EUCLIPSE

EU Cloud Intercomparison, Process Study & Evaluation Project

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Deliverable D3.5 SCM equilibrium states in the Hadley circulation.

Delivery date: 30 months

EUCLIPSE Description of Work: Deliverable 3.5

D3.5: Equilibrium solutions of SCMs, with an emphasis on the equilibrium cloud-top height, cloud liquid water path, cloud fraction, and drizzle rate. Identification of the key quantities that control these quantities.

Involved EUCLIPE Partners: TUD, KNMI.

Background, motivation and aim

The main purpose is to understand how low clouds respond to a change in the sea surface temperature and perturbed large-scale forces in a future climate. To this end we have followed three pathways. Stratocumulus clouds are studied with a mixed-layer model, and shallow cumulus clouds with a large-eddy simulation model. In each case the models are run to a steady-state. The results are analyzed with aid of the governing budget equations for heat and moisture, which demonstrates the key role cloud-top entrainment is playing. The response of the stratocumulus cloud amount is studied for a wide range of external conditions defined by the large-scale divergence, horizontal wind speed, the sea surface temperature and the thermodynamic state of the free troposphere. As a last step, a similar approach is followed to study the stratocumulus response with SCMs.

1. The effect of single changes in cloud-controlling factors on stratocumulus amount

De Roode et al. (2012) use a mixed-layer model to study the response of stratocumulus to changes in cloud controlling factors. The mixed-layer model assumes a vertically well-mixed boundary layer, and includes the relevant physical processes acting in stratocumulus clouds such as a net radiative cooling at the top of the cloud and turbulent fluxes of heat and moisture (see Figure 1 for a schematic representation). The surface fluxes are calculated from a bulk formula including a drag coefficient, the horizontal wind speed, and the difference between the mixed-layer and surface value of the quantity considered. To close the model the entrainment parameterization proposed by Nicholls and Turton (1986) was used.

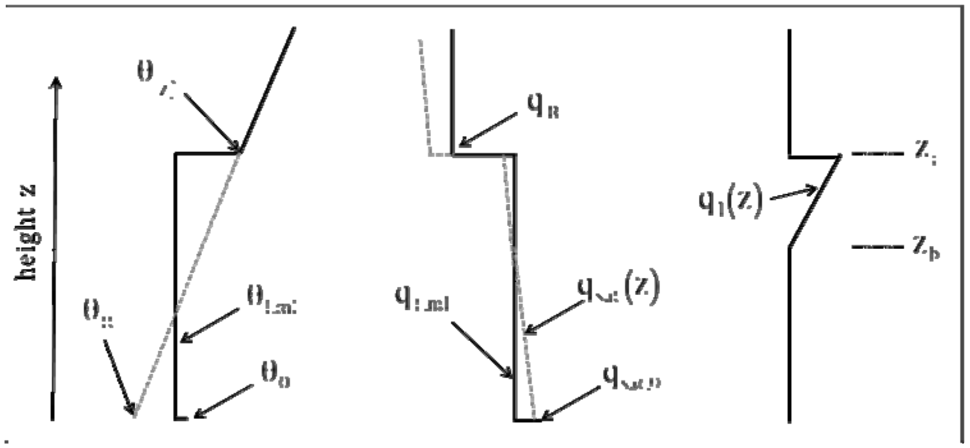

Figure 1: Schematic of the vertical profiles of the liquid water potential temperature, total specific humidity and liquid water specific humidity in the mixed layer model.

In the reference case, equilibrium state solutions were computed for a wide range of values for the low tropospheric stability (LTS) and total specific humidity values in the free troposphere q_{ft}. The radiative forcing was set to a constant value. Figure 2a shows that for low LTS values, relatively high LWP equilibrium values are found. This can be understood from the fact that the entrainment rate will become large if the buoyancy jump across the inversion becomes relatively small which is the case for low LTS values, such that for this regime the highest entrainment rates and consequently the deepest mixed layers are found. Figures 2b and c also show that the effect of q_{ft} on the entrainment rate is subtle, with maximum values for the entrainment rate w_e roughly at about q_{ft} = 5 g/kg. Although q_{ft} has only a weak effect on the entrainment rate, Figures 2d, e and f show that it has a distinct influence on the thermodynamic structure of the boundary layer as quantified by the liquid water potential temperature and total specific humidity in the boundary layer, $\theta_{l,ml}$ and $q_{t,ml}$, respectively, and on the cloud base height z_b.

