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TELLUS

# Observed climate change constrains the likelihood of extreme future global warming

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ABSTRACT

If cooling due to present-day levels of atmospheric aerosol is suppressing global temperatures, future reductions in aerosols emissions would allow the full greenhouse gas induced warming to be realised. The many uncertainties in aerosol physics and chemistry mean that a large range of present-day aerosol cooling is possible which could imply a large climate sensitivity, extremely large future warming and the increased risk of catastrophic consequences.

Despite large uncertainties in aerosol physics and chemistry, observed spatial and temporal patterns of past temperature change allow quantitative assessment of the strength of present-day aerosol cooling. Such observational constraints provide a probabilistic framework in which to assess the likelihood of extremely large warming if a very large suppression of global warming by aerosols were to be removed. The likelihoods of future warming extents are calculated assuming four scenarios of future anthropogenic emissions. While such results are still subject to uncertainty, they indicate that future warming by the end of the 21st century is likely to be between the extremes implied by very strong or very weak present-day aerosol cooling. It is very likely that present-day aerosol cooling is suppressing a major portion of current greenhouse warming.

## 1. Introduction

A change in radiative forcing due to raised levels of atmospheric greenhouse gas concentrations (most notably $CO_2$) results in a generally warmer climate. Observations indicate an increase in global average surface temperature of $0.74 \pm 0.18$ °C when calculated as a linear trend over the period between 1906 and 2005 (Brohan et al., 2006), corresponding to a period when atmospheric greenhouse gas concentrations have been increasing and causing a perturbation to Earth's radiative balance. Radiative forcing is also influenced by other factors; after well mixed greenhouse gases, the most important anthropogenic forcing is due to changes in concentrations of atmospheric aerosols. The net effect of sulphates, dust and other aerosols is to exert a negative radiative forcing which acts to reduce near surface temperatures whereas carbonaceous aerosols can exert a positive forcing by absorbing incoming solar radiation and heating the lower atmosphere. In addition to the direct effect of aerosols on the Earth's radiation balance, aerosols also have an indirect effect by changing cloud properties. There are a variety of such indirect effects including the cloud albedo effect whereby increasing aerosol concentrations can make clouds brighter, the cloud lifetime effect whereby aerosols could change precipitation efficiency, and the semi-direct effect whereby absorption of solar radiation by absorbing aerosols can lead to evaporation of cloud droplets. As a consequence of the complexity of processes involved there remains a large uncertainty in aerosol forcing (Anderson et al., 2003).

Such large uncertainty in the net radiative forcing for the period between pre-industrial and present in turn implies a very large uncertainty in estimates of climate sensitivity (Gregory et al., 2002; Andreae et al., 2005, Meehl et al., 2007) and consequently a large uncertainty in predictions of future warming for a particular scenario of future anthropogenic forcings (Hegerl et al., 2007; Meehl et al., 2007). Andreae et al. (2005) demonstrate this precise problem using a "box" global heat balance equation and considering a 21st century in which greenhouse gases continue to rise throughout the period but aerosol pollution decreases during the latter half of the century. They compare temperatures simulated by their simple heat balance model, when it is run with a range of climate sensitivities and current aerosol forcing values, with past observed temperature changes. They show what good agreement between past modelled and observed temperature changes implies for future warming, assuming that

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the time evolution of radiative forcing from sulphate aerosols is proportional to past emissions of $SO_2$ and future emissions as specified in a range of emissions scenarios from the IPCC's Special Report on Emissions Scenarios (SRES, Nakićenović and Swart, 2000). They argue that if radiative cooling due to aerosols is zero, then fitting their heat balance model to the current temperature record implies a relatively low warming of about 2K over the next century for the SRES A2 scenario. If, on the other hand, current aerosol cooling is suppressing warming corresponding to a very high climate sensitivity, they calculate that future global mean temperature increases could be more than 6K over the next century for the same emissions scenario. Andreae et al. (2005) make no attempt to assign likelihoods to either of these extreme cases, but how plausible each future could be is clearly a critical question.

