DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

Improving Mesoscale Prediction of Cloud Regime Transitions in LES and NRL COAMPS

David B. Mechem
Atmospheric Science Program, Department of Geography, University of Kansas
1475 Jayhawk Blvd., 213 Lindley
Lawrence, KS 66045
phone: (785) 864-5707 fax: (785) 864-5378 email: dmechem@ku.edu

Award Number: N000141110518
http://www.geog.ku.edu/

LONG-TERM GOALS

Accurate predictions of cloud and precipitation processes in the marine boundary layer are critical to U.S. Navy operations, as well as being more broadly important to improving seasonable predictability and the performance of NWP models. The major goal of the project is to develop and test state-of-the-art boundary layer and microphysical parameterizations in order to better represent the continuum of cloud regimes from stratocumulus to trade cumulus, with particular emphasis on cloud regime transitions.

OBJECTIVES

Accurate prediction of cloud-topped marine boundary layers in regional forecast models is currently hindered by the inability of the models to represent shallow cumulus boundary layers and transitions between different cloud regimes.

In order to improve the ability of mesoscale models to correctly represent the continuum of cloudy boundary layers across the oceanic basins, our project has the following objectives:

1. Implement a new warm-rain microphysical parameterization developed for shallow convection and cloud regime transition zones (Kogan 2013) into COAMPS.
2. Re-implement the Khairoutdinov and Kogan (2000) bulk microphysical parameterization. Much of the code for this parameterization remained in COAMPS from an earlier implementation, but it appeared not to be completely supported.
3. Test the performance of the warm-rain microphysical parameterizations by performing multiday simulations and compare the results to observational data from the VOCALS–REx field campaign over the southeast Pacific. Our analysis focuses on a short, 4-day period (which we summarize in this report) and simulations running the full length of the field project:
    a. A 4-day (12–16 Nov 2008) simulation over a period of VOCALS.
    b. A 2-month (October–November, 2008) simulation over the full VOCALS field campaign.

4. Coordinate a model intercomparison for large-eddy simulation (LES) and single-column models (SCMs) based on field data collected during the DRI-funded observational campaign.

APPROACH

Despite the recent improvement in how mesoscale models represent solid stratocumulus, the same models continue to struggle representing cloud regime transitions that exist between stratocumulus and the broken trade cumulus regime. These cloud regimes are typically characterized by one of the following: cumulus rising into stratocumulus, strong precipitation, a decoupled/stratified boundary layer, or broken cloud areas. Shallow cumulus dynamics can become an important component of the cloud systems, even for high cloud fraction cases. The overarching goal of the project is to improve the parameterization of cloud regime transitions in NRL COAMPS in order to better represent the trade cumulus regime and regions where cloud regime transitions are associated with shallow convection. This goal will be accomplished via the following specific research objectives:

1. *Implementation of a new warm-rain microphysical parameterization developed for shallow cumulus*

We are working with Yefim Kogan (also funded under this DRI) to implement the new warm-rain microphysics parameterization he developed (Kogan 2013, referred to here as K2013) into COAMPS. This parameterization is similar in approach to a previous parameterization developed with ONR support (Khairoutdinov and Kogan 2000, which is referred to here as KK2000). The K2013 parameterization is based on nonlinear regression of large-eddy simulation (LES) output with size-resolving (bin) microphysics. It has been extensively evaluated in an LES framework and appears to have more general applicability than the original KK2000 parameterization. Under previous ONR funding, the PI implemented and tested the KK2000 parameterization in COAMPS, and because of the similarity between KK2000 and the new microphysical parameterization (K2013), implementation into COAMPS is straightforward.

In addition to implementing and testing K2013, we are also evaluating a K2013 variant that does not employ the self-collection term in order to determine the importance of the precipitation self-collection process on simulation results. We hypothesize that self-collection may not be important in shallow, stratocumulus-topped boundary layers and that the mechanism may have more of an effect in deeper clouds, where drops reach bigger sizes and rain rates are higher.

In order to spur collaboration across the DRI, the PI is coordinating an intercomparison involving SCM and LES models based on the RF01 flight from the observational component of the DRI (UPPEF; Unified Physical Parameters for Extended Forecast). During the afternoon RF01 flight, the CIRPAS Twin Otter sampled a rapidly dissipating cloud system associated with a strong west-to-east SST gradient. We seek to scrutinize LES/SCM performance on representing cloud properties and the timescale of cloud dissipation.

