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A limited-area-model case study of the effects of sub-grid scale variations in relative humidity and cloud upon the direct radiative forcing of sulfate aerosol

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Abstract. A limited-area non-hydrostatic model with a horizontal spatial resolution of 2km by 2km is used to assess the importance of sub-grid scale variations in relative humidity and cloud upon the direct radiative forcing (DRF) by tropospheric sulfate aerosols. The DRF from the limited-area model for both clear and cloudy regions is analyzed and the results compared against those obtained using general circulation model (GCM) parameterizations that perform the computations over coarse horizontal grids. In this idealized model study, the GCM calculations underestimate the clear sky DRF by approximately 73% and the cloudy sky DRF by approximately 60%. These results indicate that, for areas where the relative humidity is high and where there is substantial spatial variability in relative humidity and cloud, GCM calculations may considerably underestimate the DRF.

Introduction

Sulfate aerosols scatter solar radiation back to space thereby enhancing the planetary albedo and cooling the earth/atmosphere system (e.g. Charlson *et al.* (1991)). Relative humidity effects are considered important in increasing the amount of back-scattering due to the hygroscopic nature of sulfate particles. GCM studies of the DRF due to sulfate aerosol include those of Kiehl and Briegleb (1993), Boucher and Anderson (1995) and Haywood *et al.* (1997) each of which uses a different approach to account for the increased back-scattering of sulfate aerosol with relative humidity. However, every one of these studies used a single value of the relative humidity in each grid-box of the GCMs to represent properties over coarse ($> 10000km^2$) horizontal dimensions; no account is taken of the sub-grid scale variations in relative humidity or of the effects of sub-grid scale cloud. A third potentially important sub-grid scale effect is that sulfate concentrations are unlikely to be uniform (see Benkovitz *et al.* (1994)) due to clouds acting as the major sink of sulfate aerosol via incorporation into cloud drops and subsequent rain-out. This effect is not accounted for in this study although the preferential loading in cloudy regions is likely to reduce the overall DRF.

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This idealized study uses a version of the GFDL limited-area non-hydrostatic model (LAN) (Held *et al.* (1993)) to assess the sub-grid scale effects of both relative humidity and cloud upon the DRF of sulfate aerosol. The relative humidity distributions calculated by the LAN are compared against recent measurements from the UK Meteorological Research Flight (UKMRF). Convective conditions are examined in this study as this allows investigations of the DRF in both clear and cloudy conditions.

Method

A three-dimensional version of the GFDL LAN is used with a spatial resolution of 2km by 2km in the horizontal and 500m in the vertical, the domain being periodic with horizontal dimensions of 220km by 220km and a vertical dimension of 16km. A region of 160km by 160km is used in these investigations as this region is sufficient to provide a reasonable spatial variation in relative humidity and cloud amount. The model was initialized by applying perturbations to a vertical profile of water vapor mixing ratio observed in GATE (GARP [Global Atmospheric Research Program] Atlantic Tropical Experiment) (Thompson et al., 1979). The perturbations vary in the horizontal but are constant throughout the lowest 1.5km in each column of the model. The perturbations are horizontally random, generated from a uniform distribution between ± 2g kg^{-1}. Large-scale tendencies in temperature and water vapor were imposed using observations from GATE. Water vapor mass mixing ratios, temperatures and pressures from the LAN (at a stage in the integration just prior to the initiation of deep convection, which exhibited substantial small-scale structure in the water vapor field), together with a tropical ozone profile and a constant carbon dioxide mixing ratio of 330ppm, were used as inputs to the single column radiative transfer code.

The radiation code is a 56 band two-stream δ-Eddington adding code based upon that of Ramaswamy and Kiehl (1985) that includes gaseous absorption and a parameterization for Rayleigh scattering and cloud optical properties (Slingo (1989)) (see Held *et al.* (1993) Appendix B for further details). The Lambertian surface albedo is 0.07, there is no diurnal cycle and the solar zenith angle is set to 53^o, which is consistent with that used in generating the cloud and relative humidity fields. The DRF will be solar zenith angle dependent (e.g. Pilinis *et al.* (1995), Nemesure *et al.* (1995), Haywood and Shine (1997)); this source of variation is ignored in this idealized study.

