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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 a consistent eddy-diffusivity mass-flux (EDMF) or shallow convection boundary layer parameterization in COAMPS
2. Implement into COAMPS a new warm-rain microphysical parameterization developed for shallow convection
3. Evaluate the shallow cumulus and microphysical parameterizations cases spanning the continuum of boundary layer cloud regimes

APPROACH

Traditional boundary-layer parameterizations incorporated in mesoscale models are based on an eddy-diffusivity (K–theory) approach and perform admirably for dry convective boundary layers and reasonably well for well-mixed, stratocumulus-topped boundary layers. Over a range of grid spacing

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from ~4–10 km, however, the mesoscale models exhibit a hysteresis, as surface fluxes of heat and moisture increase boundary layer instability (convective available potential energy; CAPE) more rapidly than the subgrid-scale boundary layer scheme can diffuse the instability. Eventually, the amount of instability is sufficient that explicit convection develops on the mesoscale grid, and the magnitudes of updraft, liquid water content, and precipitation associated with these resolved circulations are unrealistically large.

Marine boundary layer cloud structures vary across the oceanic basins and include solid stratocumulus, cumulus rising into stratocumulus, and trade cumulus (Fig. 1). In addition, intermediate boundary layer structures exist between pure stratocumulus and pure trade cumulus. We refer to these intermediate forms as *cloud regime transitions*, either temporal transitions as a stratocumulus cloud system breaks up into a field of trade cumulus, or a spatial transition, as a field of stratocumulus is adjacent to or interspersed with more broken cloud areas (termed "POCs" or pockets of open cells). Substantial improvements have been made over the past 15 years in how stratocumulus-topped boundary layers are represented in mesoscale models, but the models currently perform rather poorly when confronted with boundary layer cloud regimes containing a shallow convection component. 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.

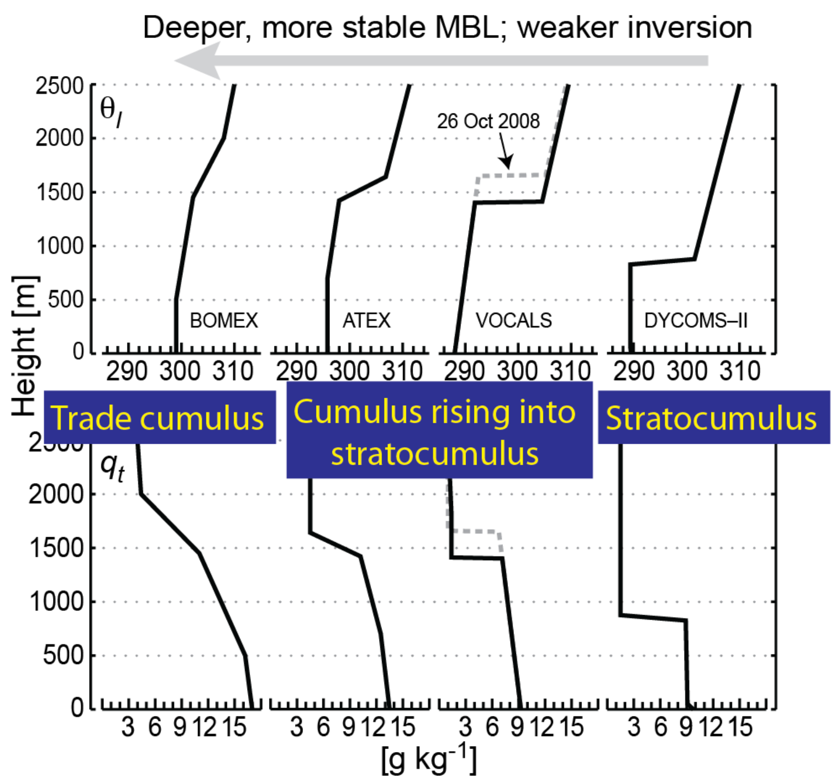

Figure 1. Conceptual model of the continuum of cloudy boundary layers across the oceanic basins. The dashed lines in the VOCALS profiles represents the strong drizzle case of 26 Oct 2008 (from Mechem et al. 2012) [graph: As one moves westward and equatorward over the oceans, the marine boundary layer becomes deeper and more stable, and the inversion becomes weaker. This transition is accompanied by substantial differences in cloud types.].

1. *Implementation of shallow convective parameterization in COAMPS*
A shallow convection scheme based on non-local transports can overcome the build-up of surface-layer instability discussed above. 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.

