A Framework to Evaluate Unified Parameterizations for Seasonal Prediction: An LES/SCM Parameterization Test-Bed

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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 and evaluation 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 main objective of this particular project is to develop a framework to test and evaluate unified parameterizations in NAVGEM using Large-Eddy Simulation (LES) models. In particular we will: i) develop a Single Column Model (SCM) version of the latest operational NAVGEM that can be used to simulate GEWEX Cloud Systems Study (GCSS) case-studies; ii) use the LES developed at JPL to simulate the GCSS case-studies and to evaluate and develop parameterizations iii) develop an integrated framework to use the NAVGEM SCM and the LES model as a parameterization test-bed.

APPROACH

It is well accepted that sub-grid physical processes such as turbulence, convection, clouds, aerosols and radiation play an essential role in the accuracy of ocean-atmosphere coupled prediction systems. Unfortunately most of these small-scale processes are extremely difficult to represent (parameterize) in global models such as the Navy's NAVGEM. The Marine Boundary Layer (MBL) in particular is known to play the key role in regulating the interaction between the ocean and the atmosphere. A common strategy on how to tackle MBL parameterization development has been developed during the last 15 years by the GEWEX Cloud Systems Study (GCSS) working groups. In this project we will follow this GCSS strategy by creating a unified framework to develop and evaluate parameterizations in NAVGEM using high-resolution Large-Eddy Simulation (LES) models.

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 and its testing using LES models.
- T. Hogan (NRL) uses his expertise in global modeling to assist with the investigations related to NAVGEM within the context of this ONR DRI.
- G. Matheou and M. Inoue (JPL/Caltech) develop and implement the LES code in the context of the parameterization evaluation framework for the NAVGEM model.

WORK COMPLETED

1) Development and testing of the NAVGEM Single Column Model (SCM)

2) LES simulations and utilization of LES data to evaluate and calibrate parameterizations:
  i) LES simulations and NAVGEM evaluation in stratocumulus and cumulus GCSS cases;
  ii) LES simulations and NAVGEM new parameterization evaluation in transition GCSS cases.

3) Development of specific LES case-studies and diagnostics targeting parameterization development

RESULTS

Implementation
The LES code numerically integrates the filtered (density-weighted) anelastic approximation of the Navier–Stokes equations (Ogura and Phillips, 1962). The base-state density $\rho_0(z)$ is calculated from the hydrostatic balance at Θref and p_{ref} = 1000hPa. In the cases where precipitation is included, the double-moment bulk microphysical parameterization of Seifert and Beheng (2001) is used. The fourth-order fully conservative advection scheme of Morinishi et al. (1998) is used to ensure that any dissipation arises purely from the subgrid scale closure. To preserve conservation of water, a second-order MC flux-limited scheme that ensures monotonicity is used to advect rain mass and raindrop number. Time is advanced using the low-storage third-order Runge–Kutta scheme of Spalart et al. (1991). The subgrid condensation scheme is all or nothing (e.g. Cuijpers and Duynkerke, 1993). The buoyancy-adjusted stretched-vortex subgrid-scale model (Misra and Pullin, 1997; Voelkl et al., 2000; Pullin, 2000; Chung and Matheou, 2014; Matheou and Chung 2014) is used to account for the unresolved turbulent physics. The horizontal boundaries are periodic and the top and bottom boundaries are impermeable with a 'sponge' region near the top boundary to minimize undesirable gravity wave reflection.

Unlike previous LES applications in simulations of atmospheric boundary layers, the present LES is used to simulate a diverse set of conditions without any tuning or change in the setup. In the following pages, results for various cases are briefly documented. In all these cases the model setup is identical, the only difference is initial and boundary conditions, and large-scale forcing. A main aspect of the simulations reported here is the performance of the implementation as the grid resolution changes. This is a consistency check, that although simple in nature, it is difficult to achieve in practice. The LES predictions of the present framework exhibit good resolution independence, even for grids that are typically considered coarse. The JPL LES uses a shared memory (MPI) parallelization strategy to take advantage of multiprocessor computers. There is no inherent limitation on the number of computer processors than can be used. Runs utilizing up to 4096 CPU-cores have been carried out with good parallel performance.

Shallow precipitating cumulus

A trade-wind precipitating cumulus-topped boundary layer is simulated by the JPL LES model. Conditions correspond to the RICO campaign (Rauber et al., 2007). The setup of the case and model inter-comparison is detailed in VanZanten et al. (2011). The domain size is 20x20x4 km^3. Three grid resolutions were used at Δx=20, 40, and 80 m.

