

# Simulations of Aerosol Indirect Effect for IPCC Emissions Scenarios

*C.C. Chuang, J.E. Penner and Y. Zhang*

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## SIMULATIONS OF AEROSOL INDIRECT EFFECT FOR IPCC EMISSIONS SCENARIOS

Catherine C. Chuang\*

Lawrence Livermore National Lab., Livermore, California

Joyce E. Penner and Yang Zhang

University of Michigan, Ann Arbor, Michigan

### 1. INTRODUCTION

It has been estimated that the present-day global anthropogenic emissions contribute more than half of the particle mass in sub-micrometer size primarily due to sulfate and carbonaceous aerosol components derived from fossil fuel combustion and biomass burning (IPCC, 1996). These anthropogenic aerosols modify the microphysical properties of clouds by serving as cloud condensation nuclei and enhance the reflectivity of low-level water clouds, leading to a cooling effect on climate variation (primary indirect effect). Increases of anthropogenic aerosols may also alter the development of precipitation by affecting initial size distributions of cloud droplets and thereby influencing the cloud lifetime (Albrecht, 1989). The increased cloud longevity could give rise to a higher cloud cover fraction and further enhance the cooling effect on the global radiation balance (secondary indirect effect).

In this paper, we used a fully coupled climate/chemistry model to estimate the present and future projections of aerosol forcing associated with the primary indirect effect. The model scenarios were designed for an IPCC model intercomparison workshop held at Hamburg, Germany in July 1999. Simulations were based on the newly developed IPCC anthropogenic emissions for the time period 2000 to 2100. We will present variations of solar radiation flux at the top of the atmosphere for each model scenario to address issues on aerosol/cloud/climate interactions.

### 2. COUPLED CLIMATE/CHEMISTRY MODEL

The coupled model used in this study is the improved version of the one described in Chuang et al. (1997). The chemistry model GRANTOUR now can calculate global concentrations of sulfate, dust,

sea salt, and carbonaceous aerosols (biomass and fossil fuel organic and black carbon). Sulfate is formed through gas to particle conversion processes from its gas phase precursor  $\text{SO}_2$ . Other aerosol types are assumed to be injected into the global model in the aerosol form. The climate model that was originally derived from the NCAR CCM1, has also been enhanced by a unique capability to take into account the absorption of solar radiation by black carbon associated with clouds. Black carbon is distinguished by its resistance to chemical and thermal attack and by its ability to strongly absorb solar radiation; specific absorption coefficients are estimated in the range of 3 to 20  $\text{m}^2/\text{g}$  (Liousse et al., 1993). This ability lowers the single scattering albedo of aerosols, therefore reducing the amount of solar radiation reflected by the aerosols. The presence of black carbon in clouds may also reduce the cloud albedo. We developed a parameterization for the single scattering albedo of cloud as a function of cloud droplet size and the volume fraction of black carbon inside the droplet for each wavelength band in our shortwave radiative module (Chuang et al., 1999). This solar radiation module has been updated with a higher spectral resolution; 9 wavelength bands for the UV-Visible and 3 for the near-IR spectral range (Penner et al., 1998; Grant et al., 1999).

The effect of aerosols on initial cloud drop number concentration is parameterized as a function of aerosol size distribution, total number, and updraft velocity at cloud base (Chuang and Penner, 1995). This parameterization is based on a mechanistic description of droplet formation and the chemical processes controlling the formation of sulfate. It accounts for anticipated changes in aerosol size due to changes that result from the deposition of sulfate formed in aqueous reactions and the condensation of sulfate formed in homogeneous gas phase reactions. We have evaluated this parameterization by comparing the predicted effective droplet size with those retrieved from satellites and comparing the droplet/aerosol correlations with measurements (see Chuang et al., 1997).

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\*Corresponding author address: Catherine C. Chuang, Lawrence Livermore National Lab. (L-103), Livermore, CA 94550; e-mail: chuang1@llnl.gov.

