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DACCIWA

"Dynamics-aerosol-chemistry-cloud interactions in West Africa"

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1 Introduction

The DACCIWA project (Knippertz et al., 2017; Flamant et al., 2017) has as one of its goals to better understand the behaviour of low clouds in South West Africa. Near the coast, the transition between stratified cloud, i.e stratocumulus, to buoyant clouds, i.e., shallow cumulus, is still very crudely represented in models. This transition can be influenced by the presence of anthropogenic aerosols that affect directly and indirectly the cloud formation. Low clouds in this part of the world have long been known to be misrepresented by models, in spite of their large coverage and common presence (van der Linden et al, 2015). This leads to major errors at surface radiation (Knippertz et al., 2011; Hannak et al., 2017) and, thus, affect the evolution and development of the atmospheric state at large parts of the area. What is more, key environmental aspects like the ventilation of air pollutants or the amount of surface radiation for agricultural purposes depend strongly on correct representation of clouds in regional models in this area.

One of the main problems in global models deals with the need to parameterize turbulent and cloud motions given their limited resolution. This is of extreme relevance in clouds like stratus, stratocumulus, which require very strong and localized gradients (Wood, 2012). Thus, in order to obtain a reliable parameterization on regional weather models, we need first to understand and reproduce explicitly the stratocumulus and shallow cumulus. Our research includes the realization of idealized numerical experiments with stratus/stratocumulus clouds at a very high resolution by Large Eddy Simulation model (LES) to adequately represent the gradients and the motions within the lowest part of the atmosphere. These numerical experiments are inspired in the meteorological campaign carried out as part of the DACCIWA project during the summer of 2016 (Kalthoff et al., 2018)

The final aim of this study is to simulate a cloud thinning and break up transition during the day based on idealized conditions of the DACCIWA campaign, and to evaluate the main factors that lead to the maintainance of low stratus, its thinning and its break up, as it was very often observed during the meteorological campaign of DACCIWA (Kalthoff et al., 2018). Currently the needed equilibrium in cloud conditions before adding the thinning and break up factors is being explored and defined.

We describe briefly the model used, the settings and the initial conditions and large scale forcings used in Section 2 of this report. Section 3 includes the results of the reference simulation for equilibrium as well as sensitivity studies on cloud droplet concentrations, large scale advection and shortwave radiation. Conclusions and plans for further work are explained in Section4.

2 Methods

2.1 The Dutch Atmospheric Large Eddy Simulation

The Dutch Atmospheric Large Eddy Simulation is a numerical model which explicitly solves around 90% of the cloud motions and turbulence in the atmosphere. It is based on the preliminary work by Nieuwstadt and Brost (1986) and has been further developed during the last years (Heus et al., 2010; Ouwersloot et al., 2016). It explicitly resolves the motion of the flow down to the resolution of the domain, and parameterizes the subgrid turbulence. The version used for this study is DALES4.1 with additions on the land surface model, accounting for the different penetration capacity and sensitivity of the canopy by direct and diffuse shortwave radiation (Pedruzo-Bagazgoitia et al., 2017). DALES has been already and extensively tested to successfully

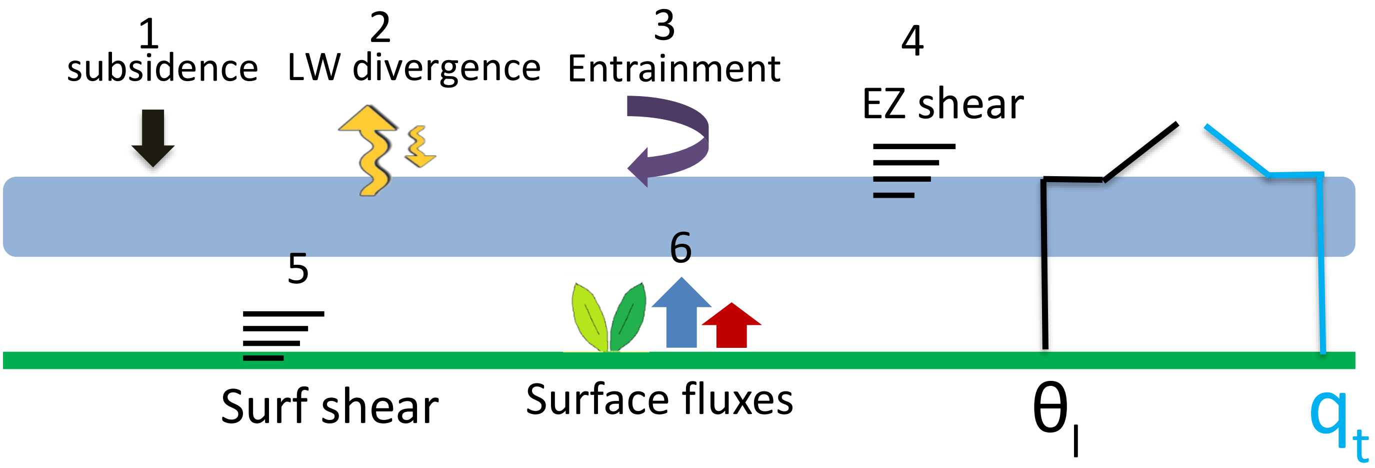

Figure 1. Schematic overview of local factors affecting the maintenance, evolution and dissipation of stratus/stratocumulus clouds. On the right, typical profiles for liquid water potential temperature θ_l and total water mixing ratios q_t.

represent cases with shallow cumulus clouds (VanZanten et al.,2011), stratocumulus clouds (Duynkerke et al., 2004) as well as the stratocumulus-to-cumulus transition (de Roode et al., 2016).

2.2 Experimental set up

The first part of the project has been focused on designing the numerical experiment based on observations. As Figure 1 shows, there is a high complexity and a wide range of factors and interactions that play a role in the development and maintenance and/or dissipation of stratus and stratocumulus clouds:

- Large scale subsidence (1 in Fig.1)
- Cooling at the cloud top by the divergence of the longwave radiative flux (2 in Figure 1)
- Entrainment of air from above the cloud layer due to its turbulent character (3 in Figure 1)
- Wind shear within the entrainment zone contributing to further entrainment (4 in Figure 1)
- Wind shear at the surface (5 in Figure 1)
- Surface fluxes (6 in Figure 1)

The domain of our simulations is of 3.6 x 3.6 x 3.0 km^3 with a gridbox size of 50 x 50 x 10 m^3. Further work will include simulations with larger domains, although preliminary tests have not shown big sensitivity to domain size or number of grids in the reference experiment. The domain will be enlarged to 24 x 24 km^2 for final simulations.