Figure 1 shows the radiance distribution at the top of the atmosphere for the RICO precipitating shallow cumulus case. The radiance field was calculated with the MYSTIC three-dimensional radiative transfer model (Monte carlo code for phYSically correct Tracing of photons In Cloudy atmospheres). The solar zenith angle is 45°, the solar azimuthal angle is 25° (i.e., the Sun is at southwest) and a virtual sensor is north looking toward the south (top of figure) at a 45° viewing angle from the nadir direction. The calculation is for a red wavelength of 671 nm and assumes a Gamma size distribution for the cloud droplets with effective radius, r_{eff} = 10 μm, and variance of 0.1 to convert liquid water content into cell opacity. The dark areas correspond to the cloud shadows on the ocean surface, which is assumed uniform and modeled as a rough Fresnel interface with the Cox–Munk distribution of slopes for a wind speed of 10 ms^{-1}.

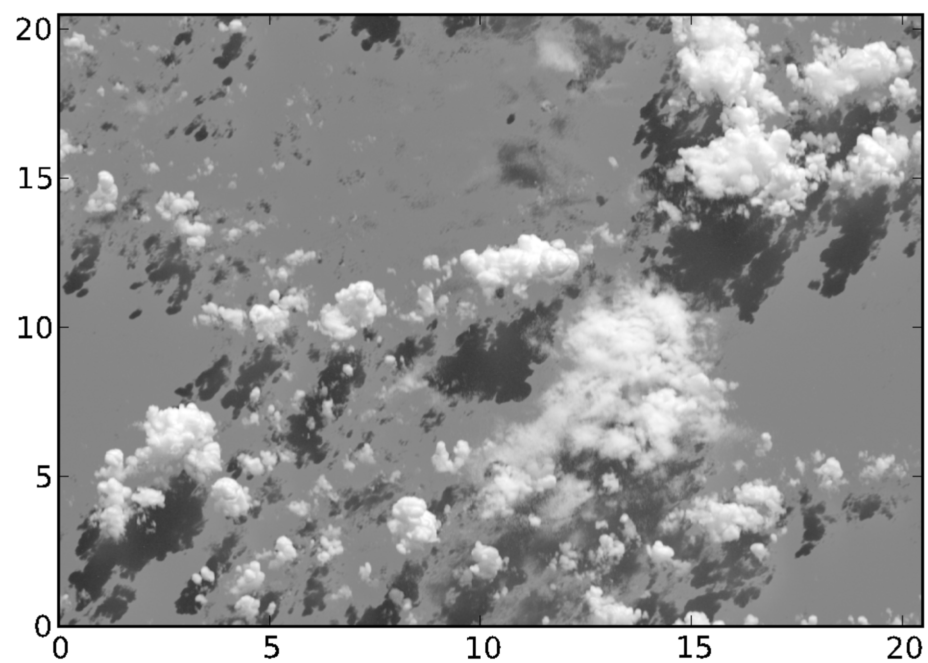

Figure 1: Precipitating shallow cumulus. The evaporation of precipitation in the sub-cloud layer creates cold pools, areas void of cloud, with convection forming upwind of the cloud pools. Small anvils form at the top of the larger clouds. The scale is in km.

Marine stratocumulus
A stratocumulus-topped boundary layer corresponding to the first research flight (RF01) of the second Dynamics and Chemistry of Marine Stratocumulus (DYCOMS-II) field study is investigated in detail. The setup follows that of Stevens et al. (2005) with the exception of the surface fluxes. The surface fluxes are computed using the Monin–Obukhov theory with Charnock's roughness length (Charnock, 1955). The grid spacing is $\Delta x = \Delta y = \Delta z = 5$ m and $\Delta x = \Delta y = \Delta z = 2.5$ m.

Figure 2 is similar to fig.1 but for the stratocumulus case. Figure 3 shows a vertical slice of specific humidity from the stratocumulus case (Figure 2). The LES captures the detailed physical interactions between thermals, turbulence, cloud and radiation in the boundary layer.

