

FY 2011 Third Quarter Report Estimate of Historical Aerosol Direct and Indirect Effects

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1.0 Introduction

The global and annual mean aerosol direct and indirect effects estimated from Community Earth System Model (CESM) simulations are -0.06 W m^{-2} and -1.39 W m^{-2} , respectively. These estimates are based on the following considerations.

Aerosol particles influence climate through a variety of mechanisms: (1) by scattering, absorbing, and emitting radiant energy in the atmosphere and at the surface when deposited on snow and ice; (2) by serving as the nuclei for droplet and ice crystal formation in clouds, and (3) by influencing the biogeochemical cycles through fertilization and acidification of soil, lakes, and the ocean.

The term *aerosol direct effects* refers to the direct impact of anthropogenic aerosol particles on the planetary energy balance through scattering, absorption, and emission of radiation in the atmosphere, without consideration of the aerosol effects of the radiative heating on clouds. The term *aerosol indirect effects* refers to the impact through the influence of anthropogenic aerosol on the optical properties of clouds by serving as the nuclei for droplets and ice crystals and thereby increasing droplet and ice crystal number concentration, which increases cloud particle surface area, suppresses droplet collisions, and increases the accumulation of liquid water and ice in clouds, all of which increase the reflectivity and emissivity of clouds.

These aerosol effects are important to the earth system. Efforts to quantify aerosol direct and indirect effects suggest a radiative cooling that is nearly as large as the radiative warming due to anthropogenic increases in CO_2 , but large uncertainties remain. These uncertainties confound interpretation of climate change due to CO_2 increases between pre-industrial and present times, and limit our ability to project future climate change.

Aerosol direct effects have been treated in climate models for at least ten years, but aerosol indirect effects have only recently been added to climate models. The CESM is one such model with a treatment of aerosol indirect effects. With support from the Department of Energy (DOE) Atmospheric System Research (ASR) and Scientific Discoveries through Advanced Computing (SciDAC) programs, an advanced representation of the aerosol lifecycle and aerosol direct and indirect effects has been incorporated within the CESM as part of version 5 of the Community Atmospheric Model (CAM5, Rasch et al. 2011). Other versions of CAM use simpler treatments of aerosols that do not include many of the aerosol processes described below.

CAM5 uses a “modal” treatment (Liu et al. 2011). All important aerosol sources (natural as well as anthropogenic) are included. The aerosol size distribution is expressed in terms of three log-normal modes, each composed of an internal mixture of all of the important aerosol components (sulfate, black carbon, organic carbon, sea salt, and mineral dust), with number as well as mass concentration simulated for each mode. Aerosol processes represented in the model include emissions of primary particles and precursor gases; oxidation of the precursor gases; new particle formation; particle growth by condensation; particle coagulation; transport by resolved winds, turbulence, and convective clouds; growth by humidification; activation to form cloud droplets and ice crystals; aqueous- phase chemistry; nucleation and impaction scavenging; and dry deposition to the surface.

The treatment of the optical properties of each aerosol mode (Ghan and Zaveri 2007) accounts for humidification effects, size dependence, and internal mixing of the aerosol components with water, which is important for treating absorption by black carbon when it is coated with sulfate, organic, and water. Aerosol direct effects are calculated by differencing radiative transfer calculations with and without aerosols.

Aerosol indirect effects are treated using a double-moment cloud microphysics scheme (Morrison and Gettelman 2008, Gettelman et al. 2008). Droplet nucleation is related to properties of all of the aerosol modes (Abdul-Razzak and Ghan 2000). Ice crystals form by homogeneous nucleation on sulfate particles and heterogeneous nucleation on dust particles (Liu and Penner 2005, Liu et al. 2007, Gettelman et al. 2010). Droplet number influences liquid water content and precipitation through its influence on the autoconversion process. Cloud optical properties depend on droplet and crystal number as well as liquid and ice water path, which together produce the aerosol indirect effect.

