Response to interactive comments by anonymous referee #1

We would like to thank the reviewer for his suggestions regarding the manuscript. On the basis of these comments we have made numerous changes to the original text. Please find a response to each of the suggestions below.

-G1: The LWP tendency is made up of five terms which compensate to yield a small residual, both in the original simulation and in the differences between the sensitivity simulations. As the authors note, the budget in Fig. 1b might lead the reader to believe that the subsidence is a negligible contributor to the LWP tendency budget, but the whole point of the paper is to show how LWP does depend on subsidence. If the authors can make a more persuasive case for the quantitative utility of the budget in explaining their results, that would strengthen the paper. In particular, the statements in the conclusions, e. g. 17242 L24-17425 L2, are well known and don't require justification with an LWP tendency equation.

Our study is strongly motivated by the results of Sandu and Stevens (2011). They did not explain why the lifetime of stratocumulus is extended if the subsidence is decreased and as a result the entrainment rate increases. In particular, more entrainment would be expected to cause a more rapid thinning of the cloud layer. This puzzling aspect can be understood by considering all terms in the LWP budget. Putting the Base and Entrainment fluxes in one single term will obscure the fact that even though the entrainment rate increases, the cloud thinning tendency due to entrainment decreases.

Another important motivation for this study is the decoupling of the boundary layer during the transition. Some studies have suggested that the decoupling will lead to a thinning of the stratocumulus clouds as it tends to diminish the upward transport of moisture to the cloud layer. For example, in the seminal paper by Bretherton and Wyant (1999) it is written that "Penetrative entrainment of dry and warm free tropospheric air by the cumuli evaporates most of the liquid water in their updrafts before it can be detrained as stratocumulus cloud, so cloud amount gradually decreases (Bretherton 1992; W97).". Our analysis clearly shows the separate contributions of entrainment and cloud base fluxes as a response to changes in the subsidence.

Textual changes have been made throughout the manuscript and we have added a figure showing the contribution of the entrainment deepening term in the LWP budget (Figure 6), as well as the LHF for the sensitivity simulations (Figure 7) to bring out these messages more clearly.

-G2: In interpreting their results, the authors should note that the 'Base' term in the LWP tendency partitioning (Eq. 3) is inseparably linked to entrainment, since there can be no entrainment drying and warming without corresponding turbulent fluxes below the inversion. Thus, except perhaps for one illustrative example, only the sum of these strongly compensating terms ('Turb'?) should be plotted. This has the conceptual advantage of isolating all the turbulent contributions to LWP tendency into one term. At the end of section 5, the authors finally reach this conclusion themselves in noting the cloud base and entrainment sensitivities of LWP tendency to subsidence rate nearly add to zero.
We deliberately choose to separate the cloud base and cloud top fluxes as it is a priori not clear how their magnitudes relate to each other. The entrainment rate is among others controlled by the net radiative loss in the cloud layer, the inversion stability and the strength of convective updrafts in the cloud layer. On the other hand, the cloud base fluxes are to some extent governed by the surface flux values. Our current analysis enables us to determine whether the stratocumulus cloud thins during a stratocumulus transition 1) due to decoupling of the boundary layer that would strongly

reduce the input of humidity to the cloud layer or 2) due to a steady increase of the drying and warming of the stratocumulus layer as a result of enhanced entrainment. These two mechanisms have been proposed frequently in literature as the main causes for stratocumulus cloud thinning. We emphasize this among others by adding the following lines:
"The Ent and Base terms in Figure 1b are strongly anticorrelated, which is made particularly clear by the peaks that occur for both terms after approximately 22 hours. The magnitudes of these turbulence-driven tendencies are approximately equal during the first half of the simulation, so that they cancel to a large extent. Interestingly, the Base term remains roughly constant throughout most of the simulation suggesting that decoupling of the boundary layer does not significantly affect the transport of humidity to the stratocumulus cloud. The magnitude of the entrainment term, on the other hand, continues to increase throughout most of the simulation so that it becomes almost twice as large as the Base term during the second half of the transition. This can be explained from the magnitude of Δq_t that gradually increases by the combined effects of the increasing sea surface temperature and large-scale subsidence that slowly dries the free troposphere Van der Dussen et al. (2014)."

Another reason to maintain the decomposition is that we believe it is helpful for understanding and interpreting results from large-scale models which generally have difficulties in a faithful representation of the stratocumulus to cumulus transition. A similar LWP analysis for such models may shed some light on the question which of the components of the LWP budget needs to be improved. We would like to stress that in a recent paper by Ghonima et al. (2015, JAS) our budget analysis has been discussed to be a very useful approach for understanding and predicting the cloud layer evolution.

Specific comments
- 17233 Eq. 5: Should there be a factor '*h*' in front of the parenthesis to give the right hand side units of LWP tendency?
The units in Eq. (5) are correct as they are, which can be shown as follows. The units for the individual variables in the first term of the equation are:

$$[\mathrm{Ent}] = \frac{\mathrm{kg}}{\mathrm{m}^2\mathrm{s}}$$
$$[\rho] = \frac{\mathrm{kg}}{\mathrm{m}^3}$$
$$[w_e] = \frac{\mathrm{m}}{\mathrm{s}}$$
$$[\Delta q_t] = \frac{\mathrm{kg}}{\mathrm{kg}}$$
$$[\eta] = -$$

Substitution of these units in Eq. 5 gives the following for the first term:

$$\frac{\mathrm{kg}}{\mathrm{m}^2\mathrm{s}} = \frac{\cancel{\mathrm{kg}}}{\mathrm{m}^{\cancel{3}2}}\frac{\cancel{\mathrm{m}}}{\mathrm{s}}\frac{\mathrm{kg}}{\cancel{\mathrm{kg}}}.$$

This can also readily be shown for the other two terms in Eq. (5). Furthermore, Ghonima et al. (2015) checked the LWP tendency equation with a similar equation derived by Wood (2007) and found them to be in good agreement.

-17242 L10-11: Are the authors implying that there is a fundamental reason that the entrainment and cloud base contributions to LWP tendency should add to zero? If not, one could argue that this conclusion is just due to a coincidental cancellation between two other terms and is therefore not particularly meaningful. If so, please explain why the combined entrainment/base contribution should be negligibly small.
We believe this is a key finding and the reviewer's comment actually suggests that we have not been clear enough about this point. We found that even though the entrainment rate increased, the cloud

thinning tendency was reduced for weaker subsidence cases. This could not have been anticipated a priori, and was neither noticed by Sandu and Stevens. We made the discussion on this point more clear in the text:
"Figures 6a-c individually show the three terms that together constitute the contribution of entrainment to the LWP tendency of Eq. (5). The last of these terms accounts for the deepening of the cloud layer due to entrainment (Figure 6c), which according to Eq. (1) causes the inversion height and consequently the cloud top height to rise with time. It is important to note that the cloud layer thickness *h* arises in the last term on the rhs of Eq. (5) due to the fact that the maximum cloud liquid water content is present at the cloud top, with its top value being approximately proportional to the cloud layer depth. If the cloud top of a deep cloud increases due to entrainment, this will yield a larger increase in the LWP than if the cloud top of a shallower cloud rises by the same distance. Therefore, this term increases with the cloud thickness h. For the weak subsidence simulation, h is greater than for the reference simulation. This effect opposes the cloud thinning due to entrainment warming and drying, and causes the entrainment contribution to LWP for the lowest subsidence case to be positive (i.e. with respect to the reference case)."

We added Figure 6 in which the three terms that together constitute the contribution of entrainment to the LWP tendency are separately plotted to make the discussion easier to follow.

In a steady state situation (see e.g. Blossey et al. 2013, JAMES) and in the absence of source and sink terms, the cloud base contribution should cancel the entrainment contribution. However, there is no physical reason why they should balance during Lagrangian transitions. This is visible in Figure 1b, which shows that during the second half of the simulation the magnitude of the entrainment term is approximately a factor of two larger than that of the cloud base flux term. We added some discussion on this point (see the response to G2 above).

Furthermore, we added some discussion on the cancellation between the two terms:
"The sum of both contributions is therefore almost zero. This can be understood as follows. Enhanced entrainment will also cause enhancement of the cloud base fluxes as the entrained air sinks downward through the cloud layer. Similarly, strong updrafts through cloud base lead to enhanced entrainment when the updraft reaches and overshoots the inversion layer. Such anticorrelated behavior causes the cancellation of the entrainment and cloud base terms in the sensitivity experiments."

Response to interactive comments by anonymous referee #2

General comments
This study attempts to answer, given inversion strength, why weaker subsidence promotes thicker stratocumulus cloud layer and larger liquid water path (LWP), which has been suggested both modeling and observational studies. The authors utilize a recently developed LWP-budget analysis method for ASTEX large eddy simulations.
Their LWP budget analysis shows that (1) magnitude of drying due to subsidence is small, (2) weaker subsidence dries less cloud, (3) weaker subsidence reduces radiative cooling for daytime, (4) drying due to entrainment and moistening due to cloud base flux almost cancel each other for any subsidence rate. Thus, subsidence effect stands out even though its magnitude is much smaller than other processes. Overall, I think that the study improves our understanding for the subject, and the manuscript is generally well written. After clarifying some questions below, the manuscript is ready for publication.

We thank the reviewer for his kind words and useful suggestions on the manuscript. Below, we respond to each of the comments individually.

