Unified Cloud and Mixing Parameterizations of the Marine Boundary Layer: EDMF and PDF-based cloud approaches

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LONG-TERM GOALS

The long term goals of this effort are (i) the development of a unified parameterization for the marine boundary layer; (ii) the implementation of this new parameterization in the U.S. Navy NAVGEM model; and (iii) the transition of this new version of the NAVGEM model into operations at Fleet Numerical Meteorology and Oceanography Center (FNMOC).

OBJECTIVES

The objectives of this specific project are: i) to develop a unified parameterization for the Marine Boundary Layer (MBL) and ii) to implement and test this parameterization in the U.S. Navy NAVGEM model. This unified MBL parameterization will be based on two main components: (i) the Eddy-Diffusivity Mass-Flux (EDMF) parameterization of boundary layer mixing; and (ii) the Probability Density Function (PDF) cloud parameterization.

APPROACH

This unified boundary layer parameterization is based on two main components: (i) the Eddy-Diffusivity Mass-Flux (EDMF) parameterization of turbulence and convective MBL mixing; and (ii) the Probability Density Function (PDF) cloud parameterization. Together these two concepts allow for the unification of MBL parameterization in one single scheme. They also allow for the development of physical parameterizations that lead to a resolution-dependent MBL parameterization that would adjust itself to the horizontal grid resolution.

Key personnel:

- J. Teixeira (JPL/Caltech) uses his expertise in cloud and boundary layer parameterizations to guide the development and implementation of the EDMF/PDF parameterization.
- M. Peng (NRL) uses her expertise in global modeling to assist with the investigations related to NAVGEM within the context of this ONR DRI.

- K. Suselj (UCLA Research Associate) performs the development and implementation of the EDMF parameterization in the NAVGEM model.

WORK COMPLETED

1 -Evaluation of new EDMF parameterization in Single Column Model (SCM):
i) New stochastic EDMF shallow convection parameterization was evaluated against observations and LES results for GEWEX Cloud Systems Studies (GCSS) case-studies (e.g. BOMEX, DYCOMS);
ii) New stochastic EDMF shallow convection parameterization was evaluated against observations and LES results for GCSS cloud transition cases – i.e. from stratocumulus to cumulus.

2- Implementation and evaluation of new EDMF parameterization in NAVGEM SCM:
i) EDMF parameterization was implemented in NAVGEM SCM and tested for GEWEX Cloud Systems Studies (GCSS) case-studies (e.g. BOMEX, DYCOMS).

3- Implementation and evaluation of new EDMF parameterization in the full global NAVGEM model

4- Operational transition of the new EDMF parameterization into the NAVGEM model.

RESULTS
Introduction

A parameterization developed to represent convective boundary layers in a unified manner is implemented in the single-column-model (SCM) and the fully three-dimensional version of the NAVGEM model. The parameterization is based on a multiple-plume stochastic eddy-diffusivity mass-flux (EDMF) approach. In the EDMF framework, turbulent fluxes are calculated as a sum of the downgradient (eddy-diffusivity) component and a mass-flux component (e.g. Siebesma et al., 2007). In this version the eddy-diffusivity component is based on Louis et al., (1982), as implemented in the current version of NAVGEM, while the parameterization of the mass-flux is new in NAVGEM. The mass-flux component is modeled as a fixed number of steady state plumes. In a dry boundary layer, plumes represent the strongest thermals of the flow, and in the cumulus-dominated boundary layer they represent convective clouds. Therefore, the solutions have to account for a realistic representation of condensation within the plumes, and equally important, of lateral entrainment into the plumes. We have shown (Sušelj et al. 2012; 2013) that EDMF has the capability to capture the essential features of moist boundary layers, ranging from stratocumulus to shallow-cumulus regimes.

