3D-Transport of Precipitation

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1 Current diagnostic scheme for gridscale precipitation

The current scheme for gridscale precipitation assumes column equilibrium for sedimenting constituents like rain or snow. That is, sedimentation can be considered to be a fast process compared to the characteristic time of cloud development. In the model's framework rain or snow are falling through all lower model levels within a single time step. Consequently, the precipitation fluxes of rain P_r and snow P_s are used as dependent model variables and are used to compute the various source terms. The full prognostic equation for the mass fraction of rain q^r or snow q^s degenerates to the diagnostic expression

$$-\frac{1}{\rho}\frac{\partial P_x}{\partial z} = S_x \tag{1}$$

in which x stands for r (rain) or s (snow), respectively.

2 Limitations of the diagnostic scheme

With the refinement of model's mesh size and time step, the assumptions made above get more and more unrealistic. Cumuliform clouds come into a resolvable scale. Advection and inside cloud temporal interactions of rain and snow can't be ignored any longer for a realistic forecast. Although q^c (cloud water) and q^v (specific humidity) are advected in the current model, the lee side precipitation is not sufficiently recognized by the model. With a prognostic scheme this lack is hoped to be reduced as well as the unrealistic spurious maxima and minima of precipitation amount in mountainous regions.

3 Prognostic scheme for gridscale precipitation

The full prognostic equation for rain or snow reads

$$\frac{\partial q^x}{\partial t} + \vec{v} \cdot \nabla q^x - \frac{1}{\rho}\frac{\partial P_x}{\partial z} = S_x. \tag{2}$$

The reformulation of the model requires

1. the use of q^x as dependent and now prognostic model variable instead of P_x,
2. the explicit treatment of the sedimentation term and
3. a positive definite advection scheme for moisture variables.

3.1 Reformulation of the model in terms of q^x

The reformulation of the model in terms of $q^x = \rho^x/\rho$ is easily done by the use of the relation

$$P_x = \alpha_x \left(\rho^x\right)^{e_x} \tag{3}$$

where α_x is a constant factor and e_x is a constant exponent. These numbers follow from the parameterisation assumptions of the Kessler scheme. The reformulation of the source terms S_x is now straightforward.

3.2 Sedimentation

The explicit treatment of precipitation turns out to be more difficult. Because of the sedimentation velocity is a nonlinear function of the specific amount itself and sometimes larger than allowed by the Courant number an explicit treatment of sedimentation requires a smaller time step.

Here, the time step is adjusted to the layer thickness and a number of intermediate shorter time steps are used only when required. But this requires the use of a first order upstream scheme

$$\left(\rho^x\right)_k^{\nu+1} = \left(\rho^x\right)_k^{\nu} - \frac{\Delta t_i}{\Delta z_k}\left(v_{z,k}^{\nu}\left(\rho^x\right)_k^{\nu} - v_{z,k-1}^{\nu}\left(\rho^x\right)_{k-1}^{\nu}\right). \tag{4}$$

Here, ν counts the intermediate time steps which have the length of Δt_i. The sum of the intermediate time steps equals one model time step $\sum_i \Delta t_i = \Delta t$.

In practice, the loop is done from the highest model layer to the lowest (the direction of decreasing layer thickness). If it turns out that the time step has to be reduced the time step is halved. The flux over one intermediate time step is assumed to be constant. So, the sedimentation scheme requires only information from the current and the next upper layer. Furthermore, no fluxes have to be interpolated. Despite the diffusivity and the numerical costs this scheme has the advantage to avoid unnecessary computations and is automatically positive definite. We hope that because of the relatively small number of time steps for sedimentation the effect of the diffusivity of the scheme is of minor importance.

Moreover, process splitting is done so that first sedimentation is computed for $\Delta t/2$, than the microphysical conversion rates and source terms are evaluated and last, a second $\Delta t/2$ sedimentation step is done.

Other methods for the treatment of the sedimentation term are possible but are not implemented or tested. For instance, the highest occuring Courant number can determine the small time step for the whole column in combination with a higher order scheme[1]. An other possibility is the use of the flux form semi-Lagrangian technique which avoids small time steps at all[2].

3.3 Advection

Advection of q^r and q^s is done with a positive definite van Leer scheme as for advection of cloud ice q^i.

4 Problems and limitations of the prognostic scheme

Advection as well as sedimentation are discretised as schemes acting on two time levels. This causes problems in mass and energy conservation because other related variables such as q^c, q^v and T are defined on three time levels. The scheme thus requires the LM as two time level discretisation. Currently, a positive definite advection scheme for three time levels is investigated. Besides, a formulation with the use of partial densities ρ^x would be more consistent in relation with the conservation of mass.