To estimate aerosol indirect effects, it is necessary to isolate aerosol effects on clouds from other influences on clouds. This is typically accomplished by changing aerosol emissions while holding constant the greenhouse gas concentrations, sea surface temperature, and sea ice. Recent work also suggests that it is helpful to constrain the winds by nudging simulated winds toward observed winds. Direct and indirect effects can then be estimated from the simulated changes Δ in the radiative flux at the top of the atmosphere, written as a statement of identity with two separate terms:

$$\Delta F = \Delta(F - F_{no_aer}) + \Delta F_{no_aer} \quad (1)$$

where F is the radiative flux from the simulation and F_{no_aer} is the radiative flux separately calculated by neglecting all scattering, absorption and emission of radiation by the aerosols. The first term in (1) represents the direct effects of the changes in the aerosol due to changes in emissions. The difference $F - F_{no_aer}$ is the direct radiative effect of all of the aerosol, accounting for the dependence on the distributions of clouds as well as the aerosol. The change $\Delta(F - F_{no_aer})$ thus quantifies the change of the direct effect. Note that changes in clouds will affect both F and F_{no_aer} in similar ways, so the first term is insensitive to changes in clouds.

Since equation (1) is just a statement of identity, the second term in (1) simply completes the identity. However, because F_{no_aer} neglects the direct influence of aerosols on the radiative flux, ΔF_{no_aer} is only directly influenced by changes in clouds or in the surface temperature and reflectivity. If sea surface temperature and sea ice are constant, changes in surface temperature and reflectivity are small, and changes in clouds are entirely due to changes in the aerosol. The cloud changes can be considered to be the indirect effect, although the term also includes the radiative effects of cloud changes induced by radiative absorption, scattering, and emission from changes in the aerosol (known as the semi-direct effect). Isolating the semi-direct effect from the indirect effect would require a separate simulation that neglects radiative absorption, scattering, and emission by the aerosol. Since the semi-direct effect is usually much smaller than the indirect effect, the distinction is often neglected, so the second term in (1) could be considered a measure of aerosol indirect effects. In this report we will call the second term aerosol indirect effects, although we acknowledge that some of the signal is due to semi-direct effects that have not been quantified for the CESM.

Although it is possible to estimate aerosol direct and indirect effects continuously as emissions change (Takemura et al. 2006), the effects are more commonly estimated by contrasting two different emissions scenarios, such as present day and preindustrial. We have done the latter. A pair of six-year simulations by the CESM was performed using present-day (year 2000) ocean surface conditions (sea surface temperature and sea ice) and oxidant (O_3 , OH, NO_3 , HO_2) concentrations, one with present-day emissions of primary aerosol (organic carbon, black carbon, and SO_4) and aerosol precursor gases (SO_2 , volatile organic compound), and one with preindustrial (year 1850) emissions of aerosol and precursor gases. Direct and indirect effects of anthropogenic aerosol are estimated from the difference Δ between the two simulations.

The global mean direct forcing is smaller than most estimates: -0.06 W m^{-2} . This result is due to enhanced warming by black carbon (compared with most other estimates) because the CESM treats enhanced absorption when black carbon is internally mixed with water and soluble aerosol components, and CESM assumes black carbon is always internally mixed with other components in the accumulation mode. The direct forcing for each component is diagnosed using radiation calculations with each component removed separately. The global annual means, shown in Figure 1, indicate that nonlinear interactions between the components produce a 0.09 W m^{-2} difference between the total direct forcing and the sum of the contributions of each component to the forcing.

