Midlatitude Aerosol-Cloud-Radiation Feedbacks in Marine Boundary Layer Clouds

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LONG-TERM GOALS

The development and improvement of cloud microphysical parameterizations for use in cloud and numerical weather prediction models

OBJECTIVES

Conduct detailed studies of marine stratocumulus cloud microphysical processes in order to achieve a better understanding of interactions between microphysical, radiative and boundary layer thermodynamical processes and to improve their formulation in numerical weather prediction models. Develop parameterizations of individual cloud physics processes for use in numerical weather prediction models.

APPROACH

The research is based on the CIMMS high-resolution large eddy simulation (LES) model of marine low layer clouds with explicit formulation of aerosol and drop size-resolving microphysics. The LES simulations, as well as observations from field projects are used to study rain formation in marine stratocumulus and shallow cumulus convective clouds.

WORK COMPLETED

The following tasks have been completed this year:

1. The results of the study of the effects of sea-salt aerosols on rain formation in shallow cumulus convective clouds and its implication for parameterization of aerosol effects have been analyzed. The paper has been submitted and accepted for publication in the Journal of Atmospheric Sciences.

2. The results of the LES study of low layer stratiform clouds formation and evolution over continental areas have been analyzed and published in the Journal of Atmospheric Sciences.

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RESULTS

1. Effects of sea-salt aerosols on precipitation in simulations of shallow cumulus and its implication for parameterization development

The influence of aerosol on cloud and precipitation properties of shallow cumulus was evaluated by following the evolution of a population of nearly 400 clouds over the 24-hour simulation period. The common understanding is that the addition of large (small) size sea-salt nuclei tends to accelerate (suppress) precipitation formation. This seems to be supported by our simulation experiments when realistic sea-salt spectra are specified as a function of the surface wind. In this case the effect of the larger nuclei to enhance the precipitation predominates, and accumulated precipitation increases with the wind speed. This effect, however, is strongly influenced by the choice of background CCN spectrum. The same specification of sea-salt spectra, but in an environment with a higher background aerosol load, resulted in a decrease in accumulated precipitation with increasing surface wind speed. This result has an important implication for the task of identifying the aerosol parameters necessary and most essential for parameterization development. Our study demonstrates that at least three parameters of aerosol distribution are essential for accurate parameterization of sea-salt aerosol effects on precipitation: the concentration of Aitken size nuclei, the concentration of large/giant nuclei, and the aerosol load of the ambient environment.

The study also addressed the unresolved issue in the formulation of the CCN activation process, namely the growth of sea-salt aerosols in the subcloud layer and the parameterization of the so called "wet" radius of newly activated drops at cloud base. Following Ivanova et al (1977), a simple parameterization is frequently employed where the wet radii of large CCN is set to their dry radii multiplied by a factor k (e.g., Kogan 1991). We evaluated the sensitivity of simulations to the parameter k by conducting a simulation in which the concentration of large nuclei is reduced. The reduction of large nuclei concentration by a factor of 5 in the experiment LN5 resulted in slightly smaller accumulated precipitation during the initial phase of cloud system development; however, as clouds mature the main rain-producing mechanisms (condensation and coagulation involving mid-size drops) dominate, and the total precipitation by the end of simulation only slightly deviates from the control simulation TOT (see Fig. 1). It is concluded that changing concentrations in the large nuclei part of the CCN spectrum (or equivalently the choice of k) has little effect on the overall precipitation amount, at least in the conditions characteristic for the RICO field project.

The finding of our study that the increase of sea-salt aerosol production due to stronger surface winds may not always lead to precipitation enhancement, but depends also on the background aerosol concentration, has a clear physical interpretation in the well-understood competing effects between an increase in precipitation initiation from embryos formed on large/jet CCN and a decrease from the reduction of supersaturation by the abundance of small/film aerosols. A paper describing the results of the sea-salt aerosol effects has been accepted for publication in the Journal of the Atmospheric Sciences.

