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Physics Parameterization for Seasonal Prediction

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LONG-TERM GOALS

This 6.1 project is part of a long-term effort to identify and solve the major challenges of parameterizing the impacts of physical processes on atmospheric predictions extending out to seasonal time scales. Achievement of this goal will represent a significant step towards the development of an operational global earth system model targeted by the national Earth System Prediction Capability-Research, Development, and Operations (ESPC-RDO) effort, in which the United States Navy is a participant.

OBJECTIVES

This project targets development of a "unified" treatment of atmospheric mixing processes, including interactions with clouds, within the Navy Global Environmental Model (NAVGEM) suitable for extended range prediction that includes not only boundary layer mixing, but mixing by shallow to mid-level convective clouds, as well as deep convection. The project will pursue a more consistent and realistic treatment of the relative magnitudes of these various mixing processes, focusing on the hydrologic cycle, but also addressing related momentum drag balance issues.

APPROACH

We are focusing on ensuring a more comprehensive representation of key processes in the hydrologic cycle in NAVGEM. We continue to work towards improved fidelity of our physics codes to current understanding of atmospheric processes, and are seeking to adapt and test new physics treatments as well, particularly those developed under this DRI. A significant question remains concerning the key physics requirements for simulation of important modes of predictability on extended timescales, particularly the Madden Julian Oscillation (MJO). We are continuing our participation in the project "Vertical Structure and Diabatic Processes of the MJO", a joint effort between the Year of Tropical Convection (YOTC) Program and the Global Energy and Water Cycle Experiment (GEWEX) Cloud System Study (GCSS). This large collaborative effort is investigating the sensitivity of the representation of the MJO to various model formulations, providing us an excellent opportunity to leverage our development efforts under this DRI project. Evaluation of progress achieved will include

a range of global data sets, and will be aided through analysis of errors on shorter timescales using the state-of-the art data assimilation component of NAVGEM.

The key performers on this project are Drs. James Ridout (PI) , Melinda Peng (Co-PI), Maria Flatau and Shouping Wang, all employed by NRL in the Marine Meteorology Division, and Dr. Piotr Flatau, a visiting scientist from Scripps Institute.

WORK COMPLETED

1) Modified Kain-Fritsch Convection Scheme Update. A major focus of our parameterization effort this year was atmospheric convection. We made considerable progress further refining the modified Kain-Fritsch convection scheme of Ridout et al. (2005), building on efforts made under this project in FY14, and described in our report last year.

a) Coupling of convection with boundary layer plumes. Forcing of convection by plumes in the convective boundary layer is of considerable importance over the tropical warm pool regions, where the resultant cumulus and cumulus congestus are ubiquitious (e.g., Mapes 2000). The process is thought to be of critical importance in the physics of equatorial waves and the MJO. For our present work with the modified Kain-Fritsch convection scheme, the parameterization of this process is a fairly simple algorithm by which plumes from the NAVGEM EDMF (Eddy-Diffusivity/Mass-Flux) scheme provide information on vertical velocity and temperature perturbations at cloud base level, as well as a first estimate of the convective cloud base mass flux of the turbulence-forced convection. The treatment includes a capping of the plumes in the EDMF scheme as described in the FY14 report. Changes this year fall into two major categories: i) EDMF plume and capping details, ii) impact of wind shear. The work completed this year under each category is as follows:

i) The capping treatment in the NAVGEM EDMF scheme depends strongly on the estimated boundary layer depth. This year we replaced in our development code the computation from NAVGEM 1.3 with one based on the treatment in the planetary boundary layer (PBL) scheme by Troen and Mahrt (1986), which includes a consideration of thermals and counter-gradient transports. The new formulation is better suited for application to the convective boundary layer than the simple gradient Richardson number treatment used previously. In addition, in recent tests we have examined the impact of simple modifications of the EDMF plume characteristics within the boundary layer.

ii) The current EDMF scheme has no explicit dependence on winds other than their impact on the surface buoyancy flux, which is used to estimate initial plume properties. There is reason to consider incorporating a more explicit wind dependence, including evidence cited by Stull (1994) that wind shear can play an important role in the growth of such plumes. Work by Grossman(1982), as well as more recent work, e.g., Zheng et al. (2015) can also be cited. Based on such evidence, Ridout and Reynolds (1998) proposed a "thermal growth parameter" t_g that scales between 0 and 1 based on the "mixed layer Richardson number" introduced by Stull (1994) for boundary layer regime classification. The parameter t_g was used as a type of trigger for boundary layer turbulence generated convection. In FY15, we began tests in which the parameter t_g was utilized along with the modified Kain-Fritsch scheme in NAVGEM to scale the cloud base mass flux for turbulence-forced convection and to limit EDMF plume height for forced convection conditions to the top of the boundary layer. The "deep-convection" or "dynamically-forced" mode is not directly impacted by this treatment.