The EDMF method was described in previous ONR reports (see ONR report, 2012, 2013). We improved the method by tuning the parameters defining the surface properties of the mass-flux and the entrainment rate, so that it optimally describes the SCM cases as well as the three-dimensional dynamics. The three-dimensional version of NAVGEM is evaluated against analysis and observations. These results show that EDMF in NAVGEM improves (with respect to the control version which is the version of NAVGEM without EDMF) the forecast of most of the relevant atmospheric parameters. As a result of the success of the EDMF parameterization, the stochastic EDMF became part of the operational NAVGEM in November 2013. This version of EDMF is fully documented in a recent paper by Sušelj et al. (2014).

We are developing the multiple-plume stochastic EDMF further. In this new version, which we call the stochastic precipitating EDMF, the stochastic mass flux is coupled with cloud microphysics in order to represent precipitating convection. This new parameterization represents the boundary layer and shallow non-precipitating and precipitating convection processes in a unified manner. In the near future, we will test this new parameterization in the NAVGEM model.

NAVGEM model results

We show selected results from the SCM model for marine (BOMEX) and continental (ARM) shallow convection cases. The SCM results are compared to the Large-Eddy-Simulation (LES) results from Siebesma (2003) for the BOMEX case and the LES results used in Sušelj et al. (2013) for the ARM case. For the SCM we use 91 vertical levels that correspond to the ECMWF vertical levels. The forcing and the initial conditions for the SCM are defined the same way as for the LES simulations. The three-dimensional results are obtained by running NAVGEM in a forecast mode. We compare the forecast results of the control and EDMF version of the model against analysis.

a) SCM model results

Fig. 1 compares the moist conserved variables and the turbulent fluxes from the EDMF SCM and an ensemble of LES. In the SCM, the sub-cloud layer (below around 600 m) is almost well mixed which is in agreement with the LES results. Both moist conserved variables have a slight kink at the surface. The reason for that is the strong peak of the turbulent flux from the eddy-diffusivity part of the parameterization. The moist conserved variables from the SCM agree relatively well with the LES results in the cumulus-dominated layer (from around 600 m to 2000 m). Compared to the LES, the lower part of the cloud layer is slightly drier and the upper part is slightly moister. This is a consequence of an unrealistic peak of the turbulent fluxes of total water mixing ratio in the lower part of the cloud layer in the SCM. The reason that SCM represents the profiles of moist conserved variables well is its realistic representation of turbulent fluxes (lower panel on Fig. 1).

