Exploring the transition from shallow to deep convection using a dual mass flux boundary layer scheme

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Introduction

Recently Kuang and Bretherton (2006) used cloud resolving model (CRM) simulations to show that certain concepts typical of moist boundary layer convection are still applicable to the transition from shallow to deep convection; these include i) the entraining plume model, ii) its application as part of an ensemble framework, iii) a relation between cloud size and entrainment (e.g. Grabowski et al., 2006), and iv) moist convective inhibition, These results motivate further studies of the transition from the perspective of boundary layer modelling. To this purpose single column model (SCM) simulations are performed with the new ECMWF boundary layer scheme, in which these concepts are represented. Specific questions that will be addressed are:

- Is the boundary layer scheme capable of reproducing a realistic transition? If so, why?
- What controls the speed of the transition in the model?
- What is the role of subcloud layer i) variance build-up and ii) cold pools in the shallow-deep transition, and which process dominates?

A short model description

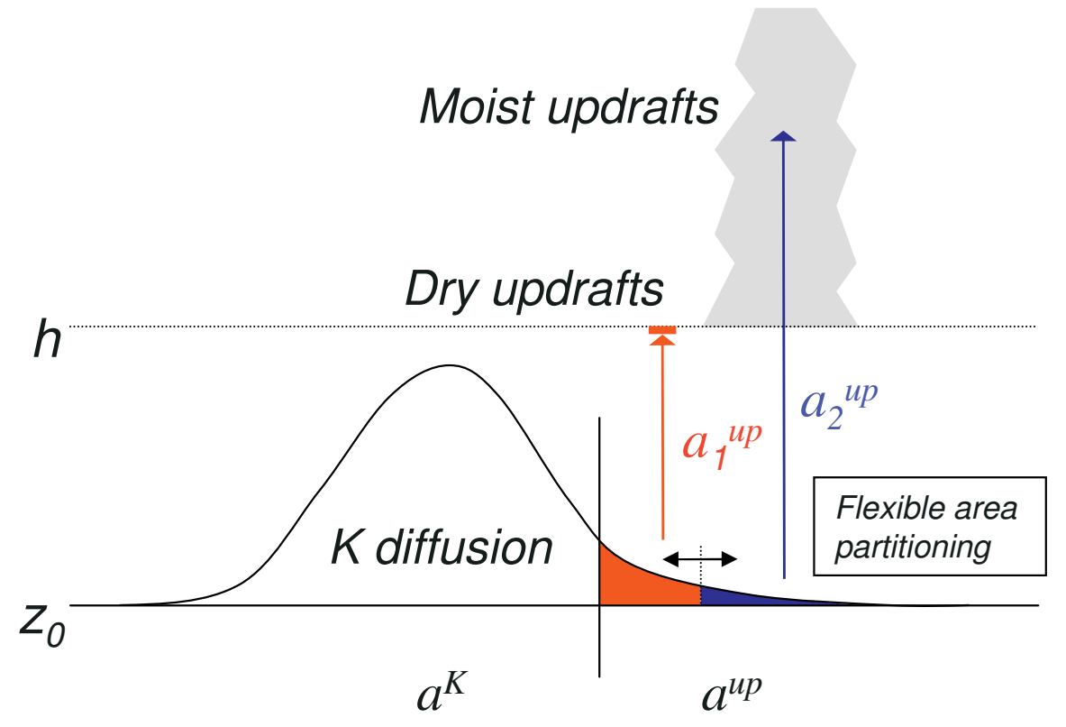
The Eddy Diffusivity Mass Flux (EDMF) framework for turbulent transport, featuring multiple updrafts:

$$\overline{w'\phi'} = a^K\,\overline{w'\phi'}^K + a^{up}\,\overline{w'\phi'}^{up}$$

$$\phi \in \{\theta_l, q_t\}$$

diffusive flux: $$a^K\,\overline{w'\phi'}^K = -K_x \frac{\partial\overline{\phi}}{\partial z}$$

advective flux: $$a^{up}\,\overline{w'\phi'}^{up} = \sum_{i=1}^{N} a_i^{up} w_i^{up} (\phi_i^{up} - \overline{\phi})$$



The entraining plume model:

$$\frac{\partial \phi_i^{up}}{\partial z} = -\varepsilon_i^{up}\left(\phi_i^{up} - \overline{\phi}\right) + \mu_i^{up}$$

$$\frac{1}{2}\frac{\partial w_i^{up\,2}}{\partial z} = -b\varepsilon_i^{up} w_i^{up\,2} + B_i^{up} + P_i^{up}$$

The same budget model is applied to all model updrafts. This requires the entrainment rate ε to be flexible, as a function of the state of the updraft. In this scheme updraft entrainment is parameterized as an inverse dependency on its vertical velocity (Neggers et al, 2002).

