An integrated prognostic approach for clouds, precipitation and convection

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As long as convection is not completely resolved by the model grid, a subgrid deep convection scheme has to provide its contribution to the clouds and precipitation. How to combine this with the contribution from resolved condensation, in a way to get results independent of numerical issues, is a tough problem.
From the Clausius-Clapeyron and the energy equations, it can be shown that the saturation moisture decreases when the vertical velocity increases. This is also true at the scale of the grid box averages. In presence of convective updraughts on a fraction of the grid box $\sigma_u \ll 1$, the resolved vertical velocity $\overline{\omega}$ results from averaging large updraught velocities ω_u with a near zero upwards velocity ω_e in the updraughts environment. Considering a single equivalent updraught (mass flux scheme):

$$\overline{\omega} = \sigma_u \omega_u + (1 - \sigma_u)\omega_e \approx \sigma_u \omega_u$$

In this case, the reduction of the grid box area induces a proportional increase of the updraught area and of the resolved upwards velocity. The saturation moisture is then lower. Also in weak convective situations, the vertical velocity is likely to take higher extreme values when reducing the grid box width.
But the lowering of the saturation moisture will imply more condensation only where the local moisture is correlated with the upwards motion. Therefore it is difficult to foresee the trend of the resolved precipitation when varying the mesh size.
The model normally forecasts mean grid box values, which correspond to the maximum precipitation only for stratiform rain bands which are wider than the individual grid boxes. For convective precipitation covering only a fraction of the grid box, the presented mean values are lower than the peak precipitation.
So even in a perfect model, the precipitation amounts do not have to be conserved when varying the mesh size; but this does not free us from the need to be coherent in the water budgets. In the case of a closure of the convective scheme by moisture convergence, the double counting may be avoided by considering that the total moisture convergence towards the grid box is parted between the detrainment of moisture by the updraught and the *total* condensation, i.e. convective and resolved. This was applied for a while with some success in the Aladin model. But it did not solve everything: we are still attempting to superimpose two separate non linear schemes.

The quasi-equilibrium (QE) hypothesis has been widely used in the convection parametrization. It assumes that the adjustment time of the convection ($\tau_D \sim 10^3 - 10^4 s$) is much smaller than the so-called 'large scale' forcing ($10^5 s$). But the actual processes affecting the forcing of the convective scheme may include anvil clouds, or local turbulent processes, which have much shorter characteristic times, at least comparable to τ_D. The QE hypothesis is then no longer bearable and it becomes necessary to include some memory of the convective activity from one time step to the next. Representing the updraught mass flux as the product of a mesh fraction σ_u by an updraught velocity ω_u allows to use a vertical motion equation for the latter. Using $\omega^* = \omega_u - \omega_e$ the relative updraught velocity, it takes the form

$$\frac{\partial \omega_u^*}{\partial t} \quad = \quad -F_{\text{buoy}} \quad + \frac{{\omega_u^*}^2}{p}(1 + \mathcal{K}_f) \quad - \frac{1}{2}\frac{\partial {\omega_u^*}^2}{\partial p}$$

where the RHS is composed of a buoyancy term, a dissipation term and a vertical advection term. This equation is actually valid for a single bubble or plume. In a mass flux scheme, we represent the grid box variability composed of various updraughts of different lifetimes, by a single equivalent updraught. Applying the same prognostic equation to this mean updraught may be questionable.
Using a closure by moisture convergence, a prognostic equation for the mesh fraction σ_u, may be derived, expressing that the latent heat brought by the mositure convergence is either absorbed in

