# REPRESENTING STRATOCUMULUS CLOUDS IN NUMERICAL MODELS: SENSITIVITY TO MODEL PHYSICS AND VERTICAL RESOLUTION

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## 1. INTRODUCTION

Stratocumulus clouds are a key component of the climate system playing a crucial role in the surface radiation budget. The presence of subtropical stratocumulus clouds can reduce the mean surface radiation flux by up to 300Wm$^{-2}$ through reflection of incoming solar radiation (Duynkerke and Teixeira(2001). The albedo of stratocumulus clouds is a complex function of the liquid water path (LWP), droplet size distribution and spatial variability of the water field. The LWP of stratocumulus clouds is often in the range 50-300 gm$^{-2}$, small variations in the LWP can therefore lead to large changes in cloud albedo. It is important that climate and NWP models accurately simulate stratocumulus LWP and associated radiative effects for a realistic prediction of the surface temperature.

In this paper we explore the balance between various physical parameterizations controlling the LWP and albedo of model stratocumulus clouds. In particular we assess the sensitivity of liquid water amounts to model vertical resolution and to the parametric representation of drizzle and cloud top mixing. The relative balance between competing parameterizations, acting to control the cloud water content, changes as the model vertical resolution increases. Cloud top mixing becomes an increasingly important term controlling the water balance of the cloud as vertical resolution is increased. We introduce a parameterization of cloud top entrainment into the model in order to simulate this important sink of water at lower vertical resolutions.

## 2. CASE DESCRPITION AND MODEL

A problem in simulating stratocumulus clouds is the need for an accurate specification (or simulation) of the large scale subsidence rate directly above the clouds. This term, along with the associated thermodynamic jumps at the boundary layer top, play a key role in determining the stratocumulus cloud depth and water content. To avoid this problem the EUROCS project designed a one dimensional (1D) case, based on the FIRE 1987 Stratocumulus campaign (Albecht etal. 1988).

In the 1D case, the subsidence rate, large scale advection, SST and surface pressure are all prescribed in a manner consistent with observations. The case is 40 hours in duration, allowing an analysis of the diurnal cycle. Use of prescribed large scale forcing in a 1D setting allows single column versions of climate and NWP models (SCMs) to be run with identical forcing to 3D Large Eddy Simulation Models (LES models). LES models explicitly resolve most of the cloud scale turbulence and mixing, thereby offering a relatively accurate reference against which SCM results can be compared (Duynkerke etal 2004). In this manner improved parameterizations may be developed using LES as guidance. Results are presented from a single column version of the SMHI Rossby Centre Regional Climate Model (RCA1D)[1] (Jones etal. 2004). RCA1D uses a prognostic, moist

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[1] The physical parameterizations in the RCA model follow closely those in the operational version of the HIRLAM model at SMHI.

conservative turbulent kinetic energy (TKE) scheme (Lenderink and Holtslag 2004) coupled to a statistical cloud scheme to simulate boundary layer turbulence and cloud processes. The cloud scheme is embedded within the turbulence scheme and uses the parameterized turbulent length scale and saturation deficit to estimate both cloud fraction and cloud liquid water. The resulting cloud fraction and water are then used in the parameterizations of radiation and precipitation.

## 3. RESULTS AND SENSITIVTY TESTS

The standard configuration of the RCA1D model has 40 levels in the vertical with a vertical resolution of ~100m in the boundary layer. Figure 1 shows a timeseries of the RCA1D simulated precipitation rate, LWP and surface solar radiation flux. Also shown is the MESO-NH LES results. (Note that both LES and RCA1D simulated overcast conditions throughout all the simulations). All LES models participating in the intercomparison assumed the case to be non-precipitating. This may not necessarily be a valid assumuption, in fact recent observations of stratocumulus in the DYCOMS II experiment off California (Stevens 2003) indicate frequent precipitation from stratocumulus clouds of order ~0.5mm/day. RCA1D simulates a diurnal cycle in LWP and drizzle, but overestimates the LWP by some 50-100 gm$^{-2}$. This causes a significant underestimate in the surface solar radiation flux of ~200Wm$^{-2}$ relative to the LES results. There is minimal compensation for this error by increased long wave emission from clouds, due to the low cloud base and high cloud emissivity. This type of surface flux error would lead to a severe underestimate of the sea surface temperatures in a coupled climate model.