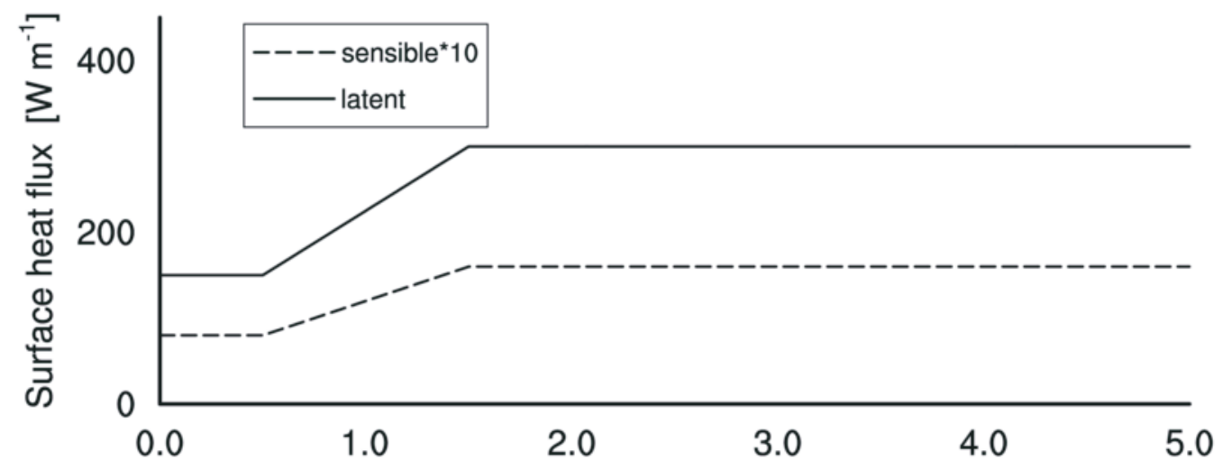
$$\boxed{\varepsilon_i^{up} \sim \frac{1}{\tau\, w_i^{up}}}$$

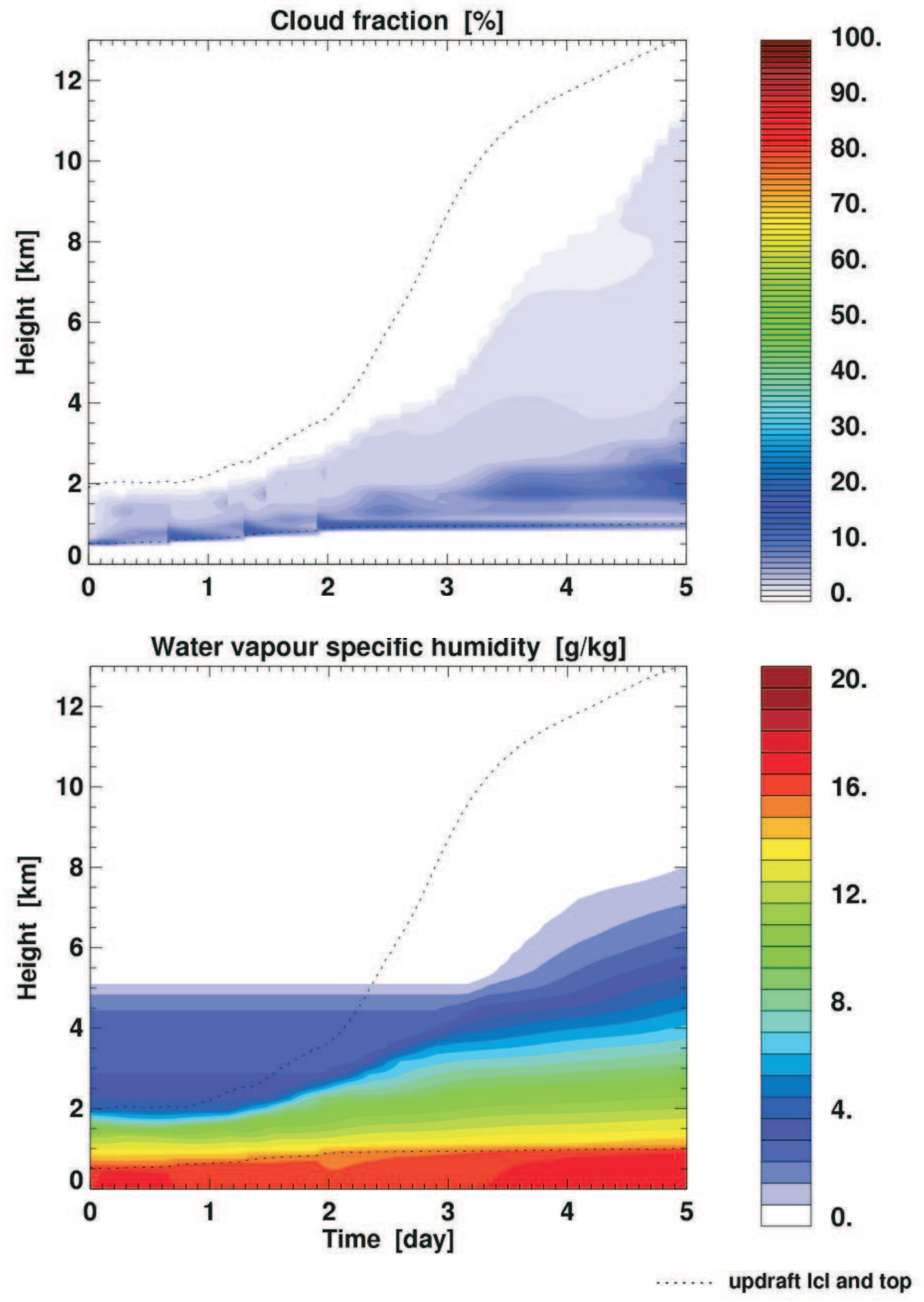
This relation can be interpreted in two ways. First, it expresses that a slower updraft spends more time in a certain layer, and thus has more time to interact with its environment. Second, by substituting a constant turn-over timescale τ=h/w the entrainment rate becomes inversely proportional to the size of the updraft (ε~1/h). This relation is commensurate with early tank experiments (Turner, 1973), expressing that the cores of larger eddies are screened-off more effectively from their environment.