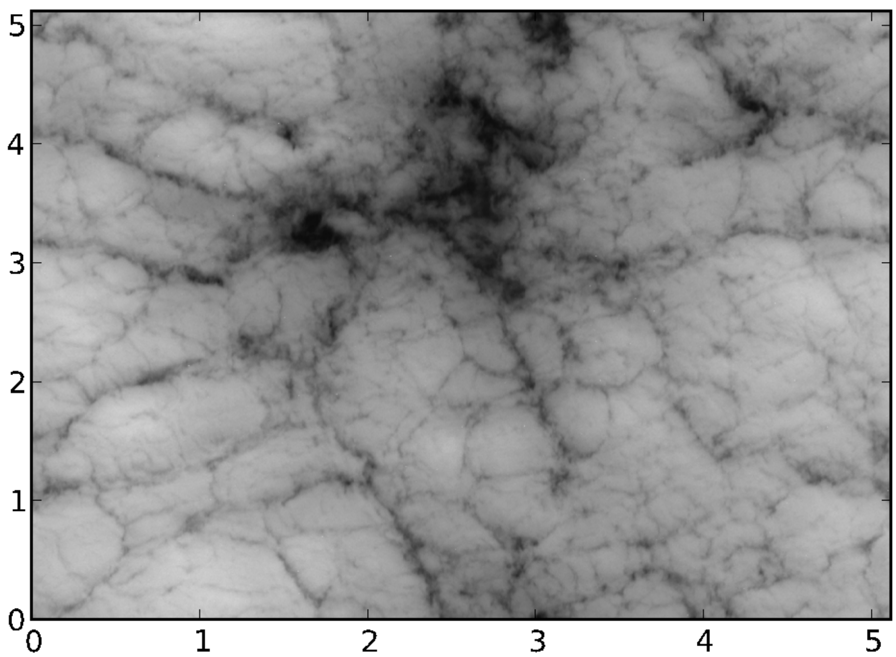

Figure 2: As in figure 1 but for the DYCOMS stratocumulus case. The rich structure of the cloud top is captured by the LES. The scale is in km.

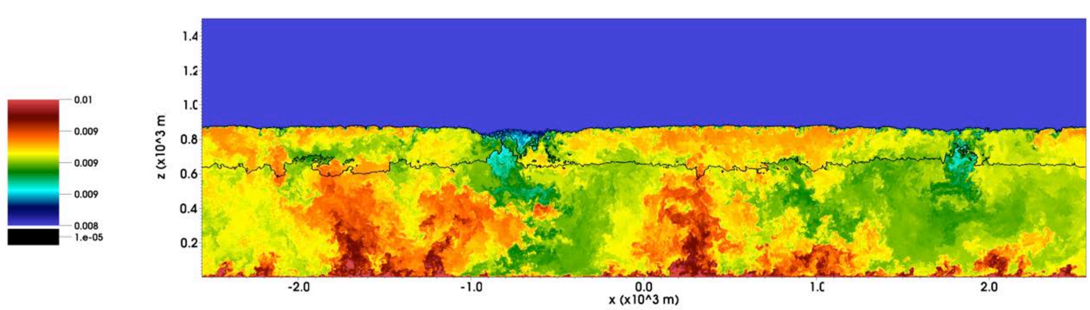

Figure 3: Specific humidity in g/kg on a vertical plane from the stratocumulus simulation of Figure 2. The black contour denotes the cloud boundary.

Stratocumulus-to-cumulus transition

For this stratocumulus-to-cumulus experiment the LES is initialized using the Atlantic Stratocumulus Transition Experiment (ASTEX) initial conditions (Duynkerke et al 1999). The boundary layer is driven by SST-dependent Monin-Obukhov surface fluxes assuming full surface saturation at SST. A simplified radiation scheme is employed.

In this LES experiment the flow moves from the left (colder SSTs) to the right (warmer SSTs) of the domain. The size of the domain is roughly 120 km x 5 km in the horizontal and 3 km in the vertical. The resolution is 80 m in the horizontal and 40 m in the vertical direction. A transition in the cloud structure is apparent in figures 4 and 5, from cumulus under stratocumulus on the left of the domain, to more typical open cell cumulus structures to the right of the domain.

The spatially developing simulation of the stratocumulus-to-cumulus transition has several advantages compared to a "Lagragian simulation" where the horizontal boundaries are periodic and the evolution of the boundary layer is driven by time-depended forcings. In a spatially developing simulation, all of the forcing is provided by the boundary conditions leading to a simulation that is more dependent on physical conditions.

When the inflow and outflow boundary conditions are specified, the LES of a stably stratified boundary layer turns out to be challenging because spurious reflections of waves at the boundary accumulate inside the domain. To tackle this problem, a fringe method with an auxiliary LES running concurrently is applied to enforce upstream/downstream boundary conditions. An artificial forcing term is applied within a fringe region located at the beginning of the main LES domain in order to ensure statistically stationary inflow boundary conditions. The auxiliary LES, which is horizontally homogeneous in a doubly periodic domain, is used to determine the inflow condition of the main LES domain.

The fringe method is applied to a simulation of the stratocumulus-to-cumulus transition where the transition is triggered by increasing the sea surface temperature (SST), see figure 4. The LES runs until a statistically steady evolution of the transition is achieved. The flow statistics are compared with those from a recycling-type method (figure 4) and it is found that the fringe method is more suitable for LES of spatially developing boundary layers. Figure 5 shows boundary layer profiles along the transition.

