies to the prescribed SST for a 15ka scenario. These anomalies are obtained from SSTs in two previous 15ka AOGCM experiments, one of which includes freshwater hosing in the northern North Atlantic. They represent changes in SST specifically due to freshwater hosing (leading to a weakening or collapse of the Atlantic thermohaline circulation) and are characterized by large cooling in the North Atlantic and warming in parts of the South Atlantic and the Southern Ocean.

Figure 3 shows a comparison of summer (JJA) precipitation and wind anomalies across South and East Asia for the mid-resolution (a) AGCM and (b) AOGCM and (c) high resolution AGCM. These indicate changes in the South and East Asian paleomonsoons between typical stadial and interstadial states. All models show an increase in precipitation in the tropical Pacific, a decrease in the northern subtropical Pacific and a northerly wind anomaly between these two regions during the stadial state, indicating a southward shift in the intertropical convergence zone (ITCZ). Precipitation also decreases across the Arabian peninsula and the southern Indian Ocean while it increases over the northern Indian Ocean. Although the patterns show general agreement among the models, there are local differences. Fig. 3d shows the locations of selected proxy data. These are derived from sediment cores on the Oman margin [14], planktonic foraminifera and sediment cores in the Sulu Sea [15,16] and stalagmites in Hulu Cave in eastern China [17] and in Maboroshi Cave in Japan [18].

Oxygen isotope records of stalagmites from Hulu Cave resemble those of Greenland ice cores between 75-11ka and suggest that summer monsoon dominance correlates to warm North Atlantic interstadials. Precipitation during JJA is reduced over eastern China in the hosing experiment of the high resolution AGCM, in agreement with those records. However, this is not seen in the mid-resolution models. Marine cores off the coast of Oman suggest a weakening of the monsoonal winds. High denitrification (reduction of nitrate to gaseous nitrogen) is recorded at cold phases corresponding to stadials, suggesting weaker summer monsoonal winds. This is seen in all model results, but in the mid-resolution models, weakening also extends across most of the Arabian Sea. $\delta^{18}\text{O}$ values from

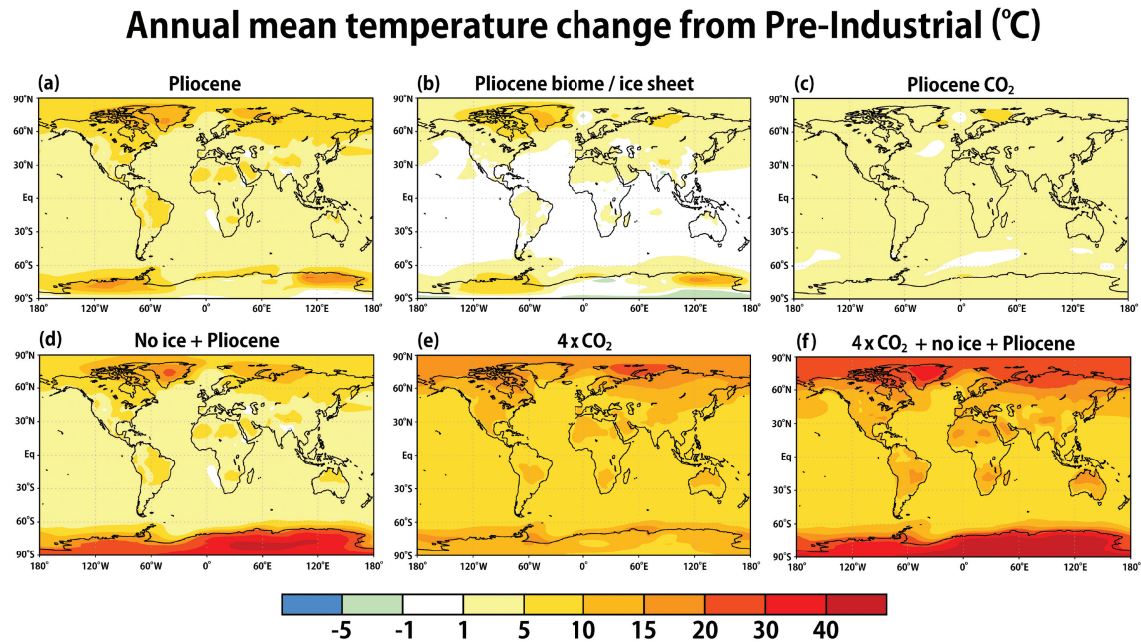


Fig. 2 Increase in annual mean surface air temperature compared to a pre-industrial experiment for six different cases: (a) complete mPWP as specified in PlioMIP, (b) using mPWP vegetation distribution and ice sheet extent, (c) setting atmospheric CO₂ level to the mPWP value of 405ppm, (d) complete mPWP with all ice sheets removed, (e) quadrupling of atmospheric CO₂ level, (f) quadrupling of atmospheric CO₂ level with all ice sheets removed and vegetation distribution changed to that of mPWP.

