

# Climate commitment in an uncertain world

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Climate commitment—the warming that would still occur given no further human influence—is a fundamental metric for both science and policy. It informs us of the minimum climate change we face and, moreover, depends only on our knowledge of the natural climate system. Studies of the climate commitment due to CO<sub>2</sub> find that global temperature would remain near current levels, or even decrease slightly, in the millennium following the cessation of emissions. However, this result overlooks the important role of the non-CO<sub>2</sub> greenhouse gases and aerosols. This paper shows that global energetics require an immediate and significant warming following the cessation of emissions as aerosols are quickly washed from the atmosphere, and the large uncertainty in current aerosol radiative forcing implies a large uncertainty in the climate commitment. Fundamental constraints preclude Earth returning to pre-industrial temperatures for the indefinite future. These same constraints mean that observations are currently unable to eliminate the possibility that we are already beyond the point where the ultimate warming will exceed dangerous levels. Models produce a narrower range of climate commitment, but undersample observed forcing constraints.

## 1. Introduction

Our ability to predict future climate changes rests fundamentally on two factors: firstly, how our future human activities will influence climate forcing and secondly, how our physical models of climate translate that forcing into climate change. The first factor depends on societal choices beyond the scope of science. The second factor depends on our confidence in the climate models. In turn, this confidence is predicated on the ability of the models to reproduce past climate changes, given our knowledge of previous human (and other) influences.

The concept of a ‘climate commitment’—the climate change that would still occur given no further human influence—has proven useful in distinguishing between these two factors of climate prediction. It allows for a clear separation between the uncertainties in our physical climate models, which we wish to study, and the highly-uncertain future human influence on climate. The climate commitment can also be regarded as the minimum climate change we are constrained to because of human activities already undertaken.

Early efforts to estimate climate commitment considered the additional warming that occurs as the climate system

comes into equilibrium with the present atmospheric composition and radiative forcing. Under this assumption, an additional warming of about 0.6°C is ‘in the pipeline’ due to the thermal inertia of the world oceans [Wigley, 2005; Meehl *et al.*, 2005; Hansen *et al.*, 2005], committing us to future climate change that approaches ‘dangerous’ levels [Ramanathan and Feng, 2008].

There has recently been a resurgence of interest in the climate commitment [Ramanathan and Feng, 2008; Hare and Meinshausen, 2006; Plattner *et al.*, 2008; Solomon *et al.*, 2009; Matthews and Weaver, 2010] in which an alternative, ‘zero emissions’, definition has been proposed. Under zero emissions, the atmospheric composition changes according to natural processes, and future warming is determined by only the physical inertia of the climate system and the residual greenhouse gas climate forcing. Matthews and Weaver [2010] argue that this definition is the correct measure of the present climate commitment. They make the worthwhile and important point that the previous measure—constant climate forcing—conflates the physical response of the climate system to past emissions with the response to the future emissions that are necessary to maintain a constant atmospheric composition.

Several studies [Plattner *et al.*, 2008; Solomon *et al.*, 2009; Matthews and Weaver, 2010] consider the zero emissions commitment with respect to CO<sub>2</sub>. Carbon dioxide is naturally removed from the atmosphere on multiple time scales. Under zero emissions, CO<sub>2</sub> would fall off to about 40% of its peak enhancement above pre-industrial levels within a few centuries [Solomon *et al.*, 2009; Archer, 2005], while further recovery would occur over many thousands of years [Archer *et al.*, 2009]. In the context of climate commitment, the CO<sub>2</sub> that persists for multiple millennia defines the ultimate radiative forcing with which the climate must come into equilibrium. In such a zero emissions scenario, global average surface temperature is projected to remain near current levels, or even decrease slightly, in the millennium following the cessation of emissions [Plattner *et al.*, 2008; Solomon *et al.*, 2009; Matthews and Weaver, 2010]. However, these studies have overlooked the important role of the non-CO<sub>2</sub> greenhouse gases (such as methane and nitrous oxide) and aerosols. Aerosols are widely known to be one of the chief uncertainties in the modern climate, and make a considerable difference to the answer. Ramanathan and Feng [2008] do consider the effect of removing anthropogenic aerosols, however they fix CO<sub>2</sub> at modern levels. The full consequences of the cessation of human activities must include both influences.

