Reply

J.M. Haywood

AOS Program, Princeton University, Princeton, NJ

V. Ramaswamy and L.J. Donner

Geophysical Fluid Dynamics Laboratory, Princeton, NJ

We thank Ghan and Easter (GE) for drawing attention to this interesting aspect of the aerosol radiative forcing problem. They suggest that the effects of sub-grid scale variations in relative humidity in calculating the radiative forcing due to sulfate aerosols by Haywood *et al.* (1997) (hereafter HRD) may be an overestimate due to the neglect of activation of aerosol particles at relative humidities equal to or exceeding 100%. They extrapolate the data from Figure 2a of HRD and find that 6.6% of the 6400 grid-points considered by HRD are at relative humidities $\geq$ 100%. Then, by taking the ratio of the optical depth at $0.55\mu m$ when sub-grid scale variations in relative humidity are included to when the sub-grid scale variations are excluded they determine that the optical depth is approximately 30% higher when sub-grid scale variations in relative humidity are included. They assume in this calculation that all aerosols are activated at 100% relative humidity and exclude them from the calculation of the direct radiative forcing. A more realistic calculation that assumes only the fraction of aerosol particles with dry radii greater than $0.1\mu m$ are activated reveals the optical depth is approximately 56% larger when sub-grid scale variations in relative humidity are included. Thus, for apparently the same conditions as those used in HRD, the effect of aerosol activation is to increase the optical depth by between 30-56%. HRD found a corresponding increase in the *radiative forcing* due to the inclusion of sub-grid scale effects to be 73%.

Analysis of the data from the limited-area non-hydrostatic (LAN) model used by HRD reveals that only 2.6% of the grid-points are $\geq$ 100% (compared to the 6.6% estimated by GE using linear interpolation). If the calculations of HRD are repeated excluding all of the points at relative humidities $\geq$ 100% (i.e. all the aerosol particles become activated) then the radiative forcing including the effects of relative humidity is approximately 60% greater than excluding sub-grid scale effects. As GE also point out, not all of the aerosols become activated at 100% relative humidity. If only a fraction of the aerosol particles become activated then the direct radiative forcing including sub-grid scale effects will be higher than 60%. Thus the results of HRD are not significantly altered. More importantly, the fundamental conclusion of the study i.e. the substantial sensitivity of the direct radiative forcing to sub-grid scale variations in relative humidity, at least for the case study of HRD, remains unchanged even when points with relative humidities $\geq$ 100% are excluded.

GE fail to mention that HRD explicitly include the effect of clouds in their penultimate section, although clouds are placed above rather than in the aerosol layer. The calculations presented by HRD suggest that, for this particular case study, the direct radiative forcing when clouds are present is underestimated by 60% which is very close to that obtained when points with relative humidities $\geq$ 100% are excluded. This is because the direct radiative forcing in cloudy regions where the cloud has a reasonable optical depth is small [e.g. Haywood and Shine (1997)] and the issue of activation is of minor importance (the indirect effect is not included in this study). These results further substantiate the principle that sub-grid scale variations in relative humidity and cloud may play important roles in determining the direct radiative forcing due to sulfate aerosol.

As in HRD, it should be emphasized that this analysis involves a single idealized case and that further studies including the sub-grid scale effects of both relative humidity and fractional cloud amount from a variety of models and observational case studies are needed to assess the influence of sub-grid scale variations on the global direct aerosol radiative forcing.

References

Haywood, J.M., Ramaswamy, V., Donner, L.J, 1997. 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. *Geophys. Res. Lett.*, 24, 143-146.

Haywood, J.M., and Shine, K.P., 1997. Multi-spectral calculations of the direct radiative forcing of tropospheric sulfate and soot aerosols using a column model. *Q. J. R. Meteorol. Soc.*, 123, 1907-1930.

J.M. Haywood is now at Met. Research Flight, DERA, Farnborough, Hants, GU14 0LX, UK.

(Received November 20, 1997; accepted January 26, 1998.)

Paper number 98GL00518.
0094-8534/98/98GL-00518$05.00