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Interhemispheric Effect of Global Geography on Earth's Climate Response to Orbital Forcing

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Abstract

The climate response of the Earth to orbital forcing shows a distinct hemispheric asymmetry due to the unequal distribution of land in the Northern versus Southern Hemispheres. This asymmetry is examined using a Global Climate Model (GCM) and a Land Asymmetry Effect (LAE) is quantified for each hemisphere. The results show how changes in obliquity and precession translate into variations in the calculated LAE. We find that the global climate response to specific past orbits is likely unique and modified by complex climate-ocean-cryosphere interactions that remain poorly known and difficult

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to model. Nonetheless, these results provide a baseline for interpreting contemporaneous proxy climate data spanning a broad range of latitudes, which maybe especially useful in paleoclimate data-model comparisons, and individual time-continuous records exhibiting orbital cyclicity.

1. Introduction

The arrangement of continents on the Earth's surface plays a fundamental role in the Earth's climate response to forcing. This global "geography" is primarily the result of the horizontal and vertical displacements associated with plate tectonics. While these processes are ongoing, the global continental configuration has been close to its present form since the mid-Cenozoic. Today, more continental land area is found in the Northern Hemisphere (68%) as compared to the Southern Hemisphere (32%). These different ratios of land vs. ocean in each hemisphere affect the balance of incoming and outgoing radiation, atmospheric circulation, ocean currents, and the availability of terrain suitable for growing glaciers and ice-sheets. As a result of this land-ocean asymmetry, the climatic responses of the Northern and Southern Hemisphere differ for an identical change in radiative forcing (Barron et al., 1984; Deconto et al., 2008; Kang et al., 2014; Loutre, 2003; Short et al., 1991).

A number of classic studies have shown interhemispheric asymmetry in climate response of Northern and Southern Hemispheres. Climate simulations made with coupled atmosphere-ocean GCMs typically show a strong asymmetric response to greenhouse-gas loading, with Northern Hemisphere high latitudes experiencing increased warming compared to Southern Hemisphere high latitudes (Stouffer et al., 1989; Flato and Boer,

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2001). GCMs also show that the Northern and Southern Hemispheres respond differently to changes in orbital forcing (e.g. Philander et al., 1996). While the magnitude of insolation changes through each orbital cycle is identical for both hemispheres, the difference in climatic response can be attributed to the fact that Northern Hemisphere is land-dominated while Southern Hemisphere is water dominated (Croll, 1870). This results in a stronger response to orbital forcing in the Northern Hemisphere relative to the Southern Hemisphere.

The changing continental configurations as a result of plate tectonics have been linked with climate change over a wide range of timescales (e.g. Crowley and North, 1996; DeConto, 2009; Fawcett and Barron, 1998; Hay, 1996). The distribution of continents and oceans have an important effect on the spatial heterogeneity of the Earth's energy balance, primarily via the differences in albedos and thermal properties of land versus ocean (Trenberth et al., 2009). The latitudinal distribution of land has a dominant effect on zonally averaged net radiation balance due to its influence on planetary albedo and ability to transfer energy to the atmosphere through long-wave radiation, and fluxes of sensible and latent heat. The latitudinal net radiation gradient controls the total poleward heat transport requirement, which is the ultimate driver of winds, and ocean circulation (Stone, 1978).

Oceans have a relatively slower response to seasonal changes in insolation due to the higher specific heat of water as compared to land, and mixing in the upper ~10-150 m of the ocean. As a result, in the ocean-dominated Southern Hemisphere, the surface waters suppress extreme temperature swings in the winter and provide the atmosphere with a

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64 source of moisture and diabatic heating. In the land-dominated Northern Hemisphere, the
65 lower heat capacity of the land combined with relatively high albedo results in greater
66 seasonality, particularly in the interiors of large continents of Asia and North America.

67 The continentality of the Northern Hemisphere manifests itself in different
68 hemispherically asymmetric climatic phenomenon, like the well-known Asian monsoonal
69 circulation system. The intertropical convergence zone (ITCZ) is considered to be the
70 region of low-level convergence and convective precipitation. The ITCZ moves further
71 away form the equator during the Northern summer than the Southern one due to the
72 continentiality of the Northern Hemisphere (Kang et al., 2008; Philander et al., 1996).
73 The land surface available in a particular hemisphere also affects the potential for
74 widespread glaciation. The extreme cold winters associated with large continents provide
75 the means of accumulation of winter snow, while the critical factor for formation of ice-
76 sheets is annual ablation and can be estimated by the sum of Positive Degree Days (PDD)
77 in a year (e.g. Huybers, 2006).

78 Continental geography has a strong impact on polar climates, as is evident from the very
79 different climatic regimes of the Arctic and the Antarctic. Several early paleoclimate
80 modeling studies using GCMs investigated continental distribution as a forcing factor of
81 global climate (e.g. Barron et al., 1984; Hay et al., 1990). These studies demonstrated that
82 an Earth with its continents concentrated in the low latitudes is warmer and has lower
83 equator-to-pole temperature gradients than an Earth with only polar continents. Although
84 these early model simulations did not incorporate all the complexities of the climate
85 system, the results provided valuable insights from comparative studies of polar versus

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equatorial continents in the Earth and showed that changes in continental configuration has significant influence on climatic response to forcing.

2. Methods

2.1 Experimental design

We use the latest (2012) version of the Global ENvironmental and Ecological Simulation of Interactive Systems (GENESIS) 3.0 GCM with a slab ocean component (Thompson and Pollard, 1997) rather than a full-depth dynamical ocean (Alder et al., 2011). The slab-ocean predicts sea surface temperatures and ocean heat transport as a function of the local temperature gradient and the zonal fraction of land versus sea at each latitude. While explicit changes in ocean currents and the deep ocean are not represented, the computational efficiency of the slab-ocean version of the GCM allows numerous simulations with idealized global geographies and greatly simplifies interpretations of the sensitivity tests by precluding complications associated with ocean model dependencies. In addition to the atmosphere and slab-ocean, the GCM includes model components representing vegetation, soil, snow, and thermo-dynamic sea ice. The 3-D atmospheric component of the GCM uses an adapted version of the NCAR CCM3 solar and thermal infrared radiation code (Kiehl et al., 1998) and is coupled to the surface components by a land-surface-transfer scheme (LSX). In the setup used here, the model atmosphere has a spectral resolution of T31 (~3.75°) with 18 vertical layers. Land-surface components are discretized on a higher resolution 2°x2° grid.