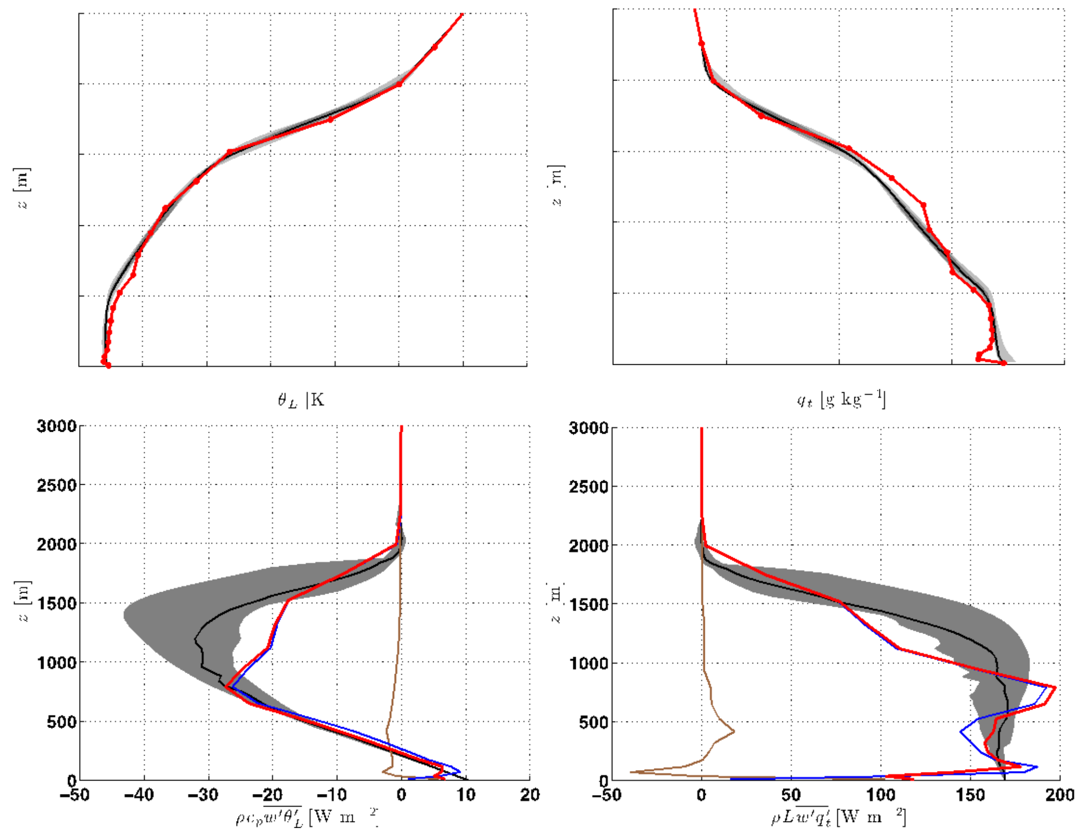

Fig.1: BOMEX case. Profiles of moist conserved variables (upper left: liquid water potential temperature, upper right: total water mixing ratio) and turbulent fluxes (lower left: sensible, lower right: latent heat flux) averaged between second and third simulation hour. The red lines represent the SCM results (circles denote the vertical levels of the model) and the black lines the LES mean. The grey shading is the interquartile range from LES. In the lower panel the brown line represents the eddy-diffusivity (ED) part of the turbulent flux, blue the mass-flux (MF) part and red the total flux (ED + MF).

The ARM case is an example of non-stationary convection over land characterized by time-varying surface latent and sensible heat fluxes and the gradual growth of the boundary layer, which is initially dry, and then transitions to a cloud-topped boundary layer. Fig. 2 shows hourly averaged vertical profiles of moist conserved variables and the corresponding turbulent fluxes every two hours throughout the simulation. The boundary layer deepens over the course of the day and is well mixed and topped by a shallow cumulus layer after the fifth simulation hour. The SCM represents the deepening of the boundary layer well. The profiles of liquid water potential temperature agree well with the LES results. In the SCM, the well mixed sub-cloud layer is more moist than in the LES results and consequently the cumulus dominated cloud layer is drier compared to the LES results. The turbulent fluxes of moist conserved variables are reasonably well represented. In the first simulation hours the turbulent fluxes tend to reach zero values at high altitudes, in agreement with higher cloud tops.

