# IMPACT OF RADIATIVE COOLING AND SUBGRID-SCALE MIXING ON THE EVOLUTION OF STRATOCUMULUS-TOPPED BOUNDARY LAYER

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## 1 Introduction

Stratocumulus-topped boundary layer (STBL) is an important element of the climate system due to significant impact on the Earth's radiative budget. Properties of STBL strongly depend on the small-scale cloud-top turbulent mixing between the cloudy STBL air and the free-tropospheric air from above the STBL inversion. The mixing influences the amount of condensed water and cloud droplet size distribution, which in turn affect the dynamics of the entire STBL by their impact on the evaporative and radiative cooling. In large-eddy simulation (LES) small-scale turbulent processes are included through subgrid-scale (SGS) parameterizations. Recent LES studies (e.g. Stevens et al. 2005) demonstrate significant model-to-model variability of STBL properties and systematic underestimation of the cloud cover when compared to observations. One of the key reasons is poor understanding of the behavior and details of SGS models as well as uncertain representation of small-scale processes driving STBL dynamics. Because of the range of scales involved (from kilometers down to fraction of a centimeter), the situation cannot be improved by simple mesh refinement.

LES simulations by Kurowski et al. (2009), suggest that entrainment into STBL is driven by local shears at the STBL top in regions where the model-resolved convective updrafts impinge upon the overlaying inversion. Because of the inversion, these updrafts are forced to diverge horizontally and produce local shears large enough to drive SGS mixing near the cloud top. In this paper we present sensitivity studies extending results reported in Kurowski et al. (2009). A range of parameters in forcing terms important for the cloud-top entrainment (and consequently affecting STBL characteristics) are systematically varied. The modifications impact the strength of radiative cooling, the SGS turbulent mixing, and the delay of the phase change (i.e., cloud water evaporation) during the stirring phase of the cloud-clear air turbulent mixing.

## 2 Simulation setup

LES simulations described in this study are based on the modeling setup presented in Stevens et al. (2005). Nocturnal nondrizzling stratocumulus is simulated using the anelastic nonhydrostatic model EULAG (e.g. Prusa et al., 2008, and references therein; see also http://www.mmm.ucar.edu/eulag/). STBL is forced by the longwave radiative cooling at the stratocumulus top and constant in time and space surface sensible and latent heat fluxes. The simulations exclude effects of the diurnal cycle and allow better understanding of the influence of fundamental processes affecting STBL. The model setup is based on observations from the DYCOMS-II field campaign.

## 3 Results of simulations

### 3.1 Sensitivity to the radiative cooling

A simple radiative scheme employed in the model follows Stevens et al. (2005). It mimics a strong longwave radiative cooling at the stratocumulus top, weak warming around the cloud base, and weak cooling of the free troposphere. Effects of shortwave radiation are excluded. To investigate sensitivity of the STBL to the radiative cooling, we performed a series of simulations with the radiative forcing term as detailed in Stevens et al. (2005) multiplied by factors of 0.5, 0.8, 1.5 and 2. All other simulation parameters remained unchanged. Such a wide range of longwave radiative cooling is arguably larger than all experimental uncertainties in the DYCOMS-II campaign and it allows investigating the importance of radiative processes for the

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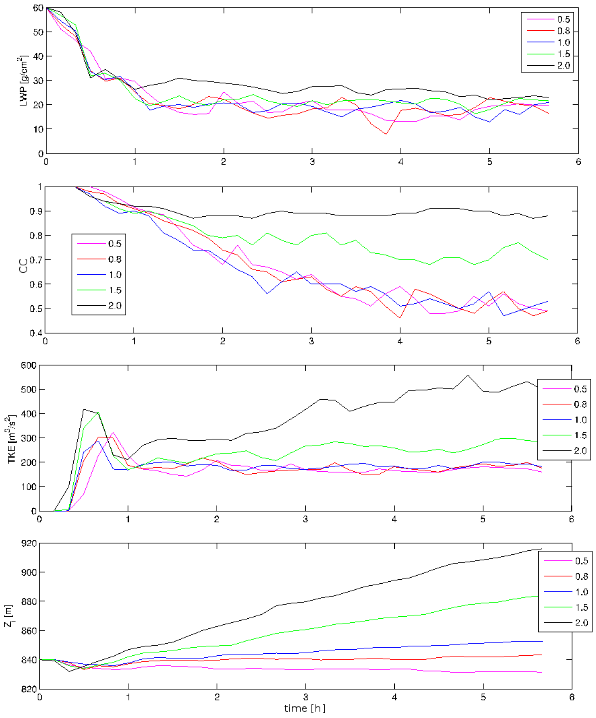

