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Interactive comment on "Interhemispheric Effect of Global Geography on Earth's Climate Response to Orbital Forcing" *by* Rajarshi Roychowdhury and Robert DeConto

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1 – As clearly acknowledged in the body of the manuscript, we agree with Referee#2 that there are limitations with not using a fully coupled atmosphere-ocean GCM. We hope to spark future studies using true coupled models to study the interesting role of geographical hemispheric asymmetry on Earth's climate. While there are limitations to our model, its computational efficiency has the advantage of allowing a wide range of orbital parameter space to be explored, while minimizing ocean-model dependencies on the results.

In line 174 and 267, the "almost asymmetrical results" refer to almost symmetric re-

sults for positive degree days (PDD). This asymmetry arises from precession and location of perihelion with respect to each hemisphere's summer, as mentioned in the paper and also pointed out by the Reviewer. However, the calculation of PDD is autonomous of the choice of calendar. The definition of PDD, or the analogous Summer Energy (total integrated summer insolation, as defined in Huybers 2006) depend on a fixed threshold of daily average temperature to determine the duration and timing of summer. The choice of calendar does become important when we consider average summer temperatures. In our present results, we assumed a modern calendar, and defined summer in Northern Hemisphere as June-July-August and in Southern Hemisphere as December-January-February. Following the reviewers recommendation we have modified the approach by choosing a summer definition based on an insolation threshold (See point 4).

For the simulations shown here, the choice of averaged eccentricity was empirical, rather than theoretical. As rightly pointed out by Anonymous Referee #2, using zero eccentricity would make the orbit circular, thus muting any effect of precession. This is undesirable, as we wish to include the possible effects of astronomical forcing in the measured hemispheric asymmetry effect. On the other hand, using a high eccentricity intensifies the effect of precession, which may enhance its influence on the measured asymmetry. Please note that we are not discussing the role of hemispheric asymmetry on the TOA insolation forcing itself (because it is same regardless of the continental arrangement on Earth). Instead, we wish to discuss the role of hemispheric asymmetry on the climate, at different insolation forcings (corresponding to different orbits). Thus, a 'true discussion' of the role of asymmetry would involve simulations at every possible orbital configuration, including all possible eccentricity values. Keeping in mind the concise format of this paper, we show our results with a representative value of averaged eccentricity (0.034). However, we would like to mention that our conclusions regarding the hemispheric effects are not modified by using a different value of eccentricity (the values of individual model grid cells vary in the final figures, but the spatial patterns remain the same).

1b. Our paper does not focus on any specific time period in the past. We regret the confusion in our wording, and would like to clear any contradictory statements we might have inadvertently made. In line 408, we mention: "the amplification (or weakening) of the response to insolation changes at precessional and obliquity periods might explain some of the important features of late Pliocene-early Pleistocene climate variability". We do not mean that any geographical change due to plate tectonics has led to modification of the Earth's response to astronomical forcing. What we intend to stress is that the asymmetric continental configuration has an important control on the climate response of the Earth that might be relevant to interpretations of Plio-Pleistocene climate variability based on proxy records. Here we refer to specific climatic features of the Plio-Pleistocene, such as the dominance of obliquity over precession in the 40-kyr world benthic isotope records. The glacial cycles during the late Pliocene to early Pleistocene ($\sim$1-3 myr) had dominant 40-kyr frequencies. The primary frequency associated with the benthic δ18O records from this period corresponds to variation in the obliquity phase. This raises a major contradiction to Milankovitch's theory of orbital forcing, which predicts precession should be the strongest frequency in glacial-interglacial cycles. Raymo (2006) suggested that the glacial cycles are controlled by local summer insolation (dominated by the 23-ky precession period), but are out-of-phase between Northern and Southern Hemispheres. In addition to this, we suggest that in each hemisphere, the precessional effect on ice-volumes is muted due to hemispheric asymmetry (Roychowdhury and DeConto, Nature Communications, 2017, in review). When summers are warm in one hemisphere due to precession (precession varied in isolation, obliquity kept constant), the hemispheric asymmetry makes it colder than expected, and when it is cool due to precession, the interhemispheric asymmetry makes it warmer. We regret the confusion caused due to our vague wording, and have rephrased our statements in our revised manuscript to remove any such confusion.

