THE EFFECT OF CLOUD TOP ENTRAINMENT ON THE AEROSOL INDIRECT EFFECT

R. Sheppard and U. Lohmann[1]
Institute for Atmospheric and Climate Sciences, ETH, Zurich, Switzerland

Entrainment in stratocumulus-topped planetary boundary layers is one of the most challenging problems in boundary layer research. Not only is there a limited understanding in the physical processes that control entrainment, but their parameterization in GCMs has been difficult or non-existent.

A recent paper by Chlond *et al*. (2004) compared Large-Eddy Simulations and the ECHAM Single Column Model (SCM) from MPI, Germany. They find that the liquid water path in the SCM is much too low. Further, the turbulent kinetic energy is unrealistically large within the cloud layer. Both these findings are found to be due to a numerical instability arising from a decoupling or radiative and diffusive processes. Chlond et al. (2004) make improvements to the SCM results by adding an explicit entrainment closure at the boundary layer top.

This work will extend the work of Chlond *et al*. (2004) in two ways. Firstly, the ECHAM version used here has been extended to include aerosol effects. Secondly, an explicit entrainment parameterization at the top of the boundary layer will be introduced to both the SCM and the full GCM.

ECHAM5 Description

ECHAM5 is the fifth generation climate model developed at the Max-Planck-Institute for Meteorology in Hamburg, which evolved from the operational forecast model of the European Centre for Medium-Range Weather Forecasts (ECMWF). ECHAM5 uses prescribed climatological sea surface temperatures (SSTs) and sea ice. The model resolution used for this study is T63 (corresponding to 1.8° x 1.8°). This study uses a vertical resolution of 31 hybrid levels, with the highest resolution in the boundary layer and a time step of 15 minutes.

The model is based on primitive equations with 6 layers in the boundary layer, the highest at roughly 1500 m. The prognostic variables include vorticity, divergence, logarithmic surface pressure, temperature, specific humidity and the mixing ratios of cloud water and cloud ice. Full details of the model can be found in Stier *et al*. (2004) and Roeckner *et al.* (2004).

ECHAM5-HAM Description

The development of the ECHAM5-HAM aerosol model includes microphysical interactions between internally and externally mixed aerosol populations, as well as identifying their size distribution and composition.

1 Correspondence to U. Lohmann, Institute for Atmospheric and Climate Sciences, ETH Zurich, Switzerland; email: ulrike.lohmann@env.ethz.ch

The stratiform cloud scheme includes prognostic equations for cloud liquid water and cloud ice. Equation 1 is used to determine the temporal evolution of the cloud droplet number concentration, $\frac{\partial N_l}{\partial t}$ with the inclusion of cloud top entrainment.

$$\frac{\partial N_l}{\partial t}=R(N_l)+Q_{nucl}-Q_{autn}-Q_{self}-\frac{N_l}{q_l}(Q_{racl}+Q_{sacl}+Q_{frz}+Q_{evc}+Q_{ctei})+Q_{mlt} \qquad \text{Eq. 1}$$

where $R(N_l)$ represents the advective and turbulent transports of N_l, q_l is the cloud liquid water, Q_{nucl} is the nucleation of cloud droplets, Q_{autn} is the autoconversion, Q_{self} is the self-collection, Q_{racl} is the accretion of cloud droplets by rain, Q_{sacl} is the accretion by snow, Q_{frz} is the freezing of cloud droplets, Q_{evc} is the evaporation of cloud droplets, Q_{ctei} is the entrainment at the cloud top and Q_{mlt} is the melting of ice crystals. The cloud top entrainment has been included to account for the dissipation of a cloud due to cloud top entrainment instability (CTEI). In this study, the parameterizations for CTEI from del Genio *et al*. (1996) and Chlond *et al*. (2004) are both used. Other, more sophisticated methods exist (see Lilly, 2002 for a review of other methods currently available), but require a much finer vertical resolution in the boundary layer than present in ECHAM5-HAM.

In this study, ECHAM5-HAM was run in single column mode, which is a one dimensional model that includes the same cloud processes as the full GCM. The model is run with constant forcing using observations from the FIRE (First ISCCP Regional Experiment; Albrecht *et al*., 1988) campaign for the forcing of moist and dry advection at each time step. Full GCM results are intended to be shown on the poster.

<u>Results</u>

Figure 1 shows the humidity versus moist static energy jump at the cloud top interface produced by ECHAM5-HAM using the original parameterization, and with the addition of the entrainment parameterizations of del Genio *et al*. (1996) and Chlond *et al*. (2004). Observations of the humidity and moist static energy jump significantly vary, but are consistently below the solid line $\Delta\theta_l=0$, as can be seen in Figure 1 of Kuo and Schubert (1988). As can be seen in Figure 1 here, the model seems to agree well with the observations, even without the addition of entrainment. This implies that the model is representing the boundary layer inversion with reasonable accuracy.

