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Improving Mesoscale Prediction of Shallow Convection and Cloud Regime Transitions in 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.

OBJECTIVES

Accurate prediction of cloud-topped marine boundary layers regional forecast models is currently hindered the ability 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 into COAMPS a new warm-rain microphysical parameterization developed for shallow convection
2. Implement a consistent eddy-diffusivity mass-flux (EDMF) or shallow convection boundary layer parameterization in COAMPS
3. Evaluate the shallow cumulus and microphysical parameterizations cases spanning the continuum of boundary layer cloud regimes

APPROACH

The representation of marine boundary layer clouds in mesoscale models has improved over the past 15 years, particularly for solid (overcast) stratocumulus. The models continue to perform rather poorly, however, in shallow convection. Marine boundary layer cloud regimes range from pure stratocumulus

to trade cumulus. Intermediate forms, which we refer to as *cloud regime transitions*, exist in between stratocumulus and trade cumulus. 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 (termed "POCs" or pockets of open cells). These transition regions are typically characterized by a substantial shallow cumulus convection component, even for cases with high cloud fraction. The overarching goal of the project is to improve the parameterization of shallow convective processes 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 into COAMPS the new warm-rain microphysics parameterization he developed (Kogan 2013, referred to here as K2013). This parameterization is similar in approach to a the previous parameterization developed with ONR support (Khairoutdinov and Kogan 2000, which is referred to as KK2000). The 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 extend the function of KK2000 to have more general applicability. 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 will be straightforward.

2. *Implementation of shallow convective parameterization in COAMPS*

Lack of representation of shallow cumulus in regional models like COAMPS can lead to errors in cloud properties and the vertical distribution of heat and moisture. A shallow convection scheme based on non-local transports can overcome the build-up of surface-layer instability. The eddy-diffusivity mass-flux (EDMF) approach is a one consistent, elegant way of implementing a shallow convective parameterization. The EDMF is attractive because it naturally combines with the model boundary layer parameterization by decomposing the turbulent fluxes into local (diffusive) and nonlocal (convective) contributions, which enables it to represent the different boundary layer cloud regimes and transitions between them. A well-constructed EDMF parameterization does this naturally by varying the fraction of turbulent fluxes between the local (diffusive) and nonlocal contributions.

Instead of developing a full EDMF approach, which is being performed by other ONR DRI researchers, our approach is to implement the shallow convective parameterization of Bretherton et al. (2004). Although this shallow convection parameterization does not follow the EDMF formalism (Siebesma et al. 2007; Neggers et al. 2009) exactly, it nevertheless has been demonstrated to perform admirably on cases of trade cumulus and the ASTEX Lagrangian transition case. Since this effort is also being pursued at the Naval Research Laboratory (NRL) in Monterey, we are pursuing an Educational Partnership Agreement between NRL and the University of Kansas in order to enable sharing of parameterization codes.

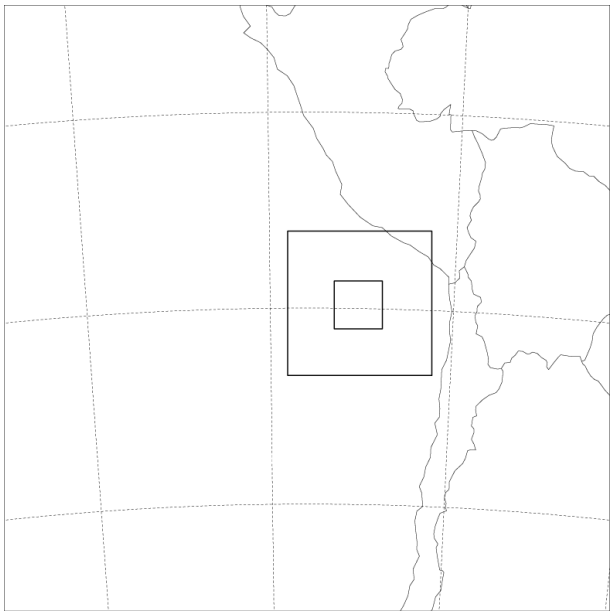

Figure 1. Map of the COAMPS domain and nests employed. Results from the outer 27-km domain are reported here. Finger domains have grid spacings of 9 km and 3 km. [graph: The outer COAMPS domain stretches from Chile up through Peru and includes a portion of the South American continent in addition to the southeast Pacific. The inner domains are centered at 20 degrees south and 75 degrees west, which roughly corresponds to the location of the NOAA research vessel RHB during this period.].