As a next step, De Roode et al. perturb cloud controlling factors one by one in order to assess the influence of single changes on the stratocumulus cloud amount. Figure 3 shows the LWP response to changes in the potential sea surface temperature θ_0, the free tropospheric potential temperature θ_{ft} and the specific humidity q_{ft}, respectively, the horizontal wind speed U, and the large-scale divergence D. In the lower right corner of the phase space in Figure 3a, that is for a relatively warm and dry free troposphere, the total response of the LWP is negative for an increase in θ_0. In this regime the rise of the cloud base height is larger than that of the cloud top, leaving a thinner cloud layer and a lower LWP. Furthermore, a moistening of the free troposphere, or an increase of the wind speed will yield a thicker stratocumulus cloud deck. The possibility that the large-scale divergence will also change in a future climate has an important consequence for the stratocumulus liquid water path, as an increase will cause a cloud thinning.

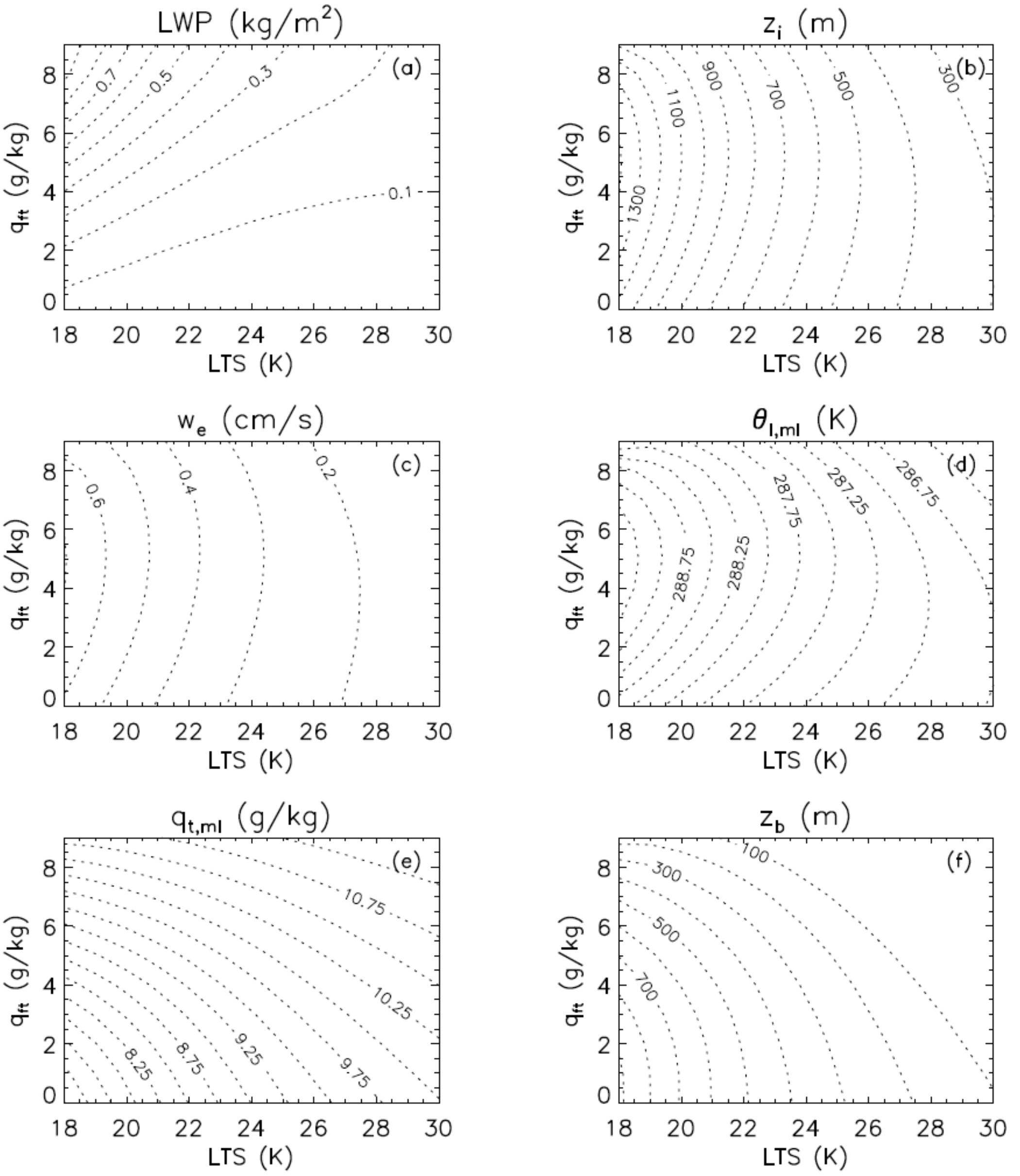

Figure 2: Steady-state solutions as a function of the lower tropospheric stability (LTS) and the free tropospheric specific humidity (q_{ft}) for (a) the liquid water path LWP, (b) the inversion height z_i, (c) the entrainment rate w_e, (d) the liquid water potential temperature $\theta_{l,ml}$ and (e) total water specific humidity in the mixed layer $q_{t,ml}$, respectively, and (f) the cloud base height z_b.