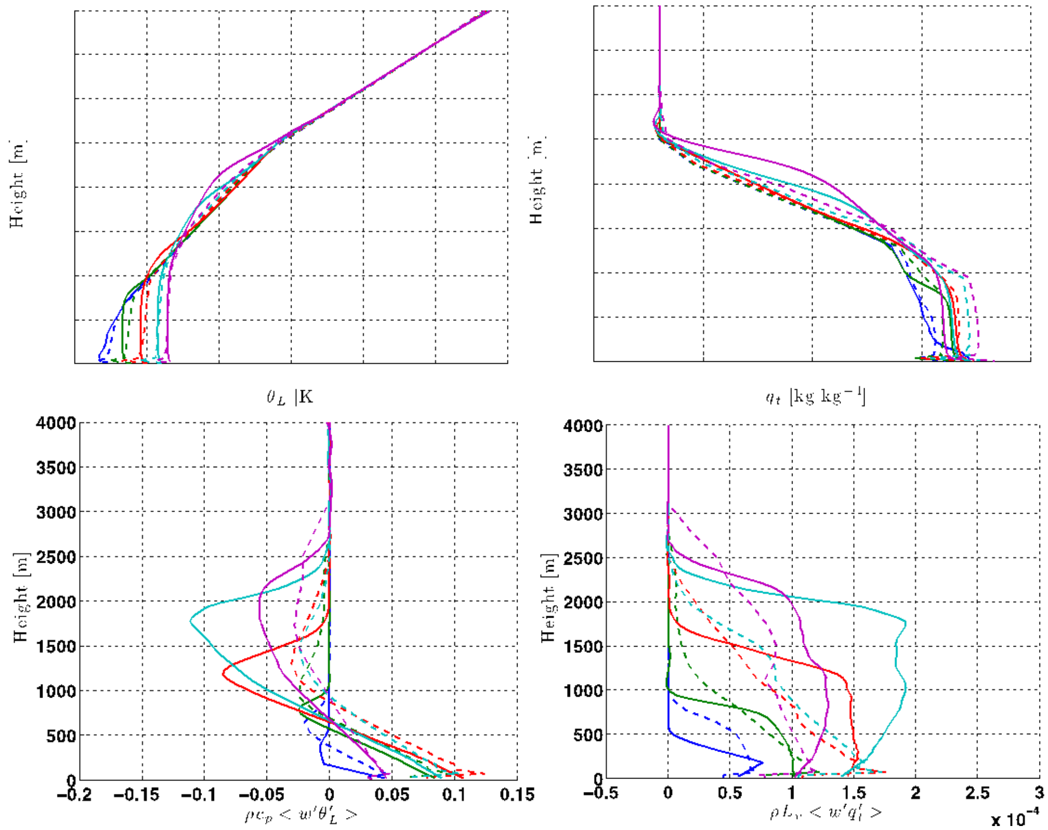

Fig. 2: ARM case. Profiles of moist conserved variables (upper panel) and the corresponding turbulent fluxes (lower panel) from SCM (dashed lines) and LES (full lines). The results are hourly averaged values centered on the third (dark blue), fifth (green), seventh (red), ninth (light blue) and eleventh (violet) simulation hours.

b) Three-dimensional NAVGEM model results

To investigate whether EDMF in NAVGEM improves the forecast skill and reduces forecast errors, full data assimilation/forecast tests were performed on two versions of NAVGEM: *Control* (which is identical to the operational version of NAVGEM before November 2013) and EDMF (which is identical to the Control version, except the boundary layer parameterization is replaced with the EDMF parameterization). The performance of both versions was tested for two northern-hemisphere winter (January - February 2013) and summer (August - September 2013) months. Figs. 3 and 4 show examples of the improvement due to EDMF for January and August 2013 (the results of the other two months: February 2013 and September 2013 are practically the same). Many other forecast variables show a significant improvement with the EDMF parameterization.

The forecast skill is characterized in terms of the anomaly correlation (AC) and mean biases as a function of forecast time (up to 120 hours). Fig. 3 shows the 500 hPa geopotential height AC from both versions of NAVGEM for the winter and summer months. The skill of the EDMF version is considerably better than the Control for both hemispheres in their corresponding winters. For both hemispheres in their corresponding summers, the skill of the Control and the EDMF versions is essentially the same. Fig. 4 shows the 120-hour monthly mean temperature bias, respectively. In the Control version the tropospheric temperatures throughout most of the tropics, subtropics and midlatitude are consistently colder compared to the analysis. This negative bias in the sub-tropics and mid-latitudes is likely due to the interaction between the surface and troposphere being too weak as a result of the sub-grid mixing by the boundary layer parameterization being too weak. In the tropics the negative bias is probably the consequence of convective transport that is too weak. These negative temperature biases are to a large degree improved by the EDMF as the vertical mixing is increased. The EDMF version also greatly improves the moisture budget as increased moisture is being moved in the troposphere. This is also evident in the fact that the EDMF scheme has a 10% increase in total precipitation compared to the Control version (not shown).

