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 US Navy NOGAPS model; and (iii) the transition of this new version of the NOGAPS model into operations at Fleet Numerical Meteorology and Oceanography Center (FNMOC).

OBJECTIVES

The objectives of this project are: i) to develop a unified parameterization for the Marine Boundary Layer (MBL) and ii) to implement and test this parameterization in the Navy Operational Global Atmospheric Prediction System (NOGAPS). 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 will be 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 NOGAPS within the context of this ONR DRI.

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

WORK COMPLETED

Evaluation of new EDMF/PDF parameterization in Single Column Model (SCM):

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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.

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

RESULTS

Introduction

A parameterization which is suited to represent moist convective boundary layers is implemented in the NOGAPS single-column-model (SCM). The parameterization is based on a stochastic eddy-diffusivity mass-flux (EDMF) approach. In the EDMF framework, turbulent fluxes are calculated as a sum of the down-gradient (eddy-diffusivity) based component and a mass flux component (e.g. Siebesma et al., 2007). The eddy-diffusivity component is based on Louis et al., (1982), as implemented in the current version of the NOGAPS SCM, while the parameterization of the mass-flux component is new in NOGAPS.

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) that the EDMF model has the capability to capture the essential features of moist boundary layers, ranging from stratocumulus to shallow-cumulus regimes.

The EDMF parameterization is implemented in the NOGAPS SCM. We show that the new parameterization improves the parameterization of convective boundary layers. The results from two sets of cases are shown: i) various dry convective boundary layer cases forced by a surface sensible heat flux, and ii) shallow moist convection (BOMEX case). In all simulations we use 91 vertical levels that correspond to ECMWF vertical levels.

Results from NOGAPS-SCM

Dry convective boundary layer

The NOGAPS-SCM is first tested on a dry boundary layer forced by positive surface latent and sensible heat fluxes. We perform the same simulations as in Witek et al. (2011). The initial conditions are described below. The well-mixed boundary layer has a height of 1350 m. In the boundary layer, the potential temperature is constant ($\theta = 300$ K) and the total moisture at the surface is $q = 5\times10^{-3}$ with a vertical gradient of $\partial q/\partial z = -3.7\times10^{-4}$ km^{-1}. Above the boundary layer height: $\partial q/\partial z = -9.4\times10^{-4}$ km^{-1} and $\partial \theta/\partial z = 2$ K km^{-1}. Only a small wind speed is prescribed (u=0.1 ms^{-1}). Three experiments are performed. They differ by the amount of prescribed surface sensible heat flux (see Tab. 1 for a list of experiments). The moisture flux was kept the same for all the experiments ($\overline{w'q'} = 2.5\times10^{-5}$ m s^{-1}).

The NOGAPS-SCM model results are compared to large-eddy simulation (LES) results (Figs. 1-3 compare the profiles of potential temperature and water vapor). The control NOGAPS-SCM does not represent the boundary layer well. The turbulent mixing is too weak and confined to the shallow layer near the surface (boundary layer height is too low). Due to the prescribed surface fluxes, near surface temperatures and total water mixing ratios are too high. Part of the reason is that the Louis et al., (1982) scheme is not well suited to work in the limit of free (no shear) convection. In Louis et al., (1982) turbulent mixing is a function of bulk Richardson number which in the limit of free convection approaches infinity. The NOGAPS-SCM with EDMF shows an obvious improvement with respect to the control simulation in terms of the depth of the boundary layer as well as the stability in the boundary layer. The boundary layer height is better represented as well as the gradient of potential temperature and total water mixing ratio. Adjusting the eddy-diffusivity parameterization could eventually produce further improvements in the model.

Simulation	Sensible heat flux (Kms^{-1})
A	0.03
B	0.06
C	0.12

Tab.1: List of dry convective boundary layer experiments.