The GCM uses various geographical boundary conditions (described below) in 2°x2° and spectral T31 grids for surface and AGCM models, respectively. For each set of

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experiments, the model is run for 50 years. Spin-up is taken into account, and equilibrium is effectively reached after about 20 years of integration. The results used to calculate interhemispheric effects are averaged over the last 20 years of each simulation. Greenhouse gas mixing ratios are identical in all experiments and set at preindustrial levels with CO_2 set at 280 ppmv, N_2O at 288 ppbv and CH_4 at 800 ppbv. The default values for $CFCl_3$ and CF_2Cl_2 values are set at 0 ppm. The solar constant is maintained at 1367 Wm^{-2}.

2.2 Asymmetric and symmetric Earth geographies

The GCM experiments are divided into three sets: 1) Preindustrial CONTROL 2) NORTH-SYMM and 3) SOUTH-SYMM. The Preindustrial CONTROL experiments use a modern global geography spatially interpolated to the model's 2°x2° surface grid (Koenig et al., 2012). The geography provides the land-ice sheet-ocean mask and land–surface elevations used by the GCM.

To simulate the climate of an Earth with meriodionally symmetric geographies, we created two sets of land surface boundary conditions: NORTH-SYMM and SOUTH-SYMM. For the NORTH-SYMM experiments, the CONTROL experiment boundary conditions are used to generate a modified GCM surface mask, by reflecting the Northern Hemisphere geography (land-sea-ice mask, topography, vegetation, soil texture) across the equator into the Southern Hemisphere. Similarly, in the experiment SOUTH-SYMM, the land mask and geographic boundary conditions in the Southern Hemisphere are mirrored in the Northern Hemisphere. The NORTH-SYMM and SOUTH-SYMM

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129 boundary conditions are shown in Figure 1B and 1C, with the CONTROL (Fig. 1A) for
130 comparison.

131 **3. Asymmetry in the Earth's climate**

132 We begin our study by investigating the asymmetry in the Earth's climate. In our first
133 experimental setup, we run the GCM with modern day orbital configuration, i.e.
134 eccentricity is set at 0.0167, obliquity is set at 23.5° and precession such that perihelion
135 coincides with Southern Hemisphere summer. Figure 2A shows the present day summer
136 insolation intensity and Figure 2B shows present day Summer Energy for reference. The
137 Summer Energy (J) is defined as defined as:

138 $$J = \sum_i \beta_i (W_i \times 86{,}400) \quad \ldots(1)$$

139 where W_i is mean insolation measured in W/m^2 on day i, and β equals 1 when Wi ≥ τ and
140 zero otherwise. τ = 275 W/m^2 is taken as the assumed threshold for melting of ice at the
141 Earth's surface). Mean Summer Temperatures (ST) are calculated from the GCM as the
142 mean of the average daily temperatures for the summer months in each hemisphere (JJA
143 in Northern Hemisphere; DJF in Southern Hemisphere). Figure 2C shows the mean
144 summer temperature for a simulation with modern orbit. The zonal averages (calculated
145 for each latitude) demonstrate the inherent asymmetry in the Earth's climate between
146 Northern and Southern Hemispheres, especially evident in the higher latitudes. A better
147 indicator of the Earth's climate system, which quantifies both the intensity of summer as
148 well as the duration of the melt season, is the sum of Positive Degree Days (PDD). The
149 sum of Positive Degree-Days is calculated as:

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$$PDD = \sum_i \propto_i T_i \quad \ldots(2)$$

where T_i is the mean daily temperature on day i, and α is one when $T_i \geq 0°C$ and zero otherwise. The PDD captures the intensity as well as the duration of the melt season, and has been shown to be indicative of the ice-sheet response to changes in external forcing. Figure 2D shows the PDD for modern orbit, and the zonal averages are plotted in the log scale. The extreme asymmetry between the Northern and Southern Hemispheres observed in the summer temperatures is also evident in the calculated PDDs.

The observed asymmetry in the Northern and Southern Hemispheres can be attributed to three primary causes: (i) variation in insolation intensity across the Northern and Southern Hemispheres caused by the precession of the equinoxes (today perihelion coincides with January 3, just after the December 21 solstice, leading to slightly stronger summer insolation in the Southern Hemisphere); (ii) the effect of the continental geography on climate; and (iii) the effect of interhemispheric continental geography on climate, i.e. the effect of Northern Hemisphere continental geography on Southern Hemisphere climate and vice-versa. Here, we attempt to isolate the effect of interhemispheric continental geography on climate (i.e. cause (iii) above) by comparing results from GCM simulations using modern versus idealized (hemispherically symmetric) global geographies (Fig. 1).

Next, we maintain a modern orbit to test the effect of meriodionally symmetric continents (Fig. 2E-H). Figure 2E and 2F show the summer temperature and PDD from a simulation in which the Northern Hemisphere geography is reflected in the Southern Hemisphere (thus making the Earth geographically symmetric). Figure 2G and Figure 2H shows the

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summer temperature and PDD from a hypothetical simulation with symmetric Southern Hemisphere continents. Symmetric continents make the climates of Northern and Southern Hemispheres almost symmetric (>95%), with some small remaining asymmetry due to the current timing of perihelion with respect to the summer solstices.

The simulations with modern and idealized (symmetric) geographies are used to quantify the different climate responses to a range of orbits. By comparing the climatic response from simulations with different geographies, we isolate and estimate the effect of interhemispheric continental geography and the influence of one hemisphere's geography on the climate response of the opposite hemisphere.

