Effect of Subgrid Cloud Variability on Parameterization of Indirect Aerosol Effect in Large-Scale Models

M. Ovtchinnikov and S. J. Ghan
Pacific Northwest National Laboratory
Richland, Washington

X. Dong
University of Utah
Salt Lake City, Utah

M. H. Zhang
State University of New York
Stony Brook, New York

Introduction

An adequate parameterization of cloud microphysics is essential for estimating the indirect aerosol effect in large-scale models. Such a parameterization must rely on a physically sound treatment of spatial variability that affects many microphysical processes in a complex and nonlinear way. For regional and global climate models, much of this variability falls into a subgrid scale and must be parameterized. Large-eddy simulation (LES) models, on the other hand, can resolve the cloud structure explicitly. By using identical microphysical parameterizations in an LES model and a single-column model (SCM) driven by identical boundary conditions, we can isolate the differences caused by the treatment of small-scale spatial variability. Following this approach, a single-layer warm cloud observed at the Southern Great Plains (SGP) site on September 25, 1997, during the SCM intensive operational period (IOP) is simulated using LES and SCM frameworks. The prescribed aerosol characteristics, horizontal advective tendencies, and surface boundary turbulent fluxes are the same for both models and were derived from objective analysis of available measurements. Nudging toward the analyzed temperature and humidity is applied in all simulations. The LES model is run with 100-m horizontal and 40-m resolution for a 10-km by 3.2-km domain. Cloud microphysical processes are either neglected, treated explicitly, or parameterized with a bulk scheme similar to that used in the SCM. The SCM is run with 48 levels, 20 of which are in the lowest 2 km. Cloud microphysical processes are either neglected or parameterized in terms of the bulk cloud water and droplet number concentration using the Khairoutdinov and Kogan (2000) scheme. Droplet number is either prescribed or predicted following Ghan et al. (1997). Subgrid variations in cloud water are either neglected or treated by expressing the subgrid probability distribution of total (water vapor plus cloud) water as triangular function, with the variance of total water related to the turbulence kinetic energy and the vertical gradient of the total water. The grid cell mean cloud fraction, cloud water, and autoconversion rate are determined by integrating over the subgrid frequency distribution of water. Subgrid vertical transport is parameterized using a level 1.5 turbulence closure scheme.

The triangular distribution can approximate subgrid frequency distributions with any mean, any variance, and with skewness between -0.56 and 0.56. To evaluate the triangular distribution, we use it to match the mean, variance, and skewness of total water mixing ratio from the three-dimensional (3D) LES simulation for 3Z September 25. As seen in Figure 1, the triangular distribution represents the simulated frequency distribution very well (note that the distribution simulated with the two-dimensional (2D) LES model is not nearly as smooth because of the limited degrees of freedom available to characterize the distribution). This suggests that if a cloud parameterization can correctly predict the mean, variance, and skewness of total water and if the skewness is within the limits of the triangular distribution then the triangular distribution provides a simple and accurate approximation to the subgrid frequency distribution of total water. The skewness for the cloud simulated for this case is always within the limits of the triangular distribution, but clouds driven by convective available potential energy are likely to be skewed outside those limits.

Figure 2 compares the vertical distribution of the horizontal mean cloud water simulated by the 2D LES model and SCM without cloud microphysical processes. The vertical distribution of cloud water simulated by the SCM and LES models are quite different, even for the same forcing. The SCM cloud forms at a much lower level than the LES cloud and is much thicker. The SCM boundary layer is well mixed, while the LES boundary layer is not. Differences in the vertical distribution of heat and moisture transport cause the difference in the cloud simulation.

How well does the SCM diagnose the variance of total water? Figure 3 compares the total water variance diagnosed by the SCM and predicted by the LES model. The SCM tends to concentrate total water variance within the cloud. The LES model produces weaker variance within the cloud and stronger variance below.

