Cloud Structure and Entrainment in Marine Atmospheric Boundary Layers

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LONG-TERM GOALS

Our long term goals are to understand the dynamics of atmospheric motions on scales of order 10 m - 10 km in sufficient detail to be able to provide a consistent subgrid scale model that will represent the influence of turbulent transport across a range of scales.

OBJECTIVES

The chief objective of the present grant is to better understand the physical processes that control cloud and circulation structure in the atmospheric boundary layer and rate of entrainment of heat and moisture across the capping inversion. This understanding will be used to formulate a consistent, robust single-column model to represent these processes in Mesoscale models for a broad range of boundary layer conditions and forcings.

APPROACH

This research utilizes high resolution turbulent transport codes and theoretical understanding developed under previous ONR support. Our principal approach is to employ large eddy simulations (LES) to conduct controlled numerical studies of the effects of different boundary layer forcings and conditions (initial temperature and moisture profiles, surface heat and moisture fluxes, cloud-top radiation, wind shear, etc.) on the boundary layer dynamics, cloud structures and entrainment rates that result. The simulations are motivated by and compared with field observations when available. The simulation results are used to develop and test theoretical models for the basic physical processes at work, in order that these effects can be incorporated consistently into lower resolution and single-column models.

WORK COMPLETED

Starting from our existing LES model of the atmospheric boundary layer we have constructed a version that may be run with reduced numbers of horizontal degrees of freedom and different possible imposed symmetries. The resolved Navier-Stokes equations have been reformulated in terms of

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horizontal area coordinates and perimeter grid factors. Different horizontal symmetries of circulations (planar, axisymmetric, hexagonal, square, more general mixtures, etc.) can be represented with appropriate choices of the relations between the horizontal coordinate, cumulative grid area, and grid cell perimeters. A general direct pressure solver has been implemented for this and the finite differencing tailored to allow the model to be run on minimal grids (providing models that functionally behave as single column models but with resolved pressure and advection terms included). Yet to come is allowing full variability of horizontal grids and symmetry factors with height (in progress); subgrid modeling more consistent with assumed symmetries (currently only axisymmetric-like, planar-like or 3D limits are incorporated); and adaptive variation of grids so that a small number of grid degrees of freedom can be tailored to the developing flow.

We have also continued to perform LES of stratocumulus and shallow cumulus for different cases.

RESULTS

An accurate representation of the atmospheric boundary layer (ABL) is a necessary ingredient for good performance of mesoscale or global meteorological models. The critical mechanisms at work in different types of boundary layers (dry convection, stratocumulus, shallow and deep cumulus, etc.) vary significantly. As a result, approximations that are tailored for one regime generally fall short in others. To model the ABL within a mesoscale or global model, different submodels are usually employed for different regimes, with somewhat limited success, particularly in transitions between regimes. Alternatives include attempts at unified models suitable for all regimes (e.g., Lappen and Randall, 2001), or coarsely yet explicitly resolving the ABL dynamics (e.g., 2D "superparameterizations", Khairoutdinov et. al., 2005).

We have developed a version of our boundary-layer LES model restructured so that it may be run with progressively reduced numbers of degrees of freedom -- from 3D to 2D to what are effectively single-column models-- and with different symmetries assumable for the horizontal degrees of freedom.

This allows resolved circulation structures to be constrained and to some extent controlled, permitting further exploration of the effects of different circulation structures on mean boundary-layer statistics, the feedbacks that govern the circulation structure, and what minimal degrees of freedom are required to properly "resolve" boundary-layer physics in different regimes.

We have found, supporting some of our previous 3D LES studies, that distinct equivalence classes of solutions arise depending on the degrees of freedom made available and their symmetry. Within a given class the mean statistics (e.g., fluxes, thermodynamic profiles, variances, entrainment rate) are relatively insensitive to subgrid modeling choices and gridding details. This makes some boundary-layer dynamics relatively straightforward to reproduce robustly with a reduced set of degrees of freedom but others distinctly challenging. For example the circulation structure and mean statistics of a dry convective boundary layer driven by surface heating arrayed in widely separated spots is quite accurately represented by a 2D axisymmetric simulation (even without any azimuthal fluctuations accounted for). For suitably chosen radial grid spacing the basic character can be reproduced by as few as three radial grid points (producing an "updraft/downdraft/environment" model). On the other hand, the familiar dry convective boundary layer (CBL) driven by a uniform heat flux from the surface is poorly represented (fig.1,2) by the straightforward 2D simulation with planar symmetry, even at high resolution (or, less surprisingly, by a 2D axisymmetric simulation). Those degrees of freedom do not allow the characteristic circulation structures present in the CBL to be represented (narrow walls of small updraft plumes near the surface, merging into fewer, isolated, nearly-axisymmetric plumes above). In our current model the CBL equivalence class of solutions can be realized (fig.1,2) with the degrees of freedom provided by 2D grids of more general symmetry, in particular a class of periodic-quasi-axisymmetric ones (these can be thought of roughly as smoothed versions of the grid structure one would obtain by cutting across a plane tiled by regions of hexagonal symmetry). On such grids both wall-like structures and converging or diverging plumes can naturally occur. This type of grid has proved successful in representing more complex cloudy boundary layers as well (c.f. fig. 3).