3.1 Effect of Southern Hemisphere on Northern Hemisphere climate

To estimate the effect of Southern Hemisphere continental geography on the Northern Hemisphere, we compare the NH climate from the CONTROL simulation (asymmetric, modern orbit) and NORTH-SYMM (symmetric Northern continents in both hemispheres). In these simulations, the only difference in setup is the Southern Hemispheric continental distribution. Thus the differences in Northern Hemisphere climate from the two simulations, if any, can be safely ascribed as the 'effect of Southern Hemisphere continental geography on Northern Hemisphere climate'. We quantify this interhemispheric effect of Southern Hemisphere continental geography on NH climate as:

$$\widehat{e_{Summer\ Temp}} = \frac{1}{n}\sum_i^n (T_i^{control} - T_i^{north}) \quad \ldots(3)$$

$$\widehat{e_{PDD}} = PDD^{control} - PDD^{north} \quad \ldots(4)$$

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where $T_i^{control}$ and $PDD_i^{control}$ are the mean daily temperature on day i and PDD from the control simulation, and T_i^{North} and PDD_i^{North} are the mean daily temperature on day i and PDD from the simulation with the North-symmetric geography. 'n' is the number of days in the summer months in each hemisphere (JJA in Northern Hemisphere; DJF in Southern Hemisphere)

Figure 3A and 3B show the effect of Southern Hemisphere continental geography on Northern Hemisphere summer temperature and PDD respectively. For the Northern Hemisphere, the summer temperatures are calculated over the months of June, July, and August when the insolation intensity over the Northern Hemisphere is strongest. The asymmetry in the Southern Hemisphere landmasses leads to weakening of the summer warming over North America and Eurasia (blue shaded regions correspond to cooling). Consequently, summer temperatures over Northern Hemisphere continents are lower by 3-6°C relative to a symmetric Earth. There is a positive warming effect in the North-Atlantic Ocean, and in general the Northern Hemisphere oceans are slightly warmer relative to a symmetric Earth. The general trends in the interhemispheric effect on PDD (Fig. 3B) mimic those of the summer temperatures (Fig. 3A).

3.2 Effect of Northern Hemisphere on Southern Hemisphere climate

Similarly, we estimate the effect of Northern Hemisphere continental geography on the Southern Hemisphere by comparing the SH climate of the CONTROL simulation (asymmetric, modern orbit) and the SOUTH-SYMM (symmetric southern continents in both hemispheres). In these simulations, the differences in Southern Hemisphere climate in the CONTROL and SOUTH-SYMM simulations, if any, can be ascribed as the 'effect

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of Northern Hemisphere continental geography on Southern Hemisphere climate'. We quantify this interhemispheric effect of Northern Hemisphere continental geography on SH climate as:

$$\widehat{e_{Summer\ Temp}} = \frac{1}{n}\sum_i^n (T_i^{control} - T_i^{south}) \quad \ldots(5)$$

$$\widehat{e_{PDD}} = PDD^{control} - PDD^{south} \quad \ldots(6)$$

where $T_i^{control}$ and $PDD_i^{control}$ are the mean daily temperature on day i and PDD from the control simulation, and T_i^{south} and PDD_i^{south} are the mean daily temperature on day i and PDD from the simulation with the south-symmetric geography.

Figure 3C and 3D show the effect of Northern Hemisphere continental geography on Southern Hemisphere summer temperature and PDD, respectively. For the Southern Hemisphere, the summer temperatures are calculated over the months of December, January, and February when the insolation is most intense during the year. Southern Hemisphere landmasses, except Antarctica, generally show a cooling response during summer, due to Northern Hemisphere geography. Over Antarctica, summer temperatures are higher in the control simulations than in the symmetric simulations, leading to the inference that there is a warming (increase) in summer temperatures due to interhemispheric effect. Also, the Southern Ocean shows a strong positive temperature effect (warming) relative to a symmetric Earth, although this Southern Ocean response might be different or modified if a full-depth dynamical ocean model were used.

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4. Interhemispheric effect on the Earth's climate response to orbital (astronomical) forcing

Next, we examine the effect of the opposite hemisphere on the Earth's climate response to changes in obliquity (axial tilt) and precession (positions of the solstices and equinoxes in relation to the eccentric orbit). The orbital parameters used in these experiments are idealized and do not correspond to a specific time in Earth's history. Rather, they are chosen to provide a useful framework for studying the Earth's climate response to precession and obliquity. HIGH and LOW orbits approximate the highest and lowest obliquity in the last three million years (Berger and Loutre, 1991). NHSP (Northern Hemisphere Summer at Perihelion) and SHSP (Southern Hemisphere Summer at Perihelion) orbits correspond to Northern and austral summers coinciding with perihelion, respectively, and represent the two extreme configurations of precession, with obliquity set at its mean value averaged over the last 3 million years. Eccentricity is set at the same moderate value (mean eccentricity over the last 3 million years) for all simulations. Table 1 summarizes the orbits used in the ensemble of model simulations. Here, we focus only on the sum of the Positive Degree Days (PDD) calculated from our simulations. PDD is a better indicator of air temperature's influence on annual ablation over ice-sheets than summer temperature, since this metric captures both the intensity and duration of the melt season.

4.1 Interhemispheric effect on precessional (cycle) response of the Earth's climate

Changes in precession primarily affect seasonal insolation intensity that is well known to be out-of-phase in both hemispheres (e.g. Raymo et al., 2006). The out-of-phase summer

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energy (J) variation is shown in Figure 4A for reference. In one precessional cycle lasting ~23-kyr, the perihelion position of the Earth's orbit moves from the Northern Hemisphere summer solstice (NHSP) to the Southern Hemisphere summer solstice (SHSP), which are also the two extreme precessional configurations. We run the simulations at these two extreme precessions, keeping all other orbital parameters constant at their mean values. The difference in the calculated PDDs from the two simulations (represented as $\Delta PDD_{precession}$) gives an estimate of the Earth's climate response to the combined effect of the two precessional motions (wobbling of the axis of rotation and the slow turning of the orbital ellipse). Figure 4B shows the precessional response of the Earth in terms of PDD, and it is observed that the Northern and Southern Hemisphere responses are not symmetrical. Running the same simulations with a North-symmetric Earth (Fig. 4C) and a South-symmetric Earth (Fig. 4D) results in a nearly symmetrical climate responses to the precessional cycle.