Our simulations in DALES make use of a simple all or nothing microphysical scheme, although it considers the droplet sedimentation within the cloud layer following Bretherton et al. (2007). As shown in their article, such a phenomenon is sensitive to the number of cloud droplets per volume, Nc. This is of special relevance in the current study, as air quality and aerosol concentration observations are scarce on South West Africa. Therefore, it is critical to test the sensitivity of the model to such variables. Our experiment REF uses a cloud droplet concentration Nc=300 #/cm^3, representing a moderately polluted atmosphere. Further sensitivity tests on this value are shown in section 3.2. There, the experiments are identical to REF except for the prescribed Nc that are: a value of 70 #/cm^3 (experiment micro_70) representing an very clean and atmosphere, and a more polluted case according to 400 #/cm^3 . The polluted scenario concentrations have been obtained

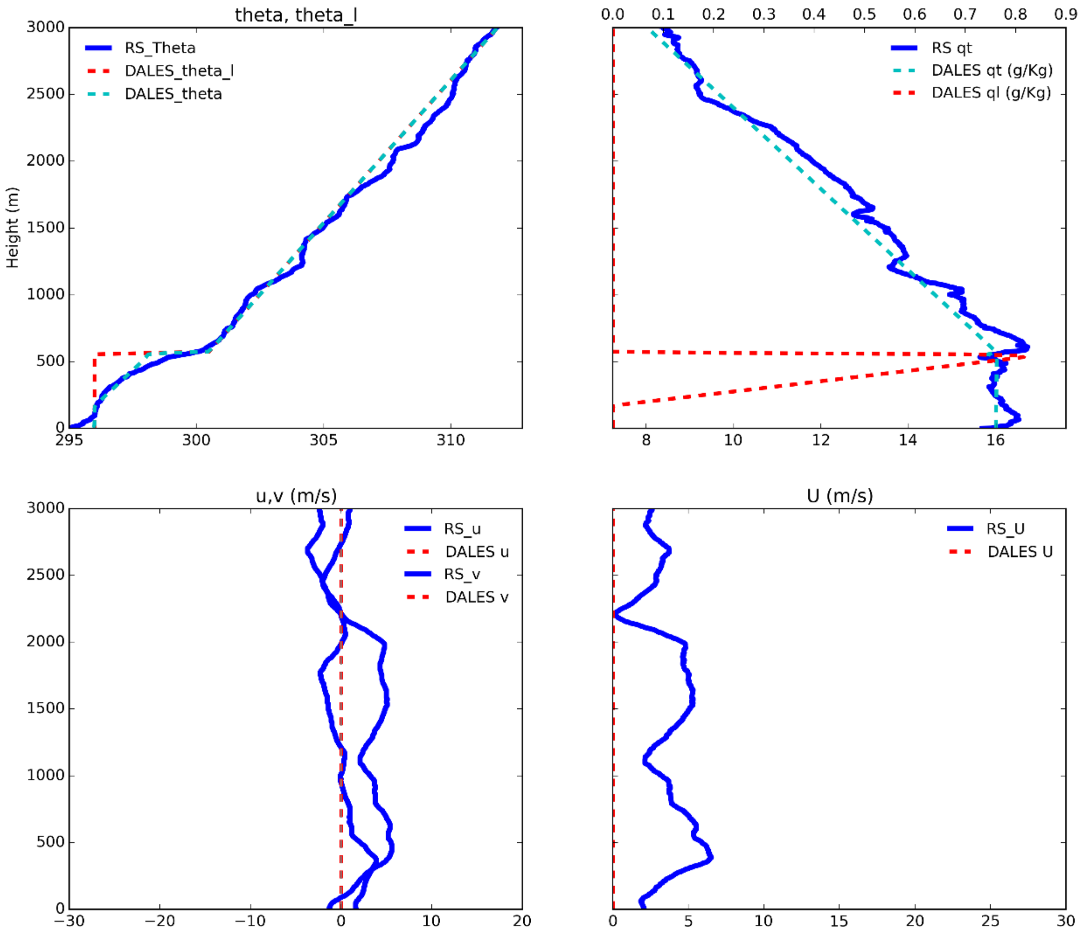

Figure 2. Vertical profiles of potential and liquid potential temperature (top left), total and liquid water mixing ratio (top right), horizontal wind components (bottom left) and horizontal wind (bottom right) obtained by the radiosounding on 26th June at 4 UTC at Savé supersite (dark blue lines), and as used by DALES as initial profiles (red and light blue dashed lines) for all experiments.

from aircraft observations during the DACCIWA campaign (Jonathan Taylor, personal communication).

We make use of the interactive Rapid Radiative Transfer Model (RRTMG) by Iacono et al. (2008). This allows us to rely solely on the cooling at the top of the clouds driven by the calculated longwave flux divergence, as opposed to other studies where the divergence flux at the top of the clouds is prescribed.

2.3 Initial conditions and large scale forcings

The initial profiles used for our experiments are inspired in the information obtained from the radiosounding launched on 26th June 2016, during IOP 3, in the Savé supersite and shown in Figure 2. We modified the initial profiles to initialize our simulations with a perfectly well mixed layer up to 550 meters, and simplified the profiles above to show a constant lapse rate for both temperature and moisture. The initial simulations do not include any wind, although studying the effects of wind and wind shear is expected in further work.

