Is Shallow Convection Sensitive to Environmental Heterogeneities?

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Abstract  The key assumption underlying convection parameterizations is that rising plumes develop in a horizontally homogeneous environment. With this in mind, we investigate the impact of environmental cloud layer heterogeneities on shallow convection using large-eddy simulation that applies a master-slave methodology. In the master-slave approach, two independent sets of thermodynamic variables (master and slave) are driven by one dynamics (coupled with the master) to remove the impact of internal variability of the dynamical system considered. The two thermodynamic sets include either a realistic heterogeneous environment or an environment that is homogenized outside clouds. The key is that homogenization also excludes subsiding shells surrounding cumulus clouds. The results show a small impact of the homogenization on cloud field properties. The physical explanation highlights the role of the subsiding shell shielding a shallow cumulus cloud from its environment.

Plain Language Summary  Coarse-resolution weather and climate models need to use convection parameterizations for representing vertical transport by ascending plumes or bubbles. Those parameterizations typically assume that convective elements develop in a homogeneous environment. This key assumption was recently questioned in a study showing that plume properties critically depend on the local environment in which they rise. The current study revisits this assumption by explicitly simulating the development of shallow convective clouds using a method that facilitates comparing the same portions of cloudy air undergoing two different scenarios: mixing either with a heterogeneous or homogeneous environment. The results highlight an insignificant impact of environmental temperature and moisture perturbations on the cloud development and strongly support the homogeneous environment assumption in convection parameterizations.

1. Introduction

The necessity of using convection parameterizations by coarse-resolution atmospheric models has already been recognized five decades ago. The early works of Ooyama (1971) and Arakawa and Schubert (1974) laid the theoretical foundations for the currently most popular mass flux approach that has been adopted in many large-scale atmospheric models (e.g., Bechtold et al., 2001; Donner, 1993; Emanuel, 1991; Moorthi & Suarez, 1992; Suselj et al., 2014; Tiedtke, 1989; Zhang & McFarlane, 1995). The key assumption is that convective transport can be solely represented by one or more convective plumes developing in a homogeneous environment and that the small-scale interactions between the plumes and their environment determine the large-scale properties of convection.

There is an ongoing debate on what controls the lifecycle of convective plumes in shallow convection. Romps and Kuang (2010) distinguish the impact of initial conditions (“nature”) from the entrainment history during the plume ascent (“nurture”). They find the stochastic entrainment to be primarily responsible for the variability among cloudy plumes. Suselj et al. (2019) show that this also holds for a multiplume stochastic convection parameterization. Brast et al. (2016) added a new element to the debate by investigating how the environment of entraining plumes affect their development. They show that the local environment variability is significantly more important in determining the fate of rising parcels than the entrainment rate formulation.

The present study uses a different approach to argue that a shallow cumulus field develops similarly within heterogeneous and homogeneous cloud environments. For this, a master-slave method, also referred to as
the piggybacking (Grabowski, 2014, 2015, 2018; Grabowski & Morrison, 2016), is applied to a large-eddy simulation (LES) of shallow convection. The next section presents the model and modeling setup, explains the master-slave approach, and discusses its specific application. Results are presented in section 3. A brief discussion and summary in section 4 conclude the paper.

2. Materials and Methods

2.1. The Model and Modeling Setup

Numerical simulations are performed using the anelastic version of the EULAG model (see Prusa et al., 2008, and references therein). EULAG is an established computational tool for simulating a wide range of fluid flows, including multiscale atmospheric circulations (e.g., Grabowski & Smolarkiewicz, 2002; Kurowski et al., 2014, 2015, 2016; Margolin et al., 1999; Pedersen et al., 2018; Rosa et al., 2011; Smolarkiewicz et al., 2014). In the application discussed here, the model solves prognostic equations for the momentum, potential temperature, and mixing ratios for the water vapor, cloud water, and rain water.

Following Brast et al. (2016), we use the RICO case (van Zanten et al., 2011), a weakly precipitating marine shallow convection modeling case driven by prescribed temperature and water vapor tendencies and by interactive surface latent and sensible heat fluxes. To better resolve cloud-scale dynamics, the grid spacing is refined from the original 100/40 m (horizontal/vertical) to 20/20 m. The domain is 9 × 9 × 4 km³, with a sponge layer above 3,600 m. The time integration is 6 hr, shorter than in the van Zanten et al. (2011) setup but sufficiently long for our specific purpose. Homogenization of the cloud environment (to be discussed in the next section) is enabled after 3 hr when the turbulent flow is fully developed.