The entrainment model introduces an additional coupling between the updraft budget equations. Slower updrafts will entrain more, diluting the updraft and reducing its buoyancy. As a result, its velocity decreases even more, enhancing entrainment, and so on. In practice, this positive feedback acts to enhance sensitivity to i) updraft initial values and ii) updraft environment. Dry and warm layers become extra effective in stopping the updrafts, which can be expressed as an enhanced sensitivity to environmental relative humidity (Derbyshire et al., 2004).

Results

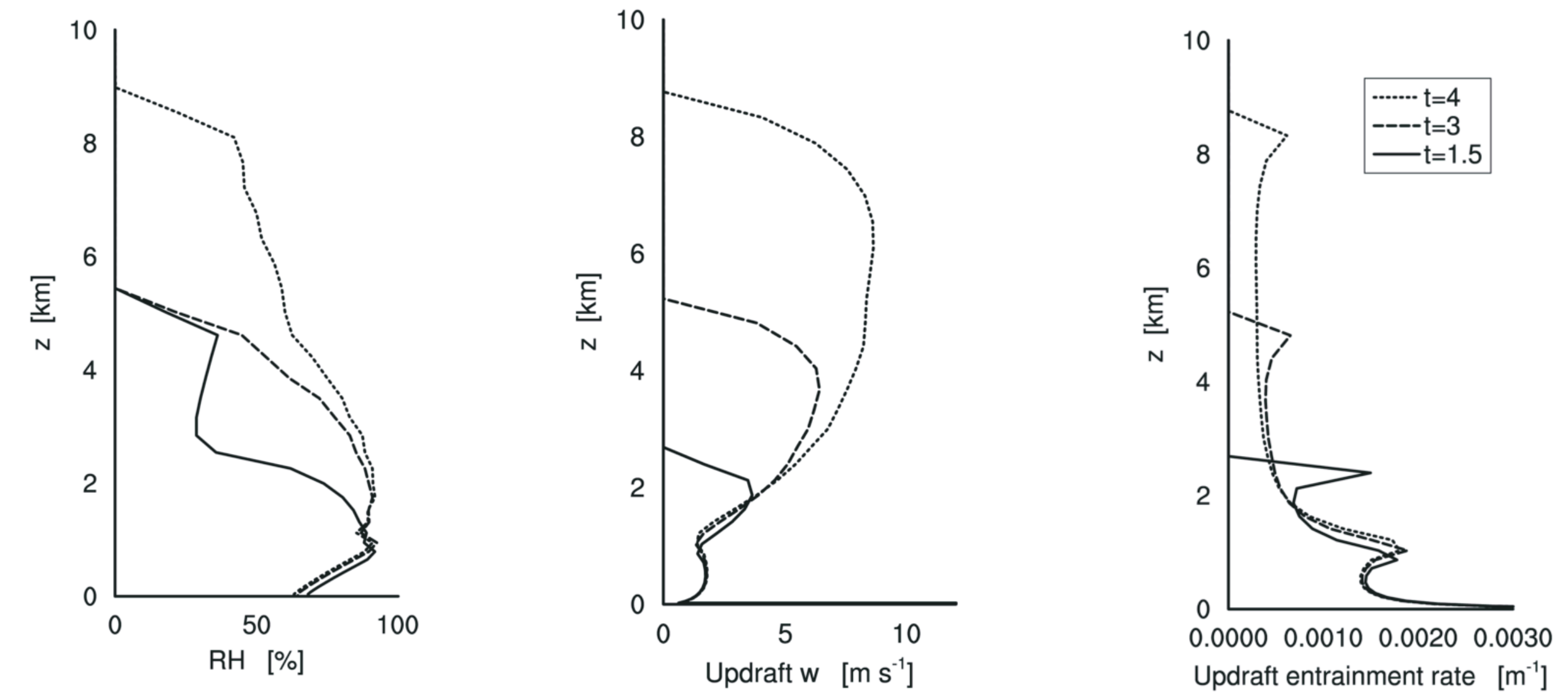
Simulations are performed of a marine shallow-deep transition case during which the transition occurs relatively slowly, facilitating sensitivity studies. Starting conditions are those of a prototype Trade-wind shallow cumulus case (Barbados Oceanographic and Meteorological Experiment, or BOMEX), with prescribed surface fluxes. These are doubled between 0.5 and 1.5 days, preserving their Bowen ratio. The native deep convection scheme of the ECMWF model is switched off during the simulations, while the updrafts of the boundary layer scheme are allowed to rise to unlimited heights.