## 2. Transient and ultimate climate commitment

Following the elimination of emissions, aerosols would fall to their pre-industrial levels on time scales of days to weeks [Forster *et al.*, 2007], while the non-CO<sub>2</sub> greenhouse gases would persist for decades to centuries [Forster *et al.*, 2007; Solomon *et al.*, 2009]. The sudden loss of the cooling effect of aerosols would result in a rapid transient warming as the surface temperature adjusts to the full greenhouse gas radiative forcing. Due to this significant transient warming, we propose two separate measures of climate commitment:

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a ‘transient commitment’, defined by the peak temperature following the cessation of emissions; and an ‘ultimate commitment’, defined by the temperature once the climate system has fully equilibrated with the persistent fraction of the CO<sub>2</sub> radiative forcing.

How well constrained is the climate commitment? Conservation of energy must obviously apply to the global energy budget, a linearization of which is

$$H = R - \lambda^{-1}T, \quad (1)$$

where  $\lambda$  is the climate sensitivity parameter,  $T$  is the global average surface temperature (above pre-industrial),  $R$  is the radiative forcing, and  $H$  is the ocean heat uptake.

For a permanent forcing  $R_\infty$ ,  $H$  must ultimately go to zero giving an ultimate commitment of

$$T_\infty = \lambda R_\infty. \quad (2)$$

Eliminating  $\lambda$  gives

$$T_\infty = \left( \frac{R_\infty}{R - H} \right) T. \quad (3)$$

Thus,  $T_\infty$  depends only on observed constraints ( $T$ ,  $H$ , and  $R$ ) and the ultimate forcing ( $R_\infty$ ). For the current climate,  $T$  is  $0.76 \pm 0.19^\circ\text{C}$  [Trenberth *et al.*, 2007] and  $H$  is  $0.74 \pm 0.13 \text{ W m}^{-2}$  [Lyman *et al.*, 2010; Purkey and Johnson, 2010].

The Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) outlines constraints on  $R$ . Total anthropogenic radiative forcing (Fig. 1) is approximately  $1.6 \text{ W m}^{-2}$ , with a 90% confidence range of  $0.6 \text{ W m}^{-2}$  to  $2.4 \text{ W m}^{-2}$  [Forster *et al.*, 2007]. Therefore,  $T$  and  $H$  are well constrained,  $R$  less so. Uncertainties in aerosols ( $-0.5 \text{ W m}^{-2}$  to  $-2.2 \text{ W m}^{-2}$ ) [Forster *et al.*, 2007] dominate the uncertainty in  $R$ , and thus dominate the uncertainty in  $T_\infty$ .

The time evolution of climate requires a representation of the ocean, for which we use a simple upwelling-diffusion model. The model is the same as that in Baker and Roe [2009], which is similar in form to those used in previous studies (e.g., Hoffert *et al.* [1980]; Raper *et al.* [2001]). All parameters are as described in Baker and Roe [2009], except  $R$  and  $\lambda$ , which we vary as described below. Such models are robust, and successfully reproduce observations of ocean heat uptake at the global scale [Raper *et al.*, 2001].

### 3. Results

The weak bounds on aerosols means a broad envelope of uncertainty in total forcing over the industrial era. This is illustrated in Fig. 2a, where an idealized representation of forcing trends has been employed. Forcing reaches its modern value in year 200, and from then on a climate commitment scenario is assumed. Once emissions are terminated,  $R$  is governed by the respective decay time scales of the various atmospheric constituents (see Fig. 2).

