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ASSIMILATION OF RADAR DATA IN THE MESOSCALE NWP-SYSTEM OF DWD

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ABSTRACT

The limited-area model Lokal-Modell (LM) of DWD is a non-hydrostatic mesoscale model for short-range numerical weather prediction (NWP). For operational purposes, the LM gets boundary values provided by the global model (GME) of DWD and the initial state is generated by an assimilation scheme based on the nudging technique. Using conventional data like surface, radiosonde, aircraft and windprofiler measurements the focus is on the analysis of meso-alpha-scale structures. In view of the development of a very high-resolution version of LM dedicated to very short range NWP of severe weather, high-resolution precipitation data derived from radar networks are introduced in the assimilation. Using the Latent Heat Nudging (LHN) technique the thermodynamic quantities of the atmospheric model are adjusted in such a way that the modeled precipitation rates resemble the observed precipitation rates. Recent changes in model dynamics include a prognostic treatment of precipitation, which takes into account the drifting of precipitation. This is found to limit the validity of the basic assumption of LHN. The results from real case studies show that precipitation patterns are introduced in the analysis (data assimilation mode) in good agreement, both in position and amplitude, with those observed by radar if precipitation is calculated diagnostically. The performance of LHN becomes worse if the prognostic treatment of precipitation is deployed. During the free model run (forecast mode) the impact of LHN is limited to several hours. However, some recent tests show, that several adaptations to the conventional LHN scheme are necessary in order to reestablish the good performance of LHN during the assimilation run and to get a positive impact on the free forecasts.
After a short introduction to the LMK project the challanges of a prognostical treatment of precipitation are lined out. The impacts on the LHN algorithm will be discussed and possible adaptations will be illustrated. Finally the results of a short assimilation expieriment are shown.

1 INTRODUCTION

The project 'LMK' ('LM-Kuerzestfrist') was established at the German weather service (DWD) in mid 2003 within the scope of the 'Aktionsprogramm 2003'. The goal of this project is to develop a numeric weather prediction system for the very short forecast range (up to 18 h) and with a resolution on the meso-gamma scale (about 2.8 km). The emphasis of this development lies in the prediction of severe weather events related on the one hand to deep moist convection leading e.g. to super- and multi-cell thunderstorms or squall lines and on the other hand to interactions with fine scale topography which can induce e.g. severe downslope winds or Föhn-storms. The currently used LMK-configuration covers the domain of Germany, smaller parts of its neighbouring countries and also a bigger part of the Alpine region with $421 \times 461 \times 50$ gridpoints and a horizontal resolution of 2.8 km. The dynamical formulation of the LMK is based on the LM of the DWD (Doms and Schättler, 2002): it is a non-hydrostatic, fully compressible model in advection form. But there are some differences in the numerical formulation. LMK now uses a two-timelevel integration scheme based on the Runge-Kutta-method of third order for the prediction of the 3 cartesian wind components u, v, w, the pressure perturbation p' from a hydrostatic base state and the temperature T. This allows the use of an upwind advection scheme of fifth order in the horizontal with

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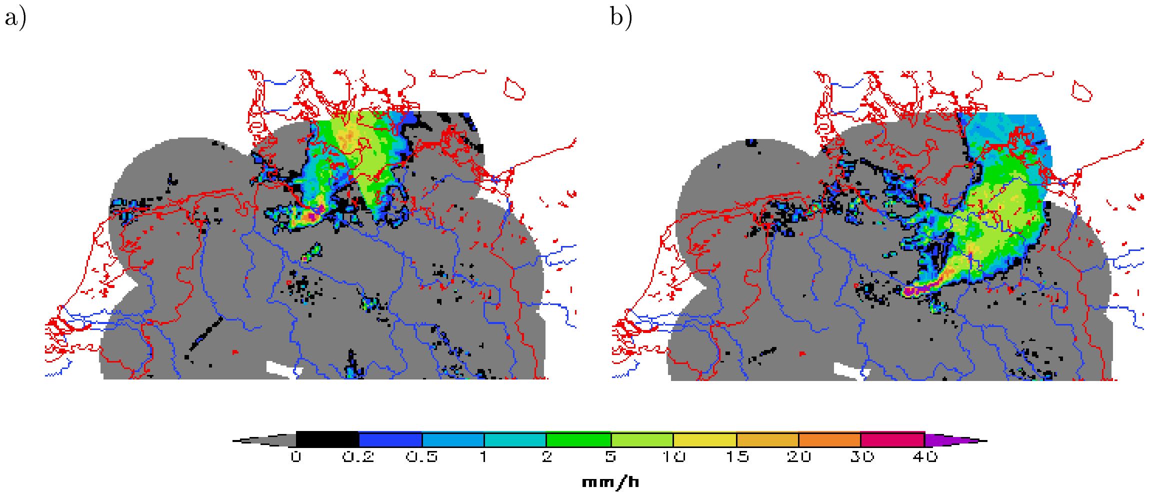