3. *Comprehensive evaluation of the shallow cumulus and improved microphysical parameterizations using a suite of cloudy boundary layer cases*

The implementation of the new microphysical and shallow convective parameterizations into COAMPS will be evaluated with a suite of simulations based on different boundary layer cloud regimes. We will employ datasets and large-eddy simulation results from BOMEX (Barbados Oceanographic and Meteorological Experiment), RICO (Rain in Cumulus over the Ocean), and VOCALS (VAMOS Ocean–Cloud–Atmosphere–Land Study). Datasets from these field projects have been analyzed, and BOMEX and RICO have been the subject of large-eddy simulation intercomparisons (with the PI participating in the RICO GEWEX Cloud Systems Study (GCSS) LES intercomparison), with output results readily available. 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. Our greatest efforts are focused on evaluating the parameterizations over the southeast Pacific (the VOCALS–REx region; see Fig. 1).

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.

(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:

1. Develop multi-day mesoscale model simulations from VOCALS to serve as a benchmark for evaluating microphysical and shallow cumulus parameterizations.
2. Processing VOCALS observational data from the NOAA R/V Ronald H. Brown (RHB) and the DOE AMF (ARM Mobile Facility) to serve as a testbed for evaluating improvements to COAMPS (and WRF).
3. Beginning implementation of shallow cumulus and microphysical parameterizations into COAMPS.

RESULTS

We have constructed a benchmark COAMPS simulation based on the 12-16 November 2008 period during the VOCALS–REx field campaign. 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. Fig. 1 shows the configuration of all three COAMPS nests over the southeast Pacific. Horizontal grid spacings of the three nests are 27, 9, and 3 km. The location of the inner two meshes corresponds to the approximate 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.

The 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 120 hours in order to evaluate intrinsic behavior between model microphysics, radiation, and boundary-layer dynamics unconstrained by observations. We do not perform data assimilation beyond early stages of the simulation.

Our effort toward implementing the KK2000 and K2013 parameterizations has begun by incorporating the autoconversion formulation from each parameterization. This first step is done in recognition of the hypothesis that the autoconversion of the Kessler scheme is perhaps the greatest offender in trying to produce a credible boundary layer cloud system. Furthermore, through this approach we can evaluate whether this step is sufficient by itself to drastically improve MBL cloud forecasts.