Specific comments / technical corrections
- I think that the authors should add something like "for the same inversion properties (e.g., inversion strength and thickness)" when they introduce past studies that suggest increase of LWP and increase of cloud amount as subsidence is weaken. If the inversion properties are different, weaker subsidence may not result in larger LWP.
Indeed, the statement that weaker subsidence results in a larger LWP is only valid when all other properties, in particular the inversion properties, are kept the same. We changed the text as follows: "LES results and mixed-layer model studies show that for fixed large-scale conditions such as the SST and the horizontal wind speed, a reduction of the large-scale subsidence causes the stratocumulus steady-state liquid water path (LWP) to increase, e.g. Bretherton et al. (2013) and De Roode et al. (2014). "

Bretherton, CS, PN Blossey, and CR Jones (2013), Mechanisms of marine low cloud sensitivity to idealized climate perturbations: A single-LES exploration extending the CGILS cases, J. Adv. Model. Earth Syst., 5, 316–337.

De Roode, S. R., A. P. Siebesma, S. Dal Gesso, H. J. J. Jonker, J. Schalkwijk, and J. Sival, 2014: A mixed-layer study of the stratocumulus response to changes in large-scale conditions. J. Adv. Model. Earth Syst., 6, DOI: 10.1002/2014MS000347.

- Equation (4): Is there a problem if the authors use actual lapse rate of q_l from their LES data?
There is no problem when the actual lapse rate of q_l is diagnosed from the LES data. In fact, this actual lapse rate is very close to the adiabatic lapse rate of q_l as the cloud fraction is very close to unity throughout the cloud layer. When the LWP budget equation was developed, it was attempted to reduce the amount of input parameters for the LWP budget equation to the minimum, hence the lapse rate of q_l (which is a dependent variable) was approximated. To clarify, we added the following text: "Following Van der Dussen et al. (2014) the value of Γ_{ql} is approximated by assuming a moist adiabatic temperature lapse rate. As the stratocumulus cloud layer is typically vertically well-mixed, this is in good agreement with the actual value of Γ_{ql} that can be obtained the vertical profile of q_l."

-How is z_i measured?
The inversion height is defined as the top of the inversion layer, z_i^+. We clarified this:
"We define the inversion height z_i as the top of the inversion layer, z_i^+, since the evaluation of the turbulent fluxes at this height results in the best closure of the LWP budget as discussed in Section

2.2. The inversion layer is usually only several tens of meters thick, so this somewhat unconventional definition of zi has negligible impact on the remaining terms in the budget."

- Equation (5): How is entrainment velocity measured?
The entrainment velocity is measured as the change of the inversion height in time (see our response to the previous question on the detection of z_i) corrected for the influence of subsidence, according to equation 1. We added the following to clarify this:
"The entrainment rate w_e is determined from the diagnosed time evolution of the inversion height and the prescribed subsidence at the inversion height using Eq. (1)."

- Typo at line 16, page 17234: "Eqs. (4)-8)" should be "Eqs. (4)-(8)".
Thank you for noticing.

- What is the authors definition of cloud fraction?
We added the definition used for the cloud fraction right below Eq. (9):
"Here c_f (z) is the fraction of grid cells in a horizontal slab at height z for which $q_c > 0$. Note that this definition excludes the presence of rain water."

- Add more description for DALES in 3.2. Too short.
We agree. We rewrote the section to the following, which is more informative in our opinion:
"The Dutch Atmospheric LES (DALES) model version 4.0 (Heus et al., 2010; Böing et al., 2014) was used to perform the simulations in this study. This model features, among others, an anelastic core, fifth-order hybrid weighted essentially non-oscillatory advection (Jiang and Shu, 1996; Blossey and Durran, 2008), the RRTMG scheme for radiation (Iacono et al., 2008), bulk microphysics (Kogan, 2013) and subgrid-scale turbulence following Deardorff (1980). The model version and settings are identical to those used by Van der Dussen et al. (2015)."

Böing, S. J., 2014: The interaction between deep convective clouds and their environment. Ph.D. thesis, Technical University Delft, Delft, 133 pp (Available from Technical University Delft, Delft, The Netherlands, http://repository.tudelft.nl).

Deardorff JW. 1980. Stratocumulus-capped mixed layers derived from a three-dimensional model. Bound.-Layer Meteor. 18: 495–527.

- "thinning contribution", "thinning tendency", and "cloud thinning": When these are used for LWP tendency, they should be replaced by "drying". Cloud layer thins, but not LWP.
Indeed, in general referring to a decrease of the LWP as a thinning of the cloud might not be correct. However, as we are dealing with a stratocumulus cloud layer that is vertically well-mixed and has a cloud cover of 100%, the LWP and the thickness of the cloud layer are inseparably linked. Hence, our loose use of the word thinning. We have some objections against using "drying" when referring to a LWP tendency, as this could be confused with a tendency of total humidity. Actually, a LWP tendency can also be caused by a change of the temperature. In that case, mentioning a drying of the cloud layer is probably correct, but slightly confusion.
We chose to put a remark explaining our use of the word thinning when referring to the LWP tendency at the beginning of the article:
"Note that in the discussion below we will loosely refer to a negative LWP tendency as a thinning of the stratocumulus layer, as the LWP is closely related to the cloud thickness as long as the cloud cover is unity. Because the stratocumulus cloud decks we are investigating are vertically well mixed, the LWP is approximately proportional to the cloud layer depth squared (Albrecht et al., 1990). Ghonima et al. (2015) actually demonstrated that the LWP budget and the tendency equation for the cloud layer thickness derived by Wood (2007) are analogous."

B. A. Albrecht, C.W. Fairall, D. W.Thomson, and A. B.White, 1990: Surface-based remote sensing of the observed and the Adiabatic liquid water content of stratocumulus clouds, GRL, 17, 89-92.

Mohamed S. Ghonima, Joel R. Norris, Thijs Heus, and Jan Kleissl, 2015: Reconciling and Validating the Cloud Thickness and Liquid Water Path Tendencies Proposed by R. Wood and J. J. van der Dussen et al.. J. Atmos. Sci., 72, 2033–2040.

Wood, R. (2007). Cancellation of aerosol indirect effects in marine stratocumulus through cloud thinning. Journal of the Atmospheric Sciences, 64(7), 2657–2669. doi:10.1175/JAS3942.1

- Fig. 1a: add vertical line to indicate sun rise and sun set.

We chose to make the nighttime grey in Fig 1a and we changed the figure caption accordingly. Thanks for this suggestion.

- The discussion in page 17238 is hard to follow.

We agree and rewrote much of the discussion, to hopefully make it easier to follow:
“After about 8 hours of simulation, the sun rises. The stratocumulus layer absorbs a fraction of the solar radiation, which causes a warming tendency that partly offsets the longwave radiative cooling of the cloud. Therefore, the net cloud thickening effect due to radiation diminishes during the day. This has a pronounced effect on the total LWP tendency, which becomes negative leading to the sharp decrease of the LWP with time as shown in Figure 1a. As the LWP decreases, the stratocumulus layer produces less precipitation, such that the thinning tendency due to precipitation reduces to approximately zero after about 14 hours. This shows that the feedback of the LWP on the generation of precipitation acts as a buffering mechanism that levels out variations of the LWP on timescales of several hours.
The decrease of the net radiative cooling during the day also diminishes the production of turbulence in the cloud layer. This is reflected by a weakening of the Ent and Base terms in Figure 1b that are both turbulence driven. Interestingly, the response of the turbulence intensity to the change of the radiative forcing is delayed by several hours, which is particularly clear for the Base-term. As a result, the minimum LWP in Figure 1a occurs about two to four hours after local noon.”

- "Surprisingly" in line 24, page 17238: Show time series of precipitation. Is large precipitation expected?

Thanks for this remark. We consider the choice of the word “surprisingly” as inappropriate, as the LWP at this stage is low, so little precipitation is expected. Hence we rewrote the sentence.
“At this stage the LWP has become low, resulting in little precipitation and hence a negligible drying tendency due to precipitation.”
We deem it unnecessary to include time series of the precipitation rate, as this is very similar to its LWP tendency (in Fig. 1b) according to Eq. (8).

- What is the authors definition of cloud cover?

To clarify we added the following definition:
“Figure 2a shows the projected cloud cover σ, fraction of LES vertical sub-columns with $q_c > 0$, for the three sensitivity simulations in which the large-scale subsidence velocity is varied.”

- Second paragraph in page 17239: I think that this is very hand wavy argument. Any evidence?

We propose the most likely cause for the difference in the moment of stratocumulus breakup between the original and the idealized simulations as we think that further speculation will distract too much from main message of this article. Hence, we chose to state more clearly that we provide only the most likely explanation about the differences:
“A prominent difference however is the moment of stratocumulus breakup, which occurs approximately 10 hours earlier in the original ASTEX transition. As a possible explanation this is most likely due to the magnitude of the horizontal wind that decreases in the second half of this transition and causes a drastic reduction of the surface humidity flux. In the sensitivity experiments on the other hand, the horizontal wind speed is constant in time possibly leading to a greater moisture supply to the stratocumulus layer, which prolongs its lifetime. The latent heat flux results of our idealized LES sensitivity experiments are consistent with a recent model intercomparison study on

Lagrangian stratocumulus transitions (De Roode et al. 2015), which explains that for a constant wind speed and a linearly increasing SST with time the LHF should increase exponentially with time."

de Roode, S. R., I. Sandu, J. J. van der Dussen, A. S. Ackerman, P. Blossey, D. Jarecka, A. Lock, A. P. Siebesma, and B. Stevens, 2015: Shallow cumulus control on the stratocumulus lifetime: LES results of EUCLIPSE/GASS Lagrangian stratocumulus transitions. Revised version to be submitted to J. Atmos. Sci.

