EUCLIPSE

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Deliverable D 3.4 Identification and comparison of the key quantities used in ESM parameterization schemes with LES results and observations.

Delivery date: 30 months

EUCLIPSE Description of Work: Deliverable 3.4

D3.4: Identification and comparison of the key quantities used in ESM parameterization schemes with LES results and observations.

Involved EUCLIPSE partners: <u>TUD</u>, KNMI, METO, ECMWF, MF-CNRM,

1. Background, motivation and aim

The analysis of the ASTEX results of the cloud cover show that the ASTEX SCM results exhibit a large scatter (see Figure 1). By contrast, the LES results show a much better consistency among the models as is clear from the solid cloud deck that is maintained during the first full day of the simulation.

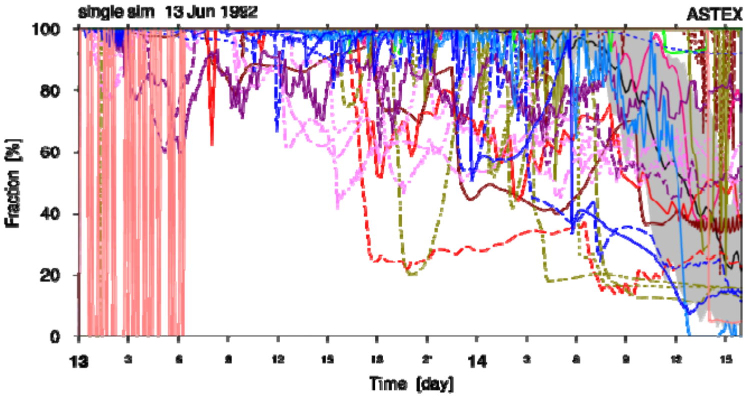

Figure 1. Cloud cover for the ASTEX case as calculated by the participating single-column model versions (lines). The grey band shows the LES model ensemble results.

Lock (2009) investigated the relation between the cloud cover and a factor κ that is related to the inversion stratification according to,

$$\kappa = \frac{\Delta\theta_e}{(L_v/c_p)\Delta q_T} = 1 + \frac{\Delta\theta_L}{(L_v/c_p)\Delta q_T} \qquad (1)$$

with θ_e and θ_L the equivalent and liquid water potential temperature respectively, q_T the total specific humidity, L_v the latent heat of vaporization, c_p the specific heat of dry air. The symbol Δ indicates the jump across the inversion layer (see Fig. 2 for a schematic representation).

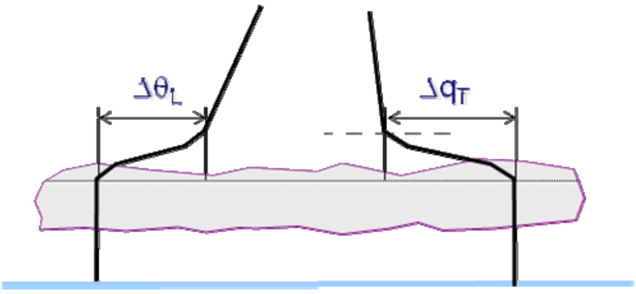

Figure 2: Schematic representation of the vertical profiles of θ_L and q_T. The thin horizontal grey lines near the

cloud top indicate the bottom and top of the inversion layer, across which the inversion jumps $\Delta\theta_L$ and Δ q_T are determined.

Lock showed that the cloud cover rapidly decreases for κ-values that are approximately larger than 0.2 (see Fig. 3). To assess whether there are systematic differences in the cloud cover and the inversion strength we first diagnosed the relation between the κ-factor and the cloud fraction for the LES models and the SCMs. As a next step, we use the budget equation for the liquid water path derived by Van der Dussen et al. (2012) in order to quantify the contribution of processes like entrainment warming and drying to the LWP tendency. In a manuscript that is in preparation by Van der Dussen et al. (2013), the LWP tendency equation is expressed as a function of the κ-factor.

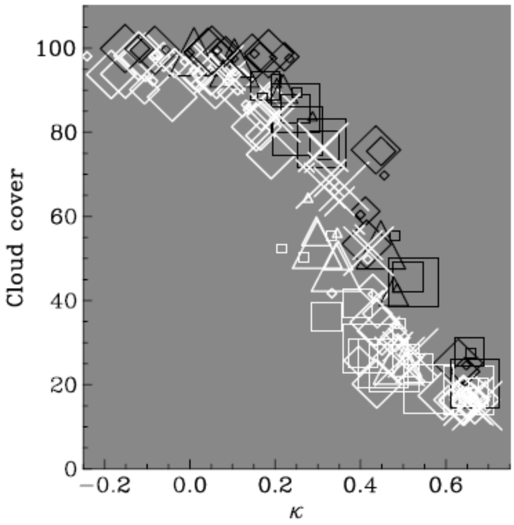

Figure 3: Relation between cloud cover and the inversion stability factor κ (from Lock 2009).