From Eq. 1 the relatively strong constraints on  $T$  and  $H$  mean that  $R$  and  $\lambda$  can be thought of as pairs wherein strong (weak) aerosol forcing is balanced by high (low) climate sensitivity. This compensation occurs within AR4 and older models [Schwartz *et al.*, 2007; Kiehl, 2007; Knutti, 2008]. Figure 2b shows temperature trajectories for pairs of  $R$  and  $\lambda$ , whereby past temperature trends are approximately reproduced. It is a graphical representation of the inherent trade-off between uncertainties in climate forcing and uncertainties in global temperature following the cessation of emissions: even though past temperature changes are well

constrained and future forcing (under zero emissions) well understood, uncertainty in past forcing implies uncertainty in future temperatures.

It is important to emphasize that  $R$  and  $\lambda$  are not independent. In other words, a high climate sensitivity and a low aerosol forcing are inconsistent with the observed constraints on surface temperature and ocean heat uptake. Two recent studies that consider the effects of the loss of aerosols [Hare and Meinshausen, 2006; Ramanathan and Feng, 2008] treat  $R$  and  $\lambda$  as independent, and also fail to span the full range of either  $R$  or  $\lambda$ . This has the effect of producing a narrower range of climate commitment than allowed by propagating the observed constraints through Eq. 3.

We next reproduce and explain the results of previous studies [Plattner *et al.*, 2008; Solomon *et al.*, 2009; Matthews and Weaver, 2010] that considered climate commitment with respect to only CO<sub>2</sub> emissions (non-CO<sub>2</sub> greenhouse gases and aerosols remain at their modern concentrations). For modal estimates of modern radiative forcing, this gives  $R_\infty \approx 0.8 \text{ W m}^{-2}$ . The dashed black lines in Fig. 2 show this forcing and the response—a gentle decline in temperature following the cessation of CO<sub>2</sub> emissions. The result follows directly from surface energetics (Eq. 3):  $R_\infty$  is very near the modal value of the current surface forcing ( $R - H \approx 1 \text{ W m}^{-2}$ ) so the ratio of forcings (i.e.,  $R_\infty/(R - H)$ ) and therefore the ratio of the responses (i.e.,  $T_\infty/T$ ) is near, but slightly less than, one.

Turning now to the case in which all anthropogenic emissions cease, there is an immediate unmasking of greenhouse gas forcing as aerosols are quickly washed from the atmosphere. The effect is an abrupt rise in climate forcing (Fig. 2a) to a peak value of around  $3 \text{ W m}^{-2}$ , which is relatively well constrained as it depends only on greenhouse gases. The response is a rapid and substantial warming (Fig. 2b), with a transient commitment of between  $0.1^\circ\text{C}$  and  $1^\circ\text{C}$  above the modern temperature. Thereafter, forcing declines over the next few centuries as greenhouse gases are partially, but not completely, removed from the atmosphere. At the low end of the climate response, temperature falls to less than half of its peak value. At the high end, temperature continues to increase because the system has not yet attained equilibrium due to the long adjustment time scales of high sensitivity systems [Baker and Roe, 2009].

The long-term temperature response depends only on modern surface energetics and  $R_\infty$ . Figure 2 accounts only for uncertainties in aerosols. This gives an ultimate commitment of  $T_\infty = 0.6^\circ\text{C}$  with a 90% confidence range of  $0.3^\circ\text{C}$  to  $6.1^\circ\text{C}$ , which follows directly from Eq. 3 or by integrating the climate model to equilibrium.

The lower bound on climate commitment is robust due to the form of Eq. 3. On the other hand, the upper bound is very sensitive to uncertainties in observed global energetics and  $R_\infty$ . Moreover, following the IPCC, we have taken the 90% confidence interval on aerosol climate forcing: if one were to factor in other sources of uncertainty, in either ocean heat uptake or greenhouse gas forcing, or use more conventional statistical bounds (i.e., a 95% range), one could not rule out the disconcerting possibility that the observed 20th century warming has transpired with little to no effective surface forcing (i.e.,  $R \approx H$ ).

