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

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Award Number: N0001411IP20069

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 part of the development and implementation of the EDMF parameterization in the NAVGEM model.

WORK COMPLETED

<u>1 -Evaluation of new EDMF parameterization in Single Column Model (SCM)</u>:

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 a 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 down-gradient (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, 2014). 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 a newer version, the EDMF parameterization 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 addition, some other aspects have been improved: in particular, the EDMF plumes now start form a surface PDF of thermodynamic properties.

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. Fig. 1 shows an example 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. Fig. 1 shows the 120-hour monthly mean temperature bias. In the Control version the tropospheric temperatures throughout most of the tropics, subtropics and mid-latitude 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).

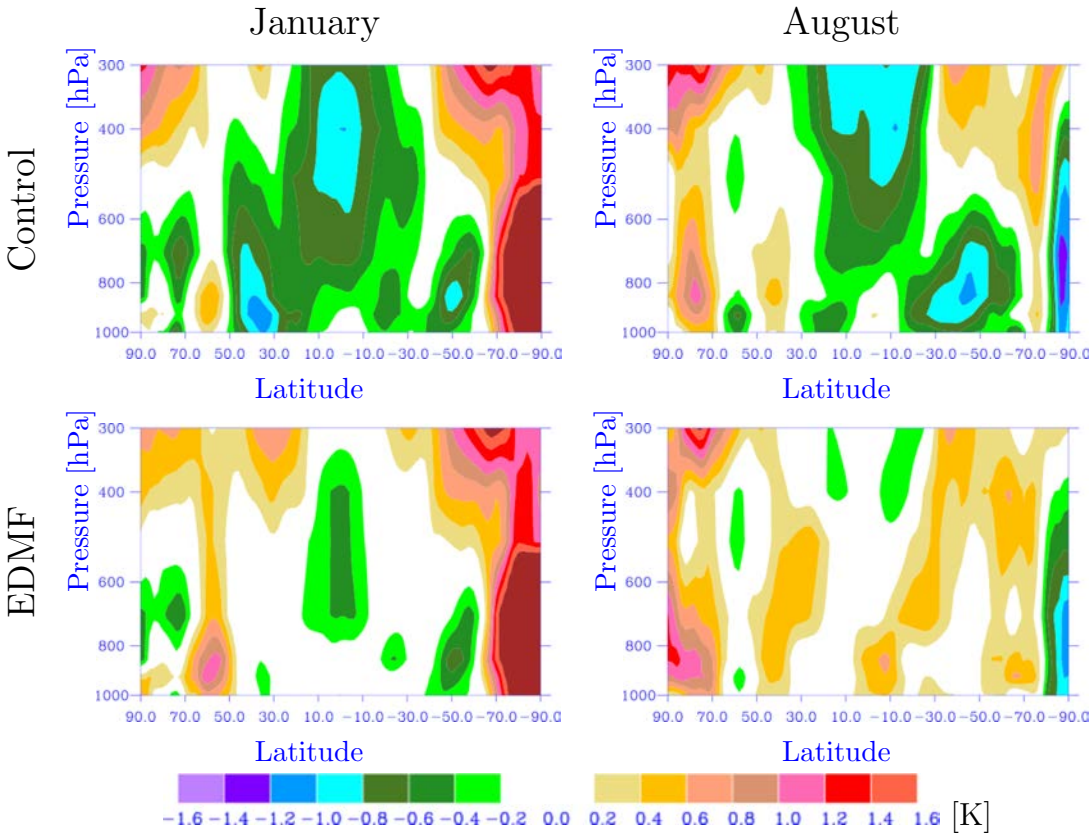


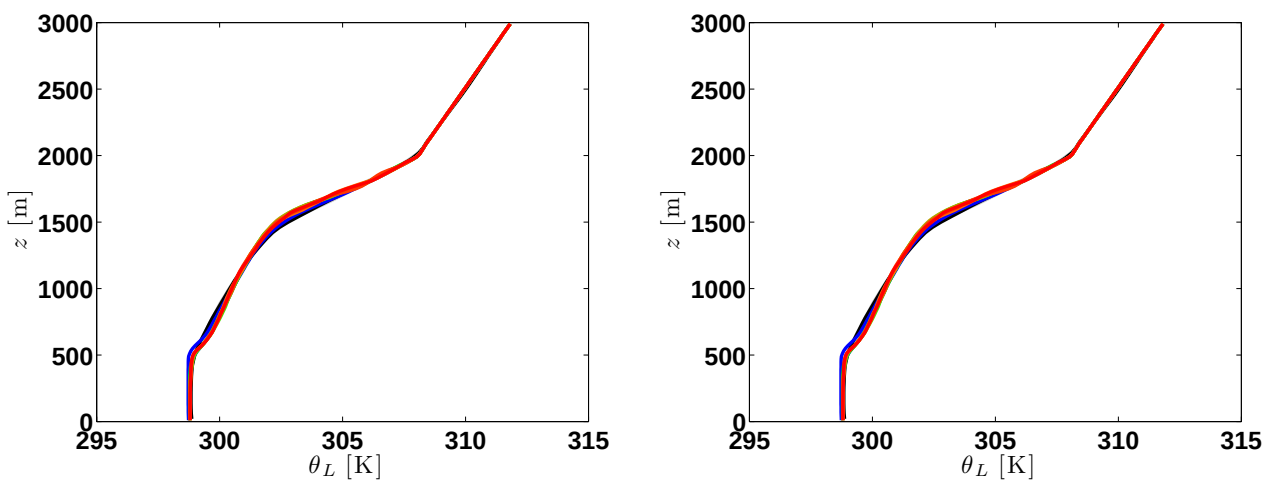
Fig.1: Zonal mean bias of NAVGEM temperature with respect to the analysis for the 120th simulation hour. Upper panel for Control simulation, lower for EDMF. Left panel for January 2013, right panel August 2013.

Recent Developments of the EDMF parameterization

We improved the current EDMF model, which is fully described in Suselj et al. (2012, 2013). One of the key differences between the older and the new parameterization is the assumption about the fractional area of the updrafts. In the older version (and also in virtually any other EDMF models) it is assumed that the fractional area of the updrafts is small, but this is not the case for the new model. As a result of this, all turbulent fluxes are computed as a sum of three terms: the eddy-diffusivity, the mass-flux and the environment-mean term. In the older version of the model, the environment-mean term is assumed to be zero which follows from the assumption of small updraft fraction area. The new decomposition of the turbulent fluxes is physically more justified and is the key reason that the sensitivity of the model to the surface fractional updraft area is small. In the new model, the way the updraft equations are solved is modified. Instead of integrating a single updraft from the surface,