5 Experimental studies

A simple test case is the 2-dimensional flow over a mountain ridge in a wet atmosphere. In the experiment, the mountain has a maximum height of 1000 m and a half width of 50 km on a 7 km mesh, its peak is located at gridpoint 33 in the following figures. A flow of 10 m/s wind speed is coming from the left and the atmosphere has a relative humidity of 95% in the middle troposphere. As shown in figure 1 after 12 hours of integration, the total amount of rain and snow $q^{r,s}$ is advected to the right in comparison to the diagnostic scheme where precipitation particles are not advected at all. The sedimentation velocity of snow is sometimes

[1] Confirm the MM5 model description

[2] Confirm Kato, T., 1995: A Box-Lagrangian Rain-Drop Scheme. J. Meteor. Soc. Japan, 73, 241-245

as small that snow is more advected than sedimented which diffuses these particles troughout the model domain in a very small concentration. This is indicated in this figure by the large area covered with a very small snow amount. Figure 2 shows the total amount of precipitation after 12 hours. The maximum precipitation amount is shifted to the right by about 1 mesh size. This seems to be plausible. The overall amount of precipitation is lower (84%) than that of the compared diagnostic scheme. The reason for that is not known but this effect is also significant in other experimental studies (see below).

A first realistic test case is the Brig case. The Brig flood in September 1993 caused a lot of damage in the Brig valley. It was not sufficiently forecasted by the LM with the diagnostic precipitation scheme, it even gave no precipitation for the Brig grid point itself. The station data in figure 3 show the luv side (and even the lee side) of the Alps with a considerable amount of precipitation. Figure 4 compares LM forecasts with prognostic and diagnostic gridscale precipitation schemes. With the diagnostic precipitation scheme the lee side of the mountains has little precipitation and the Rhone valley is almost completely without precipitation. The maximum amount of precipitation is found to be in the southwestern part of figure domain. With the prognostic precipitation scheme, the lee side of the Alps gets more precipitation, there are no dry valleys and the maximum precipitation amount for a single gridpoint is reduced to about one half of that achieved with the diagnostic scheme. The region of maximum precipitation has moved northeast and is thus more towards the region of observed maximum precipitation. The precipitation field is much smoother. This is an encouraging result for the prognostic precipitation scheme. But again, the total amount of precipitation in the considered domain is reduced by about 25%.

An other example shows impressively the transport of precipitation over large distances. Figure 5 shows the distribution of total amount of rain and snow in a west–east vertical cross section over the Rhine valley near Freiburg. Arrows indicate horizontal wind vectors and vertical spacing is on model levels. The result is that $q^{r,s}$ can be advected over about 5 gridpoints (35 km) before reaching the surface. As a result, the lee side of the mountains can get more precipitation. This is also to be seen in figure 6 comparing the total precipitation of both schemes for the same case in southern Germany.

6 Conclusion

The gridscale precipitation scheme with prognostic treatment of specific contents of rain and snow shows encouraging results and seems to overcome problems in the forecast of precipitation, especially in mountainous regions. Surely, the numerical implementation can be improved to come to a more efficient formulation. For future versions of LM this precipitation scheme should be taken into account.

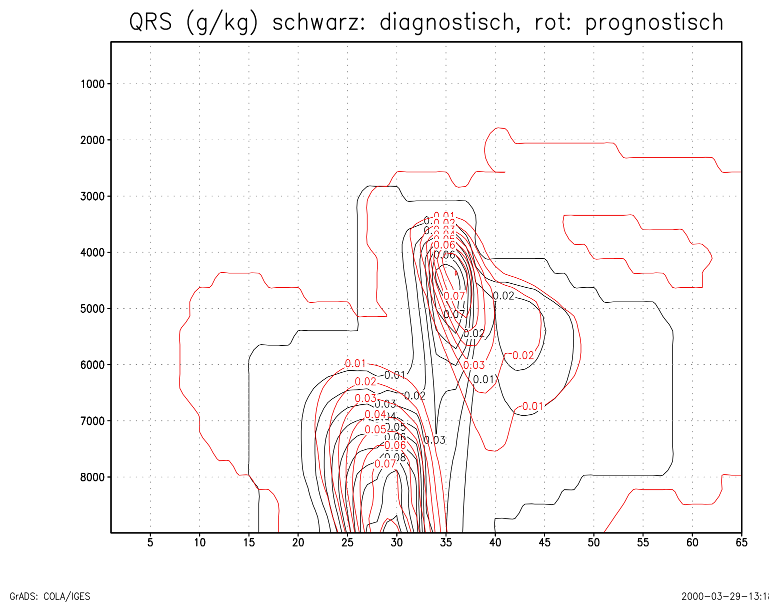

Figure 1: Idealized 2D test case: Sum of rain and snow content for the diagnostic scheme (black) and the prognostic scheme (red).