2. *Comprehensive evaluation of improved microphysical parameterizations during VOCALS–REx*

The implementation of the new microphysical parameterization into COAMPS is first evaluated with a suite of simulations (Table 1) based on a 4-day period during VOCALS–REx. The PI is active in the VOCALS community, which is appropriate since VOCALS contains some of the best (and most challenging to simulate) examples of cloud regime transitions. We compare simulation results with observations collected during VOCALS–REx, specifically liquid water path (LWP), boundary layer depth, stability, and surface fluxes. The greatest novelty in or validation effort is our comparison of simulated precipitation behavior with precipitation rate estimated from C–band radar aboard the NOAA R/V Ronald H. Brown (RHB).

Table 1: A table detailing the current list of completed COAMPS simulations for different values of initial CCN concentration (cm^{-3}). [graph: We have completed the operational Kessler simulation and thirteen of fifteen simulations assessing the sensitivity of the different microphysical parameterizations (KK2000, K2013, and K2013 without self-collection) for five different CCN concentrations.]

CCN Conc.	Kessler	KK2000	K2013	K2013 – No S.C.
CCN = 90	Completed	Completed	Completed	Completed
CCN = 177 (control)	Completed	Completed	Completed	Completed
CCN = 290	Completed	Completed	Completed	Completed
CCN = 340	Completed	Completed	In Progress	Completed
CCN = 700	Completed	Completed	Completed	In Progress

(Please note that some of the content in this "Approach" section stems from our original proposal.)

WORK COMPLETED

The following tasks are completed or near completion with regard to implementation and testing of K2013 in a mesoscale model:

1. We have implemented K2013 into COAMPS and 'reactivated' the previous implementation of KK2000.
2. Develop multi-day mesoscale model simulations from VOCALS to serve as a benchmark for evaluating microphysical and shallow cumulus parameterizations. See Table 1 for list of completed runs.

3. Processing VOCALS observational data from the RHB to serve as a testbed for evaluating improvements to COAMPS (and WRF).
4. Process model output for numerical and statistical comparison with observations in the form of time series, PDFs, and error analysis.
5. Formulated initial conditions and forcing for the LES/SCM intercomparison based on the 31 August 2011 UPPEF DR01 flight. This effort includes researchers from NPS and JPL.

RESULTS

We have constructed a benchmark COAMPS simulation based on the 12-16 November 2008 period during the VOCALS–REx field campaign, as well as additional simulations using KK2000 and K2013, and one variant of K2013 that does not include self-collection. We choose this period because of the availability of extensive data from the NOAA RHB (de Szoeke et al. 2010) and its location in a region of cloudiness transitions. The model employs a nested configuration with horizontal grid spacings of 27, 9, and 3 km. The location of the inner meshes corresponds to the location of the NOAA RHB during the simulation period (approximately 20°S and 75°W). We use a vertical grid configuration with 45 points and the configuration of Wang et al. (2011), which includes additional grid points compared to the operational grid in order to better resolve the boundary layer.

Our baseline simulation employs the operational microphysics, which includes the Kessler warm-rain parameterization. NOGAPS (Navy Operational Global Atmospheric Prediction System) provides initial and boundary conditions for the COAMPS simulation. Simulations run for a total of 123 hours in order to evaluate intrinsic behavior between model microphysics, radiation, and boundary-layer dynamics constrained only by SST and boundary conditions on the outer mesh. We do not perform data assimilation beyond early stages of the simulation, and the first 26 hours of the simulation are treated as spinup and discarded from analysis.

Liquid water path (LWP) forecasts over the outer (27 km) mesh at 72 hours (Fig. 1) show substantial differences between the operational (Kessler) parameterization and the KK2000 and K2013 parameterizations. All three produce similar patterns in cloud cover, in particular the southern extent near 30°S and the strip of lower LWP near the shoreline. The simulations differ most in LWP magnitude, with the KK2000 and K2013 LWP values being nearly double those from the Kessler parameterization in some places.