This question can be addressed by examining the observed patterns of temperature change across the surface of the Earth. Anthropogenically induced changes to atmospheric aerosol concentrations exhibit strong geographical variation whereas $CO_2$ increases are well mixed. In addition, the time history over the last century of aerosol emissions is different from that of greenhouse gas emissions and of natural forcings associated with explosive volcanic eruptions and changes in solar irradiance. Coupled Atmosphere Ocean General Circulation Models (AOGCMs) can be used to determine the likely contribution of individual anthropogenic and natural forcings to observed patterns of temperature change. This is done by simulating the pattern of temperature response to each individual forcing in isolation. The observed and modelled patterns of change are compared to each other in a regression procedure. This expresses the observed changes as a linear sum of simulated changes resulting from external (both natural and human induced) forcings and also changes due to internal variability. Such a regression procedure (called 'optimal detection'; e.g. see IDAG, 2006) is applied in this paper to estimate, in a probabilistic sense, the likely range of past and future balance of greenhouse warming and aerosol cooling. This procedure allows the scaling of patterns to take account of the possibility that the climate model might under- or overestimate the real-world transient climate response to the relatively well-known greenhouse gas forcing or that the climate model might under- or overestimate the relatively poorly-known aerosol forcing.

The response to natural forcings is included explicitly in our analysis, thus allowing for the possibility that past temperature changes might not have been primarily driven by anthropogenic forcings. Our approach differs from Andreae et al. (2005) in this respect, who considered only anthropogenic factors. Even if anthropogenic factors dominate (which, unlike Andreae et al., we do not assume a priori) a correct understanding of the effects of anthropogenic effects could require inclusion of natural factors in the analysis. Another important component of our regression procedure is an estimate of the climate's internal variability which is obtained from a long control simulation of the climate model in which external forcings are held constant. It is important to ensure that this model-based estimate of internal variability is validated against an observed estimate of internal variability and found to be not inconsistent, as is the case for the model-based estimate of internal variability used here (e.g. see Hegerl et al., 2007).

## 2. Analysis

An optimal detection analysis compares the observed evolution of 20th century temperature with spatial and temporal patterns of temperature change from AOGCM simulations driven by different components of radiative forcing. It is such analyses that led the IPCC Fourth Assessment to conclude, 'Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations.' (IPCC, 2007). This method of matching simulated and observed patterns of temperature change allows estimates of relative likelihoods of different magnitudes of the net aerosol forcing to be made, that take account of the effects of other forcings, including natural forcings. Using this methodology which exploits the constraints provided by the observational record, the greenhouse warming trend over the last century is found to be less than 1.3 °C with 95% confidence (Stott et al., 2006) and aerosol cooling less than 0.8 °C, implying a range of aerosol forcing between −1.4 and −0.4 $Wm^{-2}$ (5–95 percentile range, Stott et al., 2006), corresponding to a transient climate response (TCR) of 1.5–3.1 °C. (TCR is the measure of the transient surface temperature response to greenhouse gas forcing and is defined as the change in global surface temperature, averaged over a 20-yr period, centred at the time of $CO_2$ doubling, that is at year 70 in a 1% per year compound carbon dioxide increase experiment). This uncertainty estimate is potentially subject to additional, unquantified uncertainties due to any model errors that are not fully accounted for by the optimal detection methodology, such as might result from missing processes or missing forcings in the climate model simulations. Patterns of response to forcings missing from models could project onto the model's patterns of response to aerosol forcings which could lead to errors in the attributed trends. Also, different models will have different patterns of response and this pattern uncertainty is not accounted for in these results, although Stott et al. (2006) did explore the uncertainty of derived aerosol forcing to modelling uncertainty in three climate models and found that the 5–95 percentile ranges lay between −1.5 and −0.3 $Wm^{-2}$. Note that gross systematic model errors are accounted for in the optimal detection methodology by scaling model patterns of response to particular forcings up and down so as to be consistent with the observed patterns of response.

