Cloud Structure and Entrainment in Marine Atmospheric Boundary Layers

David C. Lewellen
MAE Dept., PO Box 6106, West Virginia University
Morgantown, WV, 26506-6106
Phone: (304) 293-3111 (x2332) Fax: (304) 293-6689 email: dclewellen@mail.wvu.edu

W. Steve Lewellen
MAE Dept., PO Box 6106, West Virginia University
Morgantown, WV, 26506-6106
Phone: (304) 293-3111 (x2371) Fax: (304) 293-6689 email: wslewellen@mail.wvu.edu

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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 forcing 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

During the past year we have continued to concentrate on incorporating results learned from our previous work on buoyancy flux modeling and cloudtop entrainment (Lewellen and Lewellen, 2004a; Lewellen and Lewellen, 2002) into a fully coupled single-column model for use in parameterizing a

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14. ABSTRACT
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.

15. SUBJECT TERMS

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full range of atmospheric boundary layers. The major new development is a consistent implementation of three dimensional pressure gradient forces within a single column model, derived from the fluid equations of motion.

We have also formulated and added a new drizzle parameterization – a version of Khairoutdinov and Kogan (2000) but with fewer prognostic variables – into our LES model. Using this model we performed a series of simulations of nocturnal drizzling stratocumulus off the California coast as part of a GCSS (GEWEX Cloud Systems Studies) Boundary Layer Cloud Working Group model intercomparison, based on observations taken during the second DYCOMS II research flight.

Several papers have been shepherded though the review process to final publication.

RESULTS

An accurate representation of the atmospheric boundary layer (ABL) is a necessary ingredient for good performance of mesoscale or global meteorological models. LES has proved a successful tool for modeling the ABL, but is numerically far too expensive to embed within a mesoscale model as a practical tool. Instead, much work in recent years has focused on trying to build into single-column models as much of the critical ABL physics deduced from LES or observations as possible. Closure and plume (mass-flux) based models, and mixes of the two, have met with varied but incomplete success. The basic unit of dynamics generally governing the behavior of the ABL for different conditions – the recirculating eddy – is at best only partly represented. In particular, the pressure forces that are critical in overturning physical eddies are modeled crudely if at all.

We have found for both clear and cloudy boundary layers that even extremely under-resolved LES can often be made to outperform single column models, provided the basic boundary-layer scale eddy is represented. In recent work we have pushed this concept to its logical extreme – considering the bare minimum variable set for which we can directly solve a discretized version of the fluid equations of motion – to produce a single column model.

For dry convection a minimal set of four prognostic variables is employed: mean vertical velocity and temperature within the updraft plume, temperature within the downdraft, and horizontal velocity defined on the boundary between updrafts and downdrafts. The updraft size is allowed to vary with height and time (though in the present version is externally specified). The form of the basic equation set is derived by integrating the fluid equations of motion at each height over updrafts or downdrafts, supplemented by LES inspired "subgrid modeling" of small-scale transport. At each time step pressure profiles at three locations (along the updraft and downdraft centerlines, and along the updraft/ downdraft boundary) are solved for diagnostically using a discrete version of the Poisson equation to guarantee continuity – in direct analogy with a complete Navier-Stokes solution. These equations are significantly complicated by allowing the plume size to vary with time and height. The resulting model has some similarities in spirit with the recent version of Lappen and Randall's higher-order mass flux model (Lappen and Randall, 2005), but differs in its choice of prognostic variables, direct solution of the momentum equations, and treatment of pressure.

Figure 1 illustrates a sample of the results. Though it has few enough degrees of freedom to be legitimately characterized as a "single-column" model, it properly represents the basic physics of a recirculating, convectively driven eddy: a buoyantly driven updraft with pressure gradients properly turning the flow between vertical and horizontal modes at the inversion and surface.

