Final Technical Report of ASR project entitled "ARM Observations for the Development and Evaluation of Models and Parameterizations of Cloudy Boundary Layers" (DE-SC0000825)

1. *Developing novel numerical approach of using multiple scale WRF simulations for boundary layer cloud research.* This development is based on the consideration that the current large eddy simulation (LES) studies on cloudy boundary layer have been limited to horizontal homogeneous conditions where periodic boundary conditions are applied to lateral directions. Periodic boundary conditions are clearly inappropriate for conditions that are inhomogeneous in horizontal directions where turbulent fluctuations at the inflow boundary may be substantially different from those at the outflow boundary. This is particularly true for boundary layer clouds at the ARM SGP site that has a complex terrain and land-uses. We used a different approach to simulate boundary layer clouds in a hindcasting mode. It utilizes the two-way nesting technique of Weather Research & Forecasting (WRF) model to gradually downscale the atmospheric flow from synoptic scale to large turbulent eddy scale. It features a nested LES that can be configured at any location to simulate boundary layer clouds in all weather conditions. The hindcasting WRF-LES overcomes the deficiencies of idealized LES and can properly simulate the boundary layer clouds in heterogeneous conditions, particularly for boundary layer clouds that are directly linked to synoptic systems and modulated by mesoscale organizations. Using WRF-LES, we simulated various boundary layer cloud cases, such as continental stratocumulus, particularly the post front stratocumulus at the SGP site, and maritime shallow cumulus observed at the TWP site and Azores. The first focus is on examining the performance of WRF-LES and its capability to reproduce the observed cloud properties and cloud dynamics retrieved from ARM observations. The analyses from several case studies show that the multiple scale WRF simulations not only capture the large-scale low cloud geographic distributions derived from the satellite observations but also well reproduce the cloud radar detected cloud properties and vertical velocity fields at the fine scale. The work has been published in *J. Geophys. Res.*

2) *Addressing issues of PDF schemes for parameterizing sub-grid scale cloud radiative properties.* One of the great challenges in climate simulations is to provide a physically robust representation of sub-grid cloud radiative properties in GCMs. One approach that presumably can provide self-consistent cloud radiative properties, such as cloud fraction and hydrometeor content, is the probability density function (PDF) cloud scheme pioneered by Sommeria and Deardorff (1977) and Mellor (1977). Since then, numerous PDF schemes have been proposed. However, it is not clear if a skewed PDF can be universally applied to the cloudy atmosphere. We investigated this issue using LESs of many well documented cloudy cases in different climate regimes. It is found that dynamic and thermodynamic variables skew differently in the cloud layer of shallow cumulus, stratocumulus, and deep convective clouds. Vertical velocity is positively skewed, but the skewed dynamic structure cannot account for the large skewness of positively skewed total water mixing ratio and negatively skewed liquid water potential temperature. It is, thus, not physically sound to assume that the sub-grid variation of different variables follows the same skewed PDF. The simulations further show that the weighted standard deviations of total water mixing ratio and liquid water potential temperature have the same order of magnitude in all types of clouds. This indicates that the variations of temperature and moisture are the equally important factors for sub-grid clouds. Thus, neglecting either one of them in a statistical cloud scheme may introduce significant bias in the parameterized clouds.

The result from this study has been published in *Geophy. Res. Letters.*

3) Investigating the impact of mesoscale cloud organizations on the evolution of boundary layer clouds. Cloud mesoscale organizations are often observed during the evolution of boundary layer clouds. One of the advantages of the WRF-LES developed in this project is its ability to simulate mesoscale cloud structures. We examined the impact of mesoscale organizations on the development of continental stratocumulus at the SGP site and maritime boundary layer clouds at the Azores site. It is found that the cloud fields exhibit cloud band structures aligned nearly parallel to the mean wind directions. The cloud bands with large liquid water path are associated with the upward motions with downdrafts distributed in between, suggesting that they are linked to the meso-gamma roll-like circulations driven and maintained by cloud-top longwave radiation cooling and evaporative enhancement. Since the meso-gamma circulations generally have a scale equivalent to or larger than the typical domain of LESs, without considering mesoscale organizations, the turbulent and cloud statistics from LES under horizontal homogeneous assumptions may be biased. But currently the impact of mesoscale organizations on cloud turbulent statistics has not been thoroughly evaluated and considered in the cloud parameterization development. Although the mesoscale cloud organizations can be well reproduced by WRF-LES, how to quantify (or separate) the effects of mesoscale organizations from a spectrum of scales simulated by WRF-LES is a challenging task. We have developed a 2D wavelet transform (WT) package for analysis. The WT, which decomposes a 2D signal onto scaled and translated versions of a 'mother wavelet' to match the variations of different scales, provides an improved fitting to nonlinear, irregular data. Using 2D WT, we decomposed the simulated dynamic and thermodynamic fields by WRF-LES. It is found that mesoscale cloud organizations contribute a significant proportion to the turbulent kinetic energy (TKE), but they only have a limited contribution to momentum and heat transport, which appears to be dominated by large turbulent eddies. Moreover, beyond a critical scale TKE has weak a correlation to fluxes. This result has important implications and leads us to rethink the classic treatment of turbulence in the cloud topped boundary layer using TKE closure scheme. A paper based on this work has been submitted to *J. Geophys. Res.*