Despite these additional unquantified uncertainties, our estimate is broadly consistent with inverse estimates of aerosol forcing using different techniques (Andronova and Schlesinger, 2001; Knutti et al., 2003; Forest et al., 2006). The IPCC Fourth



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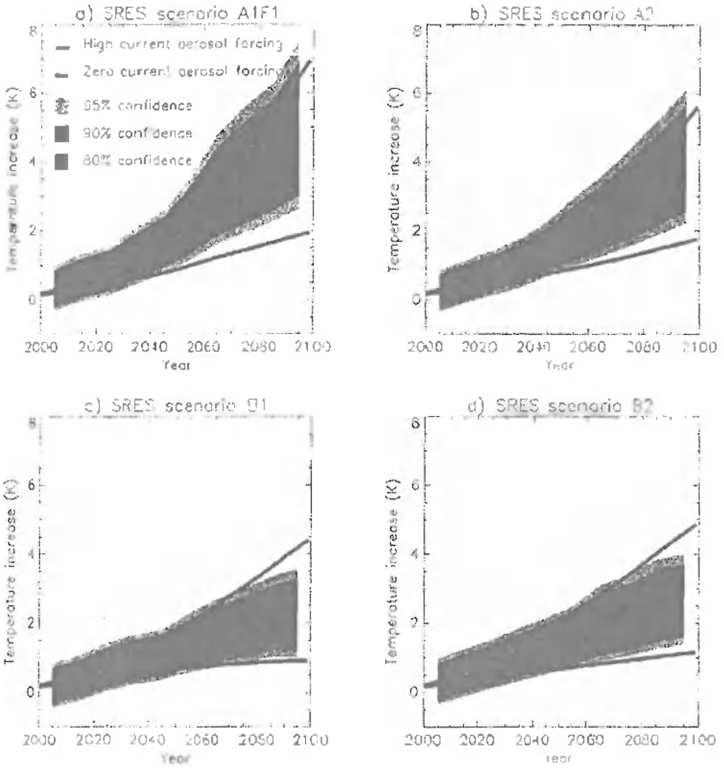


*Fig. 1.* Comparison between the observationally constrained probabilistic predictions of future global mean temperature (relative to 1980–1999, grey values) following four SRES scenarios and simple climate model predictions assuming no present-day aerosol cooling (blue curve) and strong present-day aerosol cooling (corresponding to a present-day aerosol forcing of $-1.7$ Wm$^{-2}$, red curve). Probabilistic predictions represent the possible range of decadal mean temperatures observed in future relative to the forced temperatures in the 1980–1999 period and includes an estimate of future natural variability.

Assessment Report concluded from such inverse estimates that the likely range for the net aerosol forcing was between $-1.7$ and $-0.1$ Wm$^{-2}$ a slightly broader range than that found by Stott et al. (2006) since it accounts for the probability of other forcings projecting onto the models' patterns of response (Hegerl et al., 2007). Nevertheless, the overall consistency of these results demonstrates that, as expected, the scaling procedure used in an optimal detection analysis corrects for gross model error in the overall magnitude of aerosol forcing and magnitude of the transient climate response.

This observationally based constraint on the contributions of greenhouse gases, aerosols and other factors to past climate change (including natural forcings dues to changing solar irradiance and stratospheric aerosols from explosive volcanic eruptions) can be used to generate constraints on likely warming rates into the future by assuming that a model that over- or underestimates the climate response to past forcing will continue to do so by the same fraction in the future (Allen et al., 2000; Stott and Kettleborough, 2002; Kettleborough et al., 2007). This methodology has been dubbed ASK (Allen, Stott, Kettleborough) and the method is reviewed and compared to an alternative approach using large ensembles of intermediate complexity models by Stott and Forest (2007), while the assumptions inherent in this procedure and the errors associated with using a linear relationship to relate past and future warming are discussed in detail by Kettleborough et al. (2007).