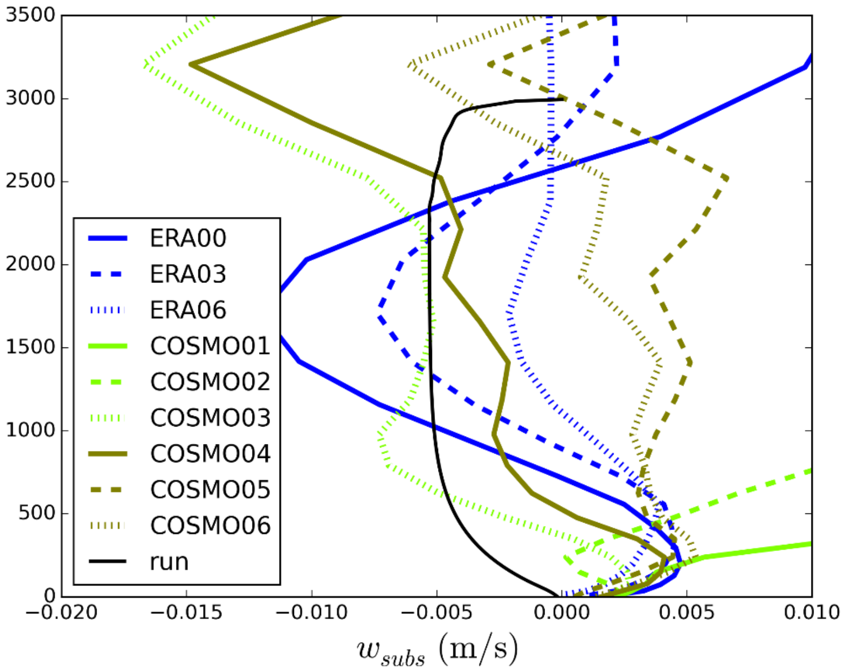

Figure 3. Mean vertical velocity at nearest gridpoint to Savé as given by the regional model COSMO (green) on 26th June 2016 hourly between 01 and 06 UTC, and as given by ERA-interim dataset at 00, 03 and 06 UTC. The prescribed profile for our simulations is shown in black.

As for large scale effects, we prescribe an exponentially growing (in absolute value) mean downwards velocity representing subsidence within our LES domain following Bellon and Stevens (2012). Figure 3 shows the prescribed subsidence profile in comparison with the subsidence profiles given by the regional model COSMO and ERA interim dataset at the nearest gridpoint at times close to the launch of the radiosounding. The large discrepancies between models justifies our freedom for prescribing the selected exponential-like subsidence. In order to keep the free troposphere in equilibrium (i.e.,$\frac{\partial T}{\partial t} = 0$ and $\frac{\partial q_t}{\partial t} = 0$), we prescribe an advection of moisture to compensate the drying by subsidence. The extra moisture in the free troposphere drives an additional cooling further compensated by including a warm advection above the cloud layer (550 meters). The profiles for moisture and temperature advection are shown in Figure 4, and include an exponential-like decrease between the free troposphere and the surface. An additional experiment with a drying tendency within the mixed layer (dryML) is carried out and shown in section 3.3.

The reference experiment REF consist of a perpetual night experiment where stratus clouds are maintained. Thus, there is no shortwave radiation nor surface fluxes, and the wind is set to zero for the current experiment. Further work will gradually include additional processes. An exploratory first experiment adding such factors is the REF_SW experiment (Section 3.4), where the diurnal cycle of shortwave radiation is incorporated, although not accounting for the surface flux response to it.

An overview of the experiments shown in this study and its settings is given in Table1.

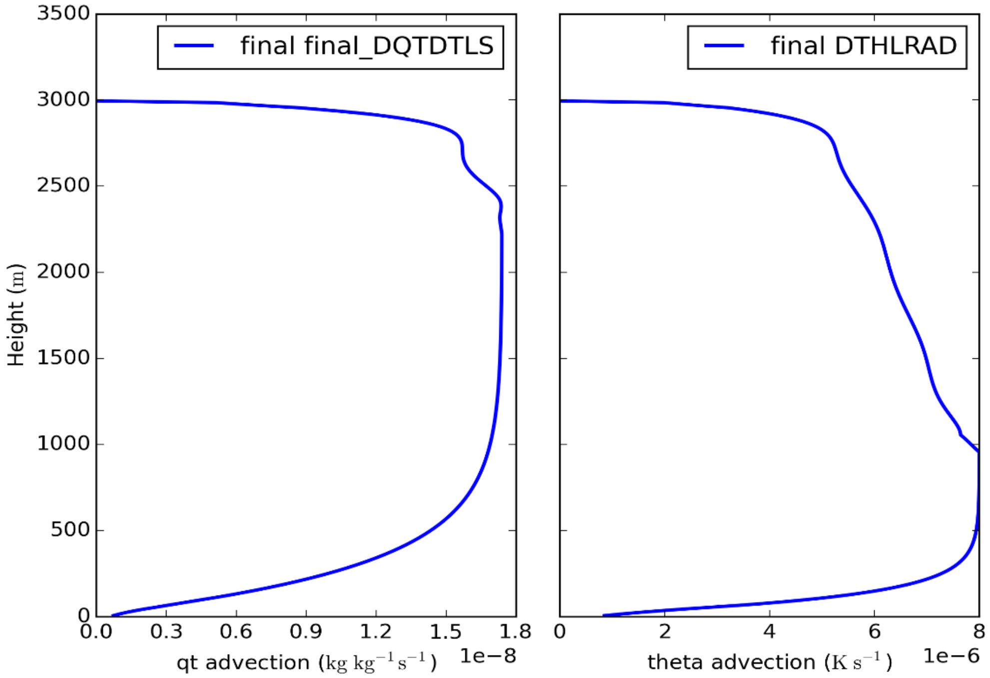

Figure 4. Profiles for moisture (left) and temperature (right) prescribed large scale tendencies for all experiments unless stated otherwise.

3 Results

3.1 Thermodynamic and cloud development in reference simulation

We present here the thermodynamics of the stratus-stratocumulus clouds in our idealized numerical experiments. We focus on the vertical profiles of temperature and humidity, as well as on the liquid water mixing ratio as they allow us to draw conclusions on the development of the lowest part of the atmosphere and the cloud layer.

