# Modeling of Cloud-Top Entrainment


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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 parameterizations utilized in lower resolution models.

## WORK COMPLETED

During the past year we have concentrated on extending our studies (Lewellen and Lewellen, 2002, LL02 hereafter) of entrainment and circulation structure in convectively-driven, cloud-topped boundary layers. This has included improved treatment of entrainment and buoyancy flux modeling in partly cloudy layers and tests of the effects of cloud-top radiative cooling on layer decoupling. Many additional large-eddy simulations have been performed in support of this work.

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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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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. Results from a shallow cumulus intercomparison study were written up and submitted for publication (Siebesma, et al. 2002).

**RESULTS**

A longstanding challenge in the study of cloudy atmospheric boundary layers is the representation of the horizontal mean buoyancy flux for partly cloudy conditions. We can schematically write the mean buoyancy flux as,

$$\langle w'B' \rangle = (1-R)D + RW \qquad (1)$$

where D(z) and W(z) represent the "dry" and "wet" buoyancy fluxes that would result if the layer were all clear or all cloudy, respectively, at height z, and R(z) represents the ratio of the actual liquid water to the liquid water flux that would arise for completely cloudy conditions. To good approximation D and W can be expressed as linear combinations of the fluxes of two conserved quantities, liquid potential temperature and total water. If the vertical velocity and cloud water were completely uncorrelated then (1) would hold with R(z) equal to the mean partial cloud fraction. This is generally not the case, however, particularly for shallow cumulus, where the actual R can exceed the cloud fraction realized by a large factor, as may be seen by comparing fig. 1a with fig. 1b.

In a large set of LES results compiled for our entrainment and decoupling study LL02, we have found empirically that R(z) rises approximately linearly through the depth of cumulus columns within cumulus-coupled boundary layers. Using this we have formulated a simplified 1-parameter set of approximate, piecewise linear R(z) profiles. Obtaining the mean buoyancy flux via (1) is then a matter of choosing amongst this one-parameter set. We have used this predictively in two different ways, illustrated in figs. 1 and 2, which we now summarize.

In LL02 we argued that for quasi-steady, cumulus-coupled layers, the cloud-layer and subcloud-layer circulations will equilibrate with each other. We used this to derive a successful prediction of the cloud-top entrainment rate for these cases based on the maximum negative buoyancy flux which the subcloud circulation could support, as parameterized by a large-eddy entrainment efficiency (Lewellen and Lewellen, 1998). Using the simplified R profiles to apply this parameterization to the cloud-layer circulation, and demanding that the resulting cloud-top entrainment prediction agree with that from the subcloud circulation, singles out an R profile from our 1-parameter set. From this we can compute a predicted buoyancy flux using (1) and the entrainment prediction. The results are shown for three sample cases in figs. 1b-c, comparing the predicted R and <w'B'> profiles with those given by our LES. It should be emphasized that these predictions are made independent of any knowledge of the cloud fraction or flux profiles realized in the simulations; the predictions depend only on the surface heat and moisture fluxes, ratio of total water and temperature jumps at the layer top, and ratio of lifting condensation level of subcloud parcels to total layer height. While the class of boundary layers we have so far considered is very restricted (in particular quasi-steady and forced only by surface fluxes), the predictive success is considerable.