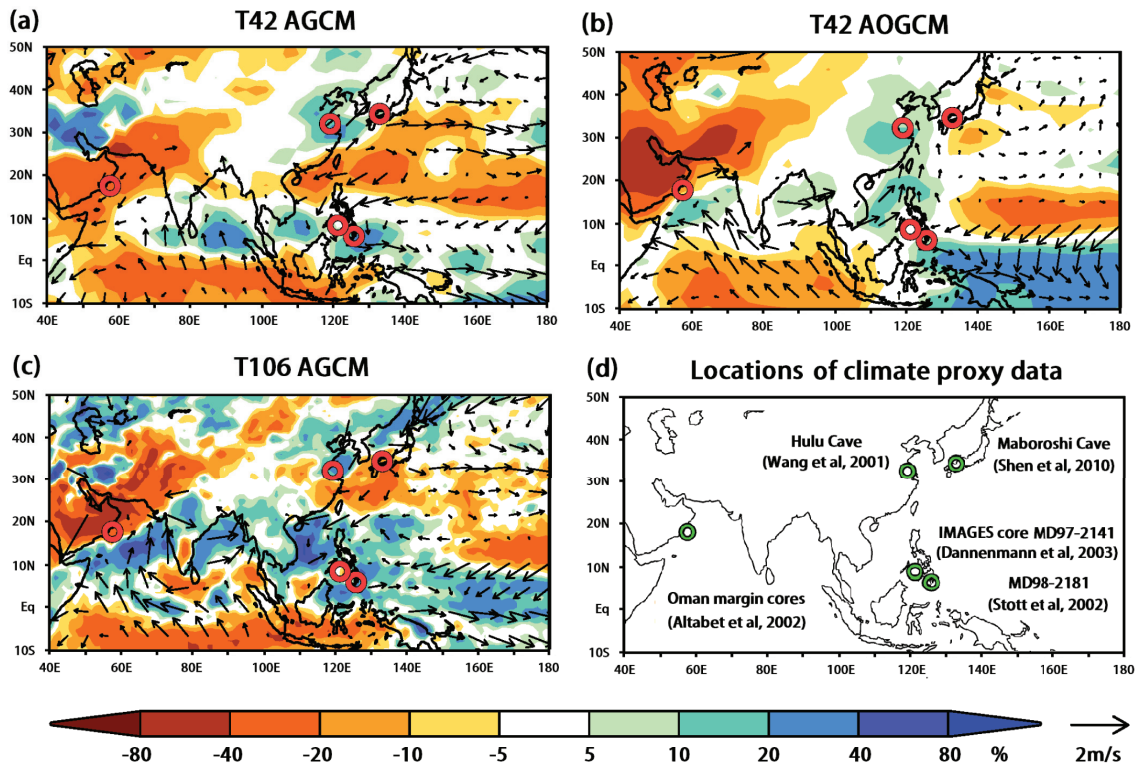


Fig. 3 850hPa wind anomalies (vectors) and precipitation changes (color shading) during June-August (JJA) in the (a) mid-resolution AGCM, (b) mid-resolution AOGCM and (c) high resolution AOGCM. Positive values indicate stronger winds and increased precipitation in the stadial state. The locations of climate proxy data used in the present study are shown in (d).

marine cores in the Sulu Sea suggest that seawater salinities were lower during North Atlantic interstadials, implying a decrease in precipitation during stadials. Decreases can only be seen in the high resolution AGCM, albeit in a small region. Thus, the high resolution AGCM can show better agreement with proxy data in determining some local changes in the Asian paleomonsoons during stadials.

4. Modeling the climate of the last millennium

A series of LM simulations were carried out with the Model for Interdisciplinary Research on Climate, medium-resolution version, MIROC3.2 and MIROC4m. The 20th century simulations, future projections, and other experiments with MIROC3.2, are archived as the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset. MIROC4m is essentially the same as MIROC3.2 but is renamed after a bug fix related to the calculation of surface fluxes over ice sheets.