Table 1. Overview of numerical experiments and the modifications between experiments

Experiment name	Cloud droplet concentration (# cm^{-3})	Heat advection	Moisture advection	SW diurnal cycle
REF	300	Standard	Standard	No
micro_70	70	Standard	Standard	No
micro_400	400	Standard	Standard	No
dryML	300	Standard	Drier in mixed layer	No
REF_SW	300	Standard	Standard	Yes

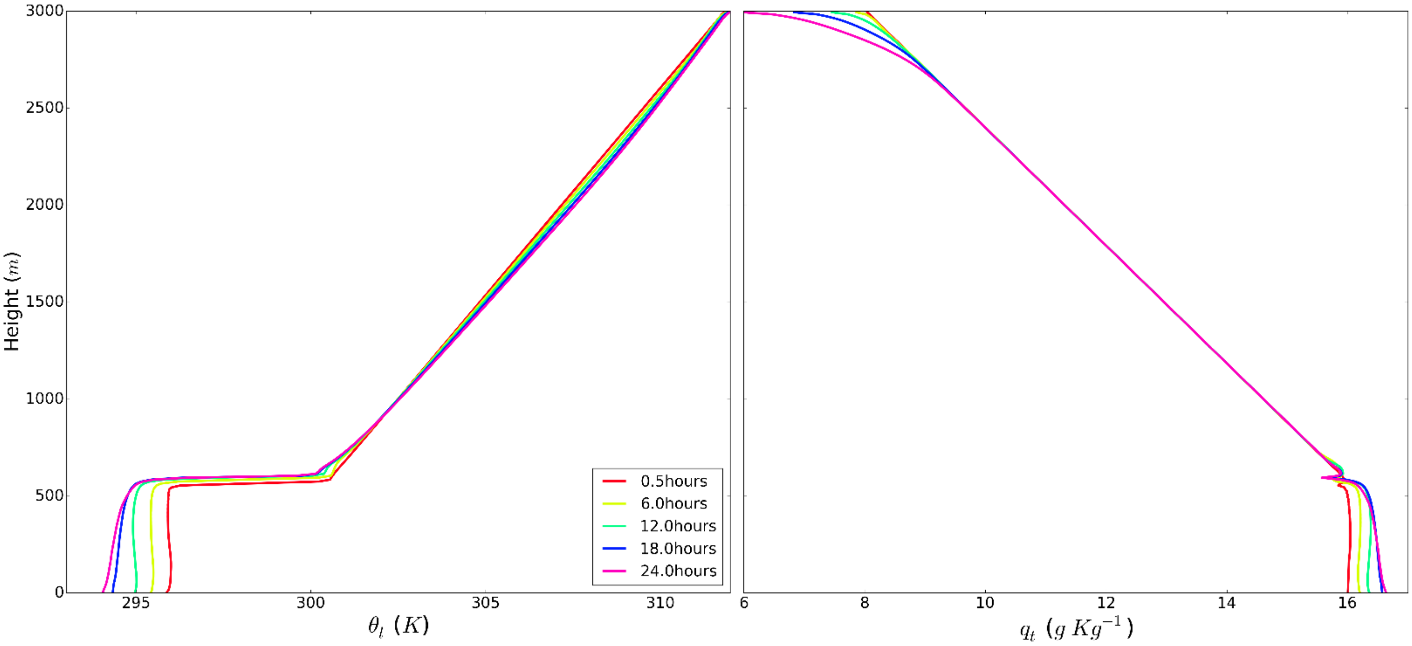

Figure 5. Vertical profiles of domain averaged liquid potential temperature (left) and total water mixing ratio (right) for the REF experiment.

The potential temperature and total water mixing ratio profiles evolution during 24 hours of our reference simulation is shown in Figure 5. There, we observe, for the first hours, a well mixed layer up to 550 meters with a strong and growing temperature jump above of about 4 kelvin (initially). The temperature above remains fairly constant, proving the correct advection of temperature (Fig.

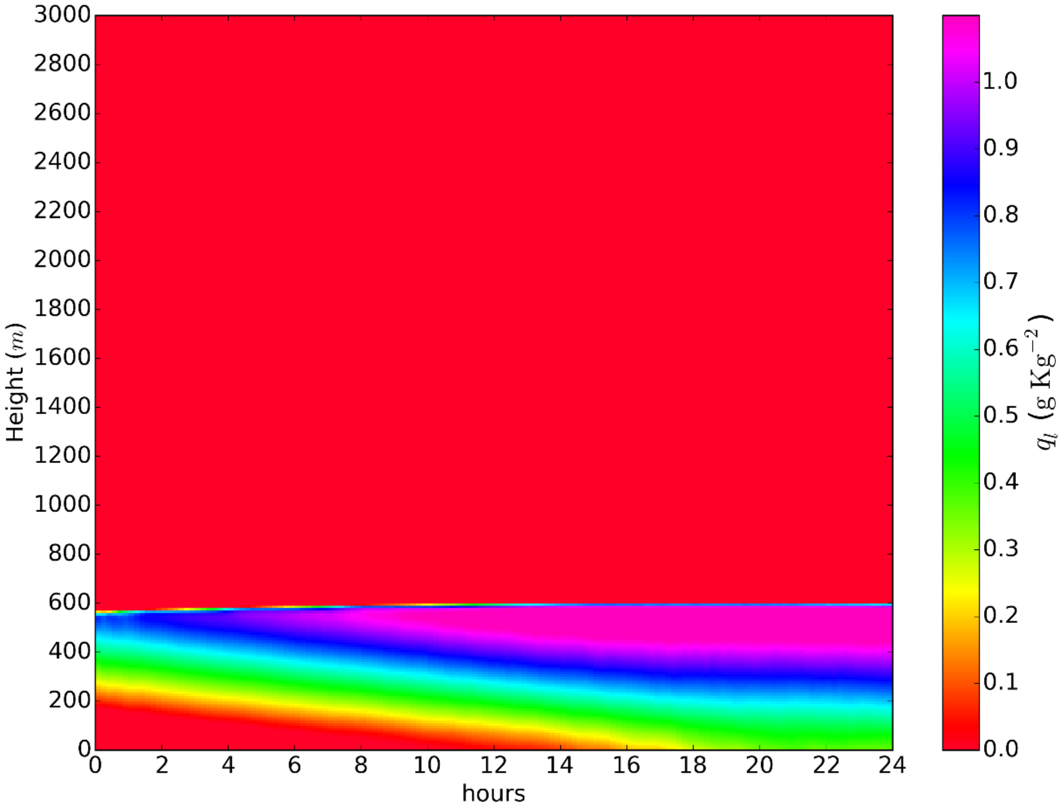

Figure 6. Time series of domain average liquid water mixing ratio for the REF experiment.

