1 Modified shallow cumulus scheme

A modified shallow convection scheme with a cloud base mass-flux closure which uses the surface buoyancy flux was implemented in COSMO. The cloud base mass-flux is given by $\rho a_{cc} w_{cc}$, where a_{cc} is the convective core fractional area and w_{cc} a convective scaling velocity. Neggers et al. (2004) have argued that this closure can successfully represent the diurnal cycle of shallow cumulus convection over land. Although a convection scheme would ideally have a stochastic nature at the kilometer-scale (see e.g. Sakradzija et al., 2014), in the present scheme the mass-flux depends on the prognostic fields in a deterministic manner. The implementation makes use of the routine src_conv_shallow.f90 in COSMO, and uses this routine to determine the properties of a test parcel at cloud base. These properties are found by lifting a surface parcel along a dry adiabat to the level where it first condenses. However, the modified scheme differs from the Tiedtke (1989) parameterization for shallow cumulus convection in a number of ways.

1. The determination of the cloud base mass-flux is the largest change. The cloud core velocity at cloud base is given by

$$w_{cc} = \gamma w^*. \tag{1}$$

The pre-factor γ is set to 0.84, following Ouwersloot et al. (2014). w^* is a convective velocity scale, which in turn depends on the surface buoyancy flux (Deardorff, 1970):

$$w^* = \left(g h_{base} \frac{(\overline{w'\theta'_v})_s}{\overline{\theta_{v,s}}} \right)^{1/3}. \tag{2}$$

Here, h_{base} denotes the cloud base height, θ_v the virtual potential temperature, the overline a horizontal average (in this case over the grid-box) and the subscript s a surface value.

Two variants of the scheme are tested: the first assumes a fixed updraft fraction at cloud base of 3.6 % in each column where the scheme is active, which gives a mass-flux that is consistent with Grant (2001). The second variant takes into account the non-dimensional saturation deficit of the test parcel (subscript *tp*), following Cuijpers and Bechtold (1995), Neggers et al. (2004) and Van Stratum et al. (2014):

$$a_{cc} = 0.15 + 0.108 \arctan\left(-1.55 \frac{\overline{q_{sat}} - \overline{q}}{2(q_{tp} - \overline{q})} \right). \tag{3}$$

We clip the updraft fraction at a maximum of 15%, which is similar in magnitude to the 10% value that Neggers et al. (2009) argue for.

Above cloud base, the evolution of the mass-flux of the cloud ensemble is given by

$$\frac{1}{M}\frac{dM}{dz} = \epsilon - \delta. \tag{4}$$

Here, ϵ and δ denote the fractional entrainment and detrainment rates, respectively.

In the absence of precipitation, the vertical evolution of a scalar conserved variable ϕ (e.g. total moisture content) in the cloud core is parameterized as

$$\frac{d}{dz}\phi_{cc} = -\epsilon\left(\phi_{cc} - \overline{\phi}\right). \tag{5}$$

2. The fractional entrainment rate $\epsilon = \alpha/z$ (with $\alpha = 1$) as argued in e.g. Siebesma et al. (2003) and Böing et al. (2012), rather than constant with height.

3. Detrainment relates to properties of environment. A non-dimensional mixing fraction χ_{crit}, which indicates how much buoyancy the ensemble of updrafts loses due to evaporative cooling as it mixes with its environment, determines the fractional mass-flux loss per unit height (see Kain and Fritsch, 1990, De Rooy and Siebesma, 2008 and Böing et al., 2012 for more details).

   Here, we use (note the change of sign with respect to equation 4)

   $$-\frac{1}{M}\frac{dM}{dz} = \delta - \epsilon = \frac{1}{\lambda}f(\chi_{crit}). \tag{6}$$

   We set $f(\chi_{crit}) = 1 - 3\chi_{crit}$, following Böing et al. (2012), and clip this function to be between 0 and 1, i.e. the mass-flux does not increase with height or fall off quicker than the length scale. In the implementation in COSMO, a constraint that the detrainment between 2 levels should not be more than 75 % of the mass-flux has been retained.

   The length scale λ is chosen proportional to cloud base radius. We relate this radius to the cloud base height ($\lambda = 0.17h_{base}$) following Stirling and Stratton (2012).

   The updraft is terminated when it either becomes negatively buoyant (overshoots are not accounted for), or when the mass-flux falls below 10 % of its cloud base value.

4. The decrease in cloud core fraction at higher levels is proportional to the decrease in mass-flux (in agreement with Neggers et al., 2009 and Böing et al., 2012).

5. The total cloud fraction (which includes not only cloud cores but also passive clouds) and total amount of liquid water for use in the radiation scheme are made proportional to the cloud core fraction and total liquid water. Proportionality factors of 2 and 1.4 are used respectively, i.e. the passive clouds contain less water per volume than the cloud core. Typical values for BOMEX (Siebesma et al., 2003) and the ARM LES intercomparison study (Ouwersloot et al., 2014) are of this order.

   The radiation scheme in COSMO assumes maximum random overlap. This would typically lead to an underestimation of the total cloud cover in the radiation scheme (see Neggers et al., 2011). In order to reduce this bias, the cloud fraction at the lowest level and at a temperature inversion is scaled with a factor of 3.3 and the liquid water content with a factor 2. This is an ad-hoc correction, based on the approximate proportionality found between cloud cover and maximum cloud core area in Ouwersloot et al. (2014), and motivated by the fact that a relatively large amount of passive clouds/anvils occurs either near cloud base or near the inversion. Ideally one would fix the overlap assumption, as discussed in e.g. Neggers and Siebesma (2013).

6. As a last modification, we remove the constraint that moisture convergence has to be positive for moist convection to occur. Remaining constraints are that the test parcel has to be moister than its environment, and condensation has to occur before the parcel reaches a virtual temperature deficit with respect to its environment of 0.5 K.

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