The optical properties of dry sulfate aerosol were determined by Mie theory by assuming that the aerosol consists entirely of ammonium sulfate, modeled using a log-normal distribution with a geometric mean radius of $0.05\mu m$ and a geometric standard deviation of 2.0 (Kiehl and Briegleb (1993)). The amount of water taken up by the hygroscopic ammonium sulfate particles is determined; the volume weighted refractive indices of ammonium sulfate and water and the hydrated geometric mean radius are used in a Mie code to determine the optical properties of the hydrated aerosol (see Haywood *et al.* (1997)).

Sulfate aerosol was placed in the lowest model layer (0-500m) with a constant dry optical depth at $0.55\mu m$ of 0.1. Two radiative calculations were performed offline for each grid box, one including aerosols and one excluding aerosols, the difference in the top of the atmosphere net irradiance gives the instantaneous DRF. The aerosol radiative effects do not feedback into the prognostic equations in the LAN; this approach is justified as changes in the radiative heating rates due to the inclusion of aerosol are negligible.

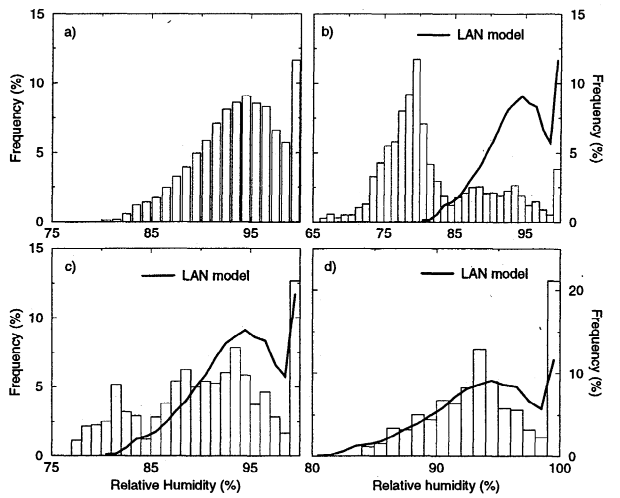

Figure 2. The frequency distribution of the relative humidity (%) in a) 160km by 160km domain of the LAN, b) ~100km UKMRF flight path, c) ~30km UKMRF flight path, d) ~15km UKMRF flight path. The LAN frequency distribution is shown in the other figures for purposes of comparison.

Experimental results

Calculations excluding cloud

To demonstrate the non-linear effects associated with estimates of the DRF when sub-grid scale variations in relative humidity are included, calculations were performed excluding cloud from all regions of the LAN. Figure 1 shows the non-homogeneous spatial distribution of the relative humidity throughout the lowest layer of the LAN. The relative humidity in the lowest layer of the model ranges from approximately 80% to 100% with a spatial variability spanning the entire x-y domain.

Figure 2a shows that the frequency distribution of relative humidity from the LAN resembles a Gaussian distribution truncated at 100% relative humidity with a second narrow mono-modal distribution imposed at relative humidities of 99-100%. This distribution of relative humidity is similar to that used in prognostic GCM parameterizations of cloud amount (e.g. Smith (1990)).

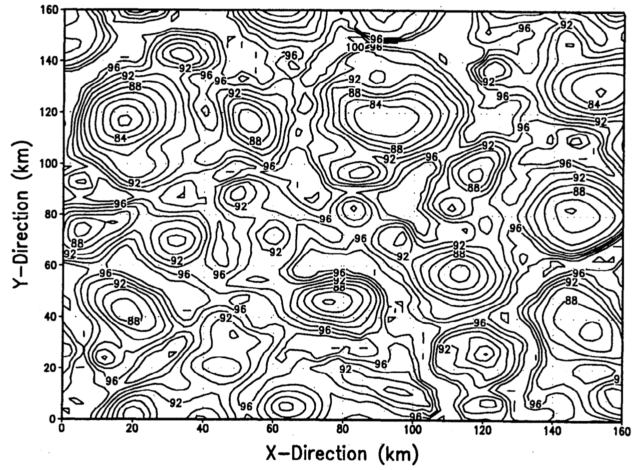

Figure 1. The spatial distribution of the relative humidity (%) in the lowest layer (0-500m) of the LAN. The contour interval is 2%.

The mode relative humidity is 99-100% due to the predominance of areas close to saturation shown in Figure 1 and the mean relative humidity calculated from the mean temperature and specific humidity is 93.4%.

To investigate whether this model distribution of relative humidities is representative of the real atmosphere poses significant problems as measurements of the relative humidity distributions of a suitable spatial scale are not routinely available. However, a UKMRF aircraft encountered some areas of shallow convection off the coast of Florida during the recent TARFOX (Tropospheric Aerosol Radiative Forcing Observational Experiment) campaign. The UKMRF measurements are in the boundary layer at a resolution of approximately 25m and the total flight path length during the measurements is approximately 100km.

