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

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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. The evaluation of the parameterizations is performed by extensive comparison with observations and assessing the microphysical self-consistency of the simulations.

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, 'K2013') into COAMPS (performed in prior year).
2. Re-implement the Khairoutdinov and Kogan (2000, 'KK2000') 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 (performed in prior year).
3. Implement a number of variations on these parameterizations, including a version of KK2000 that includes the critical droplet radius threshold function from Liu and Daum (2004), a version of K2013 without the self-collection term, and a variation of K2013 without the coalescence processing of cloud droplets from autoconversion and accretion.

4. 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). The evaluation centers on a statistical comparison of COAMPS results against ship-based measurements from VOCALS, and an evaluation of the microphysical consistency of the COAMPS results against established observational and theoretically derived scalings for precipitation rate and coalescence processing. We believe this is the first study to systematically evaluate mesoscale model results directly against precipitation rate measurements calculated from C-band radar.
5. 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.

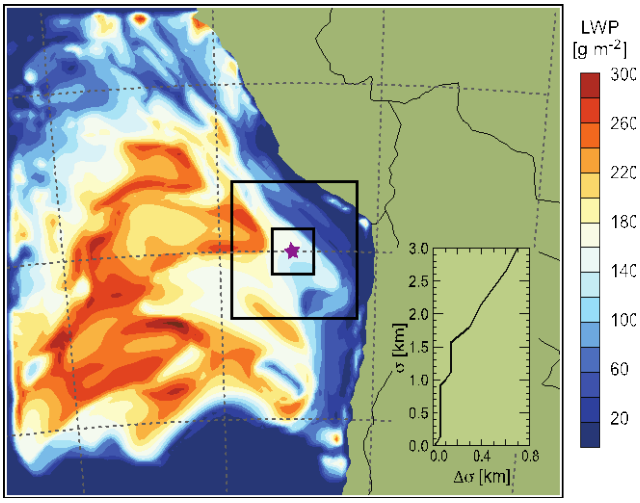

Figure 1: Filled contour plot of LWP for the K2013 parameterization at a simulation time of t =~72 hours. Inner bold lines show the second and third nests, respectively. The purple star indicates the location of the RHB throughout the simulation period. The vertical grid configuration is inset on the LWP plot. [graph: Except for a clear strip right at the coastline, a solid deck of stratocumulus is present over much of the southeast Pacific. Characteristic LWP values range from about 140 grams per meter squared up to over 300.]

APPROACH

MBL cloudiness is not characterized by a single cloud type but rather by a continuum of cloud regimes and transitions. Oceanic cloud regimes transition from unbroken stratocumulus near the coast, to open-cell shallow (trade) cumulus further west, followed by cumulus congestus and deep convection in the western tropical oceans (Albrecht1995; Stevens 2005}. Because many of the processes that occur in clouds (lateral and cloud-top entrainment, microphysical processes) are smaller than a mesoscale model grid volume, they must be parameterized (McCaa and Bretherton 2004; Wang et al. (2011). Regional forecast (mesoscale) models have consistently struggled with accurately representing MBL cloud processes. While the ability of numerical weather prediction (NWP) models to represent MBL cloud systems has improved since their inception, the drawbacks of using single-moment microphysics parameterizations such as Kessler (1969) or Manton and Cotton (1977) for boundary layer clouds are well known (Baker 1993; Chen et al. 1987). The overarching goal of the project is to improve the

parameterization of boundary layer clouds and cloud regime transitions in NRL COAMPS. This goal will be accomplished via the following approach.

We have been working with Yefim Kogan (also funded under this DRI) to implement the new warm-rain microphysics parameterization he developed (K2013) into COAMPS. We describe this effort in previous annual reports. In addition to K2013 and the previously implemented K2000 parameterization, we have implemented into COAMPS the following variations on these parameterizations and have performed additional sensitivity simulations:

- The K2013 parameterization also includes a term that represents the self-collection of precipitation droplets that KK2000 does not incorporate. To test the importance of including this self-collection term in a mesoscale model setting, we perform a suite of simulations of K2013 omitting this self-collection term ('K2013–No S.C.').
- Previous research has hinted that the KK2000 parameterization may overestimate autoconversion for high droplet concentrations (Wood 2005). Mechem and Kogan (2008) addressed this issue through the addition of the critical droplet radius threshold of Liu and Daum (2004) to the KK2000 autoconversion rate. We include this formulation as an additional suite of simulations ('KK2000–Threshold').
- In our final suite of simulations, the coalescence processing of cloud droplets due to autoconversion and accretion ('K2013–N.P.) is neglected. This was not one of our original simulation suites but is conducted in order to address the overestimation of precipitation by all of our simulations.