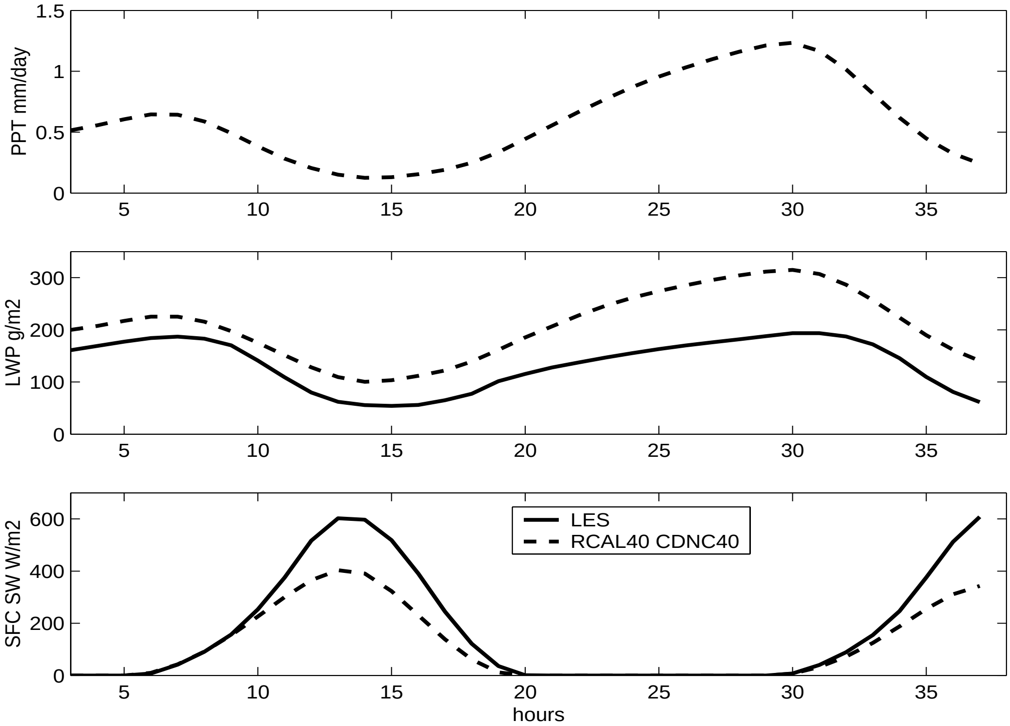

Figure 1 Timeseries of simulated precipitation (mm/day), LWP (gm$^{-2}$) and surface solar radiation flux (Wm$^{-2}$) from RCA1D with 40 levels and CDNC=40cm$^{-3}$ Also shown are MESO-NH LES results. The x-axis shows hours after model start (00Z local time)

Figure 1 indicates that drizzle rates and LWP are correlated. This is not too surprising as the parameterization of drizzle in RCA1D requires cloud water to exceed a certain threshold value before autoconversion of cloud water to precipitation can begin The figure also suggests that drizzle controls the amount of LWP (i.e. LWP increases are limited by increasing drizzle removal of water). The parameterization of autoconversion follows the ideas of Chen and Cotton (1987). An assumed cloud droplet number concentration (CDNC) is specified and combined with the prognostic liquid water content (LWC), determines the mean droplet size distribution in the simulated clouds. The cloud water content must increase so that the parameterized droplet radius exceeds a prescribed threshold (9µm) before autoconversion can begin.