Is the different distribution of total water variance diagnosed by the SCM related to the simulation of turbulence? Figure 4 compares the variance of vertical velocity simulated by the SCM and LES models. The variance of vertical velocity simulated by the SCM is much higher than that simulated by the LES model, both within the cloud and below. This suggests the excessive variance of total water within the cloud simulated by the SCM is associated with excessive variance of vertical velocity. Below the cloud variance of total water is weak not for lack of turbulence, but because the boundary layer in the SCM simulation is well mixed. The excessive vertical velocity variance in the SCM simulation has implications for droplet nucleation.

How does the excessive updraft velocity affect the simulated droplet number? Figure 5 compares the droplet number concentration simulated by the SCM and LES models. Consistent with the stronger updrafts in the SCM simulation, droplet number concentrations are higher than in the LES simulation.

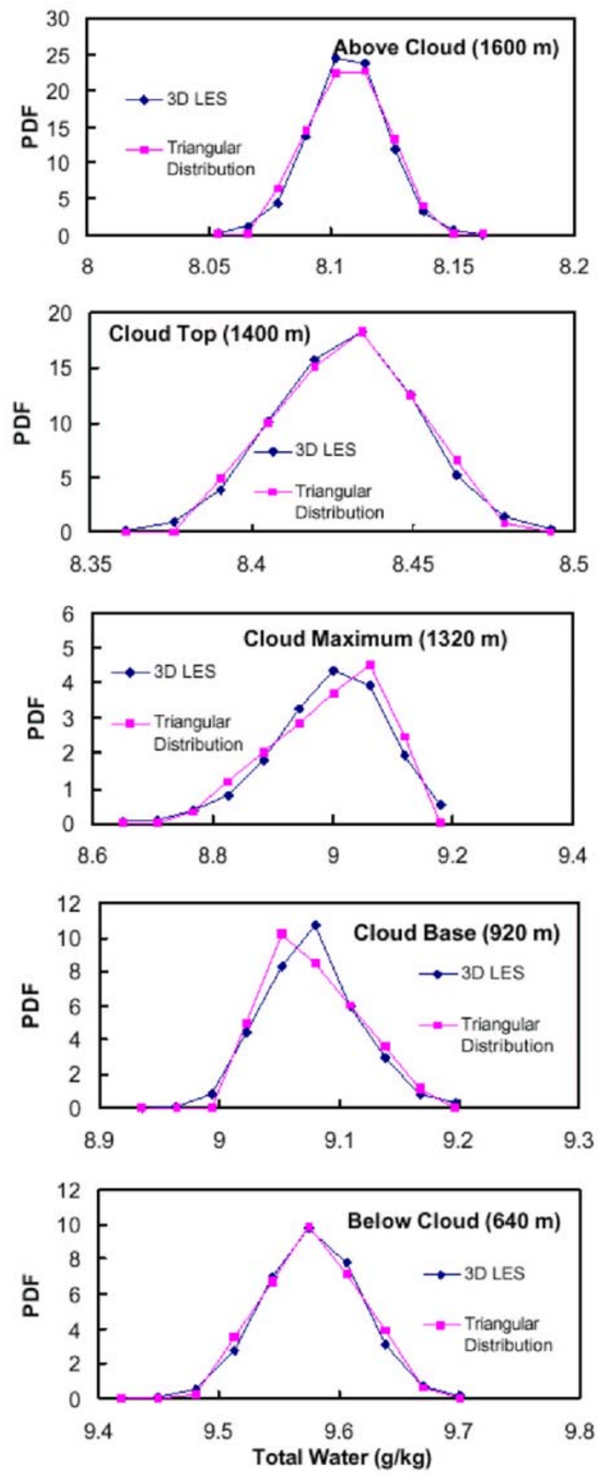

Figure 1. Subgrid frequency distribution of total water as simulated by the 3D LES model and as represented by a triangular distribution with the same mean, variance, and skewness, at levels below cloud, near cloud base, near the maximum cloud water, near cloud top, and above cloud, at 3Z September 25.