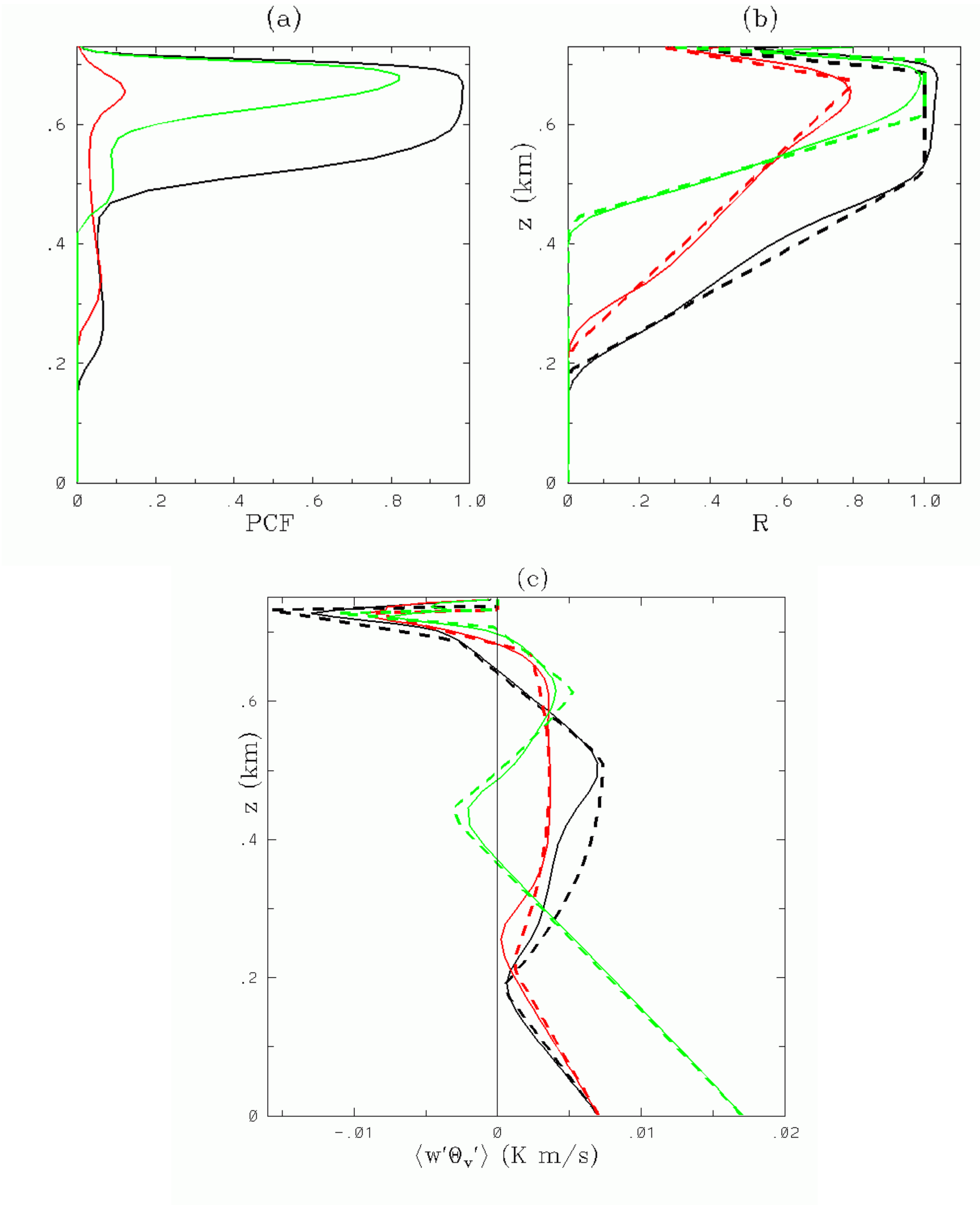


***Figure 1.* Profiles from 3 sample large eddy simulations (red, black, and green lines) showing: partial cloud fraction (a), liquid water flux R described in the text (b), and buoyancy flux (c). The solid lines represent a horizontal time average of the LES data and the dashed lines the predictions discussed in the text. The predictions provide a good representation of the LES data.**

Alternatively, using information from the mean cloud fraction profile (e.g., height at which 50% cloud fraction is reached, or maximum cloud fraction) to choose the R profile from amongst the 1-parameter set of simplified profiles, we can predict the cloud-top entrainment rate based on the cloud-layer circulation, independent of the prediction from the subcloud circulation. This prediction can be used even for less steady conditions where the cloud and subcloud circulations have not equilibrated with each other. Figure 2 shows the nondimensionalized entrainment flux given by LES versus that predicted, applied to the data set from LL02, showing good agreement.