computing partial cloudiness and splitting it into multiple updrafts at the cloud base, the new parameterization integrates multiple updrafts from the surface and does not need to split them at the cloud base. The sub-cloud entrainment rate in the new parameterization is modeled as a stochastic process in the same way as it is done in the cloudy layer. The surface conditions for the updrafts are specified assuming that the updrafts represent the tail of a normal distribution of vertical velocity and correlated distributions of thermodynamic variables. In the new parameterization, the entrainment length scale is computed as a function of surface convective velocity scale instead of the depth of convective layer. This modification seems to be more suitable for a large range of convective cases.

Fig. 2 and 3 show an example of shallow convection (the BOMEX case) results modeled with the new EDMF model, and sensitivity of the EDMF results to the prescribed surface updraft fraction area and the number of surface updrafts. In essence, Fig. 2 shows that the profiles of mean thermodynamic variables (liquid water potential temperature and total water mixing ratios) are well represented, which is a result of turbulent fluxes being reasonably modeled. To the large part the success of modeling of turbulent fluxes is due to the convective updrafts being properly represented (the lower panel on Fig. 2 compares selected properties of moist updrafts with the LES results). One of the most important results of Fig. 2 is that the EDMF results are not overly sensitive to the updraft surface area as long as the updraft surface area fraction exceeds a threshold value of around 5%. The reason for the small sensitivity in the subcloud layer is a well represented balance between the three turbulent components. As a result of surface updraft conditions and the stochastic entrainment rate only a small proportion of the surface updrafts become moist and continue rising in the cloudy layer. As long as the updraft surface area exceeds the above mentioned threshold value, the fractional cloud area is fairly independent of the fractional surface updraft area. Fig. 3 shows the EDMF sensitivity results in more detail. It shows the sensitivity of the cloud cover and liquid water path on the surface updraft fraction area and the number of surface updrafts used in the EDMF model. The results again show a small sensitivity to the surface updraft fraction area as long as its value exceeds the threshold value of around 5%. The sensitivity to the number of surface updrafts is also small. However the results of the numerical experiments with a smaller number of updrafts appear to be noisier.