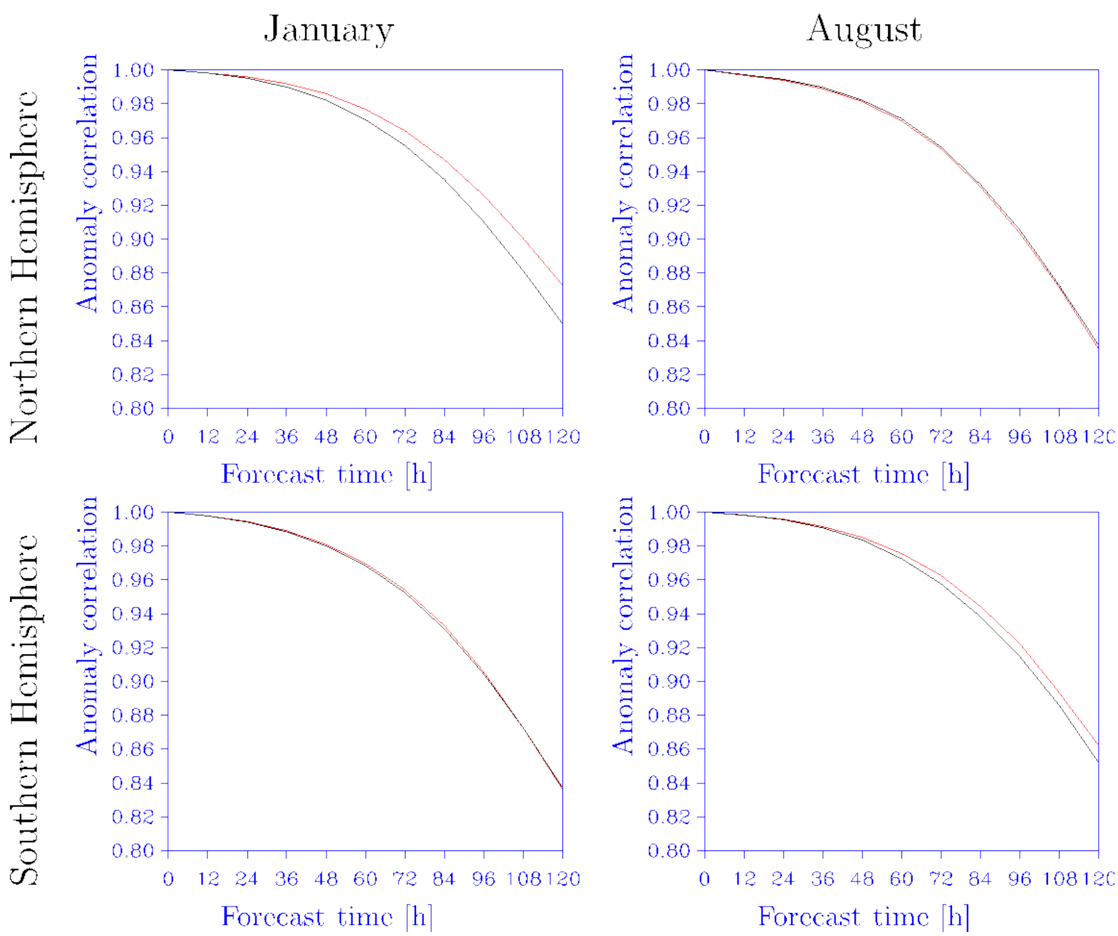

Fig.3: 500 hPa geopotential height anomaly correlation for both NAVGEM versions (red line for EDMF, black line for Control) as a function of forecast time. Upper panel for northern hemisphere, lower for southern. Left panel for January 2013, right panel August 2013.