We evaluated the suite of COAMPS simulations through extensive comparison with the RHB observations. We also evaluate the internal consistency of model microphysical processes by exploring how well simulated cloud properties adhere to observationally and theoretically derived scalings for precipitation rate and coalescence processing. (Please note that some of the content in this "Approach" section stems from our original proposal and from a conditionally accepted manuscript submitted to *Monthly Weather Review* on 8/2015.)

WORK COMPLETED

We have completed the following tasks over the past reporting period:

1. Implemented into COAMPS a number of variations on the KK2000 and K2013 microphysical parameterizations
2. Completed a large suite (26) of COAMPS simulations over a 4-day period during VOCALS–REx field campaign
3. Finished processing VOCALS observational data from the RHB to serve as a testbed for evaluating improvements to COAMPS (and WRF)
4. Performed analysis of COAMPS simulation suite and VOCALS observations, concentrating on model comparisons with the data and microphysical consistency against known scalings for precipitation rate and coalescence scavenging

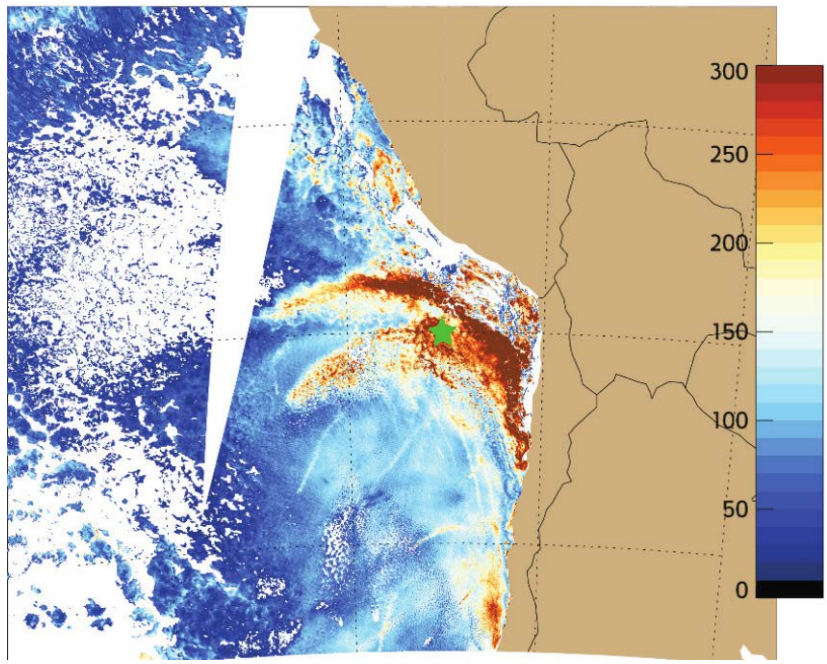

Figure 2: Plots of droplet concentration N_c calculated from MODIS cloud product effective radius and optical thickness following Painemal_Zuidema (2011) at 1 km resolution for DOY 317 at 1510 UTC. The green star indicates the approximate position of the RHB. Linear features in the calculated droplet concentration product are ship tracks. [graph: At this time, a band of high CCN concentration is present over the ship, but upstream to the south-southwest, the CCN field is more homogeneous, and the concentration is lower.]

RESULTS

A full description of the simulation suite is given in our conditionally accepted manuscript (Nelson et al. 2015). Figure 1 shows the bounds of all three COAMPS nests, and the purple star at the center represents the location of the NOAA R/V Ronald H. Brown (RHB) during the simulation period. We follow Wang et al. (2011) and use the same 45-level vertical grid spacing (Fig. 1 inset), which is a trade-off between resolution and operational computational feasibility.