Figure 1: Time evolution of LWP, CC, vertically-integrated TKE, and $Z_i$ for radiative cooling sensitivity tests. Numbers in the legend indicate factors by which basic radiative forcing term was multiplied (see text for details).

development of simulated STBL and their possible couplings with other processes.

Time evolutions of the domain-averaged characteristics, namely the liquid water path (LWP), the cloud cover fraction (CC), the vertically-integrated turbulent kinetic energy (TKE), and the inversion height ($Z_i$) are presented in Fig. 1. Additionally, evolution of the parameter describing vertical mixing of STBL in terms of the total water mixing ratio $q_t$ defined as (cf. Stevens et al. 2005)

$$\delta q = \int_{100m}^{200m} q_t dz - \int_{700m}^{800m} q_t dz \qquad (1)$$

is presented in Fig. 2. Vertical profiles of the buoyancy flux, the second and third moments of the vertical velocity are shown in Fig. 3.

The model spin-up is about one hour and subsequently a slowly-evolving STBL is simulated. In general, weakening of the radiative forcing with respect to the standard value has a minor effect when compared to the simulations with enhanced forcing. This suggests that the evaporative cooling due to mixing at the cloud top is a dominant factor influencing STBL circulations in the standard configuration of the model. On the other hand, enhanced radiative cooling affects almost all domain-averaged characteristics of the simulated STBL, except for the mean LWP which seems insensitive to the radiative forcing. The enhanced radiative cooling leads to the increase of TKE due to production of TKE by buoyancy forces (cf. the buoyancy flux in Fig. 3). This results in an enhanced vertical mixing across the STBL depth (as shown by the temporal evolution of $\delta q$ in Fig. 2) and an increased variance of the vertical velocity (cf. profiles of $< w'w' >$ in Fig. 3). More efficient turbulent mixing at the cloud top increases entrainment velocity that leads to the faster growth of the STBL depth (cf. evolution of $Z_i$ in Fig. 1). In consequence, dry air entrained from above the inversion mixes with the cloudy air at the cloud top. Resulting evaporation of liquid water compensates the average condensation and forces the radiative cooling and LWP to remain constant. While the domain averaged LWP does not change, cloud cover fraction increases with the increase of the radiative cooling, suggesting that condensation (production of cloud water) due to evaporative cooling may play an important role in a thin region near the clod top. This is supported by profiles of the vertical velocity third moment $< w'w'w' >$ (cf. Fig. 3).

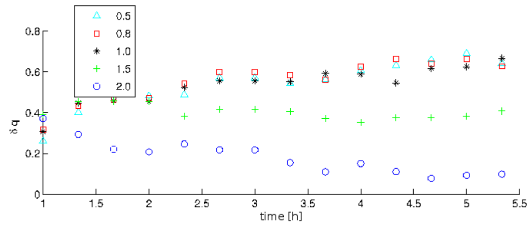

Figure 2: Time evolution of $\delta q$ for radiative cooling sensitivity tests. Numbers in the legend indicate factors by which basic radiative forcing term was multiplied.