- Line 28 in page 17239 "the entrainment rate is found to increase...": Does the inversion strength become weaker for the weak subsidence case? Provide figure for inversion strength for all cases. Climatologically, subsidence and inversion strength are positively correlated. Is it also true for these simulations?

We added a figure with the inversion jumps of humidity (figure 4a) and liquid water potential temperature (figure 4b) as suggested. We also added some discussing on this point:
"The inversion strength, as measured by $\Delta\theta_l$, is hardly affected by the change of the subsidence rate as is shown in Figure 4b, because the change of θ_l is about as large in the cloud layer as in the free troposphere. The differences in the entrainment rate therefore cannot be explained by changes of the inversion strength. This is somewhat unexpected as large-scale subsidence and lower tropospheric stability are positively correlated at longer time-scales (e.g. Myers and Norris, 2013)."

- Line 2 in page 17240 "...most likely the result of the larger stratocumulus thickness h,...": Show the time series of cloud thickness for all cases.

The time series of the cloud thickness looks virtually identical to the time series of the LWP in Fig. 2b, which is the result of the cloud cover of 100% throughout the entire LES domain for most of the simulation time. Adding a figure showing stratocumulus thickness would hence not be very informative (see remark about ghonima paper above).
We however chose to rewrite this line somewhat, to clarify the reasoning:
"Such an increase was also found by Sandu and Stevens (2011) and it is most likely the result of the larger LWP (see Fig. 2b). This typically causes the cloud layer to be more energetic…"

- Line 18 in page 17241 "...for the lowest subsidence case...": Show the time series of three terms for the entrainment contribution term.

Following your suggestion, we decided to add another figure showing the three terms of Eq. (5) separately to make the discussion easier to follow. We refer to this figure in the text as follows:
"Figures 6a-c individually show the three terms that together constitute the contribution of entrainment to the LWP tendency of Eq. (5). The last of these terms accounts for the deepening of the cloud layer due to entrainment (Figure 6c), which according to Eq. (1) causes the inversion height and consequently the cloud top height to rise with time. It is important to note that the cloud layer thickness *h* arises in the last term on the rhs of Eq. (5) due to the fact that the maximum cloud liquid water content is present at the cloud top, with its top value being approximately proportional to the cloud layer depth. If the cloud top of a deep cloud increases due to entrainment, this will yield a larger increase in the LWP than if the cloud top of a shallower cloud rises by the same distance. Therefore, this term increases with the cloud thickness *h*. For the weak subsidence simulation, *h* is larger than for the reference simulation. This effect opposes the cloud thinning due to entrainment warming and drying, and causes the entrainment contribution to δLWP for the lowest subsidence case to be positive (i.e. with respect to the reference case).
Note furthermore that for weaker subsidence the boundary layer grows deeper, causing the cloud layer to become drier with respect to shallower boundary layers (Park et al., 2004;Wood and Bretherton, 2004). Hence, the magnitude of the inversion jump of humidity Δq_t decreases as subsidence is weakened as is shown in Figure 4a. This decrease exceeds 0.5 g kg^{-1} at the end of the simulations, which causes the entrainment drying term in Figure 6a to be practically identical for all three cases, despite the difference in the entrainment velocities."

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How Large-Scale Subsidence Affects Stratocumulus Transitions

J. J. van der Dussen[1], S. R. de Roode[1], and A. P. Siebesma[2,1]

[1]Department of Geoscience and Remote Sensing, Delft University of Technology, Delft, The Netherlands
[2]Royal Netherlands Meteorological Institute (KNMI), De Bilt, The Netherlands

Correspondence to: Johan van der Dussen (johanvanderdussen@outlook.com)

Abstract. Some climate modeling results suggest that the Hadley circulation might weaken in a future climate, causing a subsequent reduction in the large-scale subsidence velocity in the subtropics. In this study we analyze the cloud liquid water path (LWP) budget from large-eddy simulation (LES) results of three idealized stratocumulus transition cases each with a different subsidence rate. As shown in previous studies a reduced subsidence is found to lead to a deeper stratocumulus-topped boundary layer, an enhanced cloud-top entrainment rate and a delay in the transition of stratocumulus clouds into shallow cumulus clouds during its equatorwards advection by the prevailing trade winds. The effect of a reduction of the subsidence rate can be summarized as follows. The initial deepening of the stratocumulus layer is partly counteracted by an enhanced absorption of solar radiation. After some hours the deepening of the boundary layer is accelerated by an enhancement of the entrainment rate. Because this is accompanied by a change in the cloud-base turbulent fluxes of moisture and heat, the net change in the LWP due to changes in the turbulent flux profiles is negligibly small.

1 Introduction

As subtropical marine stratocumulus clouds are advected by the tradewinds over increasingly warm water they are often observed to transition into shallow cumulus clouds. Such transitions involve a rapid decrease of the cloud cover and the cooling effect due to the presence of low clouds is hence diminished. Therefore, a change of the pace of stratocumulus transitions in a future climate could potentially be of importance for the magnitude of the cloud-climate feedback.

Some general circulation model results suggest that the Hadley-Walker cell may weaken as a result of climate warming (e.g. Held and Soden, 2006; Vecchi and Soden, 2007). In the subtropical part of the Hadley cell there is a mean subsiding motion of air, which is schematically shown in Figure 1. It is therefore reasonable to assume that the large-scale subsidence in subtropical areas will weaken in a future climate. ~~A weakening~~ Large-eddy simulation (LES) results and mixed-layer model studies show that for fixed large-scale conditions such as the sea surface temperature and the horizontal wind speed, a reduction of the large-scale subsidence ~~caused an increase of the~~ causes

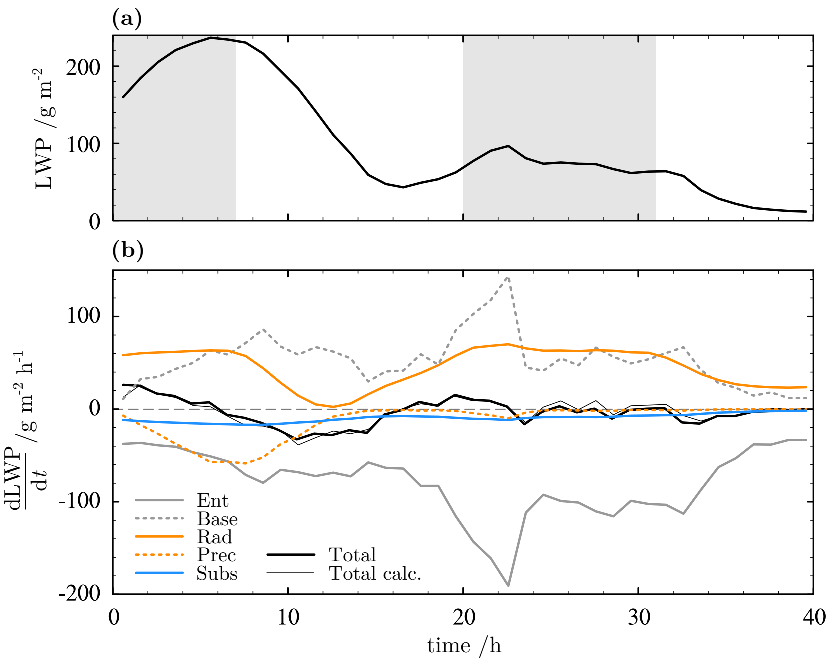

Figure 1. A schematic representation of the Hadley circulation and the cloud types that typically occur within this large-scale circulation (after Arakawa, 1975; Emanuel, 1994) . The bottom panel zooms in on the stratocumulus transition regime within the Hadley circulation.

the stratocumulus steady-state liquid water path (LWP) ~~of stratocumulus layers within a steady-state Eulerian framework (Blossey et al., 2013; Bretherton et al., 2013)~~ to increase (e.g. Bretherton et al., 2013; De Roode et al., 2014) . As such, reduced subsidence might be one of the few processes to cause additional cloudiness in a future climate scenario (Bretherton and Blossey, 2014). It is therefore of paramount importance to have a thorough understanding of how a weakening of the large-scale subsidence increases the LWP and the ~~life-time~~ lifetime of stratocumulus clouds.

Together with the entrainment rate, the subsidence velocity determines the rate of deepening of boundary layers that are capped by an inversion, as follows

$$\frac{\mathrm{d}z_\mathrm{i}}{\mathrm{d}t} = w_\mathrm{e} + \overline{w}(z_\mathrm{i}). \quad (1)$$

Here, z_i is the height of the inversion, t is time, w_e is the entrainment velocity and $\overline{w}$ is the large-scale subsidence velocity. A lower subsidence velocity ~~therefore leads~~ would therefore lead to a more rapid deepening of the boundary layer if the entrainment velocity ~~remains unaffected. Such deeper boundary layers are often assumed to be less well mixed than shallow boundary layers (Park et al., 2004; Wood and Bretherton, 2004) . It was therefore~~ would remain unaffected. This deepening would increase decoupling of the boundary layer (Park et al., 2004; Wood and Bretherton, 2004) and therefore it was hypothesized that weaker subsidence ~~could~~ would increase the pace of stratocumulus transitions (e.g. Wyant et al., 1997; Bretherton et al., 1999).