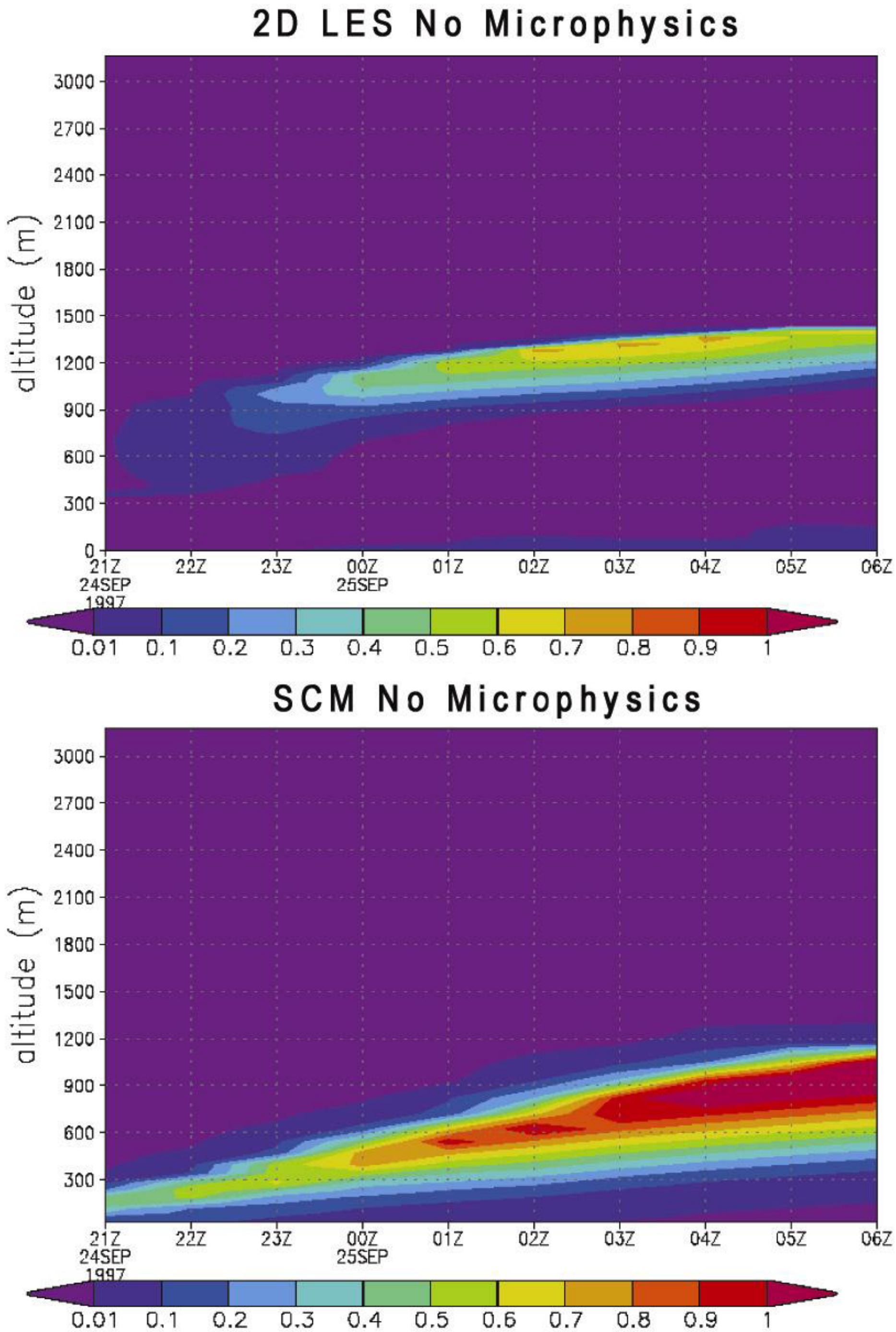

Figure 2. Vertical distribution of horizontal mean cloud liquid water mixing ratio simulated by the 2D LES model and the SCM, both without cloud microphysical processes.