A large CDNC will lead to a given LWC being distributed amongst many, small droplets, limiting the onset of drizzle. In contrast, a small CDNC, will give, for the same LWC, relatively fewer droplets of larger radius. Drizzle will therefore begin at a lower LWC for clouds with a lower assumed CDNC. In the standard integration CDNC was set to 40 cm$^{-3}$ for the stratocumulus clouds. Figure 2 shows results when CDNC is increased to 150 cm$^{-3}$. The change in the parameterized droplet size changes the balance between LWP and drizzle. LWP increases and drizzle rates decrease. Also shown in figure 2 is the RCA1D results when precipitation is disabled. This model configuration is most directly comparable with the LES set up. Non-precipitating, stratocumulus clouds in RCA1D greatly overestimate LWP and the resulting surface solar radiation flux is underestimated by some 300Wm$^{-2}$.

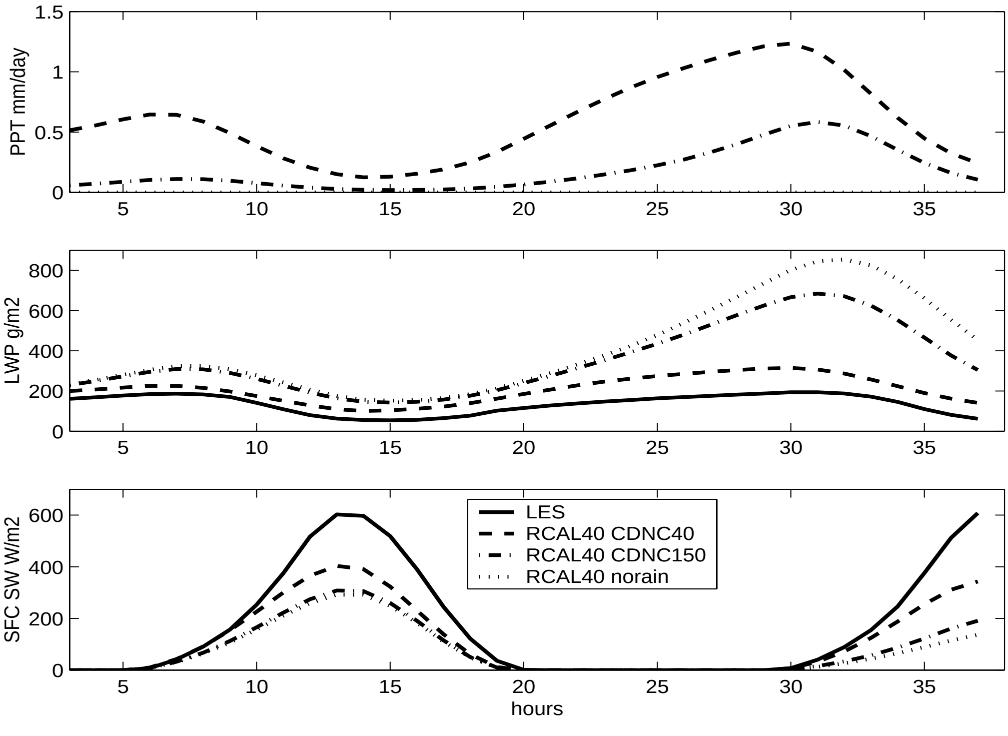

Figure 2 As in figure 1, with RCA1D 40L using CDNC=150 cm$^{-3}$ and with precipitation disabled.

The results suggest that the primary mechanism for water removal in the standard RCA1D simulation is drizzle. When drizzle is disabled RCA1D LWP values rise to unrealistically high amounts, compromising the surface energy budget. We contend the RCA1D model run at ~100m vertical resolution, lacks a key mechanism for removal of liquid water from clouds, namely entrainment at cloud top.

