PROGRESS

Strong present-day aerosol cooling implies a hot future

Meinrat O. Andreae[1], Chris D. Jones[2] & Peter M. Cox[3]

Atmospheric aerosols counteract the warming effects of anthropogenic greenhouse gases by an uncertain, but potentially large, amount. This in turn leads to large uncertainties in the sensitivity of climate to human perturbations, and therefore also in carbon cycle feedbacks and projections of climate change. In the future, aerosol cooling is expected to decline relative to greenhouse gas forcing, because of the aerosols' much shorter lifetime and the pursuit of a cleaner atmosphere. Strong aerosol cooling in the past and present would then imply that future global warming may proceed at or even above the upper extreme of the range projected by the Intergovernmental Panel on Climate Change.

'Climate sensitivity' measures how strongly the Earth's climate system responds to a given perturbation, and is often expressed as the equilibrium rise in global temperature resulting from a doubling of atmospheric CO_2. Because it is the key parameter that translates scenarios of future atmospheric composition into projections of climate change, accurate estimates of climate sensitivity are essential. Unfortunately, climate models yield a wide range of sensitivities, depending on the parameterizations they contain[1–3], and thus cannot reliably constrain the true climate sensitivity. Alternatively, climate sensitivity can be deduced by relating an observed climate change (for example, the global warming over the last century) to an estimated magnitude of forcing. Such forcing estimates are, however, also highly uncertain, mostly because of incomplete understanding of the climate forcing by atmospheric aerosols[4–6].

Future changes in the balance of climate forcing factors—such as increasing greenhouse gases (GHG) but decreasing aerosol burdens—mean that historical changes are not sufficient to constrain future projections. The climate will become more dependent on climate sensitivity as the aerosol burden is reduced. Furthermore, the response of the natural carbon cycle to future climate is also dependent on the climate sensitivity, implying large uncertainties in future CO_2 concentrations.

Climatic effects of aerosols

In the first IPCC report[7], climate change was considered to be driven predominantly by anthropogenic GHG emissions. Aerosol effects on climate were mentioned, but our knowledge was considered inadequate to estimate their magnitude, or even sign. Since then, the number of aerosol-caused climate effects considered and the estimates of their cumulative magnitude have steadily grown.

All aerosol types (sulphates, organics, mineral dust, sea salt, and so on) intercept incoming sunlight, and reduce the energy flux arriving at the Earth's surface, thus producing a cooling[8]. Some aerosols (for example, soot) absorb light and thereby warm the atmosphere, but also cool the surface. This warming of atmospheric layers may also reduce cloudiness, yielding another warming effect. In addition to these 'direct' radiative effects, there are several 'indirect', cloud-mediated effects of aerosols, which all result in cooling: more aerosols produce more, but smaller, droplets in a given cloud, making it more reflective. Smaller droplets are less likely to coalesce into raindrops, and thus the lifetime of clouds is extended, again increasing the Earth's albedo. Finally, modifications in rainfall generation change the thermodynamic processes in clouds, and consequently the dynamics of the atmospheric 'heat engine' that drives all of weather and climate. The recent tremendous growth in knowledge of the climatic effects of aerosols, along with the emergence of the likelihood of positive feedbacks between climate and the carbon cycle[9,10], have transformed the orderly picture of climate change of the early 1990s, dominated by GHG warming, into a complex mix of opposing effects[11,12].

Aerosols and climate sensitivity

Constraints on the value of climate sensitivity (expressed as $\Delta T_{2\times CO_2}$, the equilibrium temperature response to a doubling of CO_2, see Box 1) are sought by two main approaches. The 'bottom-up' approach, used in General Circulation Models (GCMs), relies primarily on improved representation of the feedbacks in the climate system, including ever more complex representations of physical processes within higher-resolution coupled ocean–atmosphere models[1]. These efforts have yielded many interesting scientific insights, but have

Box 1 | Climate sensitivity

The problem of predicting global climate change can be symbolically represented by a simple heat balance equation:

$$c\frac{d(\Delta T)}{dt} = \Delta Q - \lambda \Delta T$$

Here ΔT is the global mean temperature change arising from a change in radiative forcing ΔQ. ΔQ represents the total climate forcing (in $W\,m^{-2}$) due to changes in natural factors (such as volcanoes and solar variability), as well as human-induced changes in the concentrations of greenhouse gases and aerosols. The long-term equilibrium response to a radiative forcing (such as doubling of CO_2) is given by the parameter λ as follows: $\Delta T_{2\times CO_2} = \Delta Q_{2\times CO_2}/\lambda$, where $\Delta Q_{2\times CO_2} = 3.7\,W\,m^{-2}$. λ itself depends on many climate feedback processes, such as those arising from changes in water vapour, snow cover and clouds. The left-hand side of this equation is a heat storage term which determines how quickly the climate system approaches this equilibrium state. The heat capacity c can be estimated from observations of ocean heat uptake[24] and recent warming trends[13] as $1.1 \pm 0.5\,GJ\,m^{-2}\,K^{-1}$. However, there is a wide range in projections of future climate change primarily because of uncertainties in both λ and the future ΔQ.