4) to keep a free-tropospheric equilibrium. 12 hours after the simulation start, however, the layer below the inversion shows a stabilization, suggesting the cooling at the top of the stratus clouds is not enough to maintain a well mixed layer. This is corroborated by the total water mixing ratio, showing a similarly well mixed layer until about 12 hours after the start, and an increasing moisture near the surface for the rest of the simulation.

The reason for this stabilization lays on the fact that the cloud layer reaches the surface between 6 and 12 hours after the simulation start. Figure 6 shows an initial cloud base height of around 200 meters, consistent with what was observed on the campaign for that day. Afterwards there is a constant lowering of the cloud base, until the cloud reaches the surface at around 12 UTC. Thus, the REF experiment simulates a well mixed stratus layer for the first 10 hours, with a fixed cloud top as the growth by entrainment is compensated by the downwards subsidence, and a lowering cloud base due to the cooling and moistening of the mixed layer (see Figure 5). After 12 UTC the simulation does not provide the well mixed layer typical of marine stratus.

We observe a drying, more evident at later stages, at the top of the domain in the moisture profiles of Figure 5. This is due to an incorrect compensation of drying by subsidence and moisture advection that grows over time. Note that as long as this drying does not reach the cloud layer it has no effect on it.

3.2 Sensitivity to cloud droplet number

We show here one clean-air case with Nc=70 #/cm^3 as opposed to the reference simulation shown in the previous section with Nc=300 #/cm^3. Figures 7 and 8 show the evolution of the micro_70 experiment.

Figure 7 shows that when the cloud droplet concentration is reduced there is no well mixed layer created within the cloud layer nor below. The presence of few very large drops prevents a correct