Figure 1: Current precipitation rate in mm/h (derived from radar) on 9th June 2004 at 6 UTC (a) and 8 UTC (b)

Courant-numbers up to 1.4. For the 6 humidity variables (mass fractions of moisture, cloud and rain water, cloud ice, snow and graupel) several Courant-number-independent Euler- and Semi-Lagrange-schemes can be used. Idealised tests of this new dynamical core with linear mountain flow and nonlinear density current simulations performed very well.

One of the major changes from LM is that LMK will not longer use a deep convection parameterisation. Instead of this, LMK shall resolve at least the biggest parts of convection. For the smaller scales of convection the sligthly modified shallow convection scheme of the Tiedtke Cumulus parameterization scheme is used. This parameterization especially delivers the transport of moisture from the boundary layer to a height of about 3 km and therefore avoids the overestimation of low cloud coverage. Without a deep convection parameterization the need for a faster sedimenting ice phase seems to be necessary. Therefore the former 5-class microphysics scheme was extended by a new sedimenting class 'graupel'.

Within the framework of the development of LMK it is intended to use remote sensing data for the continuous data assimilation stream of LMK (Doms and Förstner, 2004). As the main focus of LMK is on the prediction of severe weather, we expect a beneficial impact from radar measurements on meso-γ scale structures in the assimilation cycle of LMK. Thus, in addition to the assimilation of conventional data, like surface and radiosonde measurements, as a first step 2D radar reflectivities derived from the German radar network will be introduced in the nudging-type analysis of LMK. Using the LHN technique (Jones and Macpherson, 1997) the thermodynamic quantities of the atmospheric model are adjusted in that way, that the modelled precipitation rates resemble the observed precipitation rates. Therefore the LHN depents on changes in the model characteristics as shown below.

2 INTERACTION OF PROGNOSTIC PRECIPITATION AND LATENT HEAT NUDGING

Due to complaints from forecast meteorologists as well as from hydrological authorities on a non-realistic distribution of precipitation in mountainous terrain, produced by the former operational forecasts of LM, a reconsideration of the numerical treatment of precipitation quantities within LM took place. These investigations on the topic of “Prognostic Precipitation” have been carried out by Gassmann (2003) and Baldauf and Schulz (2004). Resulting from this, since April 2004, the advection of hydrometeors is taken into account in the operational LM. Because the Latent Heat Nudging algorithm is highly sensitive to the 3D thermodynamical field of cloud and precipitation physics, the LHN has to be tested under these new circumstances of a changed treatment of grid scale precipitation, which will also be used in the LMK version. Results from preliminary experiments with a purely diagnostic precipitation scheme have shown that precipitation patterns can be assimilated, using the LHN algorithm, in good agreement with those observed by radar, both in position and amplitude (Klink and Stephan, 2004 and Leuenberger and Rossa, 2003) but later experiments using the “prognostic precipitation” revealed some problems with the LHN.

In order to test the performance of the LHN algorithm under the conditions and constraints of

