Microphysical Structure of Simulated Marine Stratocumulus: Effects of Physical and Numerical Approximations

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Introduction

Over the past decade or so the evolution and equilibria of persistent decks of stratocumulus climatologically clinging to the edge of summertime subtropical highs have been an issue of increased scientific inquiry. The particular interest in the microphysical structure of these clouds stems from a variety of hypotheses which suggest that anthropogenic influences or biogenic feedbacks may alter the structure of these clouds in a climatically significant manner (e.g., Twomey 1977; Baker and Charlson 1990; Albrecht 1991; Ackerman et al. 1993; Pincus and Baker 1994).

Most of these hypotheses are quite tentative, based as they are on simple formulations of boundary layer structures and interactions between drops and aerosols. However, given the potential importance (from the perspective of the global energy balance) of the nature of the equilibrium of the cloud topped boundary layer, there is considerable interest in flushing out their validity; whether it be through ingenious observations or detailed numerical simulations of the range of interactions involved in a particular hypothesis.

Because the hypotheses discussed above are fundamentally coupled to the dynamics of the droplet spectra, their detailed simulation requires that both the droplet distribution function and its interaction with the aerosol distribution function be explicitly represented. Over the course of the past few years two groups (e.g., The University of Oklahoma group [Kogan et al. 1994] and the Colorado State University group [Feingold et al. 1994]) have begun to address this requirement by fully representing the turbulent evolution of the boundary layer via a large eddy simulation (LES) representation of the dynamics coupled to a detailed or explicit representation of the microphysics. Hereafter, the model which results from coupling an explicit microphysics (EM) component to the LES model will be referred to as an LES-EM model. The advantage of such an approach is that it provides a consistent representation of the evolution of the cloud dynamical and microphysical structure. Its major drawback is that in order to capture even the most rudimentary interactions between drops and ambient aerosol (e.g., cloud drop activation), several million degrees of freedom must be represented.

Given this background, the present work concerns itself with an assessment of the microphysical structure of marine stratocumulus as simulated by an LES-EM model. The purpose of this assessment is to address the following questions (which we believe to be relevant toward any attempt to evaluate, on the basis of numerical experiments, the hypotheses outlined above): 1) To what extent is the microphysical structure of the simulated stratocumulus similar to that observed? 2) To what extent is the simulated microphysical structure physically consistent? and 3) What is responsible for the structure of the simulated microphysical fields?

Method

In addressing the questions outlined in the introduction we make use of a family of models. Our approach is to use the LES-EM model to generate two sets of information. The first is the structure of an ensemble of trajectories which characterize the boundary layer circulations. The second is the microphysical structure of the cloud as predicted by the LES-EM model. The ensemble of trajectories is then used to drive a trajectory ensemble model (TEM) with different degrees of complexity in the representation of the microphysics. To the extent that the ensemble of trajectories dynamically characterize the simulated cloud, we can compare the microphysical structures predicted by the differing model environments and isolate the effects of a variety of model assumptions, or physical processes.

A detailed description of the models used is given by Stevens et al. (1996a), as well as an overview of the initial conditions, grid configurations, and boundary conditions. The present investigations are limited to the condensation nucleation process only, as this formulation uses the TEM to its best advantage.

Fields

In Figure 1 the layer-mean as well as the up/downdraft-mean simulated droplet concentrations are plotted. In contrast to the gradual and approximately linear increase in liquid water content (not shown), the number concentrations are quite blunt. Such a picture is consistent with activation of cloud drops at cloud base and no subsequent activation through the depth of the cloud. Increases in liquid water content are absorbed by a shifting of the mode diameter on a constant droplet population, as evidenced by the increase in average diameter (not shown) through the depth of the cloud. All of this is in qualitative agreement with the classical picture of stratocumulus microphysical structure developed on the basis of numerous observations (e.g., Slingo et al. 1982; Noonkester 1984; Nicholls 1984).

