Using a cloud-resolving model to study the effects of subgrid-scale variations in relative humidity on direct sulphate-aerosol forcing

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SUMMARY

Cloud-resolving model simulations over a tropical ocean and a mid-latitude continental region have been used to investigate the influence of subgrid-scale variations of relative humidity on the direct radiative forcing of sulphate aerosols. Offline radiation calculations based on output from a cloud-resolving model, with and without sulphate aerosol included, are used to calculate the direct radiative forcing of the aerosol. This forcing is compared with results from single-column radiation calculations typical of those produced by a climate model.

The results from this idealized study show that a typical climate model can underestimate the direct radiative forcing of aerosols by up to 80%. The errors in a climate-model calculation are largest when the mean relative humidity is high or there are moist regions within a drier domain; this is usually reflected in a larger standard deviation of the relative humidity. Over the more humid tropical ocean, a climate model may underestimate the direct radiative forcing of sulphate aerosols by 43%, on average (ranging between 30% and 80%). Over the drier continental mid-latitude region the average error is only 10%, but instantaneous values can exceed 50% during times when both the mean relative humidity and its standard deviation are large; this is typically close to convective events.

KEYWORDS: Climate model Radiation

I. INTRODUCTION

The subgrid-scale variability of relative humidity in a climate model or general-circulation model (GCM) can be important in determining the direct radiative forcing (DRF) of sulphate aerosol. Haywood et al. (1997a) (hereafter HRD) validated a distribution of relative humidity for a single time step from a three-dimensional (3-D) cloud-resolving model (CRM) against aircraft data. They then used these data to show that, for climate models, subgrid-scale variations of relative humidity played an important role in direct radiative forcing of sulphate aerosols off the east coast of the USA. In this paper I use time series longer than two days from CRM simulations of two further regions to investigate the robustness of this result. The regions are the tropical west Pacific (TWP) and the Atmospheric Radiation Measurement (ARM) southern Great Plains (SGP) site. These two regions are chosen for this study because they provide very different atmospheric conditions and have been the centres for major field programs and model inter-comparison projects, as detailed in section 2. These regions also provide very different atmospheric conditions, but each is typical of many geographical locations. The TWP is an important region for world climate (Webster and Lucas 1992) and tends to have large relative humidities near the surface. The SGP is typically drier, with more variability and strong convection in the summer months.

The TWP can have large aerosol contents when it is downwind from the many sources in Asia. It also shows meteorological conditions and, more specifically, relative-humidity distributions that are not atypical of locations such as the more commonly polluted region off the eastern seaboard of the USA (see the relative-humidity distribution measured by aircraft and illustrated in Fig. 2(b) of HRD), or those found in the Indian Ocean where recent measurements for the Indian Ocean Experiment (INDOEX) campaign have shown high concentrations of anthropogenic aerosol including sulphate (e.g. Satheesh et al. 1999). These regions are particularly important in estimates of
the direct radiative forcing due to sulphate aerosol, because the normalized radiative forcing (i.e. the radiative forcing per unit column burden of sulphate aerosol in units of W g\(^{-1}\)) is large over these areas of low surface albedo (e.g. Boucher et al. 1998; Haywood and Shine 1997). The ARM SGP site exhibits relative-humidity conditions that are typical of continental regions, such as more polluted areas of USA, and areas of central and eastern Europe. Some of these areas are heavily industrialized and are associated with very high levels of pollution, with correspondingly high atmospheric sulphate loadings. Indeed, several global chemical-transport models predict the largest direct radiative forcing over eastern Europe owing to the high sulphate concentrations (e.g. Langner and Rodhe 1991).

2. THE EXPERIMENT

The CRM used in this study is a moist version of the Met Office Large-Eddy Model (LEM) described by Shutts and Gray (1994). The TWP data used is a subset from a five-day period (20–25 December 1992) of a 2-D CRM simulation of the TOGA–COARE*. The CRM had 60 levels in the vertical, 256 grid points in the horizontal with a 1 km grid length; other features of this simulation have been detailed by Petch and Gray (2001). The ARM data used is a subset from a four-day simulation of an intensive observational period (IOP) at the SGP site beginning on 27 June 1997. For this run, the CRM had 60 levels in the vertical, 500 grid points in the horizontal and also a 1 km grid length. Both the TOGA–COARE and ARM IOPs have been used for an intercomparison project by the GEWEX† Cloud System Study (GCSS) Working Group 4. The forcing data has, therefore, been used in a large number of CRM and SCM simulations, and the results from various models (including the Met Office LEM) have been validated against observations (Krueger and Lazarus 1998; Xu et al. 2000). Petch and Edwards (1999) showed that 2-D CRM simulations gave very similar results to 3-D simulations for issues related to subgrid-scale cloud variability and, consequently, they are suitable for the work presented here.