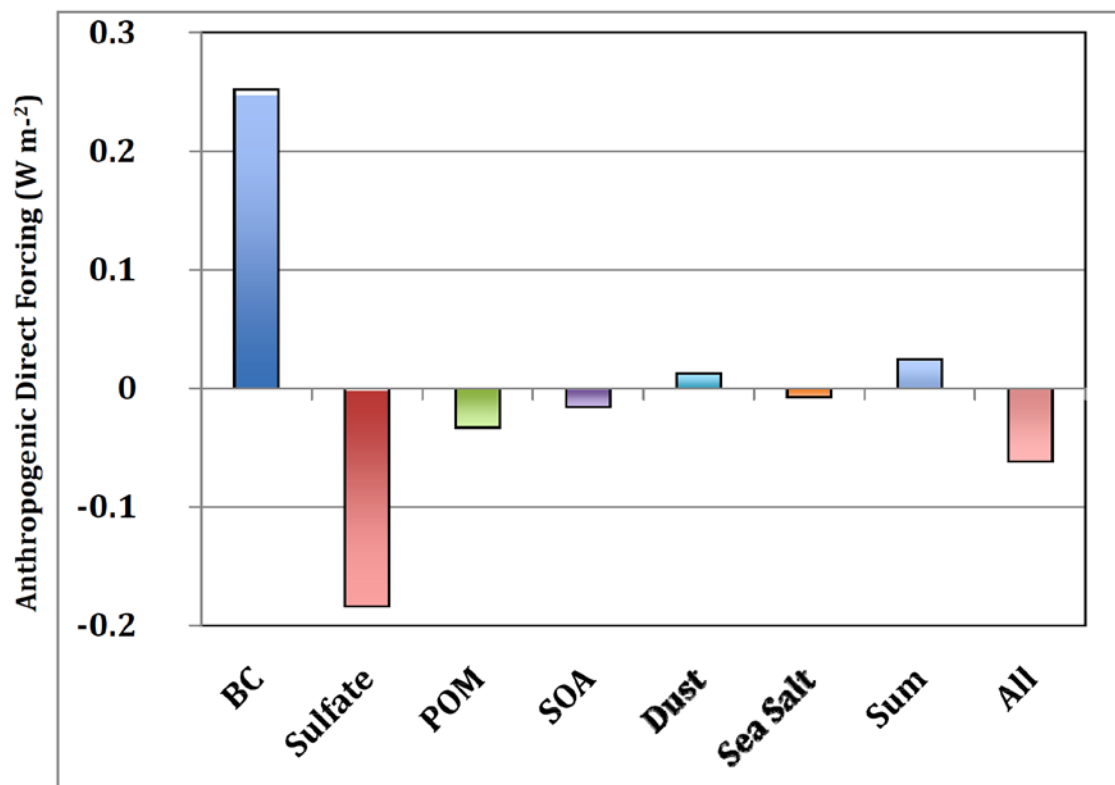


Figure 1. Global annual mean direct forcing.

Figure 2 shows the spatial distribution of the annual mean direct effects. Regions with positive and negative forcing are evident. Negative forcing occurs when anthropogenic sulfate aerosol, which mainly scatters solar radiation, accumulates over the ice-free and cloud-free ocean, which is relatively dark. The radiative cooling is most evident over the Mediterranean Sea, but is also evident over the subtropical Atlantic, Pacific, and Indian oceans.