A gradual transition is reproduced, consistent with the CRM simulations of Kuang & Bretherton (2006). Initially the boundary layer is capped by a shallow cumulus cloud layer, as characterized by the peak in cloud fraction at cloud base. During the transition the lower and middle troposphere gradually moisten. After the transition the moist updraft reaches heights up to 11km. In the deep stage the flexible $(\tau w)^{-1}$ entrainment model automatically creates entrainment rates in the middle troposphere that are much smaller than the values considered typical for shallow cumulus (e.g. Siebesma and Cuijpers, 1995).

Compared to a constant entrainment rate the $(\tau w)^{-1}$ model makes the updraft more sensitive to its environment. In this simulation this impact manifests itself most clearly near the top of the updraft, as illustrated by the peaks in the entrainment rate (see below). This behaviour ensures that updraft transport acts to first fill the dry and warm inversion layer with cold and moist air, before updrafts can rise any further. As a result, the deepening of the convective cloud layer becomes gradual.

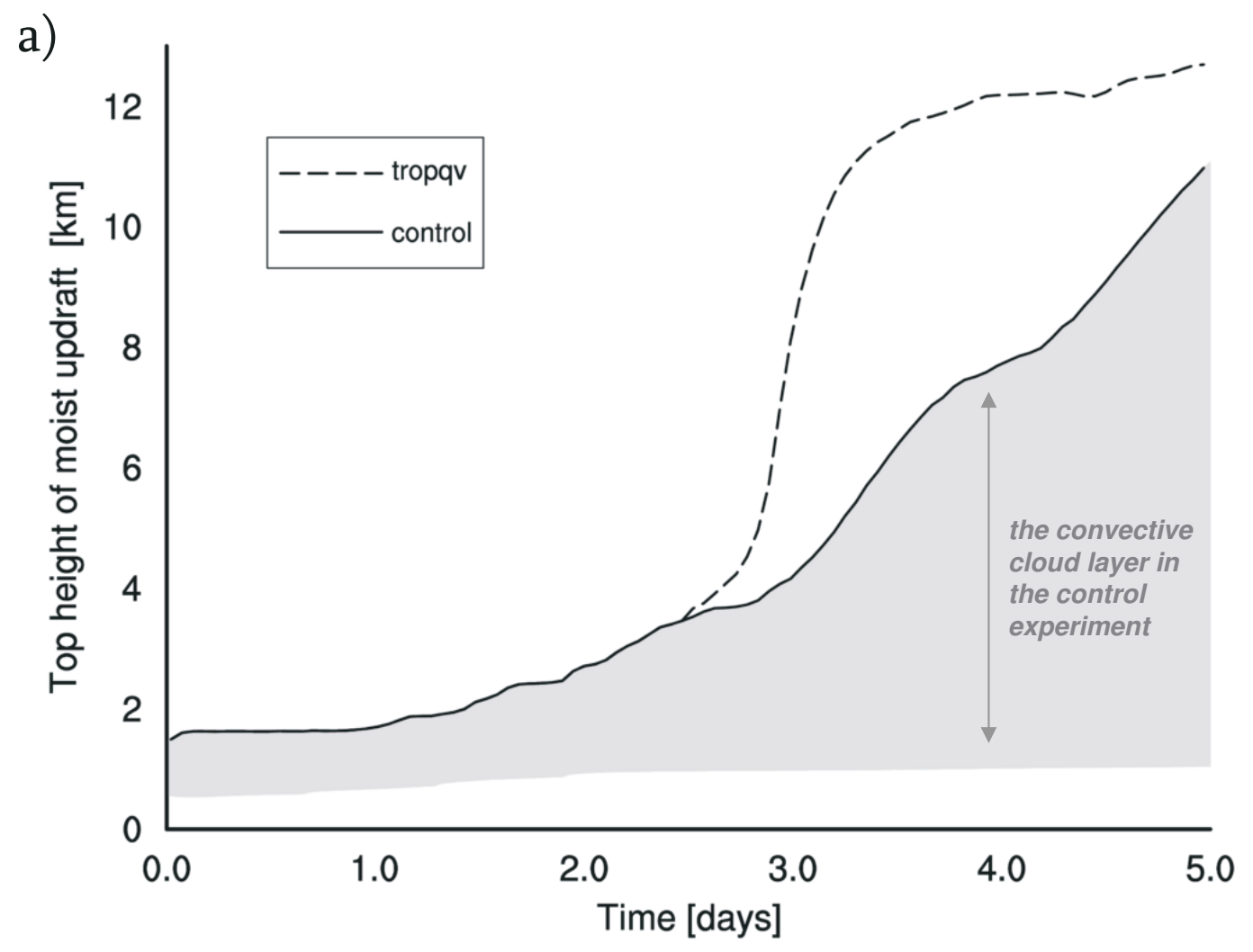


Sensitivity tests

Tropospheric humidity

Kuang and Bretherton (2006) showed that lack of tropospheric humidity initially inhibits the depth of convection, by changing the humidity profile at t=2.5 days such that it matches the profile at the end of the control run. This experiment is repeated here, to find out if the same is true in this model. Figure a) illustrates that after t=2.5 the convective cloud layer (i.e. the layer between the lifting condensation level and the top height of the moist updraft) deepens much faster compared to the control experiment.

a)