## 3.2 Sensitivity to SGS mixing

Various LES models apply different approaches to include effects of SGS mixing. SGS schemes can differ in their complexity (e.g., higher-order moments versus K-theory), may apply different simplyfing assumptions and various parameter values. For example, in neutrally stratified boundary layer the Prandtl number (i.e., the ratio between turbulent mixing coefficients for momentum and temperature, $K_m/K_h$) may be prescribed as $Pr = 0.33$ (Moeng-Nieuwstadt, cf. Nieuwstadt et al. 1991) or $Pr = 0.42$ (Schumann, 1991). In the stable boundary layer these values change to $Pr = 1$, since Monin-Obukchov scaling functions for temperature and momentum become identical (e.g. Stull, 1988). Another example are the turbulent mixing coefficients for

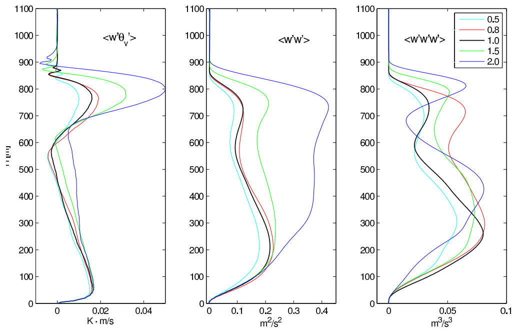


Figure 3: Domain averaged profiles of buoyancy flux ($< w'\theta_v' >$), second ($< w'w' >$) and third ($< w'w'w' >$) moment of the vertical velocity at $t = 3h$ for radiative cooling sensitivity tests. Numbers in the legend indicate factors by which basic radiative forcing term was multiplied.

moisture and other scalars, assumed to be the same as for the thermal diffusion in some models, and assumed different in other models. Such inconsistencies in the description of turbulence which drives the entrainment and mixing may cause discrepancy of results in simulations of STBL.

In order to characterize possible range of influence of such effects on modeled STBL a series of sensitivity tests of the model response to SGS turbulence was performed. The SGS parametrization is based on the K-theory with the prediction of the SGS TKE (see Margolin et al., 1999). The turbulent mixing coefficient for momentum is prescribed as

$$K_m = \Delta c_m e^{1/2}, \tag{2}$$

where $\Delta = (\Delta x \Delta y \Delta z)^{1/3}$ denotes the mixing length, $c_m$ is a constant, and $e$ is model-predicted SGS TKE. Modification of SGS parametrization includes three different mixing lengths: $\Delta$ (basic), $0.5\Delta$, $0\Delta$ (i.e. inviscid flow with no SGS transport), and three different Prandtl numbers: 0.42 (basic), 0.7 and 1.

Time evolutions of LWP, CC and TKE for this set of simulations are presented in Fig 4. Additional characteristics, such as time evolution of $\delta q$ and vertical profiles of buoyancy and second and third moment of vertical velocity are presented in Fig. 5 and Fig. 6, respectively. As the figures illustrate, all imposed modifications reduce efficiency of thermal and moisture diffusion. This leads to a significant improvement of the model ability to reproduce two basic characteristics of STBL: the cloud cover fraction and the liquid water path. Stratocumulus deck becomes ticker and more solid, with the closest agreement with observations for $Pr = 1$. For an inviscid simulation, the domain is entirely covered with Sc in agreement with results reported in Stevens et al. (2005). Influence of SGS on vertical mixing is clearly visible as decreasing values of $K_m$ and $K_h$ lead to smaller values of $\delta q$. Except for an inviscid flow, a decoupled boundary layer is always observed, as indicate profiles of $< w'w' >$ and $< w'w'w' >$ in Fig. 5.

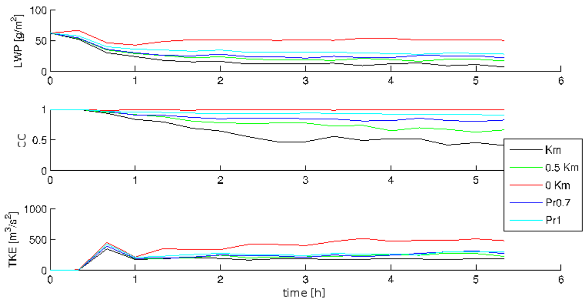


Figure 4: Time evolution of LWP, CC and vertically integrated TKE for SGS model sensitivity test. Black line corresponds to results for the basic value of turbulent diffusion coefficient for momentum.