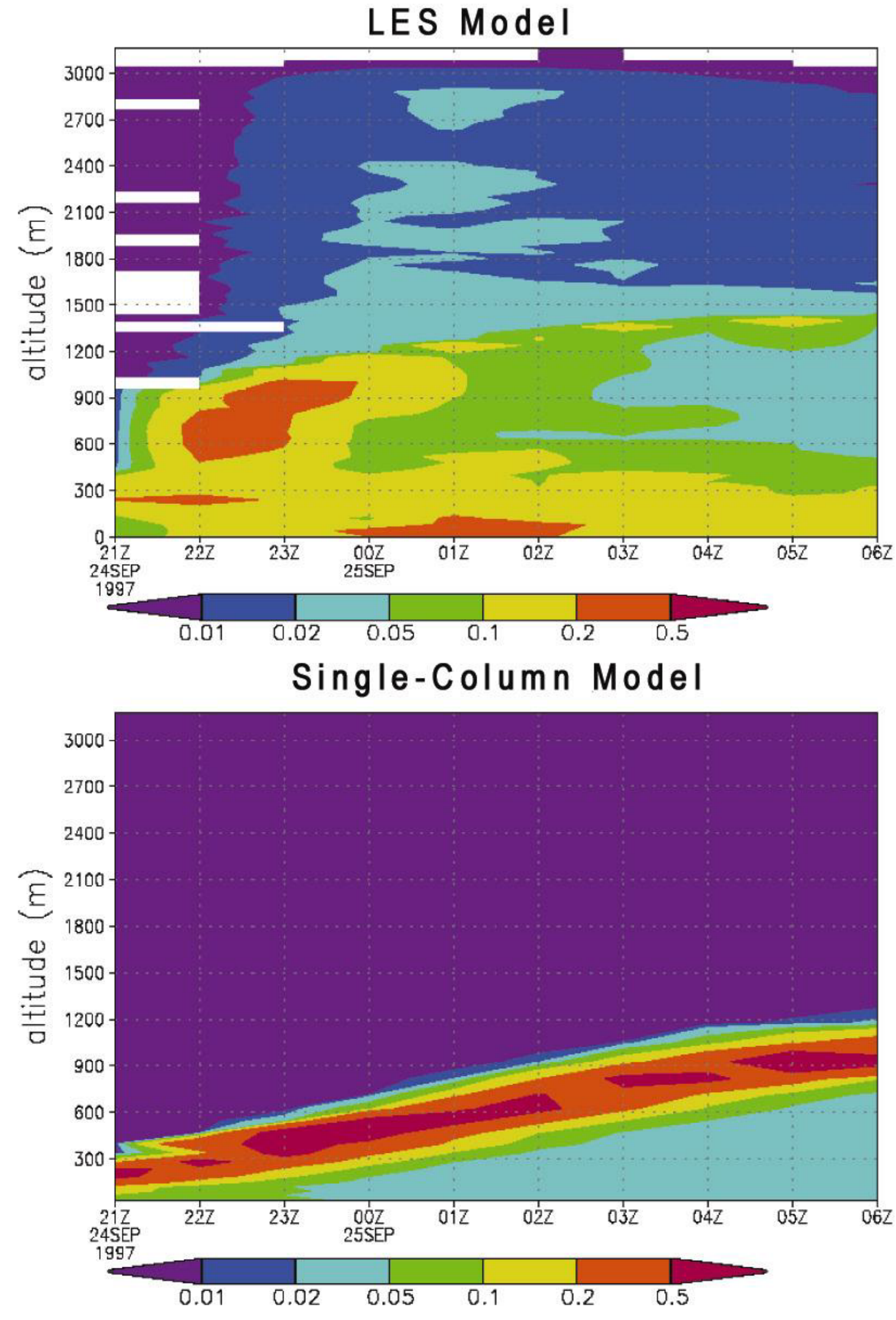

Figure 3. Vertical distribution of standard deviation of total water simulated by the 2D LES model and by the SCM.