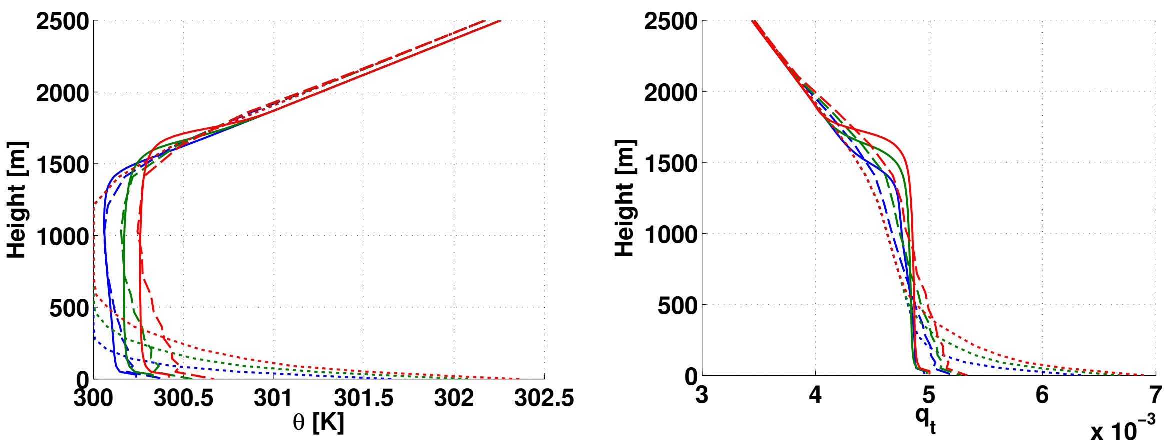

Fig.1: Potential temperature (left) and total vapor mixing ratio (right) profiles for experiment A. Solid line – LES results, dotted – control NOGAPS, dashed EDMF NOGAPS. Results are for 1 hour (blue line), 3 hours (green) and 5 hours (red) after the simulation start.

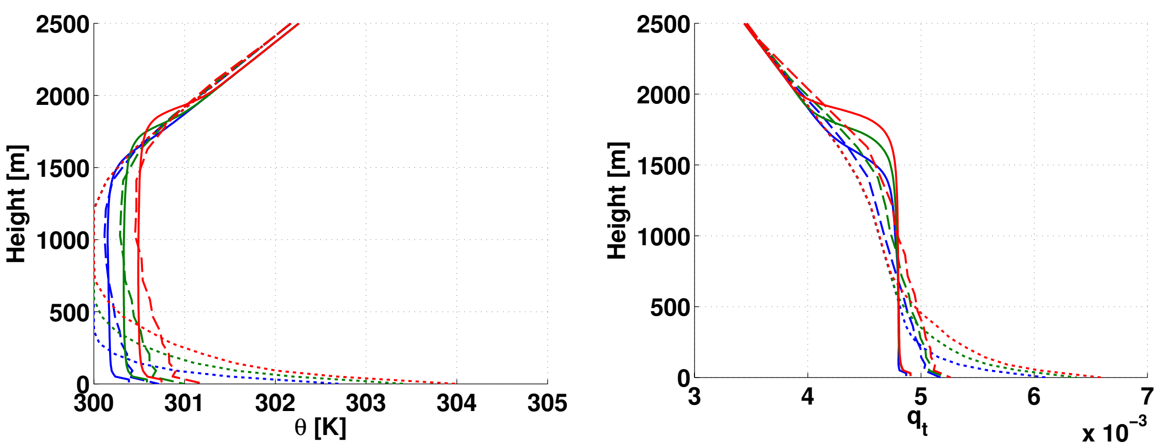

Fig.2: Potential temperature (left) and total vapor mixing ratio (right) profiles for experiment B. Lines are

