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On the role of drizzle in stratocumulus and its implications for large-eddy simulation

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SUMMARY

Large-eddy simulation (LES) of marine stratocumulus cloud-topped boundary layers show a surprisingly large sensitivity to the prescribed forcing—this being at odds with the widespread and persistent occurrence of this cloud type. However, most LES studies have not taken drizzle explicitly into account. This note explores the damping effect (i.e. reducing the sensitivity to the forcing) that drizzle might have on the stratocumulus cloud-topped boundary layer. A single-column model is used to illustrate the difference in response in one model version with drizzle taken into account and one in which drizzle is inactivated. Results are shown for a simulation of the diurnal cycle of stratocumulus clouds over sea; they support the notion that the impact of drizzle is underrated in the present-day modelling of stratocumulus-topped boundary layers.

KEYWORDS: Boundary-layer clouds Entrainment Model intercomparisons

1. INTRODUCTION

In the recent past several large-eddy simulation (LES) model intercomparisons of marine stratocumulus-topped boundary layers have been performed (Moeng *et al.* 1996; Duynkerke *et al.* 1999; Stevens *et al.* 2001). In the most recent case reported in this issue (Duynkerke *et al.* 2004) a diurnal cycle is investigated. This case has shown that apparently small differences in the simulated entrainment rate result in a rather large spread in model results when integrated over a long time period. In addition Chlond *et al.* (2004) have shown a large sensitivity of the cloud fields to the prescribed subsidence rate. This behaviour appears to conflict with the widespread and persistent occurrence of stratocumulus clouds over the subtropical ocean: How can clouds that appear to be so sensitive to small changes in the applied subsidence rate (or the simulated entrainment rate) be so common in nature?

Even more, there is another worrying aspect of most LES intercomparison cases. In most cases, rather high values of the subsidence rates are used in order to get a realistic evolution of the cloud-top height. For this reason Duynkerke *et al.* (1999) used 0.15 Pa s^{-1} at 1000 m, which was set three times higher than the subsidence rate estimated from the ECMWF analysis. Duynkerke *et al.* (2004) has used 0.1 Pa s^{-1} at 1000 m. In contrast, the background radiative-driven subsidence (Betts and Ridgway 1988) suggests 0.04 Pa s^{-1}—a value in agreement with subsidence rates in most general-circulation model results, including the ECMWF reanalysis (Siebesma *et al.* 2004).

So, summarizing, we are facing two apparent paradoxes:

1. LES model results suggest an equilibrium state for marine stratocumulus requiring a forcing (subsidence) that appears to be rather uncommon in nature;

2. this equilibrium state appears to be highly sensitive to changes in the forcing (or likewise in the simulated entrainment rate), which seems at odds with the persistent and widespread occurrence of stratocumulus.

In the paper by Duynkerke *et al.* (1999) it was already noted that the entrainment rate simulated by LES models was larger than the entrainment rate inferred from measurements. Would we be able to obtain a realistic equilibrium state using lower subsidence rates if we were able to lower the entrainment simulated by the LES models? Clearly, there is no problem in simulating a realistic evolution of the cloud-top height, since the reduced entrainment rate can be balanced with a lower subsidence rate. But, if the entrainment rate is reduced, then so is the entrainment flux of dry air into the boundary layer. Therefore, given that the LES cases have used realistic surface fluxes of moisture, the boundary layer moistens.

Drizzle acts as a moisture sink if it falls to the surface. There is ample observational evidence that drizzle might contribute significantly to the boundary-layer moisture budget (see Stevens *et al.* (2003), and the references therein). They showed drizzle to be commonplace and estimated drizzle fluxes at the surface of up to 1.0 mm day^{-1}, which is equivalent to 30 W m^{-2}. However, drizzle is neglected in most LES studies (among these, the recent Duynkerke *et al.* (2004) intercomparison case). The rather low drizzle rates that were simulated by the LESs when drizzle was included (Duynkerke *et al.* 1999) supported the omission

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of drizzle. Also, observations show that drizzle is very intermittent in space, and reliable measurements of drizzle on a larger scale (representative for grid boxes of atmospheric models) have only recently been obtained (van Zanten *et al.*, personal communication).

Finally, could drizzle be an important factor in reducing the sensitivity shown by the LES simulations? Clearly if the liquid water contained in the clouds increases one would expect increases in the drizzle rate (and vice versa). Also, drizzle feeds back onto the dynamics. Drizzle reduces turbulent mixing, and hence entrainment, due to its direct effect on the buoyancy (condensation at cloud top and evaporation of rain below cloud base). Also, drizzle changes the optical properties of the cloud, thereby affecting long-wave radiation and, hence, turbulent mixing and entrainment. These feedbacks are not new and have been discussed in the literature (see e.g. Boers 1995; Stevens *et al.* 1998; Nicholls 1987) but their implications for the modelling of stratocumulus clouds might have been underrated.