Profiles of turbulent fluxes of thermodynamic variables

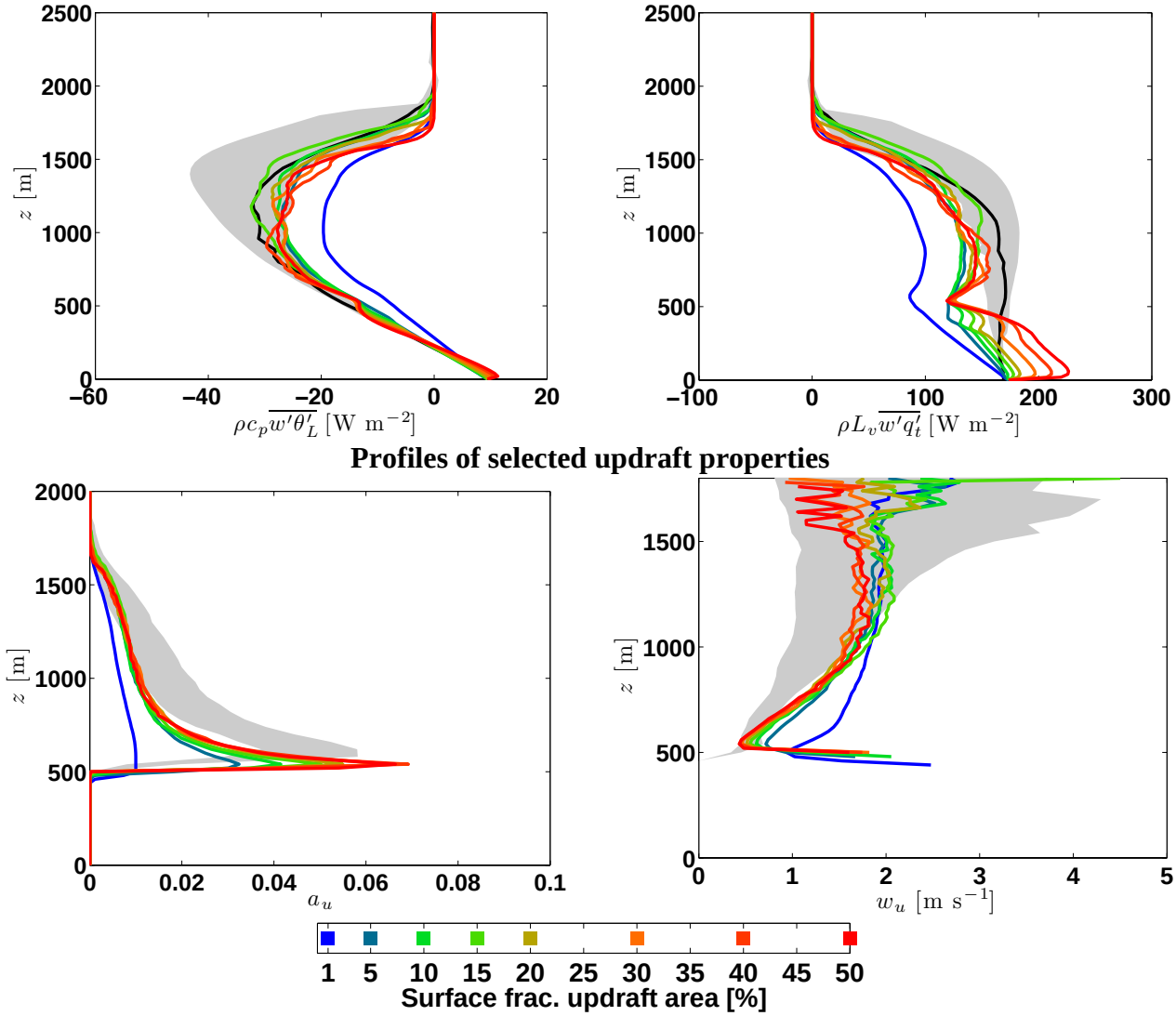
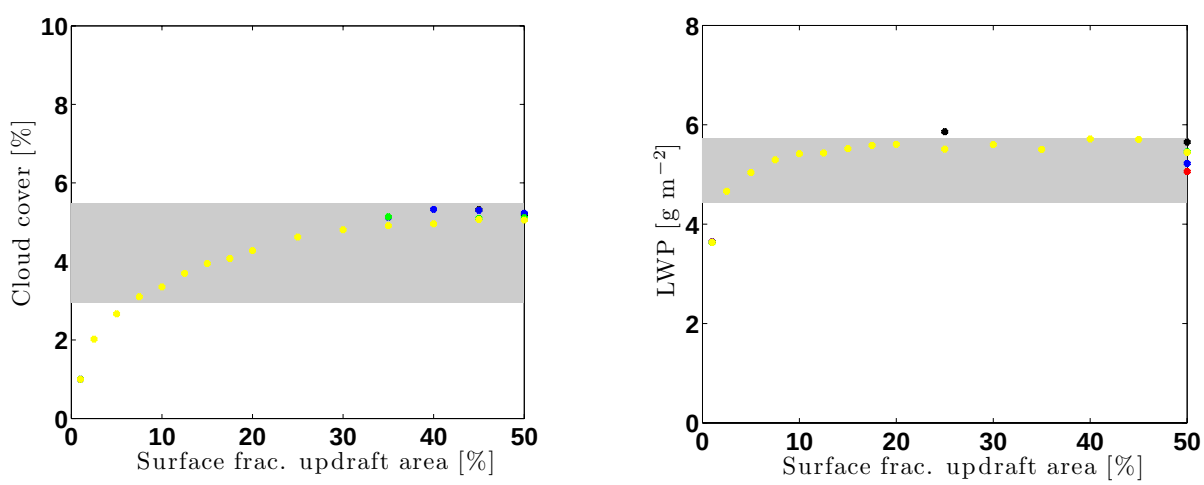