### 4. Discussion

The above analysis showed that current observational constraints allow the possibility of a very large climate commitment. Do narrower bounds exist? The ultimate commitment can alternatively be expressed as a function of  $\lambda$  (Eq. 2), reasonable bounds on which can be inferred from

IPCC AR4 in terms of a ‘likely’ (> 66% probability) and ‘very likely’ (> 90% probability) range for climate sensitivity [Hegerl *et al.*, 2007]. Exploiting the fundamental relationship between  $R$  and  $\lambda$ , and reversing the above arguments, these IPCC constraints on  $\lambda$  provide constraints on  $R$  (Fig. 3a). Any value of  $\lambda$  within the IPCC range still implies a significant transient warming (Fig. 3b), and there remains a substantial uncertainty in the ultimate commitment (though the range is smaller than that based on observational constraints).

The ability of the IPCC AR4 fully coupled climate models (hereafter AR4 models) to reproduce 20th century surface temperature [Knutti, 2008] and ocean heat uptake [Plattner *et al.*, 2008], under substantial aerosol uncertainty, has been suggested to give a false sense of the accuracy with which future climate can be predicted [Schwartz *et al.*, 2007]. However, AR4 models have achieved consistency with the observational record, in part, through compensation between  $R$  and  $\lambda$  [Knutti, 2008]. As argued by Knutti [2008], such model tuning—whether explicit or implicit—is not problematic provided that we interpret models as conditional on observations. In other words, models satisfy Eq. 1 subject to relatively tight constraints on  $T$  and  $H$ . Accurate simulation of 20th century climate may then be viewed as a necessary, but not sufficient, condition for the ability to simulate future climate, and does not alone create overconfidence in model skill. Indeed, the light blue trajectories in Fig. 3b clearly demonstrate the ability, with a model, to reproduce the 20th century temperature record yet still span the full range of uncertainty in climate commitment as allowed by observations.

The difference between the AR4 model range of climate commitment and the range allowed by observations can instead be attributed to an inconsistency between  $R$  in models and  $R$  in observations—the range of forcing among the different AR4 models [Knutti, 2008] spans only the ‘likely’ range of forcing in Fig. 3a. How can models and observations be reconciled? One way would be to achieve substantially more accurate observations of the Earth’s radiative budget. In particular, emphasis should be placed on ruling out the very low values of  $R$  that correspond to very high values of committed warming.

The alternative approach is to create populations of climate models that deliberately exploit tuning to fully span the uncertainty in climate forcing (and the implied range of climate sensitivity necessary to reproduce the observed temperature record), and then to demonstrate that some pairs of  $R$  and  $\lambda$  are inconsistent with some aspect of either the instrumental record (e.g., interannual variability, seasonal variability, spatial patterns of warming, or volcanic eruptions), or reconstructions of past climates (see Hegerl *et al.* [2007]; Knutti and Hegerl [2008]; Edwards *et al.* [2007] and references therein). Studies that pursue this approach produce a variety of distributions for climate sensitivity, many narrower than that inferred from observational constraints, some narrower than even the IPCC ‘likely’ range [Allen *et al.*, 2007; Hegerl *et al.*, 2007; Edwards *et al.*, 2007; Knutti and Hegerl, 2008]. Arguably, an important measure of the value added by models will be when the consensus is reached that such studies provide narrower constraints on the modern climate forcing than that currently provided by direct observations. The discrepancy between the reported ranges of uncertainty in climate sensitivity and observations of aerosol forcing is an important one for future rounds of the IPCC reports to resolve. Until then, model-based estimates should be treated carefully, and probably represent an undersampling of the possible climate commitment.

## 5. Conclusions

The concept of a climate commitment is an effective way of isolating the physical and anthropogenic impacts on the future evolution of the climate system. It is also the mini-

mum climate change we face absent the active and deliberate management of the Earth’s radiative budget—namely, geoengineering. The recognition of both transient and ultimate climate commitments is essential because each has a different set of climate impacts, adaptation strategies and, possibly, engineering requirements on the global energy budget.