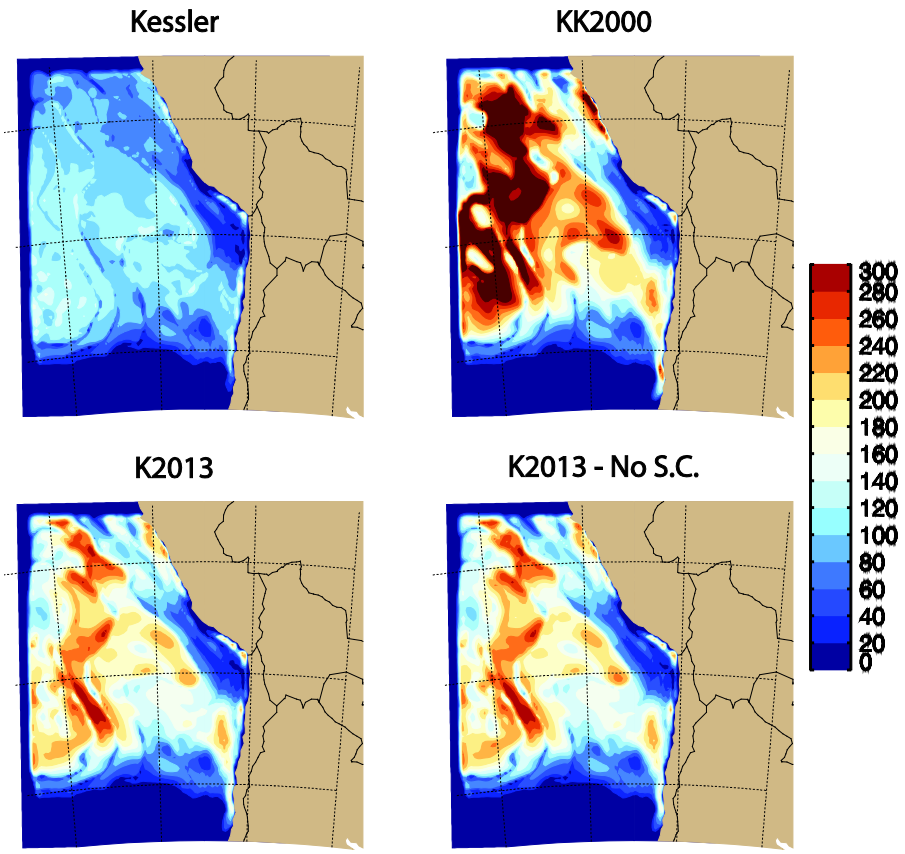

Figure 1: Liquid water path [g m^{-2}] maps from the coarse domain for each parameterization for the control CCN concentration (177 cm^{-3}). [graph: All four simulations produce a large sheet of stratocumulus and the cloud minimum right off the coast of Chile and Peru. LWP values are smallest for the operational Kessler simulation and largest for the KK2000 simulation. Little difference in LWP is apparent between the K2013 simulation and the K2013 simulation without self-collection.]