Figure 2b shows data from the UKMRF for the entire 100km flight path. The mean relative humidity calculated from the mean temperature and dew point temperature is much lower than that generated by the LAN model at 81.7% but there is a substantial spread of relative humidities from 65% to 100%. The distribution also appears to be rather bi-modal with peak relative humidities at 79-80% and 92-93%. This is because two distinct meteorological conditions are being sampled, the first maximum in relative humidity is associated with generally stable, cloud free conditions, the second with areas of shallow cumulus convection. The UKMRF data was broken down into two subsets each consisting of *continuous* data to separate convective from stable conditions. The first subset consists of continuous measurements over ~30km which contains two convective regions separated by a stable, clear sky region. The second consists of continuous measurements over ~15km made in a purely convective region. The relative humidity distributions for these subsets are shown in Figures 2c and 2d; the average relative humidities calculated from the mean temperature and dew point temperature in these regions are 89.7% and 93.7% respectively. In regions of convection, the relative humidity distribution determined by the LAN is in reasonable agreement

Table 1. The average relative humidity, $\bar{RH}$, DRF including sub-grid scale relative humidities, ΔF_{sub}, DRF excluding sub-grid scale relative humidities, ΔF_{GCM}, and the underestimate of the DRF by ΔF_{GCM} for the relative humidity distributions shown in Figure 2.

RH frequency distribution	$\bar{RH}$ (%)	ΔF_{sub} Wm^{-2}	ΔF_{GCM} Wm^{-2}	GCM under-estimate
Fig 2a	93.4	-4.54	-2.63	73%
Fig 2b	81.7	-2.10	-1.44	46%
Fig 2c	89.7	-3.70	-1.79	106%
Fig 2d	93.7	-4.99	-2.77	80%

with the measurements even though the meteorological conditions and the spatial scales are by no means identical.

The average DRF over the entire 160km by 160km area of the LAN obtained from the individual grid-box DRFs is denoted ΔF_{sub} as this includes the effects of sub-grid scale variations of relative humidity. An additional DRF calculation was made using the average temperature, pressure and humidity for the entire area. The DRF is denoted ΔF_{GCM} as this would correspond to that calculated by a GCM which does not include sub-grid scale effects of relative humidity. Similar calculations of ΔF_{sub} and ΔF_{GCM} were performed by using the relative humidity distributions from the UKMRF. Table 1 shows ΔF_{GCM} underestimates ΔF_{sub} for every case, the underestimate ranging from 46% for the relative humidity distribution shown in Figure 2b to 106% for that shown in Figure 2c.

Calculations including cloud

Sub-grid scale variations in relative humidity may have an important impact in increasing the DRF due to sulfate aerosol. However, a competing effect that acts to weaken the DRF is the co-existence of cloud and areas of high relative humidity. Generally, cloudy areas will produce a DRF that is considerably less than in clear skies (Charlson *et al.* (1991), Boucher and Anderson (1995), Haywood *et al.* (1997)); the magnitude of the decrease is dependent primarily upon the optical depth of the cloud. Since clouds exist in regions of high relative humidity, then the strong DRF at the high relative humidity is reduced, thereby weakening the overall DRF. The indirect effect of sulfate aerosol whereby the optical properties of clouds are modified due to the aerosol particles acting as cloud condensation nuclei is not considered in this study.

The cloud liquid water content from the LAN was included in a 2km layer directly above the aerosol i.e. from 500-2500m. Cloud optical properties were prescribed using the parameterization of Slingo (1989) assuming an effective radius for the cloud droplets of $10\mu m$. Cloud is not included in the lowest layer to avoid the additional complexities of mixing the aerosol and cloud particles. The vertically averaged cloud liquid water content through the 2km cloud layer is shown in Figure 3 which shows a high degree of spatial correlation with the areas of high relative humidity shown in Figure 1. The UKMRF data contains no information on the optical properties or optical depth of the cloud encountered during the flight therefore radiative calculations using UKMRF data in cloudy regions are not possible.