2. Cloud cover and inversion stability

We will first show that the κ-factor and an empirical relation between cloud cover and lower tropospheric stability (LTS) found by Klein and Hartmann (1993) are closely related. The latter authors presented a linear fit through the data points collected in the subtropical stratocumulus region, and is described by

$$\sigma = a\ \mathrm{LTS} + b, \qquad (2)$$

in which σ is the cloud cover, and $a = 5.7\ K^{-1}$ and $b = -55.73$ are fitting constants. In this case the LTS represents a seasonally averaged value, and (2) is sometimes referred to as the Klein line. Assuming a constant potential temperature lapse rate that is representative for the marine subtropical stratocumulus areas, and a typical cloud-top height of 1000 m, one can express the cloud cover σ as a function of the κ-factor. Because the κ-factor depends on both the temperature and total specific humidity (Δq_t) jumps, the substitution of (1) into (2) makes the cloud cover a function of κ and Δq_t. Figure 4 shows the results for three different values of the total specific humidity inversion jumps. What strikes the eye is the qualitative agreement between Figures 3 and 4, which both exhibit a decrease in the cloud fraction if κ exceeds some critical fraction. It is interesting to note that Figure 4 suggests that the cloud cover depends on Δq_t.

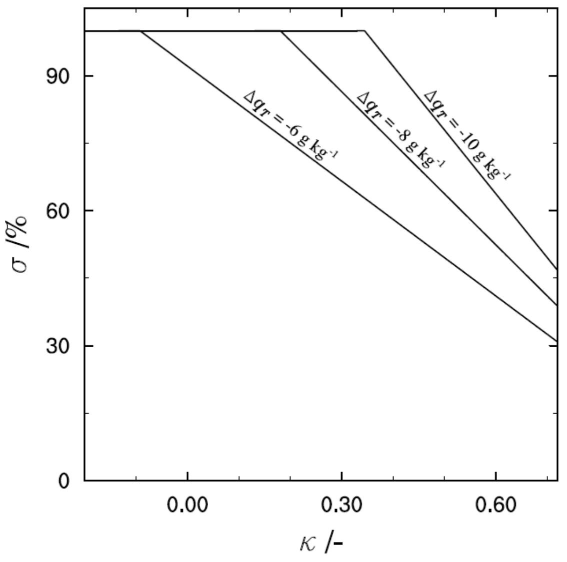

Figure 4. The cloud cover found emperically by Klein and Hartmann (1993) according to Eq. (2) expressed as a function of the inversion stability parameter κ given in Eq. (1).

We diagnosed the relation between the κ factor and the cloud cover for the ASTEX case, in addition to three "composite" cases proposed by Irina Sandu and Bjorn Stevens. The three composite transitions are based on the observational study of the transitions in boundary layer cloudiness described in Sandu et al. (2010). While ASTEX offers the opportunity to evaluate models against in situ data, this set of composite transitions represents a more idealized framework for model evaluation, which offers the possibility of comparing the models for a variety of transition cases, which differ for example in terms of amplitude or timescale of the transition. The composite reference case, and two of its variations corresponding to a faster, and respectively a slower transition in cloud fraction. A key difference in the ASTEX and three composite cases is the inversion stratification.