### 3. MODEL SCENARIOS

The specified model scenarios are given in two groups. The first one, scenarios 1 - 4, includes computations of A2 emissions scenario for 2000, 2030 and 2100 as well as B1 for 2100 with natural emissions at 2000. The A2 emissions scenario describes a very heterogeneous world where fertility patterns are not converging, population growth is high, and economic development regionally-oriented. The B1 emissions scenario describes a convergent world with rapid change in economic structures toward a service and information economy. The second group investigates the emissions feedbacks (scenarios 5 and 7) and chemistry feedbacks (scenario 6) associated with climate change at 2100. We performed simulations for model scenarios 1 - 5 as well as scenario 7. The outline of the emissions specified in each model scenario is listed in Table 1. Magnitudes of the global annual emissions for each aerosol component are presented in Table 2.

Table 1. Model scenarios designed for the IPCC Model Intercomparison Workshop

	SC1	SC2	SC3	SC4	SC5	SC7
Anthr. SO <sub>2</sub>	A2_2000	A2_2030	A2_2100	B1_2100	A2_2100	B1_2100
OC/BC	2000 <sup>1</sup>	A2_2030	A2_2100	B1_2100	A2_2100	B1_2100
Volcanic S <sup>2</sup>	2000	2000	2000	2000	2000	2000
DMS <sup>3</sup>	2000	2000	2000	2000	2100	2100
Terpenes <sup>4</sup>	2000	2000	2000	2000	2100	2100
Dust <sup>5</sup>	2000	2000	2000	2000	2100	2100
Sea salt <sup>6</sup>	2000	2000	2000	2000	2100	2100

1: from Liou et al. (1996)

2: from Andres and Kasgnoc (1998)

3: from J. Kettle

4: from A. Guenther

5: from P. Ginoux

6: from S.L. Gong

Table 2. Magnitudes of global annual emissions (Tg)

	SC1	SC2	SC3	SC4	SC5	SC7
Anthr. S	69.0	111.9	60.3	28.6	60.3	28.6
Volcanic S	4.8	4.8	4.8	4.8	4.8	4.8
Ocean S	26.1	26.1	26.1	26.1	27.8	27.8
BC	12.4	16.2	28.8	12.0	28.8	12.0
OC	81.4	108.6	189.5	75.6	189.5	75.6
Terpenes	14.4	14.4	14.4	14.4	20.7	20.7
Dust (f <sup>1</sup> )	400.3	400.3	400.3	400.3	418.3	418.3
Dust (c <sup>2</sup> )	1751.3	1751.3	1751.3	1751.3	1897.6	1897.6
Sea salt <sup>3</sup> (f)	88.5	88.5	88.5	88.5	155.0	155.0
Sea salt (c)	1066.4	1066.4	1066.4	1066.4	1866.7	1866.7

1: f represents fine particles (diameter < 2 μm)

2: c represents coarse particles (diameter > 2 μm)

3: Sea salt emissions are represented as Tg of Na

### 4. RESULTS

Our approach to simulating the primary indirect effect is to quantify two aspects of the problem: the forcing and the response. The “forcing” typically refers to the instantaneous radiative perturbation at the top of the atmosphere (TOA) that results from an increase in aerosols in the climate system. The “response” refers to the change in the climatic state that results from the radiative forcing. In our interactively coupled model simulations with sea surface temperatures prescribed, the meteorological fields such as temperature, wind, and precipitation are consistent with currently calculated species or aerosol concentrations.

Radiative forcing by primary indirect effect is calculated as the difference in solar radiative flux at TOA with and without the increase of cloud albedo associated with anthropogenic aerosols at each time the radiation routine is called. Thus, the forcing calculation does not involve any feedback from the climate system. Magnitude of climate feedback is derived from the difference in baseline solar radiative flux between each model scenario and the control run. The total change of solar radiation flux at TOA can be expressed as

$$\begin{aligned} \Delta F &= F_{\text{control}} - F_{\text{base+anthr}}^i \\ &= [F_{\text{base}}^i - F_{\text{base+anthr}}^i] + [F_{\text{control}} - F_{\text{base}}^i] \\ &= \Delta F(\text{forcing}) + \Delta F(\text{feedback}) \end{aligned} \quad (1)$$

where *i* denotes the interactively coupled model run. Magnitudes corresponding to each component in Eq.(1) for simulations presented here are listed in Table 3. It is noted that values of  $\Delta F(\text{feedback})$  for scenarios 5 and 7 account for both climate feedback as well as emissions feedback at 2100.

