Modeling of Cloud-top Entrainment

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Award #: N00014-98-1-0595
http://eiger.mae.wvu.edu

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 turbulent closure for models across a range of scales, and to be able to utilize simulated variances as a measure of forecast predictability.

OBJECTIVES

The chief objective of the present grant is to better understand the physical processes which control the rate of entrainment fluxes of heat and moisture across the capping inversion of the atmospheric boundary layer, and to formulate a closure model for cloud-top entrainment that is consistent for a broad range of boundary layer conditions and forcings. Ideally, this closure model would allow one to produce a simulation at any desired level of resolution, with the results of lower resolution simulations being approximately similar to results obtained by appropriate spatial filtering of the higher resolution simulation.

APPROACH

This research involves the utilization of the high resolution turbulent transport codes 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, in particular, entrainment rates, which result. The understanding and quantitative correlations gained can be used to better incorporate these effects into the subgrid parameterizations utilized in lower resolution models.

WORK COMPLETED

During the past year we have continued to perform extensive LES studies of boundary layer dynamics and structure and their affects on the entrainment rate through the top of the layer. In particular, a series

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **SEP 2000**	2. REPORT TYPE	3. DATES COVERED **00-00-2000 to 00-00-2000**

4. TITLE AND SUBTITLE **Modeling of Cloud-top Entrainment**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **MAE Dept., PO Box 6106, West Virginia University,,Morgantown,,WV,26506**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

of simulations has focused on varying surface Bowen ratio, cloud top moisture and temperature jumps, and cloud thickness, to study their effects on boundary layer "decoupling" and the entrainment rates at cloud top and cloud base for shallow cumulus driven boundary layers. Another series of simulations studied the effects of different patterns of nonuniform surface heating on boundary layer dynamics and entrainment rate; these provided a tool for examining the mechanism by which the boundary layer scale eddy dynamics and transport limit the overall entrainment rate (as argued in Lewellen and Lewellen 1998).

In addition, we have continued our participation in inter-model comparisons under the coordination of the GCSS (GEWEX Cloud Systems Studies) boundary layer cloud modeling working group. The most recent comparison focused on the development of shallow cumulus over land, based on observations made at the ARM site in 1997.

RESULTS

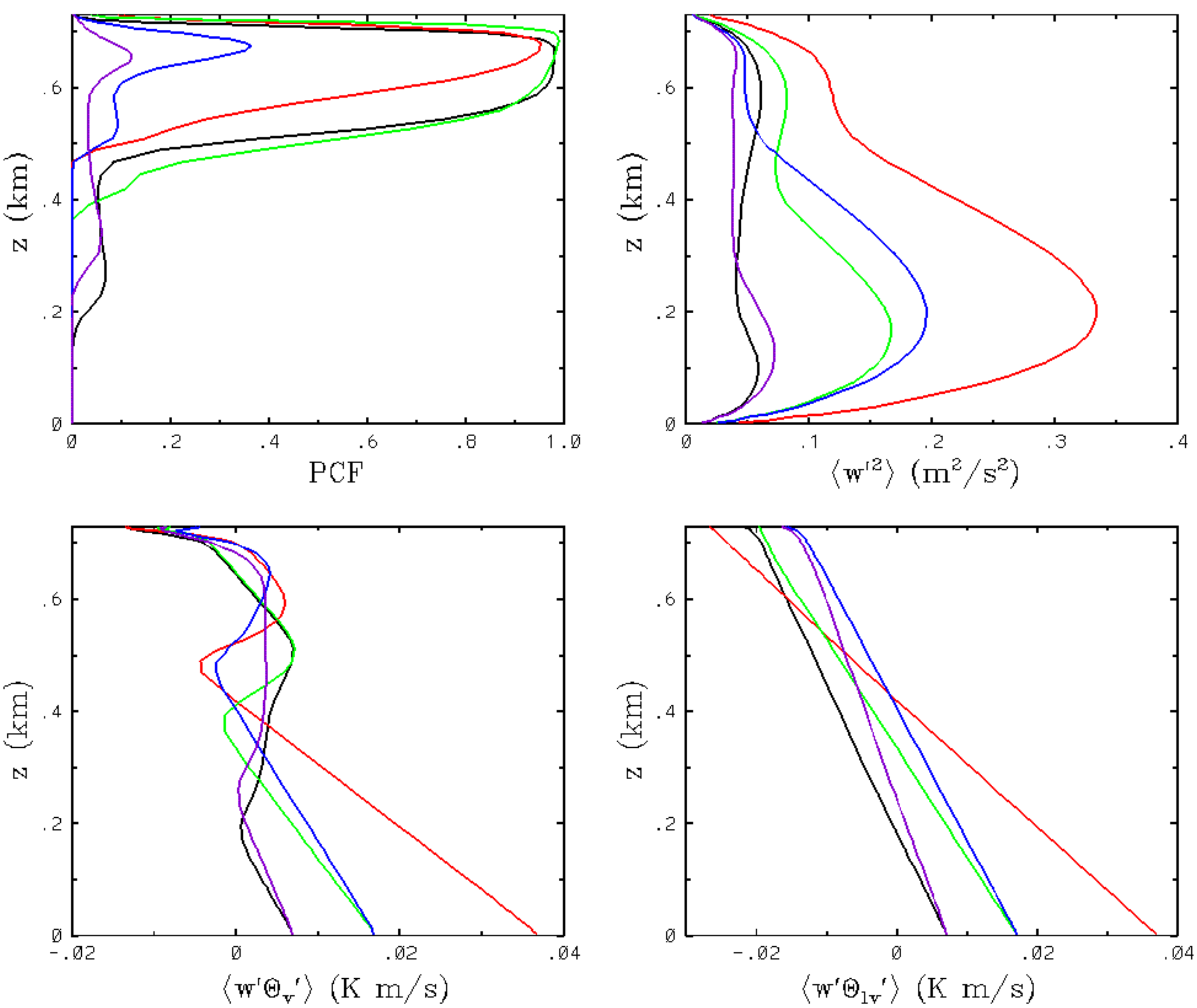
Figure 1 illustrates vertical profiles from sample LES of cloudy surface driven marine boundary layers where the latent heat flux plays a dominant role. This regime is characterized by humidity and temperature profiles which are not well mixed (developing a weak stable layer near cloud base), a bimodal cloud structure with cumulus columns and detrained stratocumulus, and two distinct circulations: a dry convective layer below cloud base, and a highly skewed circulation within the cloud layer driven by latent heat release, often with a minimum in the vertical velocity variance apparent between the two. This situation is often referred to as "decoupling" (Bretherton and Wyant, 1997). The entrainment of warmer, dryer air at cloud top plays a critical role in developing and maintaining the "decoupled" state. The rate of entrainment is enhanced by the presence of the cloud, and by the highly skewed nature of the flow (see below).