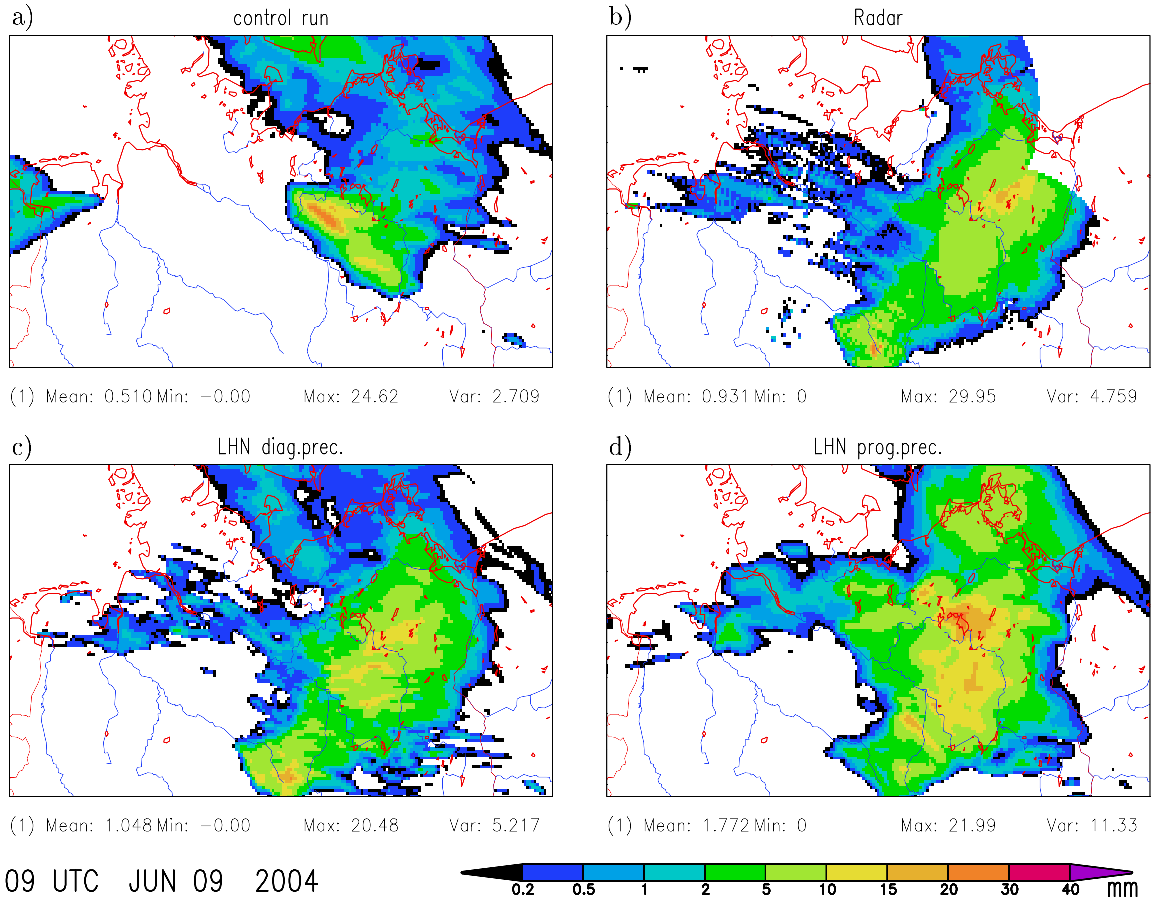

Figure 2: Hourly accumulated precipitation heights in mm on 9th June 2004 8-9 UTC: control run (a), radar observation (b), LHN run with diagnostic precipitation (c) and LHN with prognostic precipitation (d).

a prognostic treatment of precipitation a case study has been conducted for a convective event in summer 2004. During the morning hours of the 9th June 2004 a convergence line reached the northerly parts of Germany. Hamburg has been hit by a severe thunderstorm, which was part of this squall line approaching the land from the North Sea. This is outlined by fig. 1, which shows the current precipitation rate measured by the German radar network at 6 UTC (fig. 1a) and 8 UTC (fig. 1b).

