

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. This year we continued the data analysis from the RICO field project that is used as a basis for cloud physics parameterizations applicable for shallow convective cumuliform clouds.

WORK COMPLETED

The following tasks have been completed this year:

1. The study of the effect of sea-salt aerosols on rain formation in shallow cumulus convective clouds.
2. The development of the LES bulk model framework for evaluation and testing of cloud microphysics parameterizations designed for use in shallow cumulus convective clouds
3. The LES study of low layer stratiform clouds formation and evolution over continental areas.

RESULTS

1. Effects of sea-salt aerosols on precipitation in simulations of shallow cumulus

A suite of large-eddy simulations with size-resolving (bin) microphysical processes was performed in order to assess how sea-salt nuclei from the ocean surface influence the precipitation process in trade cumulus. The baseline simulation (STD), derived using observations from the Rain in Cumulus over the Ocean (RICO) field campaign, contained a background CCN spectrum of predominantly submicron aerosol. This simulation was contrasted against simulations that added sea salt at the surface corresponding to observed wind magnitudes of 12 m s^{-1} (TOT) and 17 m s^{-1} (TOT17). Two additional simulations (JET and FLM) tested the effect of adding a large concentration of sea-salt aerosol in two different size ranges.

The influence of aerosol on cloud and precipitation properties was evaluated by following the evolution of a population of cloud cells (369 in the baseline simulation) over the 24-hour simulation period. In the sensitivity simulations, the addition of large (small) size sea-salt nuclei tends to accelerate (suppress) precipitation formation. However, when realistic sea-salt spectra are specified as a function of surface wind, the effect of the larger nuclei to enhance the precipitation predominates, and accumulated precipitation increases with 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 (hiTOT and hiTOT17), resulted in a decrease in accumulated precipitation with increasing surface wind speed (Fig. 1).

Results also suggest that the slope of the relationship between vertical velocity W and the concentration of embryonic precipitation particles at cloud base N_r may indicate the role of sea-salt nuclei. A negative slope (N_r decreasing with increasing W) points to the predominance of small sea-salt nuclei, in which larger updrafts activate a greater number of smaller cloud drops with smaller coagulation efficiencies, resulting in fewer embryonic rain drops (Fig. 2). A positive slope (N_r increasing with increasing W), on the other hand, indicates the presence of large sea-salt nuclei. These large sea-salt particles are the source of large cloud drops, which grow to embryonic rain drops by condensation and coagulation.

The presence in supersaturated cloud-base regions of both nucleated cloud drops and embryonic precipitation drops suggests that nucleation parameterizations should account for both.

A paper describing the results of the sea-salt aerosol effects analysis has been submitted to the Journal of the Atmospheric Sciences. The results of the study were also presented at the 13th AMS Conference on Cloud Physics in Portland, OR.