Figure 1 presents the global distributions of annual average aerosol forcing associated with the primary indirect effect,  $\Delta F(\text{forcing})$ , for model scenarios 1, 3, 5 and 7. In contrast to the direct effect that is more significant over the land, the primary indirect effect is much more pronounced over the ocean where clouds are relatively optically thin and likely to be of higher susceptibility. Figure 2 demonstrates the dependence of cloud albedo on droplet number concentration for different cloud thickness. Droplet number concentrations in water clouds usually range from 10 cm<sup>-3</sup> in fairly clean maritime conditions to several thousand cm<sup>-3</sup> in polluted continental regions. For this range of number concentrations, an increase in the drop number concentration has the greatest effect on cloud albedo when the cloud is thin.

Table 3. Variations of solar radiation flux at TOA for each model scenario ( $\text{W m}^{-2}$ ).

	SC1		SC2		SC3		SC4		SC5		SC7	
	$\Delta F(1)$	$\Delta F(2)$										
NH	-0.89	+0.59	-1.14	+0.34	-1.37	+0.11	-0.74	+1.22	-1.13	-0.68	-0.61	+0.20
Land	-0.69	+0.87	-0.83	+0.36	-0.94	+0.12	-0.55	+1.26	-0.80	-0.06	-0.46	+1.13
Ocean	-1.01	+0.41	-1.34	+0.33	-1.66	+0.10	-0.87	+1.19	-1.35	-1.07	-0.71	-0.40
SH	-0.55	+0.18	-0.80	-0.54	-1.02	+0.31	-0.50	+0.19	-0.75	-1.65	-0.36	-1.26
Land	-0.74	+1.69	-1.10	0.0	-1.28	+1.38	-0.72	+0.31	-1.09	+0.41	-0.58	+0.51
Ocean	-0.51	-0.16	-0.73	-0.66	-0.96	+0.06	-0.45	+0.16	-0.68	-2.12	-0.31	-1.66
Global	-0.72	+0.38	-0.97	-0.10	-1.20	+0.21	-0.62	+0.70	-0.94	-1.17	-0.49	-0.53
Total $\Delta F$	-0.334		-1.066		-0.987		+0.081		-2.107		-1.016	

$\Delta F(1) = \Delta F(\text{forcing})$  in Eq.(1)

$\Delta F(2) = \Delta F(\text{feedback})$  in Eq.(1)

