Multi-Scale WRF Simulations of Boundary Layer Clouds

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1. Introduction

Boundary layer clouds have a significant impact on the radiative budget of the Earth and are intimately involved in the vertical transport of enthalpy, moisture, and momentum in the lowest layers of the atmosphere and also on the transport and processing of aerosols. Representing these processes realistically in large-scale models continues to be a challenge. In the past, high resolution simulations such as Large Eddy Simulations (LESs) have been playing an integral role in the development of parameterizations of clouds and the associated turbulence processes in GCMs. Recently, high resolution simulations have taken on a whole new meaning and have gone beyond the role that they used to play. Randall et al. (2003)'s supper parameterization concept illustrated that high resolution simulations such as Cloud Resolving Model (CRM) can directly act as an active components within large-scale models. At the current stage, although the development of supper parameterizations with a kilometer resolution basically focus on the treatment of deep convection, this approach may eventually be extended to the boundary layer cloud regime when the computational power allows sufficiently high resolution to explicitly resolve boundary layer clouds.

Over the decades, large eddy simulation (LES) has been improved dramatically since the first attempt by Deardorff (1970). However, the basic framework of LES has never been changed. It focuses on large turbulent scale circulations while neglects the temporal and spatial variation in large-scale atmospheric motions and mesoscale organizations in which turbulent eddies are embedded. Under such a framework, LESs are initialized with idealized vertical profiles and forced with uniform surface conditions and large-scale forcings. This limits the application of LESs only to certain clean cases under horizontal homogeneous conditions. The past practices of LESs, such as BOMEX, ATEX, DYCOM, and ARM-SGP cases, are all belong to this category. While such a classic LES modeling strategy may still be used as an approach to address issues concerning the macroscopic, turbulence, and microphysical properties of boundary layer clouds, it may not be the most efficient framework since it can only be applied to clean cloud cases under constant large scale forcings. Thus, it may not shed a new light on the issues that are unable to be answered by the previous studies. In fact, most of the time, the evolution of clouds are intimately involved with the changes in large-scale atmospheric fields and mesoscale organizations. But all these larger scale changes are neglected in the classic LES framework. The goal of this study aims to develop a numerical approach that can be used to explore the change in large- and mesoscale atmospheric fields in controlling the macroscopic and microphysical properties of clouds and the interactions between them.

2. WRF-LES modeling system

In this study, we developed an innovative LES framework in a hindcasting mode using a multiple two-way nested WRF to explicitly simulate a spectrum of scales from synoptic scale flow, mesoscale organizations, down to fine scale turbulent eddies in a unified system as illustrated by Figure 1. This multiple two-way nested WRF features an LES, Domain 5 in this case, which has a resolution both in horizontal and vertical comparable to the typical resolution of LES.

The WRF-LES distinguishes itself from the classic LES in many ways. First, WRF-LES is nested

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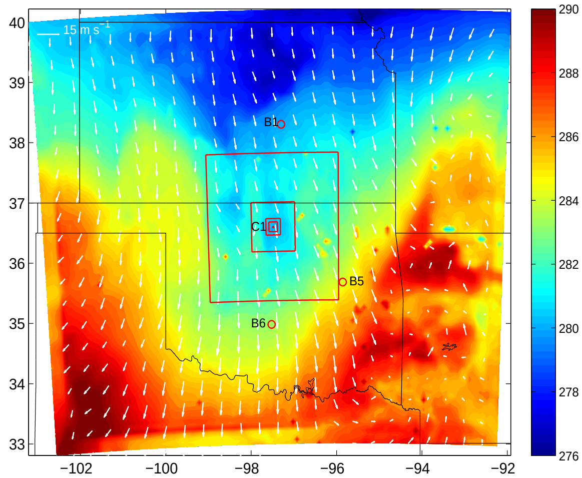

Figure 1: 2 m high potential temperature with 10 m high wind vectors at 11:30 UTC, March 25th 2005. Red boxes indicate the WRF nested domains. C1, B1, B5, and B6 are the four facilities at the ARM SGP site.

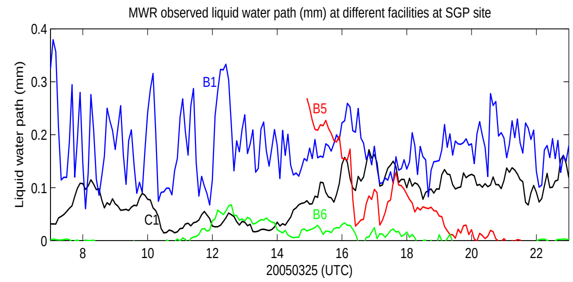

Figure 2: MWR observed liquid water path (mm) at different facilities at the SGP site.