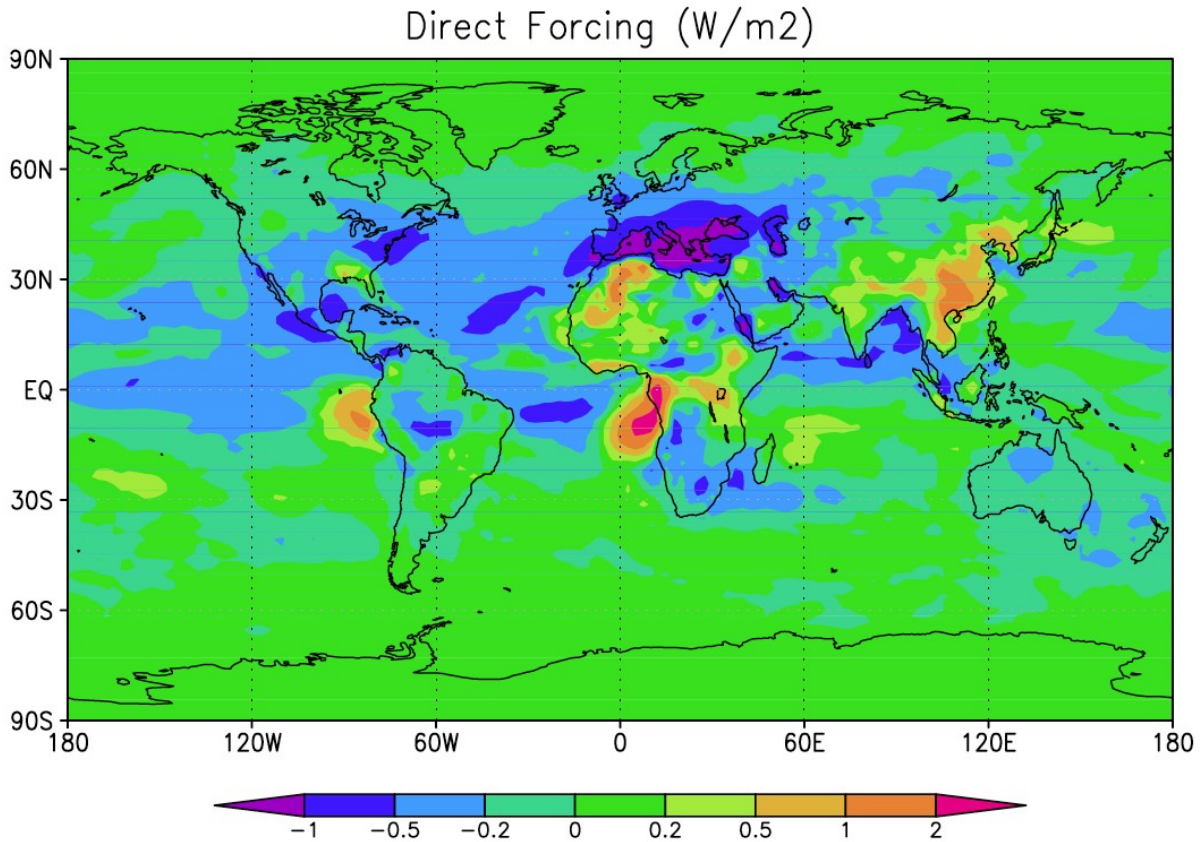


Figure 2. The annual mean direct forcing by anthropogenic aerosol at the top of the atmosphere.

Positive direct forcing occurs when black carbon accumulates above a bright surface or clouds. Although some radiative warming is simulated over the snow and sea ice in polar regions, the black carbon burdens are relatively low there and are accompanied by sulfate and organic carbon (which primarily scatter). The incoming solar is low or zero when the burdens are greatest during the winter months, so the radiative forcing there is weak. The strongest radiative warming is found near the biomass burning regions in Africa, when smoke is transported over clouds (Chand et al. 2009). Large positive forcing is also simulated over eastern China, which suggests significant black carbon is transported above clouds, and off the equatorial west coast of South America, where smoke from Amazon fires is transported over clouds there. A surprising warming is also simulated over the bright sands of the Sahara desert; this is associated with an increase in dust burden there which, because there is no anthropogenic influence on dust emissions in the simulations, is due to natural variability in the winds that lift dust from the surface.

The indirect forcing has significant contributions from longwave as well as shortwave radiation. Figure 3 shows the spatial distribution of the annual mean shortwave indirect effect. The distribution is rather noisy, with positive forcing exceeding 5 Wm^{-2} in some regions. These variations are most likely due to

random differences in the simulated liquid water path of clouds (Figure 4); although semi-direct effects could reduce liquid water path, the regions with positive indirect effects (decreased liquid water path) do not coincide with the regions with increases in black carbon burden. Strong negative indirect effects are evident oversoutheast and south Asia, Indonesia, northern Europe, the Arctic, and downwind from the sulfur sources in Chile, where the increase in liquid water path amplifies the radiative cooling due to the reduced droplet size. Weaker cooling is evident in more remote regions across the North Pacific Ocean, the North Atlantic Ocean, and northern Asia.

