GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L23704, doi:10.1029/2008GL034308, 2008

Reply to comment by Andrey Ganopolski and Thomas Schneider von Deimling on "Aerosol radiative forcing and climate sensitivity deduced from the Last Glacial Maximum to Holocene transition"

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Received 15 April 2008; revised 4 October 2008; accepted 23 October 2008; published 5 December 2008.

Citation: Chylek, P., and U. Lohmann (2008), Reply to comment by Andrey Ganopolski and Thomas Schneider von Deimling on "Aerosol radiative forcing and climate sensitivity deduced from the Last Glacial Maximum to Holocene transition," *Geophys. Res. Lett.*, *35*, L23704, doi:10.1029/2008GL034308.

[1] In our recent publication [*Chylek and Lohmann*, 2008] (hereafter referred to as CL08), we have presented an estimate of aerosol forcing and climate sensitivity based on Vostok ice core data [*Petit et al.*, 1999] for the Last Glacial Maximum (LGM) to Holocene transition. The novel feature of our analysis was the use of a cooling from a warm period about 42,000 years ago (or 48,000 depending on the time scale used) to the LGM together with the warming from the LGM to Holocene. The use of these two period together provided an additional constrain of the aerosol radiative forcing, and consequently the aerosol radiative forcing from the LGM to Holocene transition was obtained from the data rather than from the modeling as has been done in the past. Our results suggest the aerosol radiative forcing for the LGM to Holocene transition to be 3.3 ± 0.8 W/m^2 and the climate sensitivity to be between 0.36 and 0.68 K/Wm^{-2} (yielding a global temperature increase between 1.3 and 2.3 K for doubling atmospheric CO_2 concentration). For comparison the IPCC report suggests the temperature range for CO_2 doubling to be between 2 and 4.5 K (with 60% probability), with values below 1.5 K very unlikely. Thus our result supports the lower end of the IPCC suggested values.

[2] The comment on our paper [*Ganopolski and Schneider von Deimling*, 2008] (hereafter referred to as GS08) has raised several interesting questions, which we answer in the following.

[3] GS08 is correct in pointing out that the range of climate sensitivity deduced from the Vostok ice core data is well below that of the IPCC report. The IPCC stated range of climate sensitivity and confidence level stem from summarizing many different model estimates and different proxy analysis to obtain the overall range of possible climate sensitivity. The IPCC confidence level refers to an intra-model and intra-proxy range and confidence level. In our study, the range of climate sensitivity and the confidence level is based on the statistical analysis of one set of data.

[4] GS08 points out that we have used the Antarctic cooling of 10.2 K for the LGM deduced from the Vostok data without attaching an uncertainty to this value. The temperature difference used by CL08 of 10.2 K between the Holocene and the LGM was deduced from the oxygen isotope ratio δ^{18}O from the Vostok ice core [*Petit et al.*, 1999]. The EPICA Dome C ice project uses the deuterium δD to recover the temperature. Their result for the difference between the LGM and the Holocene is again around 10 K [*Jouzel et al.*, 2007]. Thus there is a good agreement between the two ice cores using two different methods to deduce the temperature differences. Although there may be some uncertainty in the Antarctic temperature LGM to Holocene difference, the 10.2 K for the Vostok site seems to be reasonable.

[5] To estimate the average global temperature during the LGM, GS08 suggests a vast range of values deduced from modeling results. Our work is based on observational data instead. The proxy data suggests that the tropical land masses and oceans were on average 3.3 K colder during the LGM than they are at present [*Ballantyne et al.*, 2005]. The ratio of the global to tropical temperature increase during the instrumental records (1880–2007) has been around 1.43 (Figure 1a). If we assume a similar ratio of global to tropical warming of 1.4 to 1.5 for the LGM to Holocene warming, we obtain the global temperature difference of 4.6 to 4.9 K. The frequently used approximation of the global temperature change during the LGM to Holocene transition is that the global temperature change has been about $^1/_2$ of the Antarctic change, which leads to values around 5 K [*Hansen et al.*, 2008]. We have emphasized the uncertainty in the global temperature during the LGM of CL08 by using three different values, namely, 4.1, 4.6 and 5.1 K. Consequently, we consider the chosen range 4.1 to 5.1 K to be adequate. On the other hand we agree with GS08 that using a variety of models might suggest a wider range depending on specific models used.