4. Evaluating parameterizations of the cumulus induced vertical transport. How to appropriately evaluate the parameterization of vertical fluxes induced by shallow cumuli is a difficult scientific question since the transport associated with clouds and some important turbulent statistical parameters needed to close a scheme, such as cloud base mass flux, are not observable. WRF-LES provides an excellent framework for evaluating parameterization schemes in a weather hindcasting mode. Combining ARM observations with the model output from WRF-LES, we evaluated the NCAR CAM5 shallow convection scheme. We have coded the shallow convection scheme into an independent executable unit ready to be executed once the input information is provided. All required input information for the scheme is provided by WRF-LES. The parameterized fluxes are then evaluated against the model resolved fluxes. This is a true diagnostic analysis in a weather hindcasting mode and can be easily applied to any shallow cumulus case observed at the ARM sites. The evaluation based on the cumulus case observed on July 21, 2009 at the Azores site show that the NCAR CAM5 shallow convection scheme can qualitatively generate the vertical structure of various flux profiles explicitly resolved by the WRF-LES. However, the simulated dependence of vertical fluxes on cloud microphysics and precipitation is not reflected in the parameterized fluxes by the scheme. A paper based on this research has been drafted and will be submitted to a scientific journal.

5. Limited area model (LAM) intercomparison study of TWP-ICE convective case. To facilitate our understanding of the structure and evolution of tropical deep convection, the ARM/GCSS/SPARC programs organized a joint model intercomparison study based on the Tropical Warm Pool - International Cloud Experiment (TWP-ICE). It consists of four components: intercomparisons of global numerical weather prediction (NWP) models, cloud resolving models (CRMs), single column models (SCMs), and limited area models (LAMs). The PI led the LAM intercomparison study. The results show that LAMs are able to produce the large-scale thermodynamic field reasonably well compared with the variational analyses based on the Atmospheric Radiation Measurement (ARM) observations. However, large inter-LAM spreads are shown in dynamic fields as indicated by large-scale horizontal divergence, vertical velocity, and the cyclone associated with the monsoonal trough. LAMs also produced a large range of cloud fraction and hydrometeor mixing ratios. The inter-LAM difference in solid phase hydrometeors, such as cloud ice, snow, and graupel, can be larger than a factor of 10. Among all the hydrometeor types, the stratiform ice clouds are simulated least consistently by the LAMs. Sensitivity tests show that the simulated hydrometeor mixing ratios are very sensitive to cloud microphysics, whereas cloud fraction appears to be more dependent on other aspects of the model, such as the vertical resolution and surface forcing. This study demonstrates that LAM approach possesses a unique capability in simulating tropical deep convection and has a potential to bridge the gap between CRMs and numerical weather prediction (NWP) models, but obtaining consistent and reliable dynamic and cloud fields remains a challenge. Several papers based on the TWP-ICE intercomparison have been published.

6. Investigating convective invigoration processes at shallow cumulus cold poll boundaries. Observations of precipitating shallow cumuli show convective invigoration on the down-wind side of their cold pools. We studied shallow convection and the induced cold pools using WRF-LES. It is found that the decrease of temperature and water vapor mixing ratio in the simulated cold pools falls within the envelope of observed cases, and the wind enhancement matches observation more closely. Cold-pool-influenced updrafts tend to exceed the other updrafts in vertical velocity, and are associated with more cloud liquid water. Cases with higher rainrates correspond to larger cloud cover through the shearing off of the upper-level cloud, consistent with observations. This study elucidates the convective triggers and cold pool recovery process. Two research papers on this work have been published in *J. Atmos. Sci.*

7. Investigating vertical transport processes in moist convection. The mass-flux approach provides a concise description of moist convection and a practical way to parameterize the convection induced vertical transport in large-scales models. However, to what extent that the convective fluxes estimated by the mass-flux approach can present the total vertical transport in the cloud layer and whether the same approach can be extended to represent the vertical momentum transport have yet to be verified. These two questions are investigated in this study using large eddy simulations (LESs) based on six well documented cloud cases including both deep and shallow moist convection. Two methods are used to decompose the LES resolved vertical fluxes: the decomposition based on the coherent convective features and the decomposition by 2 dimensional fast Fourier transform (2D-FFT). The analyses show that the convective fluxes computed using the mass-flux formula can account for most of the heat and moisture fluxes in the cloud layer of both deep and shallow moist convection when the convective updraft fraction is smaller than 5% for the cases investigated in this study. For large convective updraft fractions, the mass-flux approach substantially underestimates the vertical heat and moisture fluxes. It is also found that the mass-flux approach fails to represent the momentum transport in the cloud layer for both deep and shallow moist convection. The 2D-FFT and other analyses revealed the possible reasons responsible for the different behaviors between heat/moisture transport and momentum transport and the failure of mass-flux approach to represent the vertical momentum transport associated with moist convection. A paper based on this research has been published in *J. Atmos. Sci.*

Publications

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