What caused Earth's temperature variations during the last 800,000 years? Data-based evidences on radiative forcing and constraints on climate sensitivity

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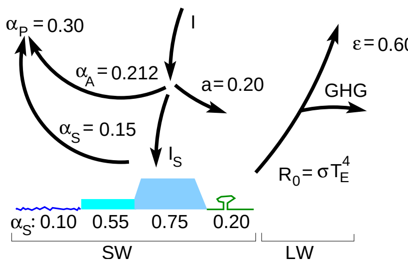
The temperature on Earth varied largely in the Pleistocene from cold glacials to warmer than present interglacials. To contribute to an understanding of the underlying causes of these changes we compile various environmental records (and model-based interpretations of some of them) in order to calculate the direct effect of various processes on Earth's radiative budget and, thus, on global annual mean surface temperature over the last 800,000 years. The importance of orbital variations, of the greenhouse gases CO_2, CH_4 and N_2O, of the albedo of land ice sheets, sea ice area and vegetation, and of the radiative perturbation of mineral dust in the atmosphere are investigated. Furthermore, changes in annual mean snow cover on surface albedo and of ice sheet elevation and sea level change on orography are considered as additional contributors to glacial cooling. Altogether we can explain with these processes a global cooling of ~4-6 K in the equilibrium temperature for the Last Glacial Maximum (LGM) directly from the radiative budget using only the Planck feedback but neglecting other feedbacks such as water vapour, cloud cover, and lapse rate. The unaccounted feedbacks would, if taken at present day feedback strengths, ask for another cooling at the LGM of 2 to 10 K. Increased Antarctic temperatures in Marine Isotope Stages 5.5, 7.5, 9.3 and 11.3 are difficult to explain. If compared with other studies, such as PMIP2, this gives supporting evidence that the feedback strength themselves are not constant, but depend on the mean climate state. The best estimate and uncertainty for the reconstructed radiative forcing and LGM cooling support a present day climate sensitivity (excluding the ice sheet and vegetation components) between 1.3 and 5.2 K, with a most likely value near 2.3 K, somewhat smaller than other methods but consistent with the consensus range of 2–4.5 K derived from other lines of evidence. Climate sensitivities above 6 K are difficult to reconcile with LGM reconstructions.

The Conceptual Radiative Balance Model



Conceptual global annual mean radiative budget of Earth's atmosphere with parameters for present day.

Some Calculations

Temperature changes: $\Delta T_{E,\infty} = \frac{-\Delta R}{\lambda}$, with λ is the climate feedback parameter

$$\lambda = \lambda_P + \lambda_{WV} + \lambda_{LR} + \lambda_C, \qquad (1)$$

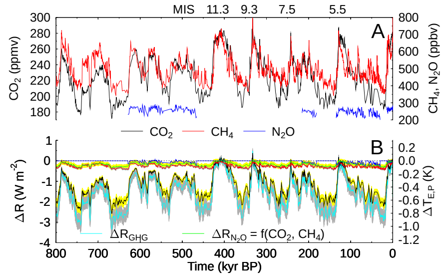
which are the Planck (P), water vapour (WV), lapse rate (LR), and cloud (C) feedback parameters.

$\Delta R = \frac{\delta R}{\delta T}|_{T=T_E} \cdot \Delta T_{E,P}$ with $\frac{\delta R}{\delta T} = 4\varepsilon\sigma T^3$

Planck feedback parameter $\lambda_P = \frac{-\Delta R}{\Delta T_{E,P}} = -3.2\ \frac{Wm^{-2}}{K}$

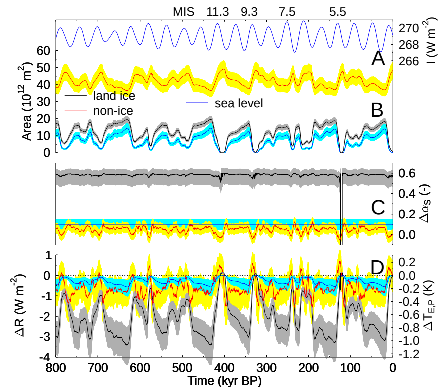
To calculate changes in the radiative balance ΔR (besides those caused by GHG) we have to compile (a) changes in insolation I, (ii) changes in albedo α, and (sometimes) (iii) changes in the respective area.
A first tentative estimate on changing temperature (right y-axes) is given by calculation of $\Delta T_{E,P}$ based only on the Planck feedback.

Greenhouse Gases



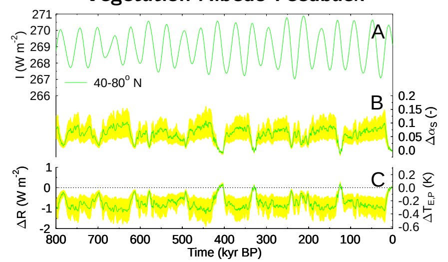
(A) CO_2, CH_4 and N_2O (Petit et al. 1999; Monnin et al. 2001; Siegenthaler et al. 2005; Lüthi et al. 2008; Spahni et al. 2005; Loulergue et al. 2008). (B) Perturbation in the radiative budget.