A CCN counter aboard the RHB supplied estimates of CCN concentration at 0.6% supersaturation, but this point measurement gave no indication of spatial variability of CCN. Remote sensing observations from MODIS products were briefly employed to assess the degree of horizontal variability of MBL aerosol over the SEP. Unfortunately, the MODIS aerosol products are column-integrated quantities and assume cloud-free conditions, which is a problem over persistent MBL cloud fields. For these reasons, we follow the methodology of Painemal and Zuidema (2011), which uses MODIS cloud product retrievals to calculate cloud droplet concentration. We then make the assumption that the number of cloud droplets can be considered a proxy for the CCN concentration, and furthermore assume that variability in droplet concentration is covariant to that of CCN concentration. Figure 2 shows the MODIS-derived droplet concentration, which indicates a band of high-CCN concentration being advected northward along the continent (the flow is predominantly southerly), leaving the RHB lying in a region of more spatially homogeneous CCN, which is confirmed by the CCN observations aboard the RHB (not shown).

Figure 3 shows the simulated mean LWP, MBL depth, and precipitation rates for the different simulations. Most of the simulations underestimate LWP relative to that observed by the RHB. The simulation-mean LWP increases as CCN concentration increases, which indicates suppression of precipitation by large CCN concentrations. All simulations exhibit the underestimate of MBL depth, a behavior that is persistent in both mesoscale and climate models. Finally, nearly all of the simulations drastically overestimate precipitation rate relative to the RHB observations, though the exact reason is not clear. Except for the KK2000-Thresh simulation, the largest LWP values come from the K2013–N.P. simulations and are associated with weaker precipitation rates, suggesting that precipitation in this case acts to strongly modulate cloud liquid water content. Of all the simulations, the K2013-N.P. simulations have the lowest precipitation rates, exhibit the most pronounced diurnal cycle, and best match the observations.

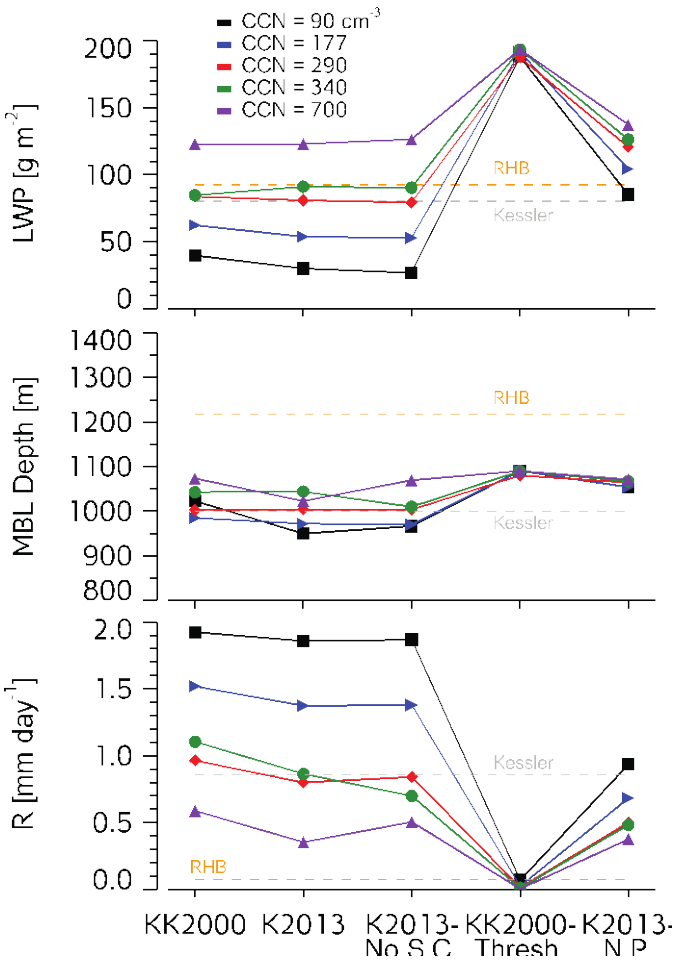

Figure 3: Simulation means of LWP, MBL depth, and R for all parameterizations and all CCN initializations. The Kessler simulation mean is indicated by the gray, dashed line. The observations from the RHB are represented by the orange, dashed line. [graph: The sensitivity of LWP, MBL depth, and precipitation rate to CCN is roughly similar for the KK2000, K2013, and K2013-No S.C. simulations. Precipitation is greatly suppressed in the KK2000-Thresh simulation, at the expense of unrealistic behavior in LWP and MBL depth. The K2013-N.P. simulation suppresses precipitation relative to the other parameterizations in a more realistic sense.]