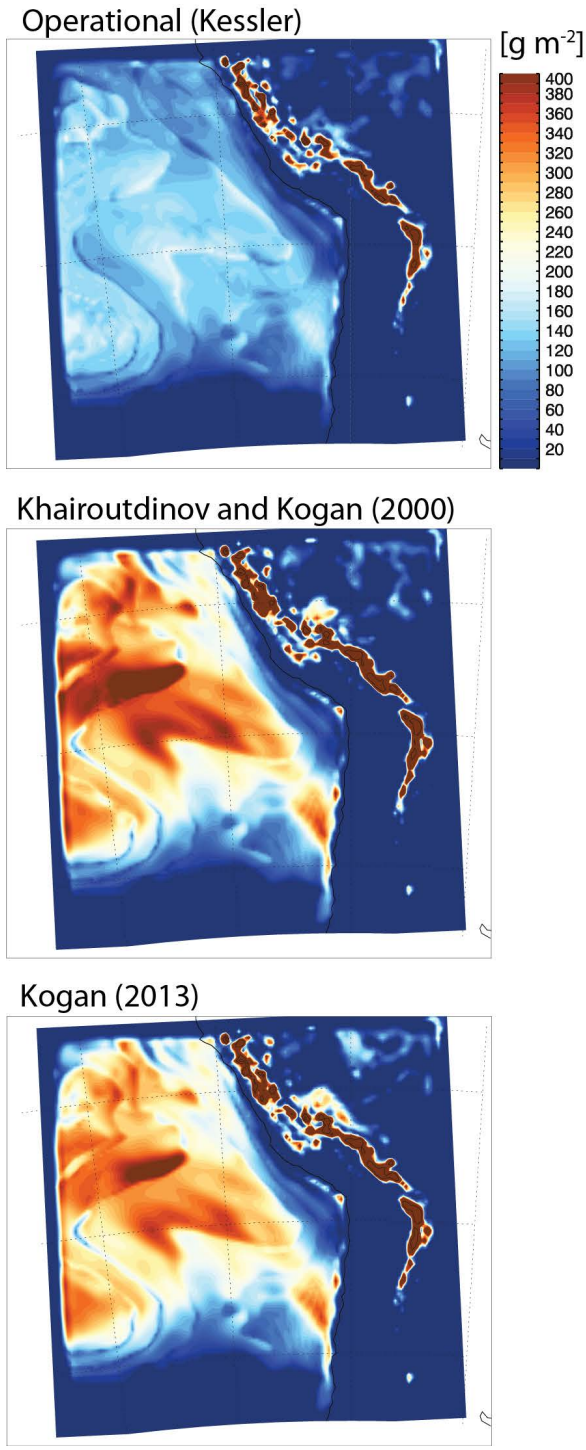

Figure 2. COAMPS forecast liquid water path over the 27-km grid at 72 h. [graph: In all three simulations, cloud is present over most of the ocean, down to a latitude of 30 degrees south. Liquid water path in the Kessler simulation is about half of the values in the KK2000 and K2013 simulations].

Liquid water path (LWP) forecasts over the outer (27 km) mesh at 72 hours (Fig. 2) 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.

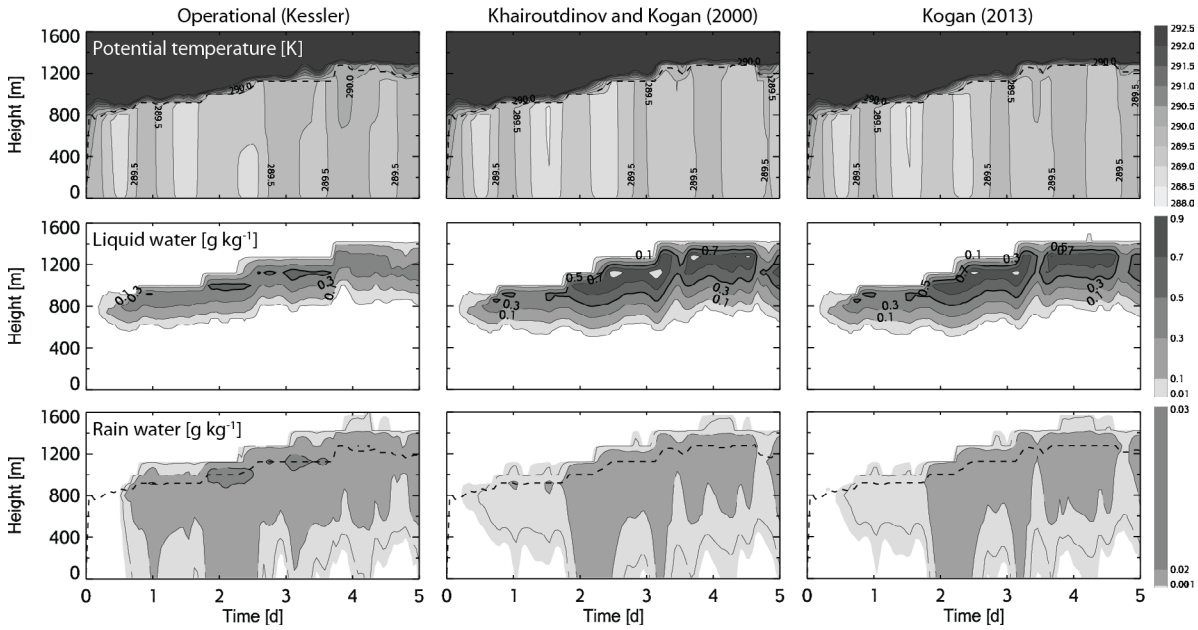

Figure 3. Time-height plots from 5-day COAMPS simulations taken from the grid point closest to the NOAA RHB. [graph: The boundary layer rises at about the same rate in all three simulations. Liquid water content is much less in the Kessler simulation, and rain water content is much greater.].