Fig. 2: BOMEX case. The profiles of thermodynamic variables (upper panel), their corresponding turbulent fluxes (middle panel) and selected updraft properties (lower panel). The black line and the gray area on the upper and middle panel represent the mean and the inter-quartile range from the multiple Large-Eddy-Simulation (LES) results. The gray area in the lower panel represents the range between the mean cloud-core and cloud-cover sampling from the LESs. The colored lines are the EDMF results for different surface updraft fraction areas. Results are averaged between hours 2 and 3.



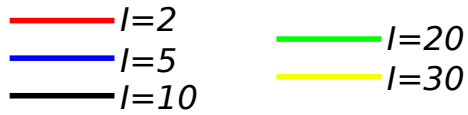
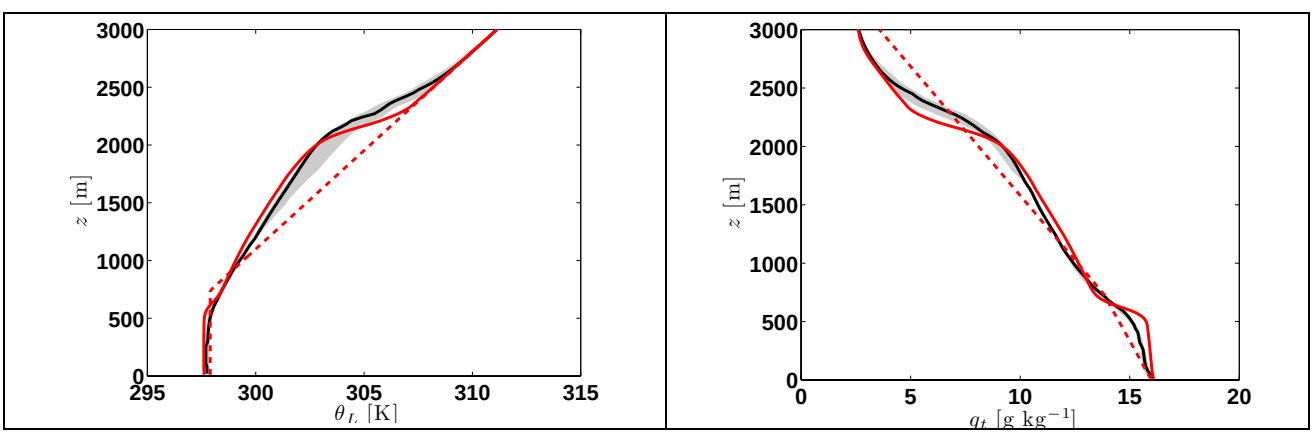