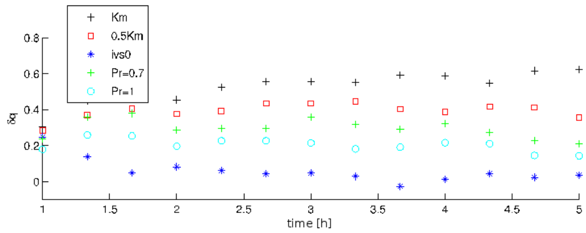


Figure 5: Same as in Fig. 2 but for sensitivity test of SGS model.

## 3.3 Sensitivity to the phase change delay due to turbulent mixing

The last series of simulations is motivated by the small-scale in situ measurements (e.g. Haman et al., 2007), where a multiscale nature of the mixing at the stratocumulus top was documented. LES models usually include the moist thermodynamics using the bulk schemes based on a concept of instantaneous saturation adjustment. The observations indicate however that a more realistic approach should consider turbulent mixing as a process that introduces delay in a phase change until homogenization within a grid box takes place. In order to examine the impact of the delay, the scheme of Grabowski (2007) was employed. The scheme adds one model variable, the length scale $\lambda$ characterizing the progress of turbulent stirring, from the initial scale of turbulent engulfment $\Lambda$ (which can be taken as the model gridlength) down to the scale at which microscale

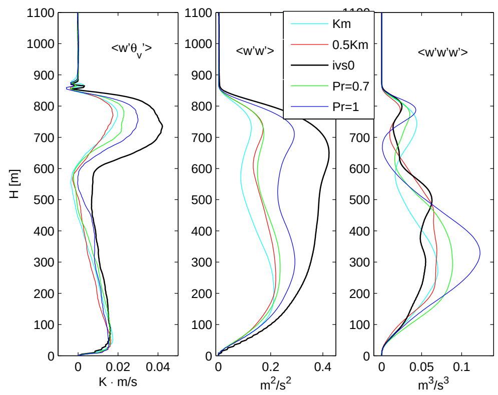


Figure 6: Same as in Fig. 3 but for sensitivity test of SGS model.

homogenization takes place $\lambda_0$ (the latter of the order of the Kolmogorov microscale). Locally, the reduction of the scale $\lambda$ during turbulent stirring is predicted as (cf. Broadwell and Breidenthal 1982)

$$\frac{\partial \lambda}{\partial t} \sim -\varepsilon^{1/3}\lambda^{1/3}, \tag{3}$$

where $\varepsilon$ is the TKE dissipation rate. The evaporation due to turbulent mixing is delayed until $\lambda$ becomes smaller than $\lambda_0$.

Sensitivity tests consider five cases: two with constant $\varepsilon$, and three with model-predicted TKE. The constant $\varepsilon$ cases assume either weak turbulence with $\varepsilon = 10^{-4} m^2/s^3$ (i.e., typical for Sc) or strong turbulence with $\varepsilon = 10^{-1} m^2/s^3$ (larger than typical for Cu). The three TKE-based simulations use local values of model predicted TKE and the TKE reduced/increased by a factor of 0.5/2.

The results of simulations are presented in Fig. 7, Fig. 8 and Fig. 9. Surprisingly, changes in LWP, CC, TKE and $Z_i$ are small when compared to other sensitivity tests despite the fact that the delay time ranges from merely a few seconds up to a few minutes for different values of $\varepsilon$. The lowest cloud cover is simulated for constant both high and low $\varepsilon$. This highlights the importance of local considerations for the effects of turbulence and not the magnitude of the dissipation rate alone. Inversion level height $Z_i$ is the lowest for the low constant $\varepsilon$, although the difference is set during spin-up of the model and after the spin-up changes in $Z_i$ are similar in all simulations. Other characteristics such as the time evolution of $\delta q$, vertical profiles of buoyancy and second and third moment of vertical velocity do not reveal any significant sensitivity to the phase change delay due to turbulent mixing either. Overall, the results suggest that the phase change delay and thus the delay in the buoyancy reversal is less important than the magnitude of SGS transport itself.