In Fig. 1 we present such probabilistic predictions of global mean temperature (based on an analysis of the HadCM3 climate model) for four of the SRES emissions scenarios, B1, B2, A1FI, A2 (Nakićenović and Swart 2000). The grey shadings in Fig. 1 show uncertainty ranges of future warming following each scenario derived using the ASK approach. These have been derived from an analysis of the observed decadal-mean near-surface temperature changes over the 1900–2000 period. A linear regression is carried out between the observed patterns of temperature change and a linear sum of simulated changes from well mixed anthropogenic greenhouse gases, other anthropogenic factors (dominated by the effects of tropospheric aerosols) and natural factors. The same scaling factors, that when applied to the model simulations of past changes provides a large scale temperature response that is consistent with the observed patterns of decadal-mean temperature response over the 20th century, are then applied to the model predicted patterns for the 21st century. We assume that it is not possible to forecast deterministically future naturally forced changes (due to changes in output from the sun and from explosive volcanic eruptions) and therefore only the anthropogenically forced component is predicted deterministically for each scenario of emissions. Extra sources of variance are added to the anthropogenically forced warming, uncertainty due to internal variability and uncertainty due to naturally forced changes, the latter being estimated from simulations of past temperature change including natural factors



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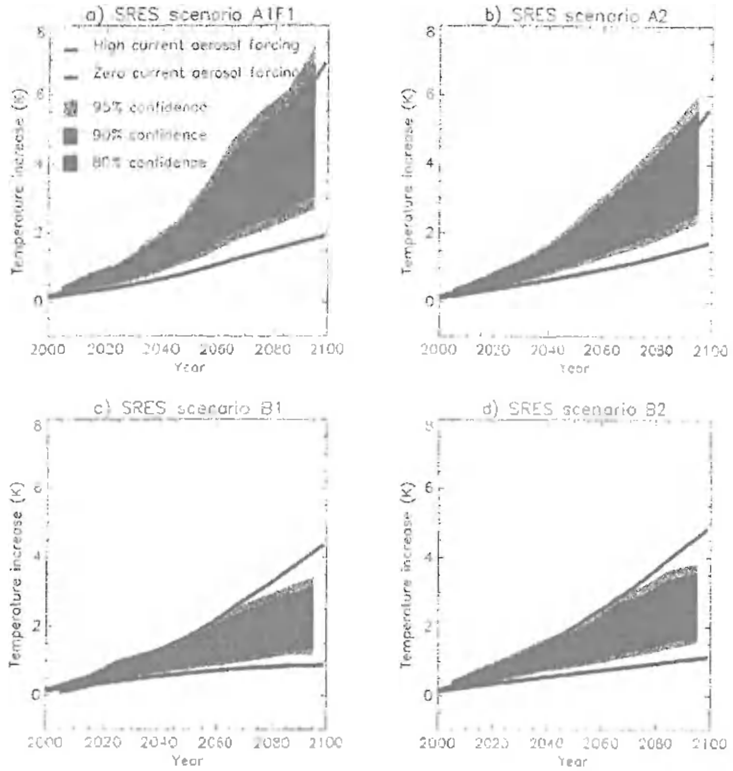


*Fig. 2.* Same as Fig. 1 but excluding some sources of uncertainty considered in observationally constrained probabilistic predictions of future global mean temperature shown in Fig. 1. Predictions now represent uncertainty in the underlying forced temperature response of the climate system (see text).

only. Further details of the procedure are given in Stott and Forest (2007).

The probabilistic ASK based estimates of future warming are compared in Fig. 1 with the simple model projections of Andreae et al. (2005) for the case in which there is no current aerosol cooling effect (blue curve, Fig. 1) and the case in which there is a strong current aerosol cooling effect (red curve, Fig. 1). For this comparison we repeat the simple climate model simulations of Andreae et al. (2005), but exclude carbon cycle feedbacks, which are likely to increase warming rates but whose exact magnitudes remain highly uncertain (Friedlingstein et al., 2006).

