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

Boundary layer entrainment is a critical, much studied, yet relatively poorly understood element of the dynamics of the atmospheric boundary layer. The entrainment fluxes of heat and moisture across the capping inversion strongly affect both the dynamics and cloud structure within the boundary layer. The chief objective of the present grant is to better understand the physical processes which control the rate of this entrainment, 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.

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WORK COMPLETED

During the past year we have concentrated on further LES explorations of the sensitivity of cloud-top entrainment to a number of variables, in an effort to determine the range of conditions for which the entrainment rate is controlled by large eddy transport rather than by the small eddies confined to the local mixing region (Lewellen and Lewellen, 1998, hereafter referred to as LL98).

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. Our LES results for a stratocumulus boundary layer similar to field data taken during ATEX were included in the 1998 workshop at Madrid, Spain (web site for case setup is http://www.asp.ucar.edu/~bstevens /atex/contents.html).

RESULTS

Preliminary results from the range of conditions currently explored suggest that the basic theme of LL98, that cloud top entrainment is often controlled by large eddy transport independent of the details of the small eddies confined to the local mixing zone within the capping inversion, holds for a fairly wide range of conditions. In the earlier study we focused primarily on quasi-steady, tightly capped, buoyantly-driven boundary layers. Since then we have performed several series of LES to extend the range of conditions studied, in particular to weak capping inversions, strong shear across the inversion zone, and dynamics driven by surface latent heat transfer.

In one series of simulations the dynamics were driven by a surface heat flux together with a layer of heating higher in the domain. For the right range of conditions a capping layer forms below the heating layer, separating two mixed layers. In this system we can study the entrainment flux across a weak capping layer in a quasi-steady system, as well as study the decoupling of mixed layers. A principal result is that the entrained heat flux across the capping layer is found to be independent of the strength of the stable layer, even for weak capping with large turbulence levels within the inversion zone. The results are consistent with the entrainment flux being controlled by the large eddy transport as in LL98 with a large-eddy entrainment efficiency (as defined in LL98) of around 30%, consistent with the results found in LL98 for strong capping inversions.

Our simulations of surface driven convection with shear across the inversion support these qualitative results as well. For small to modest levels of shear in the inversion zone, the growth rate of the boundary layer through entrainment appears to be independent of the level of shear, although the depth of the inversion layer is not. For larger values of shear, however, when the shear production of turbulence becomes of the same order as the buoyant production, the interaction becomes somewhat more complex. The inversion layer depth, as well as the mixed layer height, grow with time. At least qualitatively, the growth of the former appears to be governed by the smaller scale, shear driven turbulence within the inversion zone, while that of the latter is still governed by the buoyantly driven boundary layer scale circulations.

The effects of entrainment are particularly important for boundary layer dynamics driven predominantly by a surface moisture flux producing latent heating aloft. We have studied these effects quantitatively in a series of LES in which the mixed layer is capped by a rigid lid through which we prescribe fixed heat and/or moisture fluxes. The fraction of these fluxes which are entrained into the mixed layer appears to be governed by the large eddy transport in the mixed layer with the remainder accumulating in a thin, relatively warmer and dryer layer next to the lid. It is possible in this way to compare the layer dynamics both with and without entrainment fluxes into the layer. Such a comparison is illustrated for a particular set of conditions in figure 1. The presence of cloud top entrainment is found to lead to a significant increase in vertical velocity skewness and extended depth of column clouds within updrafts below the mean condensation level. Entrainment also leads to the growth of a stable layer at cloud base (not shown).

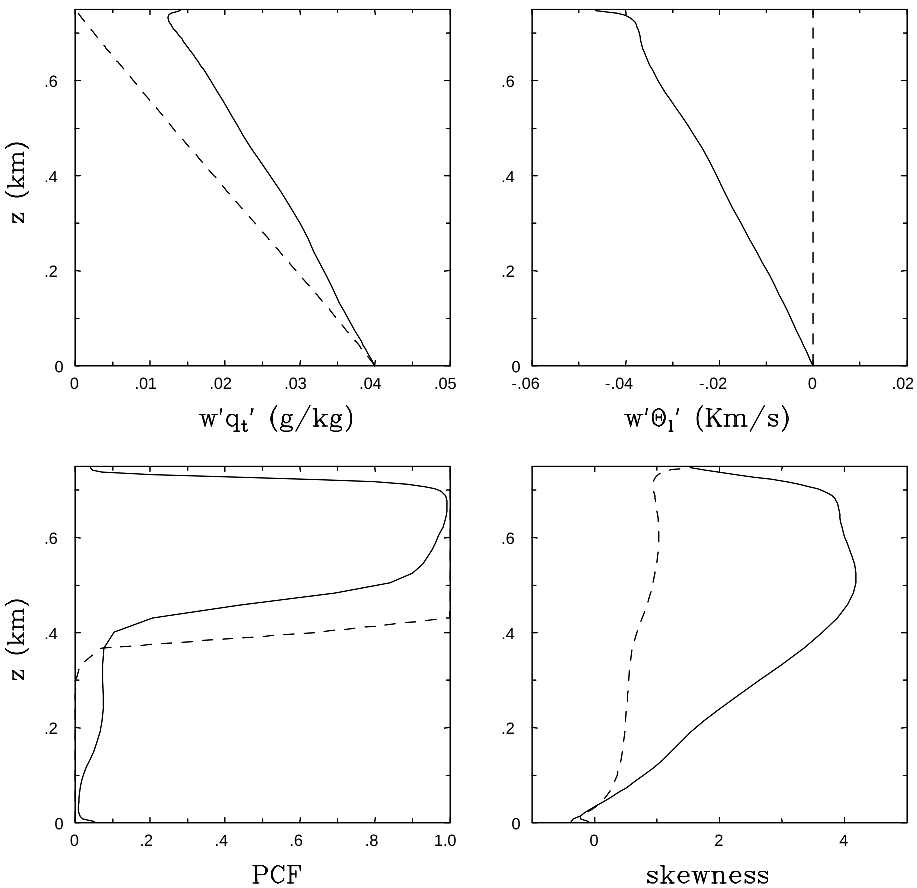

Figure. 1. Hour averaged mean vertical profiles for a sample boundary layer driven by surface latent heat flux both with (———) and without (-------) entrained heat and moisture fluxes at the top of the layer. Profiles are total water flux, liquid potential temperature flux, partial cloud fraction, and vertical velocity skewness.

IMPACT

A consistent quantitative model of cloud top entrainment is important to any model which 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).

TRANSITIONS

The ideas presented in LL98 are becoming known and stimulating discussions within the LES community. These results were introduced to some members of the experimental and observational communities in both the atmospheric and oceanographic sciences in a recent invited presentation at the workshop "Observations, Experiments and LES: A Triad for Geophysical Turbulence Studies" (Aug. 13 - 15) organized as part of the Geophysical Turbulence Program at NCAR.

RELATED PROJECTS

The LES code developed under ONR support has been modified and used to model aircraft wakes/contrails for NASA (Lewellen et al. 1998a), and to model the turbulent interaction of a tornado with the surface for NSF (Lewellen et al. 1998b). 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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