Figure 4 casts the model output from all simulations (except the KK2000-Threshold suite) in N_c–LWP parameter space. The distribution of data within the parameter space is consistent with higher precipitation rates accompanying higher CCN concentrations. Although it is well known that the highest rain rates will occur in cleaner cases, the model exhibits a sharp increase in precipitation below N_c ~30 cm^{-3}. Furthermore, variability in LWP for a given cloud droplet concentration increases as the CCN concentration increases (though this may simply be a result of increasing variance accompanying increasing means). We speculate that the low mean values of N_c relative to the observations may be a result of precipitation scavenging of droplets and a lack of a suitable CCN source in the model. The mean N_c of our results from the 2013–N.P. simulation support this hypothesis.

Letting the model run unconstrained by data assimilation cycles, forced only by SST and at the domain boundaries, gives substantial insight into intrinsic model behavior. Instead of focusing only on point-by-point comparisons between model and observations, we assess how well the simulation results adhere to observationally and theoretically derived scalings, which we interpret as a measure of microphysical consistency in the model. We use the term "microphysically consistent" to indicate that the microphysical aspects of the model seem to be internally in agreement, suggesting that model error likely has sources other than the model microphysics.

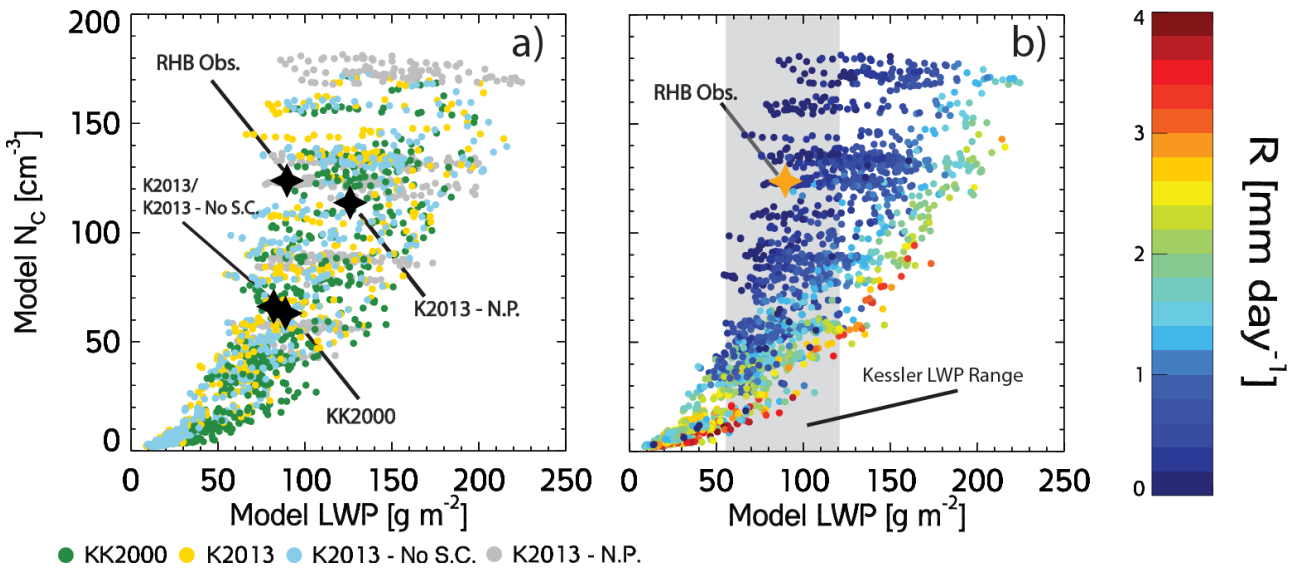

Figure 4: Scatterplots of N_c versus LWP from the inner nest for all parameterizations and all CCN concentrations. The left plot shows the distribution of points stratified by parameterization; the right plot shows the distribution of points stratified by precipitation rate. The mean N_c and LWP for each parameterization are plotted in the left plot. In lieu of scatter-points for the Kessler simulations, we use the gray bands to indicate the range of hourly domain-averaged LWP values from the Kessler simulation. [graph: Simulated LWP and droplet concentration increase together. The best match with the RHB observations occurs using the K2013-N.P. parameterization, although the simulation overestimates LWP. As expected, precipitation tends to increase with increasing LWP and decreasing droplet concentration.]