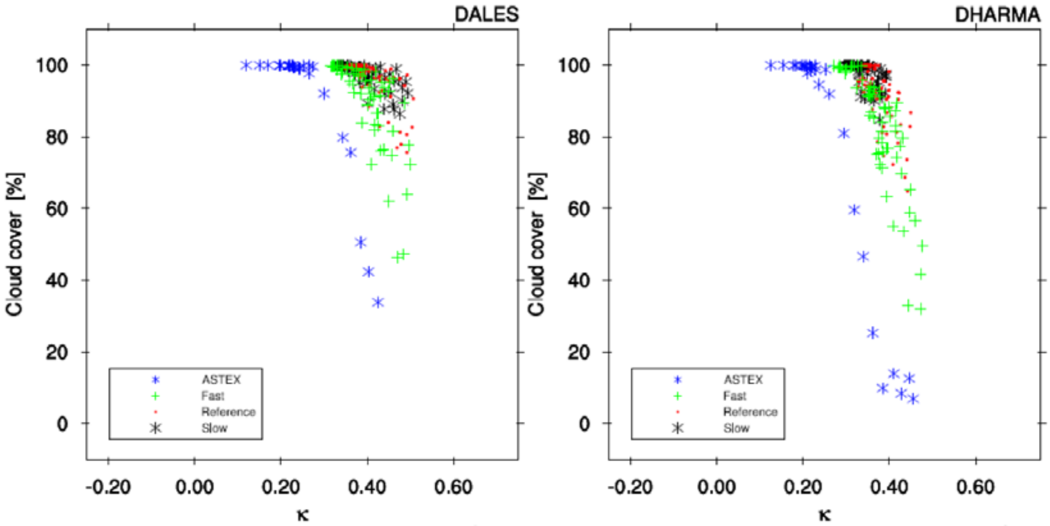

Figure 5: Relation between cloud cover and the inversion stability factor κ from two different LES models (DALES and DHARMA) for the ASTEX and three composite transition cases.

The LES model results presented in Figure 5 show a qualitative similar picture as Lock (2009) in the sense that for κ values larger than 0.2 the cloud fraction tends to diminish quickly. It is also interesting to note that the ASTEX case has the smallest humidity jump across the inversion and exhibits a break up for the smallest κ values. Although Figure 4 seems to hint at such a relation, a more critical analysis made on the basis of the budget equation for the LWP (Van der Dussen et al., 2012) suggests that the magnitude of the humidity flux at the stratocumulus cloud base height comprises a major term in the LWP budget. This means that a large positive humidity flux at cloud base supports a longer maintenance of the stratocumulus cloud deck and the inversion strength alone cannot explain the timing of the cloud break-up.

To examine why in any case for sufficiently large κ the stratocumulus cloud ultimately breaks up, we calculated the tendency of the LWP due to entrainment only, by assuming that the entrainment rate is inversely proportional to the liquid water potential temperature jump across the inversion. Figure 6 shows that the LWP tendency due to entrainment is strongly dependent on the value of κ. For κ approximately exceeding a value of 0.3, there will be a very strong negative LWP tendencies which in practice can not be compensated by any other process. It is important to note that this effect is not due to a built-in buoyancy reversal process, since a very simple entrainment parametrization that only depends on the radiative flux divergence over the cloud layer and the inversion jump of θ_L is used.

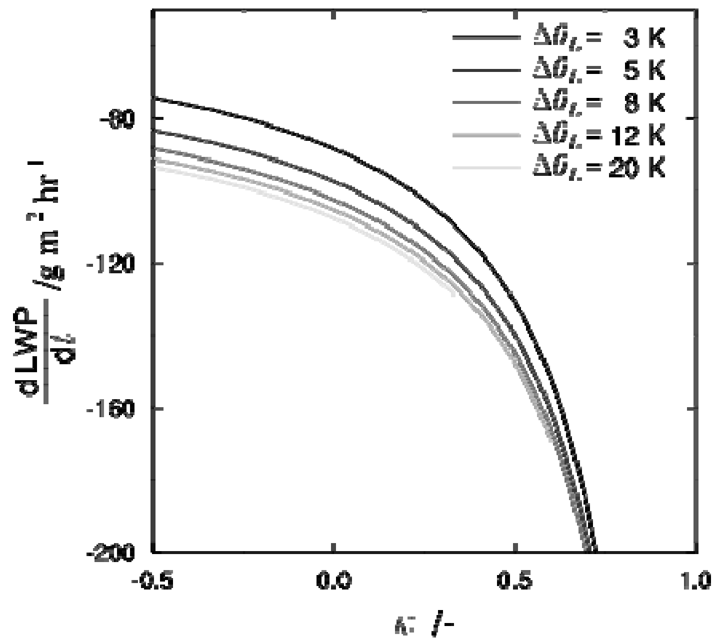

Figure 6. The LWP tendency as a function of the factor κ and for different values of the liquid water potential temperature jump across the inversion. The results are computed analytically from the budget equation for the LWP following Van der Dussen et al. (2012).

Figure 7 summarizes the SCM results. Except for the LaRC model all the SCMs exhibit a different relation between κ and the cloud cover as compared to the LES results. This suggests that the entrainment process is not adequately represented in these models. The analysis proposed by Lock (2009) seems to be an effective tool for characterizing and inter-comparing the behavior of fast parameterized physics across a hierarchy of simulations. In deliverable 3.6 it will be discussed that these diagrams for the SCM results of the transition cases are representative for the GCM behavior.