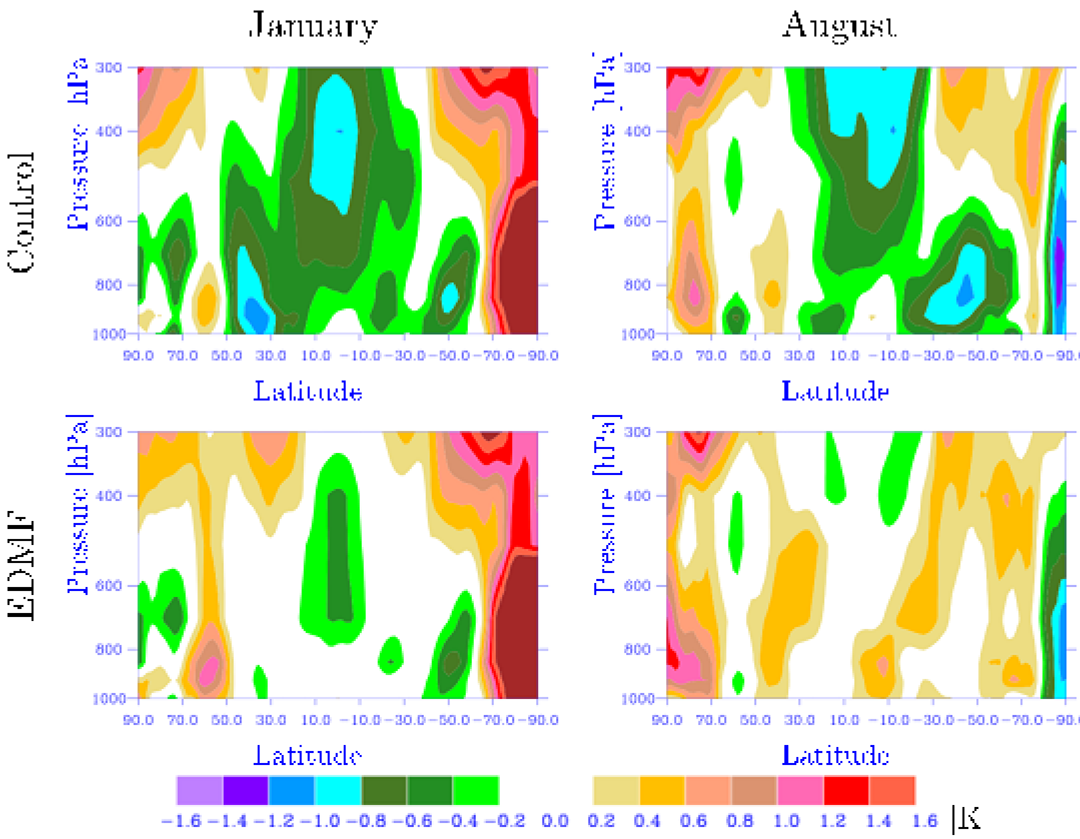

Fig.4: Zonal mean bias of NAVGEM temperature with respect to the analysis for the 120th simulation hour. Upper panel for Control simulation, lower for EDMF. Left panel for January 2013, right panel August 2013.

Results from a stochastic precipitating EDMF

The stochastic precipitating EDMF couples the convective dynamics, which is represented by the mass-flux parameterization, with a microphysical model. The microphysical model is similar to the one described by Grabowski (1998). The main challenge is to realistically represent the coupling of the microphysical model, which is described by time-dependent equations, with the steady-state plumes represented by the mass-flux parameterization. At the same time the computational cost of the new parameterization should not increase too much. We developed a method, which simplifies the microphysical parameterization and couples it to steady state mass-flux equations while it is numerically stable. The new parameterization is implemented in a version of the SCM and tested against LES simulations. Fig. 4 shows results of the precipitating EDMF SCM for a precipitating convection case over ocean (the RICO case) with an ensemble of LES results from van Zanten et al., (2011). These results show that EDMF is well able to represent the dynamics of the precipitating convection as well as the microphysical properties. In particular, the profiles of the rain rate and the time series of surface rain rates are well represented.

