Comparison of the Vertical Velocity used to Calculate the Cloud Droplet Number Concentration in a Cloud-Resolving and a Global Climate Model

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Introduction

Anthropogenic aerosols are effective cloud condensation nuclei (CCN). The availability of CCN affects the initial cloud droplet number concentration (CDNC) and droplet size; therefore, cloud optical properties (the so-called first aerosol indirect effect). However, the estimate of CDNC from a mechanistic treatment shows significant differences from the empirical schemes mainly due to the large bias of the large-scale vertical velocity (w) (Ghan et al. 1993, 1995; Boucher and Lohmann 1995; Lohmann et al. 1999; Menon et al. 2003). In general circulation models, the vertical velocity, w, is diagnosed from the large-scale horizontal convergence or divergence. Due to the coarse resolution of the general circulation model, the diagnosed w has large uncertainties. Compared with the general circulation model, a cloud resolving model (CRM) is a high-resolution model (~1-2 km in the horizontal direction). It can explicitly (at least crudely) resolve cloud structures of individual clouds and convection. The numerical domain of a CRM can often be regarded as a grid column of a general circulation model. The CRM should produce more detailed and realistic results than the general circulation model.

Model Description and ACE-2 Simulation Setup

The dynamical framework of Active Tracer High-resolution Atmospheric Model (ATHAM) (Oberhuber et al. 1998; Herzog et al. 1998) is a non-hydrostatic, fully compressible atmospheric circulation model, formulated with an implicit-time step and finite-difference scheme. Periodic lateral boundary conditions are adopted. At the lower boundary, a material surface is assumed, across which surface heat and moisture fluxes can be exchanged. The model top is a rigid lid. To minimize spurious reflection of upward propagating gravity waves, a sponge layer is applied at the upper part of the numerical domain (upper 8% of the vertical levels).

The horizontal velocity components (u and v), are nudged towards the observed background with the relaxation timescale of 2 hours [Grabowski et al. 1996; Xu and Randall 1996]. For the temperature (θ) and moisture field (q_v), a large-scale forcing from advection (Q) of the ECMWF reanalysis data is applied. In addition, advection (Adv), diffusion (Diff) and source (sink) terms (S), e.g., the micro-physical processes, are accounted for

$$\partial X / \partial t = \mathrm{Adv} + \mathrm{Diff} + S + Q \qquad (1)$$

where X is θ or q_v.

The Second Aerosol Characteristic Experiment (ACE-2) took place at the north-east Atlantic (29.4N, 16.7W) during the period from June 16 to July 24, 1997. The previous observations showed that clean air often alternated with the polluted air in the marine boundary layer. So, this area provides a good opportunity to study aerosol effects on clouds.

Here the two Cloudy Column (CC) events for June 26 and July 9, 1997, are examined. On June 26, the air was originally from the ocean (relatively clean). We denoted this as the “clean” case. On July 9, there was a large amount of anthropogenic aerosols from continental Europe, denoted as the “polluted” case. Measurement data were available around local noon. For each 1997 case, “clean” (June 26) and “polluted” (July 9), the model ran for a 48-hour period. The first day was a spin-up period. The simulation results for the second day were used to compare with the observations and General Circulation Model data from the Goddard Space Flight Center Data Assimilation Office (DAO).

Simulation Results

Figures 1 and 2 shows the cumulative distribution function of the simulated vertical velocity and the observations near local noon for the clean and polluted cases, respectively. Comparing the distribution of the simulated vertical velocity (w) at the cloud base from ATHAM with the observations, we find that the simulated w from ATHAM is close to the observations in both the polluted and clean cases, but the spectrum of the simulated w is narrower than the observed w (Guibert et al. 1996).

Since the resolution in the General Circulation Model is coarse, the sub-grid variability of w must be parameterized. There are two main methods to account for the spatial variability of w when applying a mechanistic scheme to calculate the CDNC. One method assumes that w follows a normal-distribution within a grid cell of the General Circulation Model, and chooses the grid average (large-scale) w as its mean and an observed average standard deviation $\sigma$of about 50 cm/s. Then the Probability Density Function (PDF), f(w), is given by the following (Chuang and Penner 1995)

$$f(w) = \frac{1}{\sqrt{2\pi}\sigma_N} \exp(-\frac{(w - \overline{w_N})^2}{2\sigma_N{}^2}), \quad (\overline{w_N} = w_{GCM} \ , \quad \sigma_N = 50\,\mathrm{cm/s}). \qquad (2)$$