Fig.3: BOMEX case. Cloud cover and liquid water path from convective updrafts as a function of surface updraft fraction area. Colored lines show the EDMF experiment results for different number of surface updrafts (see legend). The grey area is the range of the results from the LESs.

Transition from shallow to deep convection

In order to properly represent the transition from shallow to deep convection the following new developments in the EDMF parameterization were done: (1) Modifying the parameterization of cloud microphysics in convective updrafts to account for the ice processes. In the new model, the phase of water is a function of temperature. The ratio between ice and liquid water content is a linear function of temperature between -40°C and 0°C. Above 0°C water is assumed to be liquid and below -40°C it is assumed to be ice. (2) Inclusion of a simple parameterization of microphysical processes and formation of precipitation in the updrafts. The new model assumes simple conversion rates between cloud water and precipitating water, and for the evaporation of precipitating water. (3) Inclusion of convective downdrafts driven by evaporation of precipitation. We assume that each convective updraft has a complementary downdraft. The negative vertical velocity of the updrafts is fueled by negative buoyancy as a result of evaporation of precipitating water. (4) The organization of convection is modeled to be a function of an integrated precipitation rate. The updraft entrainment rate is a function of convective organization.

Fig. 4 shows the results for the precipitating RICO case and compares them to the LES results from van Zanten et al., (2011). This figure shows that the EDMF represents well the profiles of thermodynamic variables and the rain rate. In the EDMF model, the majority of the surface precipitation originates from the convective updrafts, but precipitation from the downdrafts is considerable. The lower right panel on Fig. 4 shows that the surface precipitation rate varies among different realizations of the EDMF model. This is primarily a result of stochastic entrainment rate and the interaction between the convective dynamics and microphysics. The variability of the surface precipitation rate among different realizations is a function of the number of the surface updrafts. In simulations with the smaller number of surface updrafts, this variability appears to be larger. The EDMF surface precipitation results are all within the spread of LES models.