Svensson et al. (2000), however, used a one-dimensional turbulence model to show that the moment of break up of the stratocumulus layer is actually delayed when the magnitude of the large-scale subsidence velocity is decreased. ~~Later, Sandu and Stevens (2011) corroborated these findings by performing several large-eddy simulations (LESs) of stratocumulus transition cases. Moreover, Myers and Norris (2013) found~~ Myers and Norris (2013) corroborated this finding by showing from observations that low cloud amount in the subtropics tends to decrease as subsidence becomes stronger.

~~This study investigates the effect of a change in the strength of the Hadley circulation, as quantified by the large-scale subsidencevelocity, on the typical time scale of the break up of stratocumulus and its subsequent transition to broken shallow cumulus. The entrainment rate as well as the subsidence velocity are typically poorly constrained by observations (Bretherton et al., 1995; De Roode and Duynkerke, 1997; Ciesielski et al., 2 by reanalysis products (Duynkerke et al., 1999) . For this reason, LES is used here. A~~ Moreover, Sandu and Stevens (2011) performed several LESs of stratocumulus transition cases and found that although the entrainment rate increased in the sensitivity run with reduced subsidence, the larger entrainment drying and warming trend of the boundary layer did apparently not lead to a more rapid cloud break up. To shed some light on this finding, a budget equation for the tendency of the LWP of the stratocumulus layer as derived by Van der Dussen et al. (2014) is used to analyze ~~the LES results~~ results of idealized LESs in order to determine the role of each individual physical ~~processes~~ process during stratocumulus transitions. Through this analysis, insight is gained into how subsidence affects the pace of stratocumulus transitions, which helps to determine the robustness of the sign of the response of stratocumulus clouds to a weakening subsidence.

The LES results provide complete information on entrainment rate and subsidence velocity, in contrast to observations or reanalysis products in which these variables are typically poorly constrained (Bretherton et al., 1995; De Roode and Duynkerke, 1997; Ciesielski et al., 2001; Carman et al., 2012; Duynkerke et al., 1999) . As discussed by Bretherton (2015) turbulence-resolving LES models using sub-100 m grid spacings over small computational domains are very suitable tools to study low cloud regimes such as stratocumulus and shallow cumulus.

The main aim of this study is to better understand the prolonged lifetime of stratocumulus during its Lagrangian advection over increasing SSTs in case the subsidence is reduced and despite the fact that the entrainment warming and drying effect is enhanced. In the next section, first the methodology is explained, which is used to assess the relative importance of each physical process that is involved in the evolution of stratocumulus-topped boundary layers. In Section 3 the details of the LESs that have been performed are described. The LWP tendency during the ASTEX transition is analyzed in Section 4, while several sensitivity studies are discussed in Section 5. In the final section, a short summary of the conclusions are presented.

2 Methodology

2.1 Contributions to the LWP Tendency

The ~~cloud albedo increases for larger values of the LWP , which is~~ LWP of an adiabatic stratocumulus cloud is here defined as

$$\mathrm{LWP} = \int_{z=0}^{\infty} \rho q_\mathrm{l} \mathrm{d}z, \tag{2}$$

where q_l is the liquid water specific humidity, which is the sum of the cloud water q_c and rain water specific humidity q_r. Furthermore, ρ is the density of air and z is height. Van der Dussen et al. (2014) extended the LWP budget analysis of Randall et al. (1984) by including the contribution of cloud-base turbulent fluxes, radiation and drizzle, in addition to entrainment. ~~The resulting LWP budget equation~~ An LWP tendency equation was derived on the basis of the budget equations for heat, water and mass and allows for the ~~evaluation of the relative~~ quantification of the contribution of individual physical processes to the LWP tendency, so

$$\frac{\partial \mathrm{LWP}}{\partial t} = \mathrm{Ent} + \mathrm{Base} + \mathrm{Rad} + \mathrm{Prec} + \mathrm{Subs}. \tag{3}$$

Here, the abbreviations indicate LWP tendencies as a result of entrainment of free tropospheric air into the boundary layer at the top of the stratocumulus layer (Ent), turbulent fluxes of total specific humidity q_t and liquid water potential temperature θ_l at the base of the stratocumulus layer (Base), divergence of the net radiative flux over the stratocumulus layer (Rad), divergence of the precipitation flux over the stratocumulus layer (Prec) and large-scale subsidence (Subs). We refer to Van der Dussen et al. (2014) for a derivation of these terms. Below, the results are repeated for convenience.

The LWP tendency due to large-scale subsidence can be written as:

$$\mathrm{Subs} = -\rho h \Gamma_{q_\mathrm{l}} \overline{w}(z_\mathrm{i}), \tag{4}$$

in which h is the thickness of the stratocumulus cloud layer, $\overline{w}$ is the large-scale vertical velocity and $\Gamma_{q_\mathrm{l}} = -\partial q_\mathrm{l}/\partial z < 0$ is the lapse rate of q_l. ~~The~~ Following Van der Dussen et al. (2014) the value of Γ_{q_l} is approximated by assuming a moist adiabatic temperature lapse rate. ~~Subsidence~~ As the stratocumulus cloud layer is typically vertically well-mixed, this is in good agreement with the actual value of Γ_{q_l} that can be obtained from the vertical profile of q_l. We define the inversion height z_i as the top of the inversion layer, z_i^+, since the evaluation of the turbulent fluxes at this height results in the best closure of the LWP budget as discussed in Section 2.2. The inversion layer is usually only several tens of meters thick, so this somewhat unconventional definition of z_i has negligible impact on the remaining terms in the budget. Equation (4) shows that subsidence acts to decrease the LWP by pushing the stratocumulus cloud top down.

Note that all variables used in the current study are slab-averages unless specifically stated otherwise. The overbar that is commonly used to indicate a slab-averaged variable is omitted for notational convenience, except for the turbulent fluxes and variances.

The entrainment contribution to the LWP tendency is as follows:

$$\mathrm{Ent} = \rho w_{\mathrm{e}} \left(\eta \Delta q_{\mathrm{t}} - \Pi \gamma \eta \Delta \theta_{\mathrm{l}} - h \Gamma_{q_{\mathrm{l}}} \right), \tag{5}$$

where Δq_{t} and $\Delta \theta_{\mathrm{l}}$ indicate the inversion jumps of q_{t} and θ_{l} respectively, Π is the Exner function and $\gamma = \partial q_{\mathrm{s}} / \partial T \approx 0.55$ g kg^{-1} K^{-1} is described by the Clausius-Clapeyron relation. Furthermore, η is a thermodynamic factor that depends mainly on temperature and is given by

$$\eta = \left(1 + \frac{L_{\mathrm{v}} \gamma}{c_p} \right)^{-1} \approx 0.4,$$

with c_p the specific heat of air at constant pressure and L_{v} the latent heat of vaporization. The entrainment rate w_{e} is determined from the diagnosed time evolution of the inversion height and the prescribed subsidence at the inversion height using Eq. (1).

The remaining three terms of Eq. (3) are

$$\mathrm{Base} = \rho \eta \left[\overline{w' q_{\mathrm{t}}'}(z_{\mathrm{b}}) - \Pi \gamma \overline{w' \theta_{\mathrm{l}}'}(z_{\mathrm{b}}) \right], \tag{6}$$

$$\mathrm{Rad} = \frac{\eta \gamma}{c_p} \left[F_{\mathrm{rad}}(z_{\mathrm{t}}) - F_{\mathrm{rad}}(z_{\mathrm{b}}) \right], \tag{7}$$

$$\mathrm{Prec} = -\rho \left[P(z_{\mathrm{t}}) - P(z_{\mathrm{b}}) \right]. \tag{8}$$

Here, $\overline{w' q_{\mathrm{t}}'}$ and $\overline{w' \theta_{\mathrm{l}}'}$ are the turbulent fluxes of q_{t} and θ_{l}. Furthermore, z_{b} and z_{t} are stratocumulus base and top height, respectively. Furthermore, F_{rad} is the radiation flux in W m^{-2} and P is the precipitation flux in m s^{-1}, both of which are defined negative downward.

2.2 Evaluation of Cloud Boundaries

The LWP budget equation described in the previous section is used to quantify the relative importance of the individual physical processes to the total LWP tendency. To this end, Eqs. (4)-(8) will be evaluated using slab-averaged vertical profiles derived from the LES. To accurately evaluate the LWP tendencies with this method, it is important to properly define the top and bottom interfaces of the stratocumulus layer.

The stratocumulus base height is defined as the minimum height where the slab-averaged cloud fraction ~~σ~~ c_{f} exceeds 0.4,

$$z_{\mathrm{b}} = \min(z), \quad \text{where} \quad \sigma c_{\mathrm{f}}(z) > 0.4. \tag{9}$$

~~The criterion is chosen such that the cumulus clouds~~ Here $c_{\mathrm{f}}(z)$ is the fraction of grid cells in a horizontal slab at height z for which $q_{\mathrm{c}} > 0$. Note that this definition excludes the presence of rain water. The criterion in Eq. (9) selects the stratocumulus cloud base height, and excludes the effect of cumulus clouds which can have their base well below the stratocumulus layer~~are ignored~~. The analysis is quite insensitive to the critical ~~σ~~ c_f value as stratocumulus base height is typically well defined in terms of the cloud fraction profile. ~~Any value between $\sigma \approx 0.2$~~ We have tested different values for the criterion, and found that any value between 0.2 and 0.8 can be used ~~.~~ to get a good correspondence between the diagnosed LWP tendency from the terms on the rhs of Eq. (3) and the tendency as diagnosed directly from the LES cloud fields.