The beauty of the EDMF approach is that it is capable of representing the continuum of cloud regimes shown in Fig. 1, including the difficult-to-model cloud regime transitions. Furthermore, the EDMF is able to do this in a conceptually unified framework. A well-constructed EDMF approach will naturally transition between the regimes through varying the partitioning of the turbulent fluxes between the diffusive and nonlocal contributions. Theoretically, situations of strong precipitation are particularly suited to the EDMF approach, since evaporating drizzle has been shown to promote a rapid transition from well-mixed stratocumulus to a broken cloud field (pockets of open cells or POCs).

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.

2. *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 2012). This parameterization is similar in approach to the previous parameterization developed with ONR support (Khairoutdinov and Kogan 2000), and its implementation into COAMPS will be straightforward.

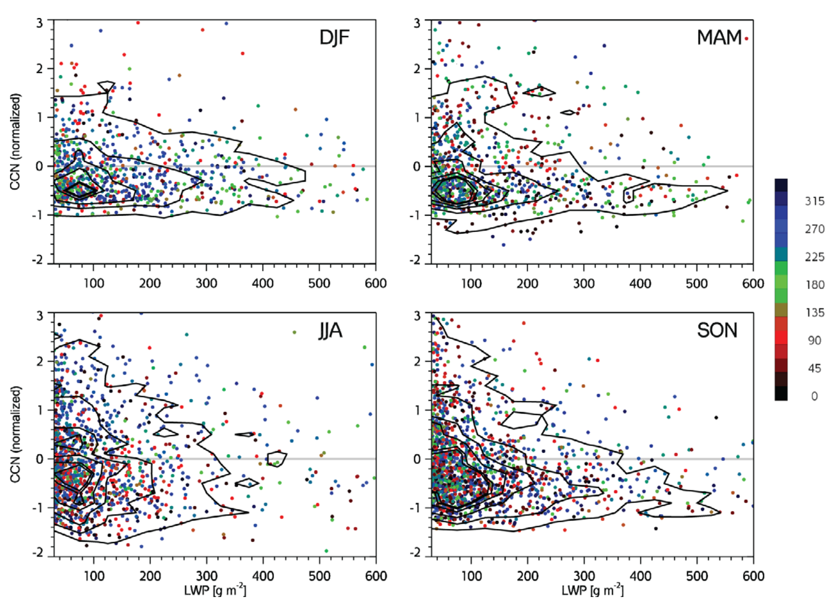

Figure 2. Joint probability distribution functions (PDFs) of liquid water path (LWP) and cloud condensation nuclei (CCN), stratified by season. CCN are normalized by monthly mean and standard deviation. Colors indicate meteorological wind direction for any given observation [graph: Joint PDFs of LWP and CCN exhibit long tails in LWP in all seasons except summer; winter exhibits the narrowest CCN distribution].

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

The implementation of a shallow convective parameterization 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. 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) 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.

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.

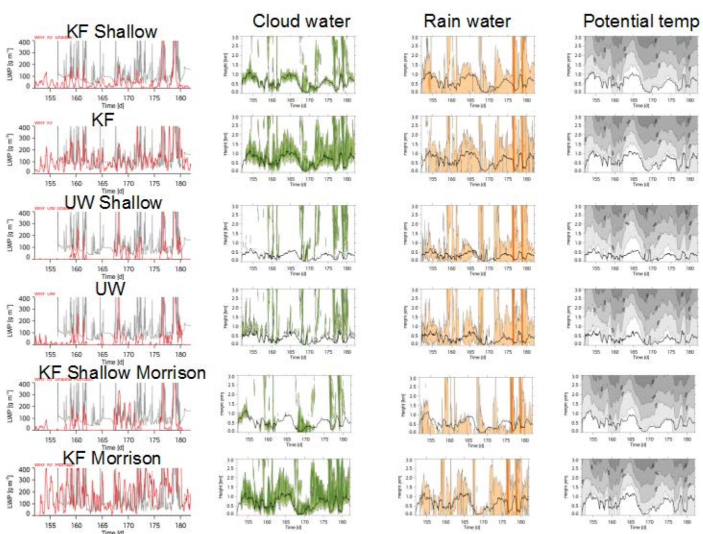

Figure 3. Time series of mean quantities from Advanced Regional WRF simulations for June 2009 (from Mechem et al. 2011). Liquid water path, cloud water, rain water, potential temperature, and inversion height are averaged over a 60×60 km² grid. Simulations shown employ either the Kain–Fritsch or UW convective parameterizations; 3-category or Morrison microphysics; and either the Kain–Fritsch or Morrison shallow convective parameterizations. The gray lines in the LWP plots represent observed LWP from the microwave radiometer retrieval [graph: Time series show substantial differences between six WRF simulations employing different parameterizations. Simulations exhibit substantial differences, with the KF parameterization, at least visually, agreeing best with the observed LWP. The UW parameterizations are frequently cloud-free during periods when clouds are observed.].