4.2 Interhemispheric effect on obliquity (cycle) response of the Earth's climate

In contrast to precession, obliquity alters the seasonality of insolation equally in both hemispheres (Fig. 4E). A reduction in the tilt from 24.5° (HIGH) to 22° (LOW) reduces annual insolation by ~17 W/m^2 and summer insolation by ~45 W/m^2 in the high latitudes. In the tropics, summer insolation increases by up to ~5 W/m^2. Loutre et al. (2004) among others predicted that global ice volume changes at the obliquity periods could be interpreted as a response to mean annual insolation and meridional insolation gradients. Similar to the experimental setup described above, we ran two simulations with the highest and lowest axial tilts, keeping all other orbital parameters constant at their mean values. The difference in the calculated PDDs (represented as $\Delta PDD_{obliquity}$) provides an

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estimate of the Earth's climate response to changes in tilt. Figure 4F shows $\Delta PDD_{obliquity}$ and the zonal averages reveal the asymmetry in the climate response to obliquity. Running the same simulations with a North-symmetric Earth (Fig. 4G) and a South-symmetric Earth (Fig. 4H) produces a nearly symmetrical climate response to the obliquity cycle.

5. Quantification of the Land Asymmetry Effect (LAE)

5.1 Effect of Southern Hemisphere geography on Northern Hemisphere climate

The effect of Southern Hemisphere continental geography on Northern Hemisphere at the two extreme precessional orbits is estimated using the same method described above, with Interhemispheric effect of Southern Hemisphere continental geography on NH climate at 'NHSP' calculated as:

$$(\widehat{e_{PDD}})_{NHSP} = PDD_{NHSP}^{control} - PDD_{NHSP}^{north} \quad \ldots(7)$$

and interhemispheric effect of Southern Hemisphere continental geography on NH climate at 'SHSP' calculated as:

$$(\widehat{e_{PDD}})_{SHSP} = PDD_{SHSP}^{control} - PDD_{SHSP}^{north} \quad \ldots(8)$$

Figure 5A shows the spatial variation of $(\widehat{e_{PDD}})_{NHSP}$. The Northern Hemisphere landmasses show a strong negative response to PDD when perihelion coincides with Northern Hemisphere summer (NHSP). In this orbit, the Northern Hemisphere experiences elevated summer insolation, but the response is weakened due to the interhemispheric effect. This dampening effect is greatest in the interiors of the Northern

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299 Hemisphere continents (Fig. 5A). According to Milankovitch theory, the Northern
300 Hemisphere should experience 'interglacial' conditions when perihelion coincides with
301 boreal summer. However, because of the interhemispheric effect, interglacial (warm
302 summer) conditions are muted relative to those on a symmetric Earth. Figure 5B shows
303 the spatial variation of $(\widehat{e_{PDD}})_{SHSP}$. When perihelion coincides with Southern
304 Hemisphere summer (SHSP), the Northern Hemisphere continents have a weak positive
305 effect, leading to slightly warmer conditions relative to a symmetric Earth.

306 Next we try to observe the interhemispheric effect on $\boldsymbol{\Delta PDD}$ for a *transition* from SHSP to NHSP
307 orbit. Thus the Interhemispheric effect of Southern Hemisphere continental geography on
308 Northern Hemisphere response to a precession cycle is:

309 $$(\widehat{e_{PDD}})_{precession} = \boldsymbol{\Delta} PDD^{control}_{precession} - \boldsymbol{\Delta} PDD^{north}_{precession} \quad \ldots(9)$$

310 The calculated effect is plotted spatially in Figure 6A, and shows a strong negative effect
311 on Northern Hemisphere PDDs. For the Northern Hemisphere, the transition from SHSP
312 to NHSP equates to a transition from cool to warm climate. The negative
313 interhemispheric effect decreases the $\boldsymbol{\Delta PDD}$ in the real Earth, thus weakening the effect
314 of precession on the Northern Hemisphere.

315 The effect of Southern Hemisphere continental geography on NH climate response at the
316 two extreme obliquity orbits are estimated as:

317 $$(\widehat{e_{PDD}})_{HIGH} = PDD^{control}_{HIGH} - PDD^{north}_{HIGH} \quad \ldots(10)$$

318 and

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$$(\widehat{e_{PDD}})_{LOW} = PDD_{LOW}^{control} - PDD_{LOW}^{north} \quad \ldots(11)$$

At HIGH obliquity, there exists a negative effect on Northern Hemisphere continents (Fig. 5C), which mutes the strong insolation intensity during summer months. In the Northern Hemisphere, as a result of continental asymmetry, a decrease in the equator to pole temperature gradient is observed. A lowering of summer temperatures and temperature gradient due to the interhemispheric effect has a negative impact on the deglaciation trigger associated with HIGH obliquity orbits. Thus the interhemispheric effect would hinder the melting of ice during high-obliquity orbits. At LOW obliquity, the negative effect over Northern Hemisphere continents is generally less intense (Fig. 5D). However, even the modest lowering of summer temperatures caused by the interhemispheric effect would support the growth of ice sheets during low obliquity orbits.

Further, we calculate the interhemispheric effect on $\boldsymbol{\Delta PDD}$ for a transition from LOW to HIGH orbit (obliquity cycle). This Interhemispheric effect of Southern Hemisphere continental geography on Northern Hemisphere response to an obliquity cycle is:

$$(\widehat{e_{PDD}})_{obliquity} = \boldsymbol{\Delta} PDD_{obliquity}^{control} - \boldsymbol{\Delta} PDD_{obliquity}^{north} \quad \ldots(12)$$

The calculated effect is spatially plotted in Figure 6C, and shows a small negative effect in the high latitudes, and a positive effect in the low latitudes. The transition from LOW to HIGH corresponds to a transition from cold to warm climate. The negative interhemispheric effect decreases the $\boldsymbol{\Delta PDD}$, thus weakening the climate response of obliquity cycle in the high latitudes. The positive interhemispheric effect increases the

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340 $\boldsymbol{\Delta PDD}$, thus strengthening the climate response of obliquity cycle in the Northern
341 Hemisphere low latitudes.