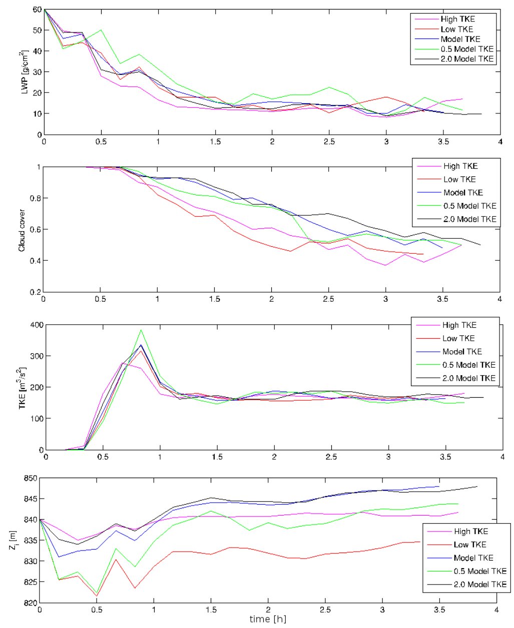


Figure 7: Same as in Fig. 1 but for sensitivity test of delay in a phase change due to turbulent mixing. High/low TKE corresponds to typical Cu/Sc turbulence, respectively (see text for details).

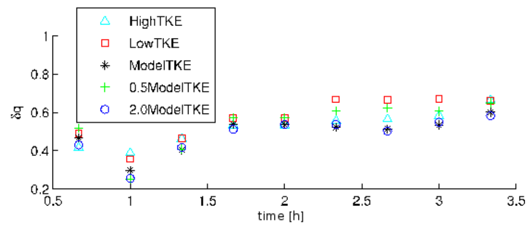


Figure 8: Same as in Fig. 2 but for sensitivity test of delay in a phase change due to turbulent mixing.

# 4 Summary and conclusions

An extensive set of sensitivity simulations to processes believed crucial for STBL evolution, such as the strength of cloud-top radiative cooling, SGS turbulent mixing, and the delay in a phase change due to turbulent mixing was run and analyzed. According to the results, mean Sc characteristics significantly depend on the strength of the cloud-top radiative cooling, with strong cooling leading to rapid STBL destabilization. Model results also show strong sensitivity of STBL to parameterized SGS mixing, in agreement with the dis-

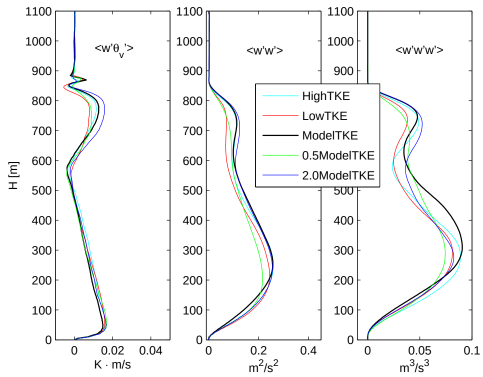


Figure 9: Same as in Fig. 3 but for sensitivity test of delay in a phase change due to turbulent mixing.

cussion in Stevens et al. (2005). In particular, significant sensitivity is observed to the assumed turbulent Prandtl number. Specific results and their comparison to observation discussed in Stevens et al. (2005) suggest that LES models typically apply too small turbulent Prandtl number in STBL simulations. More realistic approach to the turbulent mixing (i.e., with the delayed phase change and buoyancy reversal to account for the effects of turbulent stirring) does not improve LES results significantly. Excluding the SGS model improves fidelity of selected STBL features (e.g., increased cloud fraction), but deteriorates simulation of specific features (e.g., lack of cloud holes).

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