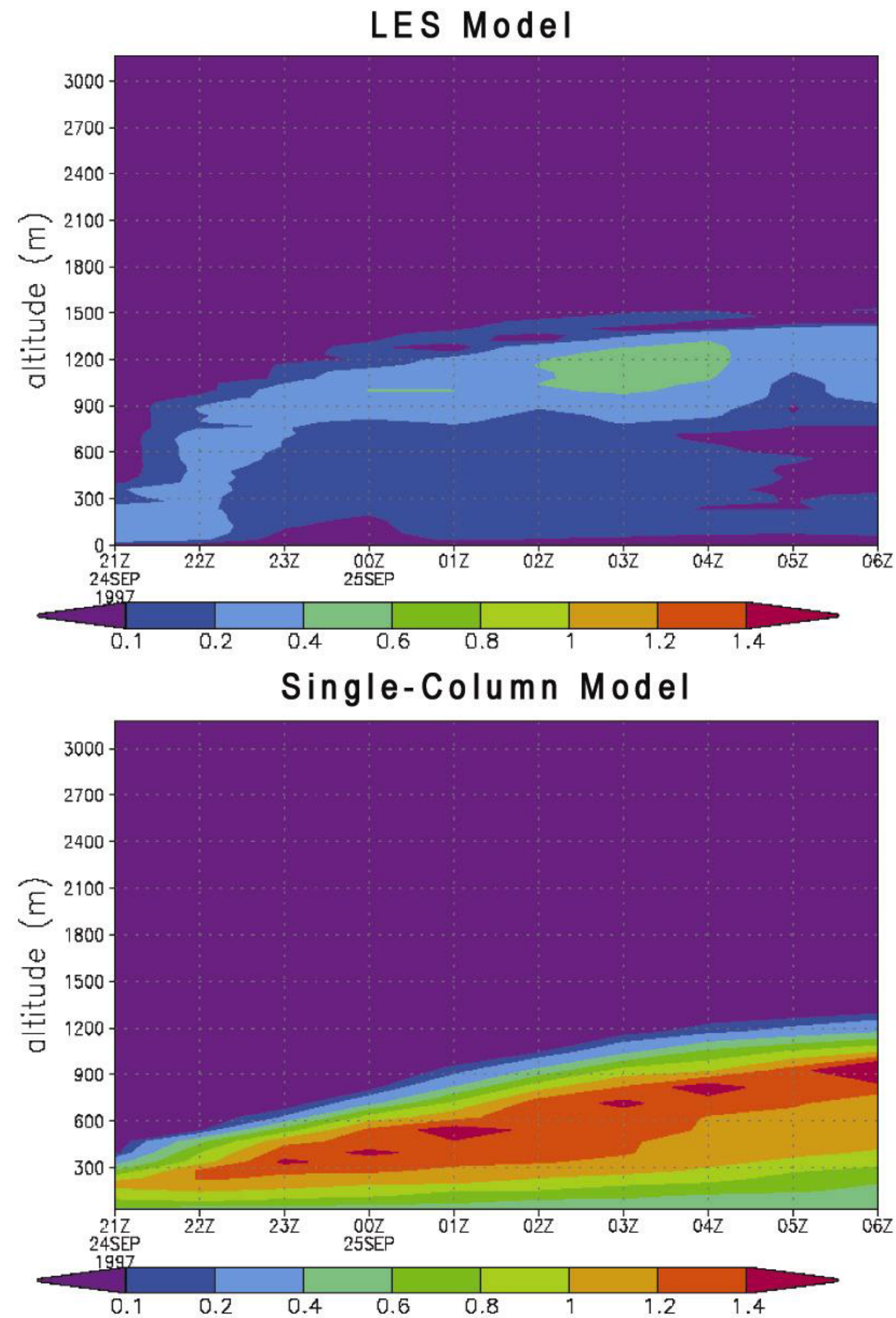

Figure 4. Vertical distribution of standard deviation of vertical velocity simulated by the 2D LES model and by the SCM.