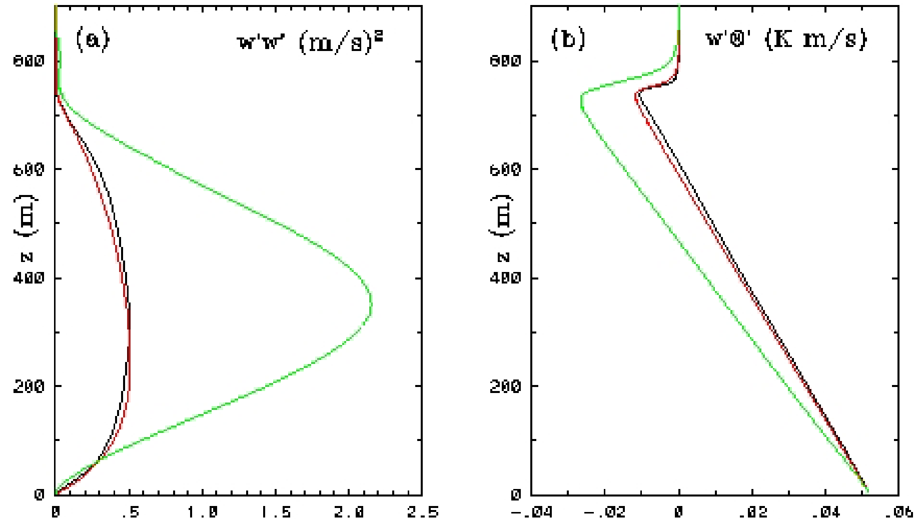

Figure 1. Mean vertical profiles of: (a) vertical velocity variance and (b) potential temperature flux, from three simulations of a dry convective boundary layer using 3D LES (red lines), 2D with planar symmetry (green), and 2D with a periodic-quasi-axisymmetric grid (black). The latter simulation faithfully reproduces the mean statistics of the full 3D simulation while the standard 2D simulation (green) equilibrates to quite different boundary-layer dynamics.

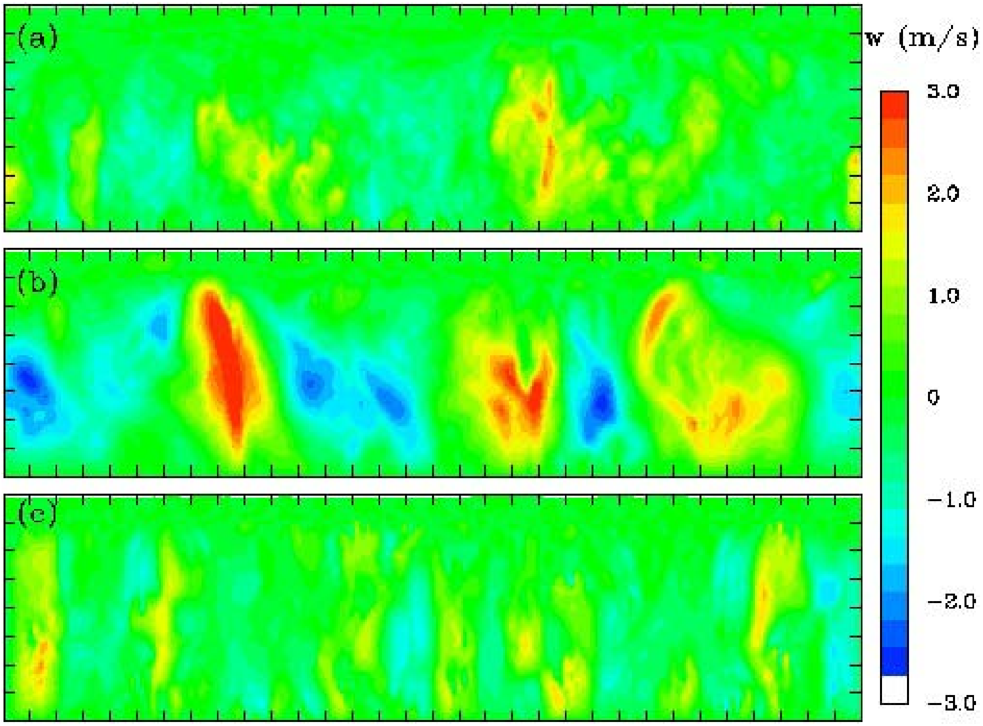

Figure 2. Sample instantaneous cross-sections showing vertical velocity structure from the three simulations of figure 1: (a) 3D, (b) 2D planar, (c) 2D periodic-quasi-axisymmetric. Again, the last simulation is much more faithful to the results of the 3D simulation than is the simple 2D planar one.