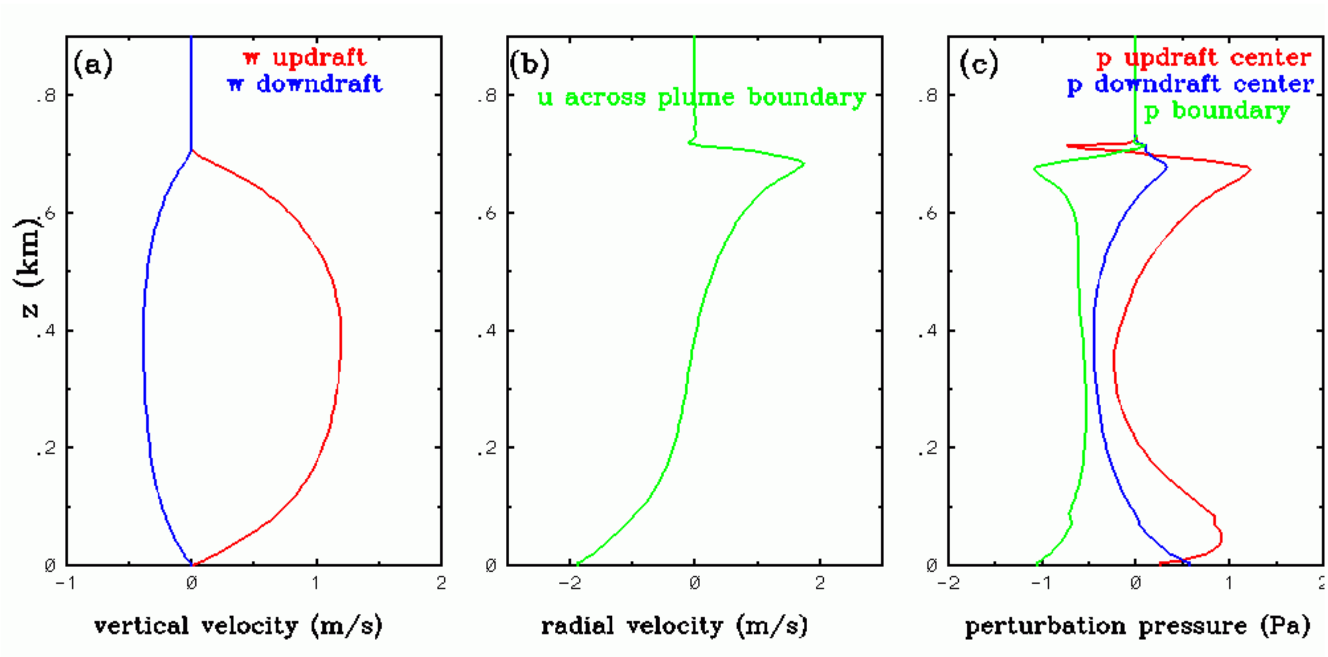

Figure 1. Sample results from a convective boundary layer simulation with a newly developed single column model that directly solves for the pressure forcing. The results show time averaged profiles of (a) mean updraft (red) and downdraft (blue) velocity; (b) horizontal velocity across the plume boundary with negative/positive sign indicating flow into/out of the updraft plume; and (c) perturbation pressure at the center of the updraft (red), downdraft (blue) and updraft/downdraft boundary (green). The vertical and horizontal pressure gradients are directly responsible for the exchange of momentum between vertical and horizontal modes, particularly at the surface and capping inversion.

In addition to its promise for use within mesoscale models, this single-column model provides a simple testing ground for exploring the interplay between circulation features (e.g., updraft area fraction or plume separation) and boundary layer properties and development, with the pressure couplings properly accounted for. In the next step this formulation will be combined with the cloud model developed last year (Lewellen and Lewellen, 2004b) and the plume size evolution actively coupled in, either dynamically, through a vertical momentum equation on the plume boundary, or by using an empirical relation between skewness and effective cloud fraction as in Lewellen and Lewellen, 2004b.

In other work we have continued LES studies of marine stratocumulus, comparing with DYCOMS-II measurements within a drizzling stratocumulus as part of a GCSS model intercomparison (http://sky.arc.nasa.gov:6996/ack/gcss9/index.html). The results show reasonable agreement with the observations overall, including entrainment rate and cloud water content, though generally under predicting the observed drizzle rate at the surface. The results demonstrate in particular the importance of cloud droplet sedimentation (much more so than drizzle precipitation alone) in reducing cloud top entrainment and increasing liquid water path, consistent with the predictions of Ackerman et al. 2004.

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. Successfully incorporating these ingredients into a single-column model is an important step towards correct inclusion in larger scale weather models such as the Navy's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS (Hodur, 1997)). The consistent incorporation of pressure gradient forces within a single column model improves upon a long-standing shortcoming of such models, and provides a new tool for studying the effects of circulation properties on boundary layer structure.

TRANSITIONS

We have contributed regularly to the intercomparison results from the GCSS boundary layer cloud 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 and Boeing (e.g., Lewellen and Lewellen, 2001), and to model the turbulent interaction of a tornado with the surface for NSF (e.g., Lewellen et al. 2004). More on either of these efforts may be seen at http://eiger.mae.wvu.edu/aircraft.html or at http://eiger.mae.wvu.edu/tornado.html, respectively. The use of closely related LES codes 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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