342 **5.2 Effect of Northern Hemisphere geography on Southern Hemisphere climate**

343 The effect of Northern Hemisphere continental geography on SH climate response at two
344 extreme precessional orbits is estimated as:

345 $$(\widehat{e_{PDD}})_{NHSP} = PDD_{NHSP}^{control} - PDD_{NHSP}^{south} \quad \ldots(13)$$

346 and

347 $$(\widehat{e_{PDD}})_{SHSP} = PDD_{SHSP}^{control} - PDD_{SHSP}^{south} \quad \ldots(14)$$

348 The spatial variation of $(\widehat{e_{PDD}})_{NHSP}$ is shown in Figure 5E. During NHSP orbit, the
349 Southern Hemisphere experiences 'glacial' (cold summer) conditions due to the weaker
350 summer insolation. The positive effect in the Southern Hemisphere leads to weaker
351 cooling relative to a symmetric Earth. Thus, when perihelion coincides with Northern
352 Hemisphere summer, the interhemispheric effect dampens the magnitude of 'glacial'
353 versus 'interglacial' conditions in both hemispheres. When perihelion coincides with
354 Southern Hemisphere summer (SHSP), the southern high latitudes experience intense
355 summer insolation. The positive warming effect (Fig. 5F) amplifies the 'interglacial'
356 conditions in the Southern Hemisphere, predicted by Milankovitch theory.

357 The interhemispheric effect on $\boldsymbol{\Delta PDD}$ for a transition from SHSP to NHSP orbit, or the
358 interhemispheric effect of Northern Hemisphere continental geography on Southern
359 Hemisphere response to a precession cycle is:

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$$(\widehat{e_{PDD}})_{precession} = \boldsymbol{\Delta} PDD^{control}_{precession} - \boldsymbol{\Delta} PDD^{south}_{precession} \quad \ldots(15)$$

The calculated effect is plotted spatially in Figure 6B, and shows a positive effect on PDD over Southern Hemisphere high latitudes. For the Southern Hemisphere, the transition from SHSP to NHSP equates to a transition from warmer to cooler climate. The positive interhemispheric effect at high latitudes decreases the $|\boldsymbol{\Delta} PDD|$ in the real Earth, thus weakening the effect of precessional cycle in the Southern Hemisphere high latitudes.

The interhemispheric effect of Northern Hemisphere continental geography on Southern Hemisphere climate at the two extreme obliquity configurations is calculated as:

$$(\widehat{e_{PDD}})_{HIGH} = PDD^{control}_{HIGH} - PDD^{south}_{HIGH} \quad \ldots(16)$$

and

$$(\widehat{e_{PDD}})_{LOW} = PDD^{control}_{LOW} - PDD^{south}_{LOW} \quad \ldots(17)$$

The spatial variations of $(\widehat{e_{PDD}})_{HIGH}$ and $(\widehat{e_{PDD}})_{LOW}$ are shown in Figure 5G and 5H, respectively. In the Southern Hemisphere, the positive interhemispheric effect on PDD over Antarctica and the Southern Ocean leads to overall higher temperatures in the high southern latitudes as compared to a symmetric Earth. During high obliquity orbits, this positive effect contributes to deglaciation and during low obliquity orbits; the positive effect (warming) hinders the growth of ice sheets.

Lastly, we calculate the interhemispheric effect on $\boldsymbol{\Delta} PDD$ for a transition from LOW to HIGH orbit (obliquity cycle):

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$$(\widehat{e_{PDD}})_{obliquity} = \Delta PDD^{control}_{obliquity} - \Delta PDD^{south}_{obliquity} \quad \ldots(18)$$

The calculated effect is plotted in Figure 6D, and shows largely a negative effect in the Southern Hemisphere, with a positive effect in the high latitudes. The transition from LOW to HIGH corresponds to a transition from cold to warm climate. The positive interhemispheric effect increases the ΔPDD, thus amplifying the effect of obliquity over Antarctica.

6. Conclusions

The unbalanced fraction of land in the Northern versus Southern Hemisphere has remained almost unchanged for tens of millions of years. However, the significance of this continental asymmetry on Earth's climate response to forcing has not been previously quantified with a physically based climate models. We find that continental geography has an important control on the climate system's response to insolation forcing, and this may help explain the non-linear response of the Earth's climate to insolation forcing.

According to classical Milankovitch theory, the growth of polar ice sheets at the onset of glaciation requires cooler summers in the high latitudes, in order for snow to persist throughout the year. During warm summers at the high latitudes, the winter snowpack melts, inhibiting glaciation or leading to deglaciation if ice sheets already exist. Thus, the intensity of summer insolation at high latitudes, especially the Northern polar latitudes, has been considered the key driver of the glacial-interglacial cycles and other long-term climatic variations. At precessional periods, at which the high latitude summer intensity

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401 primarily varies, the land asymmetry effect plays an important role by amplifying (or
402 weakening) the effect of summer insolation intensity.

403 In all the orbital configurations simulated here, we find that the geography of the
404 Southern Hemisphere weakens the temperature response of the high Northern
405 Hemisphere latitudes to orbital forcing. Consequently, this leads to a larger latitudinal
406 gradient in summer temperatures in the Northern Hemisphere compared to that of a
407 symmetric Earth. In particular, the amplification (or weakening) of the response to
408 insolation changes at precessional and obliquity periods might explain some of the
409 important features of late Pliocene-early Pleistocene climate variability, when obliquity-
410 paced cyclicity dominated precession in global benthic $\delta^{18}O$ records. In Figure 6, we have
411 demonstrated that the interhemispheric effect causes a suppression of the effects of
412 precessional cycle on the Earth's surface. In other words, the real Earth has a smaller
413 response to a precession cycle as compared to the hypothetical symmetric Earth. We have
414 also showed that the interhemispheric effect causes an amplification of the effects of
415 obliquity cycle on the Earth's surface. In other words, the real Earth has a larger response
416 to the obliquity cycle in the ocean dominated Southern Hemisphere, as compared to the
417 hypothetical symmetric Earth. Consequently, the interhemispheric effect of continental
418 geography contributes to the muting of precessional signal and amplification of obliquity
419 signal recorded in paleoclimate proxies such as benthic $\delta^{18}O$ isotope records.