within WRF mesoscale simulations to ensure robust up-scale and down-scale interactions across a spectrum of scales. This feature allows WRF-LES to be able to simulate boundary layer clouds in all weather conditions. Second, unlike the traditional LES, which is only a research tool to study specific cloud cases, WRF-LES can be developed into an operational mode. With sufficient computational power, WRF-LES can be executed at regular bases in parallel to observations such as the data routinely collected by the Atmospheric Radiation Measurement (ARM) program. This would permit a more efficient use of the ARM data and provide an extensive comparison between observations and simulation. Third, in the classic LES framework, each simulation requires lots of preparation to set up forcing and initial conditions; while in WRF-LES, these conditions are provided by WRF mesoscale simulations, which are initialized from the standard real-time forecast data or reanalyses data. This feature allows a direct comparison between WRF coarse grid simulation and the simulation by the DOE's Climate Change Prediction Program (CCPP)-ARM Parameterization Testbed (CAPT, Phillips et al. 2004) since they can be configured at the same resolution and initialized with the same real-time data or reanalyses data. The fine-scale WRF-LES simulations, then, can be used to diagnose the problems of a particular parameterization tested in CAPT in a manner similar to Siebesma and Cuijpers (1995) in a homogeneous framework. Finally, another attractive feature of WRF-LES modeling system is that the output from WRF coarse grid simulations can be used to generate forcing data for driving the existing LESs and CRMs in the community and for various analysis purposes.

3. WRF-LES feasibility demonstration

The WRF-LES has been successfully applied to a stratocumulus case observed at the ARM southern Great Plains (SGP) site during March 25th-26th 2005 to test the various features of WRF-LES stated previously. The distinction of this case is the strong synoptic influence indicated by the cold advection over the SGP site (Figure 1). The large-scale influence is also confirmed by the satellite observations (not shown here). A further complication of cloud fields due to mesoscale organizations is illustrated by Figure 2, which shows the liquid water path (LWP) observed by the Microwave Radiometers at the center facility and three boundary facilities around the SGP. Although this vertically integrated LWP does not represent the change in boundary layer clouds, the substantial variation in LWP reflects the complicated evolution of mesoscale organizations associated with weather system. Thus, this may not be the clean case that would be selected for the classic LES, SCM, and CRM studies since under homogeneous large-scale forcings LES, SCM, and CRM may have problems to capture the complicated evolution of boundary layer clouds. Testing the robustness of parameterizations under such conditions is important but

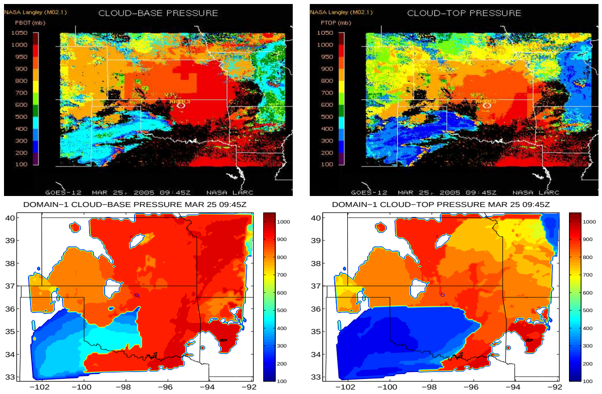

Figure 3: Comparison of low cloud boundaries between satellite observations and WRF simulations on Domain 1.

presents a great challenge for classic LESs, SCMs, and CRMs.

We configured a WRF-LES to explicitly simulate the atmospheric motion and clouds at all scales. The rectangle boxes in Figure 1 illustrate four two-way tested WRF domains including an LES, Domain-5, which has a horizontal resolution of 100 m and a vertical resolution varying from 6 to 60 m below 2 km. Two runs were executed. In the first simulation, WRF was initialized solely using the NCEP Global Tropospheric Analyses with a resolution of one degree. In the second simulation, in addition to the NCEP re-analyses, we further assimilated ARM soundings into the model during the initialization. We conducted a 24-hour simulation starting from 0 UTC on March 25th.

Figure 3 compares WRF simulations with ARM observations at two scales. The WRF coarse grid simulations reasonably capture the satellite observed large-scale horizontal cloud distributions and vertical cloud boundaries.

At the LES scale (Figure 4), the observed cloud base height, the cloud base lifting after 14 UTC, the cloud break around 12 UTC, and the LWP are all captured by WRF-LES although with biases. Note that the ASCAL and MWR observations represent a single point in the vertical, while the simulated clouds are the averaged ones over the entire domain-5, which covers an area of 1.8 by 1.8 km. A noticeable improvement due to the assimilation of the ARM sounding is shown in the early morning. In these simulations, we did not nudge the ARM observations during the model integration.

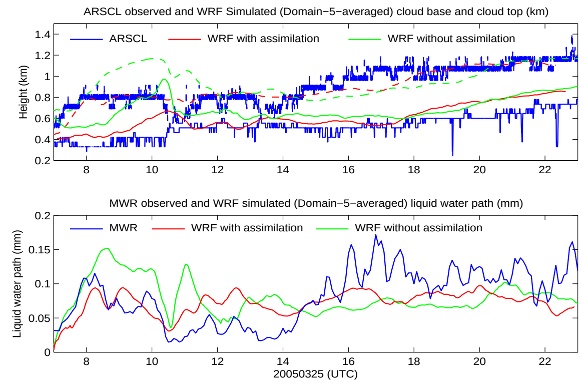

Figure 4: Comparison of low cloud boundaries and liquid water path between the ARM SGP observations and WRF simulations on Domain 5.

4. Conclusion

The comparisons between the observations and simulations indicate that WRF-LES can serve as a suitable modeling platform for investigating boundary layer cloud processes under various weather conditions.