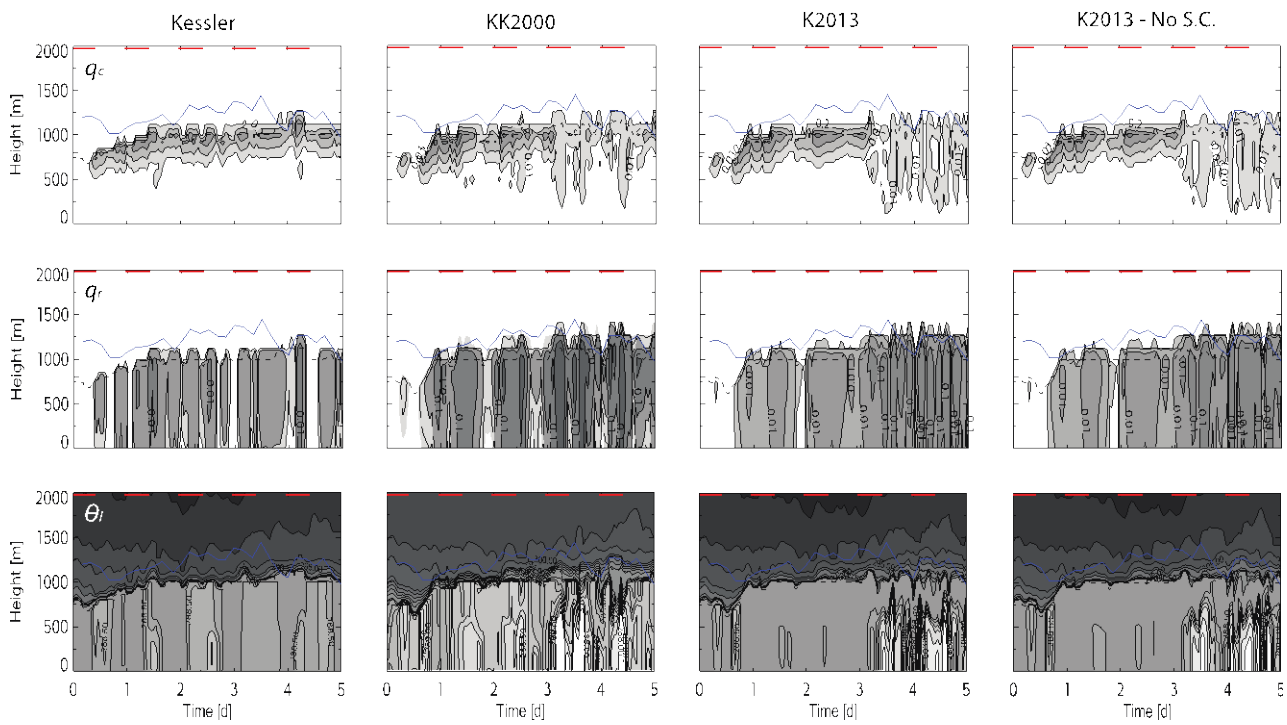

Figure 2: Time-height cross sections for the 3-km nest for each parameterization (CCN = 177 cm^{-3}). Red lines denote nighttime. Although five days are plotted, we consider the first day to be a spin-up period. [graph: All four parameterizations exhibit a cloud deck slowly increasing in height over the four day period. The operational Kessler simulation produces drizzle, but because it rapidly falls out without evaporating, it has little effect on the MBL stability. Drizzle rate in the other simulations is greater (especially in KK2000), which results in increasing MBL stability evident in the liquid water potential temperature field.]

Time-height sections in the vicinity of the NOAA RHB shed light on the differences between across all the simulations (Fig. 2). All four simulations produce a cloud system whose depth slowly increases over time. Although the operational Kessler simulation produces some drizzle it falls too rapidly to evaporate, and ultimately influences the boundary layer thermodynamic stratification very little. The stratifying effect of the drizzle produced by the KK2000, K2013, and K2013–NoSC runs can be seen in the cloud water, rain water, and potential temperature fields, especially later in the simulation.

Figure 3 shows time series of quantities over a domain restricted to the approximate size of the C–band radar volume aboard the NOAA RHB. The observed LWP lies on the low side of the model ensemble, although the simulations exhibit substantial spread. The KK2000 and K2013 simulations produce very similar behavior in LWP and precipitation rate, a striking result given the two parameterizations are developed from substantially different LES datasets (stratocumulus vs. trade cumulus). The outer nest better replicates the marine boundary layer height (MBL). All the simulations greatly overestimate precipitation rate relative to the RHB radar observations.