Some more care is required for the definition of stratocumulus top height z_t. To take into account the vertical undulations in the cloud top and in particular its effect on the horizontal slab mean flux profiles (vanZanten et al., 1999), the budget analysis is performed up to the top of the inversion layer, the height of which is defined as z_i^+. Hence, in Eqs. (7)

$$z_t = z_i^+. \tag{10}$$

There is practically no cloud water at this level, so that the precipitation flux is negligible, $P(z_t) \approx 0$.

The lower and upper boundaries of the inversion layer are determined on the basis of the profile of the variance of θ_l as follows (Yamaguchi et al., 2011):

$$z_i^+ = z, \quad \text{where} \quad \overline{\theta_l'^2} = 0.05 \cdot \max(\overline{\theta_l'^2}) \quad \text{and} \quad z > z_{max}, \tag{11a}$$

$$z_i^- = z, \quad \text{where} \quad \overline{\theta_l'^2} = 0.05 \cdot \max(\overline{\theta_l'^2}) \quad \text{and} \quad z < z_{max}. \tag{11b}$$

Here, z_{max} is the height at which the maximum of the $\overline{\theta_l'^2}$ profile is located. Linear interpolation is used between the grid levels to determine z_i^+ and z_i^-. The peak of the slab-averaged $\overline{\theta_l'^2}$ profile is very well defined ~~, such~~ so that the values of z_i^+ and z_i^- ~~do not dependent strongly~~ hardly depend on the rather arbitrary criteria in Eqs. (11).

The inversion jump of a conserved variable φ is defined as the difference between the variable at the top and at the base of the inversion layer

$$\Delta\varphi = \varphi(z_i^+) - \varphi(z_i^-). \tag{12}$$

3 Setup

3.1 Forcings and Domain

In Section 4 the LWP budget of the Atlantic Stratocumulus Transition EXperiment (ASTEX, Albrecht et al., 1995) case is analyzed, for which the initial conditions and forcings were described by Van der Dussen et al. (2013). The simulation lasts 40 h and features diurnally varying insolation. During the transition, the boundary layer evolves from relatively shallow and well mixed to deep and decoupled with cumulus updrafts underneath a thin broken stratocumulus layer. The results of this case are used here to illustrate how the methodology described in the previous section can help to understand the often complex interaction between processes that together determine the evolution of the stratocumulus layer.

Many of the forcings and boundary conditions for the ASTEX case, such as the subsidence velocity, the solar zenith angle and the geostrophic wind velocities, vary with time. This could make the interpretation of sensitivity experiments unnecessarily complicated. The forcings of the ASTEX case have therefore been idealized for the sensitivity experiments, as follows.

A diurnally averaged solar zenith angle of 68.72° is prescribed, resulting in a constant downwelling shortwave radiative flux of approximately 494 W m^{-2} at the top of the atmosphere. Furthermore, the geostrophic wind velocities are kept constant and equal to the initial horizontal velocities, which are constant with height at $(u,v) = (5.5,0)$ m s^{-1}. Hence, the mean wind speed is approximately constant in time. The microphysics parameterization scheme is disabled.

For the sensitivity simulations, the prescribed large-scale subsidence profile is kept constant with time. It is defined as:

$$\overline{w}(z) = \begin{cases} -Dz & \text{for} \quad z \leq z_D \\ -Dz_D & \text{otherwise,} \end{cases}$$

where $z_D = 500$ m and D is the large-scale divergence of horizontal winds. The only boundary condition that varies in time is the SST, which increases linearly from 291 to 297 K over the course of the 60-hour simulations.

The horizontal domain size is 4800×4800 m^2, divided into 192×192 gridpoints that are spaced 25 m apart. In the vertical direction, the resolution is varied from 10 m at the surface to 5 m for z between 500 and 2300 m. Above, the vertical grid spacing is increased by 5% per level up to a height of 3 km, resulting in a total of 500 levels.

3.2 Model Details

The Dutch Atmospheric LES (DALES) model version 4.0 (Heus et al., 2010; Böing, 2014) was used to perform the simulations ~~. Compared to version 3.2 that was described by Heus et al. (2010) , this version has~~ in this study. This model features among others an anelastic core~~(Böing et al., 2012)~~ , fifth-order hybrid weighted essentially non-oscillatory advection (Jiang and Shu, 1996; Blossey and Durran, 2008) , the RRTMG scheme for radiation (Iacono et al., 2008) , bulk microphysics (Kogan, 2013) and subgrid-scale turbulence following Deardorff (1980) . The model ~~settings and parameterization schemes that were used~~ version and settings are identical to those ~~described~~ used by Van der Dussen et al. (2015).

4 ASTEX Transition

The LWP for the ASTEX case is shown in Figure 2a as a function of time. The LWP evolution is qualitatively similar to that obtained with DALES version 3.2 (Van der Dussen et al., 2013), despite the fact that different radiation and microphysics parameterization schemes are used in the present study.

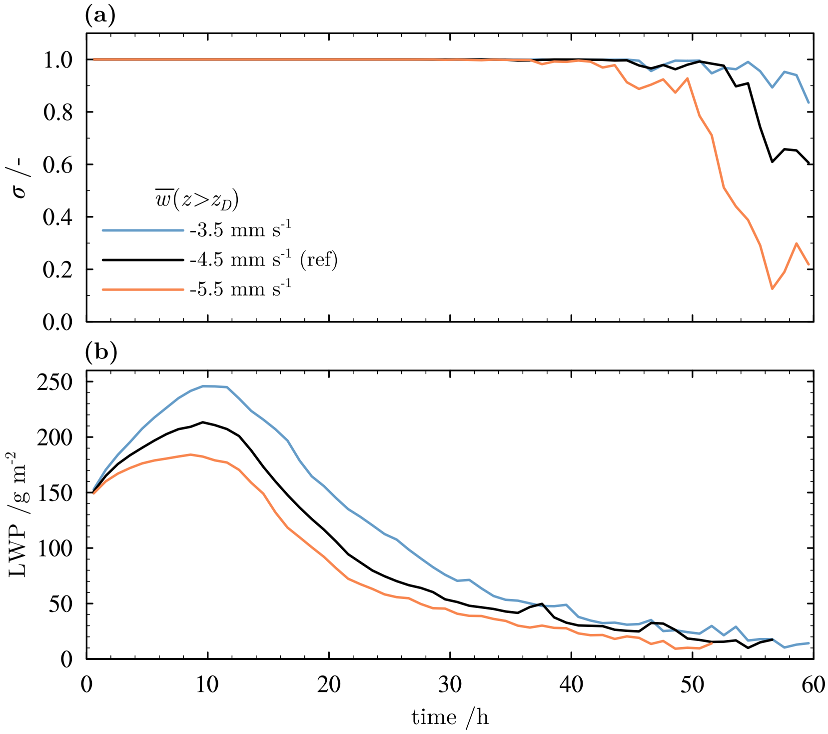

Figure 2. (a) The LWP as function of time for the ASTEX transition simulation. The grey shaded areas indicate nighttime conditions. (b) The tendency of the LWP as a function of time, split into the contributions from the individual physical processes according to Eq. (3). Line colors and styles ~~as denoted by~~ according to the legend. The horizontal dashed black line indicates the zero tendency level as a reference.

The tendency of the LWP is indicated by the thick black line in Figure 2b. The thin black line in this figure shows the net LWP tendency diagnosed using Eq. (3), which agrees very well with the actual LWP tendency. Note that in the discussion below we will loosely refer to a negative LWP tendency as a thinning of the stratocumulus layer, as the LWP is closely related to the cloud thickness as long as the cloud cover is unity. Because the stratocumulus cloud decks we are investigating are vertically well mixed, the LWP is approximately proportional to the cloud layer depth squared (Albrecht et al., 1990) . Ghonima et al. (2015) actually demonstrated that the LWP budget and the tendency equation for the cloud layer thickness derived by Wood (2007) are analogous.

Interestingly, the net LWP tendency is small as compared to the contributions from entrainment, radiation and turbulent fluxes at stratocumulus base height. The simulation starts approximately at midnight. During the initial 8 hours, the contribution of the radiation to the LWP tendency is therefore solely due to longwave radiative cooling. This contribution ~~is large~~ amounts roughly to 60 g m^{-2} h^{-1} and causes the stratocumulus layer to thicken.

The increase of the LWP triggers additional precipitation, so that its thinning contribution increases until it approximately balances the radiative tendency and the net LWP tendency decreases.

~~After~~ The sun rises after about 8 hours of simulation~~, the sun rises~~. The stratocumulus layer absorbs ~~the~~ a fraction of the incident solar radiation, which causes a warming tendency that partly offsets the longwave radiative cooling ~~so that the net~~ of the cloud. Therefore, the net cloud thickening effect due to radiation diminishes during the day. ~~The thinner stratocumulus layer supports only little precipitation, such~~ This has a pronounced effect on the total LWP tendency, which becomes negative leading to the sharp decrease of the LWP as shown in Figure 2a. As the LWP decreases, the stratocumulus layer produces less precipitation, so that the thinning tendency due to precipitation reduces to approximately zero ~~. The~~ after about 14 hours. This shows that the feedback of the LWP on the generation of precipitation acts as a buffering mechanism ~~, leveling~~ that levels out variations of the LWP on timescales of several hours.