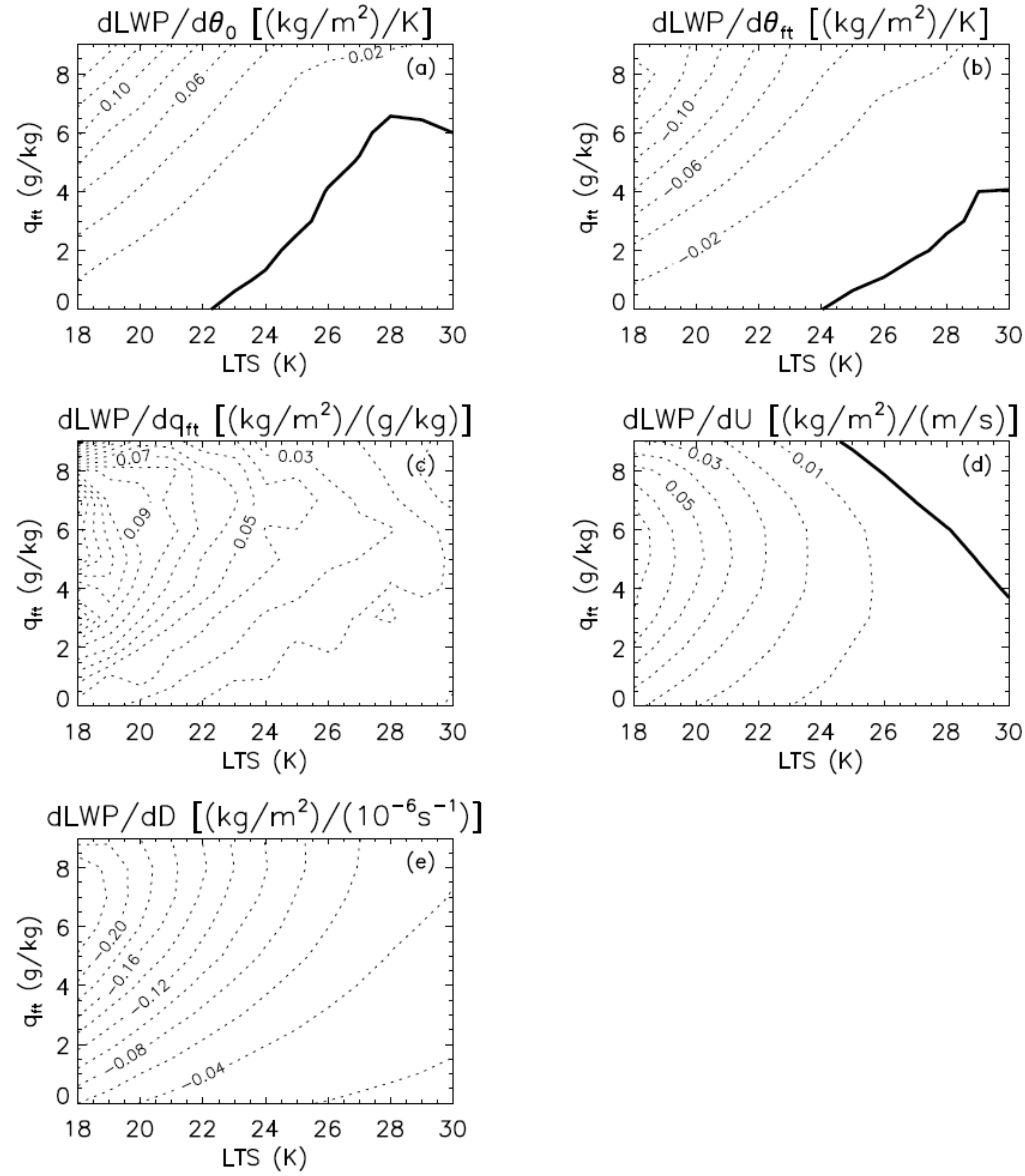

Figure 3: The total response of the liquid water path to changes in (a) the potential sea surface temperature θ_0, (b) the free tropospheric potential temperature θ_{ft} and (c) the specific humidity q_{ft}, respectively, (d) the horizontal wind speed U, and (e) the large-scale divergence D. A thick solid line indicates the zero isoline.

Zhang et al. (2012) explain that the amount of simulated low clouds in the SCMs is largely the result of moistening from the PBL turbulence schemes, radiative cooling at the cloud tops and dilution which is controlled by the shallow convection and cloud top entrainment schemes. These schemes differ greatly among the models, leading to very different cloud fields. Motivated by these findings, De Roode et al. also quantified the changes in the LWP provided that the entrainment rate would not change for perturbations in the cloud controling factors. In this way they are able to show that in a part of the phase space the sign of the LWP response can change. For example, if the entrainment is fixed for a change in the sea surface temperature the LWP tends to increase in the entire part phase space shown in Figure 3.

Figure 4 explains how the LWP will change as a result of a change in the entrainment rate. Apparently, an increase in the entrainment rate will yield a cloud thinning if the free troposphere is sufficiently dry or warm, and vice versa. This finding suggests that the differences in the LWP responses in the CGILS SCM experiments may be due to either a weak or strong response to perturbations in the cloud controlling factors.

