An Elementary Shallow Cumulus Parameterization for Tropical Boundary Layers

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ABSTRACT
Shallow Cumulus (SCu) convection is a key process in the tropical region, as it has a major impact on the partitioning of surface fluxes and the dynamics of the lower atmosphere. Since SCu clouds contribute largely to the spread in the estimation of climate sensitivities, it is essential to represent SCu convection accurately in numerical weather and climate models. In this paper we propose an improved SCu parameterization for a tropical situation, since the current one overestimates SCu convection largely (2.4 cm s^{-1} on average). With the help of LES and MXLCH modelling we were able to reduce this to an average of 0.2 cm s^{-1}.

Author Keywords
Shallow Cumulus, Mass Flux, Amazonia Tropical Forest, LES, Explicit Parameterization.

INTRODUCTION
Shallow Cumulus (SCu) convection is a key process in the tropical Amazonia region. With an average day time occurrence of 30%, these clouds have a major impact on the surface fluxes and dynamics of the lower atmosphere [8]. This lower part of the atmosphere, also known as the atmospheric boundary layer, is well-mixed by convection during day. As this well-mixed layer (MXL) plays an important role in the regulation of the atmospheric composition [5] and the partitioning of surface fluxes [9] it controls the occurrence of SCu clouds and alters their characteristics (Fig. 1).
The formation of SCu is dependent on the heat and moisture availability within the MXL (sub-cloud layer) and on surface processes that initiate strong upward movements. Since the average relative humidity at MXL top is lower than 100%, only the strongest updrafts can reach the level of condensation (LCL), which causes the non-uniform spatial distribution of these clouds. If the buoyancy of the air parcel is large enough to reach the level of free convection (LFC), the cloud maintains its growth due to the release of latent heat by condensation. The growth is inhibited when the level of neutral buoyancy (LNB) is reached, which is where the buoyancy of the environment exceeds that of the cloud (Fig. 2).
During the growth of the SCu a mass transport from the MXL to the higher atmosphere (free troposphere) occurs (Fig. 2). This transport has a negative effect on the MXL growth, since moisture and chemicals are transported outwards the MXL into the cloud layer. By doing so, the SCu limit the upward motions by decreasing the gradient of temperature and moisture between the cloud layer and MXL, resulting in a negative feedback on the formation of SCu [4].
Besides their feedbacks on the MXL, the SCu contribute largely to the spread in the estimation of climate sensitivities (-0.09 to +0.63 W m^{-2} [1]) by changing both longwave (greenhouse warming) and shortwave (reflective cooling) radiation [1, 6]. The reason can be found in the coarse resolution of the global climate models (GCMs) (~50-200km) [6] compared to the length scales of the SCu (~0.5-1km). To allow for mass transport and radiation by SCu convection, it is needed to parameterize its effects. The parameterizations are developed based on the results of high-resolution models that can resolve the smaller scales (~meters). The grid size of these models is chosen to be small enough to explicitly resolve the scales that dominate cloud processes. The Large-Eddy Simulation (LES) is such a model that can resolve ~90% of the turbulence in the convective MXL (Fig. 1). Although LESs have enhanced the understanding of SCu

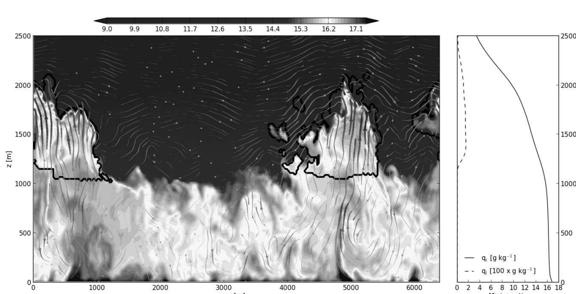

Figure 1. Visualization of a horizontal projection of LES (left) and its *x* averaged vertical profile (right). The dark colours in the lower 500m represent high moisture contents (>17 g kg^{-1}), while the dark colours above the 1000m represent low moisture contents (<14 g kg^{-1}). SCu clouds are visible at x ϵ [0-1000m] and x ϵ [4200-5200m]. Based on data from [8].