2 – We thank the Referee for his valuable suggestion to include a more comprehensive introduction. We have rewritten the introduction and provide a stronger theoretical incentive to investigate the land symmetry/asymmetry problem using a GCM framework.

3. This caveat is fully acknowledged in the manuscript. In this case, this well tested and often used slab ocean model calculates prognostic (fully varying) SSTs as a function of seasonal thermodynamics. Ocean heat transport is parameterized as a function of the local sea surface temperature gradient, the fraction of land and sea at a given latitude, and tuned to fit the modern latitudinal dependence of ocean heat convergence with respect to latitude. Because the ocean depth is limited to 50-m (enough to capture the seasonal cycle of the mixed layer), the GCM comes into equilibrium relatively quickly, allowing us to run many experiments under a wide range of orbits. While a study like this would ideally include a full depth dynamical ocean, we view this as a next step, hopefully motivated in part by the results published here. Furthermore, dynamical ocean models introduce an additional level of complexity and complex model-dependencies that we think are best avoided in this initial study.

4. The choice of calendar affects the calculation of summer temperatures in our simulations with varying precession. In today's orbital configuration, the Earth is at perihelion during Southern Hemisphere summer (SHSP). This coincides with Northern Hemisphere summer occurring when the Earth is at aphelion. During NHSP, the earth is at perihelion during Northern Hemisphere summer. Consequently, in the latter case, the duration of NH summer season is shorter than present. This is due to Kepler's laws, which states that the time elapsed between the two positions of the Earth along the ellipse are proportional to the area covered. Thus, due to precessional effects amplified by eccentricity changes, the length of seasons varies through time (Joussaume and Braconnot, 1997, etc). When summer occurs at perihelion, the duration of summer is short, but the intensity of TOA insolation is strong. When summer occurs at aphelion, the duration of summer is long but the intensity is weaker. To take into account the duration of summer, Peter Huybers suggested the use of a time integrated summer metric (Huybers, 2006). In our manuscript, we have used PDD (following the definition from Huybers 2006 paper) as a measure of climate response, and this metric is independent of the choice of calendar.

However, when we discuss the hemispheric effects in "summer temperatures", we need to address the question of defining a calendar for different orbits. To better account for the phasing of the insolation curves for different orbits, instead of seasons defined with the same length as modern, we now define seasons by an insolation threshold; which will account for the astronomical positions as well as the phasing of the seasonal cycle of insolation. In this case, we define summer as the period during which the average daily insolation is above a specified threshold (325 W/m2). [Figure 1 and 2]

5. This paper indeed focuses on measuring the 'effect', with an assumption of causal link between the Southern Hemisphere geography and Northern climate and vice-versa. Giving a comprehensive mechanism of the hemispheric effect is beyond the scope of this particular manuscript. However, we have investigated the main linkages between the hemisphere effect and various atmospheric processes. As noted in the revised paper, we find that clouds, fractional snow cover, liquid water content in the atmosphere and atmospheric heat transport has the strongest impact of hemispheric asymmetry, thus contributing to the net hemispheric land asymmetry effect.

6. This is an excellent point raised by Reviewer#2. Our choice for "extreme precessions" being the solstices stems from our original motivation for studying hemispheric asymmetry at the poles. In the revised manuscript, we add new simulation results with perihelion coinciding with the solstices. This is a substantial improvement.

7. Line 299: "According to Milankovitch theory, the Northern Hemisphere should experience 'interglacial' conditions when perihelion coincides with boreal summer" We regret the confusion caused here by the lack of clarity in our wording. What we meant is that when precession is considered in isolation, i.e. not considering any effect of obliquity, then perihelion coinciding with Northern summer would imply warm 'interglacial' type conditions in Northern Hemisphere. This wording has been changed.