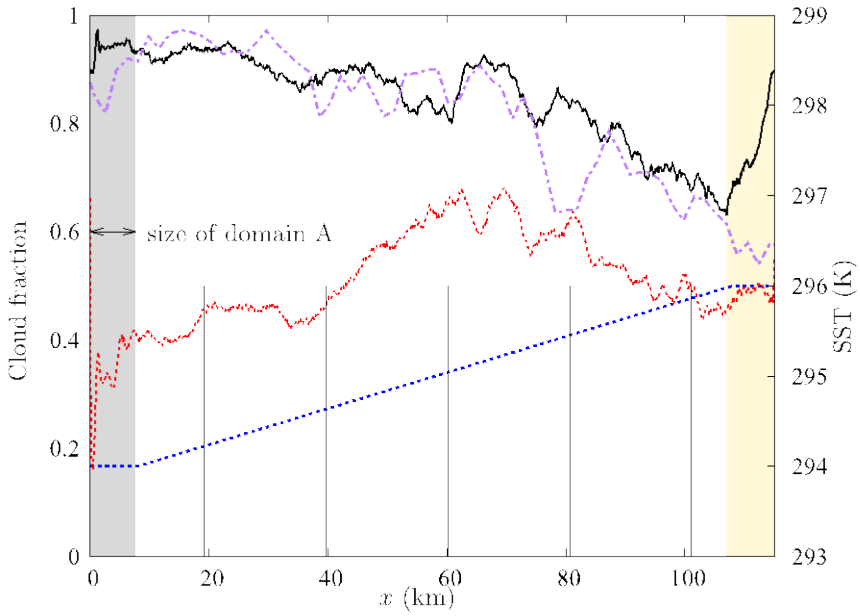

Figure 4: Cloud fraction for the fringe method (black) and the recycling method (red), and SST (blue) along the streamwise direction within the LES domain. SST increases from 294 to 296K. The vertical lines indicate the locations where the vertical profiles shown in Figure 5 are taken. The shaded areas indicate the regions contaminated by the fringe method: the fringe region (gray) and the upstream effect of the fringe region (yellow); and a horizontally homogeneous LES (purple) where time was converted to distance by use of a mean advection speed.

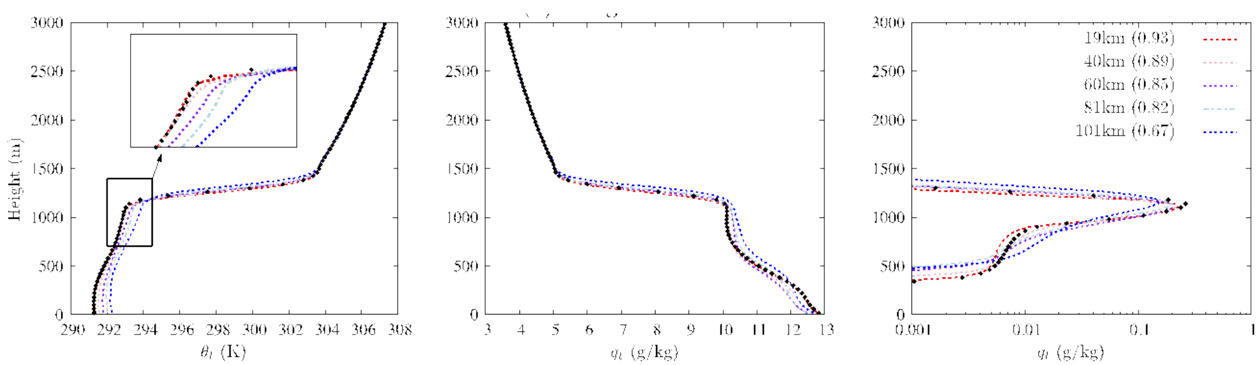

Figure 5: Vertical profiles of (left) the liquid water potential temperature, (middle) the total water mixing ratio, and (right) the liquid water mixing ratio. The black circles show the profiles of the inflow condition and the dashed lines show the spanwise averaged data at five different locations. All data are time averaged over 18 h using data with 10-min interval. Cloud fraction at each location is indicated in the legend.

IMPACT/APPLICATIONS

These LES studies have an essential impact on the weather prediction capabilities of the U.S. Navy. In particular, after the implementation of the new EDMF parameterization (evaluated and calibrated with the LES results) into 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, evaluated and improved with the LES results, has transitioned to FNMOC after implementation and testing in the NAVGEM model using the LES approach.

RELATED PROJECTS

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

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