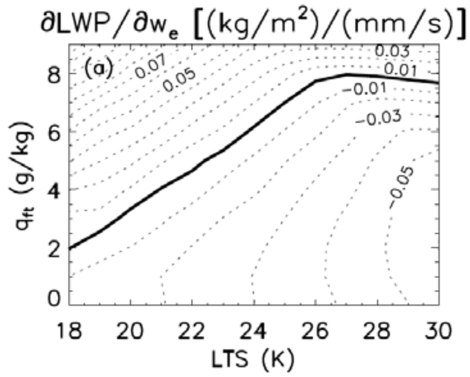

Figure 4: The partial derivatives with respect to the entrainment rate for the liquid water path LWP.

2. Equilibrium states of shallow cumulus clouds

Schalkwijk et al. (2012) present a bulk model for shallow cumulus to study equilibrium solutions for somewhat idealized large-scale conditions. The analytical results are verified with a large-eddy simulation model. The phase space they explore includes the sea surface temperature and the large-scale divergence (D). A key finding of their study is the relation found between the cloud layer thickness and these two quantities (see Figure 5). It can be seen that if a critical value for the large-scale divergence is exceeded, the atmosphere remains free of clouds. By contrast, if D decreases, or if the sea surface temperature increases, the cloud layer depth increases. For the purpose to solve the cumulus cloud system equation analytically, this study uses a radiative forcing profile which is strongly idealized. However, this study identifies and isolates some of the processes through which a cumulus layer influences the boundary layer system in response to external forcings, which may be worthwhile to study in a single-column model framework.