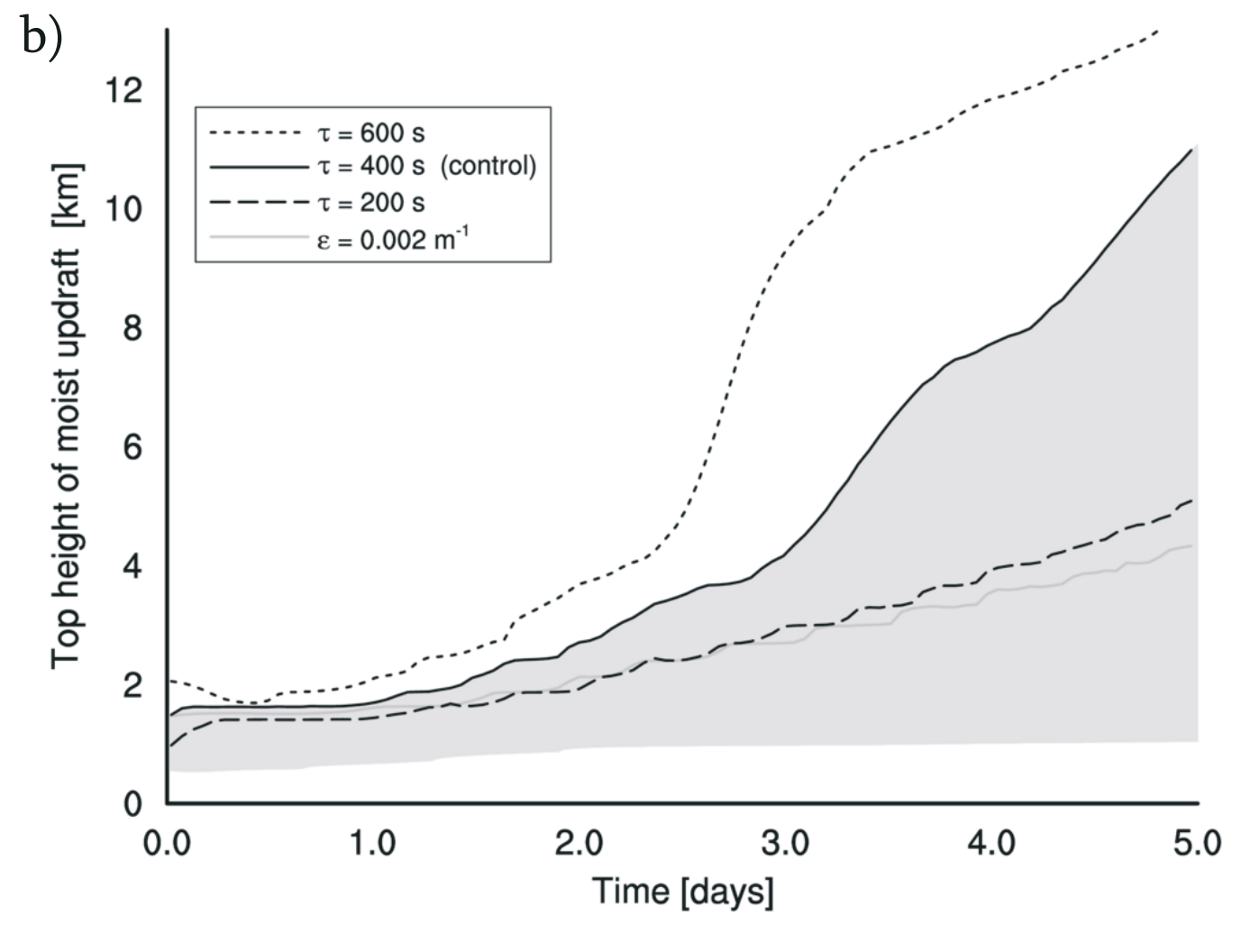


Updraft entrainment

The sensitivity to entrainment timescale τ is assessed in Fig. b), showing experiments with different values of τ in the cloud layer. A larger timescale makes the moist updraft less sensitive to its environment, resulting in a faster deepening of the convective cloud layer (see Figure b). The value of 400 s as derived from LES cloud population statistics of non-precipitating shallow cumulus gives transitions with realistic deepening rates.

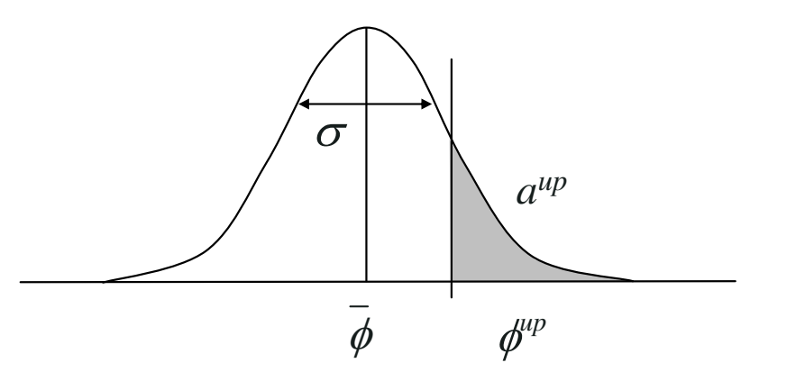
These results are compared to a simulation with constant entrainment rate ε=0.002 m^{-1}, considered a typical value for shallow cumulus convection. This illustrates that reproduction of transitions to deep convection is not possible using constant entrainment rates typical for shallow convection, and that more model complexity (i.e. flexibility) is required.

b)



