Modeling of Cloud-Top Entrainment

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: dlewelle@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 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 objectives of the present grant are to better understand the physical processes which control the rate of entrainment of heat and moisture across the capping inversion of the atmospheric boundary layer, to explore the effects of these entrainment fluxes on boundary-layer cloud structures and circulations, and to formulate a closure model for cloud-top entrainment that is consistent for a broad range of boundary layer conditions and forcings.

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 concentrated on analyzing and extending our LES data set of studies of boundary layer dynamics, cloud structure, and their affects on the entrainment rate through the top of the layer. An idealized model of the relationship between entrainment in convectively-driven, cloud-topped boundary layers and the decoupling of the cloud and subcloud layers has been developed,

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

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compared with results from the set of large-eddy simulations, and submitted for publication (Lewellen and Lewellen 2001).

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 diurnal cycle of stratocumulus off the California coast during FIRE. Results from a previous intercomparison focusing on shallow cumulus development over land were further analyzed and submitted for publication (Brown et al. 2001).

RESULTS

We have treated the decoupling of a well mixed boundary layer, such as is encountered in the stratus to trade wind cumulus transition, as a boundary layer entrainment problem. Decoupling involves the formation and maintenance of at least a weak inversion (sometimes called the transition layer) between the decoupled layers. This involves three different entrainment processes: the warming from entrainment at the top of the full layer tends to build the transition layer (as stressed by Bretherton and Wyant, 1997), and entrainment across it, driven from above by the in-cloud circulation and from below by the subcloud circulation, tends to erode the transition layer. We have treated all three entrainment processes in a quasi-steady approximation where the entrainment flux is limited by what the large-scale eddies can transport across their depth (Lewellen and Lewellen, 1998). The determination of the dominant eddy structure, cloud-top entrainment rate, and presence or absence of layer decoupling are closely tied to each other. This leads naturally to a classification of boundary layer regimes depending on which large scale circulations ultimately govern the cloud-top entrainment rate: ones across the full boundary layer (I), across the cloud layer (II), or across the subcloud layer (III).

Restricting attention to an idealized class of quasi-steady buoyantly driven boundary layers, and using fixed large-eddy entrainment efficiencies for each type of circulation, we derived a prediction of which regime a boundary layer should be in for given external boundary conditions. The sharpest and most important boundary is that between II and III representing layer "decoupling". When the boundary layer is driven only by surface fluxes, our prediction for this boundary is solely a function of the normalized layer separation height, and a simple product of surface and cloud-top flux ratios. This prediction was found to be in excellent agreement with the results from an extensive set of large-eddy simulations, as illustrated in Figure 1. When cloud-top radiative cooling is included, the prediction for the decoupling boundary is correspondingly more complex, but straightforward as long as the radiative flux input does not dominate the surface fluxes. In general, decoupling is promoted by a decrease in Bowen ratio or increase in cloud-top humidity to temperature jump ratio, ζ, and, depending on the point in parameter space, either promoted or inhibited by an increase in radiative cloud-top cooling or an increase in cloud depth. Layers can evolve from well mixed to decoupled in several natural ways, easily realized in LES results, e.g., by gradual decrease in surface Bowen ratio, increase in cloud thickness, or the natural increase in ζ as a layer warms and moistens.

In each regime we have derived predictions for the entrainment fluxes at cloud top that were also found to be in good agreement with our LES results. Figure 2 illustrates, for example, the success of the regime II entrainment prediction for simulated boundary layers predicted to be in that regime. The entrainment results in regimes I and III correlate similarly well with the predictions in those respective regimes. The success of the regime III prediction is perhaps the most surprising given that the prediction follows solely from the quasi-steadiness of the full layer dynamics and the simple convective boundary layer behavior in the subcloud layer.