The other method assumes that the sub-grid variability of w is dominated by turbulence. The updraft velocity is the sum of the grid average w and the scaled root-mean-square value of Turbulence Kinetic Energy (TKE). Its PDF is a delta-function (Lohmann et al. 1999),

$$f(w) = \delta(w - (w_{GCM} + 0.7\sqrt{TKE_{GCM}})). \qquad (3)$$

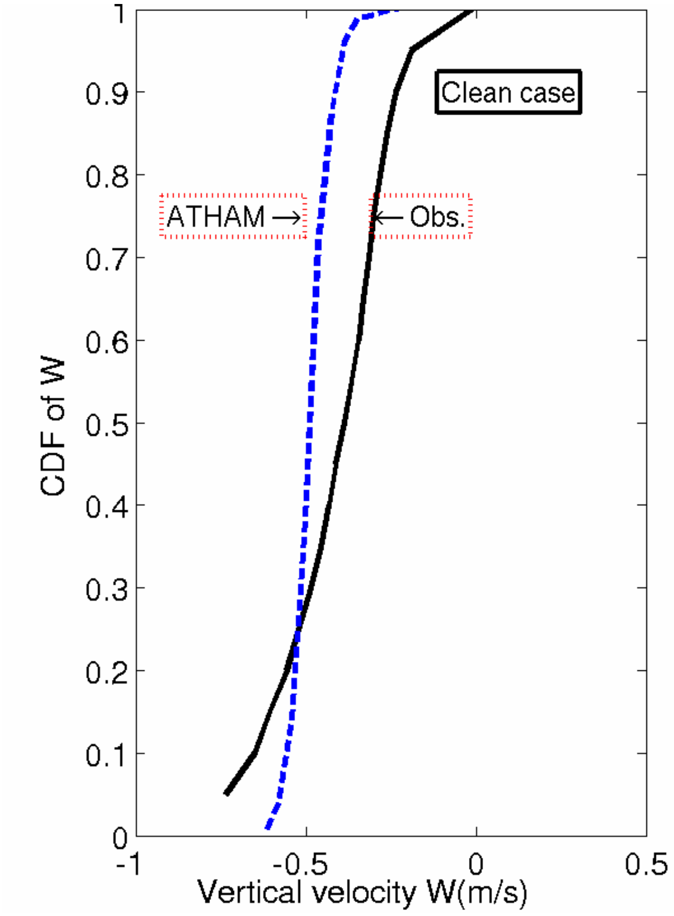

Figure 1. The cumulative distribution function (CDF) of the vertical velocity w from ATHAM and the observation in the "clean" case.

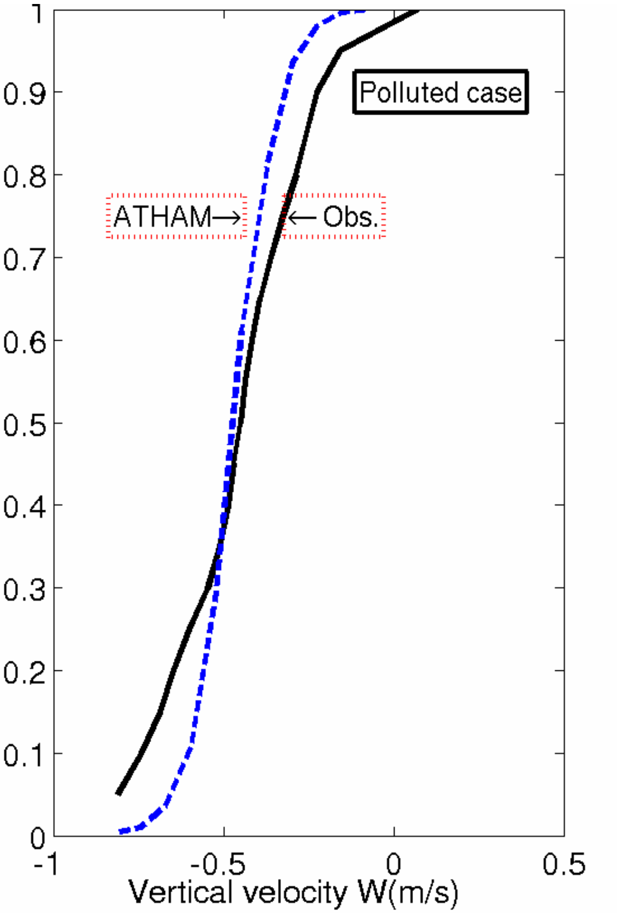

Figure 2. The same as in Figure 1, but for "Polluted" case.