In this short note we explore these points further in the context of an intercomparison case (Duynkerke *et al.* 2004) describing the diurnal cycle of stratocumulus clouds. We used a relatively simple single-column model (SCM) to illustrate the damping effect of drizzle on idealized simulations of stratocumulus, and to explore the possibility of sustaining a realistic (quasi-) equilibrium state using low(er) subsidence rates.

2. MODEL

We use the SCM model that is described by Lenderink and Holtslag (2004). It uses a prognostic equation of turbulent kinetic energy (TKE or E) combined with a diagnostic length scale to compute the eddy diffusivities for heat, moisture and momentum. The scheme uses moist conserved variables to compute the stability, and therefore includes cloud condensational effects (Roeckner *et al.* 1996). A simple statistical scheme is used to prognose cloud fraction. The model is able to simulate the typical (near) well-mixed profiles of the liquid-water potential temperature and total water that are simulated by the LES with realistic liquid-water profiles (Lenderink and Holtslag 2000). The model has a qualitative representation of subcloud decoupling (see also Lenderink and Holtslag 2004). We de-activated the cumulus convection scheme for the present integrations, which circumvents the problems associated with the cumulus scheme inadvertently switching on (Duynkerke *et al.* 2004).

The case is described extensively by Duynkerke *et al.* (2004) in this issue. Here, we only remark that the sea surface temperature and a simple parametrization of long-wave and short-wave radiation in the cloud layer are prescribed. The subsidence rate is 0.1 Pa s^{-1} at 1000 m. We used a resolution of 10 m and a time step of 60 s.

3. RESULTS

Figure 1 shows results for a set of five different simulations of the SCM model, performed without representation of drizzle and with representation of drizzle. The model was run with the standard value for the subsidence rate ($w_\mathrm{S} = 0.1$ Pa s^{-1}) at 1000 m, and with this value reduced to 0.05 Pa s^{-1}. In addition, we varied the entrainment rate by adapting the model formulation of the turbulence scheme. To this purpose we changed the formulation for the length scale, l, in stable conditions:

$$l = c\frac{\sqrt{E}}{N}$$

where N^2 is the Brunt–Väisälä frequency based on moist conserved variables. We reduced the value of the coefficient c from the standard value $c_\mathrm{S} = 0.2$ to $0.5c_\mathrm{S}$ and to $0.25c_\mathrm{S}$. Note that the corresponding decrease in entrainment is smaller due a negative feedback through buoyancy production in the cloud and, therefore, E.

The results show a clear diurnal cycle in cloud liquid-water path (LWP), with the highest values of LWP and entrainment (boundary-layer growth) during night-time. The LES intercomparison results show values of LWP in the range between 120 and 240 g m^{-2} during night-time, which is about the range that is observed (Duynkerke *et al.* 2004). For the standard value of the subsidence rate, and using the standard model with $c = c_\mathrm{S}$, entrainment is slightly overestimated in the SCM run without drizzle, as can be inferred from a LWP of 100 g m^{-2}. But using $c = 0.5c_\mathrm{S}$ leads to a modest increase in LWP of 30 g m^{-2}, and the results are now at the lower end of the range simulated by the LES. With drizzle, and using the same subsidence rate, the model outcome for the two values of c is very similar.

The sensitivity changes dramatically when the subsidence rate is reduced to the more realistic value of 0.05 Pa s^{-1}. There is a large increase in LWP in the runs without drizzle as opposed to a very modest increase in the runs with drizzle. In general, the reduced subsidence rate causes an increase in cloud-top height and a corresponding increase in cloud thickness. This will lead to higher values of LWP. In addition