b) Cloud model properties. Work was initiated in response to comparisons of ESPC coupled system hindcasts using the modified Kain-Fritsch scheme with a key diagnostic result that came out of the recent "Vertical Structure and Diabatic Processes of the MJO" project's MJO simulation intercomparison study (Klingaman et al. 2014). Models that were able to best represent the MJO were found to exhibit a characteristic pattern of net moistening as a function of pressure and rainfall rate. We were not seeing this moistening pattern in our DYNAMO period MJO hindcasts with the modified Kain-Fritsch convection, and in an effort to investigate the cause of the apparent deficiency, hindcasts were carried out for a series of changes in both the cloud model component of the convection scheme as well as the EDMF plume properties ((a), part (i) above). The cloud model changes tested include the cloud top condition as well as changes to the buoyancy sorting treatment of updraft-environment mixing to include effects of condensate loading.

2) COAMPS evaluation. In collaboration with Dr. Larry Mahrt, stable boundary layer observations of CBLAST 2002-2003 were used to evaluate the COAMPS (Coupled Ocean/Atmosphere Mesoscale Prediction System) PBL parameterization. We applied the single column version of COAMPS to simulate the cases of August 7 and 8 using observed sea surface temperature and the aircraft soundings. The August 7 case is weakly stable with a higher PBL top and stronger turbulence; the August 8 case is a strongly stable case with a wind jet level much lower than that from August 7. To improve the PBL parameterization, we performed sensitivity tests by modifying the mixing coefficient and mixing length based on the control simulation.

In collaboration with Prof. Qing Wang of the Naval Postgraduate School, we carried out an observational and large-eddy simulation (LES) study of wind shear, convective circulation and cloud organization. COAMPS-LES was applied to case RF02 from the UPPEF 2012 campaign off the California central coast near Monterey to study how wind shear affects stratocumulus organization. The LES domain covers a 5km×5km×2km region with a horizontal resoution of 10m and 5m in the vertical. Boundary layer observations were used to initialize the LES simulations with various wind shear profies. Analysis was performed to understand the impact of wind shear on cloud organization.

RESULTS

1) Modified Kain-Fritsch convection scheme update. The ongoing work on the modified Kain-Fritsh scheme was tested in FY15 primarily by means of ESPC coupled system hindcasts for the fall 2011 DYNAMO (Dynamics of the Madden Julian Oscillation) observational period in a collaborative effort with our 6.4 ESPC and NRL 6.2 MJO projects. The hindcasts were initiated on 1 Nov. when the first MJO event of DYNAMO was in stage 3 (with rainfall centered in the middle to eastern part of the Indian Ocean). The second MJO of the DYNAMO period began about 21 Nov. Hindcast results out to 30 days are shown in Fig. 1, which shows how the modified Kain Fritsch scheme implementation (including, though of lesser significance, also a replacement of the air-sea flux scheme in NAVGEM with the HYCOM COARE 3.0 scheme) compares with the NAVGEM 1.3 moist physics. Both runs include other physics developed under this ONR DRI and described in previous reports, notably the EDMF scheme (developed under the JPL group DRI project led by Dr. J. Teixeira), the NAVGEM 2-phase cloud scheme and the Xu-Randall(1996)/Ridout cloud fraction parameterization, all of which are now operational at FNMOC. We see in Fig. 1 a significant improvement with the modified Kain-Fritsch implementation, especially for the second MJO event, both with respect to rainfall and the low level zonal flow. Other tests (not shown) demonstrated strengthening and expansion of the Indian Equatorial Countercurrent in association with the westerly wind burst episode

towards the end of November. Associated feedbacks on latent heat fluxes appear to be non-negligible, with reductions of up to 10 W m^{-2}.