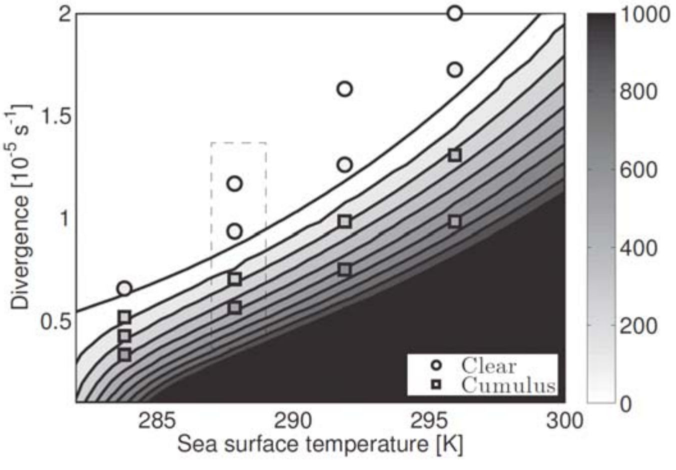

Figure 5: The cumulus cloud layer depth as a function of the sea surface temperature and large-scale divergence. The shaded contours depict the model predictions for cloud layer depth, the uppermost line thus depicting the transition from a clear to a cloudy boundary layer. The overlaid symbols each depict the state of a LES simulation after 200 hours of simulated time. Circles are clear cases, squares cumulus cases, and the symbol's fill-color represents the cloud layer depth in the LES case.

3. Conclusions

As a first step to explore the cloud response to a future climate change in a phase space consisting of cloud controlling factors we have applied simple conceptual bulk models like the mixed-layer model to study equilibrium solutions for stratocumulus and shallow cumulus clouds. Rather than applying multiple changes in the cloud controlling factors, in the spirit of partial derivatives De Roode et al. (2012) have perturbed them one by one to assess the change in the cloud liquid water path. An increase in the cloud layer thickness is found if the sea surface temperature is increased except for the situation where the free troposphere is sufficiently dry and warm. However, if the free troposphere warms, this will cause a thinning of the cloud layer. The moistening of the free troposphere, an increase in the horizontal wind velocity, or a weakening of the large-scale divergence each cause a cloud thickening.

In principle, single perturbations may also be applied in SCM runs towards equilibrium states as such experiments may help to identify whether the change in the LWP is dominated by the change in the cloud controlling factor or by a subsequent change in the entrainment velocity. On the other hand, it is also interesting to perturb more than one cloud controlling factor as to closely mimic future climate conditions. By so doing, Dal Gesso et al. (2013, manuscript in preparation) find a thinning of the stratocumulus cloud deck. They are able to identify the decrease in the longwave radiative forcing, which results from an increase in the specific humidity in the free troposphere, as the main agent responsible for the thinning. The explanation is that a reduction in the entrainment rate leads to a lower cloud-top height. Indeed, if it is assumed that the radiative forcing remains constant, Dal Gesso et al. are able to demonstrate that a cloud thickening occurs.

The mixed-layer model experiments in the LTS-q_{ft} phase space pave the way for a similar exercises with SCMs participating in EUCLIPSE. These will be carried out in the last phase of the EUCLIPSE project. The first simulations with two different models are already performed at the KNMI and show promising results in terms of cloud regimes and cloud changes under future climate conditions.

Lastly, Schalkwijk et al. (2012) studied analytical solutions of the shallow cumulus cloud top height in a phase space determined by the sea surface temperature and large-scale divergence and are able to find the conditions necessary for the formation and maintenance of shallow cumulus clouds.

Bibliography

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Zhang, M. and 39 co-authors, 2012: CGILS: First Results from an International Project to Understand the Physical Mechanisms of Low Cloud Feedbacks in General Circulation Models. Submitted to the *Bull. Amer. Met. Soc.*

4. EUCLIPSE related reports and documents

Website describing the set-up of SCM experiments,
http://www.euclipse.nl/wp3/SteadyStates/main.shtml

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Schalkwijk, J., H. J. J. Jonker and A. P. Siebesma. 2012: Simple solutions to steady-state cumulus regimes in the convective boundary layer. Submitted to the J. Atmos. Sci.
http://www.euclipse.eu/Publications_new.html

Two manuscripts discussing equilibrium state solutions in a mixed-layer model and single-column model by Dal Gesso et al. are in preparation.