THE COUPLED EFFECT OF MID-TROPOSPHERIC MOISTURE AND AEROSOL ABUNDANCE
8.4 ON DEEP CONVECTIVE CLOUD DYNAMICS AND MICROPHYSICS

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1. INTRODUCTION

The effect of mid-tropospheric moisture on convective cloud development has been studied extensively in recent years. These studies have found that convection in a dry atmosphere tends to be more readily diminished by entrainment of very dry air.

An important process that has not been considered in the previous studies is the aerosol properties of the entrained air. The buoyancy loss through entrainment is dependent on the amount of droplet evaporation, thus, on the environmental humidity and droplet sizes. Because droplet spectra depend on aerosol spectra, the effect of aerosol on the droplet spectrum is a potentially important process affecting convective clouds.

This study investigates the coupled effect mid-tropospheric moisture and aerosol abundance on a deep convective cloud. Our specific objective is to study the response of the cloud to aerosol abundance both with and without a dry layer in the mid troposphere.

2. THE MODEL AND THE EXPERIMENTAL DESIGN

The numerical model is the Model of Aerosols and Chemistry in Convective Clouds (MAC3), which is based on the axisymmetric nonhydrostatic cloud model of *Reisin et al.* (1996) and includes newly added modules of aerosol (*Yin et al.,* 2005).

Four hydrometeor species are considered: drops, ice crystals, graupel and snowflakes (aggregates). Each particle species is divided into 34 bins.

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The aerosol module includes prognostic equations for the number concentration of aerosol particles and of the specific mass of aerosols in the air and in hydrometeors, and equations for impaction scavenging of aerosol particles by hydrometeors, aerosol regeneration following complete evaporation/sublimation of hydrometeors, gas-cloud interactions and aqueous phase oxidation of dissolved SO_2 by ozone and hydrogen peroxide.

The cloud we study occurring on 19 July 1981 during Cooperative Convective Precipitation Experiment. This case is characterised by moderate instability and weak wind shear. The vertical profile of relative humidity is marked by large zigzags. A dry layer between 4.9 and 6.4 km is of particular interest in this study. We studied the sensitivity of the dynamics and microphysics to aerosol abundance (Cui et al., 2006). In order to investigate the coupled effect of the mid-tropospheric humidity and the aerosol abundance, we designed four simulations as follows. The first case, OrgDry, is the base case, where initial aerosol size distribution and the profiles of temperature and relative humidity are the same as those of the low aerosol case in Cui et al. (2006). The second case, DblDry, is the high aerosol case with the dry layer, i.e., the aerosol size distribution is the same as in the high aerosol case in Cui et al. (2006), but the profile of relative humidity is the same as in OrgDry. In the third case OrgWet, the aerosol size distribution is the same as in OrgDry, but the dry layer between 5.1-6.3 km is removed by increasing relative humidity. In the last case, DblWet, the aerosol size distribution is the same as in DblDry, but the profile of relative humidity is the same as in OrgWet.

3. RESULTS

Figure 1 shows how the cloud top height varies between the four cases. In response to the changes in mid-tropospheric humidity and aerosol abundance, the simulated clouds gradually diverge after 20 min. A distinctive feature in cloud top heights is the change from stagnation in case DblDry (at ~30-40 min) to more steady development in case DblWet. Another feature is the increase in the top height of graupel particles from ~8 km in the high aerosol case to ~10 km when the dry layer is removed (figure not shown).

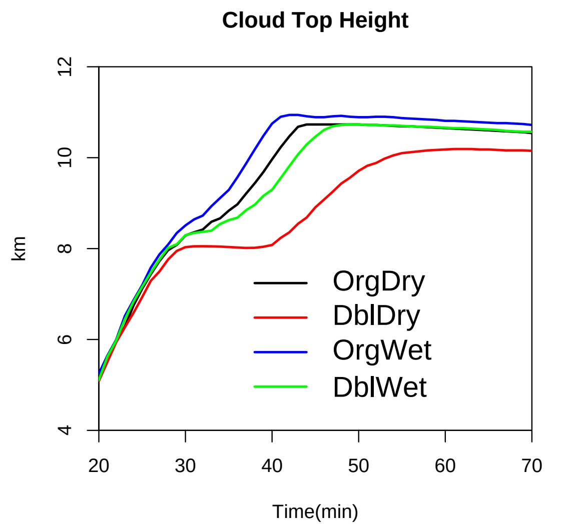

Figure 1. The temporal variation of the simulated cloud top heights.

Cloud tops reach the bottom of the dry layer at ~20 min in all cases and pass through the dry layer during 20-25 min. At 20 min, there are very small differences in the maximum specific mass of hydrometeors and the cloud top height. After passing the dry layer at ~25 min, the differences become progressively larger in the upper part of the clouds. Figure 2 shows the differences at 25 min of simulation in the specific mass and number concentrations of droplets, in the temperature, and in the vertical velocity between the wet cases (without the dry layer) and dry cases (with the dry layer). A comparison between the wet and dry cases with the same initial aerosol concentrations indicates that the removal of the dry layer leads to more vigorous clouds, in accord with previous findings. Both the specific mass (Fig. 2a,b) and number concentrations (Fig. 2c,d) of droplets increase near the cloud top and edge when the dry layer is removed, and the increase is much larger in the high aerosol cases (DblWet-DblDry). The removal of the dry layer suppresses evaporation caused by mixing and produces more droplets near the cloud top and edge. Less evaporation in wet cases results in more latent heating (Fig. 2e,f). This, in turn, promotes stronger updrafts. The differences are larger in the high aerosol cases (right column of Fig. 2) than in the low aerosol cases (left column) because the droplets are smaller and evaporate more quickly. Therefore, the cloud properties, such as the microphysical structure, cloud dynamics, and thermodynamics, are more sensitive to changes in initial aerosol abundance in a dry mid-tropospheric environment.