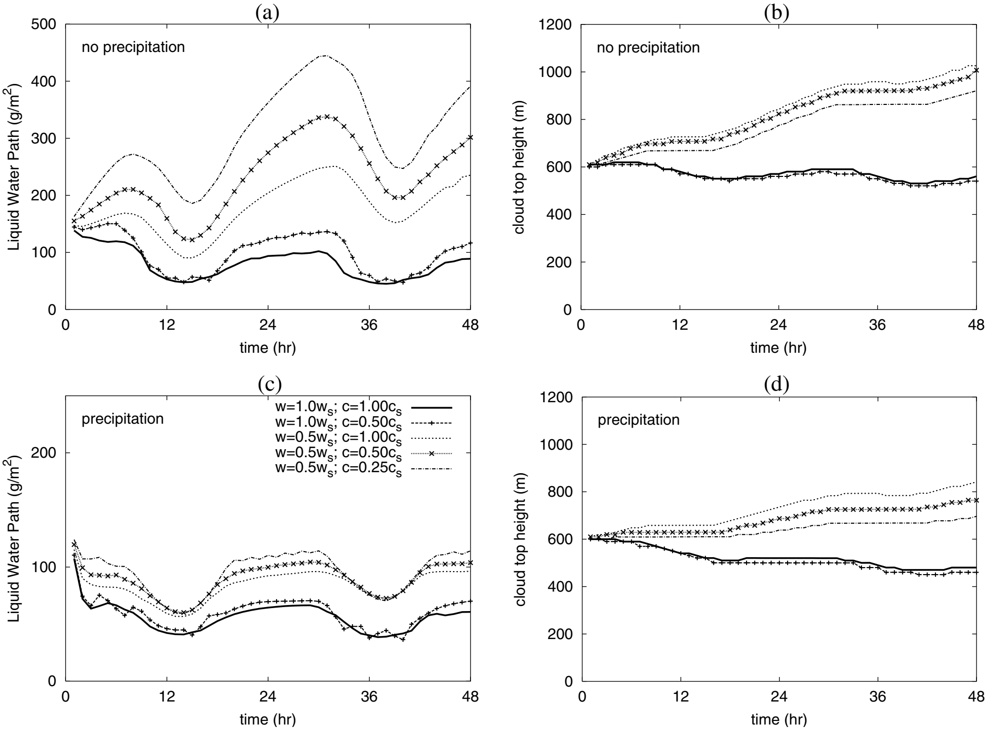

Figure 1. Time evolution of (a) and (c) the cloud liquid-water path (g m^{-2}), and (b) and (d) the cloud-top height (m), in runs (a) and (b) without drizzle, and (c) and (d) with drizzle. Runs are shown for the standard value of the subsidence rate ($w_\mathrm{S} = 0.1$ Pa s^{-1}) and a value reduced to half the original value ($w = 0.50w_\mathrm{S}$), combined with three different values for the coefficient in the formulation for the length scale in the inversion: the standard value $c_\mathrm{S} = 0.2$, and c reduced to $0.50c_\mathrm{S}$ and $0.25c_\mathrm{S}$.

there is a dependency on the entrainment rate, with the highest value of LWP for the lowest entrainment rate. The run with the lowest value of c gives a very large response of the LWP in the run without drizzle. In the runs with drizzle, this response to the entrainment-rate formulation is strongly damped. First, because there is an increasing amount of drizzle falling at the sea surface; with the standard value of c this represents about 28 W m^{-2} (latent-heat-flux equivalent) during night-time, increasing to 42 W m^{-2} with c reduced $0.25c_\mathrm{S}$. Second, in the runs with drizzle the entrainment rate is strongly reduced, leading to smaller cloud depths and correspondingly lower LWPs. These results show that a quasi-stationary state for this case can be obtained with a realistic value of the subsidence rate, provided that drizzle is included.

To assess the potential impact of the microphysics scheme (as described in the appendix) we performed a few sensitivity runs with more efficient evaporation (by multiplying c_E by 100) and modified drizzle formation rate, using the standard value of c_P multiplied by 2.0 (high autoconversion efficiency) and 0.5 (low autoconversion efficiency). Results for the surface precipitation, including those of the standard model set-up, are shown in Fig. 2. For all runs we used $c = 0.25c_\mathrm{S}$ and a subsidence rate $w = 0.05$ Pa s^{-1}. The use of more effective evaporation does not change the results much. Evaporation in the standard model set-up is small, and only 10% of the drizzle flux at cloud base evaporates in the subcloud layer leaving 90% at the surface. This is due to the high values of relative humidity in the subcloud layer. Increasing the evaporation leads to even higher values of specific humidity (close to saturation), causing a strong negative feedback. The impact of modifying the drizzle formation rate is larger. Associated with the larger drizzle rate using $2c_\mathrm{P}$ is a smaller entrainment rate (and vice versa). The cloud LWP during night-time varies between 70 g m^{-2} for the high-drizzle formation rate and 140 g m^{-2} using the low rate. In addition, the cloud-top height after 48 hours is about 100 m higher in the run with the low-drizzle formation rate. It therefore appears that the influence of the microphysics on the dynamics is considerable, leading to reduced entrainment rates with more active drizzle formation. Further analysis showed that the main impact of drizzle on the entrainment is determined by its direct impact on the buoyancy production, and not through