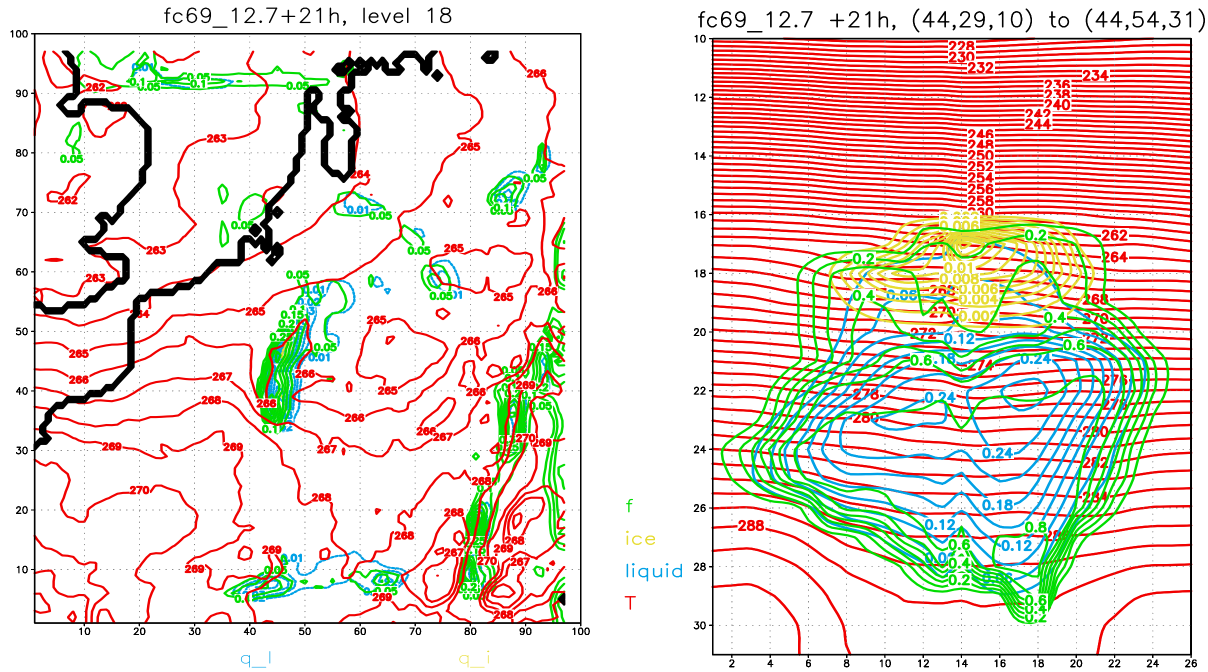

Figure 1: Left: temperature (red), cloud ice (yellow) and liquid (blue), cloud fraction (green) at model level 18 (around 575 hPa). Right: vertical cross section along a cloudy area (Y axis: model levels).

the updraught activity or stored in an increase of σ_u:

$$\underbrace{\frac{\partial \sigma_u}{\partial t} \cdot \int_{p_b}^{p_t} \left(h_u - \overline{h}\right) \frac{dp}{g}}_{\text{storage}} = \underbrace{L \int_{p_b}^{p_t} \sigma_u \omega_u^* \frac{\partial \overline{q}}{\partial p} \frac{dp}{g}}_{-\text{consumption}} + \underbrace{L \cdot TMC}_{\text{input}}$$

The profile of the updraught properties (temperature, moisture contents of the different phases, horizontal momentum) should normally also be memorized from one time step to the next, unless we keep considering it as a sequence of quasi-equilibria. The question is wether the time needed by a parcel to raise along the whole profile may be considered smaller than the characteristic time of the external forcing. In our current scheme we make this hypothesis.

The prognostic variables σ_u, ω_u are advected by the mean wind, and a geographical separation of the trigger and effect is possible, as well as a time separation. In this context, we can separate the downdraught from the updraught, allowing the former to survive the latter.
Using an explicit evaluation of the mesh fraction σ_u allows to take into account the updraught properties over it in the grid box averaging, which is important when the grid dimensions are no longer much wider than the scale of the convective events.
The integrated scheme we propose uses a microphysical package (derived from Lopez, 2002) with two cloud water variables (ice and liquid). The updraught is called first and outputs, beside the convective fluxes, detrained cloud water contents on a detrainment area. The resolved condensation is estimated outside the updraught and its detrainment area, and both are combined to enter the rest of the microphysics (auto-conversion to precipitation, Bergeron effect, collection and evaporation of precipitation). The grid box is parted geometrically between the updraught and its detrainment area, the stratiform cloud outside it, the total cloudy area, the precipitatig area, the downdraught.
There is also a mass flux scheme for a moist downdraught, based on the total precipitation evaporation.

The general structure of our deep convection scheme is still based on Bougeult (1985)'s approach, and this induces some weaknesses which are difficult to overcome. The triggering of the convection is not well modelized. The use of prescribed entrainment profiles makes it impossible to write a local mass budget from which we could either compute the mesh fractions or the detrainment. So, we merely consider (like many schemes) a constant updraught mesh fraction along the vertical, which implies a bad mass flux representation.
An example of model fields is shown in Figure 1. At the present stage, the structure of the forecasted fields appears correct in the 3D cases we tried, but the amounts of precipitation are too low. This seems to be associated to a lack of realism of the detrainment profile of the updraught, and its link to the updraught mass flux. The problem is directly related to the a priori imposition of the entrainment profile mentioned above. New tracks are now investigated, to get out of this trap.

References

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