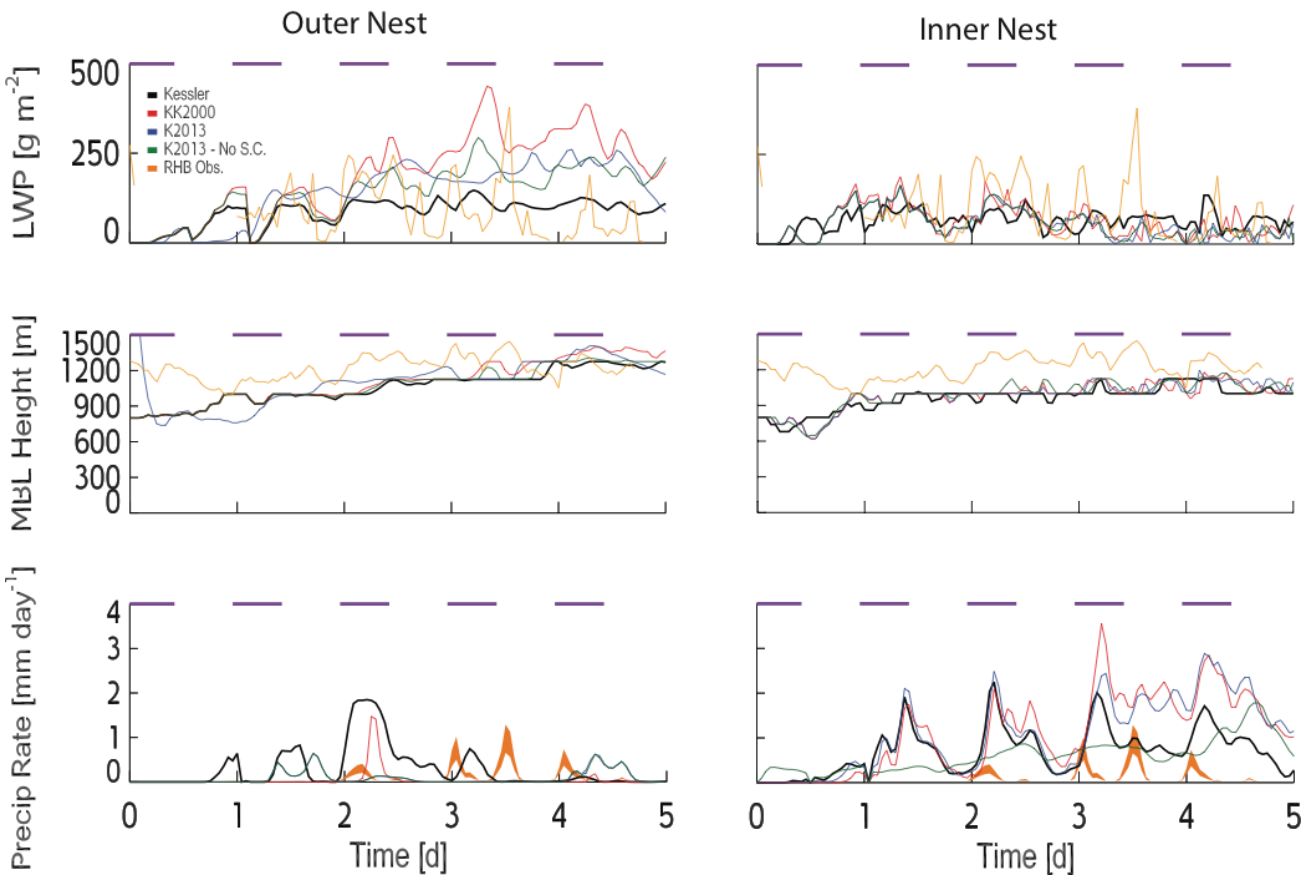

Figure 3: Time series of LWP, MBL (marine boundary layer height), and drizzle rate from the CCN = 177 cm^{-3} simulation. Purple lines denote nighttime. [graph: Observed precipitation lies on the low side of the model ensemble on the 27-km grid and on the high side of the ensemble on the fine, 3-km mesh. All simulations exhibit a low bias in MBL height relative to the observations. All fine-mesh simulations precipitation too strongly, relative to the RHB C–band radar observations.]

We take a statistical approach in looking at both the model output and the data in Fig. 4, which shows the probability density functions for model output and observations The clear result from this analysis is that the inner domain is best able to replicate the observations, particularly the LWP distribution. In addition, it also shows that the Kessler microphysics often has the highest amount of error (MAE, not shown) when compared to the observations. It is also worth noting that the models tend to consistently underestimate the MBL height, even for a sensitivity simulation where precipitation is not allowed to form. This results suggests that drizzle decreases MBL depth but not enough to explain the substantial model bias.