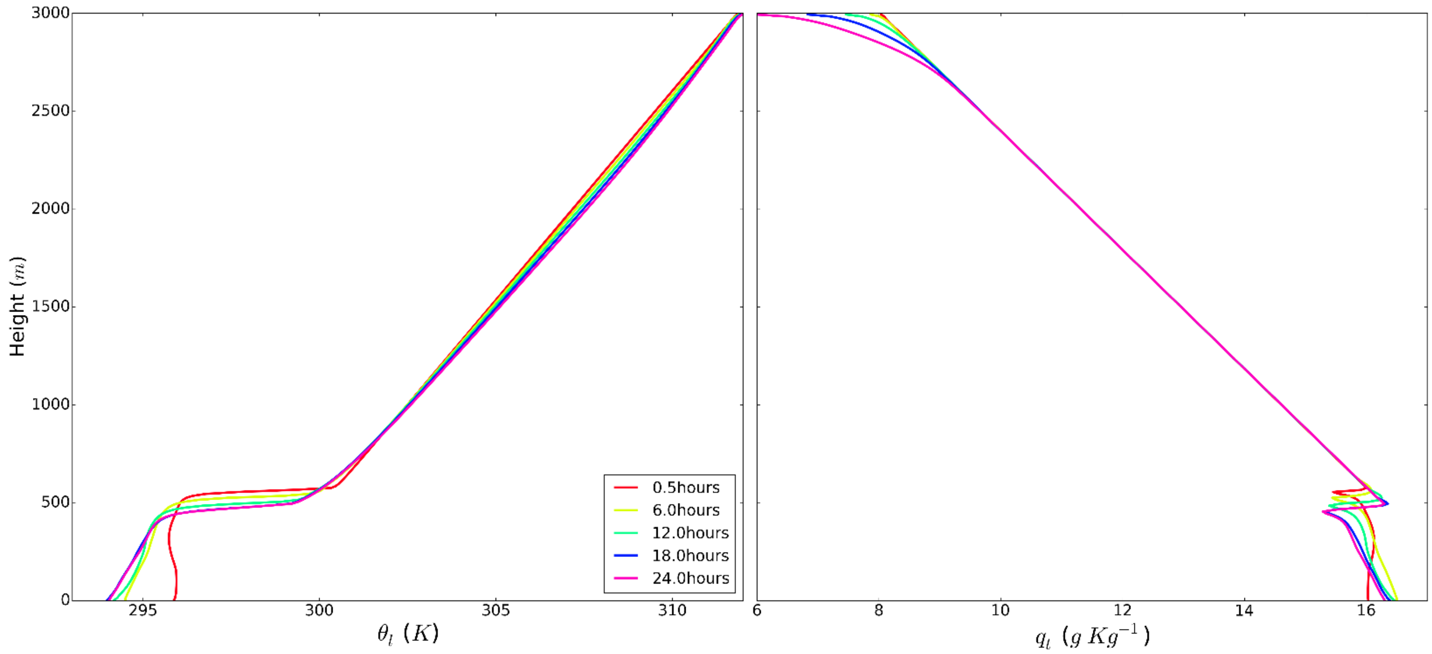

Figure 7. As Figure 4 but for the micro_70 experiment

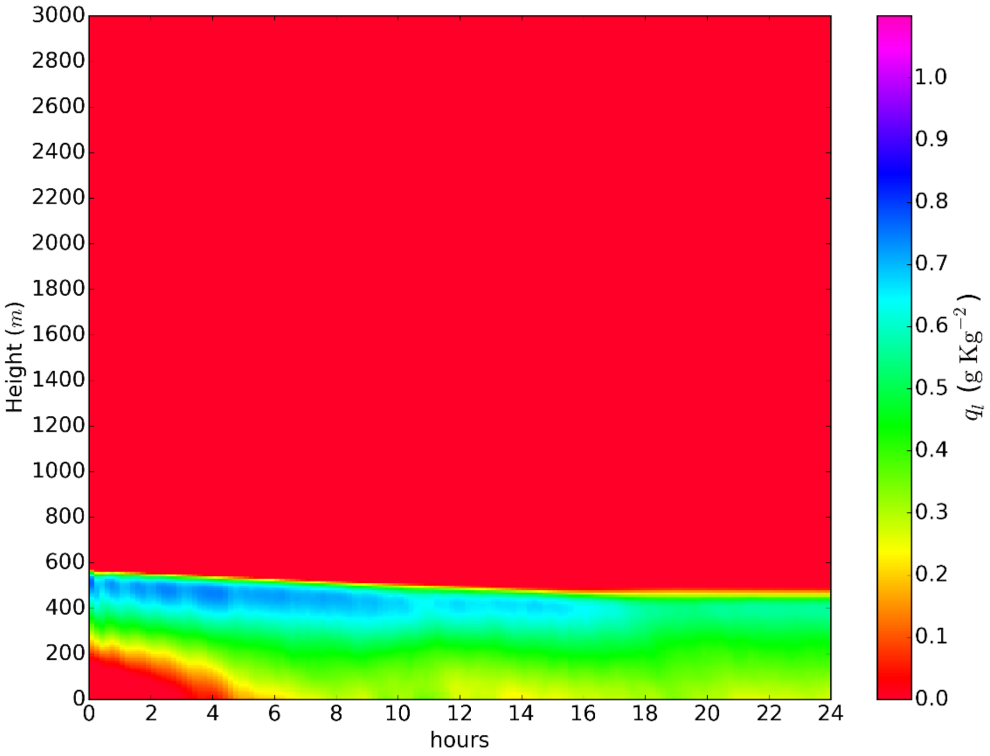

Figure 8. As Figure 5 but for the micro_70 experiment.

mixing of the layer, and the stabilization of the layer below the initial inversion. Similarly, the total water mixing ratio is not correctly mixed at any stage of the simulation.

Figure 8 shows that in this case the growth of the cloud towards the surface is much faster even though the liquid water mixing ratio is lower within the cloud layer. The micro_400 experiment is more similar to our REF experiment. Having a 30% larger droplet concentration, it delays the cloud

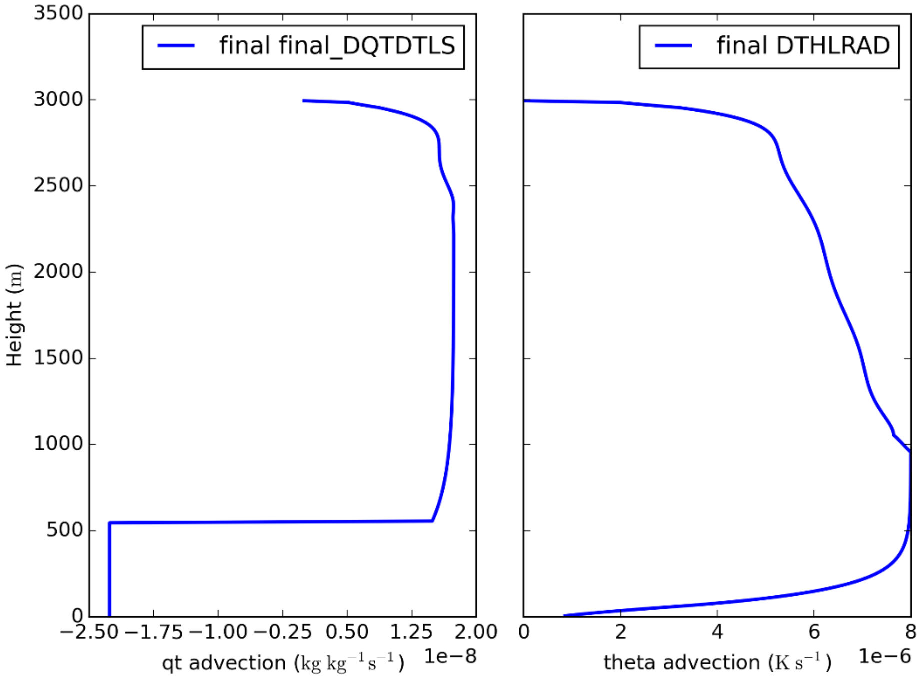

Figure 9. Profiles for moisture (left) and temperature (right) prescribed large scale tendencies for dryML experiment.

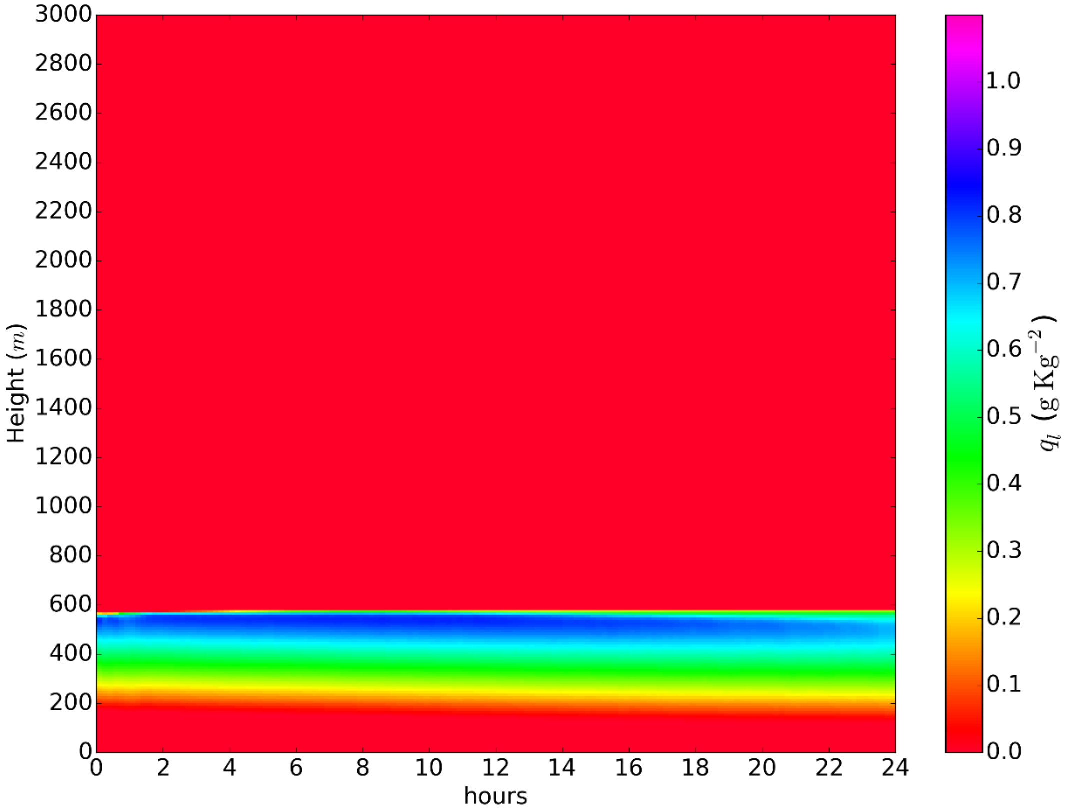

Figure 10. As Figure 5 but for the dryML experiment

base touching the surface by a few hours and thus keeps a well mixed layer few more hours, but it also increases the already high liquid water mixing ratio values within the cloud layer (not shown). These different cloud characteristics and evolution compared to the REF experiment show that even though the experiments do not account for complete microphysical processes, the impact of prescribed cloud droplet number is of high relevance.