The decrease of the net radiative cooling during the day also diminishes the production of turbulence in the cloud layer~~, which~~ . This is reflected by ~~the decrease of the magnitudes of the contributions of the entrainment and of the turbulent fluxes at stratocumulus base~~ a weakening of the Ent and Base terms in Figure 2b that are both turbulence driven. Interestingly, the response of the turbulence intensity to the change of the radiative forcing ~~seems to be delayed somewhat, causing the~~ is delayed by several hours, which is particularly clear for the Base term. As a result, the minimum LWP in Figure 2a ~~to occur~~ occurs about two to four hours after ~~midday~~ local noon.

The Ent and Base terms in Figure 2b are strongly anticorrelated, which is made particularly clear by the peaks that occur for both terms after approximately 22 hours. The magnitudes of these turbulence-driven tendencies are approximately equal during the first half of the simulation, so that they cancel to a large extent. The Base term remains roughly constant throughout most of the simulation suggesting that decoupling of the boundary layer does not significantly affect the transport of humidity to the stratocumulus cloud. The magnitude of the entrainment term, on the other hand, continues to increase throughout most of the simulation so that it becomes almost twice as large as the Base term during the second half of the transition. This can be explained from the magnitude of Δq_t that gradually increases by the combined effects of the increasing sea surface temperature and large-scale subsidence that slowly dries the free troposphere (Van der Dussen et al., 2014) .

The contribution of the large-scale subsidence to the LWP is relatively small and negative. Its thinning effect ~~decreases~~ becomes weaker as the stratocumulus cloud thins, which is due to the h dependence in Eq. (4).

During the second night, after about 20 hours, the thinning due to entrainment is approximately balanced by equal thickening contributions by the radiative cooling and the fluxes at cloud base. ~~Surprisingly, the contributions due to subsidence and precipitationare negligible at this stage~~ At this stage the LWP has become low, resulting in little precipitation and hence a negligible drying tendency due to precipitation. As a result the LWP decreases only very slightly until the cloud layer starts to break up at the beginning of the second day.

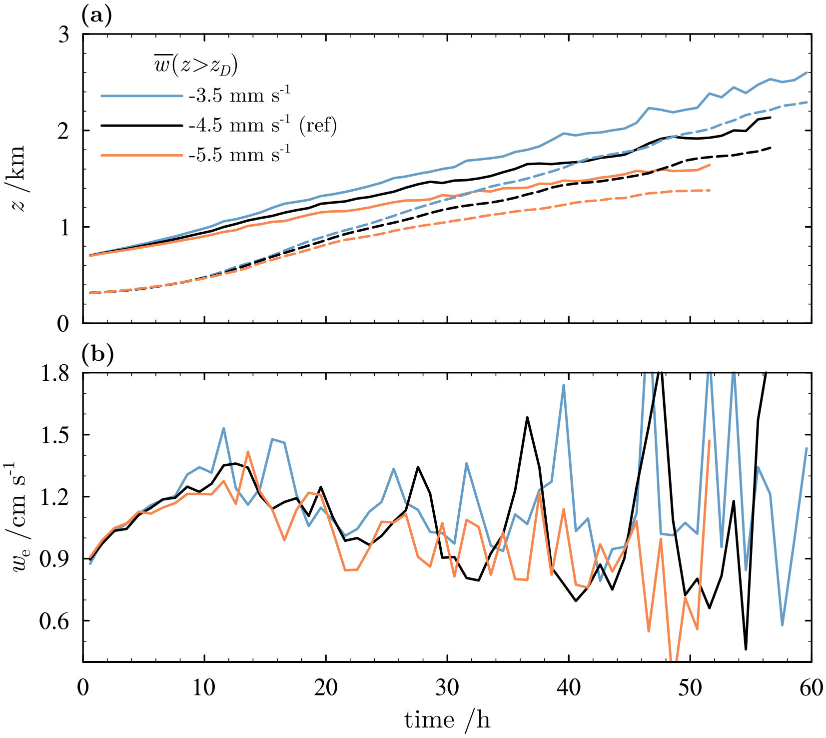

Figure 3. (a) The projected cloud cover σ and (b) the LWP as a function of time for the ~~the~~ sensitivity simulations in which the large-scale subsidence velocity is varied as indicated by the legend.

5 Sensitivity to the Large-Scale Subsidence

5.1 Effect on Cloud Properties

~~The projected cloud cover σ is shown in~~ Figure 3a shows the projected cloud cover σ, defined as the fraction of LES vertical subcolumns with $q_c > 0$, for the three sensitivity simulations in which the large-scale subsidence velocity is varied. The results demonstrate clearly that a weakening of the large-scale subsidence extends the lifetime of the stratocumulus layer, thereby corroborating the findings of Svensson et al. (2000) and Sandu and Stevens (2011). Figure 3b furthermore shows that a weakening of the subsidence causes the LWP to increase. The large differences among the simulations are somewhat ~~surprising~~puzzling, as it was shown in the previous section that the contribution of subsidence to the LWP tendency is relatively small.

Despite the absence of precipitation and a diurnal cycle, the transitions with the idealized forcings are qualitatively similar to the original ASTEX transition (Figure 2a). ~~However, the stratocumulus breakup occurs later in the sensitivity experiments. In the second half of the~~ A prominent difference however is the moment of stratocumulus breakup, which occurs approximately 10 hours earlier in the original ASTEX transition~~,~~. As a possible explanation this is most likely due to the magnitude

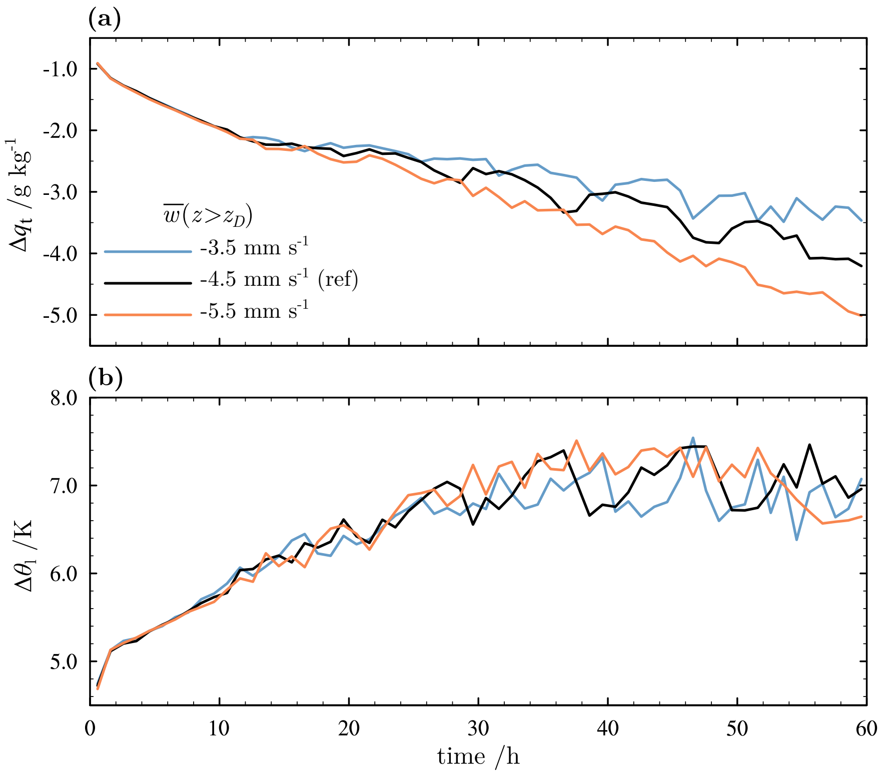

Figure 4. (a) The stratocumulus top (solid) and base height (dashed) and (b) the entrainment velocity as a function of time for the subsidence sensitivity simulations.

of the horizontal wind ~~velocity decreases , which drastically reduces the surface humidity flux and likely causes the transition to accelerate (Van der Dussen et al., 2013)~~ that decreases in the second half of this transition and causes a drastic reduction of the surface humidity flux. In the sensitivity experiments, on the other hand, the horizontal wind speed is constant in time ~~so that~~ possibly leading to a greater moisture supply to the stratocumulus layer~~is maintained longer at the end of the transition.~~ , which prolongs its lifetime. The latent heat flux results of our idealized LES sensitivity experiments are consistent with a recent model intercomparison study on Lagrangian stratocumulus transitions (De Roode et al., 2015) , which explains that for a constant wind speed and a linearly increasing SST with time the LHF should increase exponentially with time.

Figure 4a shows the top and base interfaces of the stratocumulus layer as defined in Section 2.2. Differences in stratocumulus top height start to occur soon after the start of the simulations. Stratocumulus base height, on the other hand, remains unaffected for roughly 15 hours. This suggests that the difference in the subsidence velocity does not strongly affect the temperature and humidity profiles in the bulk of the boundary layer during this period. Later on in the simulations ~~, differences in the stratocumulus base height also start occurring~~the stratocumulus cloud bases start to diverge.

It is ~~interesting~~ important to note that the differences of the inversion height among the simulations are roughly a factor of two larger than would be expected on the basis of the difference in the subsidence rate alone. As can be seen in Figure 4b, the entrainment rate is found to increase as subsidence weakens. Such an increase was also found by Sandu and Stevens (2011) and it is most likely the result of the larger ~~stratocumulus thickness h, which~~ LWP (see Fig. 3b). This typically causes the cloud layer to be more energetic eventually leading to enhanced entrainment ~~(e.g. Nicholls and Turton, 1986; Jones et al., 2014)~~ (Nicholls and Turton, 1986; Jones et al., 2014) .