2.2. The Master-Slave Method

The master-slave method is based on simultaneous time integrations of two thermodynamic states \( \{ \psi_1, \psi_2 \} \), the master and the slave, driven by the same fluid flow. Each state includes an independent set of thermodynamic variables, that is, the potential temperature \( \theta \) and all variables describing water fields \( q \) (e.g., water vapor, cloud water, and rain water mixing ratios); \( \psi_i = \{ \theta, q \} \). For the two states, only the master set is coupled to (i.e., drives) the dynamics; the slave set uses the predicted flow to transport its variables. Two complementary master-slave simulations are performed, with each of the two states being the master in one simulation and the slave in the other, that is, \( \psi_1 \sim \psi_2 \) and \( \psi_2 \sim \psi_1 \). For each simulation, differences between the master and slave results highlight the impact of a process or mechanism under investigation (Grabowski, 2014, 2015, 2018; Grabowski & Morrison, 2016). A full set of prognostic equations describing the two states can be schematically written as follows:

\[
\begin{align*}
\frac{\partial (\rho \theta_m)}{\partial t} + \nabla \cdot (\rho u_i \theta_m) &= \rho S_{\theta_m}, \\
\frac{\partial (\rho q_m)}{\partial t} + \nabla \cdot (\rho u_i q_m) &= \rho S_q, \\
\frac{\partial (\rho \theta_s)}{\partial t} + \nabla \cdot (\rho u_i \theta_s) &= \rho S_{\theta_s}, \\
\frac{\partial (\rho q_s)}{\partial t} + \nabla \cdot (\rho u_i q_s) &= \rho S_q,
\end{align*}
\]

where subscripts \( m \) and \( s \) denote the master and slave sets, respectively, and \( S_\psi \) combines all source terms for \( \psi \).

The reason for applying two thermodynamic states is to evaluate the effects caused by differences in the source terms \( S \) along the same material lines. Here, the thermodynamic states represent either a realistic reference LES solution obtained with a standard LES configuration or a solution obtained with the cloud environment void of small-scale homogeneities. If the differences in the cloud statistics between the master and slave sets are small and their amplitude is independent of which set drives the simulation, then the environmental cloud layer heterogeneities have a small impact on the cloud field development. The environmental cloud layer heterogeneities are eliminated by applying an additional source term to the temperature and water vapor equations that represents smoothing of the cloud environment. The term is given by the following:

\[
S_{\text{hom}} = -\frac{\psi_e - \bar{\psi}_e}{\tau_h},
\]

where the overbar denotes the horizontal mean, subscript \( e \) depicts the environment, and \( \tau_h \) is the time scale of the homogenization. The horizontal mean of the temperature and water vapor mixing ratio at each level is calculated over the area outside clouds and their immediate environment. The latter includes subsiding

\[
\begin{align*}
\frac{\partial (\rho \theta_m)}{\partial t} + \nabla \cdot (\rho u_i \theta_m) &= \rho S_{\theta_m}, \\
\frac{\partial (\rho q_m)}{\partial t} + \nabla \cdot (\rho u_i q_m) &= \rho S_q, \\
\frac{\partial (\rho \theta_s)}{\partial t} + \nabla \cdot (\rho u_i \theta_s) &= \rho S_{\theta_s}, \\
\frac{\partial (\rho q_s)}{\partial t} + \nabla \cdot (\rho u_i q_s) &= \rho S_q,
\end{align*}
\]
Figure 1. (upper row) Horizontal cross section through the field of total water mixing ratio 400 m above the cloud base after 4 hr, for HE (left column) and HO (right column). Moist plumes with the condensed water are marked as white regions. The four moist plumes along the cross section are marked with A, B, C, and D. (lower row) Moisture and temperature fields along the dashed lines from the upper row.

shells typically surrounding shallow convective clouds (Heus & Jonker, 2008; Jonker et al., 2008). The source term providing homogenization is only applied over the area where the environmental mean is calculated.

The master-slave method is especially useful when the investigated effects are expected to be small (and hence difficult to disentangle using statistical methods) and/or when the dynamical system is characterized by a large internal variability (cf. Grabowski, 2014). Arguably, moist convection is a dynamical system with large internal variability and investigating the impact of cloud layer heterogeneities is difficult without the master-slave method. To increase statistical significance and to compare master-slave differences to the internal variability, we apply a small ensemble of master-slave simulations as in Grabowski (2014, 2015) and Grabowski & Morrison (2016). Two ensembles of five members are executed for the dynamics coupled with either the heterogeneous (hereafter HE) or the homogeneous (hereafter HO) environments. We refer to the two master-slave configurations by using those two abbreviations. Hence, HE/HO is driven by HE, with HO slaved to the dynamics, while HO/HE is driven by HO, with the passive role of HE.

