

The role of mineral-dust aerosols in polar temperature amplification

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Changes in global temperature are generally more marked in high than in low latitudes, an effect referred to as polar amplification^{1–3}. Model simulations of future climate suggest a marked response of high-latitude climate due to elevated greenhouse-gas concentrations and associated albedo feedbacks⁴. However, most climate models struggle to reproduce the amplitude of polar temperature change observed in palaeoclimatic archives³ and may carry this bias into future predictions. With the example of mineral dust we show that some atmospheric aerosols experience an amplified high-latitude response to global changes as well, a phenomenon generally not captured by the models. Using a synthesis of observational and model data we reconstruct atmospheric dust concentrations for Holocene and Last Glacial Maximum (LGM) conditions. Radiative forcing calculations based on our new dust concentration reconstructions suggest that the impact of aerosols in polar areas is underestimated in model simulations for dustier-than-modern conditions. In the future, some simulations predict an increase in aridity in dust source areas⁵. Other aerosols such as black carbon and sulphates are likely to increase as well^{6,7}. We therefore suggest that the inclusion of the amplified high-latitude response of aerosols in atmospheric models would improve the assessment of LGM and future polar amplification.

Polar amplification has been subjected to ample scrutiny in the context of rising temperature in the near future¹. The mechanisms of this phenomenon are not yet fully understood, but variations in snow- and ice-covered areas, and the resulting albedo changes, seem to be the largest contributor^{8,9}, although additional mechanisms have been proposed¹⁰. Climate models predict a marked response of the polar areas in increased CO₂ scenarios, potentially as large as the changes between simulated LGM and Holocene climatic conditions³. However, the validity of model results obtained for climatic conditions markedly different from today's is uncertain. When compared with temperature reconstructions from palaeoclimatic archives, climate models seem to consistently underestimate polar temperature amplification during the LGM (ref. 3). This suggests that some important elements are not yet satisfactorily represented in the models.

Under LGM climatic conditions, global and equatorial temperature were around 3–4 K colder than during the Holocene¹¹. In polar areas this difference was amplified to 8–20 K (refs 3,12,13). The LGM to Holocene radiative perturbation in high latitudes due to

extended ice sheets has been estimated to be -20 W m^{-2} (ref. 14). In comparison, the global effect of reduced CO₂ concentrations during the LGM is believed to be -2.8 W m^{-2} (ref. 15). The temporal evolution of the temperature amplification factor from LGM to modern conditions is shown in Fig. 1a for the global average and three different regions. LGM to Holocene temperature changes in the Arctic and Antarctica were larger than the global average by a factor of about 5 and 2.5, respectively. Such a disproportionate response to climate change in high latitudes was not confined only to temperature. Polar dust deposition records show much larger relative glacial–interglacial changes than records from the mid- and low latitudes (Fig. 1b). As with temperature, the background dust deposition fluxes in low latitudes agree well with the estimated global average change. However, the change in dust deposition at the poles is one order of magnitude larger than the global average, possibly owing to a weaker hydrological cycle in colder climate that would reduce the washout of dust particles from the air¹⁶. On the basis of measurements of surface dust flux in palaeoclimatic archives, we propose an alternative way to estimate Holocene and LGM atmospheric dust aerosol concentrations, and show that the magnitude of change in polar dust concentrations is amplified compared with the global average. We examine the conditions during the LGM as an extreme case of dustier climate to anticipate what we may expect from enhanced atmospheric aerosol concentrations in the twenty-first century.

Dust aerosols affect radiative forcing directly by scattering and absorbing solar and thermal radiation¹⁷, and indirectly by acting as condensation nuclei for ice and water droplets¹⁸. Modern atmospheric dust concentrations can be derived from satellite measurements in certain areas¹⁹, but only dust modelling studies have provided global estimates^{20,21}. Information on dust deposition in the past can be obtained from climatic archives²². In turn, dust model emission parameters can be tuned to match the observed depositions and provide an estimate for present and past atmospheric concentrations^{20,21}. We approached the problem from a different angle and reconstructed atmospheric dust concentrations by combining depositional model parameters with observational palaeoclimatic data (see Supplementary Information). By adopting only the vertical profiles and deposition parameters from the models, thus bypassing the errors stemming from source and transport simulations, we reduce our dependency on the models and thus potentially our uncertainties, especially in polar areas where dust models perform less reliably than