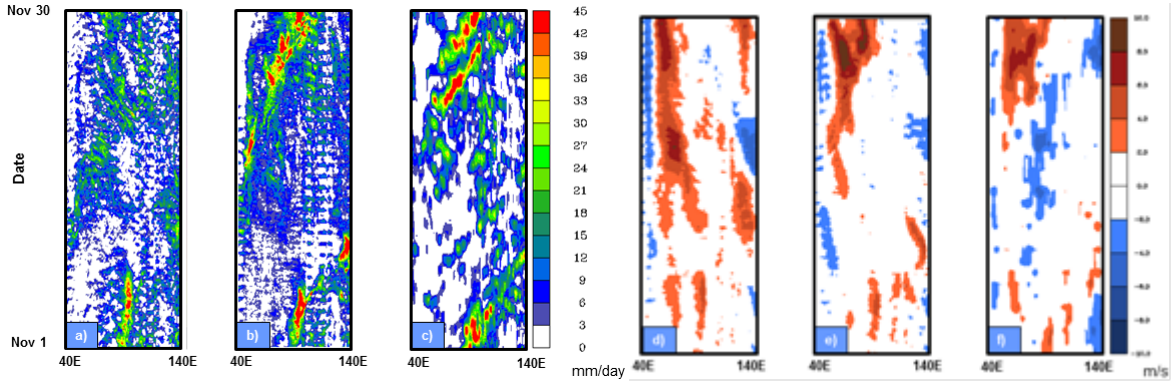

Figure 1. Hovmöller plots of rainfall (a) – (c) and 10-m zonal wind (d) – (f) averaged between 5N – 5S for Nov. 2011 as they varied with time (vertical axis) and degrees longitude (horizontal axis). Plots (c) and (f) show TRMM retrieval and NAVGEM analysis data, respectively. Hindcast results from the ESPC coupled system are shown in (a) and (d) using the NAVGEM 1.3 moist physics, and (b) and (e) using the modified Kain-Fritsch scheme along with the HYCOM COARE 3.0 air-sea flux scheme.

DYNAMO period hindcasts were also carried out in which the modified Kain-Fritsch scheme was implemented along with the treatment for shear effects on thermal growth described in section 1(a)(ii) above. Hovmöller plots of rainfall for these 40-day hindcasts are shown in Fig. 2. The plot in Fig. 2a is for a control run with the modified Kain-Fritsch scheme (same run as in Fig. 1b). Figures 2b and 2c show results obtained using the treatment for shear effects (Fig. 2c includes some tuning of the parameters for the cloud fraction parameterization). The impact of the shear effect treatment is to enhance somewhat the rate of eastward propagation, which is encouraging. Although rainfall maxima

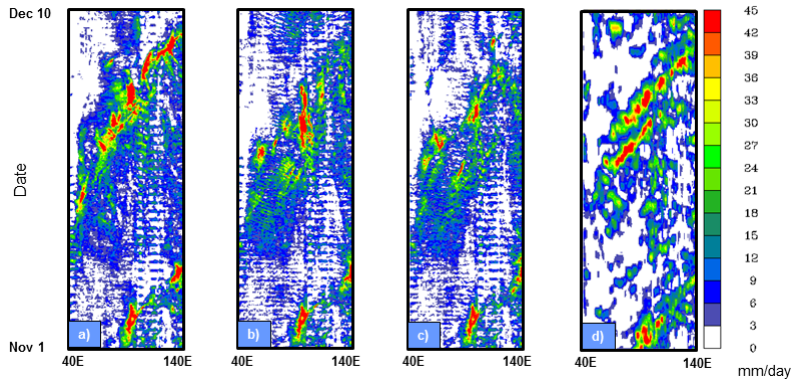

Figure 2. Hovmöller plots of rainfall averaged between 5N – 5S for November 2011 showing variability with time (vertical axis) and degrees longitude (horizontal axis). Plot (d) shows the TRMM retrieval data. The hindcast results with the modified Kain-Fritsch convection scheme (a – c) represent: (a) control, (b) shear effect treatment, and (c) shear effect treatment with modified cloud fraction scheme parameters.

are reduced somewhat too much, work is continuing on the cloud model portion of the scheme, which may provide further improvements. Further evidence of the positive impact of the shear treatment is shown in Fig. 3, which shows the heating by the two convective modes for three four-day periods during the second of the two MJO events shown in Fig. 2. There is a dramatic shift in dominance from the turbulence-forced mode to the dynamically-forced mode when the shear treatment is used. Observations (cf. Mapes 2000) suggest the dynamically-forced mode should be dominant, so this result is very encouraging. The shear treatment based on the mixed-layer Richardson number appears to greatly improve the realism of the convective mode decomposition in the modified Kain-Fritsch scheme. These results lend support to efforts to further tailor the cloud model features for the two separate convective modes.

