Numerical simulation of marine stratocumulus clouds
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Marine stratus and stratocumulus cloud (MSC), which usually forms from 500 to 1000 m above the ocean surface and is a few hundred meters in thickness, plays a crucial role in the global climate system by enhancing the global albedo and promoting turbulent heat and moisture exchange between the sea surface, the boundary layer, and the overlying troposphere. Despite improvements in observing, understanding, and modeling of MSC, serious biases persist in its horizontal extent, vertical structure, and mean albedo simulated by most general circulation models. Likely causes include inaccurate parameterizations of turbulence and entrainment, cloud fraction, cloud microphysics, and precipitation, as well as insufficient vertical resolution. As a part of the Global Energy and Water Cycle Experiment (GEWEX) Cloud System Study, Working Group 1 (WG1) has organized a series of large-eddy simulation (LES) and single-column model (SCM) intercomparison studies of stratocumulus topped boundary layers. The methodology of GCSS WG1 is to (i) use LES to simulate turbulence–cloud–radiation interactions and deduce mean cloud fraction, thickness, and vertical structure, (ii) test and improve SCMs using the LES results and (iii) test the fidelity of both LES and SCM results using intercomparisons based on well observed case studies (e.g., Duynkerke et al. (2004), Stevens et al. (2005), Zhu et al. (2005)).

Here we adopt this methodology and address the full diurnal cycle of stratocumulus based on FIRE I observations. The strategy applied here requires a two-stage procedure: In the first step the MPI-LES model is used to explicitly model the cloud topped boundary layer and to produce comprehensive 4-D datasets of marine stratocumulus. The second step of strategy is to evaluate and improve turbulent mixing scheme in the ECHAM-GCM. The intercomparison of the SCM results against the LES results enables the validation of the standard parameterization package and allows to quantify the deficiencies in the various schemes. Reasons of deficiencies for the cloud-turbulence scheme are identified and physically-grounded corrections are developed and implemented in the SCM and evaluated against the LES generated datasets.

The simulation is, and is based on measurements during the FIRE I stratocumulus experiment performed off the coast of California in July 1987. The case consists of a 37-h long simulation, starting at 0800 UTC (= 00 LT) 14 July 1987 with idealized initial profiles and large-scale forcings. The initial and boundary conditions are based on observations specified in Duynkerke et al. (2004).

The LES simulations were started on 14 July 0800 UTC (= 00 LT) lasting for 37 hours. Figure (1) shows the variation of the simulated LWP as function of time which are compared with the retrievals of a microwave radiometer from 14 and 15 July 1987, and the hourly monthly mean diurnal variation. The ensemble average is marked using a thick black line. The LES model reproduces the strong diurnal variation in LWP due to the forcing imposed by the shortwave heating of the cloud layer. In accord with the observations, the maximum LWP is found during the late night (around sunrise which occurs at 0500 LT), and the minimum of the LWP occurs shortly after local noon (which is at 1200 LT).
Now we will look at the simulated vertical turbulence structure of the stratocumulus topped boundary layer and we will make some comparisons with the observations. We will concentrate on the total (resolved plus subgrid scale) vertical velocity variance $w''^2$ which is an indicator of convective activity and the total buoyancy flux $w' \cdot \theta''$, where $\theta$ denotes the virtual potential temperature. The periods chosen for comparison are centered around local noon and midnight, where LES results represent one-hour time averages. It can clearly be seen from Figure (2) that results produced by LES agree reasonably well with the observations and are within the range of uncertainty in the observations, although the night time vertical velocity variance seems to be slightly overpredicted by the LES model. The profiles generated from the LES ensemble runs are not widely scattered, indicating that the one-hour time average is sufficient to produce reliable statistics for second order moments. Obviously, there exist marked differences in the turbulence structure during day-time and night-time. During the night both observations and calculations show that most of the buoyancy production is concentrated within the cloud layer. This implies that cloud top cooling due to evaporation of cloud droplets and radiation are the dominant buoyancy production mechanisms. The cloud top cooling is in this case strong enough to promote mixing all the way down to the sea surface. The nocturnal boundary layer is thus a well mixed layer from the inversion to the surface, driven from cloud top in a manner analogous to that of a convective boundary layer heated from below. As a result, the maximum vertical velocity variance is located in the upper half of the boundary layer. During daytime, the shortwave radiative heating becomes of the same magnitude as the longwave radiative cooling for the cloud layer as a whole but penetrates deeper into the cloud than the longwave radiative cooling. As a result, the buoyancy flux at cloud base becomes slightly negative tending to suppress vertical turbulent motions. This implies that the turbulent eddies driven from cloud top cooling cannot reach the surface anymore.

