Prognostic Precipitation in the Lokal Modell (LM) of DWD

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1 Introduction

Many atmospheric limited area models have difficulties in realistically representing the distribution of precipitation in mountainous terrain. A common feature is an overestimation of precipitation amounts on the upwind side and an underestimation on the lee side. This has been known already for the former Europa Modell of the German Weather Service, which is a hydrostatic model, and it is still found in the currently operational Lokal Modell (LM, Doms and Schättler, 2002) which is non-hydrostatic.

In the currently operational LM version the conservation equations for rain and snow

$$\rho \frac{\partial q^x}{\partial t} + \rho \mathbf{v} \cdot \nabla q^x = -\nabla \cdot \mathbf{P}^x - \nabla \cdot \mathbf{F}^x + S^x \qquad (1)$$

($x = r, s$ for rain, snow, q = mixing ratio, $\mathbf{P}$ = sedimentation flux, $\mathbf{F}$ = turbulent flux, S = source terms from cloud microphysics) are approximated stationary and without advection. This column equilibrium approach means that precipitation particles, arising from cloud microphysical processes, immediately fall down to the bottom of the column in the same time step.

In reality, rain drops with a mean fall velocity of about 5 m/s which develop for example at a height of 3 km, need a falling time of 10 minutes. If a horizontal wind speed of 10 m/s is assumed, the rain drops are drifted by 6 km. For snow with a mean fall velocity of about 1 m/s (and usually generated higher up) the horizontal drifting is even more efficient. Therefore, for the LM with a grid length of currently 7 km (in the next version (LMK) a grid length of about 2.8 km is aspired) and a time step of 40 s the column equilibrium approach is no longer valid. This was tested by case studies especially dedicated to the formation of precipitation in mountains: in many cases there is too much precipitation on the upwind side, and too little in the lee. In particular for hydrologists the solution of this problem is of high relevance: precipitation falls in the false catchment and is therefore not added to the correct river.

2 Semi-Lagrange-Advection

There are in principal two possibilities to handle the sedimentation term $-\partial P_z / \partial z$: either this term is discretized directly (for example implicitly), or one writes the sedimentation flux as a product of an effective fall velocity and the density $P_z = v_{\text{eff}} \rho q$ and treats it in the advection scheme. In the latter case one has to consider, that in LM the layers near to the ground are so thin (about 60 m), that with the currently used time step of 40 s, particles can fall through up to three layers within one time step. Therefore, one needs an advection scheme which remains stable up to vertical Courant numbers of about 3. Apart from this, the prognostic precipitation shall be implemented in the version LMK, in which horizontal Courant numbers up to 1.8 are aspired, for which most Eulerian advection schemes are no longer stable. For the advection of precipitation we therefore decided to use a three-dimensional Semi-Lagrange (SL) scheme (e. g. Staniforth and Côté, 1991) whose stability does not depend on the Courant number.

The application of the standard SL schemes consists of two steps: 1. calculation of the backtrajectory and 2. interpolation of the fields q^r and q^s at the starting point. The implicit equation of the backtrajectory (Robert, 1981) is solved by iteration. After one iteration step one gets a truncation error of order $O(\Delta t)$, after two steps of order $O(\Delta t^2)$. Simple tests show, that an error of only $O(\Delta t)$ delivers especially nonsatisfying conservation properties. This is in agreement with Staniforth and Côté (1991), who also recommend an order $O(\Delta t^2)$. Therefore, a second iteration step is needed which requires an interpolation of the three velocity components. This interpolation is a time consuming step in the staggered Arakawa-C-grid; currently it needs more then 80% of the computation time of the whole SL-scheme.

In the second interpolation step for the fields often a cubic polynomial is recommended, which shows the best relation between computational effort and accuracy; especially the cubic spline interpolation is even ideally conserving. In contrast, for the time being we use the simpler and computing time saving trilinear (i. e. linear in all three space dimensions) interpolation. It is well known that it has bad form properties (high diffusion) and only moderate conservation properties. However, the latter is probably not significant for rain and snow which remain only a few time steps in the model area. A test with a Gaussian rain particle distribution, which is advected with a given velocity ($u = 10$ m/s and $w = -5$ m/s), yielded a mass loss of 0.05% per time step. After 15 time steps (according to the example above) the mass loss is less than 1%. Similar tests with a velocity field over mountains even yielded a small gain of mass. But this could be explained by a non divergence free velocity field; in this case the advection itself does not conserve mass.

Some diffusion of the linear interpolation is even desired and could cure the problem of an unrealistic strong small scale structure of the precipitation in irregular terrain. Another advantage of the trilinear interpolation in contrast to higher order interpolation is its positive definiteness, an essential condition for the coupling to the cloud microphysics.