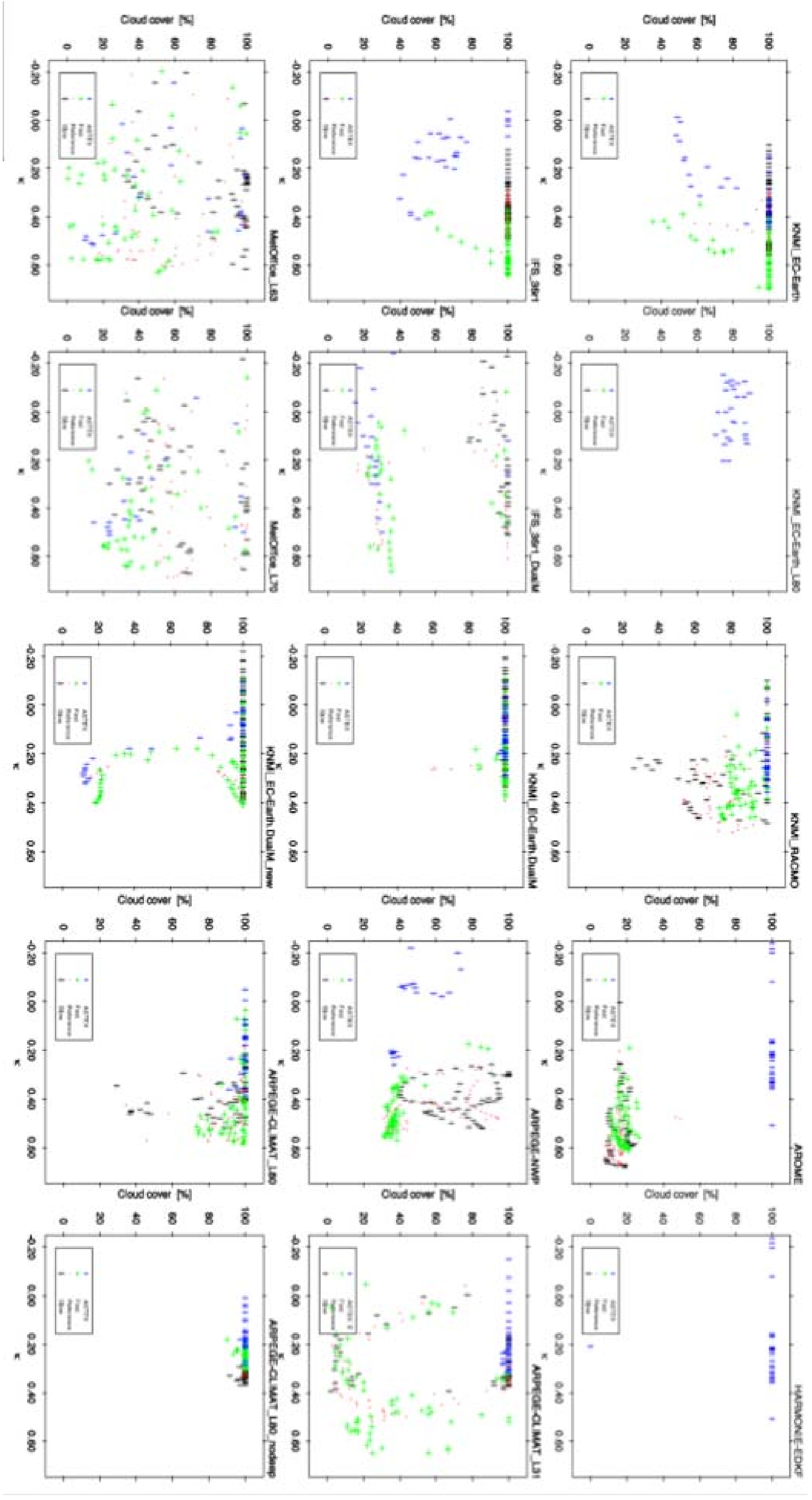

Figure 7: Relation between cloud cover and the inversion stability factor κ from different SCMs for the ASTEX and three composite transition cases.

3. Decoupling

Last, we discuss the vertical stratification of the cloud-topped boundary layer. Wood and Bretherton (2004) used aircraft observations collected in cloudy boundary layers to calculate the difference in θ_L and q_T between the cloud and subcloud layer. To quantify this difference they introduced a decoupling factor α_q,

$$\alpha_q = \frac{q_{T,cld} - q_{T,sub}}{q_{T,z_i^+} - q_{T,sub}} \tag{2}$$

with the subscripts 'cld', 'sub' and 'z_i^+' indicating the value of q_T in the cloud layer, subcloud layer and just above the inversion, respectively. An analogous factor α_θ was defined for θ_L. The factors are equal to zero if the boundary layer is vertically perfectly mixed. Wood and Bretherton found that the value for the decoupling parameter increased for deeper boundary layers. As can be seen from Figure 8, the LES models roughly follow the same trend with somewhat larger values for the decoupling factor for the total specific humidity than for the liquid water potential temperature. This difference might be explained from the fact that there are the surface moistening and entrainment drying will tend to enhance the vertical moisture gradient, whereas for heat a strong radiative cooling at the cloud top supports a more vertical well-mixed structure. It should be stressed that any models must be well capable of representing the decoupling factor, as deviations will result in an error in the liquid water content. For example, models have a too weak decoupling will tend to overestimate the liquid water content, and vice versa.