The results presented here depend only on three straightforward and well-understood aspects of climate: the net cooling effect of aerosols, the large spread of uncertainty in aerosol forcing (or, equivalently, climate sensitivity), and the geologic lifetime of atmospheric CO<sub>2</sub>. In combination they lead to considerable uncertainty in the transient and ultimate climate commitments. Our focus on the present climate commitment leads to one particular value of  $R_\infty$ . Of course, in any practical scenario, emissions will continue and  $R_\infty$  will grow. In turn, the transient and ultimate climate commitments will increase and become more uncertain. Inasmuch as a substantially improved understanding of the role of aerosols in climate remains elusive, so will our ability to constrain future climate. In order to rule out the possibility that we already face a disturbingly large climate commitment, we need to rule out the possibility that the observed climate change has been driven by a climate forcing at the lower end of the range that is currently permitted by observations.

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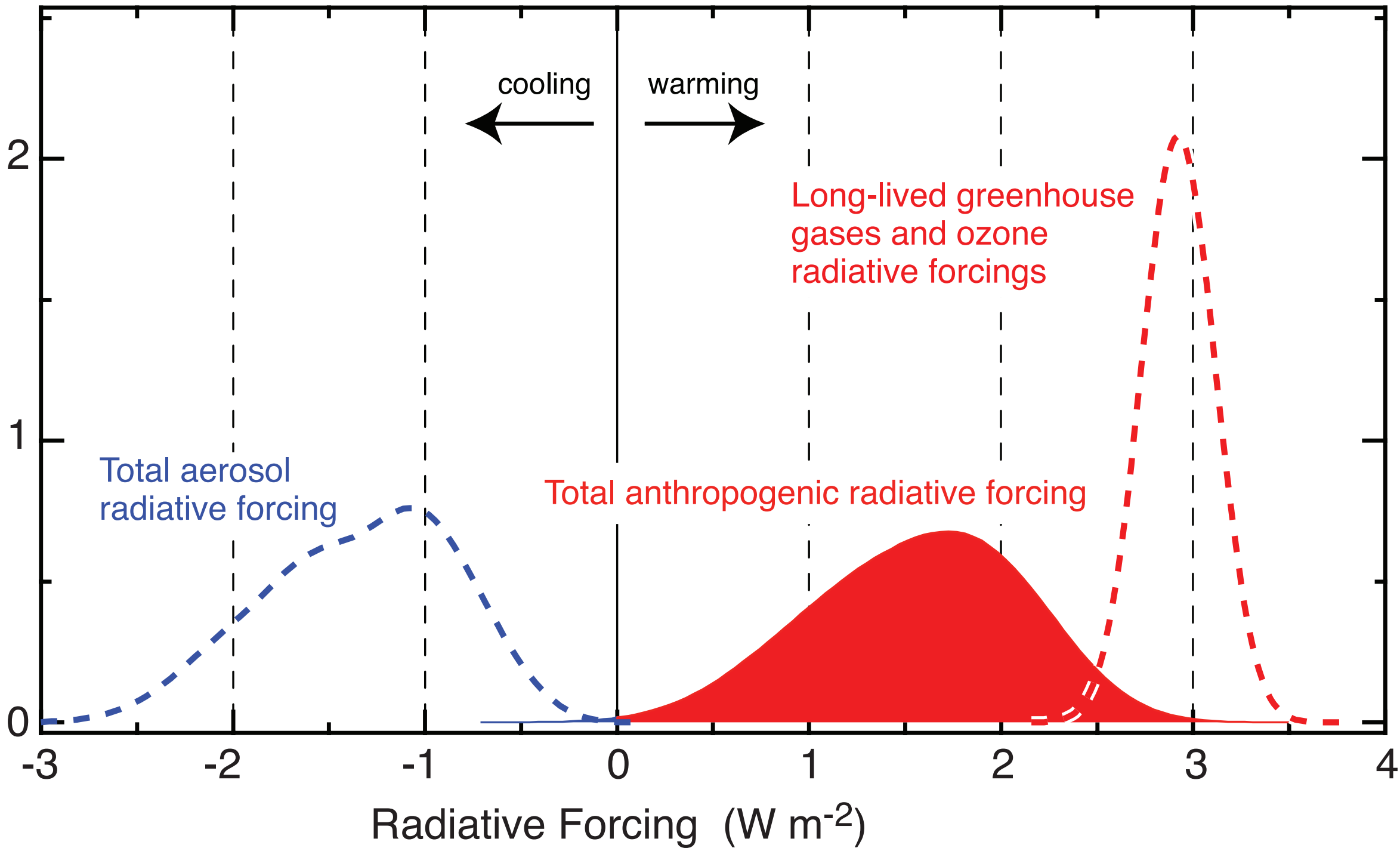
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**Figure 1.** Anthropogenic aerosol, greenhouse gas, and total radiative forcing. Reproduced from IPCC AR4 [Forster *et al.*, 2007]. The aerosol radiative forcing estimate includes only direct and cloud albedo effects. If the aerosol semi-direct effect, cloud lifetime effect, and indirect effect on mixed phase clouds were included, the forcing would be more negative and more uncertain [Forster *et al.*, 2007; Isaksen *et al.*, 2009].