As can be seen in Figure 1, adding entrainment produces a smaller humidity jump at the cloud top and a larger moist static energy jump (see Equation 2) as a result of mixing in dryer and warmer air from above,

$$h=c_pT+Lq+gz \qquad \text{Eq. 2}$$

where c_p is the the specific heat of dry air at constant pressure, T is the temperature, L is the latent heat of condensation/deposition, q is the specific humidity, g is the acceleration due to gravity and z is the height.

The difference between the del Genio *et al*. (1996) and Chlond *et al*. (2004)

parameterizations is much smaller than the difference to using no entrainment, showing that both parameterizations give quite similar results.

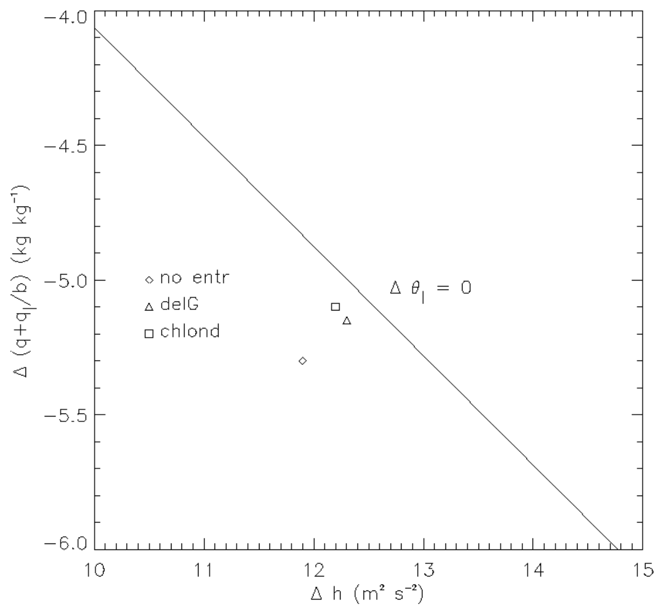

Figure 1 – The humidity versus moist static energy jump as produced in ECHAM5-HAM using no entrainment parameterization (no entr), and the parameterizations from del Genio *et al*. (1996; delG) and Chlond *et al*. (2004; chlond). The solid line shows $\Delta\theta_l = 0$.

Figure 2 shows the liquid water path (LWP), surface precipitation and entrainment rates versus droplet concentration using the parameterizations of del Genio *et al*. (1996) and Chlond *et al*. (2004) compared to the case without entrainment. With all parameterizations, the LWP and entrainment rate increase with increasing droplet concentration whereas the surface precipitation decreases. One aspect that stands out in the figure is the extremely large droplet concentrations (1,000-10,000 cm^{-3}) required to produce entrainment and the subsequent change in LWP and surface precipitation. This is most likely due to the coarse vertical resolution used in this model which makes it difficult to resolve the cloud accurately.

It is obvious from Figure 2 that the two entrainment parameterizations give very similar results, but vary markedly from the no entrainment run. For large droplet concentrations, there is a decrease in LWP when applying entrainment due to the dryer air from above removing some of the moisture available. Similarly, the addition of entrainment into ECHAM5-HAM also decreases the surface precipitation (Figure 2), since there is less available water in the cloud.

Lastly, Figure 2 shows a good agreement between the entrainment rates for both the del Genio *et al*. (1996) and Chlond *et al*. (2004) parameterizations.

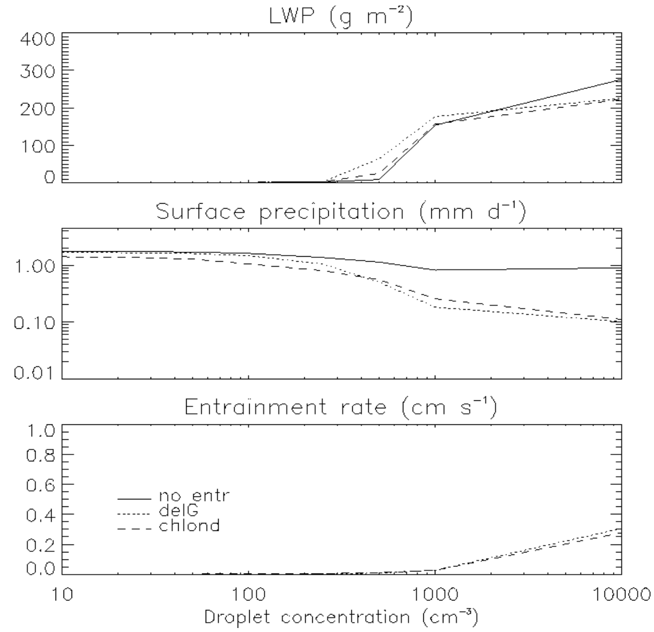

Figure 2 – LWP, surface precipitation and entrainment rate versus droplet concentration using no additional entrainment parameterization (no entr), and the parameterizations of del Genio *et al*. (1996; delG) and Chlond *et al*. (2004; chlond).

Conclusion

Results have been presented to show the impact of introducing cloud top entrainment instability to stratiform clouds in ECHAM5-HAM. The addition of entrainment appears to decrease both LWP and surface precipitation. Future work will involve adding entrainment into full GCM runs, and increasing the vertical resolution to better resolve stratiform clouds.

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