Modeling the impact of sulfate and black carbon aerosols on climate: Parameterization aspects and results from GCM simulations

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INTRODUCTION

Aerosols influence the earth's radiation budget directly through reflection and absorption of solar radiation , and indirectly through changes in cloud properties, which in turn affect the radiative budget. Here we present a modeling effort that seeks to parameterize these effects within the framework of a global climate model. The model tool is a version of the NCAR CCM3 which predicts cloud water [1], and is extended with an aerosol life-cycle module [2] and the above-mentioned parameterization schemes [3,4]. While the original CCM3 has a homogeneous sulphate aerosol in the lower 3 layers, the revised version has a composite background/sulphate/BC aerosol in all vertical layers.

LIFE CYCLE SCHEME

The life cycle scheme for sulphate (SO_4) and black carbon (BC) includes emissions of dimethyl sulfide (DMS), SO_2 and sulphate of natural and anthropogenic origins, as well as emission of BC from biomass burning and fossil fuel combustion. Chemistry and aerosol physics are parameterized based on prescribed oxidant levels and background aerosols of marine, continental and polar origins. Aqueous chemistry depends on estimated exchange rates of cloudy and clear air. Simulated turnover times are: 1.5 days for SO_2, 3.5 days for SO_4 and 4.7 days for BC for the year 2000. For the year 2100 the corresponding values are 1.6 days, 4.0 days and 4.7 days.

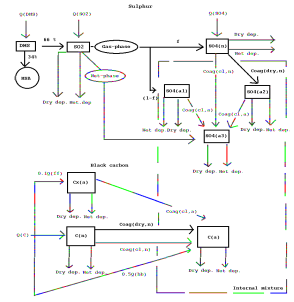

Figure 1: A schematic of the sulphate and BC scheme implemented in CCM3.

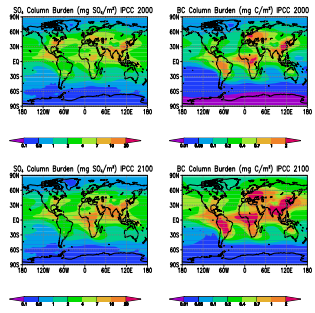

Figure 2: Calculated column burdens of sulphate ($mg(SO_4)m^{-2}$) and BC ($mg(C)m^{-2}$) in 2000 (upper) and 2100 (lower).

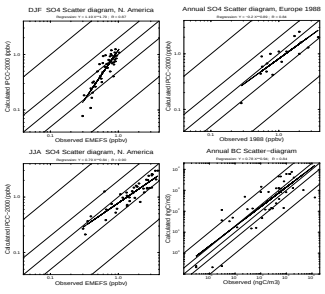

Figure 3: Observed vs. calculated averaged sulphate ground level mixing ratios (ppb(v)) for winter and summer in North America (EMEFS), yearly averaged data for Europe (EMEP), and BC measured and modeled concentrations in ng(C) m^{-3}.

AEROSOL SIZE DISTRIBUTION AND COMPOSITION

The revised CCM3 uses 3 predefined background aerosol types, internally and externally mixed with sulphate, BC and condensed water. The marine, continental and polar backgrounds are multimodal log-normal size distributions made up by linear combinations of the modes $1-10$ in Figure 4.

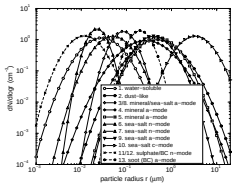

Figure 4: Normalized dry size distributions for 10 background modes and 3 externally mixed sulphate and BC modes.

Externally mixed nucleation mode sulphate and BC are put into modes 11 and 12, respectively, and BC from rapid combustion of fossil fuel in mode 13. For internal mixing we take into account condensation, coagulation and wet-phase production of sulphate, and coagulation of BC.