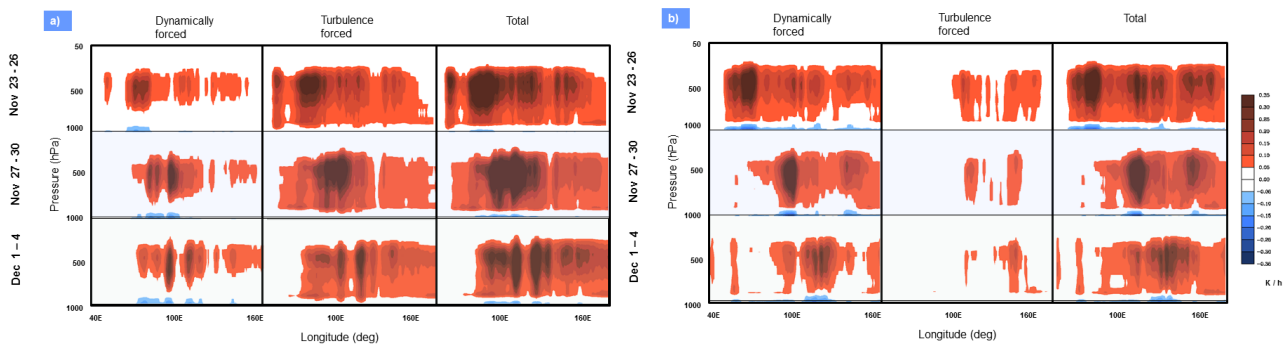

Figure 3. Vertical cross-sections of the longitudinal distribution of convective heating averaged between 5N – 5S for three four-day periods. Figure 3a shows results without the shear treatment (corresponding to Fig. 2a above), and Fig. 3b shows results with the shear treatment (corresponding to Fig. 2c above).

Because we have achieved some considerable success in improving the representation of the MJO in the ESPC coupled system , it was disappointing (and somewhat surprising) to find that our hindcasts were not able to reproduce the key diagnostic moistening pattern for MJO simulation referred to in section 1b. Recent success in this regard is illustrated in Fig. 4, which shows the published moistening rate diagnostic using the ECMWF analysis data (Fig. 4a) along with recent results obtained by a combination of modification of the plume perturbation profile in the EDMF scheme and a modified cloud top condition in the modified Kain-Fritsch scheme (Fig. 4b).

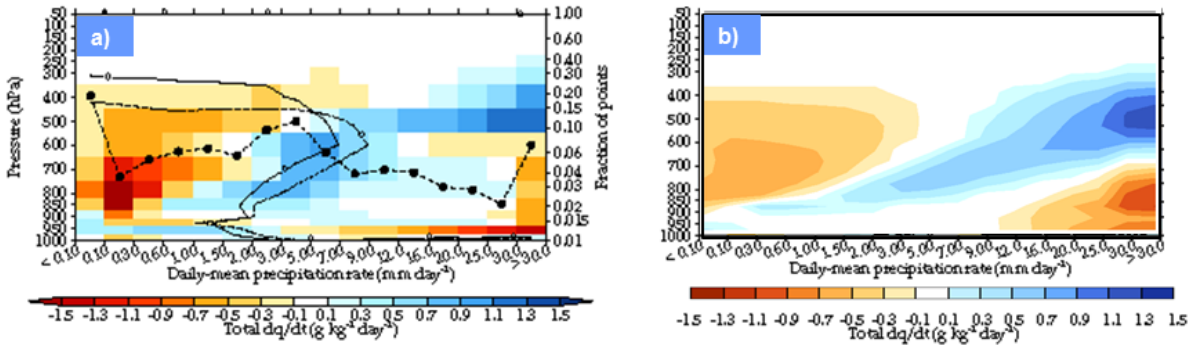

Figure 4. Vertical cross-sections of net moistening as it varied with preciptation rate (horizontal axis) for a region bounded by 10N -10S and 60E – 180E for a) ECMWF YOTC period analysis (see Klingaman et al. (2014)) and b) modified Kain-Fritsch scheme in a ESPC coupled system 20-day hindcast from 1 Nov. 2011.