[1]Max Planck Institute for Chemistry, PO Box 3060, Mainz 55131, Germany. [2]Hadley Centre for Climate Prediction and Research, Met Office, Fitzroy Road, Exeter EX1 3PB, UK. [3]Centre for Ecology and Hydrology, Winfrith, Dorset DT2 8ZD, UK.

failed to reduce the uncertainty in climate sensitivity. The first IPCC report[7] quoted a range of $\Delta T_{2\times CO_2} = 1.5$–$4.5$ K, which remains essentially unchanged in the Third Assessment Report of the IPCC[1] (IPCC-TAR). Some groups are now attempting to determine the relative likelihood of different climate sensitivities using the accuracy of simulations of current climate as weighting factors for an ensemble of climate projections[2]. However, GCM parameters are sufficiently uncertain that a recent 'grand ensemble' of more than 2,000 climate change experiments[3]—all using the same GCM—has yielded sensitivities ranging from below 2 K to more than 11 K.

An alternative 'observationally based' approach[4] makes use of the observed global warming of ~0.7 K over the 20th century, and of 0.4 K from 1940 to 2000 (ref. 13). The equation shown in Box 1 then offers a means to estimate climate sensitivity, given the net radiative forcing ΔQ over the same period:

$$\Delta T_{2\times CO_2} = 3.7 \frac{\Delta T}{\Delta Q - c\frac{d(\Delta T)}{dt}} \qquad (1)$$

ΔQ is the sum of the relatively well-known GHG forcing ($+2.4 \pm 0.3\,\mathrm{W\,m^{-2}}$ from 1750 to 2000; ref. 1), and the very poorly quantified, but potentially substantial, cooling from anthropogenic aerosols. Consequently, equation (1) shows us that a larger aerosol cooling over the historical period (and thus a smaller net forcing) implies a more sensitive climate (Fig. 1).

Climate 'protection' and future uncertainty

The range of aerosol forcings predicted by 'forward' models, using our best knowledge on the atmospheric aerosol burden and its climate effects, is vast[14], from 0 to $-4.4\,\mathrm{W\,m^{-2}}$. Thus, even if we ignore the implied possibility of a net cooling forcing over the past century, we find that adding the aerosols' effects to those of the GHG yields a net forcing that extends from the full GHG forcing down to a zero net forcing over the last century.

Although the models may disagree about the magnitude of the aerosol effect, they all agree that the net effect is cooling, and that aerosols have therefore 'protected' us from some of the greenhouse warming. The price for this 'climate protection' is, however, great uncertainty about the true magnitude of the climate change we can expect in the future. If the mix of future forcings remains the same as in the past, precise knowledge of λ would not be necessary: historical changes would constrain the future[15]. However, because we expect the proportions of GHG and aerosols to change in the future, past changes become a much weaker constraint on future behaviour (Box 2).

The twentyfirst-century climate will therefore suffer the treble hit of an increasing warming from greenhouse gases, a decreasing cooling from aerosols, and positive feedbacks from the carbon cycle, whereby increased temperatures cause accelerated release of soil carbon by decomposition[9]. The effects of anthropogenic aerosols have created great uncertainty in our knowledge of the climate sensitivity to increasing greenhouse gases. Do we live in a world with weak aerosol cooling and thus low climate sensitivity, in which case future climate change may be expected to be relatively benign? Or do we live in a highly forced, highly sensitive world with a very uncertain and worrying future that may bring a much faster temperature rise than is generally anticipated?