Run 00 (R00) was conducted with MIROC3.2, and R01-R10 were conducted with MIROC4m (Table 1). R00-R02 were reported in the report of previous fiscal year (H24 ES annual report), and the R00 result was published in [19]. The LM simulations were started after spinning up the model to the stable conditions under the perpetual 850 C.E. boundary conditions. Solar forcing is represented by altering the total solar irradiance, and volcanic forcing is represented by specifying the aerosol optical depth. Orbital variations were included following [20], and greenhouse gas (GHG) concentrations based on ice core records were taken from the PMIP3. Preindustrial (PI) conditions were specified for land use and vegetation in all experiments, and orbital variations are included in all experiments. No carbon cycle feedback was included. Readers are referred to [6] for PMIP3 LM forcing details. Figure 4 shows

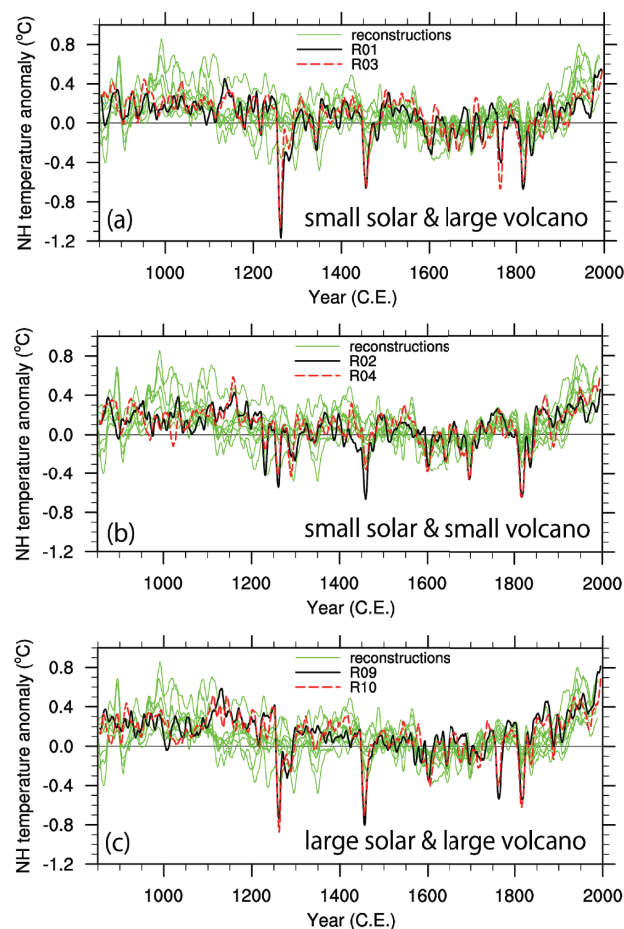


Fig. 4 Last millennial simulations with MIROC: a) R01 and R03; b) R02 and R03; and c) R09 and R10 in Table 1. Anomaly is taken from the average over 1500-1799. 11-yr Gaussian filter is applied.

Table 1 A list of experiments.

Run	Model	Solar	Volcano	GHG variations	Orbital variations	Initial conditions	Period (C.E.)
R00	MIROC3.2	BCL	G08	PMIP3+CMIP3	Included	A(= spin-up 137 yrs)	850-2000
R01	MIROC4m	DB09	G08	PMIP3+CMIP5	Included	B(= spin-up 210 yrs)	850-2000
R02	MIROC4m	DB09	C08	PMIP3+CMIP5	Included	B	850-2000
R03	MIROC4m	DB09	G08	PMIP3+CMIP5	Included	C(= spin-up 314 yrs)	850-2000
R04	MIROC4m	DB09	C08	PMIP3+CMIP5	Included	C	850-2000
R05	MIROC4m	DB09	850C.E.	850C.E.	850C.E.	B	850-1850
R06	MIROC4m	DB09	850C.E.	850C.E.	850C.E.	C	850-1850
R07	MIROC4m	c.a. 850C.E.	C08	850C.E.	850C.E.	B	850-1850
R08	MIROC4m	c.a. 850C.E.	C08	850C.E.	850C.E.	C	850-1850
R09	MIROC4m	BCL	G08	PMIP3+CMIP5	Included	B	850-2000
R10	MIROC4m	BCL	G08	PMIP3+CMIP5	Included	C	850-2000

BCL: Spliced data sets of Bard[25], Crowley[26] and Lean et al.[27].

DB09: Delaygue and Bard[28] spliced into Wang et al.[29] after 1610 C.E.

G08: Gao et al.[30] and Sato et al.[31] (updated) after 1850 C.E.

C08: Crowley et al.[32] and Sato et al.[31] (updated) after 1850 C.E.