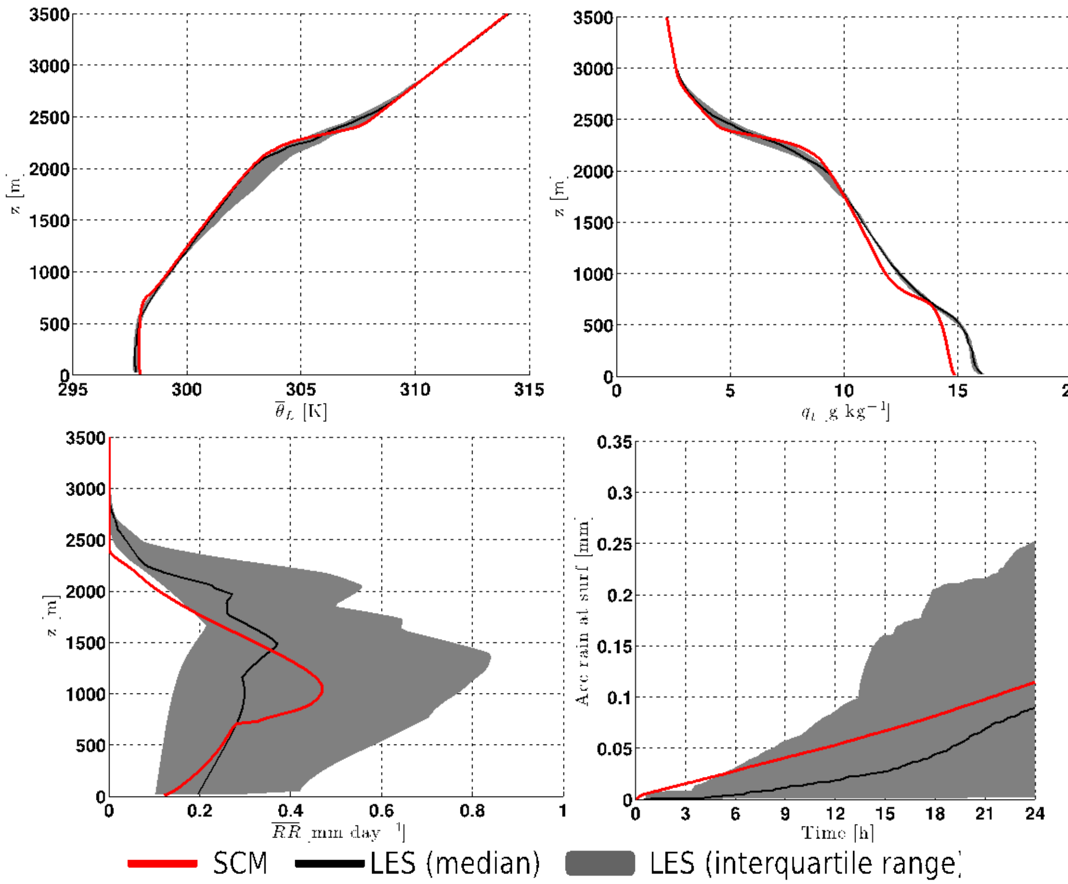

Fig. 5: RICO case. Upper panel: Profiles of liquid water potential temperature and total water mixing ratio averaged between 23rd and 24th simulation hour. Lower panel: (left) profile of rain rate averaged between the 23rd and 24th simulation hour; (right) time series of surface precipitation. The red lines show SCM results, the black line median LES results and the gray area the interquartile range from LES results taken from van Zanten et al., 2011.

Conclusions

The EDMF parameterization in NAVGEM complements the boundary layer parameterization by simulating surface forced moist convection. We show examples of SCM test cases, which cannot be reasonably simulated with the control NAVGEM SCM. The EDMF parameterization implemented in the full three-dimensional forecast NAVGEM model significantly improves the overall forecasts. We are developing a new version of EDMF that includes precipitating convection. We plan to implement and test this new version of EDMF in the NAVGEM model in the near future.

IMPACT/APPLICATIONS

As shown above the EDMF parameterization has a key impact on the weather prediction capabilities of the U.S. Navy with the operational implementation of this new parameterization in the NAVGEM model. In addition it will be the first time that a unified parameterization of the marine boundary layer has ever been developed and implemented in a global weather prediction model.

TRANSITIONS

The new EDMF parameterization was implemented operationally and tested in the NAVGEM forecast system and transitioned to operations at FNMOC.

RELATED PROJECTS

This project is part of the "Unified Physical Parameterizations for Seasonal Prediction" Departmental Research Initiative.

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