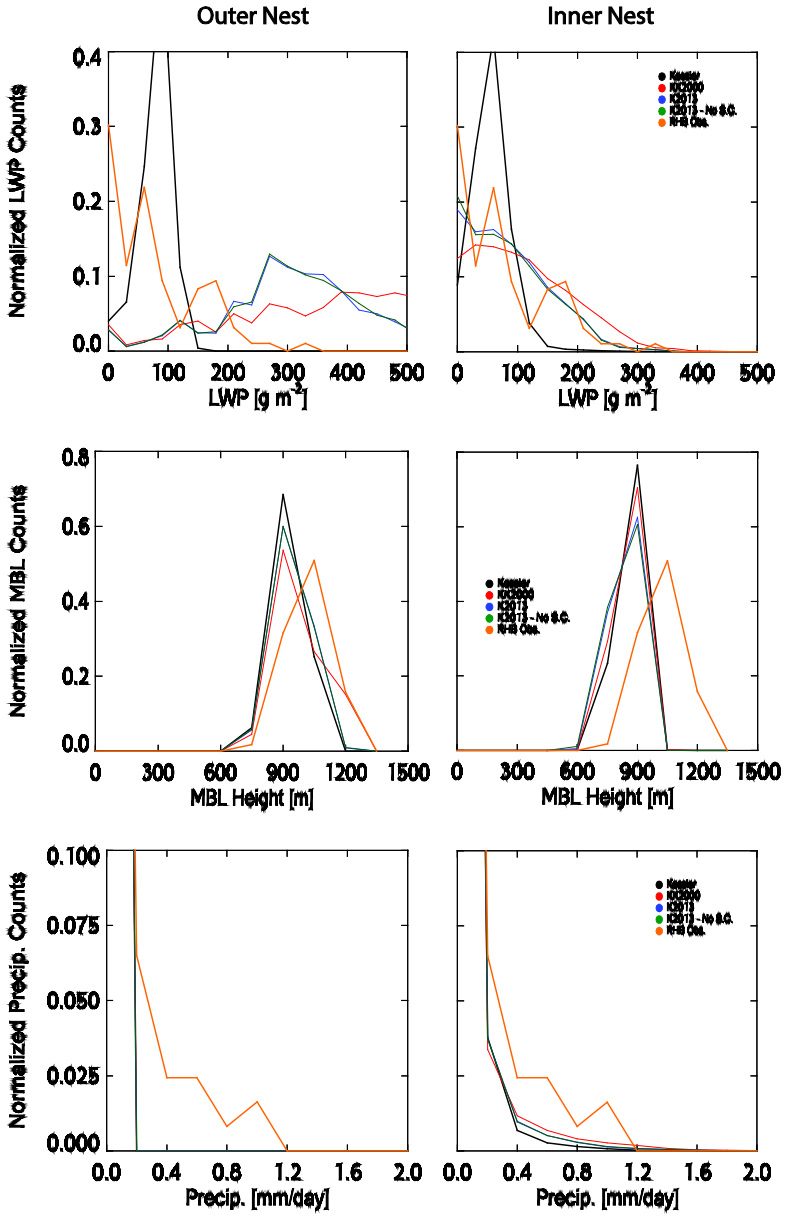

Figure 4: LWP, MBL, and precipitation rate PDFs of model output and observations for each parameterization with an initial CCN value of 177 cm^{-3} [graph: Coarse mesh PDFs of LWP differ greatly across the simulations, with the KK200 and the K2013 simulations exhibiting greater frequencies of high LWP values. The agreement between observations and simulations is better over the fine grid. PDFs of MBL height show the low bias in the simulations, which is even more prominent over the fine mesh, a result of stronger drizzle and a greater degree of decoupling.]

Figure 5 illustrates some preliminary UPPEF LES simulations using the SAM (System for Atmospheric Model; Khairoutdinov and Randall 2003) LES. The control simulation exhibits a shallow mostly dissipated cloud layer. Sensitivity runs with either shortwave radiation turned off or enhanced surface moisture flux result in a somewhat more vigorous turbulence and a more robust cloud layer, as well as increased entrainment. Changes to the vertical velocity skewness reflect the relative importance

of top-down vs. bottom-up mechanisms in driving boundary layer turbulence. The preliminary simulations exhibit substantial agreement across the LES models (SAM, the JPL LES, and COAMPS–LES). The participating SCMs (COAMPS–1D and the JPL EDMF SCM) differ more, at least partly because they differ in being able to represent all the processes active in this case (e.g., the lack of shortwave radiation in the current version of the JPL SCM).