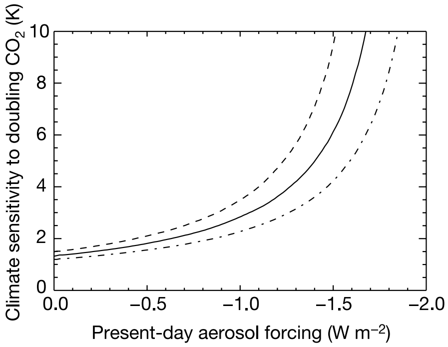


Figure 1 | Climate sensitivity required to explain the observed 1940–2000 warming as a function of the strength of aerosol radiative cooling. The solid line represents results using the central estimate of heat capacity ($1.1 \pm 0.5\,\mathrm{GJ\,m^{-2}\,K^{-1}}$) from Levitus *et al.*[24], and the dashed (dot-dashed) lines represent the higher (lower) limit of this heat capacity. More details of the model are given in Box 3.

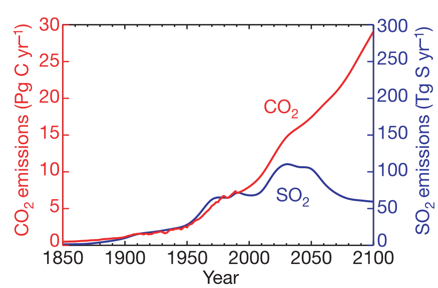
Historical constraints

To explore this issue more quantitatively, we use a deliberately simplistic approach to illustrate the impact of the uncertainties on projections of future climate (see Box 3). We apply two observational constraints: the model should reproduce both the observed global warming and the CO_2 increase from 1940–2000. The observed warming constraint yields a relationship between aerosol cooling and climate sensitivity (Fig. 1), indicating that $\Delta T_{2\times CO_2}$ is just 1.3 K for zero aerosol forcing, but exceeds 10 K for $\Delta Q_{aeros} = -1.7\,\mathrm{W\,m^{-2}}$ (ΔQ_{aeros} is the sum of all aerosol forcings). A climate sensitivity of 10 K is large, but cannot be ruled out by observations. Climate sensitivity diagnosed by this model rapidly becomes unphysically large and then negative as the aerosol forcing exceeds $-1.7\,\mathrm{W\,m^{-2}}$. We note that recent studies tend to estimate the sum of aerosol forcings to be in the range -1 to $-2\,\mathrm{W\,m^{-2}}$, that is, in the region of sharply increasing and highly uncertain $\Delta T_{2\times CO_2}$ (refs 11, 12, 16, 17).

In a similar vein, the historical CO_2 rise sets a joint constraint on the parameter determining the CO_2-fertilization of photosynthesis ($C_{0.5}$, the half-saturation concentration for photosynthesis), and the parameter determining the sensitivity of soil respiration to temperature (q_{10}—the factor by which decomposition accelerates for each

Box 2 | Future aerosol scenarios

The SRES emissions scenarios[25] used in the IPCC-TAR all suggest that aerosol emission by the middle of this century will be near or below present levels. Because aerosols are very short-lived in the atmosphere—lifetimes of days compared with decades for the greenhouse gases—they do not accumulate and the burden is almost proportional to the emissions. Consequently, as we clean up our vehicles and smokestacks to provide cleaner air and improve air quality, the aerosol loading of the atmosphere will decrease. Even population growth and increasing industrialization in the developing countries will do little to change this outcome. We are already in the process of revising downward our projections of aerosol emissions from China and other developing countries, as they are introducing cleaner technology faster than had been anticipated a decade or so ago. Because of the rapidly growing knowledge of the very serious health effects of aerosols[28] we expect that regulatory efforts will act to reduce aerosol emissions even more rapidly than anticipated when the SRES scenarios were developed.



Box 2 Figure | Historical CO_2 and SO_2 emissions from 1850–2000, followed by projected values to the year 2100 from the SRES[25] A2 scenario.

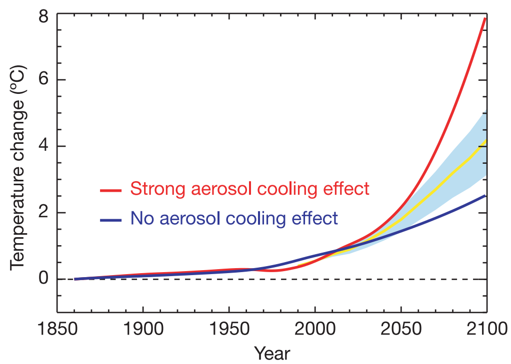


Figure 2 | Temperature change simulated by the simple model for the period 1850 to 2100. Two extreme cases are shown: strong present-day aerosol cooling consistent with 'forward' studies of aerosol effects on climate but with a climate sensitivity not ruled out by observations (red line, $Q_{aeros} = -1.7\,W\,m^{-2}$), and the case of no aerosol cooling effect (blue line). The shading and the yellow line represent the range and central projection given in IPCC-TAR, based on the same scenario used in these calculations (scenario A2, from ref. 25).