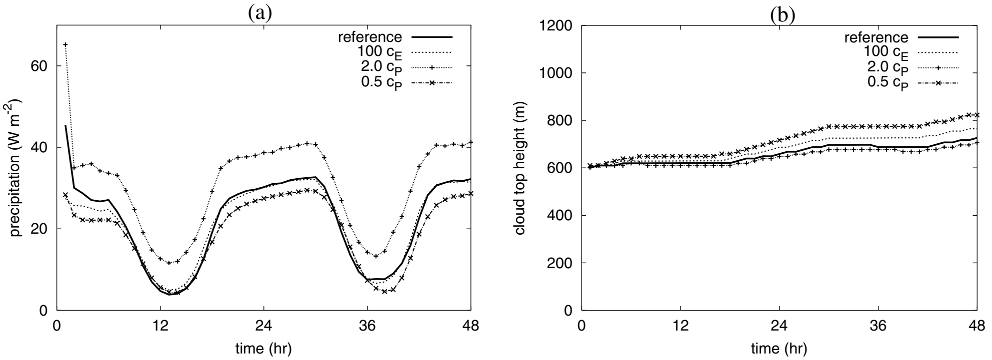

Figure 2. Time evolutions of (a) the surface precipitation (W m^{-2}) and (b) the cloud-top height in the sensitivity runs.

changes in long-wave cooling due to the cloud properties—the latter might be (partly) the result of the simple parametrization of the long-wave cooling as used in this case, depending on LWP only. We also note that an initially higher drizzle rate in response to the modifications in the microphysics cannot be sustained if there is no corresponding other change in the boundary-layer moisture budget.

4. DISCUSSION

This study emphasizes the importance of drizzle in an idealized intercomparison case of the diurnal cycle of a marine stratocumulus-topped boundary layer (Duynkerke *et al.* 2004). It is shown that, with a lower, but more realistic, value of the subsidence rate, a realistic evolution of the boundary layer can be obtained if drizzle is taken into account. Without drizzle the boundary layer shows a pronounced drift. Drizzle has an important direct damping effect on the LWP, mainly because cloud liquid water is effectively removed by drizzle above a certain threshold. Indirectly, drizzle reduces entrainment due to its effect on the dynamics. Lower values of the subsidence rate are generally associated with thicker cloud layers containing more liquid water. In the runs with drizzle, these are also linked to higher drizzle rates and, therefore, (due to the indirect effect) lower entrainment rates. This feedback reduces the sensitivity of the cloud field (mainly cloud top) to the subsidence rate.

The results are obtained in an SCM which might not capture all dynamical feedbacks in a stratocumulus cloud layer correctly. However, we think that, qualitatively, our main findings are valid since they principally depend on the entrainment flux, the drizzle rate, and the surface fluxes, all of which are reasonably well modelled with the SCM. The impact of drizzle on the dynamics of the boundary layer agrees well with an earlier study with a LES model (Stevens *et al.* 1998). Also, qualitatively, our findings are robust to changes in the microphysics parametrization.

Our findings support the notion that drizzle should have a more central role in our modelling efforts of boundary clouds, both because of its influence on the moisture budget and because of its influence on the dynamics (entrainment). As an example, it is mentioned that explicit parametrizations of entrainment that have recently been derived from LESs do not generally contain the impact of drizzle explicitly (see e.g. Stevens (2003) for a survey of these parametrizations).

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APPENDIX A

Microphysics

We use the microphysics scheme of ECHAM4 (Roeckner *et al.* 1996). In this scheme, the autoconversion rate of cloud droplets to rain is parametrized after Sundqvist (1978):

$$P_{\mathrm{coal}} = q_{\mathrm{lc}}[c_{\mathrm{P}}\{1 - \exp(-q_{\mathrm{lc}}^2/q_{\mathrm{o}}^2)\} + c_1[P]],$$

with q_{lc} the in-cloud liquid-water content, $q_{\mathrm{o}} = 0.5$ g kg^{-1} a threshold for rain formation and $c_{\mathrm{P}} = 3 \times 10^{-4}$. The last term represents the collision of cloud droplets with large rain droplets with $c_1 = 2$ and $[P]$ the rain-flux density (for this case this term is small).

The evaporation of rain is given by

$$P_{\mathrm{evap}} = c_{\mathrm{E}} \frac{q_{\mathrm{sat}} - q_{\mathrm{v}}}{1 - b}$$

with b the cloud fraction, q_{v} the specific humidity, q_{sat} the saturation specific humidity and $c_{\mathrm{E}} = 0.008$. The rain flux $[P]$ is given by the integral over P_{coal} and P_{evap} from cloud top to the surface.

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