Figure 5 shows simulation precipitation rates plotted as a function of the scalings from Comstock et al. (2004) and van Zanten et al. (2005), using simulation values of mean cloud thickness, LWP, and N_c. The observational scalings hold relatively well for the model output. The model output scalings show a wider range of precipitation values than either Comstock et al. or van Zanten et al., at least partly because our simulations so drastically overestimate precipitation rate. Our results from the K2013–N.P. simulation best follow the scalings, with the precipitation rates being substantially lower than other simulations. Both scatterplots display a prominent scale break behavior not previously seen in observations nor in LES. The scale break may derive from the fact that we are using surface precipitation instead of cloud-base precipitation estimates. Using cloud-base precipitation rates would increase the magnitude and move those points upward on the figure. The scale-break behavior may also derive from a simple water-limiting arguments, whereby the scale break is an artifact of the model's tendency to overproduce precipitation and happens to lie near the mean moisture flux value over the course of the simulation.

In addition to scalings for precipitation rate, we also explore scalings for coalescence processing, which represents the depletion rate of cloud droplets from coalescence. Figure 6 shows coalescence processing rates from all simulations, plotted as a function of the product of N_c and R, the dominant terms in two scalings found in the literature (Mechem et al. 2006; Wood 2006). Figure 6 indicates that the KK2000 parameterization holds best to both previous studies' depletion scalings across the range of N_c and R values based on how closely the KK2000 points cluster narrowly around the scaling regression lines. The somewhat wider spread of data from the K2013 and K2013–No S.C. runs nevertheless reasonably follows the scalings. The results from the K2013–N.P. simulation lie very near the scaling line from Wood (2006) and do not exhibit the same spread as the other simulations, most likely because the total particle concentration (N_c+N_{CCN}) is constrained.