3.3 Large scale effects within the boundary layer

A possibility to reduce the cloud growth towards the surface shown in Figure 6 is to include a drying tendency within the well mixed layer to partly reduce the net input of moisture into the domain. This is done in the experiment dryML, where the prescribed advection for heat and moisture are shown in Figure 9. In contrast to the default advection in Figure 4, the prescribed (negative) moisture advection from the surface up to 550 has a constant value of -2.26 10^{-8} kg kg^{-1} s^{-1}. This reduces the net moisture input by advection in the whole domain by 31%.

The experiment with updated prescribed advection shows a more stable cloud layer, with a nearly constant cloud base, cloud top and low variations of liquid water mixing ratio within the cloud layer. It also shows a well mixed layer for the 24 first hours of the simulation regarding temperature and moisture (not shown). Nonetheless, there is an overall drying of the mixed layer as opposed to the moistening in the REF experiment (Figure 5), and a cooling of the layer. This results suggest that the drying advection prescribed within the mixed layer is too large, and that a warmer advection within the mixed layer may help keep a constant temperature within the cloud layer.

3.4 Effects of solar diurnal cycle

As a first attempt to incorporate the factors leading to a cloud layer break up, we incorporate the diurnal variability of shortwave radiation in REF_SW experiment. The effects of it on the cloud layer are shown in Figure 11. The sun rises after approximately 5 hour and of 40 minutes since the start of the simulation, with its intensity (of 911 W m^2 at top of the domain,) peaking 12 hours after the starting time. The first hours of the simulation mimic what was observed in RE experiment in Figure

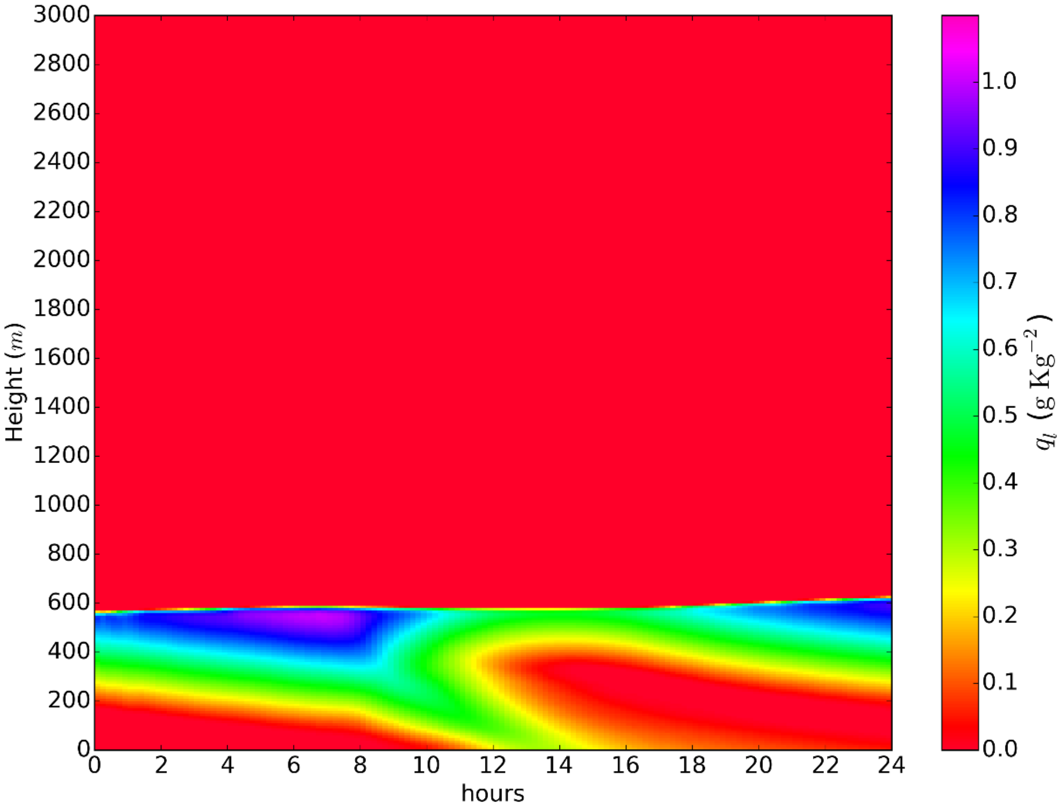

Figure 11. As figure 5 but for the REF_SW.

6, as the sun has not risen yet. First effects of the shortwave radiation are observed few hours after the sunrise at around 9 UTC, where we observe a change in the tendency of liquid water mixing ratio, specially visible at the top part of the cloud layer, i.e. between 400 and 600 meters high. The heating by shortwave radiation from above the cloud layer explains the gradual decrease of cloud liquid water starting from the top of the cloud. As the top layer becomes less dense, more light penetrates further in the cloud layer and warms. At 400 meters approximate height the warming by shortwave radiation is enough to dissolve the cloud liquid water. After that moment, the cloud evaporates both upwards and downwards. After 16 UTC the lower part of the cloud layer has dissolved and only a shallow layer between 500 and 600 meters remains, as the sharp longwave cooling at the top overcomes the shortwave heating. As the surface is not coupled to such diurnal cycle and has prescribed surface fluxes equal zero, we observe a cloud dissolution starting from the centre and spreading upwards and downwards. It is expected, however, that as soon as the surface fluxes are coupled to the diurnal variation, the lowest part of the cloud layer will dissolve faster as a consequence of the sensible heat at the surface.