The MESO-NH LES model was run with a vertical level spacing of 10m in the boundary layer. We have repeated the RCA1D integration with the vertical resolution increased to 25m (150 vertical levels), to determine if increased vertical resolution leads to higher turbulent mixing at cloud top. Figure 3 shows the results for the standard 40 level RCA1D and the identical model run with 150 levels.

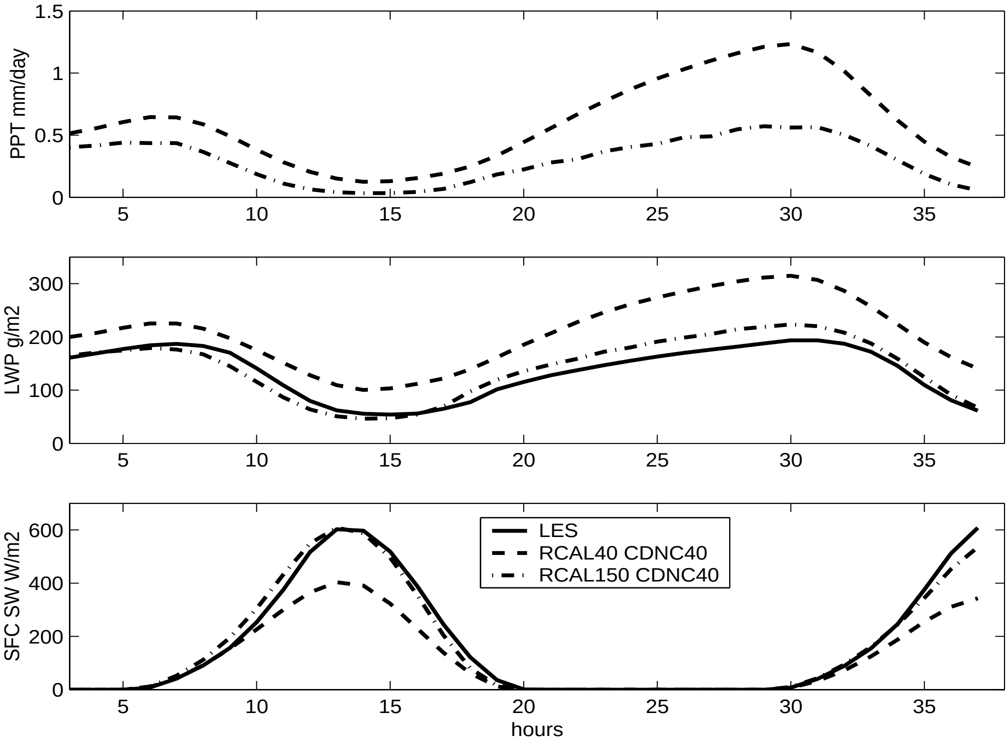

Figure 3 As in figure1, for RCA1D 40L and 150L, both with CDNC=40cm$^{-3}$.

LWP amounts are greatly reduced in the 150L simulation, being much closer to the LES values. Also the drizzle rate is reduced. We note that drizzle rates are not zero as assumed in the LES set up, but are ~0.25mm/day, a rate comparable to the DYCOMS II estimates. Increasing the vertical resolution leads to greater mixing at cloud top directly from the turbulence scheme. As a result dry air is mixed into the cloud. The turbulence scheme uses total water ($q_t$) and liquid water potential temperature ($\theta_l$) as mixing variables, both conserved in non-precipitating moist adiabatic processes. Hence entrainment of dry, high $\theta$ air into the cloud will directly lead to a reduction in cloud water to conserve $\theta_l$ and $q_t$

Increasing the vertical resolution changes the balance between terms controlling the water content of the simulated cloud. Drizzle is no longer the single dominant sink term for liquid water, cloud top mixing is now a second removal mechanism. Both mechanisms become more efficient as liquid water increases. As a result of the increased cloud top mixing, LWP and drizzle rates come into balance at a lower level. The resulting surface solar radiation flux is also greatly improved. To accurately simulate the evolution of stratocumulus clouds, inclusion of all terms in the water budget is clearly necessary.