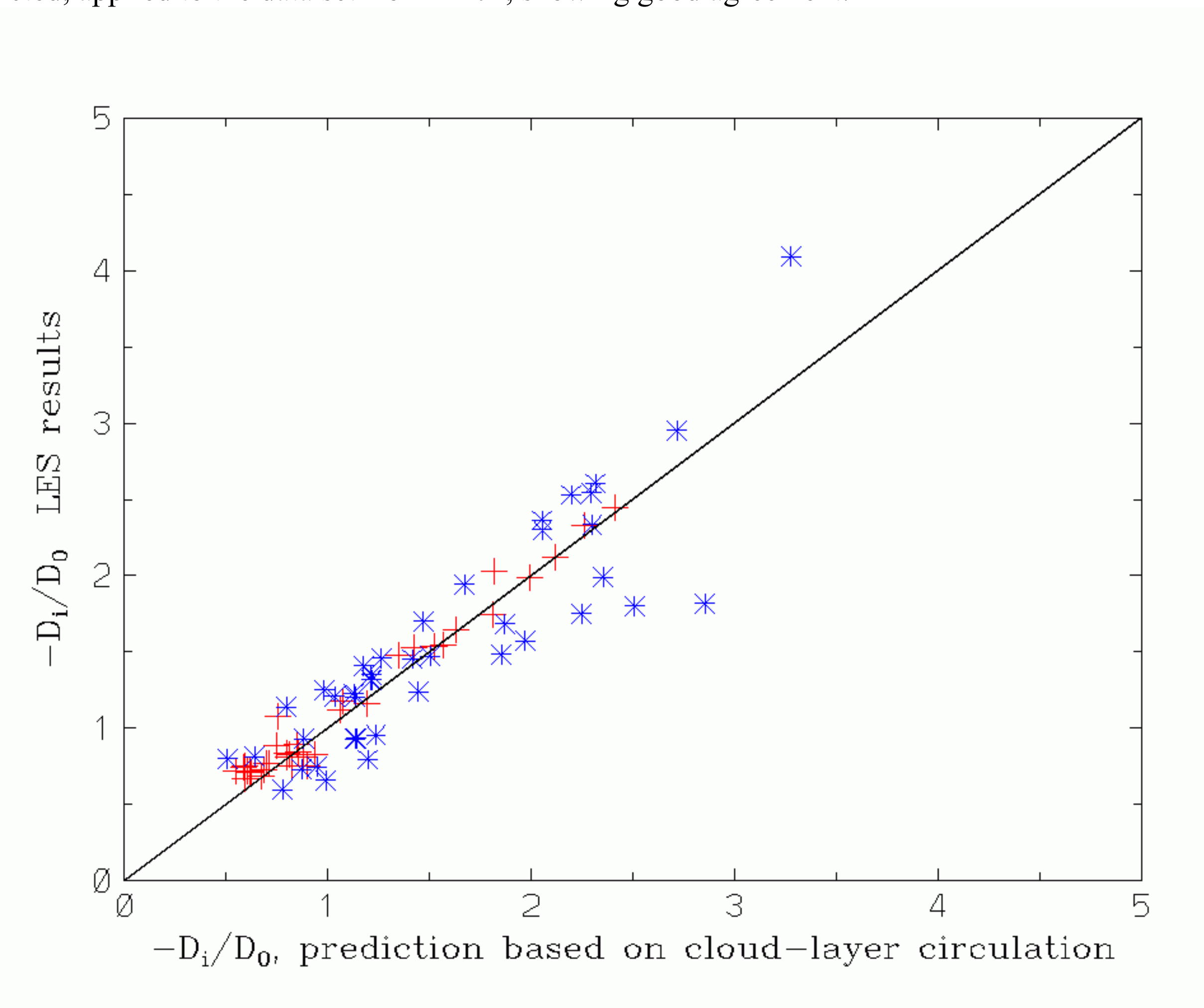


***Figure 2. Nondimensionalized entrainment flux from LES results versus that predicted based on a fixed entrainment efficiency for the cloud-layer circulation. The data set is from LL02, showing good agreement. ( + , * for Regime II, III layers, respectively.***

In other, related, results we have conducted preliminary LES tests of the predictions given in LL02 of the effects of cloud-top radiative cooling on decoupling. Generally one would expect such cooling to oppose decoupling, but the analysis of LL02 predicted that in some regions of parameter space the opposite can be true. We have confirmed within LES results that for some sample cases layers that are initially barely decoupled remain decoupled even as radiative cooling is turned on at significant levels. Also, in a series of dry convection simulations aimed at better understanding large eddy entrainment dynamics using a lidded box with a specified negative heat flux through the lid, we have found interesting scaling behavior for conditionally sampled up and down drafts as the entrainment flux is increased.

## 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 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

Intercomparison results from the GCSS (GEWEX Cloud Systems Studies) boundary layer cloud modeling working group (http://www.atmos.washington.edu/~breth/GCSS/GCSS.html) have become a standard test set for 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.

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