Boundary layer and cloud statistics from an analysis domain in the vicinity of the NOAA RHB shed more light on the differences between the three COAMPS simulations (Fig. 3). The similarity in cloud-top height and model-calculated inversion height indicate that the variation of entrainment rate across the three simulations is small. The greatest obvious difference between the simulations is the liquid water content, which reaches > 7 g kg^{-1} in the KK2000 and K2013 simulations and is only ~0.4 g kg^{-1} in the operational simulation (Fig. 3, middle row). This outcome is largely a result of the autoconversion threshold of 0.5 g kg^{-1} used in the COAMPS implementation of the Kessler microphysics and serves in boundary layer stratocumulus to set an upper bound on the cloud liquid water content. The operational simulation also results in a greater amount of precipitation production (Fig. 3, bottom row). These results run counter to previous tests of the KK2000 parameterization (Mechem et al. 2003; 2006), suggesting that implementation of the KK2000 and K2013 autoconversion parameterizations alone are not sufficient to dramatically improve mesoscale forecasts.

Fig. 4 shows time series of quantities over the same analysis domain used in Fig. 3, compared with observations from the NOAA RHB. The most credible LWP is produced by the operational simulation, though it does not sufficiently capture the variability present in the observations. As shown in the time-

height sections, the Kessler simulation produces the greatest precipitation. The KK2000 and K2013 simulations produce very similar behavior in LWP and precipitation rate, a striking result since the two parameterizations are developed from substantially different datasets (stratocumulus vs. trade cumulus). Both LHF and SHF are similar across all three simulations, although they differ somewhat from the fluxes from the NOAA RHB. The reason for this bias is not immediately clear but could be related to either model errors in sea-surface temperature, or errors in surface wind speed, temperature, or humidity. As with the time-height sections, this comparison with the NOAA RHB observations confirms that simply using the autoconversion parameterizations from KK2000 and K2013 is not sufficient.

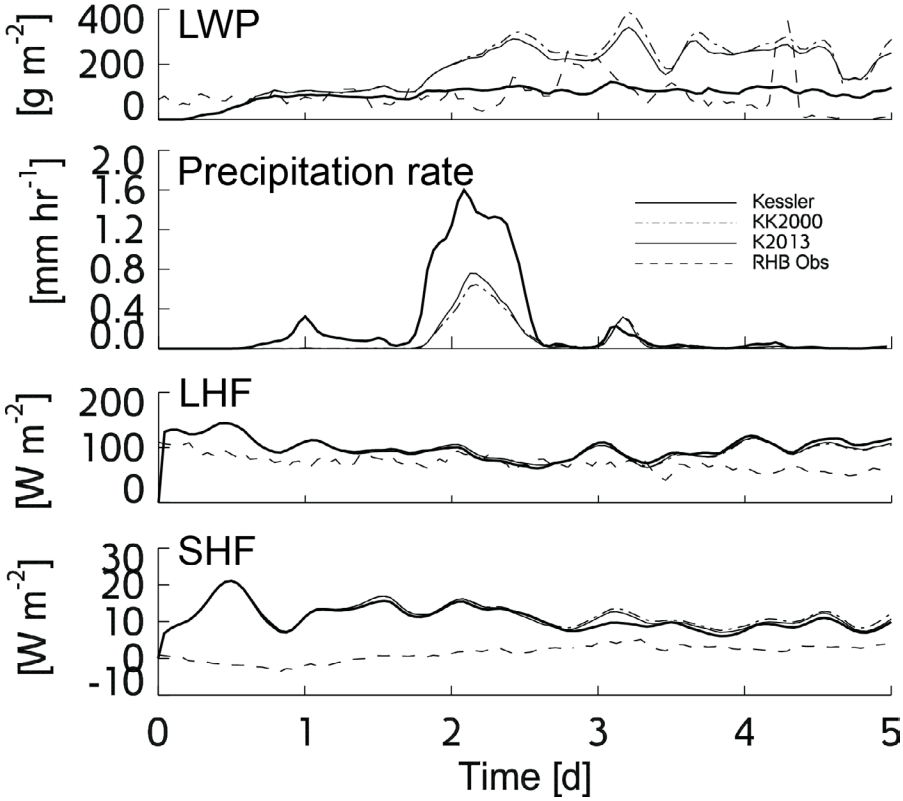

Figure 4. Time series of boundary layer properties from the 27-km COAMPS grid, taken at the grid point closest to the ship, overlaid on the observational values from the ship. [graph: Observational liquid water path is best represented by the Kessler simulation, which also produces the greatest amount of precipitation. All three simulations produce similar surface fluxes of latent and sensible heat, and all simulations are positively biased compared to the observed values.]

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.

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 2013). We also have begun 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.

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