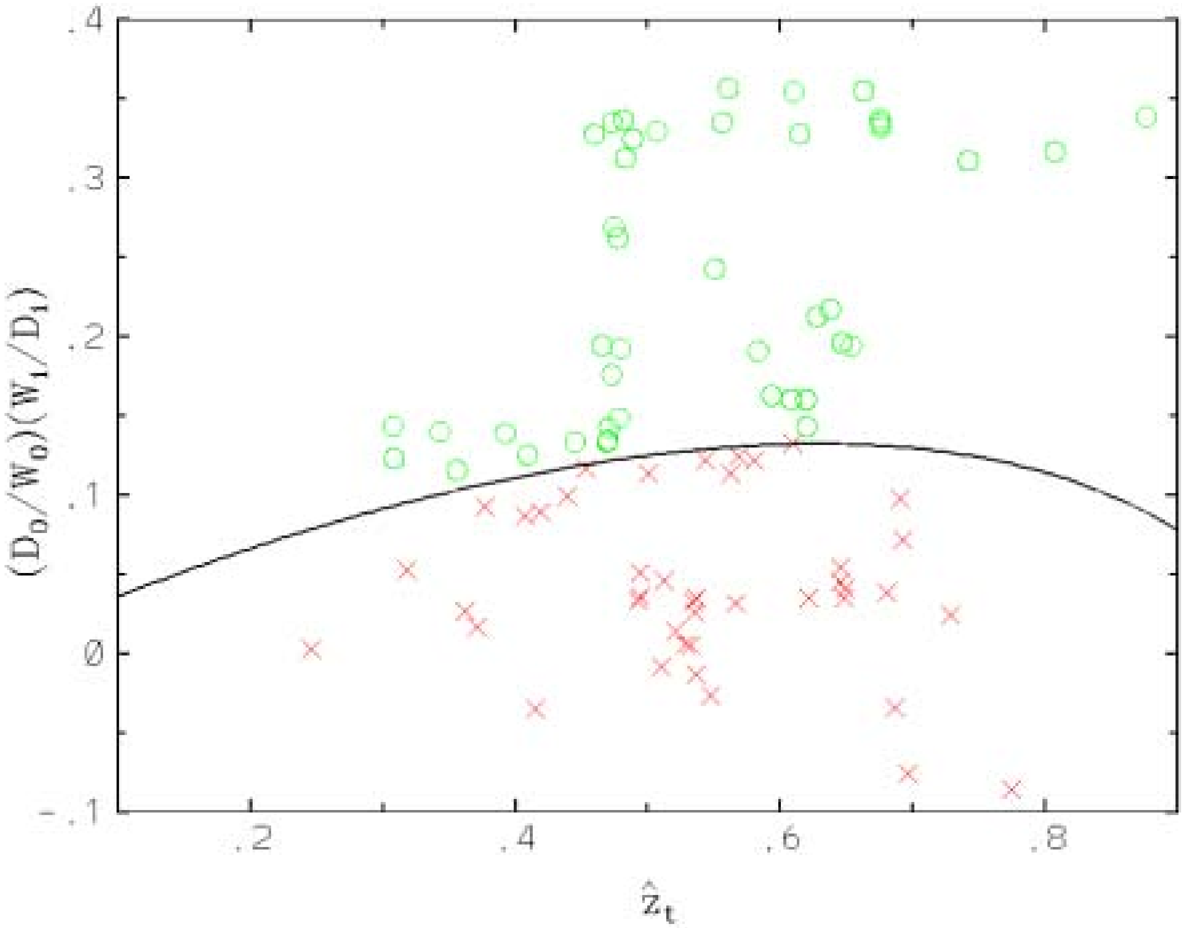
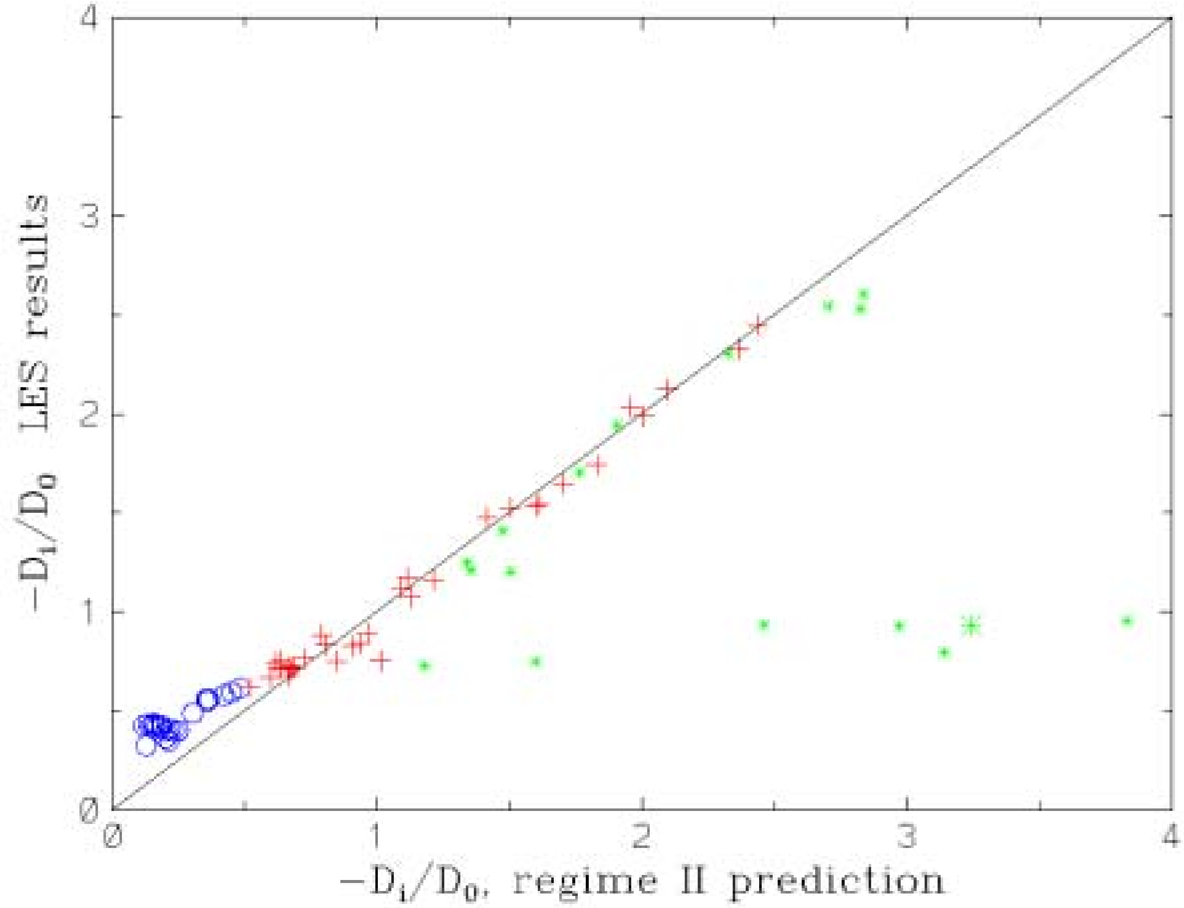