WORK COMPLETED

The following tasks are completed or near completion:

1. Processing observational data from the DOE AMF in order to serve as a testbed for evaluating improvements to mesoscale models (COAMPS and WRF)
2. Preliminary multi-week mesoscale model simulations to evaluate parameterization combinations and testbed data.
3. Beginning implementation of shallow cumulus and microphysical parameterizations into COAMPS.

RESULTS

1. *Development of testbed from the DOE AMF Azores deployment*
We have been processing the 18 months of Azores data to serve as an evaluation testbed for COAMPS (and WRF) simulations. Our work in particular concentrates on the joint variability between different quantities, in particular liquid water path (LWP) and CCN concentration. Figure 2 shows the wide range in joint-PDF behavior and seasonal variability over this region. Winter, spring, and fall exhibit long tails in LWP, indicative of intrusions of synoptic disturbances into the region. CCN during the summer and fall are highly variable, reminiscent of substantial horizontal gradients in aerosol observed during the ASTEX field campaign twenty years ago. In contrast to our initial hypotheses, the joint PDFs exhibit little dependence on wind direction.

2. *Preliminary multi-week mesoscale model simulations to evaluate parameterizations*
The long-term Azores data is well suited for multi-week (and eventually, multi-month) simulations, which will enhance the statistical validity of our evaluation of model performance. In order to begin to understand model behavior and deficiencies over this region, we have conducted preliminary numerical simulations with the Advanced Regional Weather Research and Forecasting (ARW[RF]) model for June 2009. The model was run at a coarse horizontal grid spacing (30 km) over a domain of $2220\times1830\ km^2$, with a stretched vertical grid ranging from ~10 m at the surface, 100 m at an altitude of 600 m, and 500 m at an altitude of 5 km. GFS analysis provided initial and boundary conditions. The simulations tested a number of boundary layer parameterizations, shallow convective formulations, and microphysical schemes.

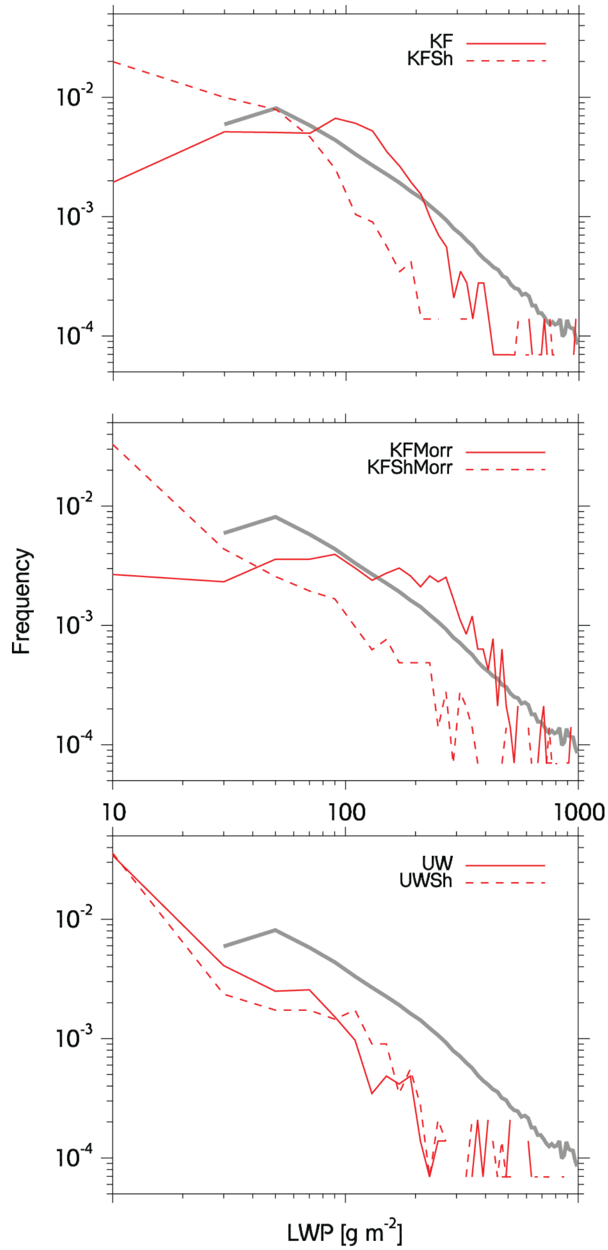

Figure 4. PDFs of liquid water path for the six different Azores simulations shown in Fig. 3. The gray line denotes PDF of the observed LWP. [graph: The Kain–Fritsch parameterizations without the shallow convective parameterizations exhibit the best agreement with the observed LWP PDF. The UW boundary layer parameterization, and all runs with a shallow convection scheme, substantially underestimate all values of LWP.].