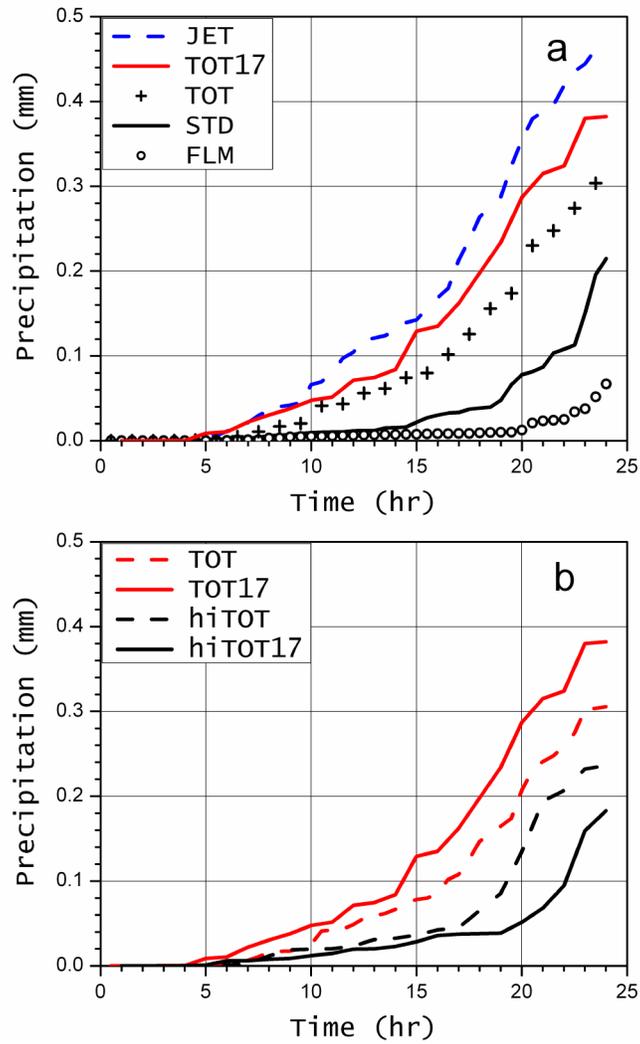


Figure 1. (a) Evolution of the accumulated surface precipitation for five simulations; (b) Accumulated surface precipitation for the TOT and TOT17 simulations as in (a), together with corresponding hiTOT and hiTOT17 simulations, which employed a larger background CCN environment.

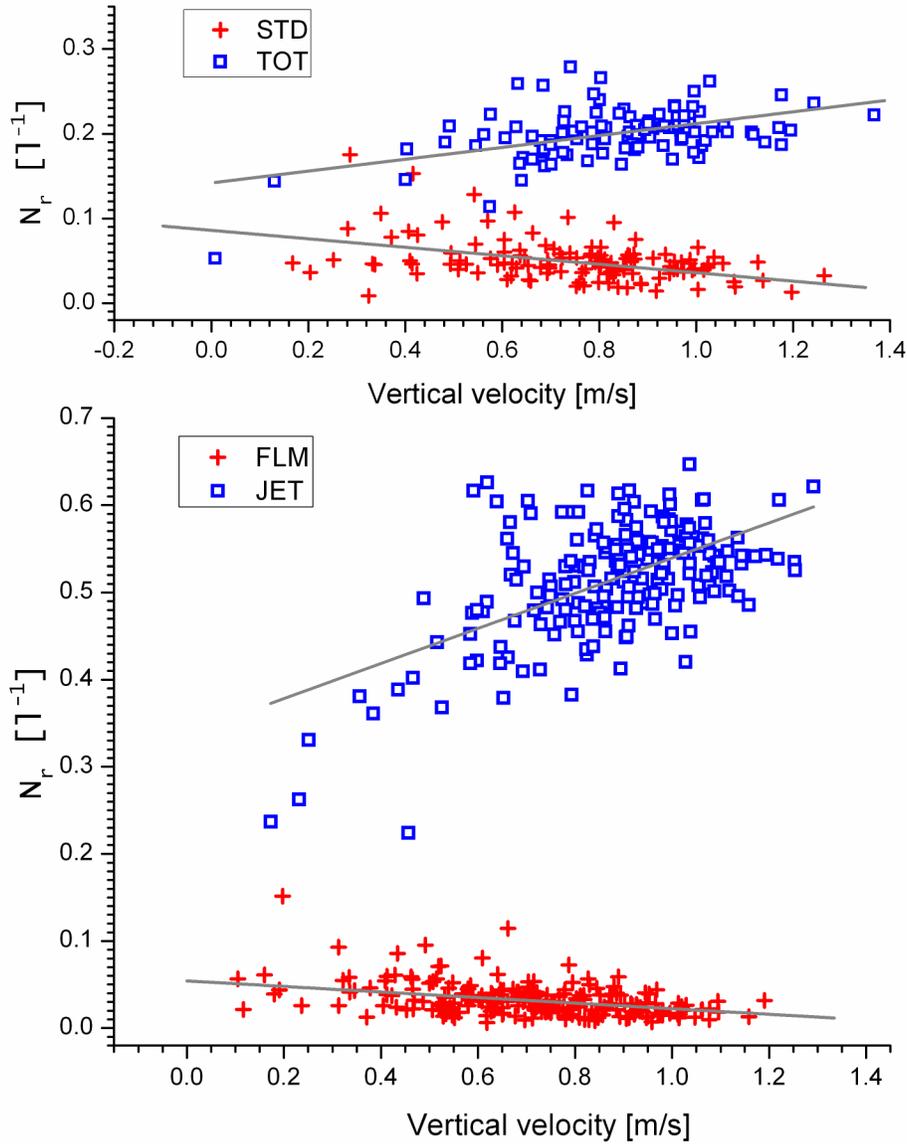


Figure 2. Scatterplots of N_r at cloud base versus W for the four simulations. Data are sampled over the cloudy regions of positive supersaturation, which largely corresponds to updraft areas. [graph: The negative slope of the best fit line indicates the lack of sea-salt aerosols (simulation STD) of the predominance of the smaller size aerosols (FLM) in the atmosphere. The positive slope indicates of the prevalence of large/jet mode aerosols(simulations JET and TOT)]