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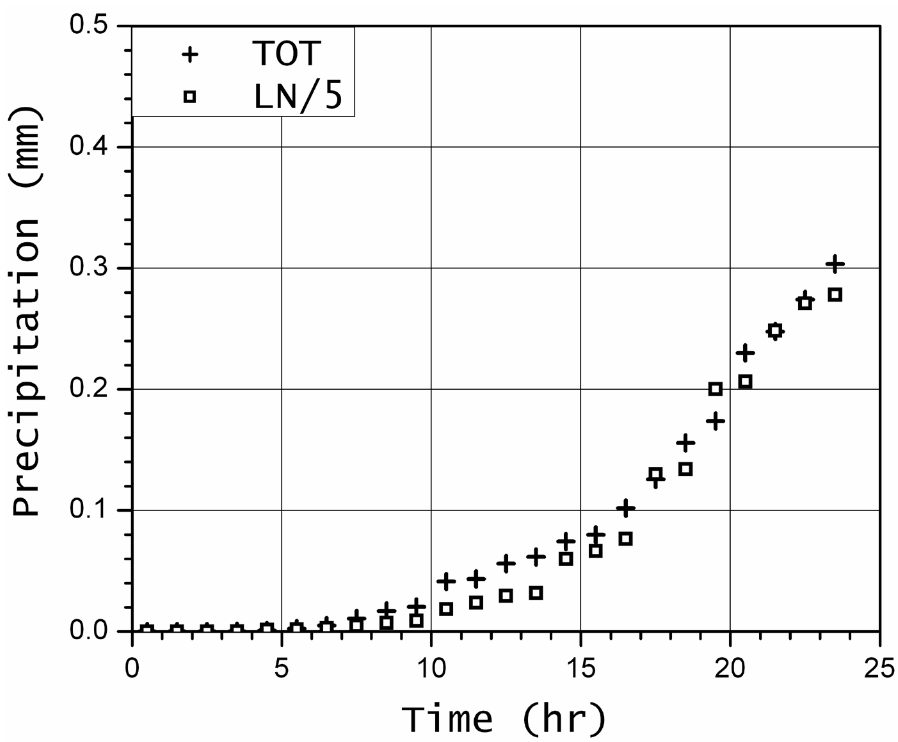

Figure 1. Evolution of the accumulated surface precipitation for the TOT and LN5 simulations. [graph: The reduction of concentration of large nuclei in simulation LN5 resulted in only slight decrease in accumulated precipitation at the initial evolution of cloud system. The total precipitation by the end of simulation only slightly deviates from the control simulation TOT.]

2. LES simulations of low layer stratiform clouds dependence on large scale forcing

The work this year focused on expanding and preparing research results obtained during previous years for publication in refereed scientific journals. In the Part I of the study we focused on large-eddy observations (LEO) of a nocturnal continental stratocumulus cloud system associated with the post-cold-frontal region of a midlatitude synoptic cyclone sampled by the SGP ACRF (Southern Great Plains ARM Climate Research Facility) in northern Oklahoma. During the last year we concentrated on publishing the results of the Part II of the study which was a modeling investigation based on large-eddy simulations (LES). Initial analyses from the NOAA/NWS/NCEP Rapid Update Cycle (RUC) model supplied estimates for the forcing terms. Turbulent statistics calculated from the LES results were consistent with large-eddy observations obtained from millimeter-wave cloud radar data. Figures 2a and 2b illustrate the comparison results by overlaying the LES profiles with vertical velocity variance and skewness profiles from the 95-GHz W-band ARM Cloud Radar (WACR). Because of the lack of scatterers in the subcloud layer, the radar gives data only for cloudy regions, and variance and skewness is not available below cloud base (750 m and 850 m for the two periods, respectively). Both

LES and WACR profiles are calculated over hour-long periods. Relative to the WACR, the LES captures reasonably well the evolution of the turbulent intensities in this case. For the two analysis periods, the maximum variance from the WACR is 0.14 and 0.16 m^2/s^2, compared with 0.13 and 0.15 m^2/s^2 from the LES. The maximum in the LES profile corresponding to the later period is noticeably deeper (~120 m) than the WACR profile, which can be attributed to the boundary layer in the model deepening over this period at a greater rate than the observed boundary layer. This discrepancy may be the result of either the LES overestimating entrainment, an underestimate in the choice for subsidence, or a result of the choice of averaging periods for the WACR data. The fact that the model represents the turbulent intensity well suggests that the entrainment rate is not the culprit for the mismatch in boundary layer depth between observations and model. Although the cloud fraction of the stratocumulus as a whole is 100%, nevertheless cloud fraction at cloud top and cloud base may be considerably less. The difference in how the turbulent statistics are calculated between LES (over the entire boundary layer) and WACR (over cloudy regions only) may explain some of the discrepancy between LES and WACR statistics near cloud base and cloud top. The time series of radar data for this case indicates that the boundary layer depth does not uniformly deepen over the 0600–1000 UTC period but rather deepens over some periods and becomes shallower over others, suggesting that more accurately representing the synoptic-scale vertical motion in the model would be appropriate. The general shape of the variance profiles are captured well, in particular the decrease in variance near cloud base that is associated with decoupling. Skewness, being a higher-order statistic, is noisier, but Fig. 2b indicates that the LES captures the negative skewness in the cloud layer (from 550–1150 m). As mentioned above, the regions of positive skewness in profiles near cloud top are not captured by the WACR, though one data point at z=1150 m in the 0900–1000 UTC profile hints at the transition to positive skewness in the upper portion of the cloud.