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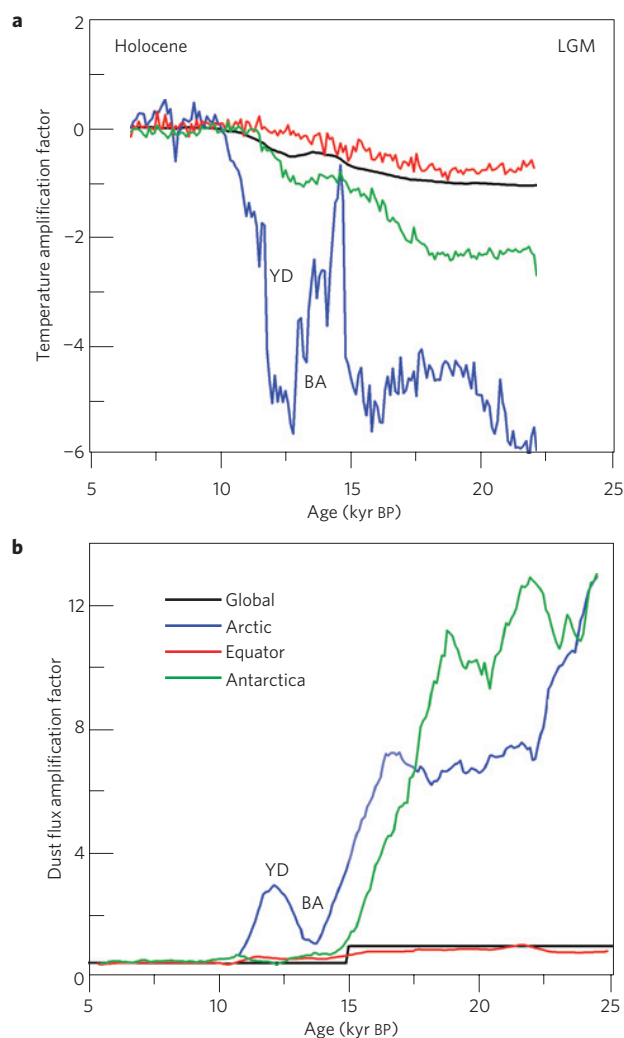


Figure 1 | Holocene to LGM amplification factors in temperature and dust flux. a, b, Temperature (a) and dust amplification (b) factors (see Methods). The variations in the Arctic record during the deglaciation show the Younger Dryas (YD) and the Bølling-Allerød (BA) interstadials, two large temperature changes that affected the Northern Hemisphere. The Younger Dryas and Bølling-Allerød events are less pronounced in the dust as Arctic dust sources in Asia were less affected than the northern high latitudes.

in lower latitudes. We use two different dust model studies to determine our uncertainties: the Community Atmospheric Model 3 coupled with the Climate Community System Model 3 (ref. 20; hereafter CCSM), as well as Tokyo University's SPRINTARS aerosol model coupled with the Model for Interdisciplinary Research On Climate²¹ (hereafter MIROC) provide two different simulations of the dust cycle, each for both Holocene and LGM conditions. Both models struggle to reproduce larger high-latitude relative changes compared with lower latitudes, as seen in observational data (see Supplementary Information). Their respective low and high dust deposition velocities result in an upper and lower bound for the reconstruction of atmospheric dust concentrations (see Supplementary Information).

Climate models usually reproduce the global LGM-Holocene temperature difference well, but underestimate the amplified polar response obtained from palaeoclimatic archives (Fig. 2a). Their ability to accurately predict future polar amplification is therefore put into question. The discrepancy between modelled and measured temperature differences is especially large in the northern polar area. The strong polar amplification signal in Greenland is