Albedo Feedback from Land Cryosphere



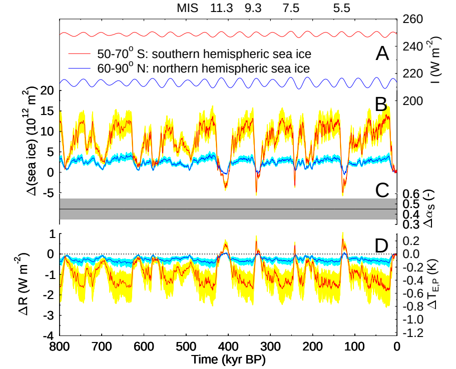
(A) Annual mean local insolation at the top of the atmosphere I at 40–80° N. (B) Area changes of (i) land ice sheets (North America and Eurasia only) and (ii) land without ice, and (iii) global shelf area effected by sea level change. (C) Changes in surface albedo α_S on areas plotted in (B) (Bintanja et al. 2005). (D) Perturbation in the radiative budget.

Vegetation-Albedo Feedback



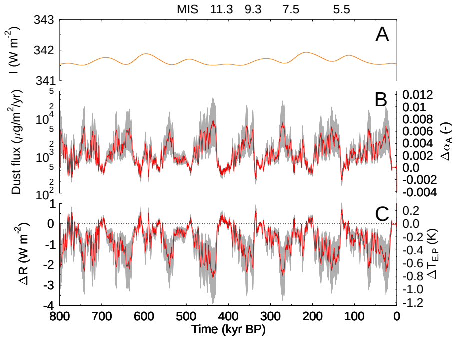
(A) Annual mean local insolation at the top of the atmosphere I at 40-80° N. (B) Changes in surface albedo α_S over vegetation in 40-80° N calculated out of continental surface air temperature changes (Bintanja et al. 2005). (C) Perturbation in the radiative budget.

Sea Ice-Albedo Feedback



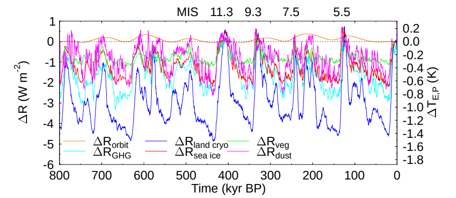
(A) Annual mean local insolation at the top of the atmosphere I at 50–70° S and 60–90° N, the regions of SH and NH sea ice, respectively. (B) Area changes of sea ice. Estimates are based on (i) Antarctic temperature changes for the SH (Jouzel et al. 2007) and (ii) northern hemispheric temperature changes for the NH (Bintanja et al. 2005; Lisiecki & Raymo 2005), linearly related to LGM to present sea ice area reconstructions. (C) Perturbation in the radiative budget..

Dust-Albedo Feedback



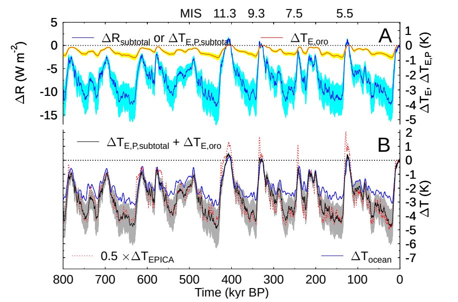
(A) Annual and global mean local insolation I. (B) Variation in dust flux (Lambert et al. 2008) and calculated changes in atmospheric albedo α_A (right y-axis). (C) Perturbation in the radiative budget.

Comparing All Processes



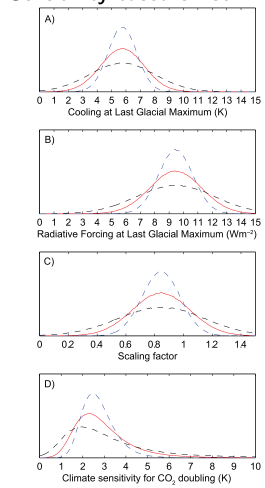
A compilation of individual radiative forcings. Orographic effects and feedbacks from water vapour, lapse rate, and clouds are omitted here.

Comparing with Temperature Estimates



(A) Sum of radiative forcing of individual processes ($\Delta R_{subtotal}$) and temperature effect of orography ($\Delta T_{E,oro}$). (B) Calculated temperature anomaly $\Delta T_{E,P,subtotal} + \Delta T_{E,oro}$ without further feedbacks of water vapour, lapse rate and clouds. Reconstructed temperature: (i) Antarctic ΔT_{EPICA} from the EPICA Dome C ice core (Jouzel et al. 2007) scaled with a constant polar amplification of two. (ii) Deep ocean ΔT_{ocean} deconvoluted from the benthic $\delta^{18}O$ stack LR04 (Bintanja et al. 2005).

Climate Sensitivity based on our ΔR @ LGM



Probability distributions of (A) global cooling at the LGM (Schneider von Deimling et al. 2006). (B) the LGM global radiative forcing relative to today from greenhouse gases, orbital forcing, ice sheets, vegetation and dust. (C) uncertainties in the scaling factor used to translate LGM climate sensitivity to present day sensitivity. (D) present day equilibrium climate sensitivity for atmospheric CO_2 doubling resulting from panels A-C. The estimated climate sensitivity includes the Planck, water vapour, lapse rate, sea ice/snow cover albedo and cloud feedbacks occurring on timescales of decades or less (equivalent to the climate model or Charney sensitivity) and is the quantity that is relevant for future climate projections on timescales of decades to centuries. The effects of ice sheets and vegetation changes are treated as a forcing. Red solid lines: standard; black: +50%; blue: −33% changes in uncertainties.

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