Aerosols and climate - How sensitive is earth's climate to atmospheric aerosols?

PRESENT PAST

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Solids or liquids suspended in the atmosphere – aerosols – influence Earth's climate by interacting directly with radiation, by modifying clouds and by perturbing biogeochemical cycles and atmospheric chemistry. Aerosols consist of sulfates, organic carbon, black inorganic carbon, sea spray, mineral dust, ammonia and nitrates, and are emitted either directly or are formed from gaseous precursors. They are released by fossil fuel combustion, biomass burning or by emissions from the land and ocean surfaces. Aerosols reside in the troposphere for less than a day to a few weeks, and up to a few years in the stratosphere (Mahowald et al. 2011).

We monitor aerosols today using ground-based and satellite-borne remote sensing devices, and by in situ sampling on the ground and via aircraft, both at local and global scales (for example, the NASA Global Aerosol Climatology Project). But, despite the large number of observations of aerosols, there are large uncertainties in their distribution in space and time and their characteristics, because of their variability in space, time and composition (Mahowald et al. 2011; Formenti et al. 2011). In addition, aerosol deposition can be studied using passive natural or human-made collectors, such as snow pits or marine sediment traps (Kohfeld and Harrison 2001). Increasingly complex atmospheric transport and chemistry models and Earth-system models complement the set of tools for the study of the aerosol-climate interactions (Stier et al. 2006).

In its fourth assessment report, the Intergovernmental Panel on Climate Change estimated that anthropogenic aerosols had a net cooling effect on climate, partly offsetting the warming from greenhouse gases. But this conclusion is tempered by the large uncertainties involved. Aerosol-climate interactions thus constitute one of the major sources of uncertainty in assessing the global average radiative forcing (RF; Forster et al. 2007), and contribute to the large uncertainty in climate sensitivity (globally averaged surface temperature change at equilibrium) of between 2 and 4.5°C for doubling of CO2 (IPCC 2007).

Aerosols affect the climate in multiple ways. The direct effect – by scattering and absorption of solar and terrestrial radiation – leads to an RF value of -0.50±0.40 Wm^{-2} compared to the +1.7±0.1 Wm^{-2} estimated for rising CO_2 levels (Forster et al. 2007). Similarly, this interaction of aerosols with radiation also appears to be contributing to the observed "dimming" or reduction in the amount of incoming solar radiation that reaches the surface (e.g. Haywood et al. 2011). Aerosols interact with clouds by modulating albedo (the "cloud albedo" effect), which causes RF of -0.7 (-0.3 to -1.8) Wm^{-2}, and by modifying cloud lifetime (Forster et al. 2007). Aerosols also modify biogeochemical cycles by providing nutrients that limit primary production (e.g. Martin et al. 1990) and by producing climate alterations, which in turn enhance carbon uptake, affecting climate indirectly with an estimated RF of -0.50±0.40 Wm^{-2} (Mahowald 2011). In addition, deposition of black carbon and dust modify the albedo of snow (Hansen and Nazarenko 2004).

Natural aerosols are a potent source of feedbacks to the climate (Carlsaw et al. 2010). The impact of stratospheric aerosols on climate is seen in the response of the surface cooling to large volcanic events (e.g. Mt. Pinatubo), which can be as large as -0.2°C globally averaged (Robock 2000). Because of the potency of aerosols for climate perturbation, they are also being considered for tools in geoengineering the climate (e.g. Shepherd et al. 2009).

Humans have significantly increased the amount of aerosol in the atmosphere over the last 130 years. In the future, because of public health concerns as well as efforts to reduce combustion of fossil fuels, it is likely that emissions of anthropogenic aerosols will decrease (Fig. 1). This reduction in aerosols in the future is likely to both increase the rate of warming (Andreae et al. 2005), as well as make reductions in carbon dioxide harder to achieve (Mahowald 2011), because of the complicated and central role of aerosols in modulating climate and biogeochemistry.

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Full reference list online under:
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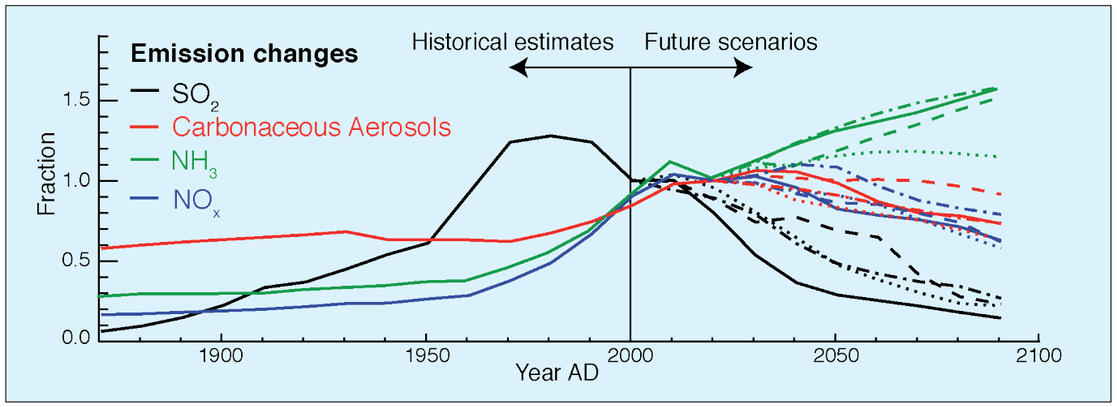

Figure 1: Historical and projected aerosol emissions relative to 2000 AD emissions. Sulfur dioxide forms sulfate aerosols, while about half the ammonia and nitrogen oxides form nitrogen-based aerosols in the atmosphere. Carbonaceous aerosols include both black and organic carbon and the estimated emissions here do not include secondary aerosol formation in the atmosphere. Calculations based on Mahowald (in press).