From each of the two simulations, 20 dumps of instantaneous values of temperature, moisture and cloud fields have been taken every three hours. These 60-hour periods were chosen to represent a range of typical atmospheric conditions for each region simulated by the CRM. The chosen period for the TWP simulation begins at 12 UTC 22 December 1992, has humidity distributions typical of many tropical oceanic regions; it is hereafter be referred to as ‘T-OCEAN’. The SG simulation begins at 6 UTC 28 June 1997, has humidity distributions typical of many mid-latitude continental regions and is hereafter referred to as ‘M-LAND’. The variability of temperature and moisture in the T-OCEAN is low and so the chosen period covers cloudy and cloud-free regions, but in the M-LAND run there is a significant temporal variability in relative humidity, cloud cover and precipitation. To provide some indication of the meteorological conditions during the 60-hour periods Fig. 1 shows the domain-average precipitation rates for the 60-hour period from the T-OCEAN and M-LAND simulations. It can be seen that there are two main periods of precipitation in the M-LAND simulation but a more constant lighter rainfall in the T-OCEAN run. The rainfall peaks at 5 mm h\(^{-1}\) at 50 hours in the M-LAND simulation and 2 mm h\(^{-1}\) also at 50 hours in the T-OCEAN simulation.

The radiative-transfer calculations are done using the Edwards and Slingo (1996) radiation code with a fixed solar zenith angle of 30° and an insolation of 1365 W m\(^{-2}\),

* Tropical Ocean Global Atmosphere–Coupled Ocean Atmosphere Response Experiment.
† Global Energy and Water-cycle Experiment.
the impact of the choice of solar zenith angle on the results from this work is discussed in section 3. The surface albedo was fixed at 0.07 for the T-OCEAN calculations and 0.2 for the M-LAND runs. Above the top of the CRM (20 km), a standard McClatchey et al. (1972) tropical atmosphere was added. Precipitation-sized hydrometeors are not included in the radiation scheme for all-sky calculations, and the cloud fields were set to zero for the clear-sky calculations. The clear-sky calculations have been included in this work to investigate the influence of the cloud on the response of the DRF of the sulphate aerosols to subgrid-scale variability of relative humidity. For both simulations, sulphate aerosol was included in all layers between 850 mb and the surface with a constant mass mixing ratio of $1 \times 10^{-8}$. As was the case with HRD, the influence of the variability of sulphate aerosol in the horizontal or vertical is not considered in this case study. This is a significant limitation of this study, and the issues of the spatial variability of the aerosol and its correlation with the relative-humidity distribution is also important (e.g. Charlson et al. 1999).

The optical properties of the dry sulphate aerosols were calculated using Mie theory assuming that the aerosol consisted entirely of spherical ammonium sulphate particles (Toon et al. 1976). As with HRD, a single log–normal size distribution was used with a dry-mode radius of 0.05 $\mu$m and a standard deviation of 2.0. A ‘growth factor’ is used to describe the influence of relative humidity on the optical properties of the sulphate aerosol. No growth factor was applied for relative humidities less than 30% and, between 30% and 81% (the region of hysteresis in the growth of ammonium sulphate), a linear-growth scheme is employed. The growth parametrization of Fitzgerald (1975) is used for relative humidities above 81%, which gives a growth factor in this humidity range similar to that used by Kiehl et al. (2000) in a climate model*. The effective refractive indices are calculated by volume-weighting the refractive indices of the ammonium sulphate with those of the associated water. Further details of the treatment of the aerosol, including a more detailed discussion of the growth rate in the hysteresis region, can be found in the paper by Haywood et al. (1997b).

Figure 2 shows the mean and standard deviation of the combined relative humidity in the CRM layers containing aerosols for the T-OCEAN and M-LAND simulations. It can be seen that, as we would expect, there is more temporal variability in the M-LAND run and the relative humidity is lower. The relative humidity ranges between 65% and 75% for the M-LAND simulation and between 80% and 85% for the T-OCEAN simulation.

* The comparison was made using Eq. (1) of Kiehl et al. (2000), noting that the left-hand side of their equation should be a direct ratio rather than the ratio of natural logarithms.
The spatial variability, represented by the plot of the standard deviation, is also larger and more variable in time in the M-LAND run. These features are important for the errors in the DRF of the sulphate aerosols due to the subgrid-scale variability. It should also be noted that, in the M-LAND run, there is only a weak diurnal signal seen in the relative humidity and, in the T-OCEAN run, there is no sign of a diurnal cycle in either the relative humidity or its standard deviation. This implies that any time from these simulations is relevant for solar radiation calculations using any zenith angle.