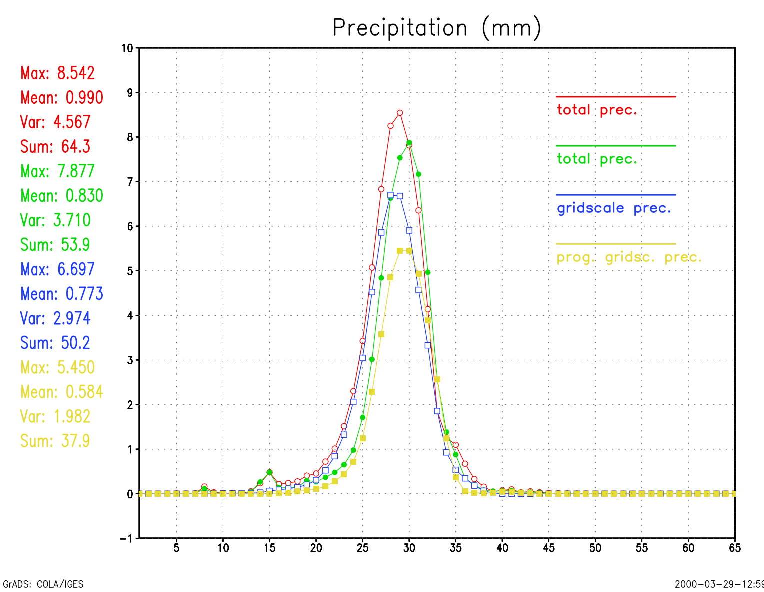

Figure 2: Idealized 2D test case: Total and gridscale Precipitation.