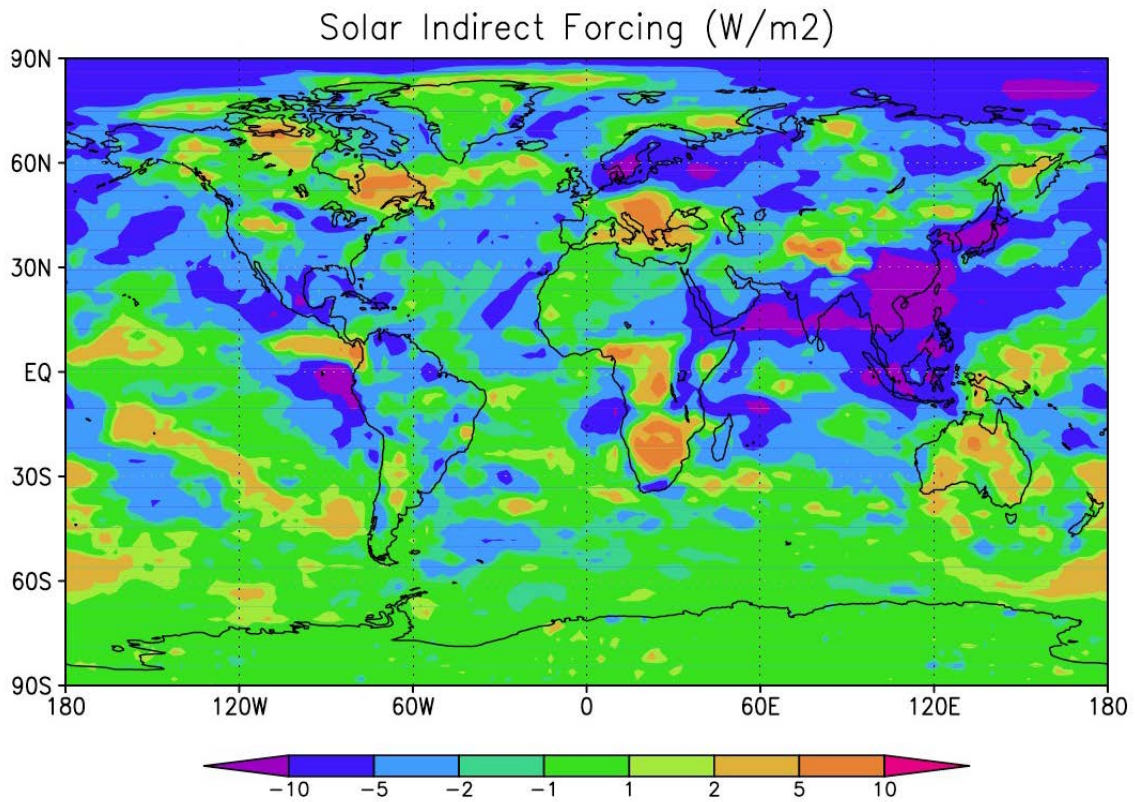


Figure 3. Annual mean solar indirect forcing.