10-K warming[18,19]). Both high fertilization + high q_{10} and low fertilization + low q_{10} are consistent with the historical rise of CO_2 and temperature, but imply different responses of the land carbon cycle to future climates and therefore very different magnitudes of the carbon cycle feedback.

Future projections

We have run the simple model on to 2100 for a range of scenarios from the IPCC's Special Report on Emissions Scenarios (SRES, see Box 2) (Figs 2 and 3). We find that a large uncertainty range of temperature increase is predicted for 2100, and that even by 2050, the model runs with strong historical aerosol cooling predict a temperature rise from 1850 of as much as 2.2 °C.

The implied high climate sensitivities are within the range of sensitivities inferred by recent observational approaches. Analyses of the probability distribution of climate sensitivities that can be deduced from climate observations suggest that there is a significant probability that the true climate sensitivity is in excess of 4 K (refs 5, 6), and maybe as high as 10 K. Recent analyses of the palaeoclimatic record also suggest fairly high climate sensitivity[20,21].

When we include the uncertainty caused by the choice of emission scenarios, we find that the range considered most plausible in IPCC-TAR (2.3–4.9 °C from 1850–2100) can be obtained only for aerosol forcings considerably weaker than predicted by current forward models (Fig. 3), which tend to estimate the sum of aerosol forcings to be in the range −1 to $-2\,W\,m^{-2}$ (refs 11, 12, 16, 17). Ominously, Fig. 3a shows temperature increases in excess of 6 °C for the climate sensitivity implied by the central estimate of aerosol forcing ($-1.5\,W\,m^{-2}$), and for all but the most optimistic emission scenario. Such an enormous increase would be comparable to the temperature change from the previous ice age to the present. Furthermore, the overall uncertainty is dominated by climate sensitivity and hence historical aerosol forcing: Fig. 3a shows that the warming range for a given scenario (for example, 2.5–7.9 K for scenario A2) is greater than the range across scenarios for a given climate sensitivity (6.8–9.6 K at its widest).

Part of the reason for this extraordinary sensitivity of future projections to the historical aerosol forcing is due to the impact of the carbon cycle feedback on projected CO_2 levels (Fig. 3b). The extent to which the land carbon cycle amplifies future CO_2 increase depends critically on climate sensitivity (Fig. 4). The positive climate–carbon cycle feedback increases markedly with climate

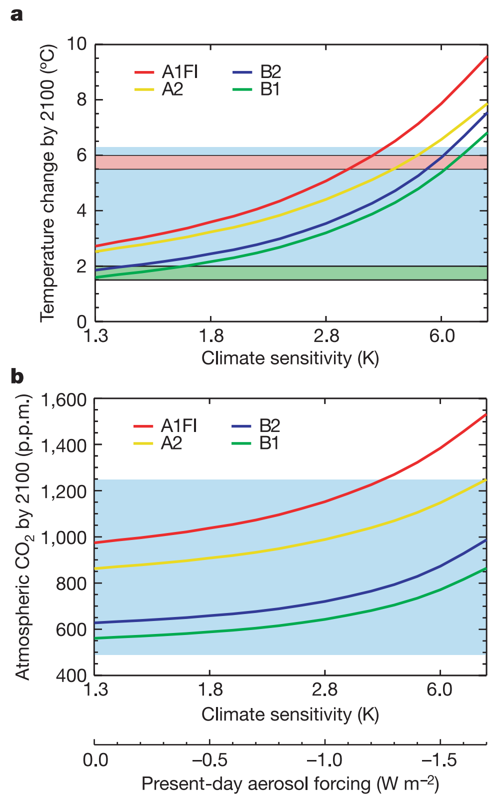


Figure 3 | Modelled temperature change and CO_2 increase by 2100 under different development scenarios. a, Temperature rise by the year 2100 for the various SRES scenarios[25] as a function of present-day aerosol cooling. The horizontal green bar indicates the threshold of 'dangerous anthropogenic interferences' in the sense of the United Nations Framework Convention on Climate Change, using an estimate of 1.5–2 °C for this value, based on arguments by different groups[26,27]. At all but the very lowest climate sensitivities this level will be exceeded unless GHG emissions are reduced below those in the SRES B1 and B2 scenarios (from ref. 25). The pink bar indicates the temperature change between ice ages and interglacials[20]. **b**, Same as **a** but for atmospheric CO_2 by 2100. The shaded areas represent the IPCC-TAR range across models and scenarios.