To show more detailed information on the spatial variability of relative humidities, one period from each simulation has been chosen. Figure 3 shows the normalized frequency distribution of the relative humidity in the lowest five layers for the T-OCEAN run at a time of 18 hours, and at 50 hours from the M-LAND simulation. Also shown is the actual relative humidity of each grid point in the model for all the levels containing aerosol (each line style is a different model level). The larger spread of relative humidities for the M-LAND simulation can be seen very clearly in this plot. The relative humidity over the M-LAND domain ranges from less that 50% up to 100%, whereas the range of humidities over the T-OCEAN is 65% to 100%. Both regions show greater spatial spread of humidities than the single case over the tropical Atlantic shown in Fig. 2 of HRD, but the peak in the distribution at 100% for the tropical Atlantic is also apparent in the T-OCEAN run shown here.
Figure 3. Plots of (a) and (b) the relative-humidity frequency distributions, and (c) and (d) the grid-point values of the relative humidity in the lowest five levels from (a) and (c) 18 hours into the T-OCEAN simulation and (b) and (d) 54 hours into the M-LAND simulation. The different line styles represent different model levels containing aerosols.

The use of these very different geographical regions (a tropical ocean and mid-latitude land site) with data at a range of times has provided a large variety of relative-humidity distribution for investigating the influence on aerosol forcing. The results from radiation calculations on all these different datasets complement the single case study of HRD and give a greater insight into the global importance of the subgrid-scale effects of relative humidity on the direct radiative forcing of sulphate aerosols.

3. The Direct Radiative Forcing of Sulphate Aerosol

Solar radiation calculations were performed for the 20 different time periods from both of the CRM simulations discussed in the previous section. Here, domain averages of the radiative forcing of the aerosol from the CRM are compared with a column-type calculation typical of one carried out in a grid box of a GCM. The column-radiation calculation used domain-average values of temperature, moisture and cloud fields along with a cloud fraction and specified cloud overlap; the overlap used is the maximum-random scheme discussed by Petch and Edwards (1999). Differences in the aerosol forcing between the CRM and the column calculation are due to the effects of subgrid-scale variability of relative humidity, and these would be ignored by any climate model.
Figure 4. Direct radiative forcing by sulphate aerosol for a 60-hour period from (a) the T-Ocean simulation and (b) the M-LAND cloud-resolving model (CRM) simulation. The solid lines represent the all-sky calculations and the dashed lines represent the clear-sky calculations. The lines with triangular symbols are the domain-average forcing from the full CRM and the lines without symbols are the forcing from the general-circulation model (GCM) single-column calculations. The x-axis shows the time after the start of the selected period for each run, as detailed in the text.

or GCM that does not parametrize this effect. To investigate the influence of the clouds on the subgrid-scale response, clear-sky radiation calculations have also been made. As mentioned earlier, the solar-radiation calculations are performed with a fixed solar zenith angle of 30°. The relationship between the direct radiative forcing of sulphate aerosol and zenith angle is well understood (Boucher et al. 1998), but later in this section we consider the impact of changing the solar zenith angle on the errors in the GCM calculations of the DRF of aerosols.

Figure 4 shows the DRF due to sulphate aerosol from the T-Ocean and M-LAND simulations for the chosen 60-hour periods. It should be noted that the two different plots use different scales because the aerosol forcing is significantly larger for the T-Ocean run. Times where the domain-average aerosol forcing from the CRM differ significantly from the GCM-type calculation correspond to times when the subgrid-scale variability of relative humidity is very important for the calculation of the DRF of the sulphate
aerosol. Clear-sky conditions can be identified when the clear-sky and all-sky forcing match.

The domain-average aerosol forcing in the CRM over the T-OCEAN runs ranges from 6 to 12 W m\(^{-2}\) for the all-sky calculations and from 11 to 17 W m\(^{-2}\) for the clear-sky calculations. The all-sky forcing is lower because the presence of clouds at any level in the CRM reduces the direct radiative forcing of aerosols. The difference in the aerosol forcing between the domain-average values from the CRM and the GCM single-column calculations is typically around 5 W m\(^{-2}\). This corresponds to relative errors in the GCM calculation of the order of 50%, ranging from 30% to 80% depending on the time. It can also be seen that the errors would be significantly larger if these relative humidities existed with no clouds; the time-mean error for the 60-hour period in the T-OCEAN run is 43% for the all-sky and 61% for the clear-sky calculations. However, it should be stressed that it is unlikely that the relative-humidity distributions seen in the T-OCEAN run for this 60-hour period would exist without the presence of some cloud.