Figure 4 shows the RCA1D results using 150 levels with the CDNC value increased to 150cm$^{-3}$. Analogous to the results with 40 levels, LWP increases and precipitation decreases as CDNC is increased to 150cm$^{-3}$. But, the sensitivity to this microphysical assumption is greatly reduced in the 150 level model. LWP now only increases to ~300gm$^{-2}$ compared to 600gm$^{-2}$ in the 40 level model. Likewise the precipitation rates are less than half those in the equivalent 40 level model.

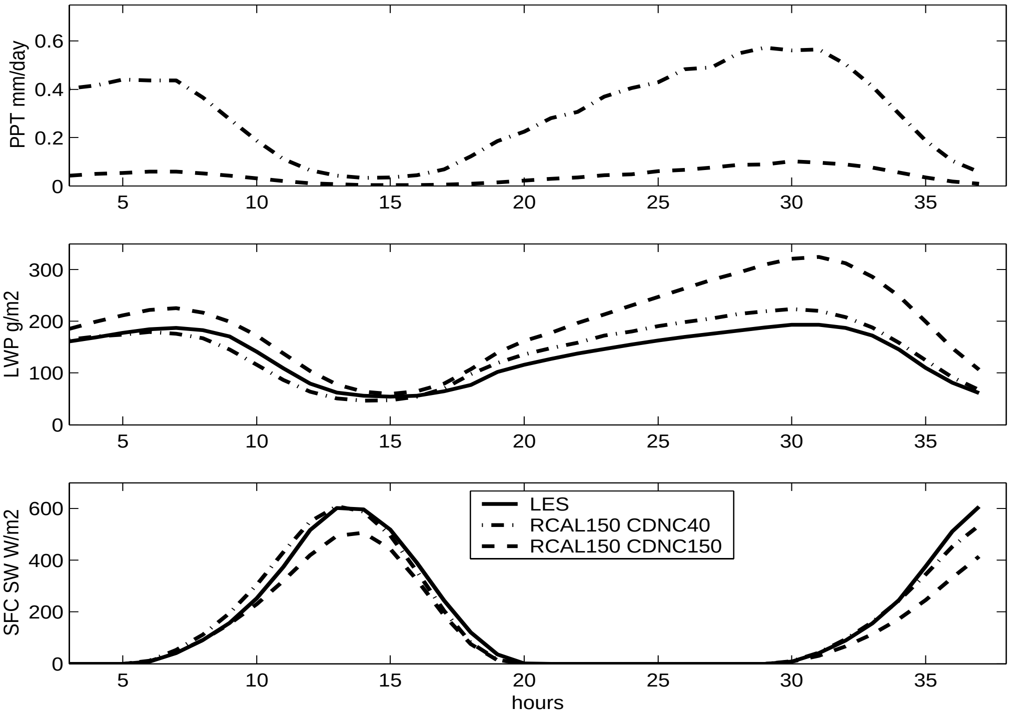

Figure 4. As in figure1, but for RCA1D 150L with CDNC equal to 40cm$^{-3}$ and 150cm$^{-3}$, respectively.

The overall water balance in the cloud has changed due to the increased cloud top mixing. With CDNC equal to 150cm$^{-3}$ drizzle will not start until LWC values are quite high (as seen in figure 2). As cloud water increases, in-cloud $\theta_l$ will decrease and $q_t$ increase. Both changes increase the gradient of the respective quantities across the cloud top. The direct result is increased vertical mixing at cloud top, reducing the cloud water amounts and the vertical gradients of the two conserved variables. Cloud top mixing therefore limits the mixing ratio of liquid water in the cloud and by implication drizzle rates from the cloud.

