**1** **Model description**

HadCM3 model has been used extensively for studies of the Pliocene climate within the Pliocene Model Intercomparison Project [1-4]. HadCM3 consists of two main components: an atmospheric component (HadAM3) and an oceanic component (HadOM3) [5-7]. The horizontal resolution of the atmosphere model is 2.5° in latitude by 3.75° in longitude and consists of 19 layers in the vertical. The atmospheric model has a time step of 30 min and includes a radiation scheme that can represent the effects of major and minor trace gases [8]. The HadOM3 spatial resolution of the ocean is horizontal 1.25° by 1.25° and vertical 20 layers. The fact that the HadCM3 consistently performs well in tests against other coupled atmosphere–ocean models [9,10] increases our confidence in its palaeoclimate simulations.

**2 Detail boundary conditions**

As abundant geological data are available and explicit boundary conditions have been designed for the middle part of the Piacenzian Stage of the Pliocene (3.264 to 3.025 Ma), which is also referred to as the mid-Pliocene Warm Period (mPWP), many paleoclimate simulations targeting this time slice have been conducted [11-14]. For this study, we also focus on the mPWP time slice, for which the required mid-Pliocene boundary conditions were supplied by the dataset of U.S. Geological Survey Pliocene Research Interpretations and Synoptic Mapping Group’s (PRISM3D) dataset [15]. This dataset includes topography and bathymetry, coastlines, land surface properties (i.e., vegetation, soil type, and ice sheet coverage) and atmospheric composition with respect to pre-industrial conditions. The Greenland Ice Sheet and the West Antarctic Ice Sheet, which currently store ~13 m sea-level equivalent ice [10,16], are thought to have largely melted during the mid-Pliocene warm period [17,18]. The mid-Pliocene atmospheric CO2 concentration was set to 405 ppmv. All other trace gases were specified at pre-industrial concentrations [2]. The realistic simulation of the modern climate by HadCM3 makes it a good candidate for investigating the response of climate to orbital forcing.

**3 Changes of** **shortwave incoming solar radiation**

On an annual mean basis, the shift in obliquity from minimum to maximum values slightly decreases the insolation at the equator by about 4 W/m2; however, it causes a much larger increase at the poles by 16 W/m2 (Fig. S1a). The zonally averaged temperature changes induced by obliquity (Fig. 2b in the manuscript) is consistent with the insolation changes. The change in precession from aphelion to perihelion results in no change of the zonally averaged annual mean insolation (Fig. S1b), which is consistent with the smallest effect of precession changes on temperature. For variation in eccentricity, the simulated annual mean shortwave incoming solar radiation results demonstrate nearly pervasive increase over the globe ((~1−3 W/m2; Fig. S1c), which is consistent with the extensive warming over the globe.

The precipitation responses occur mostly in the tropical regions (Fig. 2g−l in the manuscript), which is climatically dominated by the ITCZ. Previous studies have demonstrated that global temperature change may increase the interhemispheric temperature contrast, thus leading to a shift of ITCZ to the warmer hemisphere [19]. Although the obliquity has the most effect on temperature, the temperature increases significantly both in the northern and southern high latitudes, which essentially does not change the interhemispheric temperature contrast. However, for precession changes, the temperature decreases at northern high latitudes and increases at the southern high latitudes, leading to a large interhemispheric temperature contrast and an associated ITCZ shift. Therefore, precession change has the most effect on the precipitation at low latitudes.



Fig. S1. Zonally averaged annual mean changes of short wave (SW) incoming solar radiation at the TOA (W/m2) between (a) *E*max*P*max*O*max and*E*max*P*max*O*min, (b) *E*max*P*min*O*min and*E*max*P*max*O*min, and (c) *E*max*P*max*O*min and*E*min*P*max*O*min.