The DRF from each grid box in the LAN is shown as a function of relative humidity in Figure 4. The solid line shows the variation of the DRF including the effects of sub-grid scale cloud and relative humidity. This is obtained by assigning each of the individual DRFs from each grid box to a relative humidity "bin" of width 0.1% and averaging DRFs in each bin. The DRF is reduced by over 50% at relative humidities close to 100% but the reduction in the DRF at relative humidities of less than 90% is approximately 5-20%. The DRF weakens most in areas of high relative humidity due to the co-existence of cloud in these areas (see Figure 1 and Figure 3). The strongest DRF occurs when the relative humidity is approximately 99.7%; relative humidities higher than this tend to be associated with purely cloudy regions thus the DRF weakens (Figure 4). The mean DRF obtained by averaging the DRF from each of the grid-boxes, ΔF_{sub_cloud}, is -3.09Wm^{-2}, a reduc-

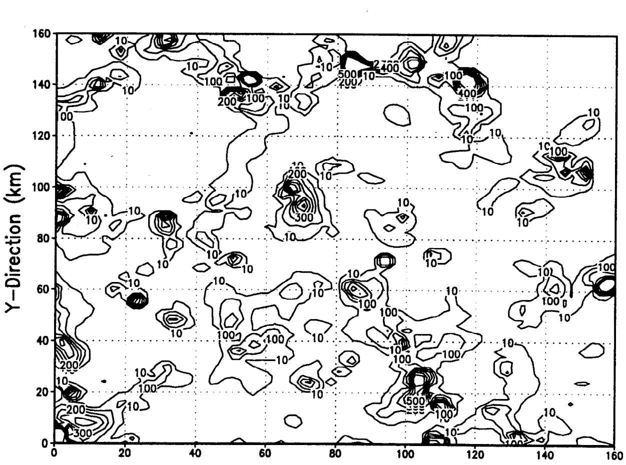

Figure 3. The average mass mixing ratio of the cloud liquid water in mg/kg for cloud in a 2km layer (500m-2500m) above the sulfate aerosol layer. The contour values are 10, 100, 200, 300, 400 and 500mg/kg. 10mg/kg corresponds to a cloud visible optical depth of approximately 3.

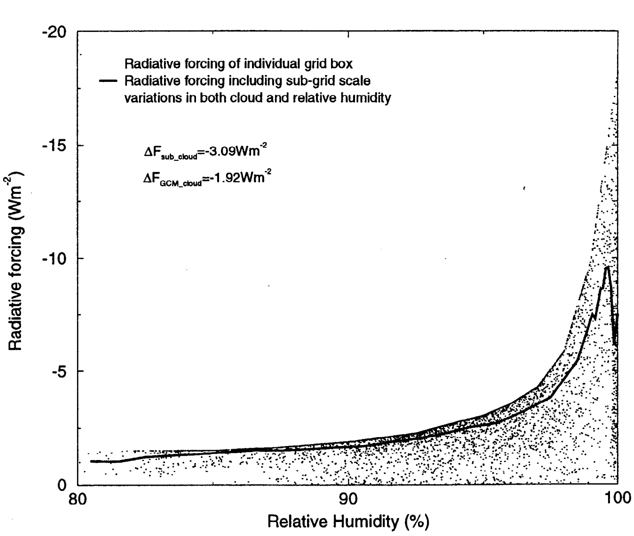

Figure 4. The DRF (Wm^{-2}) from individual grid boxes of the LAN when sub-grid scale clouds are included as a function of relative humidity. The values of ΔF_{sub_cloud} and ΔF_{GCM_cloud} are also shown.

tion of 32% from the clear sky calculation that includes sub-grid scale variations in relative humidity only.

A commonly used GCM parameterization for cloud amount upon the DRF is also investigated. The method assumes that the cloud liquid water is included only in the fractional area where cloud is present (34.9%) (see Figure 3). Such a cloud scheme is currently employed in the Hadley Centre Climate Model (Smith (1990)). The overall DRF is the fractional area that does not include cloud (65.1%) multiplied by the clear sky DRF excluding sub-grid scale effects (-2.63Wm^{-2}) plus the fractional area that includes cloud (34.9%) multiplied by the cloudy sky DRF (calculated to be -0.60Wm^{-2}). The DRF obtained using this method, ΔF_{GCM_cloud}, is -1.92Wm^{-2}. Thus the total DRF ignoring sub-grid scale variations in both relative humidity and cloud amount underestimates the total DRF by approximately 60%.

Conclusions

Although this study involves a single idealized case, it demonstrates that under atmospheric conditions where the relative humidity is high and there is a substantial spatial variation in relative humidity and cloud, GCM calculations may underestimate the DRF of sulfate aerosol. The areas affected most are those where the sub-grid scale variabilities lie in the 90-100% relative humidity range where the DRF varies non-linearly with relative humidity. These results strongly suggest that field measurement campaigns such as TARFOX will need to take account of variations in relative humidity for spatially heterogeneous atmospheric conditions, particularly when attempting to reconcile satellite measurements with point observations.