## 4. PARAMTERISING CLOUD TOP ENTRAINMENT

The standard version of RCA1D does not include an explicit parameterisation of cloud top entrainment, rather mixing at cloud top is handled by the prognostic TKE turbulence scheme The subgrid scale vertical flux of variable $\chi$ is given by:

$$\overline{\omega'\chi'} = l\overline{e^{\frac{1}{2}}}\rho g \frac{\partial \overline{\chi}}{\partial z} \qquad (1)$$

where l is a diagnosed mixing length and e is the TKE value. We have tested replacing this approach to subgrid scale vertical mixing, at the cloud top inversion, by a parameterisation of cloud top entrainment following the ideas of Grenier and Bretherton (2001). In this approach we search for the sharpest jump in $\theta_v$ between a saturated (cloudy) layer and an unsaturated layer above, searching from the surface upward. The level of maximum jump is defined as the inversion level (KINV). At KINV we replace the subgrid scale flux given by (1) with a flux derived from a parameterized entrainment velocity.

$$\overline{\omega'\chi'} = -w_e \Delta\chi \qquad (2)$$

$$w_e = \left(a_1\left(1 + a_2 E\right)\right)\frac{\overline{e^{\frac{3}{2}}}}{l\,\dfrac{g}{\theta_{v0}}\left(\Delta\theta_v\right)} \qquad (3)$$

$$E = \left(1 - \frac{\Delta_m b}{\Delta b}\right) \qquad (4)$$

$w_e$ is an entrainment velocity at the inversion level and $\Delta\chi$ is the jump in a prognostic variable across the inversion. E is referred to as the evaporative enhancement of entrainment and represents the increased energy, available for mixing at the cloud top, due to the generation of negatively buoyant mixtures of cloudy and clear air. E increases as the jumps in $\theta_l$ and $q_t$ across the inversion increase. E will also be higher for larger values of cloud water. $\Delta$b is the linearized average buoyancy of all possible mixtures of cloudy air and free-tropospheric air, relative to the pure cloudy air (for more details see Grenier and Bretherton 2001).