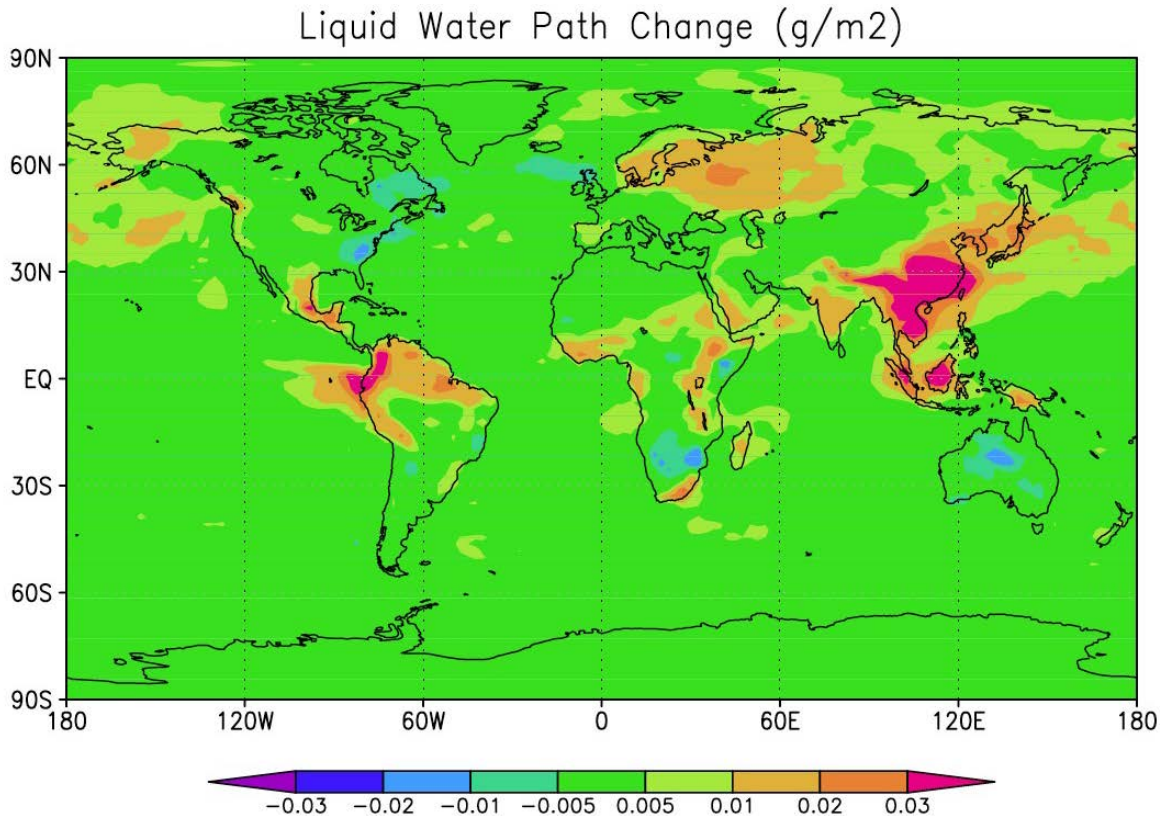


Figure 4. Annual mean change in liquid water path.

Most previous estimates of aerosol indirect effects have focused on effects on solar radiation. The CESM produces surprisingly strong aerosol indirect effects on longwave radiation. The longwave indirect effect is estimated differently from the shortwave because the changes in simulated land temperature produce a significant change in the longwave flux at the top of the atmosphere that is a signature of the response rather than the forcing. Since we want to know the forcing rather than the response, we estimate the longwave indirect effect from the change in the longwave cloud forcing, $\Delta(F-F_{\text{clear}})$. Figure 5 shows the spatial distribution of the annual mean of this estimate. Positive forcing exceeding 5 Wm^{-2} is simulated in a wide swath from Arabia to the subtropical northwest Pacific Ocean, and radiative cooling is simulated over west Africa and parts of South America.