2.3. Homogenization Rationale

Although the region immediately outside clouds may be considered as the environment (cf. Arakawa & Schubert, 1974), such a distinction is more ambiguous for shallow convection. Heus and Jonker (2008) and Jonker et al. (2008) highlight the role of unsaturated shell layer around shallow cumuli. They show that the updraft cloud mass flux is mostly balanced by a subsiding shell just outside the cloud. Heus and Jonker (2008) argue that the main driving process for the shell layer formation is the evaporative cooling at the cloud edge. In contrast, Grabowski & Clark (1991, 1993) attribute the subsiding flow to the dynamical response of the local environment. Park et al. (2017) have recently demonstrated that the dynamical compensation primarily controls the shell layer formation, with much less significant contribution from evaporative cooling. From the dynamical standpoint, shell layers form around the objects moving in a fluid due to the positive/negative pressure perturbations generated near their front/back, giving a rise to the compensating pressure gradient force (e.g., Kurowski et al., 2013; Morrison, 2016a, 2016b).
Since the cloud shell is characterized by large temperature and moisture gradients (Heus & Jonker, 2008), one can argue that it should be considered an integral part of a dynamically evolving cloud. Thus, the procedure to homogenize the environment should exclude not only clouds but also the subsiding cloud shells. Such an argument is supported by initial simulations (not shown) in which we homogenized all domain outside clouds, that is, including the shells. That caused a rapid dissipation of clouds and suggests that the shells play an important role in the cloud-environment interactions. Based on the results from Heus and Jonker (2008) and trial-and-error simulations, we select the thickness of 180 m for the region near clouds excluded from the calculation of the mean in (2) and application of the relaxation (2).

The homogenization should be relatively fast to remove small-scale heterogeneities efficiently. The average lifetime of a shallow convective cloud is around 1,000 s (e.g., Zhao & Austin, 2005), after which they disintegrate and modify the local environment for subsequent plumes (Dawe & Austin, 2012). Hence, the homogenization time scale should be shorter than that. On the other hand, the boundary layer plumes need to have enough time to penetrate into the cloud layer without being homogenized prematurely. For typical cloud base updraft velocities of 0.5 to 1 m/s, and assuming roughly a 100-m-thick transitional layer at the top of a rising plume, the time needed to start a new cloud and thus to create a region excluded from homogenization is a minute or two. Given the above constraints, we apply the homogenization time scale of 100 s.

Finally, to reduce the homogenization of unsaturated plumes rising into the cloud layer, the homogenization (2) is applied starting 60 m above the mean profile cloud base height. It extends up to the domain top.

3. Results
3.1. General Features
Figure 1 shows a cross section through the thermodynamic fields for a randomly selected HE/HO ensemble member at hour 4. The figure illustrates the essence of the master-slave methodology where both HE and HO share the same updrafts embedded in the two distinct environments. Note that, by design, the subgrid-scale turbulent mixing coefficients are also shared between the master and slave sets, and thus, the dynamics of the entrainment is identical. As expected, the HE moisture field shows many small-scale features that are smoothed out in HO. The perturbations are only similar in the close vicinity of the plumes and around the just-dissipated clouds. Cloud shells appear as thin regions of slightly drier cloud-free air advected from higher levels.
Homogenization reduces environmental potential temperature and moisture variances soon after its activation. The vertically averaged cloud layer standard deviations in a homogenized environment typically remain within $1.1-1.3 \times 10^{-1}$ g/kg and $6-9 \times 10^{-2}$ K, with slightly larger values when HO is the master. For a heterogeneous environment, the mean standard deviations of moisture are roughly twice larger, while those of potential temperature reach $1.2-1.3 \times 10^{-1}$ K when HE is the master and $1.8-1.9 \times 10^{-1}$ K when HE is the slave. The above differences indicate that the decoupling of temperature fluctuations from the dynamics removes an important mechanism providing temperature homogenization through gravity waves (Bretherton & Smolarkiewicz, 1989). In fact, the gravity wave activity is almost entirely eliminated and the turbulent kinetic energy is strongly reduced in the cloud layer for the HO/HE simulation (not shown).