One use of the updraft velocity is in the mechanistic treatment of cloud droplet nucleation ($N_d = \frac{wN_a}{w + cN_a}$, [Ghan et al. 1993, 1995]). The initial CDNC, N_d, is determined by the updraft velocity w, aerosol number concentration, N_a, and a parameter c, which takes aerosol composition and size spectrum into account.

Figures 3 and 4 shows the CDNC from ATHAM and from the DAO data assuming *w* follows the normal and delta distributions for the clean and polluted cases, respectively. Compared with the observation at local noon, the estimation from ATHAM is the closest. The assumption of the normal distribution tends to under-estimate the CDNC, while the delta distribution tends to over-estimate the CDNC in the ACE-2 case.

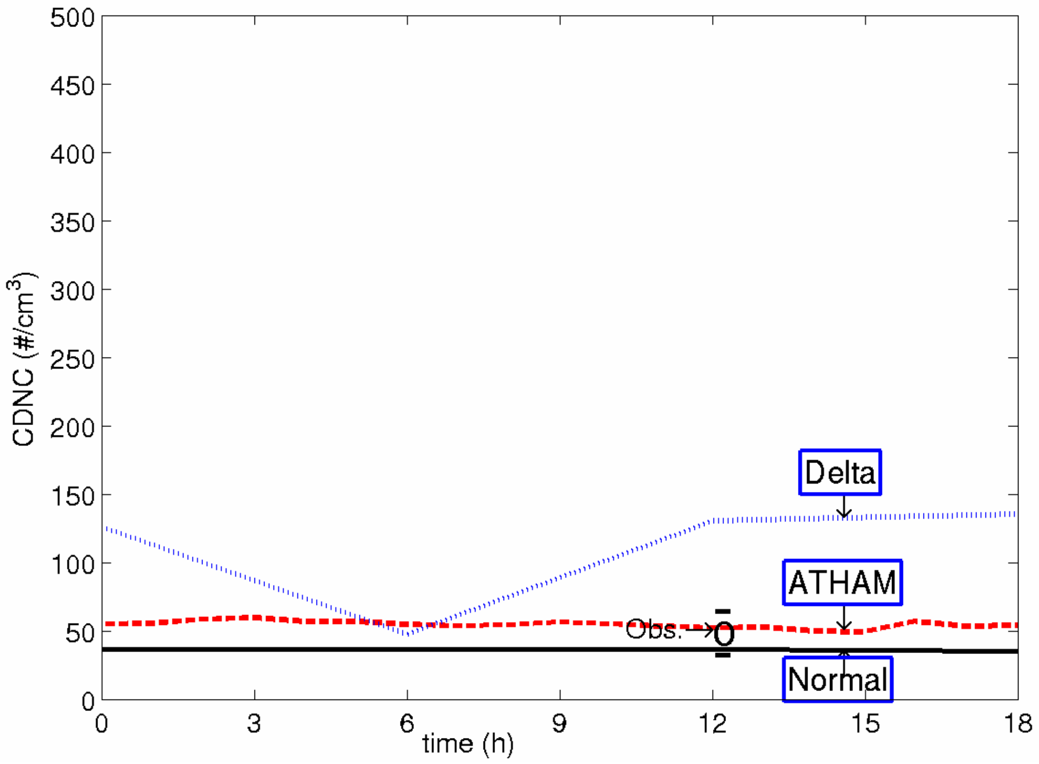

Figure 3. CDNC from ATHAM, and the normal and delta distributions in the “clean” case.