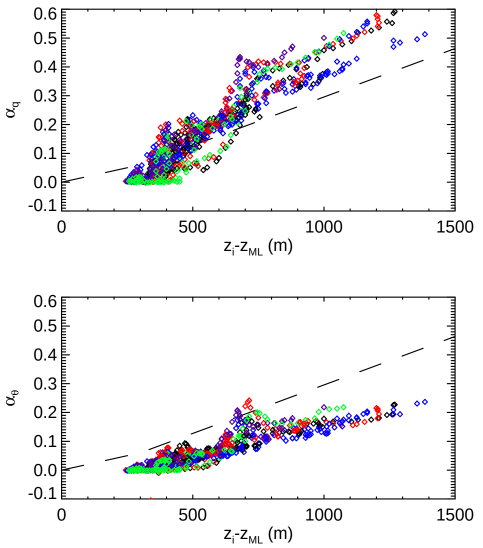

Figure 8. Decoupling parameters α_q and α_θ. The dashed lines indicate a fit using the aircraft observations of α_q presented in Figure 5 of Wood and Bretherton (2004). The colors of the data points represent results from the different LES models and for the ASTEX and three composite Lagrangian transition cases.

4. Conclusions

The cloud cover during four Lagrangian transition cases was analyzed as a function of the inversion stability as measured by the κ-factor. Although the LES results are in a qualitative agreement with the results of Lock (2009), the ASTEX case appears to break-up for a smaller κ-value then the other three composite Lagrangian transition cases. It is argued that in addition to the inversion stability, the magnitude of the moisture flux at the stratocumulus cloud base is also a key factor controlling the timing of the cloud break-up.

The fact that in any case the stratocumulus cloud breaks up for some critical κ-value is explained with aid of the LWP budget equation and a simple parameterization for the entrainment rate. In particular, if it is assumed that the entrainment rate is inversely proportional to the liquid water potential temperature jump across the inversion, it is straightforward to show that an increase in the κ-value must result in a rapid thinning of the cloud layer as a large κ-value is equivalent to a large negative tendency of the LWP. Roughly speaking the stratocumulus will thin if the entrainment thinning tendency exceeds the thickening tendency due to the humidity flux at the cloud base.

In general a wide scatter in the cloud cover behaviour is found in the SCM results indicating an poor representation of the LWP budget. We have found that the difference between subcloud and cloud layer thermodynamic properties becomes larger for deeper boundary layers, which is in agreement with aircraft observations. Because the liquid water content is very sensitive to small differences in either the temperature or total water content in the cloud layer, model biases may be better understood by diagnosing the decoupling factor.

Allthough we do not recommend to use the kappa relation as a parameterization I ESMs, it is an useful indicator for the realism of cloud and turbulence parameterizations in ESM's in their capability of the break-up of Scu in cumulus. It is also useful to diagnose how the kappa values are changing under future climate conditions.

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Wood, R. and C. S. Bretherton, 2004: Boundary layer depth, entrainment, and decoupling in the cloud-capped subtropical and tropical marine boundary layer. *J. Climate*, **17**, 3576–3588.

EUCLIPSE Relevant Documents

Van der Dussen, J, S. R. de Roode and A. P. Siebesma, 2012: LES sensitivity experiments of the EUCLIPSE stratocumulus to cumulus transition based on ASTEX. 20th Symposium on Boundary Layers and Turbulence, 9-13 July 2012, Boston, MA, USA.
http://www.euclipse.eu/Publications_new.html)

de Roode, S. R., I. Sandu, J. van der Dussen, A. S. Ackerman, P. N. Blossey, A. Lock, A. P. Siebesma, and B. Stevens, LES results of the EUCLIPSE Lagrangian stratocumulus to shallow cumulus transition cases. 20th Symposium on Boundary Layers and Turbulence,, 9-13 July 2012, Boston, MA, USA.
http://www.euclipse.eu/Publications_new.html)

A manuscript by Van der Dussen et al. (2013) on the κ-factor is in preparation for submission to a peer-reviewed journal.