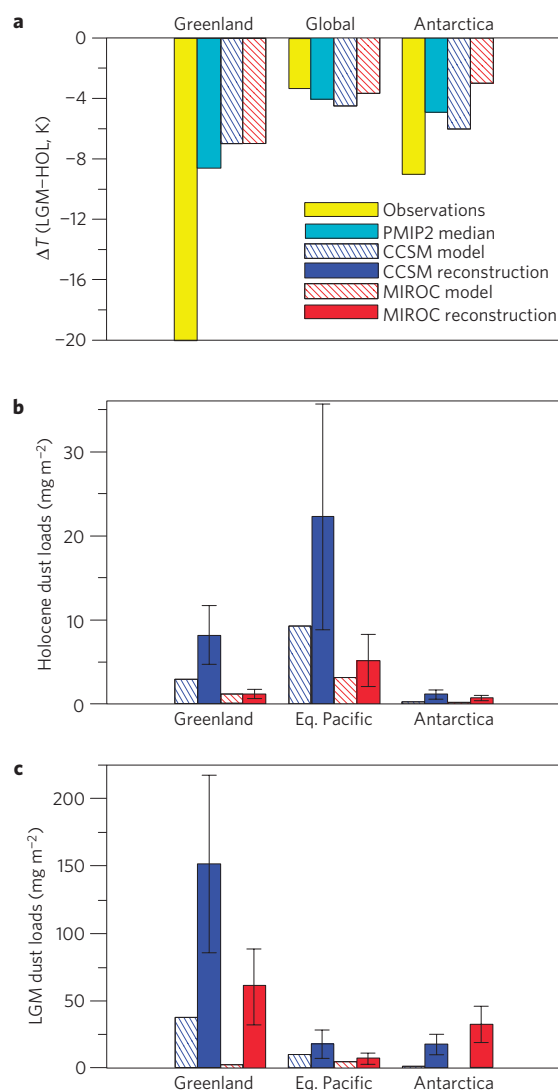


Figure 2 | Polar amplification in temperature and dust loads. a, Global and polar Holocene to LGM temperature changes illustrating the polar amplification in observations from palaeoclimatic archives^{11,12} and in Paleoclimate Modelling Intercomparison Project Phase II (PMIP2) models³. **b,** Average reconstructed and simulated^{20,21} Holocene dust loads at the sites given in Supplementary Table ST2. **c,** Average reconstructed and simulated^{20,21} LGM dust loads at the sites given in Supplementary Table ST2. The error bars in b, c represent the uncertainty of the upper (CCSM) and lower (MIROC) reconstruction bounds due to dust flux and dry deposition fraction measurements alone. Uncertainties associated with modelled parameters are not taken into account (see Supplementary Information).

thought to mainly result from changes in topography, albedo, and atmospheric and ocean circulation³. We suggest here that the much higher atmospheric mineral-dust concentrations during the LGM had a significant impact on polar climate and contributed to the polar amplification phenomenon by increasing the polar cooling.

To test our hypothesis, two sites were chosen over both the Greenland and the Antarctic ice sheet (Supplementary Table ST2), far away from dust sources. A remote site in the central equatorial Pacific provides a low-latitude comparison over a low-albedo surface. At each location, average Holocene and LGM (defined as the time period from 8 kyr BP to 2 kyr BP and from 26 kyr BP to 19 kyr BP, respectively) dust deposition fluxes were obtained from ice-core or marine-sediment data.