420 There are various ways in which the Earth's continental asymmetry affects climate. Here,
421 we have shown how these interhemispheric effects influence the Earth's climate response
422 to orbital forcing via the radiative and atmospheric dynamical processes represented in a

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423 slab-ocean GCM. While computationally challenging, future work should include
424 complimentary simulations with AOGCMs, to explore the potential modifying role of
425 ocean dynamics on the amplifying and weakening interhemispheric responses to orbital
426 forcing demonstrated here.

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427 **Table 1. Experimental Setup of Model Boundary Conditions and Forcings**

Run ID	LSX Configuration	Eccentricity	Obliquity	Precession [a]	GHGs
$CONTROL_{NHSP}$	Modern	0.034	23.2735	270° (NHSP)	Preindustrial
$CONTROL_{SHSP}$	Modern	0.034	23.2735	90° (SHSP)	Preindustrial
$CONTROL_{HIGH}$	Modern	0.034	24.5044 (HIGH)	180°	Preindustrial
$CONTROL_{LOW}$	Modern	0.034	22.0425 (LOW)	180°	Preindustrial
$NORTH\text{-}SYMM_{NHSP}$	North-symmetric	0.034	23.2735	270° (NHSP)	Preindustrial
$NORTH\text{-}SYMM_{SHSP}$	North-symmetric	0.034	23.2735	90° (SHSP)	Preindustrial
$NORTH\text{-}SYMM_{HIGH}$	North-symmetric	0.034	24.5044 (HIGH)	180°	Preindustrial
$NORTH\text{-}SYMM_{LOW}$	North-symmetric	0.034	22.0425 (LOW)	180°	Preindustrial
$SOUTH\text{-}SYMM_{NHSP}$	South-symmetric	0.034	23.2735	270° (NHSP)	Preindustrial
$SOUTH\text{-}SYMM_{SHSP}$	South-symmetric	0.034	23.2735	90° (SHSP)	Preindustrial
$SOUTH\text{-}SYMM_{HIGH}$	South-symmetric	0.034	24.5044 (HIGH)	180°	Preindustrial
$SOUTH\text{-}SYMM_{LOW}$	South-symmetric	0.034	22.0425 (LOW)	180°	Preindustrial

428 **NHSP:** Northern Hemisphere Summer Solstice at Perihelion

429 **SHSP:** Southern Hemisphere Summer Solstice at Perihelion

430 [a] Orbital precession in the GCM is defined here as the prograde angle from perihelion to

431 the Northern Hemispheric vernal equinox.

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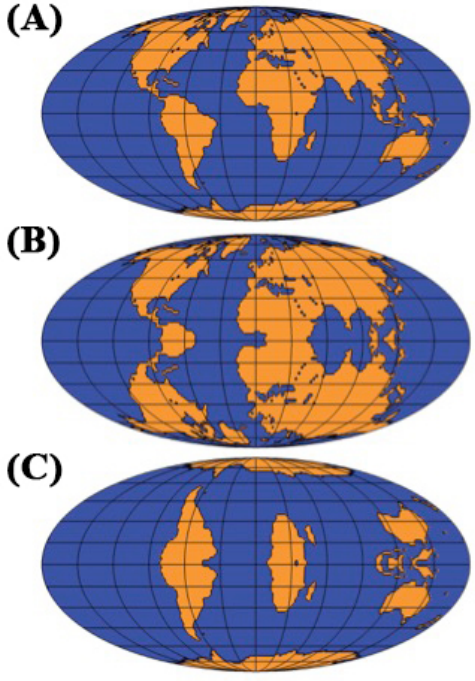

Figure 1. (A) Modern continental geography (B) NORTH-SYMM geography and (C) SOUTH-SYMM geography

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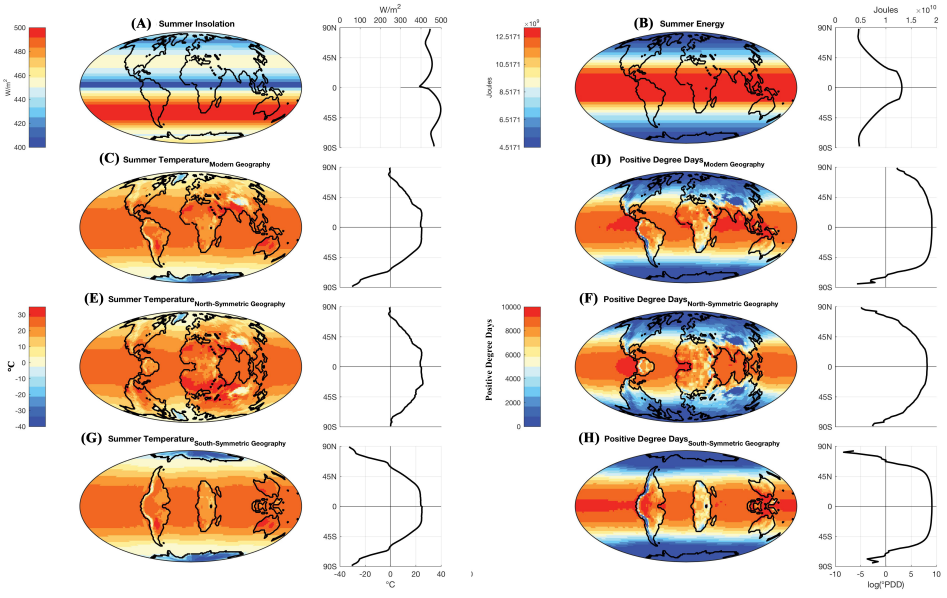

435

436 **Figure 2.** (A-D) Demonstration of Earth's asymmetric climate response to symmetric
437 climate forcing. Simulations are forced by modern day orbit: (A) Summer insolation; (B)
438 summer energy; (C) Summer Temperature; and (D) PDD. (E-H) Demonstration of
439 Earth's symmetric climate response to climate forcing when idealized symmetric Earth
440 geographies are used. Simulations are forced by modern day orbit: (E) and (F) Summer
441 Temperature and PDD for NORTH-SYMM simulation, (G) and (H) Summer
442 Temperature and PDD for SOUTH-SYMM simulation. The zonal averages are plotted on
443 the right of each Figure. Zonal averages of PDD are plotted on a log scale.