Homogenization within the cloud layer does not affect the sub–cloud layer, as the variances of thermodynamic fields and the turbulent kinetic energy both agree well between HE and HO, regardless of the master dynamics (not shown). Moreover, the interactive surface fluxes that depend on the temperature and moisture differences between the lowest atmospheric level and the ocean are also virtually the same. The differences between HE/HO and HO/HE ensemble means are smaller than the standard deviations over the ensemble members. Because the sub–cloud turbulence is largely separated from the conditionally unstable cloud layer, the initialization and formation of moist plumes near the surface are also similar for HE and HO.
Figure 4. Evolutions of the ensemble mean (a) cloud cover (CC), liquid water path (LWP), and rain water path (RWP); (b) the differences between the master and the slave sets for the same variables as in (a); and (c) the cloud base height and cloud layer thickness.

3.2. Cloud Characteristics

Figure 2 compares the conditionally averaged profiles of the cloud water, cloud fraction, and vertical velocity from the last simulation hour for the HE/HO and HO/HE ensembles. The conditional sampling includes all points with the cloud water mixing ratio larger than $10^{-2}$ g/kg. There are four cloud water and cloud fraction profiles for the two configurations of the master-slave sets and two vertical velocity profiles for the two master dynamics (HE and HO). The mean temperature and moisture profiles are not shown as they are practically identical for all sets. Overall, cloud water differences are insignificant throughout the cloud layer except near the very top, where the cloud fractions are small and are likely affected by different flow realizations between HE and HO as suggested by the vertical velocity profiles. For the cloud fraction, the largest differences occur near the cloud base, with a systematic bias between HE and HO regardless of the dynamics.

A detailed comparison between HE and HO is presented in Figure 3 for two randomly selected HE/HO and HO/HE ensemble members. The figure shows the scatter plots of the in-cloud buoyancy, expressed as the potential density temperature (i.e., $\theta_d = \theta(1 + 0.608q_v - q_c - q_r)$, with $q_v$, $q_c$, and $q_r$ being the mixing ratios of water vapor, cloud water, and rain water, respectively) perturbations from the horizontal mean, calculated using HE and HO thermodynamic variables in the lower (height of 800 m) and upper (at 1,400 m) parts of the cloud layer at the end of the simulation. Note that such a comparison is only possible through the master-slave method. We focus on the buoyancy as it directly affects cloud dynamics. Before the homogenization is activated, all the points are perfectly aligned along the 1:1 line because the master and slave thermodynamic properties are identical (not shown). With the homogenization, most data points are still clustered around the 1:1 line after another 3 hr of the simulations. However, there is a slight shift when HE is driving, implying that HO buoyancy is slightly smaller than HE. This is no doubt the impact of the homogenization. When HO is driving (lower panels), all data points are symmetrically scattered around
the 1:1 line. The scatter most likely comes from small differences between the two thermodynamic sets that gradually develop during the simulations (e.g., due to slightly different surface fluxes or precipitation) and it tends to increase as the simulation progresses (not shown). Results similar to those shown in the figure are obtained using separately the temperature or water variables.

### 3.3. Evolution of Bulk Cloud Field Properties

Figure 4a shows the temporal evolution of the ensemble mean cloud cover (CC), liquid water path (LWP), and rain water path (RWP). CC is defined as the fraction of model columns with at least one grid point having cloud water mixing ratio larger than 10^{-2} g/kg. Continuous lines depict ensemble means for the master sets (blue and red for the dynamics coupled to HE and HO, respectively), while dashed lines are for complementary slave sets. Note that solid and dashed lines often overlay. An internal variability among ensemble members is shown by a shading of one standard deviation around the master ensemble means. The quasi-steady state is reached after around 2.5 hr; this justifies enabling the homogenization after 3 hr. The temporal fluctuations of the ensemble mean CC, LWP, and RWP are similar for HE/HO and HO/HE, with both configurations featuring a considerable spread among various realizations. The largest spread is for RWP. The differences between the master (continuous lines) and the slave (dashed lines) sets are small for LWP and RWP, and larger for CC.

The differences between the master and slave sets for the three metrics are shown in Figure 4b. Each ensemble member is plotted separately to show that the master-slave differences are similar among ensemble members despite a significant variability between the realizations. This illustrates the strength of the master-slave method. Switching the master between HE and HO changes the sign of the differences while approximately preserving the amplitude. This can be interpreted as a signature of similar dynamics for the two distinct master sets (Grabowski & Morrison, 2016). The monotonic increase in ∆LWP and ∆RWP documents the accumulation of slight differences between HE and HO in time. Except for the CC, the differences after 6 hr are still of a significantly smaller amplitude than the variability among the ensemble members.