The inversion strength, as measured by $\Delta\theta_l$, is hardly affected by the change of the subsidence rate as is shown in Figure 5b, because the change of θ_l is about as large in the cloud layer as in the free troposphere. The differences in the entrainment rate therefore can not be explained by changes of the inversion strength. This is somewhat unexpected as large-scale subsidence and lower tropospheric stability are positively correlated at longer time-scales (e.g. Myers and Norris, 2013) .

5.2 Analysis of LWP Budget

To determine how much each of the physical processes that affect the LWP contribute to the LWP differences among the simulations, the terms of the LWP budget equation are shown individually in the left column of Figure 6. Note that the scale of the vertical axis of the subfigures varies significantly.

Figure 6a shows the LWP tendency due to subsidence. Evidently, the cloud thinning due to subsidence is less strong for the weaker subsidence cases. The difference among the simulations is about 3 g m^{-2} h^{-1} during the first part of the transition and slowly decreases with time. For the LWP tendencies due to radiation, entrainment and cloud base turbulent fluxes, shown in Figures 6c, 6e and 6g respectively, the data do not show a clear trend due to the significant amount of noise.

In order to obtain a clearer picture of how large the LWP differences caused by each of the individual processes are, the following steps are taken. First, the $-Dz_D = -4.5$ mm s^{-1} simulation indicated by the black lines in Figures 3~~and 4~~ -5 is chosen as a reference. Then, the differences with respect to this reference of the LWP tendency due to each process is determined. These differences are integrated in time to give the LWP difference among the simulations that is solely due to that process. So, for the subsidence term

$$\delta \mathrm{LWP}\big|_{\mathrm{Subs}}(t) = \int_0^t \delta \mathrm{Subs}(t')\mathrm{d}t' = \int_0^t \left[\mathrm{Subs}(t') - \mathrm{Subs}^{\mathrm{r}}(t')\right]\mathrm{d}t', \tag{13}$$

where δ denotes the difference of a variable with respect to the reference simulation that is denoted by a superscripted ‘r’. Similarly, the LWP differences solely due to the Rad, Ent and Base terms in Eq. (5) to (7) were calculated. The results are shown for each of the processes by the plots in the right hand column of Figure 6.

The LWP difference caused solely by subsidence is shown in Figure 6b. Consider the simulation indicated by the blue line, which has a weaker subsidence as compared to the reference simulation.

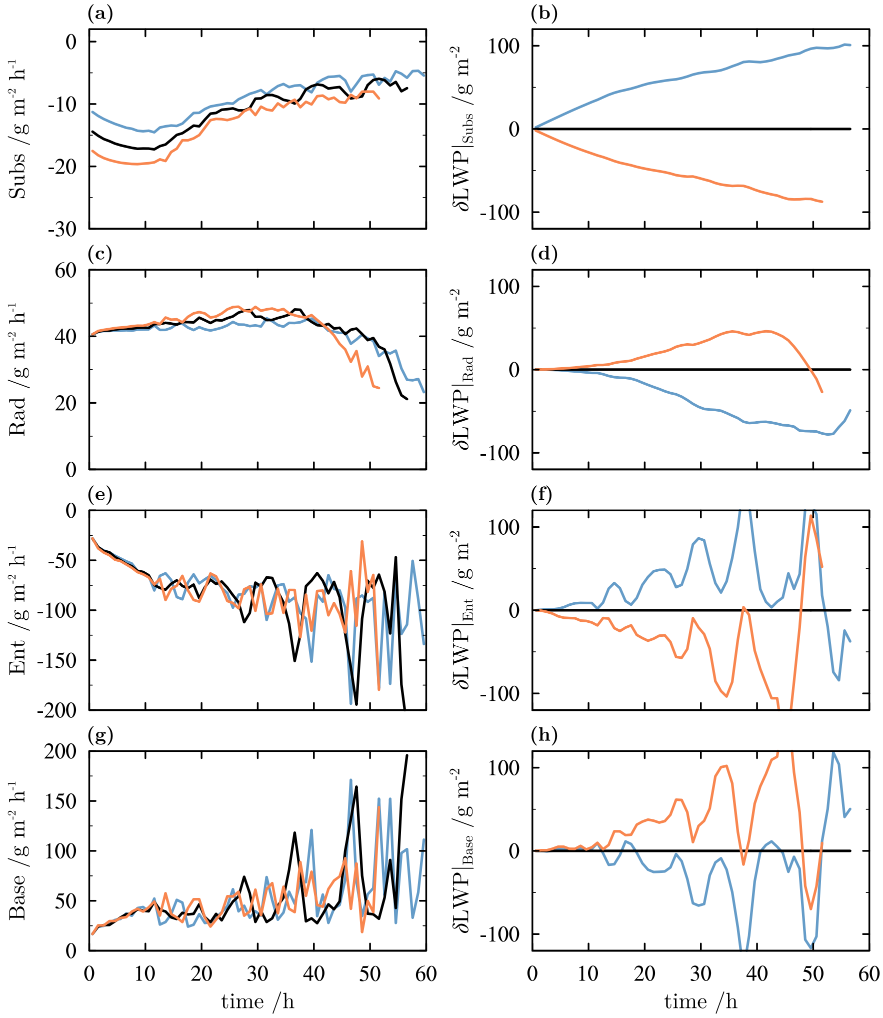

Figure 5. The inversion jumps (a) of total humidity Δq_t and (b) of liquid water potential temperature $\Delta\theta_l$ as a function of time for each of the sensitivity experiments.

The smaller cloud thinning tendency due to subsidence for this case causes a positive contribution to the LWP difference, δLWP, that increases approximately linearly with time up to a value of about 100 g m^{-2}.

The absorption of shortwave radiation by a stratocumulus layer increases with the LWP (Van der Dussen et al., 2013). So, as subsidence is weakened and the LWP increases, the absorption of shortwave radiation also increases. The net cloud thickening effect due to radiative cooling is therefore reduced. Hence, the LWP difference with the reference is negative for the weak subsidence simulation (Figure 6d) and compensates for much of the LWP difference due to subsidence in the second part of the transition.

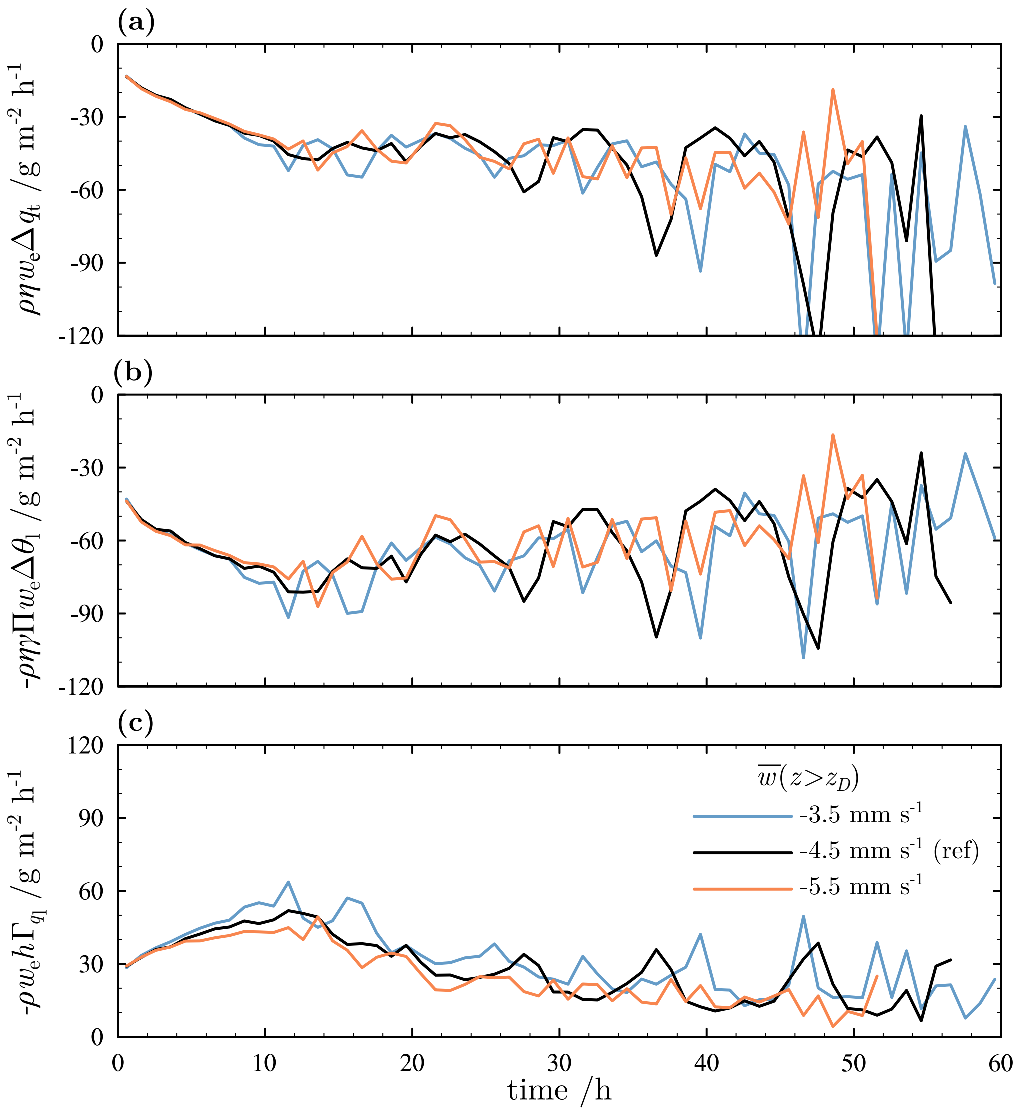

Figure 6. The LWP tendencies due to (a) subsidence, (c) radiation, (e) entrainment and (g) cloud base turbulent fluxes as a function of time for each of the sensitivity simulations. The LWP differences with the reference (black) due to each of these processes have been calculated according to Eq. (13) and are shown in panels (b), (d), (f) and (h), respectively. Colors according to the legend in Figure 45a.