Mass is added iteratively in small portions, solving continuity equations for the aerosol number and mass concentrations, using 43 size bins. Hygroscopic growth of the aerosol particles is estimated by use of the Köhler equation. In this way CCN concentrations are determined, as function of supersaturation. This scheme is coupled to the cloud microphysics scheme [1] by:

- Assuming a supersaturation of 0.05% for stratiform clouds, 0.10% for convective clouds over sea and 0.15% for convective clouds over land
- Equating the number of activated CCN to the number concentration of cloud droplets

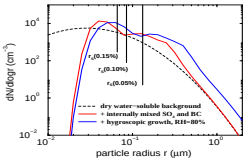

Figure 5: Example of size distribution for an internal mixture of SO_4 and BC with a water-soluble (continental) background aerosol. Selected activation radii for the mixed aerosol are also shown.

AEROSOL OPTICAL PROPERTIES

Using volume-weighted complex refractive indices (internal mixing only), Mie calculations yield aerosol single scattering albedo $\tilde{\omega}_k(\lambda_i)$, asymmetry factor $g_k(\lambda_i)$ and extinction coefficient $\beta_k(\lambda_i)$ for 13 CCM3 spectral bands i. Aerosol optical depth is given by $\tau(\lambda) = \int \beta_{ext}(\lambda, z)dz$.

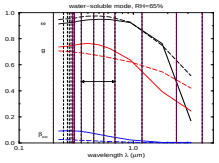

Figure 6: Optical parameters at $RH = 65\%$ for a water-soluble background mode (dashed curves) and contaminated aerosol (solid curves). Spectral aerosol bands are also shown: the 5 first bands in UV are merged to one, and a Chandrasekhar average of 3 bands is used in the visible.

CLOUD DROPLET SIZES

The first and second indirect effect are simulated for warm clouds by allowing cloud droplet size (r_e) and liquid water content (LWC) to change depending on the aerosol burden. Cloud droplet size is given by:

$$r_e = \kappa \left[(3LWC)/(4\pi\rho_w N_c)\right]^{1/3}$$

where N_c is the cloud droplet number concentration. As N_c increases due to anthropogenic aerosols, cloud droplet size is decreased, affecting cloud albedo (1^{st} indirect effect). The 2^{nd} indirect effect appears in our calculations as a reduced auto-conversion of cloud water to rain water through the equation:

$$PWAUT = \left[(C_{l,aut} LWC q_l)/\rho_w\right] \cdot \left[LWC/(\rho_w N)\right]^{1/3} H(r_{3l} - r_{3lc})$$

where q_l is cloud water mixing ratio, H is the Heaviside function and r_{3lc} is an auto-conversion threshold of 10 μm.

The figure below shows that simulated cloud droplet radii compare favourably with observational estimates.

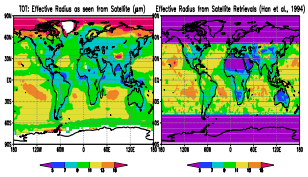

Figure 7: Cloud droplet sizes as seen by satellite. Left panel: Simulated, Right panel: From observations [5].

FORCING EXPERIMENTS

The CCM3 was run for 5 years with prescribed monthly varying SST. In order to enable calculations of the direct and indirect effect, monthly averaged aerosol concentrations from a previous run with the life-cycle model [2], based on IPCC SRES A2 emission scenarios were used. Two simulations were carried out using the new parameterization schemes for optical properties [3] and for cloud microphysics and radiation [4] (see upper panel of Figure 8):

1. background aerosol + nat. SO_4 and/or 10% of biomass burning BC (assumed natural)
2. 1 + ant. SO_4 and fossil fuel BC + 90% of biomass burning BC (assumed anthropogenic)

This setup was then repeated for the year 2100 using emission data from the IPCC SRES A2 scenario (lower panel of Figure 8).

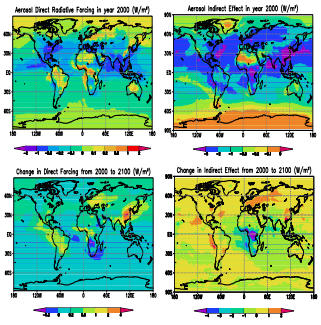

Figure 8: Anthropogenic SO_4 and BC forcing for two emission scenarios. Global means, IPCC 2000: $-0.11 Wm^{-2}$ (direct) and $-1.83 Wm^{-2}$ (indirect); IPCC 2100: $+0.11 Wm^{-2}$ (direct) and $-1.85 Wm^{-2}$ (indirect).