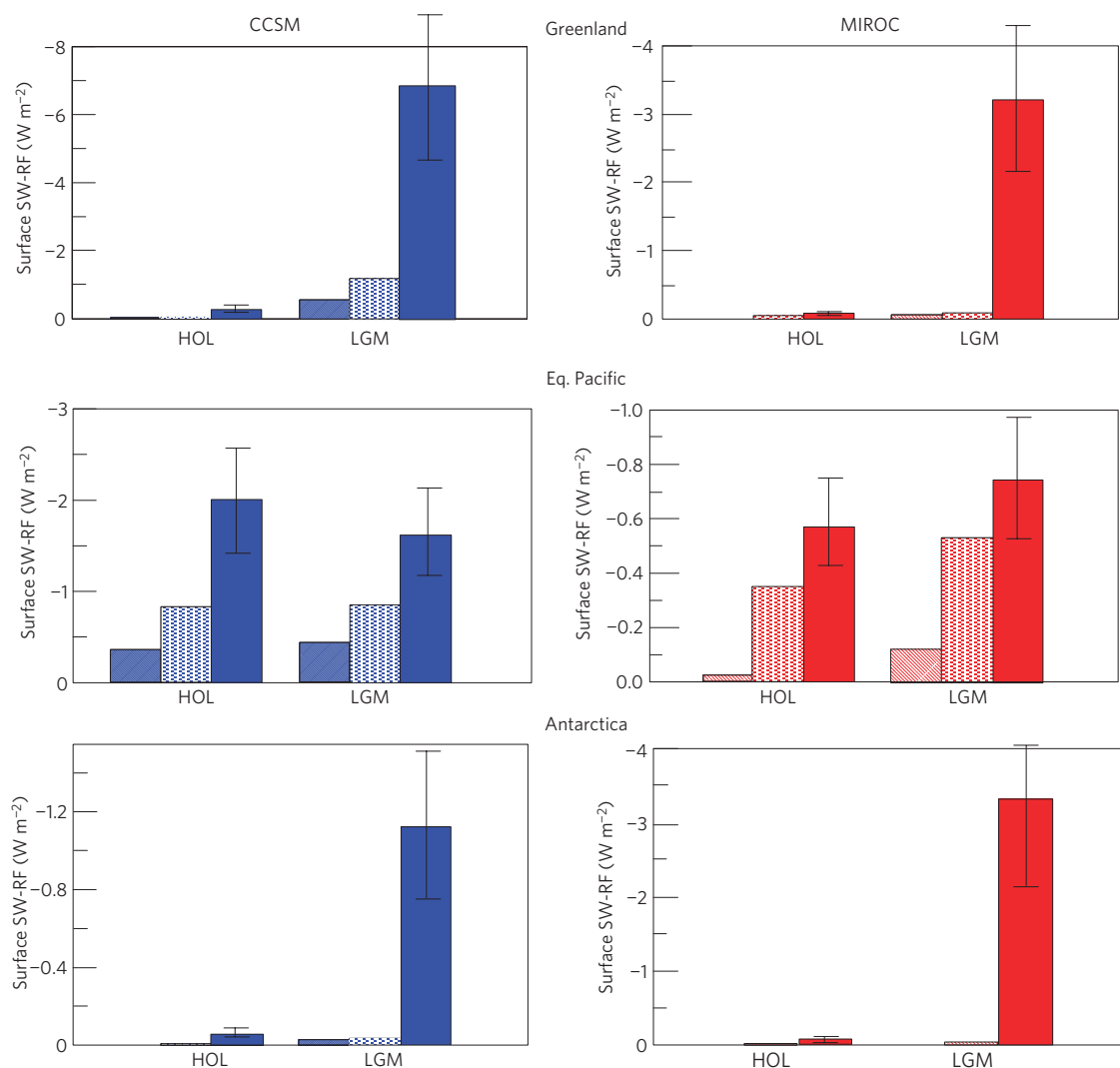


Figure 3 | Holocene to LGM changes in surface clear-sky short-wave radiative forcing at polar sites compared with a low-latitude site. Striped bars show the radiative forcing calculated in the models^{21,30}. The dotted and solid bars show the RRTM calculations performed with the models' and the reconstructed atmospheric concentrations, respectively. The error bars represent the uncertainty due to seasonality, dust flux and dry deposition fraction measurements alone. Uncertainties associated with modelled parameters are not taken into account (see Supplementary Information).

These average fluxes can be considered as originating from background atmospheric dust loads. We reconstructed atmospheric dust concentrations from the average dust fluxes using the new method (see Supplementary Information). During the Holocene, polar dust loads are relatively small compared with the equatorial Pacific (Fig. 2b). The reconstructed dust loads are similar to the model output in both high and low latitudes. In the dustier LGM conditions, the increase in atmospheric dust loads was amplified in polar areas, to the point that Greenland and Antarctic atmospheric dust loads were higher than and similar to equatorial Pacific loads, respectively (Fig. 2c). In low latitudes the MIROC reconstruction and the MIROC model output are still very similar. In polar areas, however, the reconstructed dust loads are much higher than the modelled ones, showing the inefficacy of conventional models at simulating the amplified high-latitude response of dust aerosols. The tuned CCSM model results show a substantial increase in Greenland, but not as pronounced as in the CCSM reconstruction. In Antarctica, both models show much lower loads than the reconstructions.

To determine the effect on radiative forcing of these new dust estimates, we calculated the clear-sky direct surface short-wave radiative forcing of the reconstructed dust concentrations,

using a standard one-dimensional rapid radiative transfer model²³ (RRTM), and compare it with the average summer short-wave radiative forcing simulated in the models, as well as to the short-wave radiative forcing of the models' average atmospheric concentrations calculated with the RRTM (Fig. 3). The models generally produce slightly lower radiative forcing than the RRTM, possibly owing to differences in dust aerosol parameterization. For our purpose we will compare the RRTM calculations of the reconstructed and modelled atmospheric dust concentrations, as this removes the deviations due to differences in radiative schemes and averaging. In equatorial areas the background dust concentrations do not change much between Holocene and LGM conditions and the difference in radiative forcing is small in the reconstructions as in the models. In polar regions, the Holocene dust radiative forcing is negligible in both models and reconstructions. During the LGM, the MIROC model still shows negligible polar radiative forcing, whereas the tuned CCSM model results show a small dust radiative forcing in Greenland. In comparison, the amplified increase in the reconstructed polar atmospheric dust concentrations due to the dustier global conditions results in a much more substantial polar dust radiative forcing than in the models. Although both reconstructions differ

in absolute values owing to model differences in deposition and vertical profile, they both feature a significant surface cooling effect. In Greenland the dust-induced surface radiative forcing reaches -3 to -6 W m^{-2} and is of similar strength (yearly average) as the radiative forcing due to the reduced LGM CO_2 levels. In Antarctica the surface cooling is still sizable at -1 to -3 W m^{-2} . Long-wave forcing will slightly reduce these values, although the small size of dust particles in polar areas, as well as cloud cover, may minimize the long-wave effect (see Supplementary Information).