2. The development and improvement of cloud microphysical parameterizations in cumulus convective clouds for use in numerical weather prediction models

The development of a bulk microphysical parameterization for cumulus convective clouds has continued. Our parameterization development effort is based on the new version of the CIMMS LES model (SAMEX) that includes a dynamical core capable of running on advanced, distributed-parallel computing architectures and uses an explicit drop spectrum resolving formulation of microphysics. The formulation of microphysical processes, based on first principles and the use of a large number of prognostic microphysical variables (up to 60), makes the model expensive to run in an operational mode. However, in a research mode it is a source of comprehensive datasets for bulk parameterization development. Therefore, the SAMEX model serves as a data source and a benchmark for bulk parameterization comparison. We focused on shallow trade wind cumulus clouds which are one of the most prevalent cloud types on Earth and play an important role in the energy and moisture balance of the oceanic weather system.

Using SAMEX a series of simulations of shallow convective clouds based on RICO observations has been analyzed, focusing on precipitation formation in different aerosol environments. The datasets from simulations have been organized to form a comprehensive database for derivation of conversion rates for bulk parameterization using methods of non-linear regression analysis. The new bulk LES model framework (SAMBM) was developed and tested for the marine stratocumulus case based on observation from the ASTEX project. The SAMBM bulk model serves as the framework where the bulk parameterization for convective clouds is tested. We also further developed and enhanced our cloud analysis package which allows investigation of cloud and precipitation parameters stratified by cloud size, precipitation efficiency, age, aerosol source, areas of updrafts and downdrafts, etc.

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

The low-altitude continental stratus clouds have a significant climatological signal, and, therefore, have to be accurately represented in regional prediction models. The approach of large-eddy observation (LEO) was applied to a case of 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. LEOs were obtained from millimeter-wave cloud radar and micro-pulse lidar, whereas traditional meteorological observations described the synoptic environment. The study focused on a 9-h period of a predominantly non-precipitating stratus layer 250–400-m thick, when cloud-top and cloud-base remained relatively steady. A slight thinning of the cloud layer over time was consistent with near-surface dry-air advection. Tropospheric-deep descent overlay weak ascent below, providing a mechanism for strengthening the inversion at cloud top. Time series of Doppler velocity indicate vertically coherent vertical velocities exhibited similar wavelengths and phases. The cloud layer was subadiabatic, consistent with previous observations of continental stratus. The magnitude of turbulence, as indicated by the variance of the vertical velocity, was weak relative to typical marine stratus and to other cases of continental stratus. Conditional sampling of the eddy structures indicated that strong downdrafts are more prevalent than strong updrafts, and negative skewness of the vertical velocity in the cloud both implies an in-cloud circulation driven by longwave cooling at cloud top, similar to that in marine stratus.

The observational study was complemented by modeling investigation based on the 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. The magnitude of turbulence was weaker than in typical marine stratocumulus, a result attributed to strongly decoupled cloud and sub-cloud circulations associated with a deep layer of negative buoyancy flux arising from the entrainment of warm, free-tropospheric air.

The role of different mechanisms responsible for driving cloud and subcloud layer dynamics was explored by analyzing the TKE budget. The mean TKE profile in Fig. 3 is fairly typical for a turbulent boundary layer, with peaks in the upper cloud and near the surface. The buoyancy term is positive in the cloud, resulting from cloud-top radiative cooling, but is negative and suppresses TKE generation in the subcloud layer from 175–825 m. While negative buoyancy flux is frequently present near cloud base, such a deep layer is uncommon. Over the subcloud layer, TKE transport counteracts loss from buoyancy. The most surprising result from the TKE budget is the significant contribution of shear generation acting over the entire depth of the subcloud layer. Our strong suspicion is that the boundary layer scalings, formulated for buoyancy-driven boundary layer dynamics, perform poorly when shear is a significant component in the TKE budget.