We now show results for a single-column model (SCM) with the standard ECHAM5 configuration. Figure (3) shows observed and modelled LWP from the single-column model (SCM) as function of time. The SCM predicts a solid cloud cover and reproduces a fair representation of the diurnal cycle as the liquid water path varies between 100 g m$^{-2}$ around sunrise to about 20 g m$^{-2}$ some hours before sunset. However, compared to the observations the SCM predicts a too low LWP and thus tends to thin the stratocumulus layer to quickly. Subsequently, in the SCM this leads to a much larger amount of downwelling shortwave radiation absorbed at the sea surface causing an erroneous warming bias of the sea surface temperature. Typically, the liquid water content varies linearly with height. As a result the LWP is proportional to the cloud thickness squared. Realizing the large sensitivity of the LWP with cloud thickness, this implies that even small errors due to the coarse vertical resolution of current operational GCMs or due to an incorrect description of the entrainment fluxes at cloud top can give rise to large errors in the modelled LWP and subsequently to large errors in the surface energy balance.

Based on the findings described above, we modified the standard SCM. In this paragraph we will show that the behaviour of the model for this case can be significantly improved. The applied modifications basically concerned the implementation of an explicit entrainment parameterization to specify the vertical fluxes of heat and moisture at the boundary layer top. This approach permits a realistic treatment of a stratocumulus topped
boundary layers even in a SCM/GCM with coarse vertical resolution and combines the ordinary 1.5-order turbulent closure model with an explicit entrainment formulation. To represent the entrainment interface on a discrete vertical grid we applied a numerical front tracking/capturing method which allows the computation of propagating phase boundaries in fluids. This approach is similar in spirit to the so called ‘prognostic inversion’ approach as it combines an internally varying boundary layer depth with an entrainment parameterization. The advantage of this formulation is that it permits the stratocumulus top to lie between grid levels and continuously evolving with time. This is a desirable feature for the simulation of stratocumulus clouds because cloud feedbacks on turbulence and radiation can be captured despite the coarseness of the grid. A comprehensive description of the scheme is given in Chlond et al. (2004).

Results of this revised model are displayed in Figure (4) (upper panel) showing the time evolution of the liquid water content. For comparison also the liquid water field generated by LES for the same case is shown (lower panel). The modified SCM captures the diurnal variation of the liquid water content profiles due to the forcing imposed by the shortwave radiation. Like the LES, the maximum cloud thickness is found during the night, and cloud deck gradually thins until the afternoon. In both models the computed liquid water content increases with height in the cloud and reaches a maximum at $z/z_i = 0.9$. This shows that entrainment leads to a decrease in the liquid water content just below cloud top. A peak value in the liquid water content of about $0.60 \text{ g kg}^{-1}$ was predicted by both models during the night whereas during the afternoon peak values around $0.20 \text{ g kg}^{-1}$ were produced by LES as well as by the SCM. We have also plotted the vertical velocity variance as function of time and height for both, the SCM and the LES model. Comparing in Figure (5) the SCM results to the LES results, it is seen that the SCM produces a fair representation of the diurnal cycle, although the vertical velocity variance levels are somewhat to low, in particular in the cloud layer. To summarize: It is demonstrated that with these modifications the revised SCM provides an excellent simulation of the diurnal cycle of the stratocumulus-topped boundary layer which is significantly improved compared to the one performed with the standard SCM.

References:


Figures:

Figure 1: Time series of observed and simulated LWP\textsubscript{s} generated from 16 LES-model realizations of the stratocumulus case. The ensemble average is marked using a thick black line. Open squares refer to hourly mean observations during 14 and 15 July 1987, whereas the open diamonds represent the hourly monthly mean diurnal variation.
Figure 2: Vertical profiles of (a) total buoyancy flux during the night, (b) total vertical velocity variance during the night, (c) total buoyancy flux during the day, and (d) total vertical velocity variance during the day from observations and generated from 16 LES-model realizations of the stratocumulus case. The ensemble averages are marked using thick black lines. The calculated profiles represent time averages over one hour between 23 h < t < 24 h (night-time) and between 36 h < t < 37 h (day-time). Data are marked with diamonds and refer to measurements collected by means of a tethered balloon during FIRE I.
Figure 3: Observed and simulated LWP using the standard SCM as function of time for 14 and 15 July 1987. Open squares refer to hourly mean observations, whereas the open diamonds represent the hourly monthly mean diurnal variation.
Figure 4: Time evolution of the liquid water content obtained using the revised SCM (upper panel) and the LES model (lower panel) for the reference case.
Figure 5: Time evolution of the vertical velocity variance obtained using the revised SCM (upper panel) and the LES model (lower panel) for the reference case.