**Figure 2.** Observational constraints on climate forcing and temperature response. **a**, Idealized representation of forcing trends. Forcing is ramped linearly to its modern value in year 200, and a zero emissions scenario is assumed thereafter. The lifetimes of aerosols and greenhouse gases are summarized in Solomon *et al.* [2009]; Archer [2005]; Archer *et al.* [2009]; Forster *et al.* [2007]. Upon zero emissions, aerosols are specified to fall to pre-industrial levels immediately. For simplicity, we assume a single decay ( $e$ -folding) time scale of 50 years for the non-CO<sub>2</sub> greenhouse gas radiative forcing. Carbon dioxide is assumed to fall to 40% of its peak value (above pre-industrial) with a decay time scale of 150 years. The light blue shading is the 90% confidence interval on trajectories of  $R$  as allowed by observations, where only uncertainty in aerosols is considered. The solid black line shows the modal value of  $R$ . The dashed black line shows a scenario in which aerosols and non-CO<sub>2</sub> greenhouse gases are held fixed at their modern concentrations upon the elimination of CO<sub>2</sub> emissions. **b**, As for **a**, but modeled temperature response. Values of  $\lambda$  have been paired with values of  $R$  so that individual temperature trajectories are tightly constrained, analogous to the situation for modern observations.

**Figure 3.** Illustration of what IPCC bounds on climate sensitivity imply for constraints on past climate forcing and future temperature response. **a**, Radiative forcing and **b**, Temperature response, as in Fig. 2. The dark blue shading shows the IPCC AR4 ‘likely’ range of climate sensitivity (2 °C to 4.5 °C). The medium blue shading shows the IPCC AR4 ‘very likely’ range of climate sensitivity (1.5 °C to 10 °C—IPCC AR4 [Hegerl *et al.*, 2007] truncates the probability distributions of climate sensitivity at 10 °C so we take this value as representative of the upper bound on the ‘very likely’ range). For comparison, the light blue shading shows the 90% confidence interval as allowed by observations, as in Fig. 2. A wedge in the lower range of possible forcing translates to a wedge in the higher range of possible temperature response.

Relative probability



Total aerosol radiative forcing

Total anthropogenic radiative forcing

Long-lived greenhouse gases and ozone radiative forcings

cooling

warming

2

1

0

-3

-2

-1

0

1

2

3

4

Radiative Forcing ( $\text{W m}^{-2}$ )