Figure 1. Results from quasi-steady LES versus the decoupling boundary prediction described in the text. Symbols indicate whether a column cloud in the mean cloud fraction profile (a distinct marker of regime III) is present in the mean cloud fraction profile (red crosses) or not (green circles). The predicted boundary is the line plotted as $(D_o/W_o)/(D_i/W_i)$ versus z_t, the ratio of the subcloud layer height to the cloud top height. D/W refers to the ratio of the unsaturated to saturated buoyancy flux, while the subscripts o and i refer to the surface and cloud-top values, respectively. The surface ratio of D/W is essentially a function of Bowen ratio only, while the cloud top value is a function of ζ. The analytical boundary decreases slowly from a maximum $(D_o/W_o)/(D_i/W_i)$ of ~0.12 at z_t ~ 0.6, and provides a clear division between the simulations found to be in regime III, and those in regime II or I.



2. Normalized entrainment flux from LES results versus idealized regime II model predictions showing a good correlation for all of the regime II simulations, represented by the red plus points. Simulation results for cases found to be in regime III, represented by the green star points (many of which fall to the right, off the scale of the plot), and those from regime I, represented by the blue circle points, are not correlated with the prediction except for those cases lying near the border with regime II.

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 discussed and used in other entrainment studies, both observational, such as the current DYCOMS field experiments, and LES studies, particularly among the GCSS (GEWEX Cloud Systems Studies) boundary layer cloud modeling working group. Results from recent GCSS model intercomparisons are being used in the development and evaluation of parameterizations used in numerical weather predictions and climate models.

RELATED PROJECTS

The LES code developed under ONR support has been modified and used to model aircraft wakes/contrails for NASA (Lewellen and Lewellen, 2001), 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.

SUMMARY

An idealized model was developed for predicting under what conditions different low-level cloud structures will occur. The rate of transfer of warm and dry air from above the cloud top down through the cloud and subcloud layers plays a key role, and is also predicted by the theory. The predictions were compared with results from an extensive set of high resolution numerical simulations, with good results. After further generalization and verification of the model over the next two years, we expect it to be useful in improving the accuracy of regional forecast models. We are also hopeful that the model may be extended to give predictions of other important features of cloudy boundary layers, such as the fraction of cloud cover.

This ONR-sponsored work has allowed a small group at WVU to be at the forefront of research in atmospheric turbulence.

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