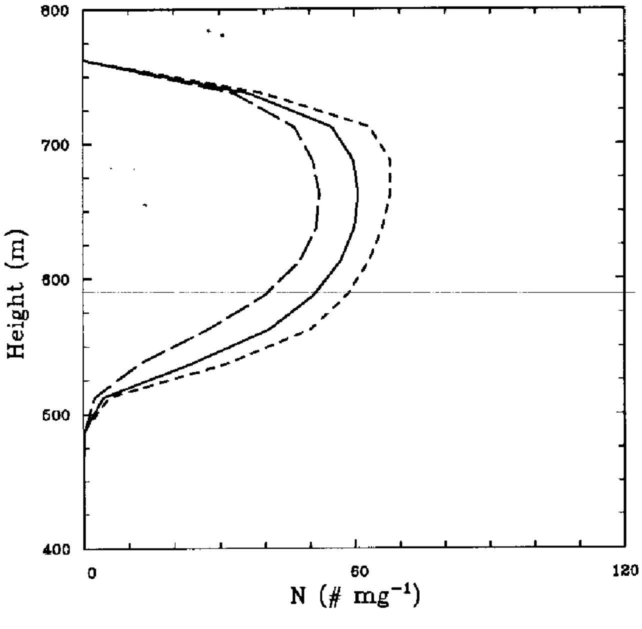

Figure 1. Ensemble average profile of number concentration field predicted by LES-EM model. Layer mean (solid line), updrafts (short-dash), downdrafts (long dash).

Although supersaturations in clouds are not directly measurable, several investigators have made indirect estimates of cloud base supersaturations. For instance, Hudson and Frisbie (1991) found that, for stratocumulus measured during the First International Satellite Cloud Climatology Project Regional Experiment, median effective supersaturations were between 0.24 and 0.42%, while Martin et al. (1994) show results which limit cloud base supersaturations in stratocumulus to under 0.8% with median values of order 0.4%. Such results are consistent with the predictions of the model (see updraft average in Figure 2). Moreover, if we estimate the supersaturations produced by the model using our knowledge of the specified cloud condensation nuclei (CCN) spectra and the mean value of the activated fraction of CCN, we obtain an effective cloud base supersaturation of 0.25-0.30%.

The mean supersaturation plotted in Figure 2 increases with height, but is negative through the depth of the cloud, indicating that the important structure of the supersaturation field is not revealed in the mean. More information may be extracted by conditionally sampling over up and downdrafts, which through the depth of the cloud are positively and negatively supersaturated,

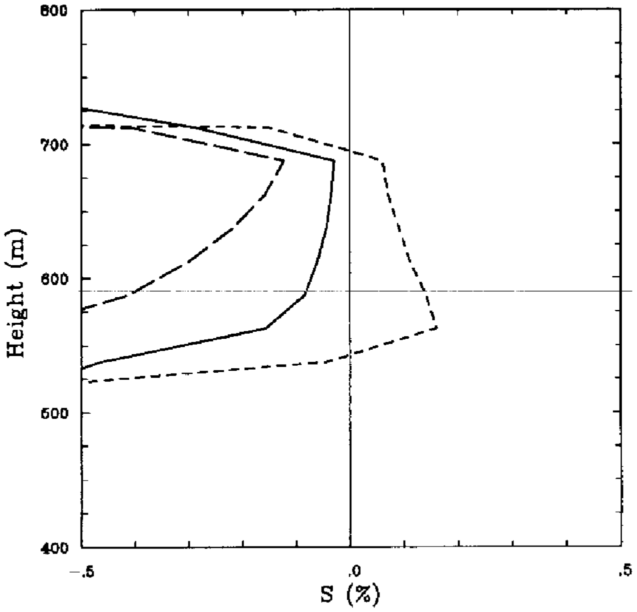

Figure 2. Same as Figure 1, but for supersaturation field.

respectively. Furthermore, the supersaturation in the updrafts is peaked near cloud base and falls off through the depth of the cloud as one expects based on classical theories.

Updrafts are considerably moister than downdrafts so that departures from adiabaticity in the mean are largely a function of the quantity of entrained air in the downdrafts. Furthermore, because we are considering layer averages, the presence of dry air in downdrafts at a given level also leads to observed decreases in the drop concentrations (see Figure 1) and the liquid water content (not shown).

Noonkester (1984) plotted profiles of dispersion (standard deviation normalized by the mean) from his observations of stratocumulus off the Californian coast. Using these as a basis for comparison we have constructed similar profiles for the number concentrations, liquid water, and mean diameter. Qualitatively we found that the model generated a similar structure in the dispersion profiles, with cloud top and cloud base maxima. Quantitatively the LES-EM simulations also agreed quite well, although the predicted incloud minimum in diameter dispersion was slightly less while the number dispersion was slightly higher than observed by Noonkester.