Both the probabilistic predictions and the simple climate model simulations are expressed as temperature anomalies relative to the period 1980–2000. The red and blue curves correspond to present day aerosol forcing of $-1.7$ Wm$^{-2}$ and zero respectively, as in Andreae et al. (2005), and the future aerosol radiative forcing from the respective SRES scenarios through the 21st century are then scaled to be consistent with these present-day aerosol forcings.

Relative to the period 1980–1999, our probabilistic predictions are for temperatures to rise by the end of this century to between 3.0 and 6.9 °C (5–95 percentiles) for the A1F1 SRES scenario, between 2.5 and 5.6 °C for the A2 scenario, between 1.2 and 3.3 °C for the B1 scenario, and between 1.6 and 3.7 °C for the B2 scenario. For all scenarios, by 2100 the simple model simulations corresponding to zero present-day aerosol cooling (blue curves, Fig. 1) fall below the 5% confidence limits from the probabilistic predictions constrained by observed spatial and temporal temperature data. This finding is consistent with detection of the response to aerosol forcing in the optimal detection analysis (Stott et al., 2006) and therefore the high likelihood of a non-zero present day aerosol cooling.

The ASK predictions shown in Fig. 1 (grey plumes) include variations of decadal temperatures about the underlying anthropogenically forced response due to internally and naturally forced variability whereas the red and blue simple model curves do not include these extra sources of uncertainty. Therefore to make the ASK predictions more comparable with the simple model predictions, in Fig. 2 we recalculate the ASK probabilistic predictions but exclude the extra sources of uncertainty due to natural decadal variability about the underlying anthropogenically forced response. Note that in both Figs. 1 and 2 the ASK predictions include uncertainty due to only having a small number of future model projections from which to estimate the underlying forced response.

The resultant predictions shown in Fig. 2 are very similar to those shown in Fig. 1 towards the end of the century and give almost the same rates of temperature rise by 2100. However the differences between the two become larger earlier in the century as the ratio of natural internal and forced variability becomes larger relative to the signal of anthropogenic temperature change. The simple model simulations corresponding to high aerosol forcing



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(red lines, Fig. 2) for the SRES A1FI and A2 scenarios fall within the inner 80% confidence range of the probabilistic predictions for almost the entire century, although towards the end of the century they become increasingly unlikely (see Fig. 2a and b). After the middle part of the 21st century aerosol pollution is reduced rapidly under these scenarios and the warming therefore accelerates as the masking effect of aerosols is removed, revealing the consequences of a high transient climate response to increased greenhouse gas forcing. Given that the ocean heat uptake efficiency is reasonably well constrained by observations of ocean heat content (Levitus et al., 2005), future extreme warming levels are largely associated with high climate sensitivity. By the end of the century, for these two scenarios, the simple model simulation corresponding to the very high climate sensitivity case becomes more unlikely than it is earlier in the century.

In the B1 and B2 scenarios there is less early 21st century compensation of greenhouse warming by aerosol cooling than in the A1FI and A2 scenarios and therefore a greater initial spread of the blue and red curves for the B1 and B2 scenarios. For these scenarios, both simple model predictions corresponding to the strong and no aerosol cooling cases lie outside the 95% confidence range from the GCM-based probabilistic predictions by the second half of the century. Thus, observational constraints on the likely range of climate sensitivity indicate that the very high climate sensitivity case corresponding to the red lines in Fig. 2c and d is unlikely. Differences between emission scenarios of the position of the simple model predictions within the GCM plume (particularly when comparing A1FI and A2 against B1 and B2) suggest structural variation between the simple model and the GCM; for example differences in the representation of ocean heat uptake in the two models. Whereas ocean heat uptake is very crudely modelled in the simple model approach, the ASK predictions are based on a climate model that includes a fully coupled ocean model and therefore represents many more processes. This suggests that the systematic shifts of the predictions derived using the simple model (coloured lines) and the ASK ranges for rapid rates of forcing increase (A1FI and A2 scenarios) could be related to different ocean diffusivities in the simple and complex climate models Generally, especially later in the century, the anthropogenically forced component of future warming is predicted to lie between the two simple model extremes shown in the red and blue curves in Fig. 2, although over the next few decades under the B1 and B2 scenarios, natural variability could lead to temperatures lying outside this narrow range, and under the A1FI and A2 scenarios future warming over the next few decades could be greater than suggested by either of the two simple model extremes.