Box 3 | Simple climate-carbon cycle model

We use a zero-dimensional climate-carbon cycle model[29], which updates the global temperature using the equation in Box 1 and accounts for potentially large positive carbon cycle feedbacks by updating CO_2 interactively on the basis of the emissions scenario. It uses a simple fit to the ocean and land uptake of CO_2 derived from the Hadley Centre's climate-carbon cycle GCM[9], but with alternative sets of possible land sensitivity parameters chosen to fit the observed CO_2 rise. The land carbon cycle responses produced by this simple fit therefore span the range simulated by other potentially realistic models. The size of the climate-carbon cycle feedback depends critically on the opposing effects of CO_2-fertilization on plant growth, and enhanced soil decomposition as the climate warms. The latter is dependent on the degree of climate warming, as well as the sensitivity of soil respiration to temperature[18,29].

The major anthropogenic forcings are considered: CO_2, other well-mixed GHGs, and sulphate aerosols. The radiative forcing from CO_2 and other well-mixed GHGs are derived from well-known formulae[1]. The radiative forcing from sulphate aerosols is assumed to be proportional to global mean sulphate loading, which in turn is assumed to be proportional to SO_2 emissions. To avoid undue influence of other forcing factors (in particular natural forcing from solar and volcanic sources) we consider just the portion of the historical record that is dominated by anthropogenic influence—namely 1940 to present[30].

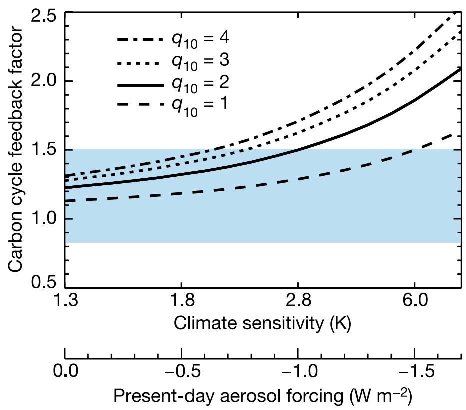


Figure 4 | Strength of climate-carbon cycle feedback as a function of climate sensitivity. The feedback factor is defined as the CO_2 concentration rise projected between 1860 and 2100, divided by the CO_2 rise predicted in the absence of climate effects on the carbon cycle. Results are shown for the A2 scenario as a function of climate sensitivity/present-day aerosol cooling, for various sensitivities of soil respiration to temperature. The shaded area represents the range of feedback factor estimated from the IPCC-TAR range of CO_2 concentrations relative to the standard A2 concentration scenario. q_{10} values of 1, 2, 3 and 4 correspond to $C_{0.5}$ values of 295, 485, 676, 866 p.p.m., respectively, in order for the model to recreate the observed CO_2 record.

sensitivity, especially if soil decomposition is more sensitive to temperature (that is, for higher q_{10} values). With a best estimate[22] of $q_{10} = 2$, we find that for climate sensitivities greater than 3 °C, the carbon cycle feedback will accelerate CO_2 growth by more than 50%. This dependence of the carbon cycle feedback strength on climate sensitivity may explain a large part of the divergence amongst the first generation climate–carbon cycle GCMs[23].

Thus research over the past decade has shown evidence of the importance of a considerable number of aerosol climatic effects, which on balance cool the Earth and have therefore reduced the effect of greenhouse warming. Because of the stabilizing emission of aerosols and their short lifetime, this 'protection' will diminish in the future, leaving us vulnerable to both greater climate change and greater uncertainty. Incomplete consideration of aerosols in current climate models may have led to underestimation of the true climate sensitivity. We cannot quantitatively assess the probability of a given climate sensitivity within the limited scope of this paper, but our analysis suggests that there is a possibility that climate change in the twentyfirst century will follow the upper extremes of current IPCC estimates, and may even exceed them. Such a degree of climate change is so far outside the range covered by our experience and scientific understanding that we cannot with any confidence predict the consequences for the Earth system.

To reduce these uncertainties a multi-pronged approach is needed. First, there is a great need for *in situ* studies that investigate the response of cloud microphysics and dynamics to enhanced aerosol concentrations. Second, at the regional and global scale, the effects of aerosols on cloud properties and abundance must be studied using remote-sensing data from the newly available and upcoming satellite sensors. Third, parameterizations of cloud processes and feedbacks in GCMs must be improved. Finally, uncertainties in feedbacks that are strongly dependent on climate sensitivity, such as the carbon cycle feedback, must also be reduced, through process studies and model improvements.

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