Clim. Past Discuss., 3, S488–S493, 2007
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Climate of the Past Discussions

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Interactive Comment

Interactive comment on "Tropical cooling and the onset of North American glaciation" *by* P. Huybers and P. Molnar

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Received and published: 26 July 2007

Both reviewers provide useful guidance to improve the manuscript, and we address each of the points they raise below.

The first reviewer suggests that we provide a more thorough discussion of how our estimates of the change in northern North American (NNA) positive degree days (PDDs) compare with recent modeling studies which have simulated North America's response to increased eastern equatorial Pacific (EEP) sea-surface temperatures (SSTs) (*Barreiro et. al*. 2006; *Haywood et. al*., 2007). While we did provide some discussion of the relevant modeling studies in the introduction, an explicit comparison of our estimates with these simulations does seem appropriate. Note that detailed comparison with modeling results is hampered by the modeling studies reporting only winter and summer seasonal averages, whereas consideration of spring and fall temperature

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anomalies and, more to the point, changes in positive degree days, is pertinent for determining the implications of the simulation for glaciation.

Haywood et. al. (2007) show the temperature anomaly induced in a warm Pliocene-like climate when temperatures are made to be uniform across the Pacific, such that summer and winter EEP SSTs increase by 1 to 5 degrees respectively, and WEP SSTs increase in the winter and decrease in the summer by approximately one degree. Note this SST anomaly differs from the paleo-estimates of SSTs relative to today where WEP temperatures are thought to have been warmer on an annual average basis. Nonetheless, we can assign a rough two degree EEP warming to this simulation. The winter warming appears to average two degrees Celsius in NNA and the summer warming about half a degree Celsius, so that rather than the 1:1 ratio between EEP SSTs and NNA temperatures that we estimate, *Haywood et. al.*'s simulation indicates a relationship closer to 2:1. The pattern of warming is dissimilar between our estimates and Haywood et al's simulation — the warming we find is concentrated in the continental interior and their's more so at the fringes.

Barreiro et. al. (2006) specify a zonally uniform tropical temperature, but which unlike *Haywood et. al*. (2007) is seasonally varying. An approximately four degree Celsius annual average warming is imposed on the EEP, which in *Barreiro et. al.*'s simulation results in the interior of Northern North America warming by approximately four degrees C. Maximum warming is concentrated in the interior of NNA. Thus, both the spatial distribution and the magnitude of warming that we extrapolate from modern El Nino events is born out in the simulation of *Barreiro et. al.* (2006).

The sensitivity of NNA temperature to assumed EEP SSTs in the simulations of *Haywood et. al*. (2007) and *Barreiro et. al.* (2006) differ by approximately a factor of two. Presumably this owes to different anomalies and different seasonal cycles in SSTs being specified, that the models are themselves different, and that the anomalies are calculated away from different basic states. Of these, the last point is perhaps the most important. *Haywood et. al*. (2007) specify an already warm climate relative to the

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present, and then calculate anomalies away from this climate induced by warming EEP SSTs, thus obtaining sensitivities referenced to a different background state than we consider in our study. Reassuringly, however, we find that the changes in ablation are twice as large as necessary to preclude glaciation and, thus, even the weaker sensitivity implied by *Haywood et. al.*'s simulation ought to still be consistent with the absence of glaciation.

Both reviewers suggest giving greater attention to changes in precipitation. Indeed, it has been argued that an El Niño-like state will enhance the fall/winter moisture supply and thus enhance glacial accumulation (*Kukla et. al*., 2002). We have estimated the anomaly in precipitation which occurs during the year preceding and following an El Niño event. In the mid-latitudes, from 25° to 50°N, precipitation is seen to increase by 5cm and 8cm for the year preceding and following an El Nino event respectively, consistent with other observational analysis (*Phillips el. al*., 1999). At North American latitudes above 50°N, however, we find that changes in precipitation are small — the regional average change is less than 1cm/year. These results appear consistent with the simulation of *Barreiro et. al*. (2006, their Fig. 7).

We anticipate that the changes in ablation associated with El Niño are much more significant than the changes in accumulation. Consider that a typical El Niño event is associated with a 90 degree-day increase in NNA positive degree days, translating to somewhere between 30cm and 70cm of ablation, depending on which scaling coefficient is selected. Changes in precipitation are about an order of magnitude smaller at mid-latitudes and at the more relevant, high latitudes are even smaller. The first reviewer emphasizes the requirement of a moisture source for building an icesheet, and we will include changes in moisture supply from the Pacific in the discussion of possible mechanisms for initiation of glaciation. But, as is generally the case for glaciers and icesheets (e.g. *Patterson*, 1994), the temperature effect is anticipated to be a far more important determinant of mass balance.