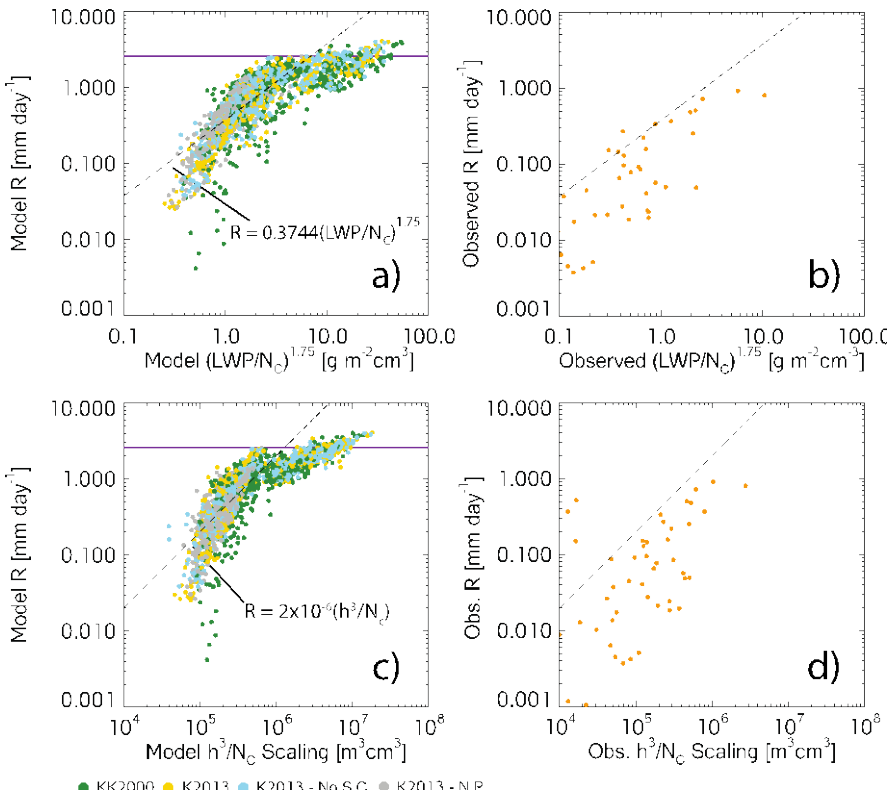

Figure 5: Precipitation scalings for the inner nest and observations from RHB. The top row scalings follow Comstock et al. (2004), and the bottom row scalings follow van Zanten et al. (2005). The equations for each scaling have been adapted from both previous studies to the units used in this study. The solid purple line indicates a rain rate calculated from the equivalent mean latent heat flux from all simulations. [graph: Simulation output broadly speaking follows the Comstock and van Zanten precipitation rate scalings, although the model exhibits a curious scale break, which may coincide with precipitation rates roughly equal to the surface moisture flux. The observations lie somewhat off the Comstock and van Zanten scaling lines.]

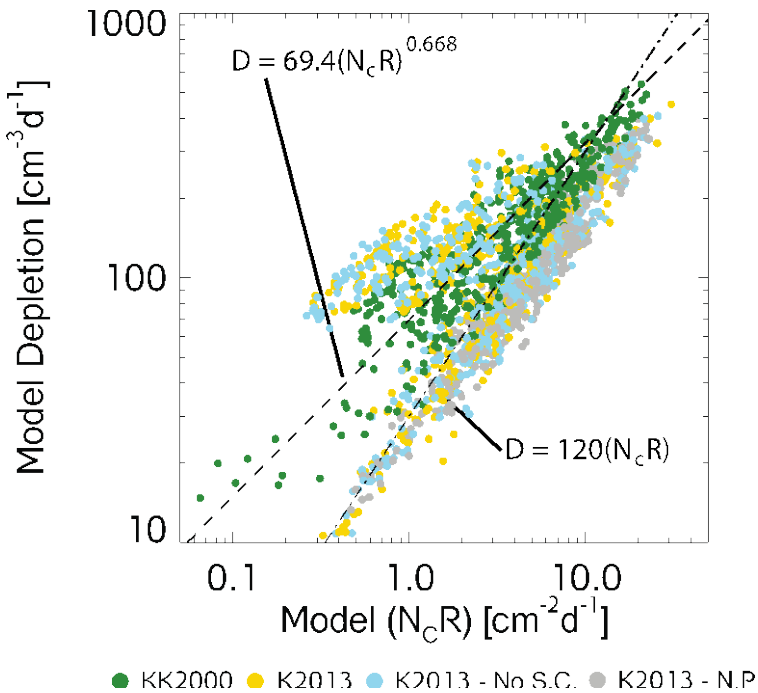

Figure 6: Scatterplot of coalescence processing as a function of N_cR. Dashed black lines represent the coalescence processing scalings of Wood (2006) and Mechem et al. (2006). [graph: Simulation output is in broad agreement with the two scalings. The K2013-N.P. simulation agrees quite well with the theoretically derived Wood (2006) scaling.]

CONCLUSIONS

Several warm-rain microphysical parameterizations are evaluated in a regional forecast model setting (using the Naval Research Laboratory's Coupled Ocean--Atmosphere Mesoscale Prediction System) by evaluating how accurately the model is able to represent the marine boundary layer (MBL). Cloud properties from a large suite of simulations using different parameterizations and concentrations of cloud condensation nuclei are compared to ship-based observations from the VOCALS-REx field campaign conducted over the southeastern Pacific (SEP). As in previous studies, the simulations systematically underestimate liquid water path and marine boundary layer cloud depth. On the other hand, the simulations overestimate precipitation rates relative to those derived from the scanning C-band radar aboard the ship. Most of the simulations exhibit a diurnal cycle, although details differ somewhat from a recent observational study of SEP cloud variability. In addition to direct comparisons with the observations, the internal microphysical consistency of simulated MBL cloud properties is assessed by comparing simulation output to a number of observationally and theoretically derived scalings for precipitation and coalescence scavenging. Simulation results are broadly consistent with these scalings, suggesting COAMPS is behaving in a microphysically consistent fashion. However, microphysical consistency as defined in the analysis is highly dependent upon the horizontal resolution of the model.

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 have been employing our observational and modeling approach to study 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 2015). 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.

We are conducting fundamental studies of microphysical processes by looking for precursor conditions associated with precipitation initiation. This study is being conducted both with high-frequency Doppler cloud radar and bin-microphysics LES. Results from this study will serve to illuminate the microphysical aspects of our COAMPS research efforts.

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