RESPONSE EXPERIMENTS

In order to calculate the climate change associated with the anthropogenic aerosols, a set of 50 year runs were also performed, in which an interactive slab ocean model replaced the prescribed SST. In these simulations the model responds interactively to the imposed forcing, and hence, gradually develops climate states that differ from one simulation to the other. We now compare the last 40 years of these climate states:

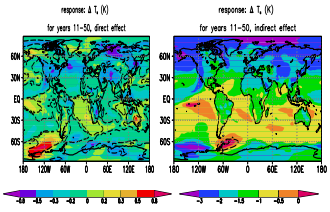

Figure 9: Temperature change due to anthropogenic aerosol forcing: Left panel: Direct effect, Right panel: Indirect effect

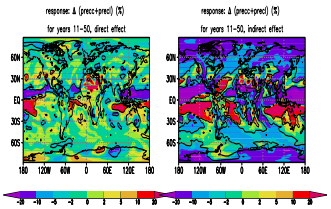

Figure 10: Change in precipitation due to anthropogenic aerosol forcing: Left panel: Direct effect, Right panel: Indirect effect

SUMMARY AND CONCLUSIONS

A new parameterization scheme for atmospheric aerosols has been implemented in the NCAR CCM3. The scheme consists of four components: (1) A life-cycle scheme for sulfate and black carbon (BC) aerosols; (2) Adding a prescribed background aerosol to the sulfate and BC in such a way that size distributions are obtained; (3) Calculation of aerosol optical properties, providing estimates of the direct effect of aerosols; (4) Aerosols determine cloud properties, enabling estimates of the aerosol indirect effect.

Validation of the life-cycle scheme yields generally good agreement with observations. Estimated global aerosol forcings due to anthropogenic sulphate and BC are $-0.11 Wm^{-2}$ for the direct and $-1.83 Wm^{-2}$ for the indirect effect, respectively. Repeating the experiment with emission data for the year 2100 (IPCC SRES A2 emission scenario), these figures become $+0.11 Wm^{-2}$ for the direct and $-1.85 Wm^{-2}$ for the indirect effect, i.e., a reduced cooling effect, mainly caused by enhanced absorption of solar radiation by BC.

Results from the 50 year climate response simulations show a globally averaged cooling of -0.10 K for the direct and -1.28 K for the indirect effect. In both cases there are large geographical variations, with the largest cooling occuring at high latitudes in the Northern Hemisphere. Another prominent feature is a marked southward shift of the ITCZ in both cases, caused by the interhemispheric differences in aersol cooling.

REFERENCES

[1] Rasch, P.J. and Kristjánsson, J.E., 1998: A comparison of the CCM3 model climate using diagnosed and predicted condensate parameterizations. *J. Climate*, **11**, 1587-1614.

[2] Iversen, T. and Seland, Ø. 2002: A scheme for process-tagged SO_4 and BC aerosols in NCAR CCM3: Validation and sensitivity to cloud processes. *J. Geophys. Res.*, **107**, (D24), 4751, 10.1029/2001JD000885.

[3] Kirkevåg, A., and Iversen, T. 2002: Global direct radiative forcing by process-parameterized aerosol optical properties. *J. Geophys. Res.*, **107** (D20), 4433, 10.1029/2001JD000886.

[4] Kristjánsson, J.E., 2002: Studies of the aerosol indirect effect from sulfate and black carbon aerosols. *J. Geophys. Res.*, **107** (D15), 4246, 10.1029/2001JD000885.

[5] Han, Q., Rossow, W. B., and Lacis, A. A., 1994: Near-global survey of effective droplet radii in liquid water clouds using ISCCP data. *J. Climate*, **7**, 465–497.