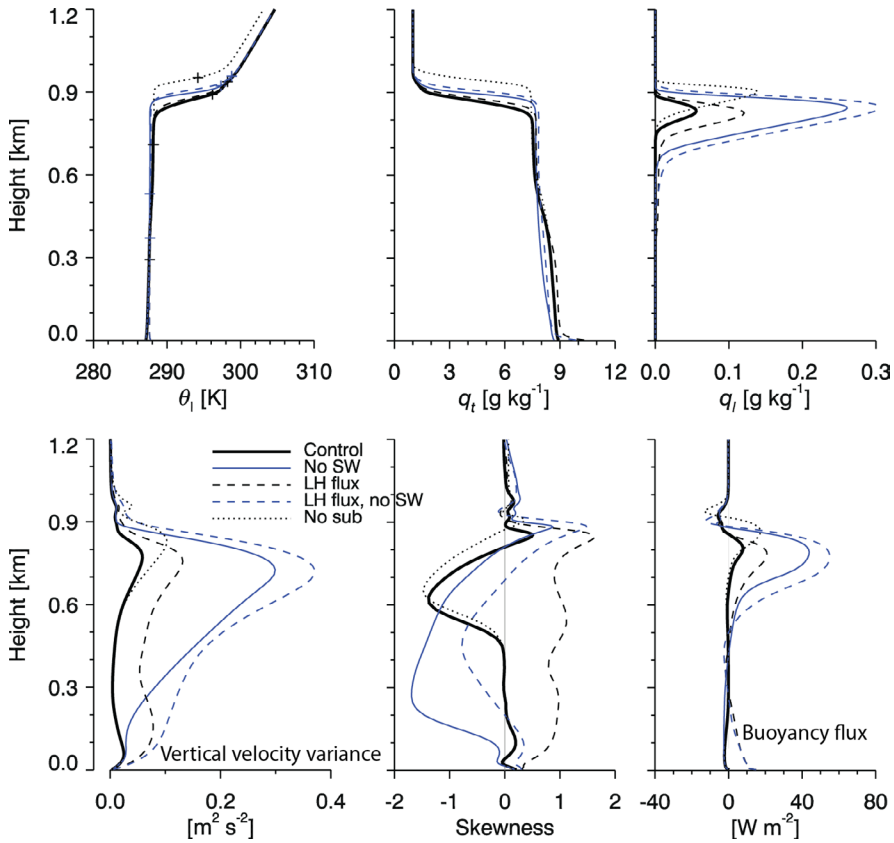

Figure 5: Mean LES vertical profiles averaged between 1 and 3 h for the control simulation and several different sensitivity experiments. [graph: Profiles of domain-mean quantities illustrate differences across all the UPPEF RF01 LES sensitivity experiments. The strong dissipation in the control case can be mediated by either omitting the shortwave heating or by enhancing the surface moisture flux.]

CONCLUSIONS

We have implemented the new K2013 microphysical parameterization and 'reactivated' the previous implementation of KK2000. It is unsurprising that higher resolution model output more closely matches the observations. Despite this, the only fields of our mesoscale simulations affected by including self-collection are an increased precipitation rate and slightly smaller cloud water content.

CCN sensitivity studies in the literature and those performed with COAMPS (e.g., Mechem and Kogan 2003; Mechem et al. 2006) have so far shown little impact of CCN on precipitation outcomes for more polluted simulations, but the microphysical effects of aerosol become much more interesting for cleaner atmospheres. We are currently evaluating whether or not COAMPS with the implemented microphysical parameterizations will produce this expected behavior. One innovative aspect of our work — comparison between model precipitation behavior and the retrieved precipitation rate from the RHB — showed that the simulated precipitation behavior where the model is precipitating is quite good. On the other hand, the model simply contains too many precipitating cells.

Our preliminary LES and SCM simulations of the UPPEF RF01 case suggest some promising results for such a challenging transient cloud system case. First and foremost, we are learning how best to initialize LES and SCM models for such a transient case. Furthermore, the models seem to exhibit some skill in representing the timescale of MBL cloud dissipation. Finally, sensitivity experiments such as increasing surface moisture flux or omitting shortwave radiative heating cast light on the most prominent mechanisms governing MBL cloud system behavior.

IMPACT/APPLICATIONS

More sophisticated boundary layer and microphysical parameterizations implemented into COAMPS will result in more accurate mesoscale weather prediction for U.S. Navy operations and improved seasonal prediction. Of particular emphasis are accurate forecasts of boundary-layer cloud properties and radiative quantities, including metrics for timescales of cloud persistence and dissipation.

RELATED PROJECTS

This project continues to rely on our NOAA-funded efforts investigating cloud system variability (employing large-eddy simulation and ship-based C-band precipitation radar) during the VOCALS field campaign. The VOCALS cloud systems constitute a stringent test for mesoscale models. We will also employ our observational and modeling studies of marine boundary layer cloud systems over the Azores (DOE grant) during the Atmospheric Radiation Measurement Program Mobile Facility deployment (AMF) to test long-term COAMPS simulations of a wide variety of boundary layer cloud systems. We are beginning to transition our Azores simulations from WRF over to COAMPS. We are continuing our long-term collaborations with Yefim Kogan (OU/UCSD) to improve and evaluate microphysical parameterizations and parameterizations of cloud system variability (Kogan and Mechem 2014). We are also continuing collaborations with Shouping Wang (NRL) to establish an Educational Partnership Agreement in an effort to enable us to more easily exchange model codes. This will greatly aid in implementing and testing the shallow convection parameterization in the future.