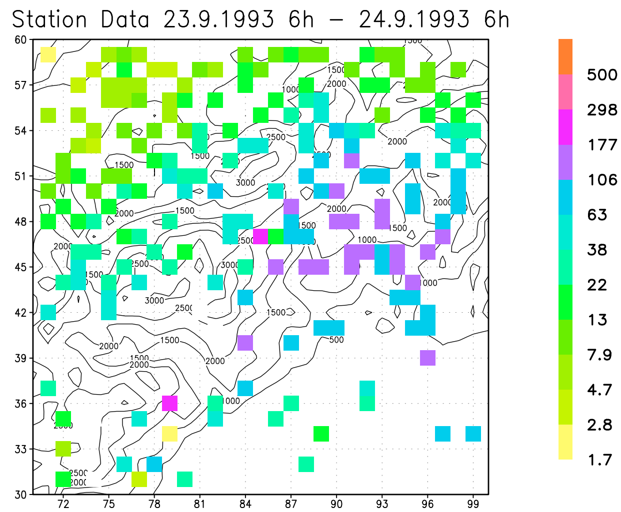

Figure 3: Brig case: Station data for precipitation

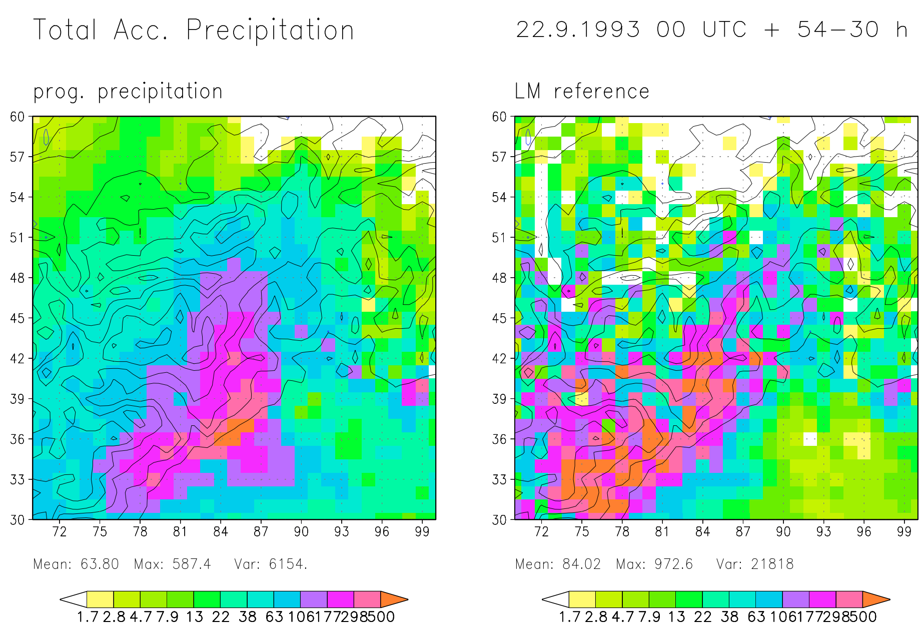

Figure 4: Brig case: Prognostic and diagnostic scheme precipitation results

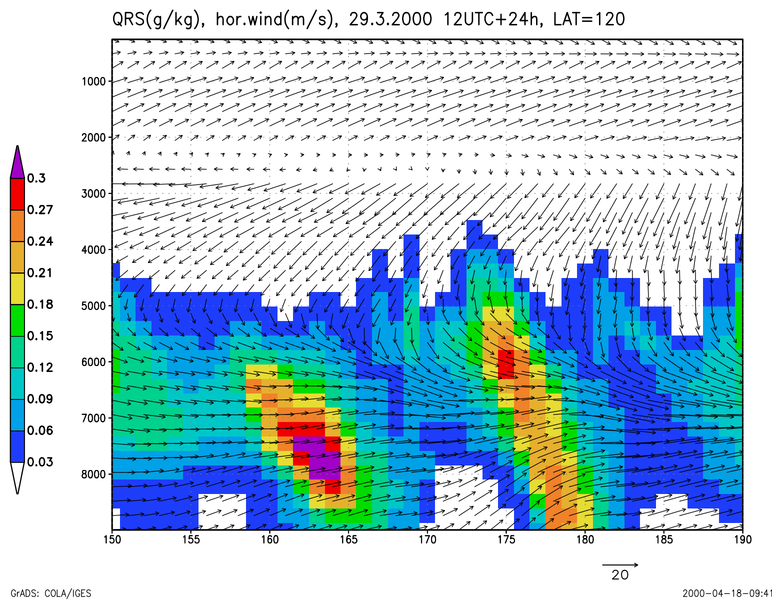

Figure 5: Vertical west–east cross section over the Rhine valley near Freiburg

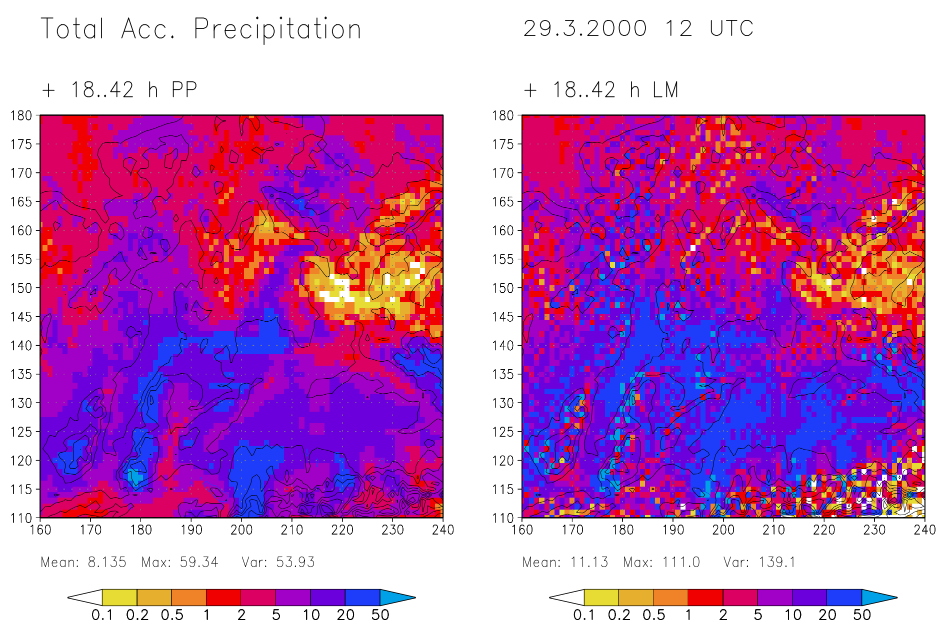

Figure 6: 29.3. 2000: Prognostic and diagnostic scheme precipitation results