Work is continuing on this issue, along with our usual coordinated NAVGEM tests in data assimilation mode to ensure a solution is obtained consistent with global application of the scheme.

2) COAMPS evaluation. The current COAMPS stable PBL parameterization results in excessive mixing for the weakly stable CBLAST case investigated (August 7), and leads to the disappearance of the low level jet *U* component and a considerable overestimate of the TKE as shown in Fig. 5a. Reducing the transfer coefficient or halving the mixing length in COAMPS slightly improves the simulation in that the BL top decreases. The turbulence intensity is still very large compared with the observations, suggesting that further modifications are needed to significantly improve the simulations. For the strongly stable case (August 8), the COAMPS simulation represents the strong low level jet and thermal profiles fairly well (Fig. 5b). Further reducing the transfer coefficient slightly improves the performance. The simulated turbulence intensity is, however, considerably weaker than the observations. These simulations suggest that the COAMPS stable PBL parameterization performs better in cases of strongly stable boundary layers than weakly stable PBLs. This is a bit surprising as we set out to focus on the extremely stable cases and are concerned about the turbulence collapse under strongly stable stratifications.

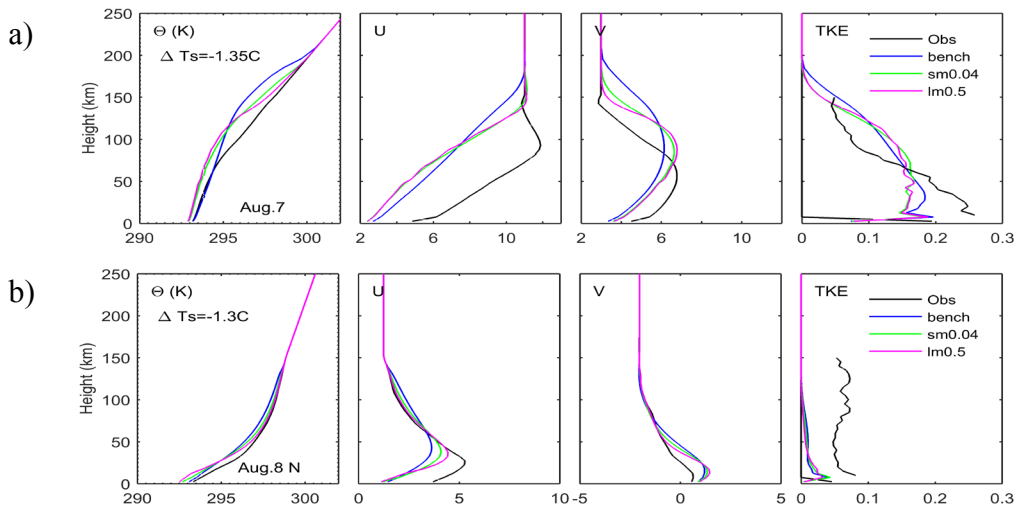

Figure 5. COAMPS single column mode simulations of the stable PBL cases from CBLAST 2002. a) weakly stable case; b) strongly stable case. Black represents observations; blue the control simulation; green the smaller mixing coefficient; and magenta the half mixing length.

The COAMPS-LES simulated mean and turbulence variables for case RF02 from the UPPEF 2012 campaign compare reasonably well with observations (not shown). In particular, the cloud water, latent heat flux and horizontal TKE are well simulated. Analysis shows that the near surface vertical velocity is organized by two scales of coherent structure: 200m wavelength streaks caused by the surface wind shear and a 1.7km wavelength cloud circulation driven by the cloud-top radiative cooling. Sensitivity simulations show that surface wind shear enhances the turbulence intensity while the inversion wind shear weakens turbulence as the mechanical mixing reduces cloud water and radiative cooling.

IMPACT/APPLICATIONS

The parameterization development under this project is expected to contribute to future strategic planning capabilities of the United States Navy. In addition to helping enable skillful extended range prediction, benefits to current short- to medium range forecasting capabilities are also expected.

RELATED PROJECTS

The NRL 6.2 project "The Madden Julian Oscillation: Key to Extended-range Predictability" (PI Dr. Carolyn Reynolds) and the 6.4 ESPC project (PI Dr. Carolyn Reynolds) provide a transition pathway for this 6.1 project.

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