the same as in Fig. 1

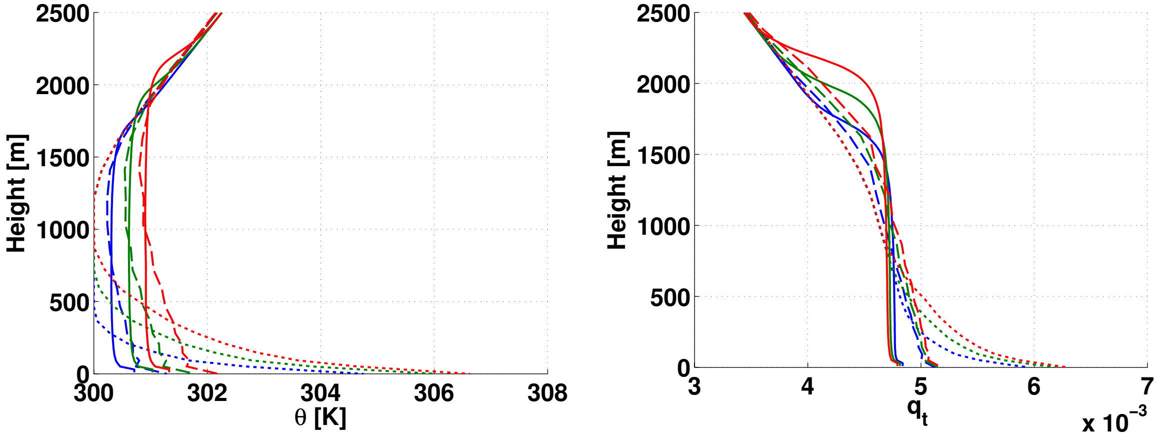

Fig.3: Potential temperature (left) and total water mixing ratio (right) profiles for experiment C. Lines are the same as in Fig. 1except that they are for 1 hour (blue line), 2 hour (green) and 3 hour (red) after the simulation start.

Shallow cumulus convection (BOMEX)

The shallow convection case BOMEX was run with the NOGAPS-SCM with the new EDMF and the model results are compared to the LES results from Siebesma et al., (2003). The BOMEX case is characterized by a dry well-mixed subcloud layer, reaching from the surface to around 600 m, topped by a non-precipitating shallow cumulus cloud layer. The boundary layer turbulence is forced mainly by buoyancy flux, the wind shear being small.

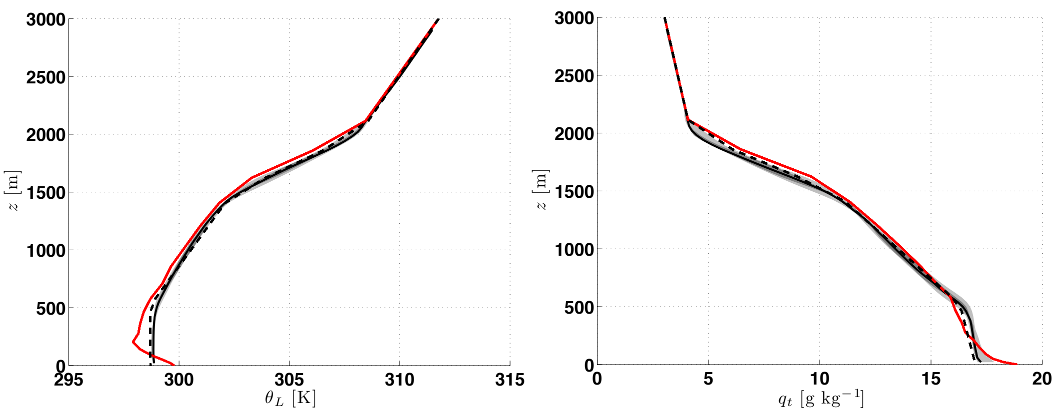

Fig.4: Liquid water potential temperature (left) and total water mixing ratio (right) from the EDMF NOGAPS-SCM (red line), LES (black line) and initial conditions (dashed black line). The shaded area represents the range from different LES models (see Siebesma 2003 for details). Both the EDMF NOGAPS-SCM and LES results are after 3 hours of simulation.