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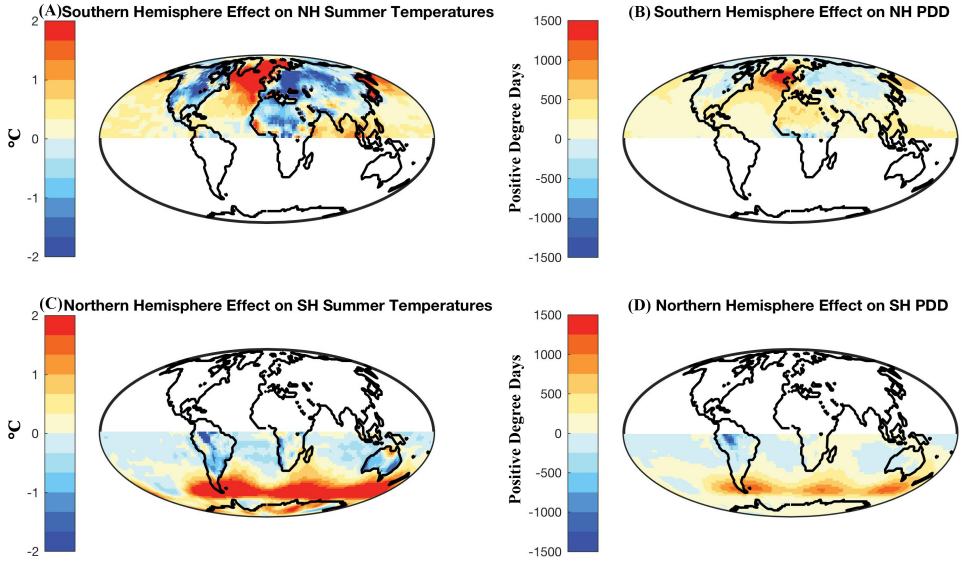

444

445 **Figure 3.** Interhemispheric effect of Southern Hemisphere continental geography on (A)
446 Northern Hemisphere Summer Temperature (ST) and (B) Positive Degree Days (PDD).
447 Interhemispheric effect of Northern Hemisphere continental geography on (C) Southern
448 Hemisphere Summer Temperature (ST) and (D) Positive Degree Days (PDD). Zonal
449 averages are plotted on the right of each figure.

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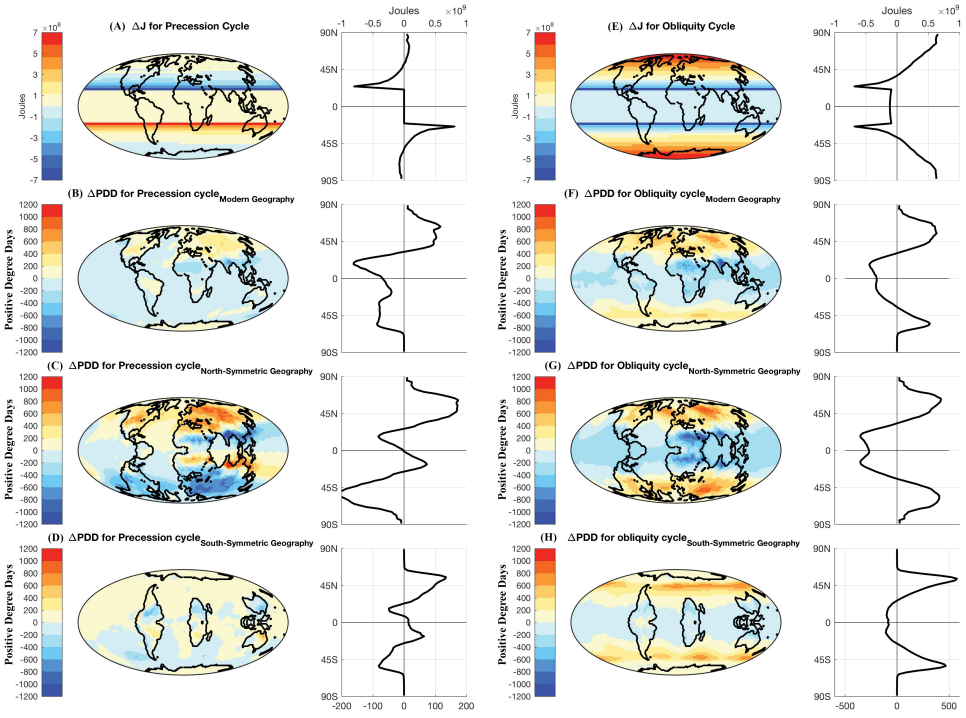

450

451 **Figure 4.** (A) Summer Energy change for a transition from SHSP to NHSP orbit and the
452 corresponding change in Positive Degree Days in CONTROL (B); NORTH-SYMM (C)
453 and SOUTH-SYMM (D) simulations. (E) Summer Energy change for a transition from
454 LOW to HIGH orbit and the corresponding change in PDD in CONTROL (F); NORTH-
455 SYMM (G) and SOUTH-SYMM (H) simulations.