Table S1 *Localities and data used in the reconstruction of the Pliocene paleoclimate*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| No. | Site | Location | Proxy data | Periodicity signal | References |
| 1 | U1338 | 2.51°N, 117.97°W | Benthic δ18O | Obliquity | [20]  |
| 2 | ODP 982 | 57.5°N, 15.87°W | Benthic δ18O; Alkenone | Obliquity | [20,21]  |
| 3 | ODP 659 | 18.08°N, 21.03°W | Benthic δ18O | Obliquity | [22] |
| 4 | U1313 | 41°N, 32.57°W | Plant leaf wax | Obliquity | [23]  |
| 5 | ODP 607 | 41°N, 33°W | Mg/Ca in fossil ostracodes | Obliquity | [21,24,25]  |
| 6 | ODP 609 | 50°N, 24°W | Benthic δ18O | Obliquity | [26]  |
| 7 | AND-1B | 77.89°S, 167.09°E | Sedimentation succession; Diatom assemblages | Obliquity | [18,27,28]  |
| 8 | U1208 | 36.13°N, 158.2°E | Alkenone; Benthic δ18O | Obliquity | [29-31]  |
| 9 | U911 | 80.5°N, 8.2°E | Total organic carbon | Obliquity | [32]  |
| 10 | Wujiamao | 37.25°N, 110.05°E | Magnetic susceptibility | Obliquity | [33]  |
| 11 | U1143 | 9.37°N, 113.28°E | Benthic δ18O | Obliquity | [25]  |
| 12 | U846 | 3.095°S, 90.82°W | Benthic δ18O | Obliquity | [34,35]  |
| 13 | U849 | 0.18°N, 110.52°W | Benthic δ18O, δ13C | Obliquity | [36]  |
| 14 | U610 | 53°N, 19°W | Ostracode assemblages | Obliquity | [37]  |
| 15 | Dawson | 64.1°N, 139.2°W | IRD | Obliquity | [38] |
| 16 | U1448 | 10.63°N, 93°E | Benthic and planktic foraminiferal δ18O, δ13C | Obliquity | [39]  |
| 17 | U552 | 56°N, 23°W | *Discoaster* abundance | Obliquity | [40]  |
| 18 | U798 | 37.63°N, 134.8°E | Sedimentation rates | Obliquity | [41]  |
| 19 | El’gygytgyn | 67.5°N, 172.08°E | Rb/Sr ratio | Obliquity | [42]  |
| 20 | Tiburon | 23.29°S, 70.49°W | Sedimentology and sequence stratigraphy | Obliquity | [43]  |
| 21 | Yabuta | 3713°N, 6.35°E | Molluscs, diatoms, and ostracodes | Obliquity | [44]  |
| 22 | U1146 | 19.45°N, 116.27°E | Benthic δ18O | Obliquity | [25]  |
| 23 | U548 | 48.92°N, 12.16°W | Benthic δ18O | Obliquity | [45]  |
| 24 | U1478 | 25.82°S, 34.77°E | Leaf waxes δDwax | Obliquity | [46]  |
| 25 | Huatugou | 38.5°N, 91.92°E | Magnetic susceptibility | Precession | [47]  |
| 26 | Orogen | 32°N, 82°E | lacustrine carbonate δ18O | Precession | [48]  |
| 27 | Spertivento | 38°N, 16°E | Organic carbon content | Precession | [49]  |
| 28 | ODP 964 | 36.26°N, 17.75°E | Chemical composition | Precession | [50,51]  |
| 29 | ODP 967 | 34.07°N, 32.73°E | Chemical composition; Aeolian dust | Precession | [50,52,53]  |
| 30 | ODP 969 | 33.84°N, 24.88°E | Chemical composition | Precession | [50]  |
| 31 | Ptolemais | 40.5°N, 21.65°E | Pollen; Sedimentary rhythmic alternations | Precession | [54-56]  |
| 32 | Punta Piccola | 37.3°N, 13.5°E | Planktonic δ18O; Biogenic compositions | Precession | [51,57-60]  |
| 33 | Cape Spertivento | 37.95°N, 16°E | Planktonic δ18O; Biogenic compositions | Precession | [57,59]  |
| 34 | Maar Lake | 41.83°N, 2.8°E | Pollen | Precession | [61]  |
| 35 | Fiumana | 44.15°N, 11.99°E | Paleoproductivity | Precession | [62]  |
| 36 | Omo Group | 3.5°N, 36.5°E | δ18O of pedogenic carbonate | Precession | [63]  |
| 37 | BTB13 | 0.55°N, 35.93°E | Leaf wax δ13Cwax | Precession | [64]  |
| 38 | Monte Singa | 38.5°N, 17°E | Mineralogical content | Precession | [51]  |
| 39 | Vrica | 39°N, 17.45°E | Mineralogical content | Precession | [51]  |
| 40 | ODP 231 | 11.89°N, 48.25°E | Biomarker | Precession | [65]  |
| 41 | Capo Rossello | 37.47°N, 13.72°E | Planktonic foraminiferal assemblages | Precession | [57,66,67]  |