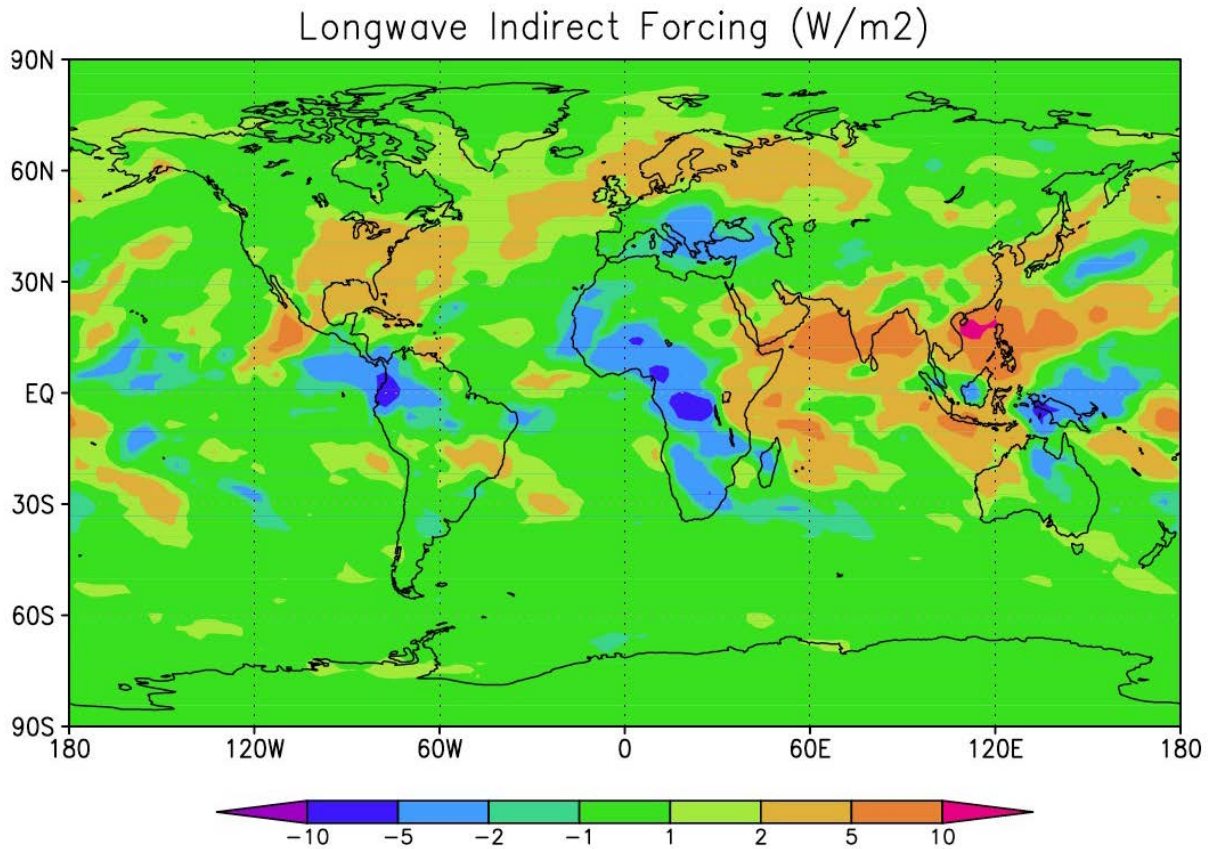


Figure 5. Annual mean longwave indirect forcing.

What is causing this large response? Figure 6 shows the change in crystal number concentration at 200 hPa. The longwave indirect forcing is strongly correlated with changes in upper troposphere crystal number concentration and resulting changes in cloud ice mixing ratio and cloud fraction. The changes in crystal number reflect changes in both deep convection (which increases some places and decreases in other places) and droplet nuclei concentration (which increases everywhere, albeit by varying degrees). This suggests enhanced homogeneous nucleation (droplet freezing) is the mechanism for the upper tropospheric changes in cloud.