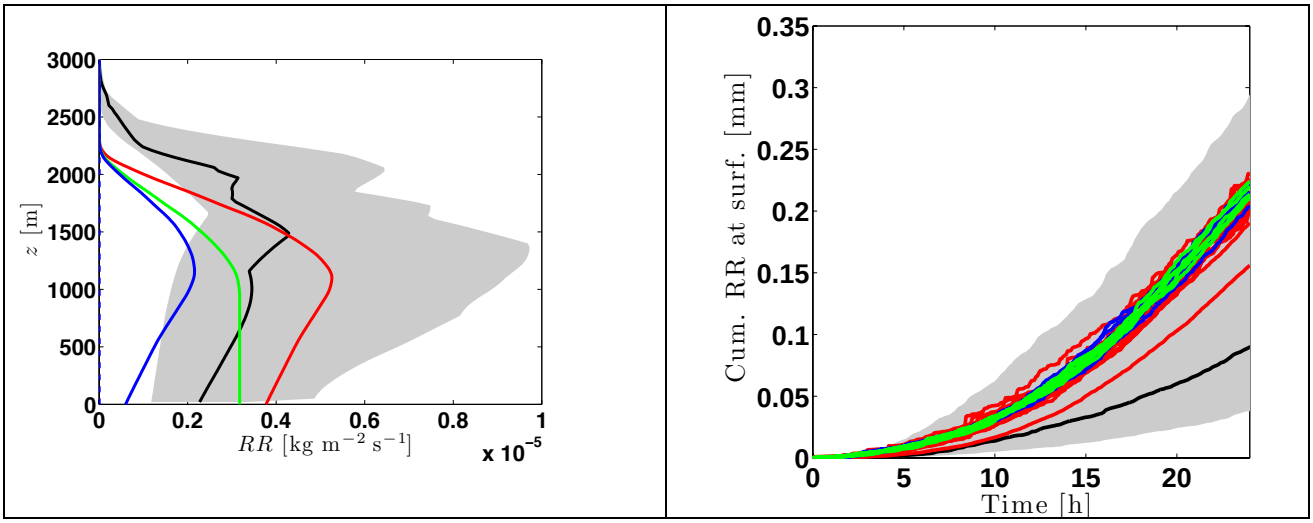


Fig.4: RICO case. Profiles of thermodynamic variables averaged between the 23rd and 24th simulation hour (upper panel). Dashed red lines are initial conditions, full red lines EDMF results. The black lines and the grey area are the mean and the inter-quartile range from the LESs. The profile of rain rate (upper left panel) averaged between the 23rd and 24th hour. The black line and the gray area are the LES results (mean and inter-quartile range), the green line is for the rain rate in convective updrafts, blue for the rain rate in the downdrafts and red line is for the total rain rate (the sum of the rain rate from updrafts and downdrafts). Cumulative surface rain rate for five EDMF experiments with 10 updrafts (red lines), 20 updrafts (blue lines) and 30 updrafts (green lines). The black line and the gray area are for the LES results.

Fig. 5 shows the results for the diurnal cycle of deep convection – the EUROCS case. It essentially shows that the EDMF is able to represent the growth of the convective layer, which is shallow at the onset, and the fast growth of the shallow convection to deep and precipitating convection. The EDMF results compare well to the cloud-resolving-model (CRM) results. This is quite a significant result, as most other parameterizations show an abrupt transition between the shallow and deep convection regimes.

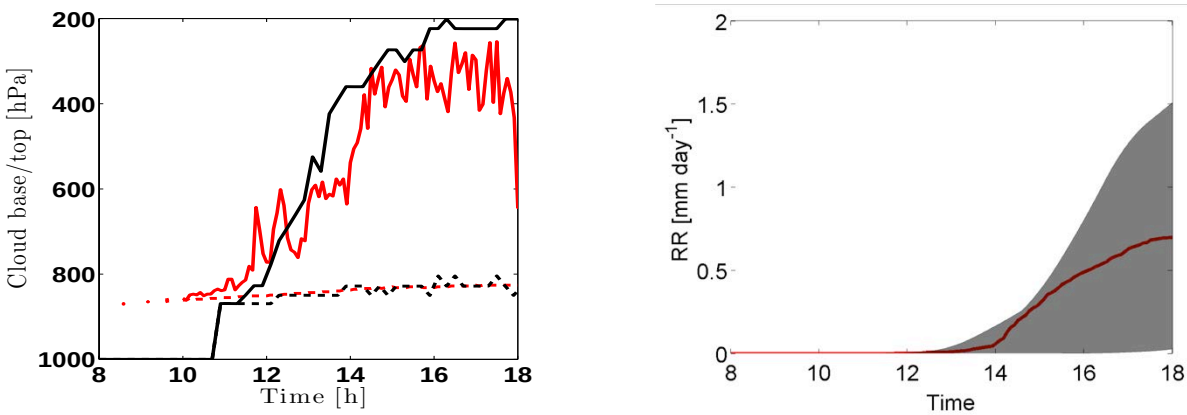


Fig.5: EUROCS case. Time series of cloud base and cloud top (left panel). Black lines are for the CRM and red lines for the EDMF results. Surface precipitation (right panel). Black area is for CRMs and red lines for EDMF results.

Conclusions

The EDMF parameterization in NAVGEM complements the boundary layer parameterization by simulating surface forced moist convection. 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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