## 3. Discussion and summary

Andreae et al. (2005) used a simple box-model of global heat balance and a range of SRES emission scenarios to assess the possible consequence of uncertainty in present-day aerosol forcing. More formal optimal detection methods use GCMs to extract climate change signals in the observed temperature record corresponding to different atmospheric forcings (including aerosols). This methodology provides probabilistic estimates of current aerosol forcing strengths and uncertainties in projections of future warming.

Here we have compared the simple model projections of Andreae et al. (2005) with such observationally constrained GCM projections of global temperature for the 21st century, corresponding to four SRES scenarios of future anthropogenic emissions. In all cases, the observational record indicates that future warming is expected to be significantly higher than would be expected for zero present-day aerosol forcing (at 95% confidence level). The simple model projection corresponding to the high present day aerosol forcing case is seen to be plausible for the SRES A1FI and A2 scenarios during the first half of the 21st century, a period when aerosol cooling continues to counteract much greenhouse warming. However for the SRES B1 and B2 scenarios the probabilistic estimates indicate that the simulations by the simple model that correspond to the very strong present-day aerosol forcing case become increasingly unlikely during the course of the next century. Overall, observational constraints indicate that the transient climate response and present-day aerosol forcing are likely to lie between the two extremes considered by Andreae et al. (2005).

Our assumption that a model that over- or under-estimates the climate response to past forcing will continue to do so by a similar fraction in future is likely to become less robust the more the forcings stabilise and therefore the more approximate becomes the simple linear relationship between errors in past and future warming (Kettleborough et al., 2007). Also, any ASK-based estimate of future warming based on a single model, as this analysis is, will have unquantified uncertainties arising from inadequacies in the model used. The scaling procedure will correct for gross model error, for example, an underestimate or overestimate in the model of the aerosol forcing, but if there are large errors in the patterns of response to aerosol forcing or if forcings are missing in the model, then additional uncertainties will result. Notable omissions from the HadCM3 model simulations used in this analysis are forcings due to carbonaceous aerosols and land use changes, both of which could have significant effects, particularly at regional scales. One study has found that the pattern of near-surface temperature response to sulphate aerosols could be very similar, but opposite in sign, to the pattern of response to carbonaceous aerosols (Jones et al., 2005), in which case our analysis would derive approximately the correct net response to sulphate and carbonaceous aerosols in the past, and to the extent that the ratio of these forcings does not change in future, approximately the correct net predictive response. However, these assumptions are only likely to hold, even approximately, at the global scale. Therefore for both global and regional temperature predictions it will be necessary to more fully evaluate uncertainty in future by incorporating more models into the analysis that



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include a greater range of forcings and processes. Nevertheless, an initial attempt to do this for three climate models by Stott et al. (2006), and to compare with intermediate complexity models by Stott and Forest (2007), shows that probabilistic predictions of global mean warming are approximately, to first order, model independent, indicating that the observational record provides robust information on likely future warming.

Andreae et al. (2005) used a simple model to illustrate that aerosols may have reduced the past warming that would otherwise have been observed, and that strong present-day aerosol cooling would imply severe impacts from a rapidly warming world in future. We have extended such analysis using GCM simulations constrained by patterns of observed climate change, and have been able to place the results of Andreae et al. (2005) in a probabilistic framework. We conclude that current aerosol cooling has suppressed the full extent of greenhouse warming, which once realised will yield larger warming than would otherwise have been expected. Our probabilistic predictions show that, under the emissions scenarios considered here, future warming by the end of the 21st century is likely to lie between the extremes implied by very strong or very weak present-day aerosol cooling.

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