Model results were highly sensitive to variations in advection of temperature and moisture and much less sensitive to changes in large-scale vertical velocity and surface fluxes. For this case, advections tended to be the governing factors in the analyzed cloud system maintenance and decay, rather than entrainment processes. The dominance of advection provides an optimistic outlook for mesoscale numerical weather prediction, and for climate models, because these classes of models represent such grid-scale processes better than they treat subgrid-scale processes like entrainment. Two papers describing results of the study have been published in the *Journal of Atmospheric Sciences*.

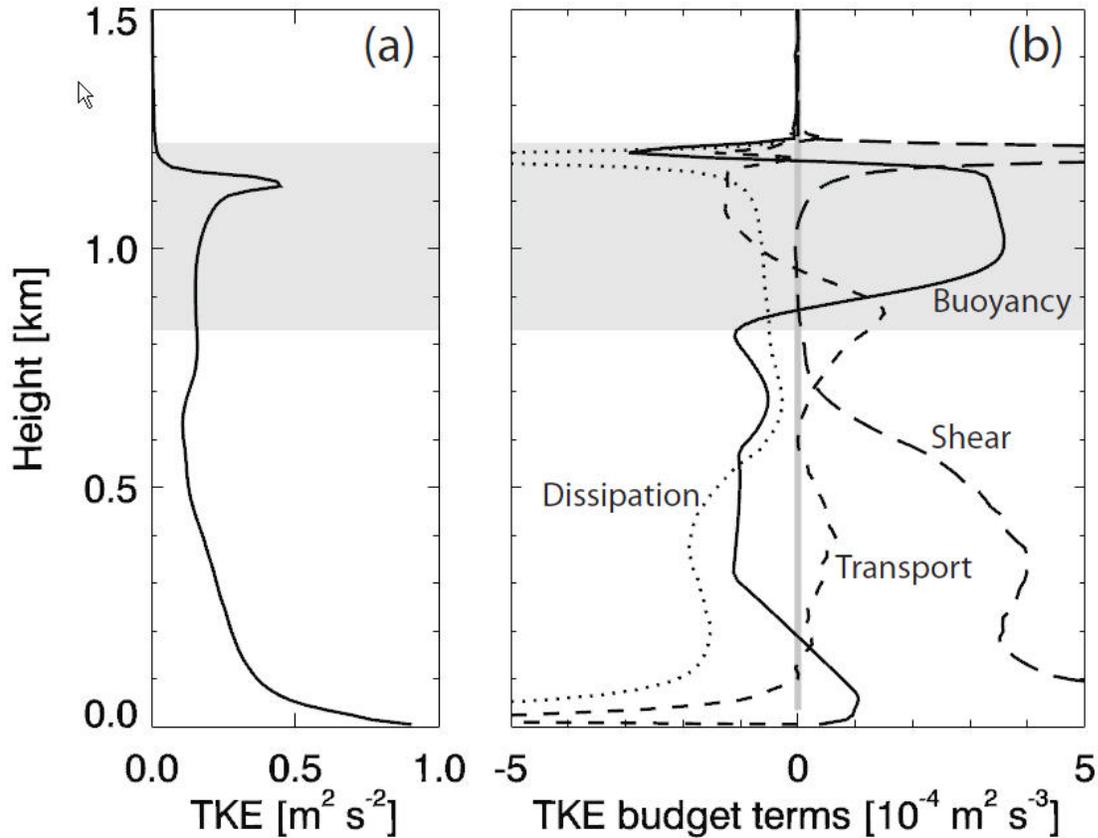


Figure 3. Mean profiles of (a) TKE and (b) TKE budget terms, calculated over the last simulation hour from 5–6 h. The region of light gray indicates the mean cloud layer.

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 three scientific meetings.

PUBLICATIONS

Kogan, Y. L., D. B. Mechem and K. Choi, 2010: Effects of Sea-Salt Aerosols on Precipitation in Simulations of Shallow Cumulus, *J. Atmos. Sci.* [submitted, referee].

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