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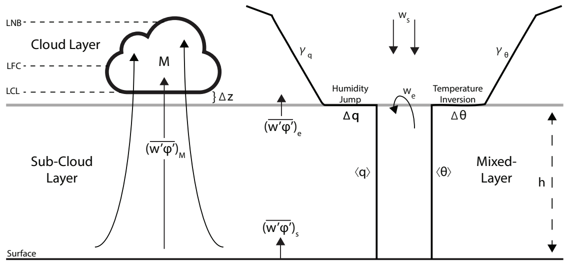

Figure 2. Schematic representation of the cloud-topped boundary layer, inspired on [8]. The subscripts *e*, *s* and *M* denote entrainment, surface and mass flux, respectively. The variables are defined in the text.

formation by revealing important feedback interactions, they cannot be used for regional areas due to computational limitations. To overcome this, conceptual mixed-layer chemistry (MXLCH) models are used with the aforementioned parameterizations to investigate the sensitivity of the system or feedbacks [11] (Fig. 1).

Although most studies focus on the oceanic (marine) MXL (e.g. [4]), which is characterized by steady-state conditions, this study focuses on the continental Amazonian MXL. The tropical continental region experiences relatively strong non-stationary surface forcings on a diurnal scale, resulting in an unsteady state. In our simulation, the surface is covered homogeneously with vegetation and geography is not taken into account. The novelty of this study is to investigate the impact of SCu transport on tropical continental MXL characteristics. First we determine how the SCu interact with the MXL dynamics, followed by a systematic analysis of the current parameterization for active SCu growth. Data from the Tropical Forest and Fire Emission Experiment (TROFFEE) [3, 10] is used to serve as inspiration for the LES.

Methodology

Mixed-Layer Chemistry model

Under typical diurnal conditions the MXL is well mixed by convection [7] (Fig. 1). This enables us to assume the MXL as a bulk layer with constant thermodynamic variables over height (Fig. 2 and 3). At the MXL top a thermal inversion is located that prevents air to escape the MXL easily. Only when an updraft is sufficiently buoyant to penetrate this inversion layer, a cloud can form. As long as the cloud can grow, mass is transported from the MXL into the cloud layer. To capture this process, the mass transfer has to be introduced in the mixed-layer equations as will be done in this section.

Dynamical effects

To take the mass transfer by SCu into account, the same approach is followed as is described in [4]. The mass flux effect is introduced in the prognostic equation for mixed-layer height:

$$\frac{\delta h}{\delta t} = w_e + w_s - M\,, \tag{1}$$

where w_e, w_s and M represent respectively the entrainment, large-scale subsidence and kinematic mass flux (Fig. 2). Following [4], the mass flux can be modeled as:

$$M = a_{cc} \cdot w_{cc}\,, \tag{2}$$

where a_{cc} and w_{cc} denote the maximum cloud core fraction (i.e. maximum vented area) and vertical cloud core velocity, respectively. M can therefore be seen as the flow rate of the vented air [in m s^{-1}]. As is shown in [5], the w_{cc} can be described with the use of the Deardorff convective velocity scale (w_*):

$$w_{cc} \approx \lambda w_* = \lambda \left(\frac{g}{\theta_{v,s}} \, (\overline{w'\theta_v'})_s \, h \right)^{\frac{1}{3}}\,, \tag{3}$$

where $\lambda = 0.84$ and g, $\theta_{v,s}$, $(\overline{w'\theta_v'})_s$ and h denote the gravitational acceleration, virtual potential temperature at surface, buoyancy flux at surface and MXL height, respectively.
[4] states that the a_{cc} can be approximated by the cloud area fraction (a_c) (i.e. based solely on liquid water and not discriminating between active or passive (not growing) clouds) [7]. The expression is based on LES research by [2]. The a_c at MXL top is described as:

$$a_c = 0.5 + \beta \cdot \arctan(\gamma \cdot Q_1)\,, \tag{4}$$

where $\beta = 0.36$ and $\gamma = 1.55$. Q_1 is the normalized saturation deficit:

$$Q_1 = \frac{q_t|_h - q_{sat}}{\sigma_q|_h}\,, \tag{5}$$

where $q_t|_h$ and q_{sat} are the total specific humidity at MXL top and the saturation specific humidity, respectively. The standard deviation of moisture at MXL top ($\sigma_q|_h$) is parameterized as:

$$\sigma_q^2|_h = -(\overline{w'q_t'})_s \, \frac{\Delta q_t}{w^*} \, \frac{h}{\Delta z}\,, \tag{6}$$

where $(\overline{w'q_t'})_s$, Δq_t and Δz represent the surface flux of moisture, humidity jump at MXL top and depth between cloud base and MXL top, respectively [4] (Fig. 2).