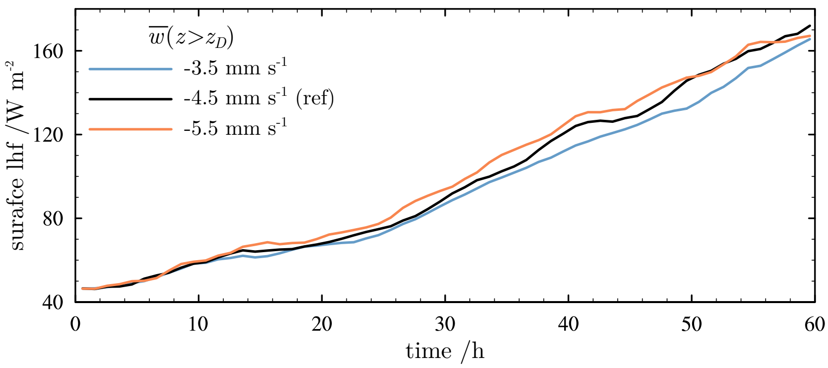

Figure 7. The LWP tendency due to entrainment split up into the three terms of Eq. (5): (a) entrainment drying, (b) entrainment warming and (c) cloud deepening due to entrainment.

The LWP difference as a results of entrainment is less straightforward to understand. In the previous section, it was shown that the entrainment rate is largest for the weakest subsidence simulation. As entrainment causes drying and warming of the stratocumulus layer, this higher entrainment velocity is expected to cause a negative contribution to δLWP. However, Figure 6f shows that it is the other way around: for the lowest subsidence case with the highest entrainment rate, the contribution of entrainment to δLWP is positive. This has two main causes. First, the magnitude of the inversion jump of humidity Δq_t decreases as subsidence is weakened. This decrease exceeds 0.5 g kg^{-1} or 10at the end of the simulations and weakens the drying of the stratocumulus layer due to entrainment. Second, the equation for the

Figures 7a-c individually show the three terms that together constitute the contribution of entrainment to the LWP tendency in of Eq. (5)consists of three terms. The last of these terms accounts for the deepening of the cloud layer due to entrainment . This term increases (Figure 7c), which according to Eq. (1) causes the inversion height and consequently the cloud top height to rise with time. It is important to note that the cloud layer thickness h arises in the last term on the rhs of Eq. (5) due to the fact that the maximum cloud liquid water content is present at the cloud top, with its top value being approximately proportional to the cloud layer depth. If the cloud top of a deep cloud increases due to entrainment, this will yield a larger increase in the LWP than if the cloud top of a shallower cloud rises by the same distance. Therefore, this term increases with the cloud thickness h. For the weak subsidence simulation, h is greater larger than for the reference simulation. Together with the smaller Δq_t, this causes the cloud thinning tendency This effect opposes the cloud thinning due to entrainment to be less strong for the weak subsidence case , despite the higher entrainment ratewarming and drying, and causes the entrainment contribution to δLWP for the lowest subsidence case to be positive (i.e. with respect to the reference case).

Note furthermore that for weaker subsidence cases the boundary layer grows deeper, causing the cloud layer to become drier with respect to shallower boundary layers (Park et al., 2004; Wood and Bretherton, 2004) .

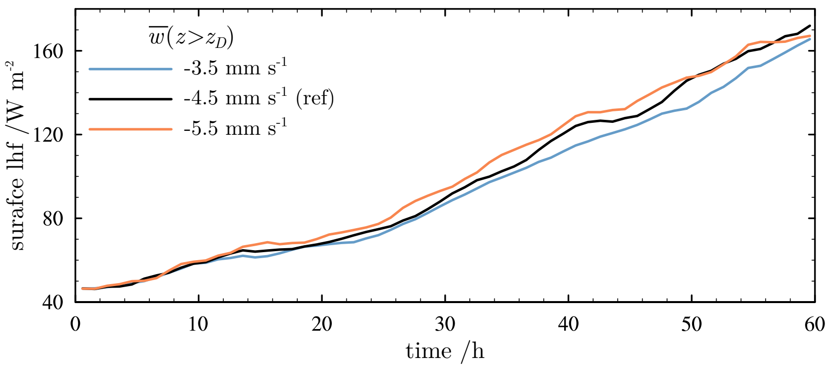

Figure 8. The surface latent heat flux as a function of time for the three sensitivity simulations.

Hence, the magnitude of the inversion jump of humidity Δq_t decreases as subsidence is weakened as is shown in Figure 5a. This decrease exceeds 0.5 g kg^{-1} at the end of the simulations, which causes the entrainment drying term in Figure 7a to be practically identical for all three cases, despite the difference in the entrainment velocities.

Figure 6h shows the contribution of cloud base turbulent fluxes to δLWP. The boundary layer is deepest for the weak subsidence simulation, which causes a slight reduction of the turbulent transport of humidity to the cloud layer. Moreover, Figure 8 shows that the surface latent heat flux is reduced when the large-scale subsidence is reduced. Hence, the contribution of the cloud base fluxes to δLWP is on average negative for the weak subsidence simulation indicated by the blue line.

From the comparison of Figures 6f and 6h it is clear that the cloud base turbulent ~~fluxes~~ flux contribution to δLWP is strongly anticorrelated with that of entrainment. The sum of both contributions is therefore almost zero. This can be understood as follows. Enhanced entrainment will also cause enhancement of the cloud base fluxes as the entrained air sinks downward through the cloud layer. Similarly, strong updrafts through cloud base lead to enhanced entrainment when the updraft reaches and overshoots the inversion layer. Such anticorrelated behavior causes the cancellation of the entrainment and cloud base terms in the sensitivity experiments. In other words, the net effect of these turbulent fluxes to the LWP difference among the cases is very small. The LWP differences in Figure 3b are therefore mainly due to the direct effect of large-scale subsidence on the LWP tendency and the subsequent change of the absorption of shortwave radiation.

6 Conclusions

Several studies have shown that as a result of warming of the climate the Hadley circulation might weaken, leading to a weakening of the large-scale subsidence in the subtropical stratocumulus areas. Several modeling studies (Svensson et al., 2000; Sandu and Stevens, 2011) and recent observational evidence (Myers and Norris, 2013) suggest that such a decrease can lead to thicker and more persistent stratocumulus clouds.

To investigate how the large-scale subsidence affects stratocumulus layers, a method is applied in the current study to analyze the individual contributions of five different physical processes to the LWP tendency of an approximately adiabatic stratocumulus layer. As an illustration of the use of this method, it was first applied to LES results of the ASTEX stratocumulus transition (Van der Dussen et al., 2013). The results show among others that subsidence tends to reduce the LWP by pushing down the cloud top, but the resulting tendency is small at only a few g m^{-2} h^{-1}. Longwave radiative cooling tends to increase the LWP by on average 60 g m^{-2} h^{-1}, while the absorption of shortwave radiation during the day almost completely diminishes the net radiative effect. Entrainment dries and warms the cloud layer resulting in a strong cloud thinning effect~~that increases~~. The analysis shows that this cloud thinning contribution becomes stronger as the transition progresses. The transport of humidity toward the cloud layer by turbulent fluxes ~~counteract~~ counteracts this drying, causing a significant positive effect on the LWP tendency. ~~The results furthermore indicate that the cloud thinning contribution of the large-scale subsidence is small as compared to the other contributions.~~

Despite ~~this~~ the relatively small contribution of large-scale subsidence to the LWP tendency, more idealized sensitivity simulations show that decreasing the subsidence velocity extends the lifetime of the stratocumulus layer. Moreover, it causes the LWP to be significantly higher throughout the entire transition. The thicker stratocumulus layer in the weak subsidence cases tends to absorb more solar radiation, which partly offsets the LWP difference due to subsidence in the second part of the simulations.

It was shown that a weakening of the large-scale subsidence causes enhanced entrainment that amplifies the differences of the inversion height among the simulations. Counterintuitively, this higher entrainment rate does not result in a stronger cloud thinning tendency with respect to the reference simulation~~, which is likely due to~~. This is mainly explained by an increase of the cloud thickness as well as by a reduction of the magnitude of ~~the inversion jumps of q_t and θ_l and the greater cloud thickness~~ Δq_t, the inversion jump for humidity.

The cloud thickening contribution of the cloud base turbulent fluxes decreases somewhat for the weaker subsidence cases as a result of the greater boundary layer depth. This decrease is strongly anticorrelated to the LWP increase as a result of entrainment, such that the total contribution of the turbulent fluxes to the LWP difference among the cases is negligible.

The results of the current study suggest that it is likely that a weakening of the large-scale subsidence in the subtropics due to the weakening of the Hadley circulation in a future climate increases the average LWP as well as the occurrence of subtropical stratocumulus clouds.

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