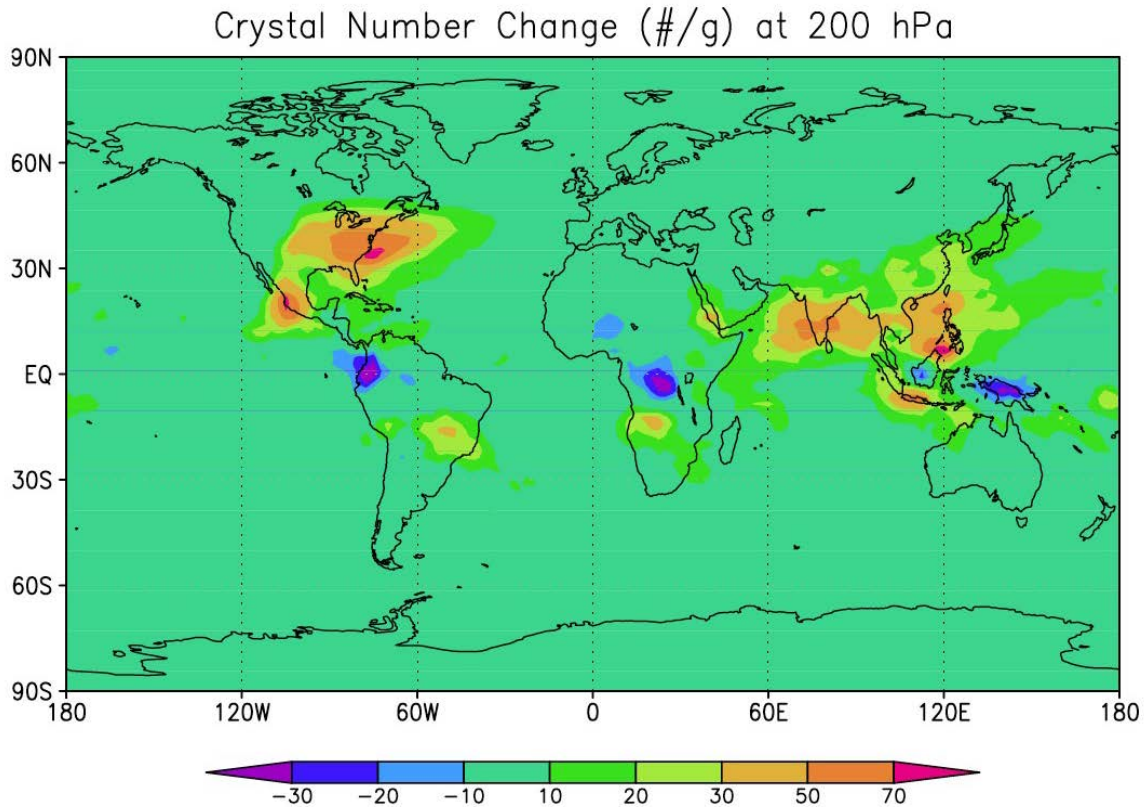


Figure 6. Change in annual mean ice crystal number concentration at 200 hPa.

The global annual mean indirect forcing is -2.02 and $+0.63 \text{ W m}^{-2}$ for shortwave and longwave radiation, respectively. The magnitude of the longwave indirect effect is larger than previous estimates by any other model, which is particularly surprising because the CESM neglects heterogeneous nucleation of ice crystals on black carbon (a largely anthropogenic aerosol). To better understand this result, we have performed an additional experiment in which the treatment of homogeneous nucleation is changed in the preindustrial and present day simulations. In the experiment, the subgrid vertical velocity used to diagnose homogeneous nucleation is reduced by a factor of two. The resulting reduction in anthropogenic enhancement of upper tropospheric cloud decreases the longwave indirect effect from 0.63 to 0.28 W m^{-2} , but at the same time weakens the total solar forcing from -2.08 to -1.75 W m^{-2} , so the total (shortwave + longwave) aerosol forcing is less sensitive to the treatment of homogeneous nucleation, changing from -1.39 to -1.48 W m^{-2} .

The treatment of aerosol direct and indirect effects in the CESM is being used in coupled atmosphere-ocean simulations of climate change for both the historical period (1850–2010) and in projections of future climate change under a variety of emissions scenarios. The aerosol direct and indirect effects for each of the future emissions scenarios will be reported in a subsequent report.

This work and much more is described in a manuscript being prepared for publication (Liu et al. 2011).

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