Over time a well developed cumulus coupled layer settles into a quasi-steady state where the conserved heat and moisture fluxes are approximately linear across the full layer -- i.e., the in cloud and below cloud circulations equilibrate with one another. In this state much can be determined about the overall dynamics by carefully analyzing the simpler subcloud dynamics. Treating the entrainment into a weakly capped convective layer as we did in Lewellen and Lewellen 2000, we find the entrainment efficiency into the subcloud layer to be consistent with that of a simple convective boundary layer ($\eta_E \approx$ 0.29), with the layer height given by a particular measure of the horizontal mean cloud base height. For quasi-steady conditions this permits a simple prediction of the entrainment flux of liquid water virtual potential temperature at cloud top $\langle w'\theta_{lv}'\rangle_i$, in terms of the surface flux $\langle w'\theta_{lv}'\rangle_o$, the ratio of the mean cloud base height to the boundary layer height (z_{cb}), and the subcloud entrainment efficiency (η_{Es}):

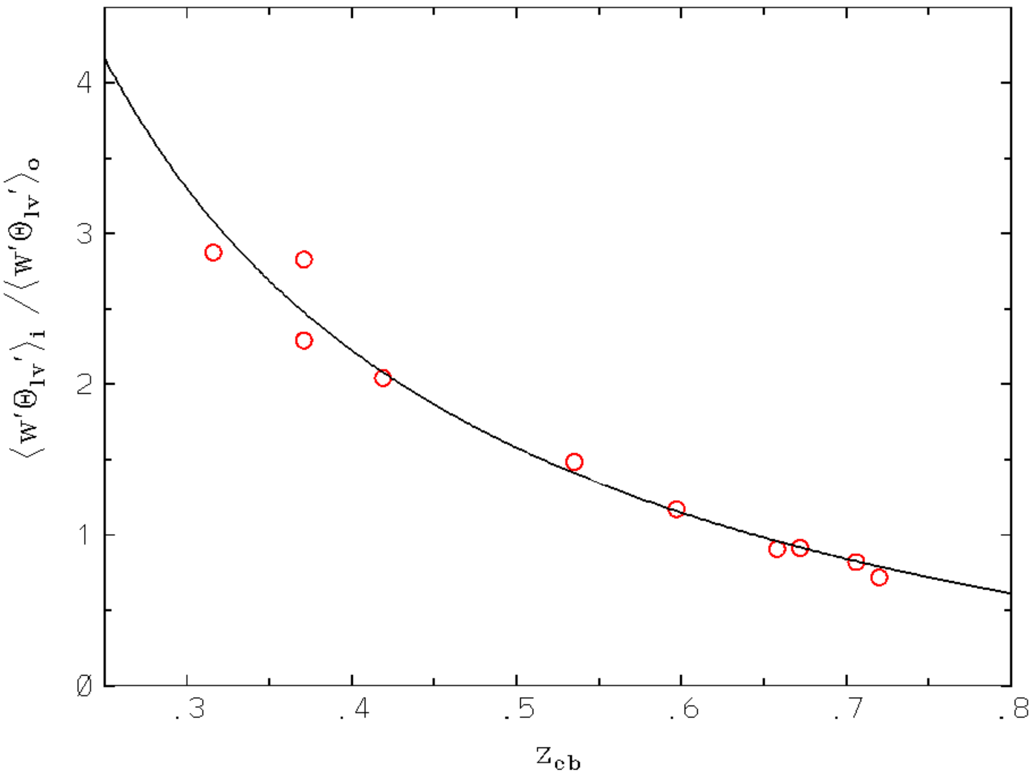
$$\langle w'\theta_{lv}'\rangle_i = \langle w'\theta_{lv}'\rangle_o (1 - (1+ \eta_{Es})/z_{cb}) \qquad (1)$$