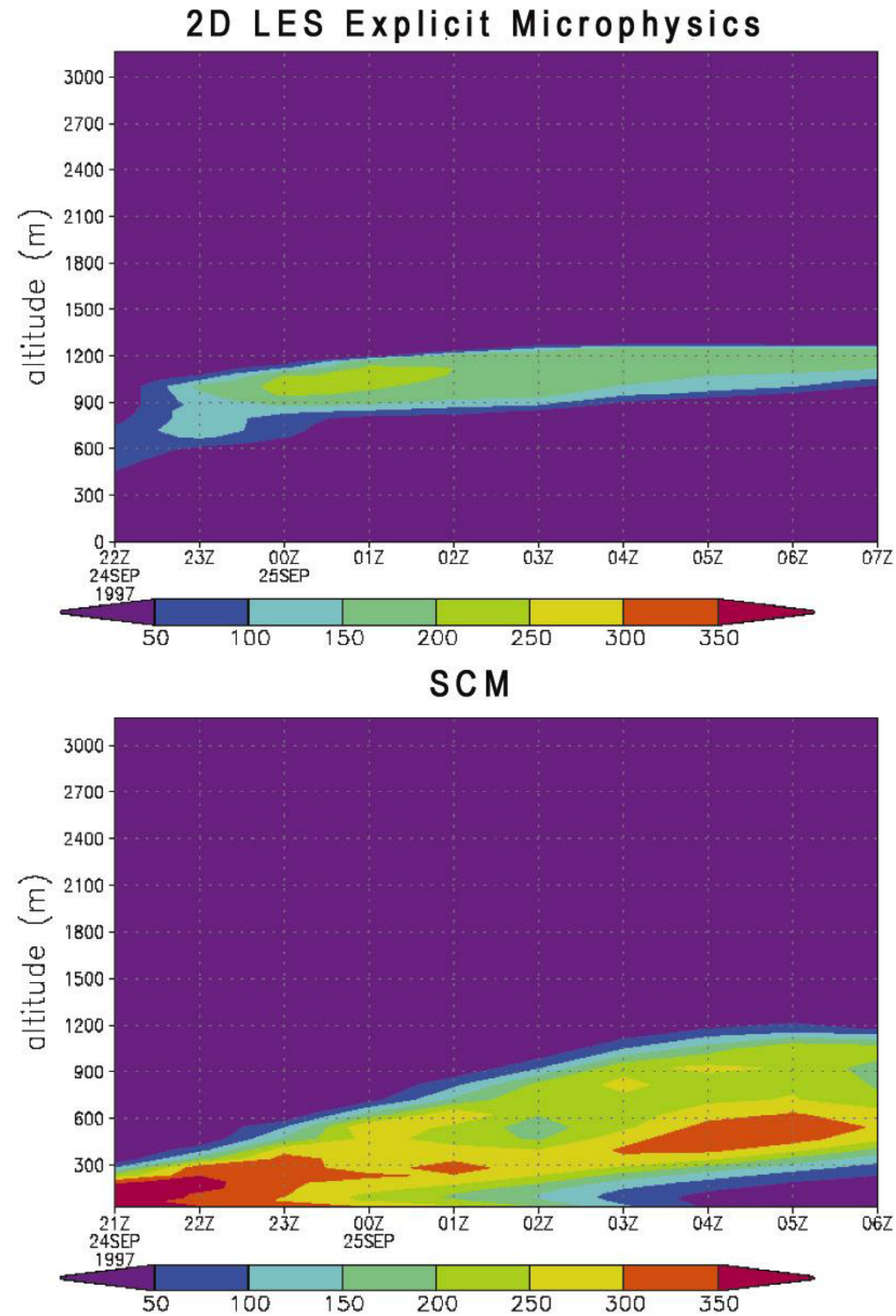

Figure 5. Vertical distribution of mean droplet number concentration simulated by the 2D LES model with explicit microphysics and by the SCM with bulk microphysics.