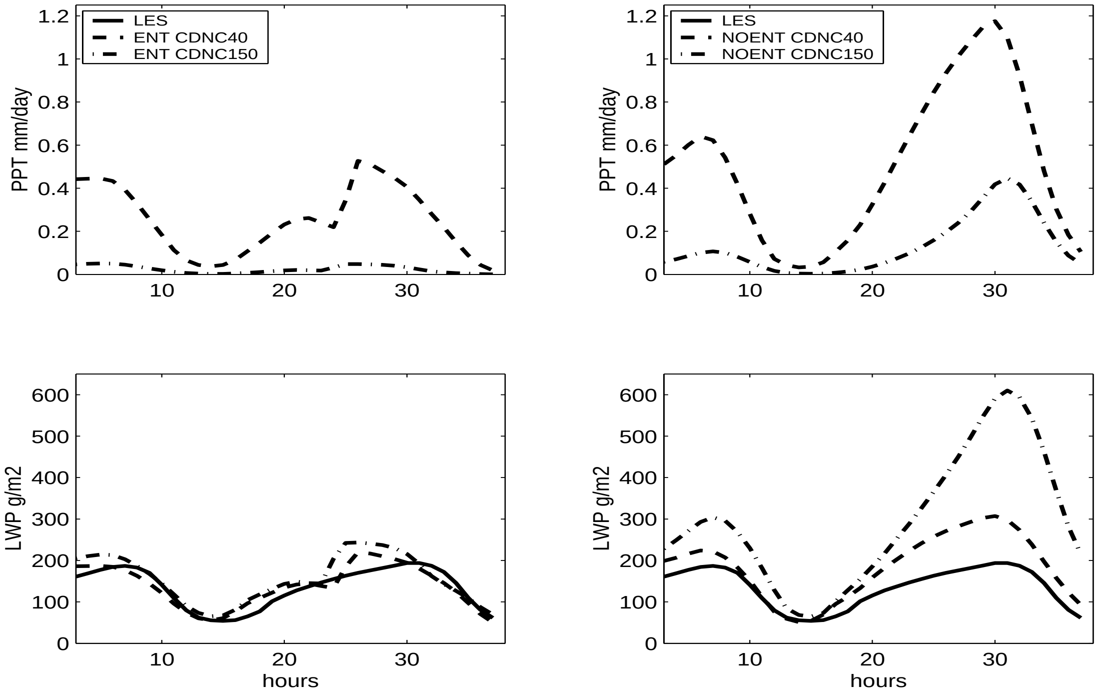

Figure 5, Sensitivity of cloud microphysics to parameterized cloud top entrainment in the RCA1D 40 level model. Left column shows precipitation (top) and LWP(bottom) for LES and RCA1D 40L with parameterized cloud top entrainment. Results for CDNC=150 and 40 cm$^{-3}$ are shown. Right column shows same results but with cloud top entrainment turned off.

Figure 5 shows the result of including this parameterization, for the subgrid scale vertical flux at KINV, in the 40 level version of RCA1D. The right column shows the sensitivity of LWP and precipitation rate, in the 40 level model, to the specification of CDNC, without parameterized entrainment. By increasing CDNC, auotconversion of cloud water to precipitation starts at a higher LWC. Drizzle is reduced but LWP is dramatically increased as a consequence. Performing the same set of experiments but with parameterised cloud top entrainment included (left column) leads to a radically different water cycle. In both CDNC experiements with cloud top entrainment, LWP is reduced as is the drizzle rate. In particular, the sensitivity of both LWP and precipitation to a change in the assumed cloud droplet number concentration (CDNC) is drastically reduced. The direct cause of this is increased mixing of dry, warm air from above the cloud top into the cloud through the parameterised entrainment term. As cloud water increases, so the negative buoyancy of mixtures of cloudy and clear air increases. This leads to an increase in the entrainment velocity in equation 3 and a larger flux of above cloud air into the cloud. By this process, cloud water increase is limited by cloud top mixing. As a consequence of this limit, precipitation production is also decreased. In the experiment ENT CDNC40, cloud top entrainement and drizzle appear to both play a role in controlling LWP. In ENT CDNC150, while LWP amounts stay rather similar to ENT CDNC40, the primary control is cloud top mixing.

## 5. CONCLUSIONS

We have presented results from RCA1D simulations of the diurnal cycle of stratocumulus clouds, based on the FIRE campaign of July 1987. The model successfully simulates the diurnal cycle of LWP and precipitation and remains completely overcast throughout the simulation, in accordance with the LES results. The standard 40 level RCA1D overestimates LWP and drizzle leading to a poor simulation of the surface solar radiation flux. The 40 level model appears to have a single dominant liquid water sink, namely precipitation. The only means by which a reasonable LWP can be achieved is through an onset of drizzle at unrealistically low LWC values, leading to both excessive drizzle occurrence and accumulations.

Increasing the model vertical resolution to 25m from the standard 100m, improves the results. Mixing of dry air from above the inversion into the cloud increases and acts as a second sink for liquid water. As a result, both LWP and drizzle rates decrease in RCA1D, becoming closer to the LES results. The reduced LWP has a profound influence on the surface radiation budget. Introduction of a parameterization of cloud top entrainment into the 40 level model also increases cloud top mixing, analogous to the 150 level model. The extra sink of water leads to a reduction of both LWP and drizzle and an improved surface radiation budget.

An accurate simulation of the radiative effect of stratocumulus clouds requires the inclusion of all physical processes influencing the cloud water budget. The relationship between drizzle production and cloud water amount is changed if cloud top mixing is active or not. This sensitivity is of great importance in the context of modeling the indirect aerosol effect in clouds where drizzle rates are coupled to changing aerosol and cloud condensation nuclei concentrations.

## 6. ACKNOWLEDGMENTS

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