Reproducing different boundary-layer types with reduced numbers of degrees of freedom is a step towards adapting this model (in different limits) into both usable single column models and efficient 2D superparameterizations. The ability to simulate the fluid-dynamic equations with degrees of freedom with restricted symmetry also allows circulation structures to be achieved -- and their effects on the resulting mean statistics to be studied -- that are otherwise not realizable. We have found, for example, that surface driven convective boundary layers with large negative skewness (i.e., broad buoyantly driven updraft regions with narrow downdraft plumes) produce negligible boundary-layer entrainment.

In other work, we have performed several large-eddy simulations of precipitating shallow cumulus as part of a GCSS (GEWEX Cloud Systems Studies) Boundary Layer Cloud Working Group model intercomparison, based on observations from the Dec. 2004 - Jan. 2005 RICO (Rain In Cumulus over the Ocean) field campaign around the Caribbean islands. The preliminary indication (e.g., fig. 3) is that, perhaps not surprisingly, precipitation is far more difficult to simulate robustly than other mean statistics in shallow cumulus layers.

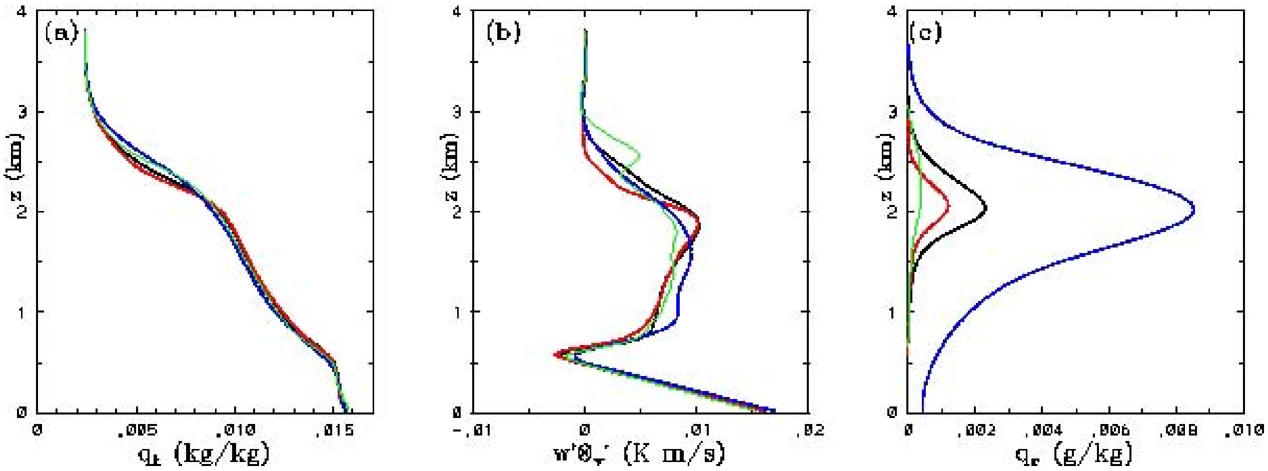

Figure 3. Sample mean vertical profiles from large eddy simulations of precipitating shallow cumulus convection (the 2006 GCSS boundary layer cloud working group intercomparison case based on RICO field observations) showing effects of varying grid resolution. (a) total water mixing ratio; (b) virtual potential temperature flux; (c) rain water mixing ratio. The grids used horizontal resolution of 50 m (red lines), 100 m (black), 200 m (blue). Also included is a 2D simulation on a 100 m resolution periodic-quasi-axisymmetric horizontal grid (green lines). The basic mean statistics (including those not shown) are found to be in good agreement with each other with the exception of rain water content, which proved highly sensitive to the grid choice.

IMPACT/APPLICATION

A valid model of the marine atmospheric boundary layer is needed not only because its dynamics are critical in transporting the surface fluxes of heat and moisture responsible for driving most atmospheric dynamics, but also because it determines the immediate environment within which many Navy operations are performed. Boundary-layer clouds directly influence both the local environment (e.g., for visual, radar, and laser communication) and the global environment (through their impact on the radiation balance). Accurate representation of the buoyancy flux, entrainment rate, and cloud/ circulation structure are critical ingredients in correctly modeling the behavior of cloudy boundary layers. Our present efforts improve on the understanding of these ingredients and their representation by resolved processes in models with dramatically reduced numbers of degrees of freedom. This may lead to efficient superparameterizations for use in global climate models and unified single column models of the ABL that could be used in larger scale weather models such as the Navy's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS (Hodur, 1997)).

TRANSITIONS

We have contributed regularly to the intercomparison results from the GCSS boundary layer cloud modeling working group, which have become a standard test set for development and evaluation of parameterizations used in numerical weather prediction and climate models. (http://www.atmos.washington.edu/~breth/GCSS/GCSS.html)

RELATED PROJECTS

The LES code developed under ONR support has been modified and used to model aircraft wakes/contrails for NASA (e.g., Lewellen and Lewellen, 2001), and to model the turbulent interaction of a tornado with the surface for NSF (e.g., Lewellen and Lewellen, 2006). The use of essentially the same LES code on these separately supported efforts works to the advantage of all three projects, particularly in fostering numerical improvements in the efficiency and accuracy of the code.

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