The surface cooling effect of mineral-dust aerosols calculated here for specific sites in Greenland and Antarctica is likely to be of similar amplitude in the rest of the polar regions covered by snow or ice. In the polar atmosphere, dust aerosols tend to cool the lower and warm the higher troposphere, thus increasing atmospheric stability, and therefore amplify surface cooling by inhibiting heat exchange between near-surface air and the free atmosphere (see Supplementary Information). Even so, the larger LGM radiative forcing due to reconstructed dust aerosol concentrations cannot account by itself for the temperature discrepancy between model simulations and observations of polar amplification. However, during polar summer when short-wave radiative forcing is active, its cooling of the boundary layer inhibits surface melting of snow and sea ice. At the margins of snow cover the cooling is especially strong because the lower albedo strengthens the dust radiative forcing. Therefore, mineral-dust aerosols may extend the area of high summer albedo, thus contributing indirectly to the cooling of the summer atmosphere.

Our results show that mineral-dust-aerosol concentration changes are not uniformly distributed around the globe, but that increased emissions in mid- and low latitudes will result in an amplified relative change in high latitudes. Although dust models seem to estimate global concentration variations correctly, the latitudinal dependency is generally not captured, and the impact of dust aerosols in polar areas may therefore be underestimated in simulations of either past or future climate. Our results show that the amplified high-latitude response of mineral-dust aerosols may result in significant radiative forcing effects in polar regions.

The strong polar response to relatively small global concentration changes highlighted in this study with mineral-dust aerosols may also apply to other aerosols such as black carbon and sulphates, which have their own impact on polar climate. The case of LGM dust shows that a moderate global aerosol emission increase can result in a strongly amplified response in polar areas. Dust emissions over the nineteenth and twentieth century have more than doubled in certain areas compared with late Holocene averages^{24,25}, part of which may be due to natural and anthropogenic climate change and part of it related to land-use change. In the future, droughts and land aridity are projected to increase^{5,26}, although CO_2 fertilization and altered wet deposition patterns may partly offset the increases in desert dust source area²⁷ and atmospheric concentration. The global anthropogenic emission of other aerosols may increase as well^{6,7}. Our quantitative results are very model dependent and considered only mineral-dust aerosols. The total effect of increased aerosol concentrations on polar climate can be calculated only with global climate models. Improving aerosol parameterizations so as to include the high-latitude response could help these models to better capture some part of the polar amplification in LGM and future climate.

Methods

The polar amplification between the LGM and the Holocene is measured by defining the amplification factor of temperature and dust as shown in Fig. 1. The difference between global LGM and Holocene levels is defined as a factor of 1. The temperature amplification factor is defined as the difference from zonal

average Holocene temperature divided by the global temperature change between Holocene and LGM: $A(t) = (T(t) - T(\text{Holocene average}))/3.5 \text{ K}$. The global temperature time series is taken from a multi-proxy record¹¹. Arctic, equatorial and Antarctic time series are stacks from the same data set with records from latitudes above 70° , between -10° and 10° , and below -70° , respectively. We added the Greenland Ice Sheet Project 2 (GISP2; ref. 12) temperature record to the Arctic stack. The dust amplification factor is defined as the zonal dust flux to average Holocene flux ratio, divided by the global Holocene to LGM dust flux ratio: $A(t) = (\text{Flux}(t)/\text{Flux}(\text{Holocene average}))/2.2$. The North Greenland Ice Core Project²⁸ (NGRIP) and Dome C (ref. 16) dust records represent Greenland and Antarctic dust flux variations, respectively. A marine sediment core from the central equatorial Pacific²⁹ gives an equatorial reference, and the global dust flux change was taken from the Dust Indicators and Records of Terrestrial and Marine Palaeoenvironments²² (DIRTMAP) data set. Note that the amplification factors for temperature and dust are defined using a difference and a ratio, respectively, and that a quantitative relationship between the two should be avoided.

Radiative forcing shown in Fig. 3 is calculated on the basis of the RRTM maintained by the Atmospheric and Environmental Research company (<http://www.aer.com>). It is a rapid radiative transfer model that uses the correlated- k approach to calculate fluxes and heating rates in a vertical air column. Its line-by-line radiative transfer code has been extensively validated against observations.

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Author contributions

F.L. wrote the paper, performed the experiments and analysed the data. F.L. and J-S.K. designed the research. All authors discussed the results and commented on the manuscript.

Additional information

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Competing financial interests

The authors declare no competing financial interests.