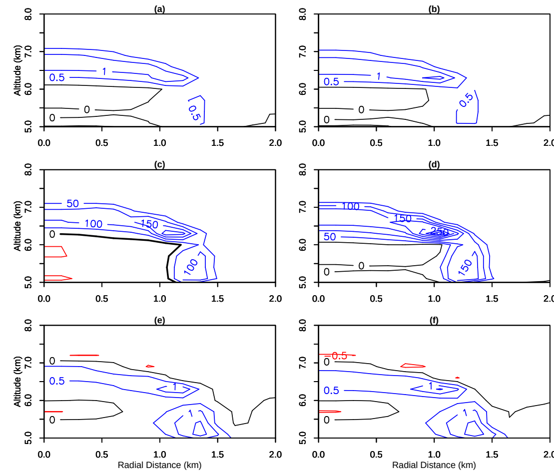

Figure 2. The differences at 25 min in drop specific mass (a & b; unit: gkg^{-1}), drop number concentration (c & d; unit: cm^{-3}), temperature (e & f; unit: ^{o}C). Left column is OrgWet minus OrgDry, while right column is DblWet minus DblDry.

The process of buoyancy depletion acts through cloud microphysical processes, which eventually affects cloud thermodynamics and dynamics. The size distribution of drops reveals how the aerosol abundance and mid-tropospheric humidity affect cloud microphysics at selected locations (Figs. 3 and 4). For cases with the same initial aerosol concentrations (OrgDry and OrgWet; or DblDry and DblWet), the drop distributions vary with mid-tropospheric humidity. In the cloud lateral boundary and the cloud top layer, the figures indicate an increase in both the number and mass distributions in the wet cases. But in the updraft core, the differences in the distributions are small between the dry and wet cases, reflecting the fact that the mid-tropospheric dry layer reduces the drops by a process of mixing and entrainment across the cloud boundaries. For cases with the same initial moisture profile (OrgWet and DblWet; or OrgDry and DblDry), the distributions of drops vary with the initial aerosol concentrations. In the cloud lateral boundary and the cloud top layer, the figures indicate an increase in both the number and mass distributions in the low aerosol cases. But in the updraft core, there are more large drops (radii ≥20 μm) for the low aerosol cases. Figures 2-4 indicate that mid-tropospheric humidity is an important factor affecting cloud microphysics, but that the magnitude of the effect depends also on the aerosol abundance.

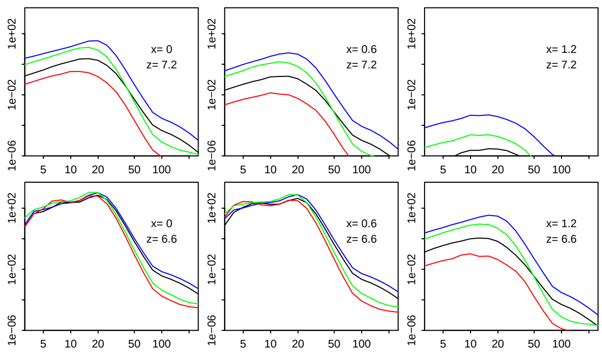

Figure 3. Drop number distribution functions at selected locations at 25 min. The radial distance (X) and altitude (Z) of the individual distributions is indicated on each panel. The units of the horizontal and vertical coordinates are μm and $cm^{-3}\mu m^{-1}$, respectively. The key to the linestyles is the same as Fig. 1.

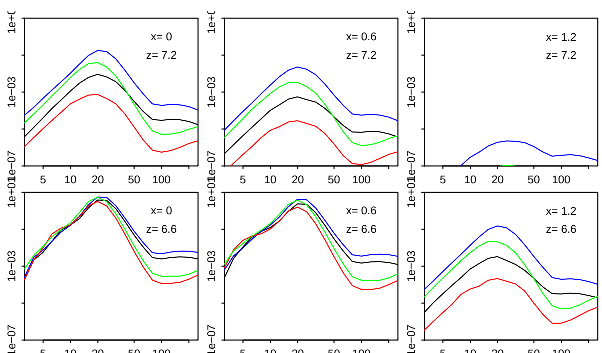

Figure 4. Same as in Fig. 3, but for drop mass distribution functions.

A comparison between 25 min and 35 min indicates that the impact of removing the dry layer becomes stronger than at 25 min. The enhancement of cloud activity is fairly large between cases DblDry and DblWet. Case DblWet still has a cloud top height lower than case OrgWet, but it overcomes the stagnation in case DblDry. The top of graupel particles grows accordingly.

4. SUMMARY

The impact of dryness in the midtroposphere varies greatly in different aerosol abundance. When the aerosol abundance is high, the impact is large enough to alter cloud dynamics and microphysics. In the high aerosol case, the development of cloud top experiences a halt with the dry layer. This phenomenon does not repeat when the dry layer is removed. We find that a dry layer in the mid troposphere leads to a reduction in cloud vigour, droplet number, liquid water content and ice mass above the layer, and that these changes are amplified in high aerosol environments.

Our simulations agree to previous studies in that midtropospheric dryness indeed suppresses convective activity. Previous studies suggest that dry layers discourage the growth of deep convective clouds by depleting buoyancy through entrainment, but statistics and mesoscale modelling prevent from examining the microphysics that causes the difference. Our study, using bin-resolved microphysics, builds a link between aerosol and buoyancy.

References

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