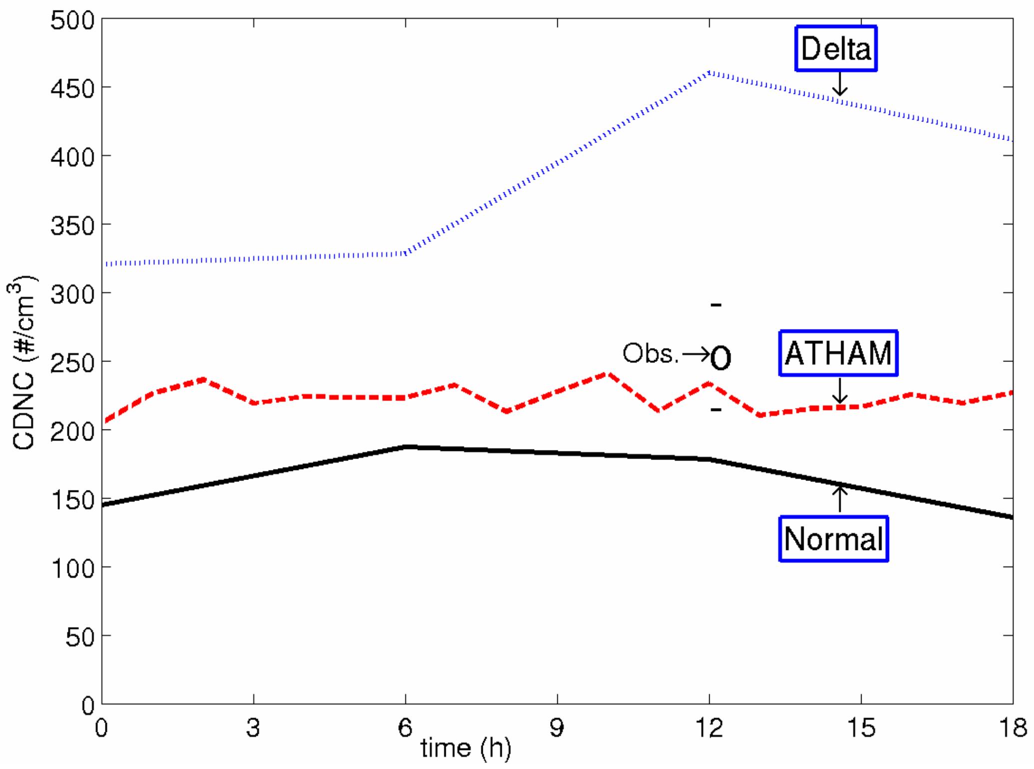

Figure 4. The same as in Figure 3, but for the “polluted” case.

Summary

The vertical velocity *w* produced from ATHAM is close to the observation. In the ACE-2 CC experiment, the CDNC in the polluted case is much higher than the clean case mainly due to the larger aerosol amounts. Two methods (normal- and delta-distribution), which are used to account for the sub-grid variability, did not yield good estimates of CDNC. Further research work is needed to include the sub-grid contributions of the vertical velocity in a global model.

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References

Boucher, O., and U. Lohmann, 1995: The sulfate-CCN-cloud albedo effect. A sensitivity study with two general circulation models. *Tellus,* **47B**, 281–300.

Chuang, C., and J. Penner, 1995: Effect of anthropogenic sulfate on cloud drop nucleation and optical properties. *Tellus,* **47**, 566–577.

Ghan, S., C. Chuang, R. Easter, and J. Penner, 1995: A parameterization of cloud droplet nucleation, II: Multiple aerosol types. *Atmos. Res.*, **36**, 39–54.

Ghan, S., C. Chuang, and J. Penner, 1995: A parameterization of cloud droplet nucleation, I: Single aerosol type. *Atmos. Res.*, **36**, 39–54.

Grabowski, W., X. Wu, and M. Moncrieff, 1996: Cloud resolving modeling of tropical systems during Phase III of GATE. Part I: Two-dimensional experiments. *J. Atmos. Sci.*, **53**, 3684–3709.

Guibert, S., J. R. Snider, and J. -L. Brenguier, 2003: Aerosol activation in marine stratocumulus clouds Part-I: Measurements validation for a closure study. *J. Geophys. Res.*, 108(D15), 8628, doi:10.1029/2002JD002678.

Herzog, M., H. Graf, C. Textor, and J. Oberhuber, 1998: The effect of phase changes of water on the development of volcanic plumes, In *Report No. 270, Max-Plank Institute for Meteorology*.

Lohmann, U., J. Feichter, C. Chuang, and J. Penner, 1999: Prediction of the number of cloud droplets in the ECHAM GCM. *J. Geophys. Res.*, **104**, 9169–9198.

Menon, S., J. -L. Brenguier, O. Boucher, P. Davison, and et al., 2003: Evaluating aerosol/cloud/ radiation process parameterizations with single-column models and Second Aerosol Characterization Experiment (ACE-2) cloudy column observations. *J. Geophys. Res.*, 108(D24), 4762, doi:10.1029/2003JD003902.

Oberhuber, J., M. Herzog, H. Graf, and K. Schwanke, 1998: Volcanic plume simulation on large scales, In *Report No. 269, Max-Plank Institute for Meteorology*.

Xu, K., and D. Randall, 1996: Explicit simulation of cumulus ensembles with the GATE Phase III data: Comparison with observations. *J. Atmos. Sci.*, **53**, 3710-3736.