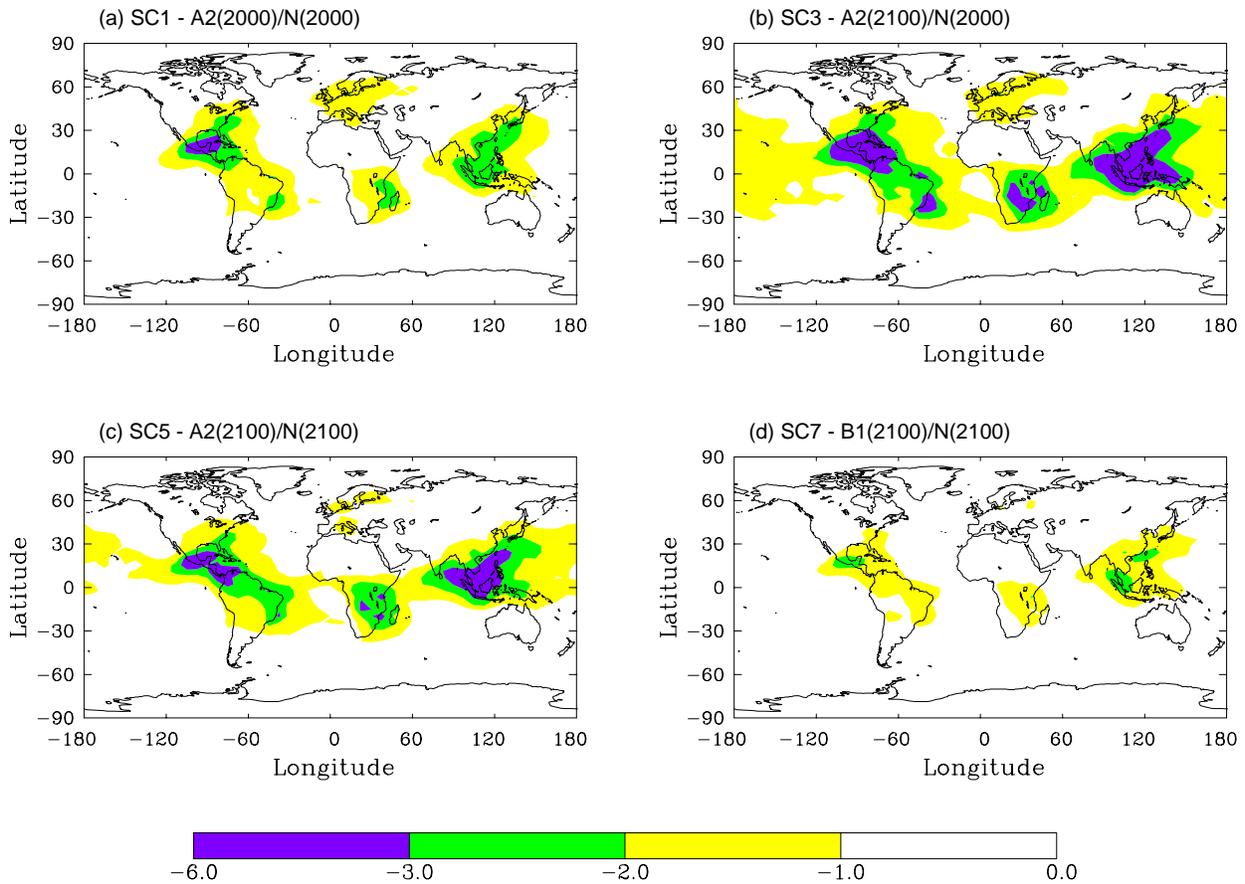


Figure 1. Global distributions of annual average aerosol forcing associated with the primary indirect effect. N(2000) and N(2100) denote the natural emissions at 2000 and 2100, respectively.

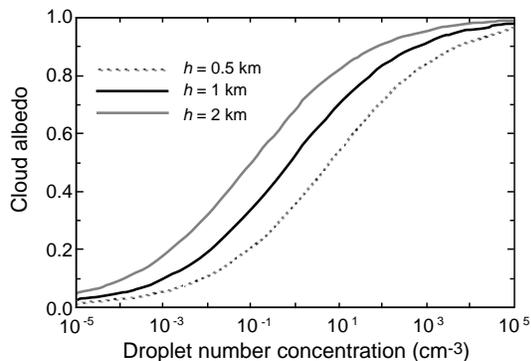


Figure 2. The dependence of cloud albedo on cloud drop number concentration and cloud thickness ( $h$ ). The liquid water content is assumed to be  $0.2 \text{ g m}^{-3}$ .

## 5. CONCLUSIONS

We used a fully coupled climate/chemistry model together with the newly developed IPCC anthropogenic emissions to simulate the climate variation by aerosols. The range of aerosol forcing by the primary indirect effect in next century is estimated between  $-0.49$  and  $-1.20 \text{ W m}^{-2}$ . This range does not include the potential natural emissions feedbacks associated with climate change. Since sea salt emissions are projected to increase from  $88.5 \text{ Tg of Na}$  for 2000 to  $155 \text{ Tg of Na}$  for 2100, the increased aerosol forcing from emissions feedbacks would be mainly over the ocean in southern hemisphere where the maximum is located. More simulations will be performed in order to identify the emissions feedbacks from the total feedbacks. This will provide us a more quantitative range for the aerosol climate forcing as compared to those from greenhouse gases.

The magnitudes of climate feedbacks calculated here are subject to uncertainties from climate system. Uncertainty can also arise from the model configuration where the sea surface temperatures are prescribed instead of using a mixed-layer ocean model or a full ocean general circulation model. To quantify these uncertainties, sensitivities tests will be performed in a future study.

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