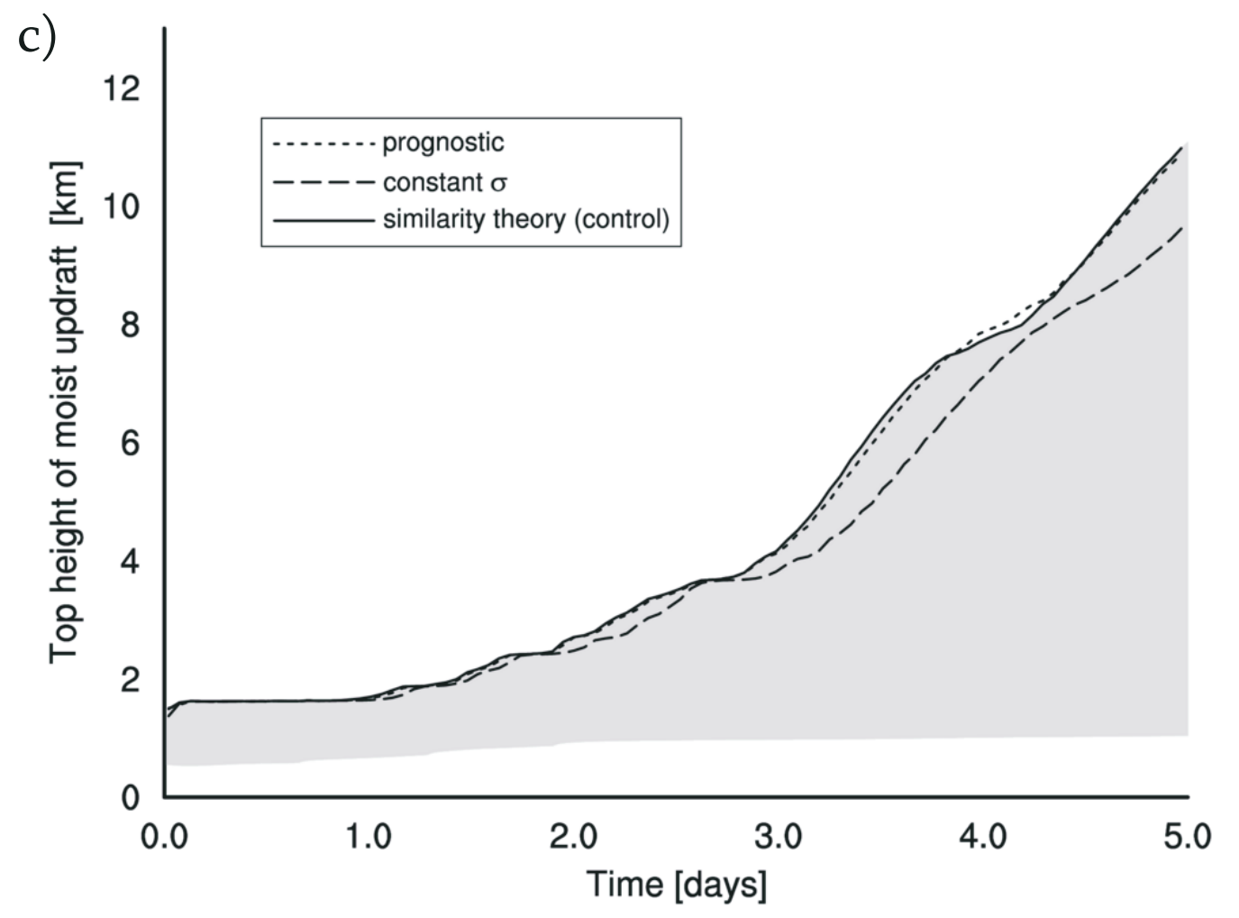
Updraft initialization I: variance

The dependence of updraft entrainment on vertical velocity enhances sensitivity of updrafts to their initial conditions. In this model updrafts are initialized with the mean value of the associated segment (or fraction) of a Gaussian joint-PDF, as illustrated below. This introduces dependence on the turbulent variance at that height. In Fig. c) the sensitivity to initialization variance is studied, showing three experiments in which the variance i) is constant, ii) obeys surface similarity theory (the control experiment), and iii) is prognostic, allowing gradual build-up with time.



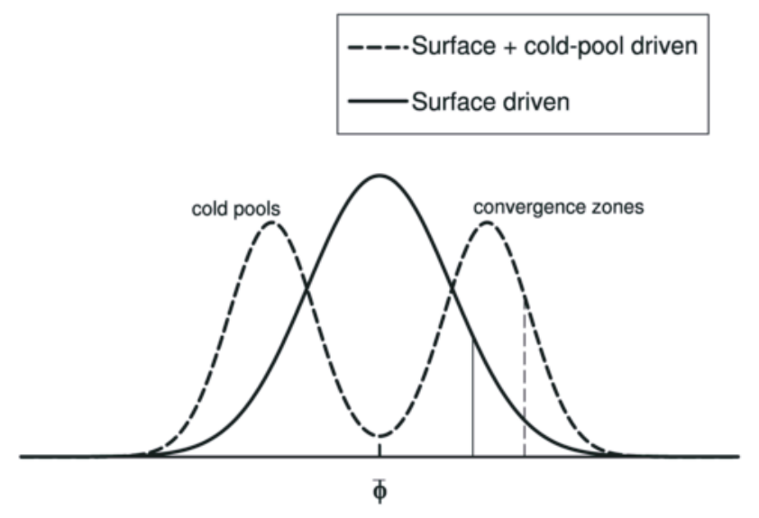
Applying surface similarity theory introduces sensitivity to the doubling of the prescribed surface fluxes, resulting in a slightly deeper convective cloud layer. Using a prognostic variance in updraft initialization does not have a significant impact; close to the surface the prognostic variance budget is dominated by flux-gradient production, keeping the variance closely coupled to the surface fluxes.

c)