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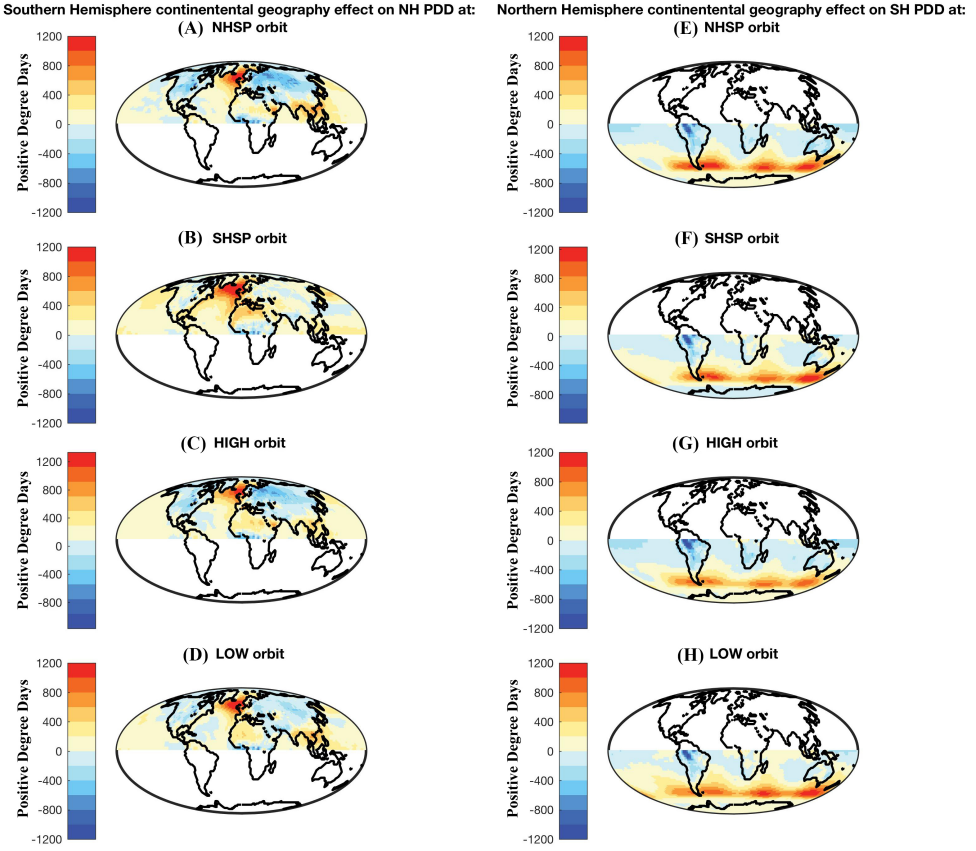

Figure 5. Interhemispheric effect of Southern Hemisphere continental geography on Northern Hemisphere climate: (A) at NHSP $[(\widehat{e_{PDD}})_{NHSP}]$; (B) at SHSP $[(\widehat{e_{PDD}})_{SHSP}]$; (C) at HIGH $[(\widehat{e_{PDD}})_{HIGH}]$; (D) at LOW $[(\widehat{e_{PDD}})_{LOW}]$.

Interhemispheric effect of Northern Hemisphere continental geography on Southern Hemisphere climate: (E) at NHSP $[(\widehat{e_{PDD}})_{NHSP}]$; (F) at SHSP $[(\widehat{e_{PDD}})_{SHSP}]$; (G) at HIGH $[(\widehat{e_{PDD}})_{HIGH}]$; (H) at LOW $[(\widehat{e_{PDD}})_{LOW}]$.

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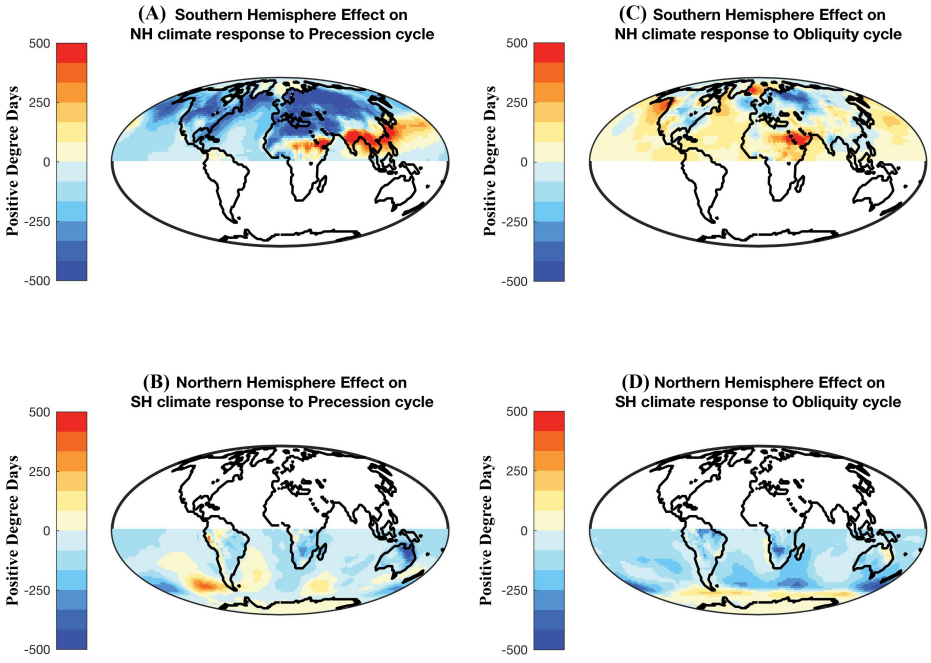

Figure 6. Interhemispheric effect of: (A) Southern Hemisphere continental geography on Northern Hemisphere $\Delta PDD_{precession}$ (response to precession forcing) $[(\widehat{e_{PDD}})_{precession}]$, (B) Northern Hemisphere continental geography on Southern Hemisphere $\Delta PDD_{precession}$ (response to precession forcing) $[(\widehat{e_{PDD}})_{precession}]$, (C) Southern Hemisphere continental geography effect on Northern Hemisphere $\Delta PDD_{obliquity}$ (response to Obliquity) $[(\widehat{e_{PDD}})_{obliquity}]$, (D) Northern Hemisphere continental geography effect on Southern Hemisphere $\Delta PDD_{obliquity}$ (response to Obliquity) $[(\widehat{e_{PDD}})_{obliquity}]$.

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