Figure 3 summarizes a number of these simulations. The LWP time series demonstrates substantial differences between the different parameterizations. The observational LWP retrieval from the microwave radiometer shows that some of the simulations match the observations rather closely. The original Kain–Fritsch parameterization — without any shallow convection, somewhat ironically — does quite well in comparison to the observed LWP. Some of the combinations fail to maintain cloud when present, although these schemes (UW and UW Shallow) are formulated for large-scale models.

Simulated time-height sections of cloud water, precipitation water, and temperature structure vary substantially between the runs but appear more-or-less internally consistent. Distributions of LWP for the different simulations are contrasted with the observed LWP in Fig. 4. Even the "better" simulations (KF and KFMorr) differ from the observed LWP distributions. Simulations incorporating the shallow parameterizations systematically underestimate LWP.

The simulations exhibit substantial differences in MBL depth (Fig. 3, rightmost column). Figure 5 shows a complicated relationship between LWP and MBL depth. Apparently, shallow convection results in a shallower boundary layer and reduced LWP. The simulations vary widely, but compared to the observed LWP, runs employing shallow convection schemes are not doing well. We are currently investigating reasons for this, including possible misinterpretation of the microwave radiometer retrieval of LWP in potentially broken cloud conditions.

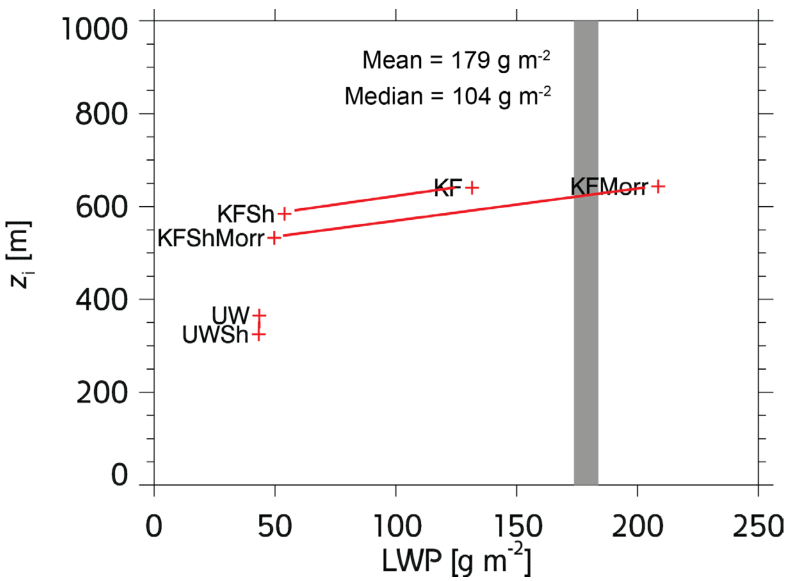

Figure 5. Comparison of the six parameterizations from Fig. 3 in LWP–z_i parameter space. The gray bar represents the observed LWP mean. [graph: Kain–Fritsch and Kain–Fritch/Morrison simulations agree best with the observed LWP. UW simulations systematically underestimate LWP and exhibit the shallowest boundary layer depth. Including shallow convection worsens agreement with observed LWP in all simulations.].

3. *Implementing shallow cumulus and the new warm-rain microphysical parameterization into COAMPS*

We have begun implementing the shallow cumulus parameterization and the improved warm-rain microphysical scheme into COAMPS. Once this is accomplished, we will be conducting COAMPS simulations similar to the WRF simulations discussed above. Our validation efforts will predominantly involve the "acid test" DOE AMF Azores dataset, with simulations ideally spanning the entire 18 months.

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 will 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 continuing our long-term collaborations with Yefim Kogan (OU/UCSD) to improve and evaluate microphysical parameterizations, and we are planning collaborations with Shouping Wang (NRL) to aid in implementing the shallow convection parameterization.

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