It can be seen that clear conditions are rare in the T-OCEAN run but occur for substantial periods in the M-LAND simulation. The two periods of precipitation (10–20 hours and 40–50 hours) seen in Fig. 1(b) can be identified in the plot of the aerosol forcing (Fig. 4(b)) as the main periods where the clear-sky and all-sky aerosol forcing calculations differ significantly. For long periods of the M-LAND simulation there is little or no cloud, as is common for this region in summer. For a significant proportion of the 60 hours the errors in the GCM calculation of the aerosol forcing are small, differing from the domain average of the CRM by less than 5%. This is because of the low relative humidities during much of this period; it was shown by HRD that the nonlinear effects of the relative humidity on the aerosol forcing only become important when humidities within the domain exceed 90% over a significant region. However, it can be seen that during the final 20 hours of the period, the GCM errors in the aerosol forcing are significant; the GCM calculation underestimates the aerosol forcing by up to 50% for both clear-sky and all-sky calculations. During this period the mean relative humidity is not higher than several other periods (e.g. 5–10 hours), but this period also corresponds to larger values of the standard deviation of the relative humidity (see Fig. 2(b)) and, therefore, contains several grid points with higher relative humidities.
The mean error in the GCM calculation of DRF for the full 60-hour period over the M-LAND simulation is 9%.

The simulations described above used a fixed solar zenith angle of 30°. As there was very little diurnal variability in the relative humidity in either the M-LAND or T-OCEAN cases, there was no reason to use a real diurnal cycle in these case studies. However, it is worth noting the impact of the solar zenith angle on the error. Figure 5 shows the all-sky DRF of the aerosols from the GCM and CRM calculations and the relative errors a GCM-type calculation would produce. The calculations are done using data from the M-LAND run at 54 hours for a range of solar zenith angles between 10° and 80°. It can be seen that the errors increase from 47% at a zenith angle of 10° to over 60% at a zenith angle of 60°, where it then drops off as the zenith angle increases further. This suggests that the errors seen in both the M-LAND and T-OCEAN case (Fig. 2) could be much larger if the sun was lower in the sky. It is also worth noting that the relative errors are largest at the zenith angles where the DRF of the aerosols are largest.

4. Conclusions

HRD showed the importance of the subgrid-scale variability of relative humidity on the direct radiative forcing (DRF) of sulphate aerosols. Using one single case from a CRM simulation of the tropical Atlantic and some aircraft observations to validate their model, they showed that a GCM could underestimate the DRF by approximately 60% for cloudy skies and 73% for clear skies. However, as pointed out in their conclusions, this result was from a single case study which had a high domain-average relative humidity with a substantial spatial variation. This paper examines the robustness of this result by using a variety of CRM datasets from simulations of two very different types of geographical regions.

The work presented here used 40 different datasets produced by a CRM, half from a simulation of a tropical ocean and half from a simulation of a mid-latitude continental region. Off-line radiation calculations were carried out on the output with and without sulphate aerosol and clouds included. The radiative properties of the sulphate aerosol included a 'growth factor' which was used to describe the influence of relative humidity on the extinction by the aerosol. Although it was not the main focus of this study, the clear-sky calculations were included to show the influence of clouds on the response of aerosol forcing to subgrid-scale variability in the relative humidity. It should be stressed that clouds can also have a strong influence on the spatial distribution of aerosol through removal in the precipitation process, and that the subgrid variability of the aerosols can also play an important role in determining the grid-box mean radiative forcing. Correlation between aerosol concentration and relative humidity would further impact on results (e.g. Charlson et al. 1999); this mechanism was not considered in this study, but will be the focus of a future study.

Results showed that, over the tropical ocean for a range of typical relative humidity distributions, a GCM would underestimate the DRF of sulphate aerosols by 43%, on average. This is somewhat smaller than the single case of HRD (60%), but that case did fit into the range seen for the various tropical ocean datasets used in this study (30% to 80%). The lower values seen in this study tended to correspond to times when the large areal extent and water content of cloud masked the aerosol forcing at saturated points in the CRM. Haywood and Shine (1997) showed that clouds with an optical depth of 5 could reduce the direct radiative forcing of sulphate aerosol by 60%, and clouds with an optical depth of 50 would completely mask any aerosol forcing. It has also been shown
here that the underestimation of the DRF by the GCM is largest at a zenith angle of 60° whereas most calculations here used a value of 30°.

Humidity distributions from the CRM simulation over the continental mid-latitude region typically had a much lower mean relative humidity, although the temporal and spatial variability was much larger than for the tropical ocean. Consequently, for this region, a GCM would underestimate the DRF of sulphate aerosols by only 10%, on average. However, there is considerable variability with time in this region and, for some periods, this GCM error in the DRF of sulphate aerosol can exceed 50%. The peaks in the error tended to correspond to times where both the mean relative humidity and its standard deviation were large, which was seen mainly during convective events.

HRD suggested that the effects of subgrid-scale variability of relative humidity on the DRF of aerosols should be parametrized in climate models. The work presented here agrees with this finding and provides a much wider range of conditions over which the parametrization should fit. The simulation also suggests that, besides links purely to relative humidity and its distribution (if available from the GCM), there may be a case for links with the convection scheme, especially over land.

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