Fig. 4 shows the profiles of moist conserved variables from the EDMF NOGAPS-SCM and compares them to LES results. The turbulent fluxes in the subcloud layer should be mostly represented by the eddy-diffusivity parameterization and in the cloudy layer by the mass-flux part (Sušelj et al. 2012). The profiles of moist conserved variables are well represented in the cloudy layer and less well in the subcloud layer. This indicates that the eddy-diffusivity part of the parameterization would need further improvements while the mass-flux part of the parameterization is well suited to represent the moist thermals (convective clouds). Fig. 5 shows the mean updraft area, vertical velocity and excesses of moist conserved variables and compares them to LES results. In general the mass-flux part of the parameterization represents well the expected values from the LES model, except for the vertical velocity. Part of the problem in parameterizing the profile of the vertical velocity is that the surface conditions are not well represented. This can be improved by making the eddy-diffusivity part of the parameterization more realistic.

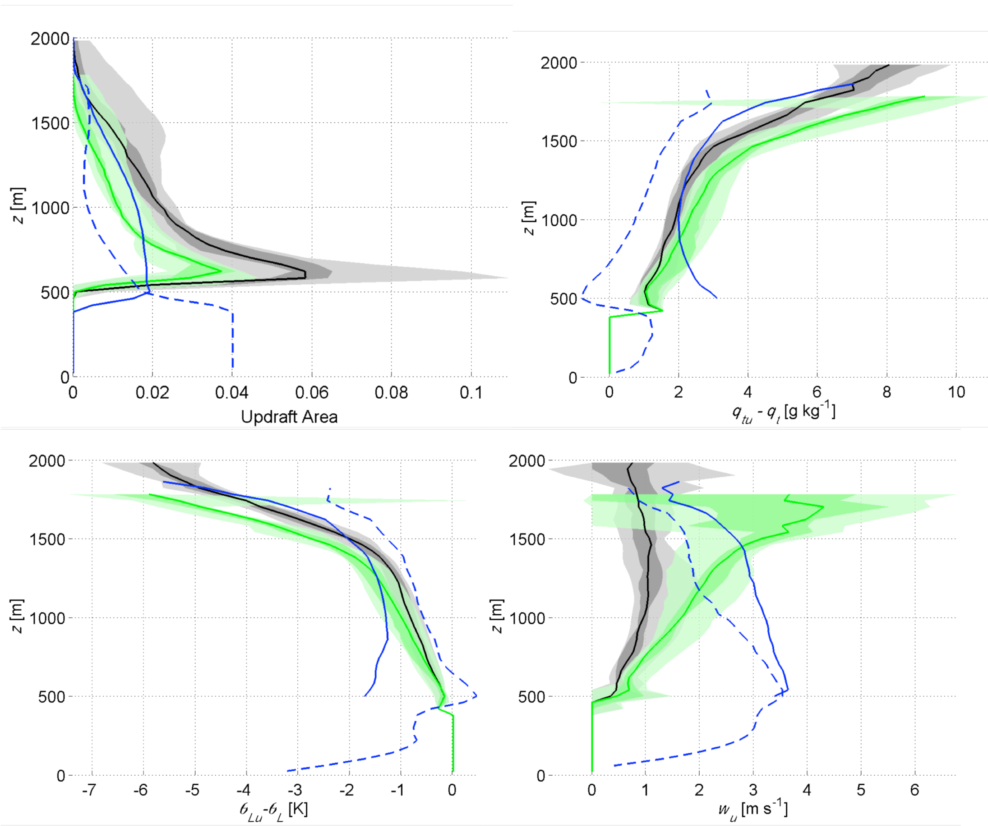

Fig.5: Updraft properties for the BOMEX case. Blue lines represent the EDMF NOGAPS-SCM (full lines the moist updrafts, dashed lines the dry). Black and green lines represent the mean of the cloud and cloud cores from LES and dark (light) green and gray areas represent the inter-quartile (total) range from LES. Cloud and cloud cores represent different sampling of LES results (see Siebesma et al., 2003 for details). The SCM results are expected to be between cloud and cloud core values.

IMPACT/APPLICATIONS

These results have an important potential future impact for the weather prediction capabilities of the US Navy after the implementation of these new parameterizations in the NOGAPS 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 will be proposed for a transition at FNMOC after implementation and adequate testing in the NOGAPS model.

RELATED PROJECTS

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

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