It should be emphasized that the calculations presented in this paper are idealized as they include only one type of atmospheric profile with specific cloud and relative humidity distributions; the global effects are difficult to assess from this result alone. However, according to Warren *et al.* (1985), the global frequency of occurrence of convective cumulus clouds is approximately 17% over land and 37% over oceans and the global frequency of occurrence of cumulo-nimbus is 11% over both oceans and land. Thus, convective regions such as those modeled here are by no means infrequent in the atmosphere and further efforts to quantify these effects are highly desirable.

Two approaches may be pursued to attempt to quantify the effect of sub-grid scale variations on the DRF of sulfate aerosol on a global scale. Surface observations and radiosonde data could be analyzed to obtain data on the spatial variability of relative humidity and cloud and the correlation between the two. Additionally, further investigations which incorporate the effects of sub-grid scale variations in relative humidity and cloud into GCM investigations of the DRF due to sulfate aerosol should be made. Models that contain an assumed sub-grid scale variation in water vapor in its prognostic cloud scheme (e.g. Smith (1990)) could be used.

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References

Benkovitz, C.M., Berkowitz, C.M., Easter, R.C., Nemesure, S., Wagener, R. and Schwartz, S.E., 1994. Sulfate over the North Atlantic and adjacent continental regions: evaluation for October and November 1986 using a three-dimensional model driven by observation-derived meteorology. *J. Geophys Res.*, 99, 20725-20756.

Boucher, O. and Anderson, T.L., 1995. GCM Assessment of the sensitivity of direct climate forcing by anthropogenic sulfate aerosols to aerosol size and chemistry. J. Geophys. Res., , 100, 26117-26134.

Charlson, R.J., Schwartz, S.E., Hales, J.M., Cess, R.D., Coakley, J.A., Hansen, J.E. and Hofmann, D.J., 1992. Climate forcing by anthropogenic aerosols. *Science*, 255, 423-430.

Haywood, J.M. and Shine, K.P., 1997. Multi-spectral calculations of the radiative forcing of tropospheric sulphate and soot aerosols using a column model. *Accepted by* Q. J. R. Meteorol. Soc., .

Haywood, J.M., Roberts, D.L., Slingo, A.S., Edwards, J.M. and Shine, K.P., 1997. General Circulation Model Calculations of the Direct Radiative Forcing by Anthropogenic Sulphate and Fossil-Fuel Soot Aerosol. *Accepted by J. Clim.*.

Held, I.M., Hemler, R.S. and Ramaswamy, V., 1993. Radiative-Convective Equilibrium with Explicit Two-Dimensional Moist Convection. *J. Atmos. Sci.*, 50, 3909-3927.

Kiehl, J.T. and Briegleb, B.P., 1993. The relative roles of sulfate aerosols and greenhouse gases in climate forcing. *Science 260*, 311-314.

Nemesure, S., Wagener, R. and Schwartz, S.E., 1995. Direct shortwave forcing of climate by anthropogenic sulfate aerosol: sensitivity to particle size, composition, and relative humidity. *J. Geophys. Res.*, 100, 26105-26116.

Pilinis, C., Pandis, S.N., Seinfeld, J.H., 1995. Sensitivity of direct climate forcing by atmospheric aerosols to aerosol size and composition. *J. Geophys. Res.*, 100, 18739-18754.

Ramaswamy, V. and Kiehl, J.T., 1985. Sensitivities of the radiative forcing due to large loadings of smoke and dust aerosols. *J. Geophys. Res.*, 90, 5597-5613.

Slingo, A., 1989. A GCM parameterization for the shortwave radiative properties of water clouds. *J. Atmos. Sci.*, 46, 1419-1427.

Smith, R.N.B., 1990. A scheme for predicting layer clouds and their water content in a general circulation model. Q. J. R. Meteorol. Soc., , 116, 435-460.

Thompson, R.M., S.W. Payne, E.E. Recker, and R.J. Reed, 1979. Structure and properties of synoptic-scale wave disturbances in the intertropical convergence zone of the eastern Atlantic. *J. Atmos. Sci.*, 36, 53-72.

Warren, S.G., Hahn, C.J., London, J., 1985. Simultaneous occurrence of different cloud types. *J. Clim.*, 24, 658-667.

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