[6] GS08 point out that our estimate of radiative forcing of 3.3 ± 0.8 W/m^2 is higher than some previous estimates. This is really the point of our paper and the reason we decided to publish it. In contrast to previous researchers we did not simulate the aerosol radiative forcing during the LGM to Holocene transition. Our value for the aerosol radiative forcing is calculated from ice core data and the assumption that the climate sensitivity in the two considered transitions: (1) from a warm period about 42,000 to 48,000 years ago (depending on time scale used) to the LGM, and

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0094-8276/08/2008GL034308$05.00

(2) from LGM to Holocene, is the same. Although there is no proof that the climate sensitivity was really the same, we believe that the assumption is reasonable, and this assumption is clearly stated by CL08. We consider the aerosol forcing ≤ 1 W/m^2 used frequently by other investigators to be a considerable underestimate. The IPCC 2007 report estimates the mean value of the current anthropogenic aerosol radiative forcing to be -1.2 W/m^2. It is hard to accept that the aerosol radiative forcing during the ice ages when dust concentration in the Antarctic and Greenland ice cores is over 50 times higher than during the Holocene, and when increased dust deposits are observed in marine sediments in Atlantic and Pacific Ocean, can be lower than the current anthropogenic aerosol radiative forcing. A radiative forcing during the LGM between 1.9 and 3.3 W/m^2 has been suggested by *Harvey* [1988]. Other researchers [*Harrison et al.*, 2001; *Claquin et al.*, 2003] pointed out that the aerosol radiative forcing during the LGM, at least in the tropics, could be as strong as the radiative forcing due to increased greenhouse gases during the LGM to Holocene transition. Our results confirm these higher values and suggest that the radiative forcing due to aerosols was, indeed, approximately equal to the radiative forcing of greenhouse gases during the LGM to Holocene transition.

[7] GS08 states that the considered warm event in Antarctica (42,000 or 48,000 years BP) does not correspond to global climate change and that the warming in Antarctica at that time was not matched by a warming in Greenland. It is not an easy task to align in time the events taking place in Greenland and in Antarctica. Since the inter-hemispherical mixing of long-lived greenhouse gases occurs on a time scale of a year the peaks in CH_4 concentration were used to synchronize the time scales of Greenland and Antarctic ice cores [*Blunier et al.*, 1998; *Blunier and Brook*, 2001; *Ahn and Brook*, 2008]. It was found that the starting point of warming in Antarctica leads that of Greenland by one or two thousands years. While the Antarctic temperature increase is gradual within a few thousand years, the Greenland warming is fast, lasting maybe as little as two or three decades [*Blunier et al.*, 1998]. Thus Greenland warming catches up with the Antarctic warming and the temperature peaks do occur in both hemispheres almost simultaneously with the Greenland delay of a few hundred years (Figure 1b) being smaller than uncertainty of the time scale (±300 yrs). Although the beginnings of warming periods are not simultaneous in the two hemispheres, the peak temperatures and the following cooling are. In the time interval selected the temperature peak of the Antarctic event A-2 coincides with the temperature peak in the Greenland Dansgaard-Oeschger event 12 [*Blunier et al.*, 1998; *Ahn and Brook*, 2008]. After that both Antarctic and Greenland temperatures are simultaneously decreasing, suggesting the synchronized climate change. Thus our analysis (CL08) of the ice core data for a time of a maximum temperature (around 42,000 to 48,000 years BP) and the minimum temperature during the LGM is justified. The dust deposits showing low values at the