The LES results from several cases (including those of figure 1) shows this prediction to be fairly successful (figure 2). Given the ratio of the moisture jump to liquid potential temperature jump at the inversion, the corresponding entrainment fluxes of these conserved variables can be easily obtained from $\langle w'\theta_{lv}'\rangle_i$ as well. In addition, as the boundary layer evolves, z_{cb} will either rise until the cloud is eliminated, fall until it reaches the surface, or, if the conditions (including any heating and/or drying from large scale advection) are conducive, reach a steady state level. In this latter case z_{cb}, as well as the cloud top entrainment fluxes can be predicted.

In a separate series of investigations we have employed different patterns of surface heating to drive dry convective boundary layers. The results suggest at least three different regimes of entrainment dynamics each associated with distinctly different boundary layer dynamics: one with $\eta_E \approx 0.3$ for relatively uniform heating; another with $\eta_E \approx 0.45$ for heating arranged in widely separated stripes; and a third with $\eta_E \approx 0.6$ for heating arranged in widely separated spots. Within each of these regimes η_E appears to be largely independent of the spot or stripe width or separation, the grid resolution used for the simulation, or the details of the inversion structure. The dynamics in spot heating cases, giving a high level of skewness and enhanced entrainment efficiency, is closely related to the dynamics of a cumulus driven layer noted above.



1. Two hour averaged mean vertical profiles for sample cloudy boundary layers driven by surface moisture and heat fluxes. Variables shown are partial cloud fraction, vertical velocity variance, virtual potential temperature flux, and liquid water virtual potential temperature flux. The same surface moisture flux was used in each case.



2. The prediction for the entrainment liquid water virtual potential temperature flux as a function of z_{cb} given in eq. 1 (solid line) vs. LES results for several quasi-steady cumulus coupled boundary layers including those of figure 1 (points).

Heating in a fixed pattern of stripes or spots allows one to sensibly consider time averaged spatial structure in the flow since the upward plume positions are correlated in time. Performing simulations with a top lid through which a heat flux is forced we can then examine the correlation between the mean large eddy dynamics and the entrainment flux for these cases by varying the top flux. When the top heat flux is small the convective plumes are turned laterally and downward near the top lid by pressure forces, driving a strong downward returning circulation which easily transports the imposed negative heat flux through the boundary layer. As the top flux is increased, the temperature gradients outside of the plumes become more stable, and negative buoyant forcing becomes increasingly important (at the expense of pressure forcing) in decelerating the plumes as they approach the domain top. Eventually the plumes are almost completely decelerated by buoyant forces with little pressure forcing, leaving as return circulation a slowly subsiding flow through a stable temperature gradient outside of the plumes. The boundary layer scale circulation at this point has reached the limit of the entrainment heat flux it can transport; any further increase in the imposed top heat flux remains at the domain top and the layer dynamics are not altered further.

IMPACT/APPLICATION

A consistent quantitative model of cloud top entrainment is important to any model that involves cloud dynamics. In addition to the navy's operational forecasting interest in clouds, an understanding of cloud dynamics on this scale is also a central issue in modeling global climate change. We expect this effort to lead to improved subgrid parameterization of entrainment in models such as the Coupled Ocean/ Atmosphere Mesoscale Prediction System (COAMPS) regional model developed at the Naval Research Laboratory (Hodur, 1997). An improved understanding of cumulus "decoupling" should allow for significant improvements in single column models that often include separate parameterizations for mixed layers and cumulus convection and need better rules for determining when to switch between the two.

TRANSITIONS

The results in Lewellen and Lewellen 1998 are being used and discussed in other entrainment studies, both observational and LES.

RELATED PROJECTS

The LES code developed under ONR support has been modified and used to model aircraft wakes/ contrails for NASA (Lewellen and Lewellen, 2000), and to model the turbulent interaction of a tornado with the surface for NSF (Lewellen et al. 2000). 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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