Budget effects

The SCu alter the bulk-averaged mixed-layer values, $\langle \phi \rangle$, by venting and can therefore be introduced as a negative term in the prognostic equation:

$$\frac{\delta \langle \phi \rangle}{\delta t} = \frac{(\overline{w'\phi'})_s - (\overline{w'\phi'})_e - (\overline{w'\phi'})_M}{h}\,. \tag{7}$$

Since only the most buoyant air parcels transport mass upward, the core fraction (ϕ_{cc}) should be used. The mass flux can then be described as:

$$(\overline{w'\phi'})_M = M\,(\phi_{cc} - \overline{\phi}) \tag{8}$$

where $\overline{\phi}$ denotes the bulk-averaged mixed-layer value.

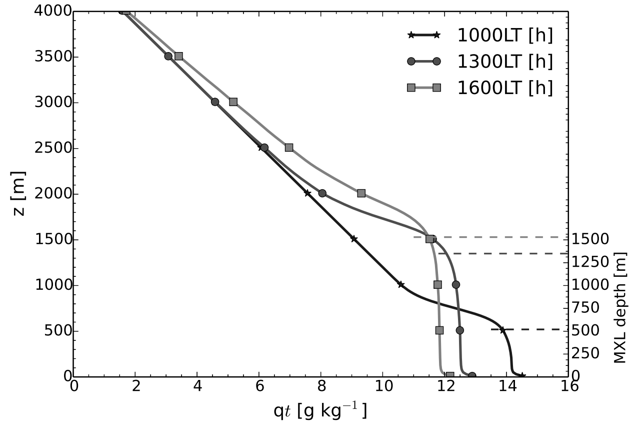

Figure 3. Evolution of the vertical profile of the total specific moisture at 1000LT, 1300LT and 1600LT using LES. SCu clouds are formed around 1000LT. The MXL height is denoted by the dotted lines.

Results

As the MXLCH is validated for cloudy mid-latitude (e.g. [8]) and clear tropical boundary layers (e.g. [10]), a novelty of the current project is to validate the tropical cloudy boundary layer. We first compare the MXLCH with the tropical LES, followed by an analysis on the deviations. As a final step we introduce our improved parameterization and explore its effects.

In Figure 4, the temporal evolution of the specific humidity and mass flux is presented. In the early morning the boundary layer is stable and shallow (~200 m) and starts to deepen from 0800LT onward. As a result, the specific humidity starts to decrease since it diffuses over a deeper layer and dry air, originating from the free troposphere, entrains

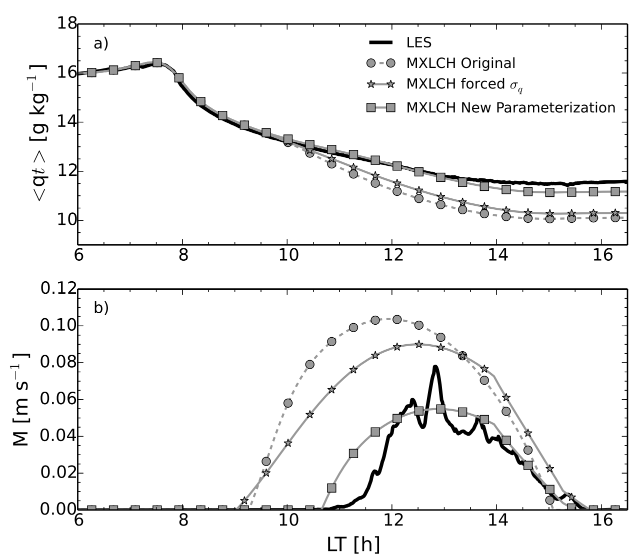

Figure 4. Temporal evolution of the a) total specific humidity, q_t, and b) mass flux, M. Black denotes LES data, while grey denotes MXLCH output. Improvements on MXLCH are explained in the text.

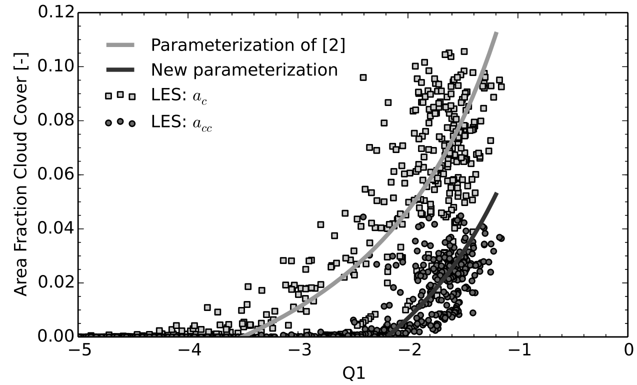

Figure 5. Area fraction cloud (core) cover as a function of the normalized saturation deficit (Q_1). Squares denote a_c, while circles indicate a_{cc}.