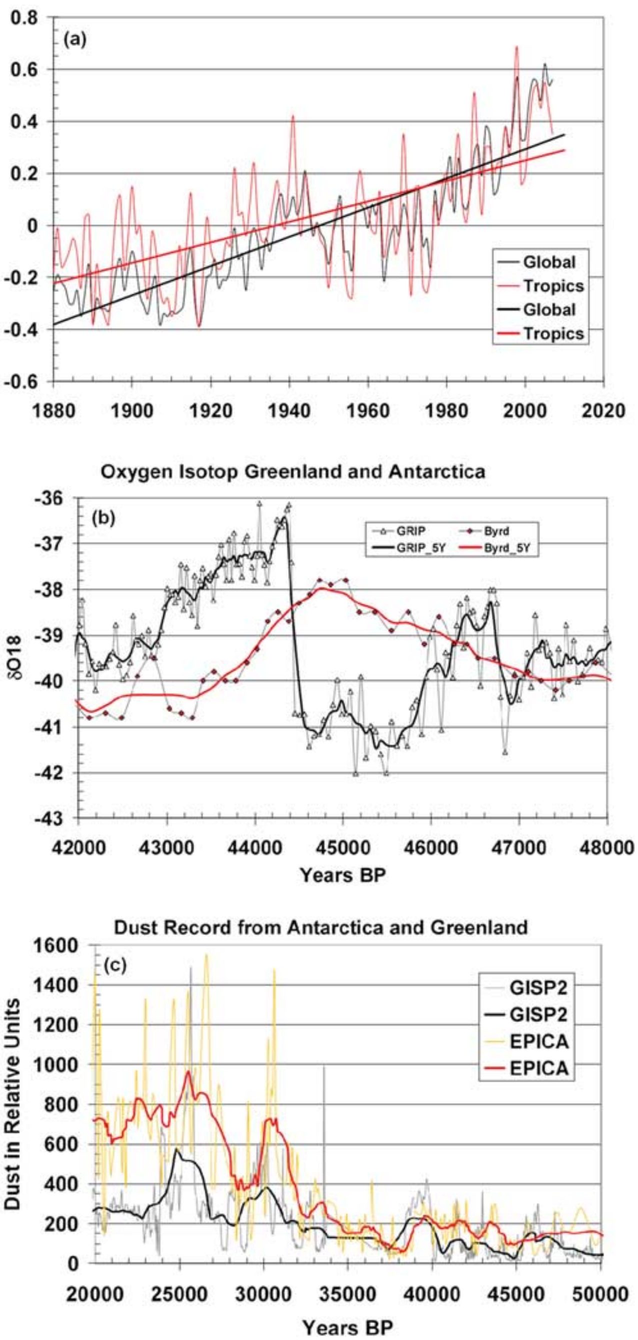

Figure 1. (a) Temperature anomaly (tropics: 24°S to 24°N and global) according to the data from the NASA GISS website suggests the ratio of the global mean to tropical temperature change of 1.43. Essentially the same slope ratio is obtained for the time spans 1880–2007 (1.43), 1900–2007 (1.42) or 1980–2007 (1.38). Thin lines connect the annual data; thick lines show the linear regressions. (b) Oxygen isotopic ratio for the GRIP and the Byrd Station ice cores (annual values and 5 year running mean) showing the Dansgaard-Oeschger event 12 (DO-12) and the Antarctic event A-2. The data used are from *Blunier and Brook* [2001]. (c) Dust concentration in the GISP2 and EPICA Dome-C ice cores in relative units. Thin lines connect individual point and thick lines represent a ten point running average. The GISP2 data are from *Ram and Koenig* [1997], EPICA Dome-C data from *Delmonte et al.* [2004]. Maximum concentrations around 25 KYBP as well as minimum around 45 KYBP occur simultaneously in both the Antarctic and the Greenland ice cores.

maximum temperatures and the following major simultaneous peaks in the Greenland and Antarctic ice cores (Figure 1c) further confirm that the changes in dustiness were global in character.

[8] Finally, our reference to agreement between our analysis and the GCM refers to the ECHAM5 GCM simulation, which we have performed with the global sources of dust increased by a factor 4 and the sources of marine aerosols by a factor of 2. The recent paper [*Winckler et al.*, 2008] suggests dust flux increases into the Pacific Ocean by a factor 2.5 ± 0.5 during the LGM. Our simulation increased the dust burden by a factor of 3.4, increased the aerosol optical depth by about 0.15 (compared to about 0.04 estimated for the post industrialization increase [*Lohmann et al.*, 2007]), and produced the aerosol radiative forcing of 3 W/m^2. Thus we conclude that the role of glacial aerosols is likely to be as large or at least almost as large as deduced from observational data of CL08 and our range of climate sensitivity is reasonable but may be a bit underestimated.

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