| 42 | ODP 653 | 40.18°N, 12.19°E | Planktonic foraminiferal assemblages | Precession | [57] |
| 43 | ODP 661 | 9.45°N, 19.39°W | Eolian dust | Precession | [68,69]  |
| 44 | ODP 662/663 | 1.39°S, 11.74°W | Eolian dust | Precession | [68,69]  |
| 45 | ODP 664 | 0.11°N, 23.22°W | Eolian dust | Precession | [68,69]  |
| 46 | ODP 721/722 | 16.62°N, 59.8°E | Eolian dust | Precession | [68,69]  |
| 47 | Shilou | 36.92°N, 110.93°E | Al/Na, Rb/Sr, and lightness | Eccentricity | [70]  |
| 48 | Liulin | 37.35°N, 110.75°E | Magnetic susceptibility | Eccentricity | [71]  |
| 49 | Lupoaia | 45.57°N, 26.92°E | Lithological cycles | Eccentricity | [72]  |
| 50 | Huatugou | 38.3°N, 91.26°E | Evaporite minerals | Eccentricity | [73]  |
| 51 | U594 | 45.52°S, 174.95°E | Benthic δ18O, δ13C | Eccentricity | [74]  |
| 52 | U1125 | 42.55°S, 178.17°W | Benthic δ18O, δ13C | Eccentricity | [74]  |
| 53 | Changgoucun  | 34.3°N, 109.5°E | Grain size | Precession and Eccentricity | [75]  |
| 54 | Lupoaia | 44.8°N, 22.97°E | Pollen | Precession and Eccentricity | [76]  |
| 55 | PL02 | 38.92°N, 106.6°E | Pollen; Magnetic susceptibility; Mean grains size | Precession and Obliquity | [77]  |
| 56 | Dongwan | 34.97°N, 105.78°E | Snail | Precession and Obliquity | [78] |
| 57 | U1359 | 64.9°S, 143.96°E | Mass accumulation rate | Precession and Obliquity | [79]  |
| 58 | Makapansgat Valley | 24.13°S, 29.18°E | Stable δ18O and δ13C of speleothems | Precession and Obliquity | [80]  |
| 59 | U659 | 18.08°N, 21.03°W | Benthic δ18O; Dust flux | Precession and Obliquity | [22,68,69]  |
| 60 | U925 | 4.2°N, 43.48°W | Magnetic susceptibility | Precession and Obliquity | [81]  |
| 61 | U926 | 3.7°N, 42.9°W | Magnetic susceptibility | Precession and Obliquity | [81]  |
| 62 | U927 | 5.5°N, 44.5°W | Magnetic susceptibility | Precession and Obliquity | [81]  |
| 63 | U928 | 5.5°N, 44.8°W | Magnetic susceptibility | Precession and Obliquity | [81]  |
| 64 | U929 | 5.98°N, 43.74°W | Magnetic susceptibility | Precession and Obliquity | [81]  |
| 65 | U806 | 0.319°N, 159.36°E | Foraminiferal Mg/Ca and planktonic δ18O | Precession and Obliquity | [82,83]  |
| 66 | VA | 40.62°N, 0.98°W | Magnetic parameters | Precession and Obliquity | [84]  |
| 67 | Wanganui | 39.93°S, 175.05°E | Benthic δ18O; Relative sea-level | Precession and Obliquity | [85-87]  |
| 68 | SG-1B | 38.35°N, 92.27°E | Rb/Sr ratio; Grain size | Precession and Obliquity | [88]  |
| 69 | XK-1 | 16.35°N, 120.35°E | Biogenic reef and carbonate deposition | Precession, Eccentricity, and Obliquity | [89] |
| 70 | Lingtai | 35.07°N, 107.65°E | Grain size; Magnetic susceptibility | Precession, Eccentricity, and Obliquity | [90]  |
| 71 | Zhaojiachun | 35.75°N, 107.82°E | Grain size; Magnetic susceptibility | Precession, Eccentricity, and Obliquity | [90]  |
| 72 | Bojizhuang | 34.53°N, 107.11°E | Grain size; Magnetic susceptibility; Carbonate content | Precession, Eccentricity, and Obliquity | [91]  |
| 73 | Xiaoshuizi | 35.81°N, 103.86°E | Grain size; Magnetic susceptibility; Carbonate content | Precession, Eccentricity, and Obliquity | [92]  |
| 74 | U1361 | 64.41°S, 143.89°E | Iceberg-rafted debris mass accumulation rates | Precession, Eccentricity, and Obliquity | [93]  |
| 75 | Xifeng | 42.73°N, 124.72°E | Grain size; Magnetic susceptibility | Precession, Eccentricity, and Obliquity | [94]  |
| 76 | 642B | 67.22°N, 2.93°E | Pollen | Precession, Eccentricity, and Obliquity | [95] |

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