There were some questions regarding details of the datasets employed in this study.

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To define the ten largest El Nino intervals we used the *Kaplan et. al.* (1998) dataset for sea-surface temperatures, which extends back to 1856. Which El Niño events are the largest will depend, to a limited extend, on which dataset and what smoothing techniques are used. We have repeated our analysis using different numbers of El Niño events and obtained results which correspond to these top ten events, and thus are confident that discrepancies over which El Niño events are the largest does not compromise our results.

The continental temperature and precipitation observations are from the GHCN dataset. The GHCN compilation provides daily resolution temperature and precipitation data from over 7000 cites, chosen to provide near global land coverage, with most records extending back to 1950 and some as far back as 1850. Temperature and precipitation records are nearly continuous but, inevitably, a small amount of data is missing. See *Peterson and Vose*(1997) for more details.

In regressing EEP and NNA temperatures against each other, we anticipate that both time-series are noisy, and thus that the regression coefficient will be biased low. To correct for this bias we choose to use what is probably the simplest method, dividing the regression slope by the estimated correlation of the two time-series (see *Frost and Thompson*, 2000, secs 2.5 and 2.6). The reference to *Frost and Thompson* (2000) was given because they provide an overview of six different methods which have been proposed to account for regression bias. We expect that the bias corrected slope is more accurate than its uncorrected counterpart. It should also be noted that this regression only serves to demonstrate consistency with our results obtained from using the ten largest El Niño events, and we do not rely upon this regression when estimating the expected change in temperature or PDDs to El Nino events or for a warmer EEP.

The second reviewer points out that, if this idea is correct, it leaves us with the puzzle of what caused the EEP to cool off on a timescale too long to invoke the atmosphere-ocean-cryosphere system by itself. We agree, and while acknowledging the Indonesian through-flow hypothesis, we feel this is a crucial problem to be addressed in future

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studies.

Response to minor comments:

"Section 1, Introduction: Please explain briefly the methodology that is used in this study."

In an earlier draft, we did give a description of the methodology in section one, but given the brevity of the manuscript it seemed redundant, and we now choose to exclude such a paragraph.

"Page 774, line 27. Could you please be more specific concerning the magnitude of the changes in precipitation and snow accumulation that are associated with El Nino events?"

We do not have snow accumulation data, although the model results of *Barreiro et. al.* (2006), which are consistent with our findings in other respects, show a decrease in annual average snow cover of approximately 2cm in northern North America. We have discussed changes in precipitation earlier in this note.

"Page 775, line 8. Please explain why a 2-year extension is chosen."

The two year interval encapsulates the period during which EEP temperature are anomalous during an El Niño event.

"Page 775, lines 20-22. 'Winter temperature can breach the freezing point at mid-latitudes, and warming is expected to increase ablation'. I am not convinced that a slight winter warming would have a large effect on ablation. As mentioned by the authors on Page 774 (line 7), a significant increase in ablation requires a summer warming. So I would suggest modifying this statement."

Yes, a small excursion above the freezing point will not cause a large change in ablation. We only mean to call attention to the fact that snow can and does melt in the winter as well. The statement is amended to, "Winter temperature can breach the freezing

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point at mid- latitudes, and warming is expected to cause a modest increase ablation."

"Page 777, line 9. 'The NINO3.4 and northern North American temperature anomalies both average 1C, giving a ratio of 1 (Fig. 3)'. This information is not in Figure 3."

Figure 3c indicates the anomaly in northern North American temperature during an El Nino event. We will change the figure callout to better indicate this.

"Page 778, lines 28-29. 'Furthermore, observation of past temperatures are spaced at centennial or lower resolution'. This statement is confusing, as it is clearly not valid for the GHCN data. Please revise."

We plan to revise this to read that proxy observations are spaced at centennial resolution.

"References: The reference to Lawrence et al. is incomplete (name of T.D. Herber t is missing) . 9. Figure 1. Label (d) is missing. 10. Figures 3 and 4. I suggest to include the units in the Figures (next to the color bars), where appropriate. 11. Caption Figure 4. 'the the tilt' should be 'the tilt'."

We plan to correct these in a revised manuscript.

Interactive comment on Clim. Past Discuss., 3, 771, 2007.