The deep region of negative buoyancy flux (200–800 m) over much of the subcloud layer (Fig. 2c) indicates that a substantial portion of the boundary layer circulation is thermodynamically indirect (cold updrafts; warm downdrafts). Whereas a negative buoyancy flux just below cloud base is one symptom of decoupling, it is less common to see such a pronounced, deep layer of negative buoyancy flux. This layer of negative buoyancy is consistent with the bimodal $w'w'$ profile, which best indicates that the cloud and subcloud layers are largely two distinct circulations. The absence of precipitation greatly simplifies the total water flux (Fig. 2d). These profiles imply a moistening from turbulent transport from the surface up to 650–700m, and a slight decrease with time from 700 m up to the inversion. The advective drying, however, is greater than this moistening, resulting in a net subcloud (and boundary layer) drying.

Stratocumulus-topped boundary layers play important role in weather prediction, but previously have been simulated by LES exclusively in marine environments. However, these cloud types are also prevalent over the continent, therefore our LES study is an important insight into advantages and limitations of the LES approach to explore these cloud types. Two papers describing results of the study have been published in the Journal of Atmospheric Sciences.

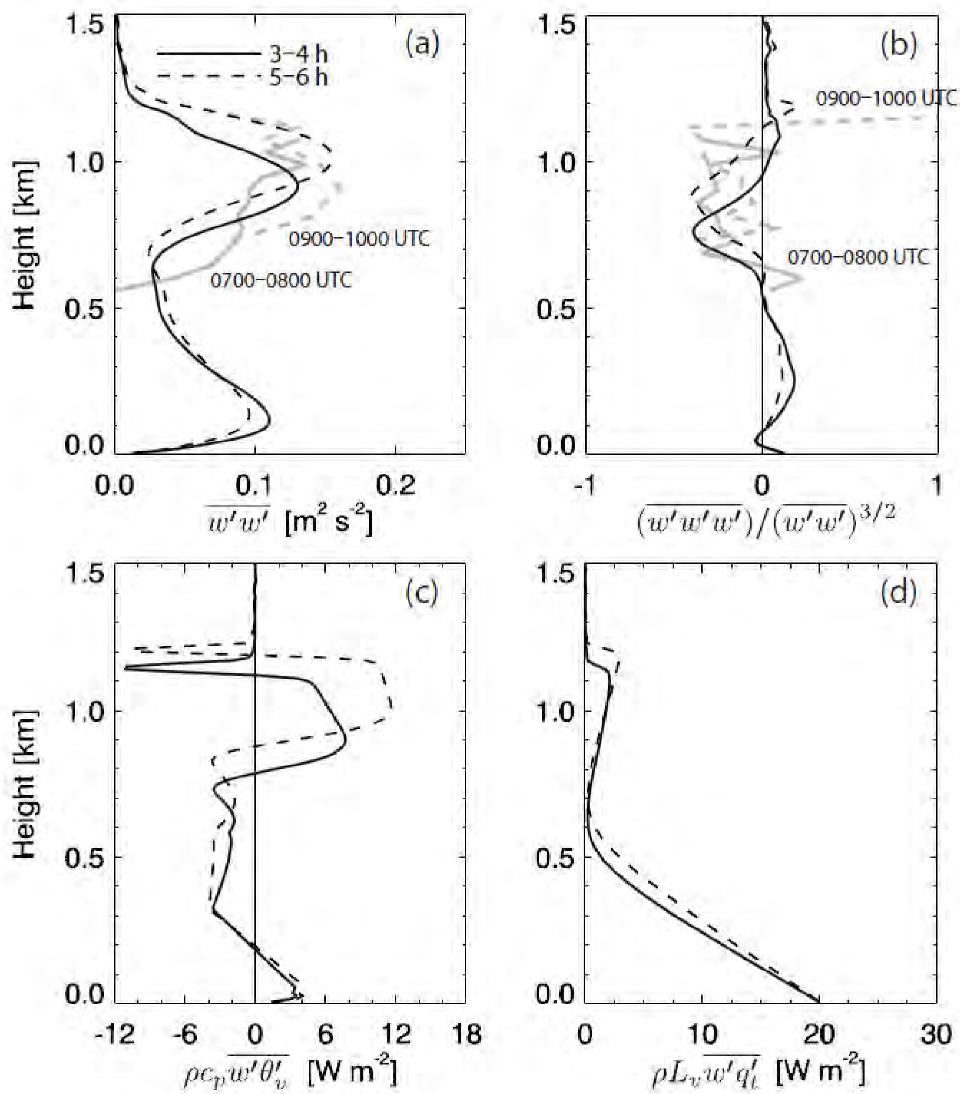

Figure 2. Mean profiles of (a) vertical velocity variance (w'w'), (b) skewness ((w'w'w')/(w'w')$^{3/2}$), (c) buoyancy flux (ρcpw'θ'$_v$), and (d) total water flux(ρL$_v$w'q'$_t$) for the control simulation. The gray lines in (a) and (b) represent variance and skewness at the indicated times, calculated from the ARM W-band cloud radar (WACR).

IMPACT

The improved parameterization of the physical processes in marine stratocumulus clouds will lead to more accurate numerical weather predictions for Navy operations.

TRANSITIONS

Our results have been published in five refereed scientific journals and reported at two scientific meetings.

PUBLICATIONS

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