into the MXL (Eq. 7, Fig. 3). The MXLCH is capable of reproducing the total specific humidity within the MXL before 1000LT, but starts to deviate when SCu clouds arise. This is also visible in the mass flux (Fig. 4b) which shows a premature SCu development, leading to a mass flux overestimation of 2.4 cm s^{-1} on average. The latter appeared to be due to a misrepresentation in the standard deviation of moisture (σ_q) of ~0.4 g kg^{-1} (not shown). We associate this deviation to a misrepresentation in the saturation specific humidity and an underestimation of the humidity jump (Δq) (not shown), therefore influencing Eq. 6. Inspired by the LES σ_q, we forced the MXLCH σ_q to ~1.05 g kg^{-1} before 1400LT, with an exponential decrease from 1400LT onward. By doing so, we could quantify whether the early SCu development was due to this σ_q deviation. The onset of SCu development did not change, but the peak in SCu occurrence was lower and over the correct time span (Fig. 4b).

As a next step, we determined if the assumption of [4] holds for the tropical continental case, since [4] validated the MXLCH mainly over the (tropical) ocean. We found that the a_{cc} is affected by the continental situation, since in our analysis a_{cc} is ~50% of a_c (not shown), causing the misrepresentation in the MXLCH when SCu arise. To analyze the parameterization of [2] in more detail, the cloud (core) area fraction is plotted as a function of the normalized saturation deficit (Q_1) (Fig. 5). There is shown that the parameterization of [2] is valid for a_c, but this parameterization cannot be used to approximate a_{cc} for the tropical continental case. To account for this misrepresentation, the parameterization of [2] is reformulated to describe a_{cc}. Where 0.5, β and γ are altered to fit the LES data best (Fig. 5). We suggest to use the following parameterizations for the a_c and a_{cc}:

$$a_c = 0.5 + \beta \cdot \arctan(\gamma \cdot Q_1), \tag{9}$$

$$a_{cc} = 0.25 + \phi \cdot \arctan(\eta \cdot Q_1), \tag{10}$$

where $\beta = 0.36$, $\gamma = 1.55$, $\phi = 0.21$, $\eta = 1.14$ and Q_1 is equal to Eq. 5.

The effect of this reformulation is shown in Figure 4. The mass flux is in the right order (average overestimation of 0.2 cm s^{-1}), although the first hour is overrepresented. This can be explained by the forcing of MXLCH σ_q, which overrepresents the LES σ_q with ~0.05 g kg^{-1} before 1200LT (not shown). Due to the better representation in the mass flux, the total specific humidity in the MXL is better represented as well. In spite of the good agreement with the mass flux, the total specific humidity is slightly misrepresented from 1300LT onward, which appears to be due to the cloud layer moistening effect that is visible in Fig. 3. During the day, the SCu transfers moisture from the MXL toward the cloud layer, resulting in moister conditions in the cloud layer. Since the MXLCH does not take the cloud layer into account, this moisture is not entrained back into the MXL and results in the underestimation of ~4% around 1600LT (Fig. 4).

Conclusions

The development of shallow cumulus (SCu) clouds over the Amazonia region is analyzed by combining three-dimensional LES results with conceptual MXLCH modeling. We explored whether MXLCH could represent the transition from a clear to cloudy boundary layer by analyzing the MXL state variables. The SCu alter these by transporting mass from the MXL into the cloud layer, which is known as the mass flux. This venting effect initiates several feedback mechanisms that in turn impact the SCu characteristics. We revisited previous parameterization based on the cloud area fraction (a_c) and found that a new formulation is needed for the cloud core area fraction (a_{cc}). By comparing with LES results, this new formulation improves the representation of SCu by delaying cloud formation and by decreasing SCu venting, thereby decreasing the overestimation in kinematic mass flux from 2.4 cm s^{-1} to 0.2 cm s^{-1} on avarage.

We plan to further extend this research to determine how both parameterizations hold for SCu development over mid-latitude and oceanic boundary layers, and by taking into account stratocumulus clouds.

Role of the Student

The work presented in this paper is carried out during the months May and June 2013. The writer had weekly discussions with the supervisors and email contact during the week. The LES data is provided by dr. ir. H.G. Ouwersloot, but the literature research, strategy and analysis of both LES and MXLCH was proposed by the writer. After 7 weeks, a thesis was written, of which this paper is a short version. This thesis was successfully defended in a seminar.

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