Sensitivity to Modelling Framework

Using the ensemble of trajectories produced by the LES to drive the TEM with different microphysical representations, we were able to examine the effects different model assumptions had on the simulated fields. We found that the effect of spatial averaging implicit in the Eulerian framework led to a slight underprediction of cloud base supersaturations. As a result, fewer drops were activated.

Two other factors led to a significant underprediction in both the number of activated drops and the cloud base supersaturation. The first was the neglect of gas kinetic effects in our condensational routines. This neglect allowed cloud base drops to grow more rapidly than they otherwise would have, thereby decreasing the phase relaxation time for the parcel and mitigating the production of cloud base supersaturations. Rooth (1957) explained this basic process; nevertheless, we were surprised at the magnitude of the differences (of order 20%). The second was the assumption that drops once activated immediately grew into the first bin. Similar to the neglect of gas kinetic effects, this assumption decreases the phase relaxation time too rapidly and underestimates the number of activated drops by 5-10%.

In addition, we found that the manner in which mixing is done in Eulerian models leads to two related, yet spurious results. First is the generation of cloud top peaks in the supersaturation and second is an underestimation in the number of drops in the downdrafts in the LES-EM data relative to the TEM data. These are not artifacts of the numerical operators (see Stevens et al. 1996b for more details), as they would occur even in the context of perfect advection. Instead they appear to be fundamentally related to the fact that the continuous evolution of a cloud boundary is being represented within a discretized spatial domain.

With respect to numerical dispersion, we found that the Eulerian representation of physical space in the LES-EM model tended to generate reduced values of droplet dispersion in the interior of the cloud. In contrast, the Eulerian representation of mass space generated values of diameter dispersion which were too large, especially in the downdrafts.

Nature of Contributing Trajectories

In order to understand how different trajectories contribute to the simulated cloud microstructure, we conducted 4 sensitivity tests. All simulations were conducted with the TEM coupled to the Lagrangian microphysical component with gas kinetic effects included. In the first sensitivity run (experiment S1) we turned off the mixing so the conserved variables were constant at their initial condition along the trajectories. The second sensitivity run (experiment S2) differed from the first in that the initial conditions of the ensemble of trajectories were set to the mean initial conditions. The third sensitivity run (experiment S3) differed from the second in that the vertical velocity was kept fixed along the trajectory. The fourth and last sensitivity run (experiment S4) differed from the third in that we only collected statistics along an updraft segment of one of the trajectories.

Table 1 shows how the dispersion in different fields responded to the experiments. Data were taken from a level in the interior of the cloud, near the minimum value of the dispersion. The baseline dispersion associated with the single parcel stems from the fact that data were

Table 1. Values of dispersion for liquid water, number concentration, and diameter from different simulations at 650m.

Experiment	σ_{q_L}/q_L	σ_N/N	σ_D/D
Control	0.252	0.138	0.129
S1	0.110	0.116	0.071
S2	0.017	0.116	0.059
S3	0.019	0.014	0.042
S4	0.014	0.000	0.040

collected over a finite height interval (7 m) so some of the dispersion is associated with variances amongst parcels over slightly different levels. Nevertheless, this table shows that the majority of the variance in the cloud liquid water and drop spectrum is due to mixing, where most of the mixing occurs at cloud top. The number concentration dispersion receives its largest contribution from the inhomogeneity in cloud base vertical velocities leading to the activation of different numbers of drops along different trajectories. This also appears to be important in the droplet dispersion.

Summary and Conclusions

We have demonstrated that an LES model with an explicit microphysics component is able to generate realistic representations of the microphysical structure of stratocumulus. Mean and variance quantities agree qualitatively and, in most cases, quantitatively with available observations.

Using a family of models we have explored the sensitivity of the simulated microphysical structure of stratocumulus to a variety of modelling assumptions. While the simulated fields qualitatively agree with observations, the neglect of gas kinetic effects and the impact of Eulerian representations in mass and physical space lead to significant underpredictions of cloud base supersaturations and the activation of too few drops.

Using a trajectory model driven by an ensemble of trajectories generated from the LES data, we have explored the causes for the dispersion in several simulated fields. In all cases, we found mixing along the trajectories (which is greatest at cloud top) to be the most significant source of dispersion.

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