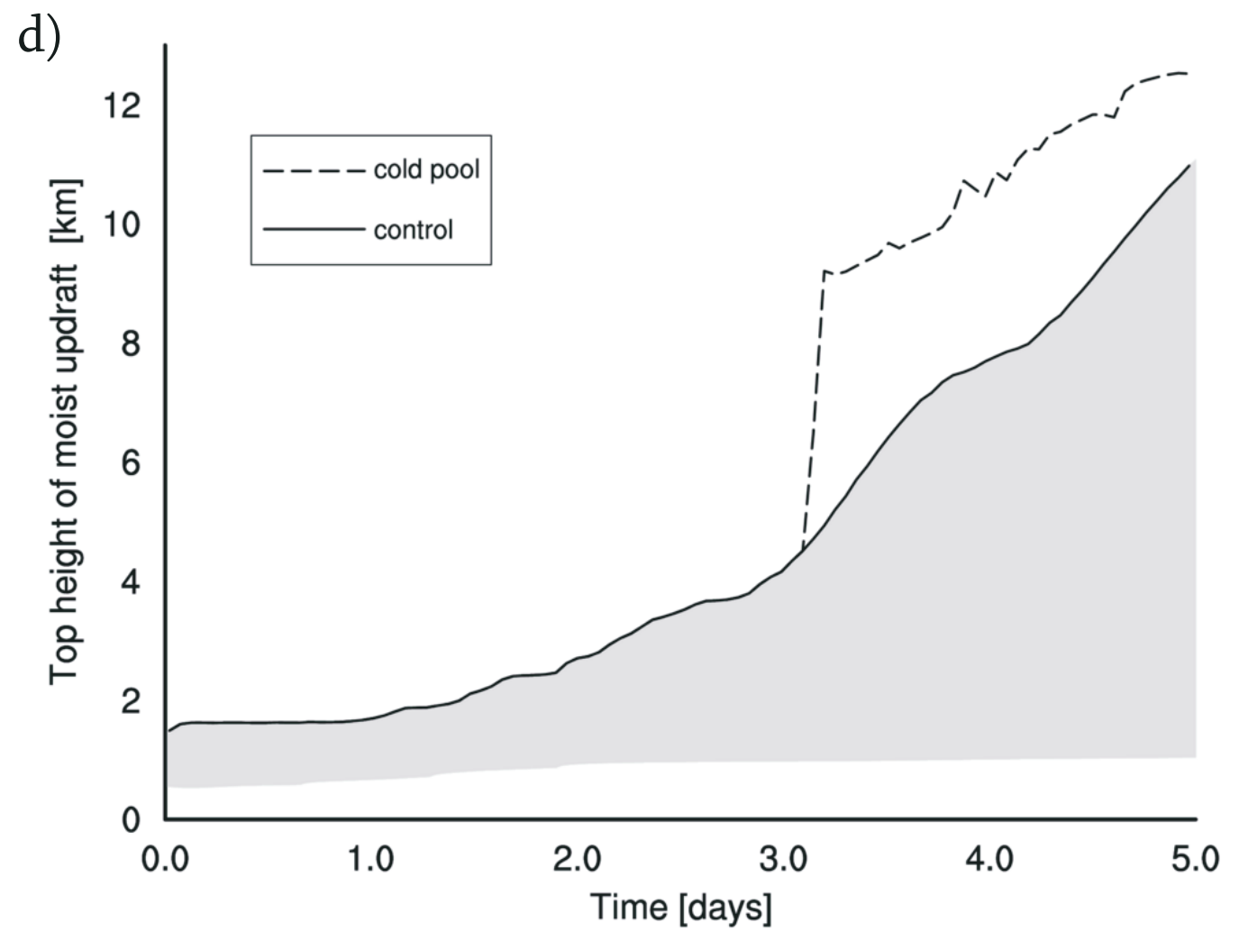
Updraft initialization II: cold pools

Next the potential impact of cold pools generated by downdrafts on updraft initialization is explored. This can be achieved through an adaptive shape function of the updraft initialization-PDF, allowing both unimodal and bimodal shapes. The two modes of the latter reflect the presence of organized large horizontal structures in the subcloud layer (Khairoutdinov and Randall, 2007), including i) dry cold pools and ii) warm and moist convergence zones (as illustrated below).



To imitate the impact of a sudden appearance of cold pools, at t=3 days the shape of the initialization-PDF is changed from unimodal to bimodal (while conserving its variance). This approximately doubles the initial updraft excesses. Figure d) shows that the resulting change in depth of the convective cloud layer is dramatic, growing instantly by about 4km.

d)



Conclusions

A single scheme is used to simulate both shallow and deep convection. The key step has been to enhance the complexity of the updraft entrainment model, by introducing an inverse dependence on vertical velocity. This flexibility reproduces the different magnitudes of updraft entrainment typical of shallow and deep convection. Its second impact is to enable gradual transitions from shallow to deep convection, by enhancing the sensitivity of updrafts to their environment.

The speed of the transition between shallow and deep convection is shown to be highly dependent on the updraft initialization scheme. This creates opportunities for representing the impact of cold pools on the updraft. The results suggest that cold pools can be very effective in speeding up the transition. The next step is therefore to implement a realistic downdraft model in the boundary layer scheme, and its associated impacts on the variance and shape of the updraft initialization PDF. Also, evaluation for continental transition cases would be educational, as these occur typically much faster.

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