3 Coupling with cloud microphysics and real test cases

The dynamic core of the current operational LM consists of a 3-timelevel-scheme with time splitting by Klemp und Wilhelmson (1978). In the frame of this dynamic core the coupling between advection and cloud physics is done with a Marchuk-splitting, this means that in one time step the SL-advection from timelevel t^{n-1} to t^{n+1} (with velocities at t^n) is calculated and then using the updated values the cloud physics scheme is carried out. The latter is formulated implicitly, as mentioned above, but can be solved quasi-explicitly, because the sedimentation velocity is always directed downwards and therefore the system of equations has bidiagonal form.

As a real test case the precipitation distribution over Southwest Germany on 20 February 2002 is presented here. In order to illustrate the importance of the transport by drifting the trajectories of (idealized) snow particles which are injected into the simulated LM wind field at different heights over Strasbourg are given in Tab. 1. It is assumed that the snow particles fall with a constant speed of 2 m/s down to the melting zone at about 850 hPa. The table shows that, for instance, a snow particle starting at 500 hPa will drift 71.4 km within 40 minutes. This is equivalent to about 10 grid cells. A particle starting at 750 hPa will drift 13.1 km, which is still almost 2 grid cells. These results show that drifting of hydrometeors is an important transport process, in particular for snow, but also for rain, especially at higher resolutions.

Start level [hPa]	Distance [km]	Duration of drift [min]
500	71.4	40
550	59.5	35
600	47.6	29
650	40.5	25
700	32.1	21
750	13.1	9

Table 1: Calculation of trajectories for LM for estimating the drifting of snow (provided by B. Fay, pers. comm., 2003).

Figure 1 shows the total precipitation (rain + snow) during a 24-h period on 20 February 2002, 0 UTC + 6h-30 h over Southwest Germany. The left figure shows a simulation with the operational LM, the right the same situation with the new prognostic precipitation scheme. The spatial precipitation distribution with the new scheme is in much better agreement with the observations (middle figure) than the current LM: the maxima are reduced (the operational LM overestimated them by up to 150%, the new version only by 20%), the maxima are shifted to the lee side and therefore the unrealistic dry regions in the lee do not appear. The observed precipitation distribution has a mean value of about 16 kg/m^2, the operational LM version yields 30% too much, the new version only about 10% too much. The computational effort for the new version is about 20% higher than for the operational one, which seems acceptable for two new prognostic variables (q_r and q_s).

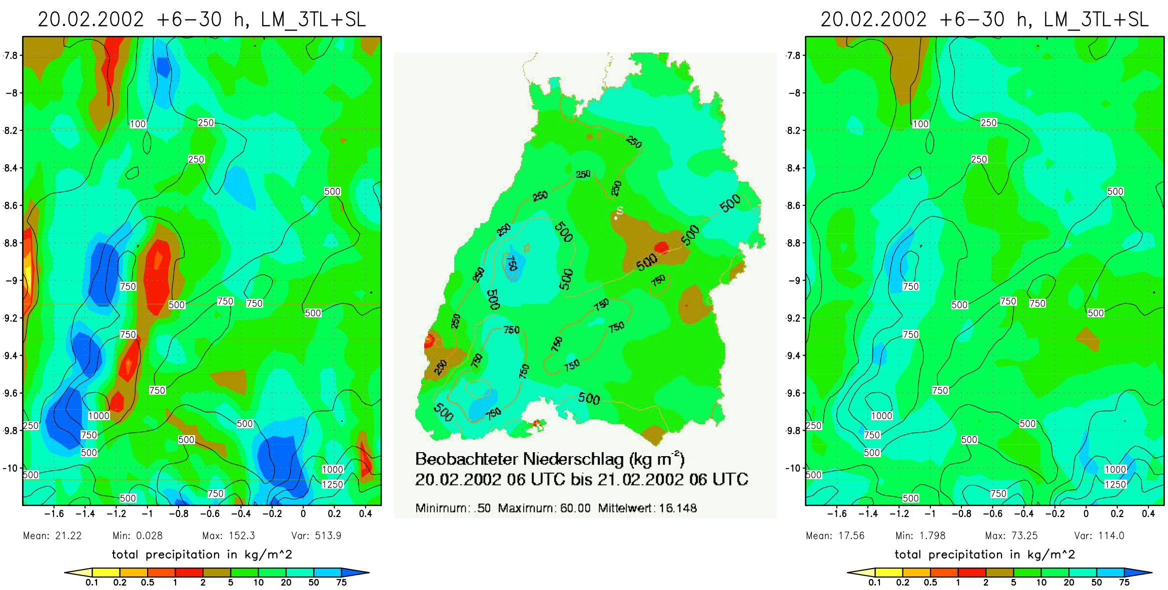

Figure 1: Precipitation forecast for 20 February 2002, 0 UTC + 6h-30 h over Southwest Germany with the currently operational LM without (left) and with (right) prognostic precipitation. Observations are shown in the middle. The isolines indicate the model orography.

References

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