4 Conclusions and further work

The numerical experiments using DALES shown in this study stablish the basis for a further analysis on the factors leading to a thinning and break up of an idealized stratus/stratocumulus layer. The first part of the study shows the subtle equilibrium and the conditions needed to obtain a cloud layer and troposphere in equilibrium. We also showed in Section 3.2 the sensitivity of our experiments to cloud droplet concentration regardless of our simple all or nothing microphysical scheme due to its influence on cloud droplet sedimentation within the cloud layer. Such a sensitivity is of special relevance in the current scenario of growing anthropogenic emissions and changing air quality in the region, as they show to have a direct impact on cloud development. Additional tests on different prescribed advection profiles showed that a drying and warming of the mixed layer is needed to obtain a cloud layer in full equilibrium, as the longwave divergence flux at the top of the cloud layer cools the mixed layer, and the moisture transported by subsidence moistens it. A first experiment including the diurnal cycle of shortwave radiation showed the potential for cloud dissipation by heating the atmosphere.

Further work will consist on obtaining a base simulation with a troposphere and cloud layer in full equilibrium. Afterwards, processes based on the observations at the Savé supersite during the DACCIWA campaign will be added to simulate the often observed stratus cloud rise and dissipation during the day. The processes, shown in Figure 1, will include the diurnal cycle of the (prescribed) surface fluxes, the presence of wind shear at surface and at the entrainment zone on the top part of the cloud layer and the already tested diurnal cycle of shortwave radiation. Finally, an interactive land surface model sensitive to direct and diffuse radiation will be used to allow for heterogeneities in surface responses and a realistic coupling between radiation and surface.

5 References

Bellon, G., & Stevens, B. (2012). Using the sensitivity of large-eddy simulations to evaluate atmospheric boundary layer models. *Journal of the Atmospheric Sciences*, *69*(5), 1582-1601.

Bretherton, C. S., Blossey, P. N., & Uchida, J. (2007). Cloud droplet sedimentation, entrainment efficiency, and subtropical stratocumulus albedo. *Geophysical research letters*, *34*(3).

Duynkerke, P. G., de Roode, S. R., van Zanten, M. C., Calvo, J., Cuxart, J., Cheinet, S., ... & Lenderink, G. (2004). Observations and numerical simulations of the diurnal cycle of the EUROCS stratocumulus case. *Quarterly Journal of the Royal Meteorological Society*, *130*(604), 3269-3296.

Flamant, C., Knippertz, P., Fink, A. H., Akpo, A., Brooks, B., Chiu, C. J., ... & Kalthoff, N. (2017). The Dynamics-Aerosol-Chemistry-Cloud Interactions in West Africa field campaign: Overview and research highlights. *Bulletin of the American Meteorological Society*, (2017).

Heus, T., Van Heerwaarden, C. C., Jonker, H. J., Siebesma, A. P., Axelsen, S., Van Den Dries, K., ... & de Arellano, J. (2010). Formulation of the Dutch Atmospheric Large-Eddy Simulation (DALES) and overview of its applications. *Geoscientific Model Development*, *3*(2), 415.

Hannak, L., Knippertz, P., Fink, A. H., Kniffka, A., & Pante, G. (2017). Why Do Global Climate Models Struggle to Represent Low-Level Clouds in the West African Summer Monsoon?. *Journal of Climate*, *30*(5), 1665-1687.

Iacono, M. J., Delamere, J. S., Mlawer, E. J., Shephard, M. W., Clough, S. A., & Collins, W. D. (2008). Radiative forcing by long-lived greenhouse gases: Calculations with the AER radiative transfer models. *Journal of Geophysical Research: Atmospheres*, *113*(D13).

Kalthoff, N., Lohou, F., Brooks, B., Jegede, G., Adler, B., Babić, K., ... & Ayoola, M. (2018). An overview of the diurnal cycle of the atmospheric boundary layer during the West African monsoon season: results from the 2016 observational campaign. *Atmospheric Chemistry and Physics*, *18*(4), 2913-2928.

Knippertz, P., Fink, A. H., Schuster, R., Trentmann, J., Schrage, J. M., & Yorke, C. (2011). Ultra-low clouds over the southern West African monsoon region. *Geophysical research letters*, *38*(21).

Knippertz, P., Fink, A. H., Deroubaix, A., Morris, E., Tocquer, F., Evans, M. J., ... & Marsham, J. H. (2017). A meteorological and chemical overview of the DACCIWA field campaign in West Africa in June–July 2016. *Atmospheric Chemistry and Physics*, *17*(17), 10893-10918.

van der Linden, R., Fink, A. H., & Redl, R. (2015). Satellite-based climatology of low-level continental clouds in southern West Africa during the summer monsoon season. *Journal of Geophysical Research: Atmospheres*, *120*(3), 1186-1201.

Nieuwstadt, F. T. M., & Brost, R. A. (1986). The decay of convective turbulence. *Journal of the atmospheric sciences*, *43*(6), 532-546.

Ouwersloot, H. G., Moene, A. F., Attema, J. J., & De Arellano, J. V. G. (2017). Large-eddy simulation comparison of neutral flow over a canopy: Sensitivities to physical and numerical conditions, and similarity to other representations. *Boundary-Layer Meteorology*, *162*(1), 71-89.

Pedruzo-Bagazgoitia, X., Ouwersloot, H. G., Sikma, M., van Heerwaarden, C. C., Jacobs, C. M. J., & Vilà-Guerau de Arellano, J. (2017). Direct and Diffuse Radiation in the Shallow Cumulus–Vegetation System: Enhanced and Decreased Evapotranspiration Regimes. *Journal of Hydrometeorology*, *18*(6), 1731-1748.

de Roode, S. R., Sandu, I., Van Der Dussen, J. J., Ackerman, A. S., Blossey, P., Jarecka, D., ... & Stevens, B. (2016). Large-eddy simulations of EUCLIPSE–GASS Lagrangian stratocumulus-to-cumulus transitions: Mean state, turbulence, and decoupling. *Journal of the Atmospheric Sciences*, *73*(6), 2485-2508.

VanZanten, M. C., Stevens, B., Nuijens, L., Siebesma, A. P., Ackerman, A. S., Burnet, F., ... & Kogan, Y. (2011). Controls on precipitation and cloudiness in simulations of trade-wind cumulus as observed during RICO. *Journal of Advances in Modeling Earth Systems*, *3*(2).

Wood, R. (2012). Stratocumulus clouds. *Monthly Weather Review*, *140*(8), 2373-2423.