Figure 4c documents gradual thickening of the cloud layer together with the lowering of the cloud base that is consistently simulated in HE/HO and HO/HE. The cloud base/top height is the lowest/highest level where the condensed water for the mean profile exceeds 10^{-3} g/kg; the cloud thickness is the difference between the cloud top and base heights. The key point is that temporal variations for the ensemble means and their standard deviations are larger than the differences between the master (continuous lines) and the slave (dashed lines) sets. Although the ensemble spread and its temporal evolution changes when the LES domain size is changed, the master-slave difference changes little. This is confirmed by a set of simulations featuring a smaller LES domain (not shown).

Note that a similar comparison of the ensemble means between the heterogeneous and homogeneous environments simulated independently (i.e., for the master sets from HE/HO and HO/HE) would yield a noisy signal with both positive and negative differences randomly distributed over time. A partial remedy would be to significantly increase the number of ensemble members to reduce the noise. However, the dominant impact of the internal variability would be difficult to eliminate. In other words, if the uncertainty due to a particular process is smaller than the internal variability of the system, disentangling the impact of that process may not be feasible. This highlights the main advantage of the master-slave approach that enables the quantification of small differences between the two states at a reasonable computational cost.

### 4. Discussion and Conclusions

This study contributes to the ongoing debate on what controls the variability of convective plumes in shallow convection, an aspect important for improving convection parameterizations in climate models. Romps and Kuang (2010) find that the stochastic entrainment along the plume ascent is more important than plume initial conditions. Brast et al. (2016) suggest that the variability of local environment within a shallow convection layer affects plume development more than different formulations of the entrainment rate. The present study uses LES with a master-slave approach to show that a heterogeneous environment has a small impact on shallow convection.

The master-slave approach applies two thermodynamic variable sets in a single LES simulation, one set driving the dynamics (the master) and the second set applying the flow predicted by the master and not affecting it (the slave). Each set serves as a master in one simulation and then as a slave in the second one. If
the results are independent of the driving set and the master-slave differences are small, then the process or mechanism under investigation (i.e., the homogeneity of the environment in our case) plays a small role in the cloud field evolution. Grabowski, (2014, 2015, 2018) and Grabowski and Morrison (2016) are examples of recent applications of the master-slave approach referred there to as piggybacking.

Results obtained applying the master-slave method show a remarkable similarity of the solutions obtained using either heterogeneous or homogeneous environments in terms of plume properties (e.g., buoyancy, condensed water, cloud fraction, and vertical velocity) and bulk cloud layer properties (e.g., CC, LWP, RWP, cloud base height, and cloud layer thickness). Moreover, the comparison of colocated cloudy grid points indicates only minor differences in the cloud buoyancy. The internal variability of the convective system is shown to exceed the differences due to homogenization.

The homogenization technique applied in simulations discussed here excludes subsiding shells separating shallow cumulus clouds from their environment (Heus & Jonker, 2008; Jonker et al., 2008). With a more aggressive homogenization that includes subsiding shells, applied in a complementary experiment, a rapid dissipation of clouds was simulated. One can thus argue that subsiding shells play an important role in the cloud-environment interactions by shielding clouds from their environment. The shielding makes clouds less susceptible to the impacts of their immediate environment. This is an important difference between cloud-environment interactions as simulated in LES and interactions considered in the entraining plume scheme in Brast et al. (2016). Moreover, Brast et al. (2016) uses all columns of the LES solution as an environment for their 1-D plume model. Consequently, some of the 1-D plumes may have developed within the LES plumes, rather than in the actual environment, contributing to the reported large spread of the 1-D plume properties.

It needs to be stressed that one should not argue that subsiding shells fully protect small cumuli from their environment because such clouds are strongly diluted by entrainment as shown by numerous observational and modeling studies. Arguably, the key aspect is that cumulus entrainment is driven by large (e.g., hundreds of meters) structures that give cumuli the unique cauliflower shape (e.g., see Figures 3 and 4 in Grabowski & Clark, 1993) and not by the small-scale “nibbling” eddy motions across the cloud-environment interface. In other words, differences in the mean environment do matter for the shallow convection, but the fluctuations within the cloud layer (e.g., due to the remnants of previous clouds) are by far less important. Such an argument is consistent with Dawe and Austin (2012) who show that clouds ascending in premoistened and dry environments have similar chances to reach the capping inversion.

In summary, the master-slave methodology demonstrates a remarkable lack of sensitivity of shallow convection to cloud layer heterogeneities and strongly supports the environmental homogeneity assumption of shallow convection parameterizations. Whether this is also true for deep convection is uncertain and requires a subsequent investigation.

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