How sensitive is the cloud simulation to the treatment of cloud microphysics? Figure 6 compares the liquid water path (LWP) simulated by the LES model and SCM. The LES model consistently simulates much smaller and more realistic LWP than the SCM. The mean LWP simulated by the LES model is nearly the same in 2D and 3D. Microphysics depletes the cloud water by 30% in the mature cloud. Microphysics also depletes the cloud water in the SCM simulation, with little sensitivity to the subgrid treatment of microphysics when the Khairoutdinov and Kogan (2000) autoconversion parameterization is used. However, much greater sensitivity is found with the (discontinuous) Tripoli and Cotton (1980) autoconversion.

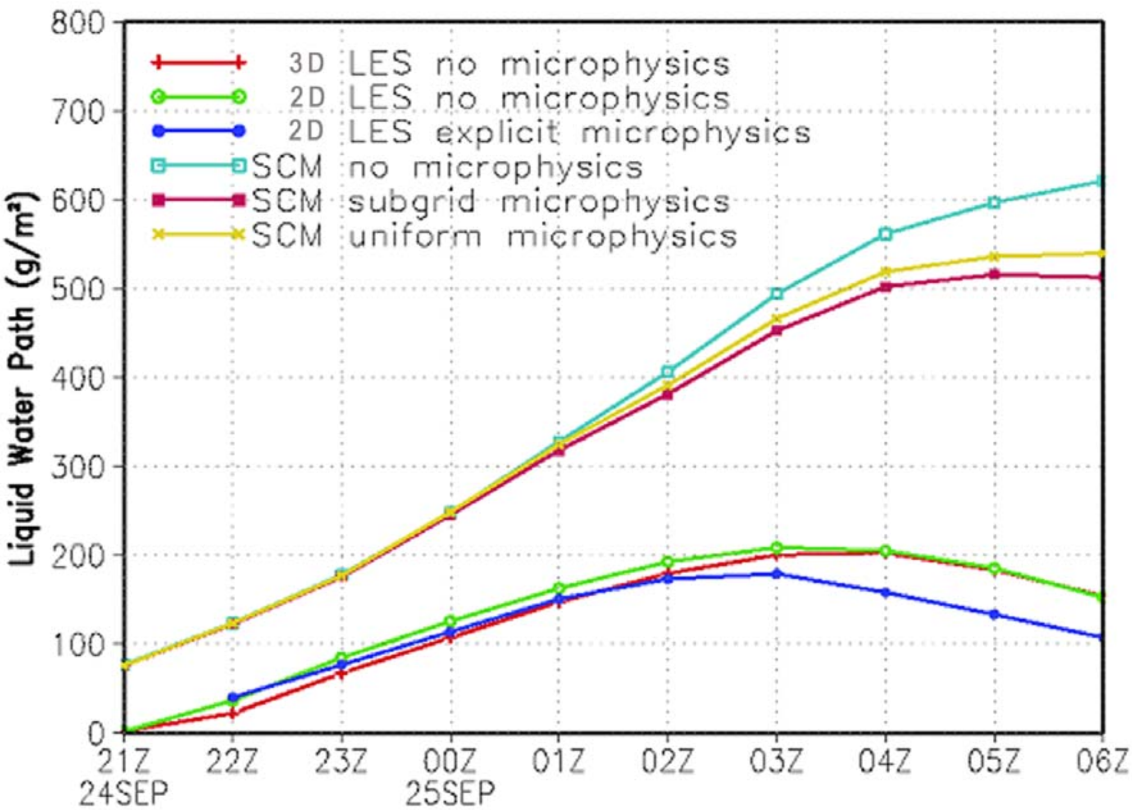

Figure 6. Time evolution of LWP simulated by the LES model and SCM. For the LES model, domain–averaged values are shown.

Most of the differences between the SCM and LES simulations are due to the stronger turbulence below cloud in the SCM simulation. The stronger turbulence produces a well-mixed boundary layer with a much lower cloud base and a much thicker cloud. It is not clear why the turbulence is stronger in the SCM simulation.

Corresponding Author

M. Ovtchinnikov, Mikhail.Ovtchinnikov@pnl.gov, (509) 372-6247

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