DB09 is one of four recommended solar forcings by PMIP3, and G08 and C08 are two recommended volcanic forcings by PMIP3.

the simulated Northern Hemisphere surface air temperature anomaly as well as reconstructions. While more quantitative and regional analysis need to be made, the effect of forcing uncertainty on the hemispheric scale temperature variations is depicted by comparing Figs. 4a-4c.

Reconstructed millennial atmospheric CO₂ concentration from ice-core ranges about 10ppm between the Medieval Warm Period (MWP) and the Little Ice Age (LIA) [21,22,23]. This difference in the atmospheric CO₂ can mainly depend on the millennial change of terrestrial carbon storage since ocean response is far smaller. Here we estimate the last millennial terrestrial carbon storage change by using a dynamic global vegetation model, Land Processes and eXchanges (LPX), which is driven by the result of MIROC4m last millennial experiments R01-R04. We also examine by using reconstructed last millennial temperature distribution [24] as input to LPX to compare with runs01-04.

Figure 5 shows that there is increase of 15Pg terrestrial carbon in the LIA relative to the MWP by using runs01-04, which is interpreted as 7.5ppm decrease of atmospheric CO₂. On the other hand, reconstructed temperature causes about 20Pg increase of total terrestrial carbon which corresponds to 10ppm decrease of atmospheric CO₂. Generally, models underestimate millennial atmospheric CO₂ range. Reconstructed temperature predicts comparable difference of atmospheric CO₂ from that of ice-core reconstruction, however, the phase of minimum and maximum do not agree.

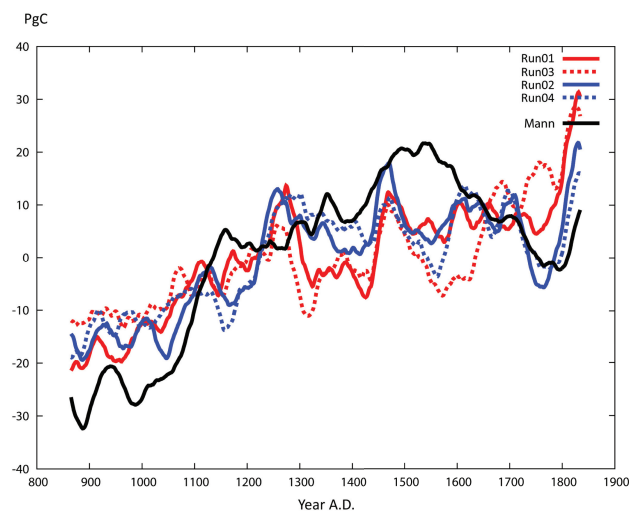


Fig. 5 Terrestrial carbon difference [PgC] from millennial averaged terrestrial total carbon storage in each experiment. All results are shown as 31 years running mean. Runs01-04 are driven by correspondent GCM runs. Mann uses reconstructed temperature instead of temperature from GCM.

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古環境研究のための多階層数値実験

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大気海洋結合モデル MIROC4m を用いて、温暖な約 3.0 ～ 3.3 百万年前の鮮新世中期 (mPWP)、氷期における千年スケールの寒冷期 (亜氷期)、過去千年 (西暦 850 ～ 2000 年) などの古気候シミュレーションを行った。MIROC4m mPWP シミュレーションは、温暖化や降水量の変化について、他の 8 つのマルチモデル平均とよく似ている。氷床や植生を変化させた感度実験を行うことにより、これらの変化が主に温暖化の空間分布を決めていることが分かった。別の感度実験により、CO₂ 濃度が高い状態で氷床の縮小が気候へ与える影響の重要性が指摘された。また、亜氷期の気候再現性を調べるために、淡水流入実験によって得られた境界条件のもとで、高解像度の大気 GCM を走らせた。初期解析の結果によると、代替指標によって示されるモンスーンの変化をよく再現している。さらに、時間変化する境界条件のもとで、過去千年の気候再現・感度実験も行われた。今後より詳細な解析が必要であるが、異なったフォーシングあるいは、一つのフォーシングのみを与えた実験によってフォーシングの効果やその不確実性の効果が気候シミュレーションに与える影響が表され、異なった初期条件を用いた実験によって気候の内部変動の効果が表された。大気海洋 GCM によって計算された気候場をオフラインの陸域炭素循環モデルに入力することによって過去千年の炭素循環に関する初期解析も行われた。

キーワード: 大気海洋大循環モデル MIROC, 古気候モデリング, 鮮新世中期, 過去千年