From 2009 to 2010, over a period of nearly 18 months, the deployment of the Department of Energy Atmospheric Radiation Measurement Program Mobile Facility (DOE A[RM]MF) was deployed on Graciosa Island in the Azores. This long-term dataset was collected in a region of substantial variability in boundary layer cloud. The Azores is formally a “transition” region that exhibits clouds ranging from solid stratocumulus to trade cumulus. Furthermore, the region lies poleward of the other stratocumulus regions and is frequently influenced by mid-latitude synoptic waves. The great degree of variability over this region provides an acid test for numerical models, and it will be the principle testbed for evaluating our improvements to COAMPS.

At some point, it may be worthwhile to evaluate the properties of these parameterizations over longer periods of time over the same area. The PI is currently formulating experiments that would simulate the VOCALS-REx campaign and compare the results to observations from multiple observational platforms, rather than primarily just the R/V RHB. Doing such experiments can help evaluate the use of these parameterizations in longer term simulations and possibly in GCMs.

REFERENCES

de Szoeke, S. P., S. E. Yuter, P. Zuidema, C. W. Fairall, and W. A. Brewer, 2010: Ship-based observation of drizzling stratocumulus from EPIC to VOCALS, *CLIVAR Exchanges*, **15**, 11–13.

Khairoutdinov, M. F., and Y. L. Kogan, 2000: A new cloud physics parameterization in a large-eddy simulation model of marine stratocumulus, *Mon. Wea. Rev.*, **128**, 229–243.

Khairoutdinov, M.F., and D. A. Randall, 2003: Cloud resolving modeling of the ARM summer 1997 IOP: Model formulation, results, uncertainties, and sensitivities. *J. Atmos. Sci.*, **60**, 607–625.

Kogan, Y. L., 2014: A cumulus cloud microphysics parameterization for cloud resolving models. *J. Atmos. Sci.*, **70**, 1423–1436.

Mechem, D. B., and Y. L. Kogan, 2003: Simulating the transition from drizzling marine stratocumulus to boundary layer cumulus with a mesoscale model. *Mon. Wea. Rev.*, **131**, 2342- 2360.

Mechem, D. B., P. C. Robinson, and Y. L. Kogan, 2006: Processing of cloud condensation nuclei by collision-coalescence in a mesoscale model. *J. Geophys. Res.*, **111**, D18204, doi: 10.1029/2006JD007183.

Wang, S., L. W. O'Neill, Q. Wang, S. P. de Szoeke, X. Hong, H. Jin, W. T. Thompson, and X. Zheng, 2011: A regional real-time forecast of marine boundary layers during VOCALS–REx. *Atmos. Chem. Phys.*, **11**, 421–437.

PUBLICATIONS

de Szoeke, S. P., S. Yuter, D. B. Mechem, C. Fairall, C. Burleyson, and P. Zuidema, 2012: Observations of stratocumulus clouds and their effects on the eastern Pacific surface heat budget along 20°S. *J. Climate*, **25**, 8542–8567.

Kogan, Y. L., and D. B. Mechem, 2014: A PDF based microphysics parameterization for shallow cumulus clouds. *J. Atmos. Sci.*, **71**, 1070–1089.

Kogan, Y. L., D. B. Mechem, and K. Choi, 2012: Effects of sea-salt aerosols on precipitation in simulations of shallow cumulus. *J. Atmos. Sci.*, **69**, 463–483.

Mechem, D. B., and A. J. Oberthaler, 2013: Numerical simulation of tropical cumulus congestus during TOGA COARE. *J. Adv. Model. Earth Syst.*, **5**, 1–15, doi:10.1002/jame.20043.

Mechem, D. B., S. E. Yuter, and S. P. de Szoeke, 2012: Thermodynamic and aerosol controls in southeast Pacific stratocumulus. *J. Atmos. Sci.*, **69**, 1250–1266.