Paleoclimate records spanning the past several million years reveal large variability in the deposition of aeolian dust and other natural aerosols. Understanding this variability represents both a challenge and a useful test for Earth system models. The production, transport and deposition of natural aerosols are controlled by numerous physical and biogeochemical processes that are still not well understood. On the other hand, aerosols affect the climate via a number of physical and biogeochemical processes (see the accompanying article by Albani and Mahowald). On short time scales (several years), sulfur aerosols from volcanic eruptions play a significant role in forcing climate. On longer time scales, it is believed that climate-aerosol feedbacks amplify climate changes caused by other factors, such as changes in Earth's orbital parameters and concentrations of greenhouse gases.

Variability of the dust cycle is especially significant at glacial-interglacial time scales (Fig. 1). Paleoclimate data and model simulations suggest that during the Last Glacial Maximum (ca. 21,000 years before present) dust deposition in tropics was several times higher than at present and over Antarctica and Greenland the dust deposition rates increased by more than an order of magnitude. Such large increase in atmospheric dustiness cannot be explained without invoking a large increase in dust sources during glacial times (Mahowald et al. 2006). There are a number of processes via which variations in atmospheric dust loading and deposition rates may contribute as amplifiers and modifiers of the orbitally forced glacial cycles. First, an increase in atmospheric dustiness leads to increased reflection of incoming solar radiation and thus contributes to global cooling. This effect can be additionally enhanced by the effect of natural aerosols on cloud albedo (the so-called indirect effect), but partly offset by the additional absorption of outgoing long-wave radiation by dust particles (Takemura et al. 2009). The net simulated climatic effect of dust on climate during glacial times is sensitive to the poorly known optical properties of dust and is therefore model-dependent but typically of a comparable magnitude (1-2 W/m^2) to other climatic factors, such as a lowering of the atmospheric CO_2 concentration and increased surface albedo due to ice sheet growth. At the same time, enhanced dust deposition over snow and ice leads to a reduction of surface albedo and thus enhances ice melt. This effect may have played a role in both preventing the ice sheets from spreading into lower latitudes (Krinner et al. 2006) and accelerating the retreat of the ice sheets during glacial terminations (Ganopolski et al. 2010).

In addition to the physical effect, enhanced deposition of dust over ocean areas where plankton growth is limited by the availability of iron can enhance biological production and thus lead to the drawdown of atmospheric CO_2 (Martin et al. 1990). Recent modeling experiments suggest that the iron fertilization effect in the Southern Ocean alone can explain a significant fraction of glacial CO_2 reduction (Brovkin et al. 2007). Further progress in understanding the role of dust and other natural aerosols in climate change therefore requires the incorporation of these processes into the new generation of Earth system models.

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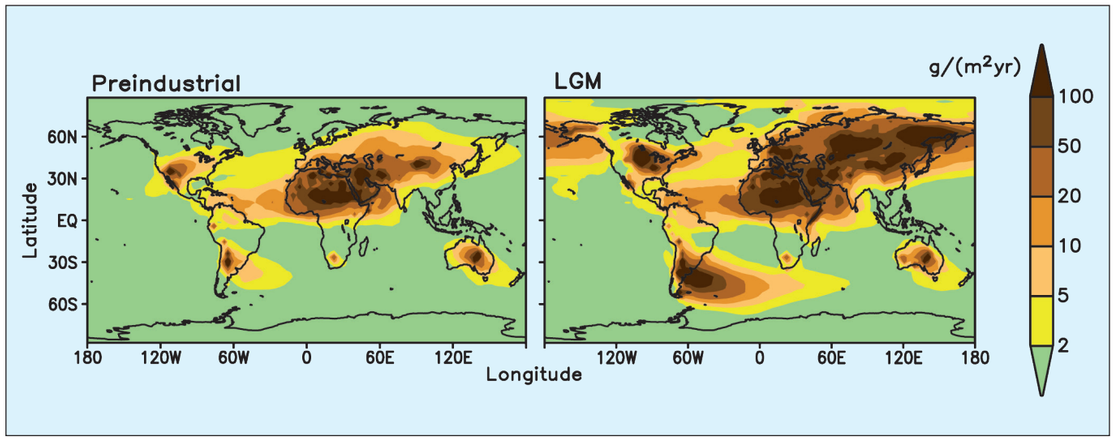

Figure 1: Modeled dust deposition under preindustrial climate conditions (left) and Last Glacial Maximum (right) based on Mahowald et al. (2006).

Paired Perspectives on Global Change