Line 400: "At precessional periods, at which the high latitude summer intensity primarily varies." We implied summer insolation intensity, and not the caloric summer insolation

(which is an integrated measure of insolation over time). The summer insolation intensity varies at precessional periods (23kyr) (Raymo et al. 2006, Huybers 2006, etc.). The caloric summer half-year at 65N, defined as the energy received during the half of the year with the greatest insolation intensity also has more than half its variance in the precession bands (Milankovitch 1941, Huybers and Tziperman 2008, etc.). This has been clarified in the revised manuscript.

8 – We agree with Referee #2's observation, and have updated the manuscript with historical references wherever applicable in the manuscript

9 – We will correct this in a revised manuscript.

References

Joussaume, S. and Braconnot, P, 1997; Sensitivity of paleoclimate simulation results to season definitions

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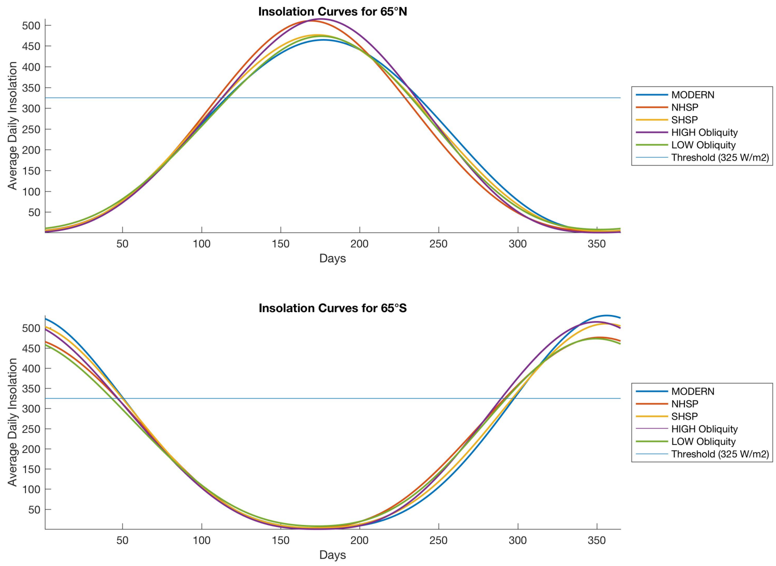

Fig. 1. Insolation curves for different orbits for Northern and Southern Hemispheres. The horizontal line shows the threshold of 325 W/m2 used to define summer

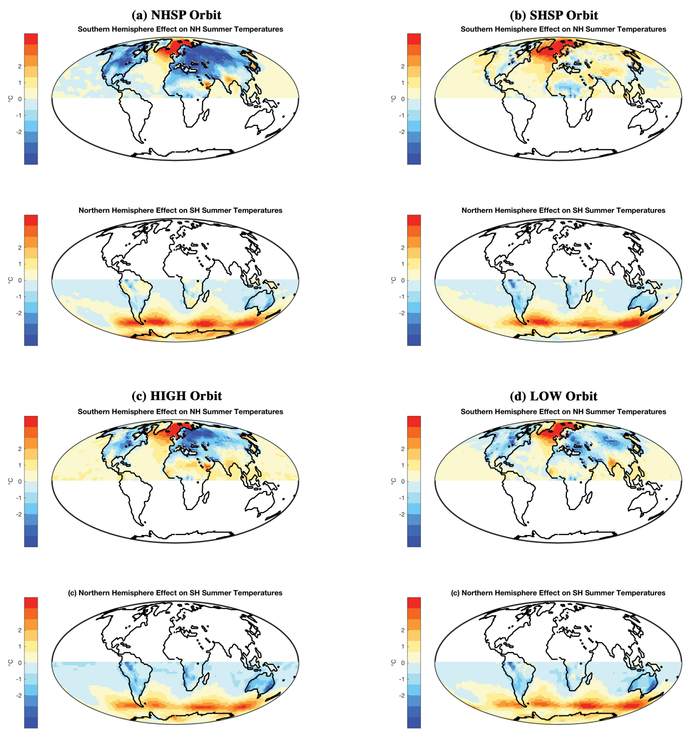

Fig. 2. Hemispheric Effects on Summer Temperature (summer defined by an insolation threshold) for different orbits (A) NHSP (B) SHSP (C) HIGH Obliquity (D) LOW Obliquity