For this case different assimilation runs testing the LHN in connection with diagnostic and prognostic precipitation have been carried out. Figure 2 displays hourly accumulated precipitation heights for the hour from 8 to 9 UTC for the radar measurements (b), the control run (i.e. Nudging without LHN) (a), a LHN run with diagnostic precipitation (c) and a LHN run with prognostic precipitation (d). When comparing fig. 2b and 2c we can see, that the LHN run with the conventional diagnostic precipitation scheme almost perfectly meets the patterns given by the radar measurements. In contrast to this, the run with LHN and prognostic treatment of precipitation (fig. 2d) shows a distinct overestimation of the mean precipitation amount. Furthermore the local maxima and minima, visible in the radar data (fig. 2b), are not in the correct position for this LHN run (fig. 2d). The results from other experiments confirmed, that there is a typical overestimation of precipitation and a misplacement of local extremes when using LHN in combination with prognostic precipitation. When searching for reasons for this bad performance of LHN under the conditions of a prognostic precipitation scheme we have reconsidered the general outline of the LHN algorithm and the basic assumption it acts on. This assumption is the proportionality between vertically integrated latent heat release and surface precipitation rate in one single column (Leuenberger and Rossa, 2003). This is based on the observation that relatively little moisture is stored in clouds. The proportionality itself allows to scale the modelled latent heating rate with the ratio of observed to modelled precipitation rate. But this relation is only valid for large scales and long time periods, where we can assume, that cloud and precipitation producing (mainly condensation) and cloud dissipating (precipitation) processes are balanced. No net storage of cloud liquid water and precipitation quantities takes place inside one column. A horizontal grid length of roughly 3 km in combination with an appropriate time step and an additional prognostic treatment of precipitation can be understood as a step towards cloud resolving models. This means, that the model itself is able to distinguish between updrafts and downdrafts inside convective systems. Because the main part of positive latent heat release (due to condensation) occurs in updrafts and strong precipitation rates are often connected with downdrafts, we can expect, that on cloud resolving scales areas with positive latent heating and patterns with strong precipitation rates will be located at different horizontal positions. Figure 3b exemplifies the changed thermal structures in convection cells, when advection of precipitation is taken into account, while fig. 3a shows the well known strong correlation of latent heat release and precipitation rate for a simulation with diagnostic treatment of gridscale precipitation. Recognising a northwesterly flow in this case, one finds that the area of positive latent heat release, which marks the region of cloud and precipitation formation, is a little bit ahead of the surface precipitation area (see fig. 3b). Due to this displacement the problem arises, that LHN temperature increments will probably be inserted in the wrong locations. The fact, that the correlation between the vertically integrated rate of latent heat release and the surface precipitation rate is significantly smaller for the simulation with prognostic precipitation compared to the diagnostic run is shown by fig. 4. Thus, we have to state, that the use of prognostic precipitation reduces the validity of the basic assumption of the LHN algorithm.

Furthermore it takes some time for the precipitation to reach the ground with the prognostic treatment. The scheme does not notice immediately, when precipitation has already been activated by the temperature increments of LHN On account of this new situation, the LHN scheme, implemented in the LM, had to be revised. Tthe following section described, which adaptations are possible and useful.

3 POSSIBLE ADAPTATIONS TO THE CONVENTIONAL LHN SCHEME

As mentioned above there are two major challenges when treating the precipitation prognostically. First of all, this is strongly related to the temporal and spatial characteristics of the prognostic precipitation itself. One can show that the temporal effect of drifting of precipitation particles is much more important for the LHN-approach than the spatial displacement. The temporal delay leads to a lack of feedback between the temperature increment and the forced precipitation. To tackle this problem an immediate information, of how much precipitation the temperature increment has initialised already, is necessary within each time step. This information is used as a reference in the comparison of modelled with the observed precipitation rates to measure the essential scaling factor. The LHN increment is calculated with respect to the ratio of observed to modelled precipitation rate. This ratio minus 1 gives the essential scaling factor:

$$
\begin{aligned}
\Delta T_{LHN}(z) &= \alpha \cdot \Delta T_{LatentHeatRelease}(z) \\
\text{with} \qquad \alpha &= \left(\frac{RR_{Obs}}{RR_{Mod}} - 1 \right)
\end{aligned}
$$

As a reference, the diagnostically calculated precipitation rate could be used. For this purpose an additional call of the former cloud microphysics scheme is enforced. This additional calculation must not have any further effect on the simulation, i.e. no feedback on other model variables is performed. It just diagnoses the amount of precipitation which will fall out at once within each separate vertical column. This reference precipitation rate can not be compared with the precipitation rate of the former diagnostic treatment. It is quite different to both the former diagnostic and the new prognostic model precipitation rate. However, it gives an indication of the effect of the LHN up to the certain time. Unfortunately this precipitation rate is hard to interpret. It does not match the actual rate and therefore has to be calibrated.

A more sophisticated solution might be the application of the vertically integrated precipitation flux as a reference. As any preicpitation constituent of the model is now a prognostic variable, the model holds the information of the amount of precipitation, which is currently stored within each single vertical column. To achieve a reference quite similar to the current precipitation rate at the ground, we have to evaluate the

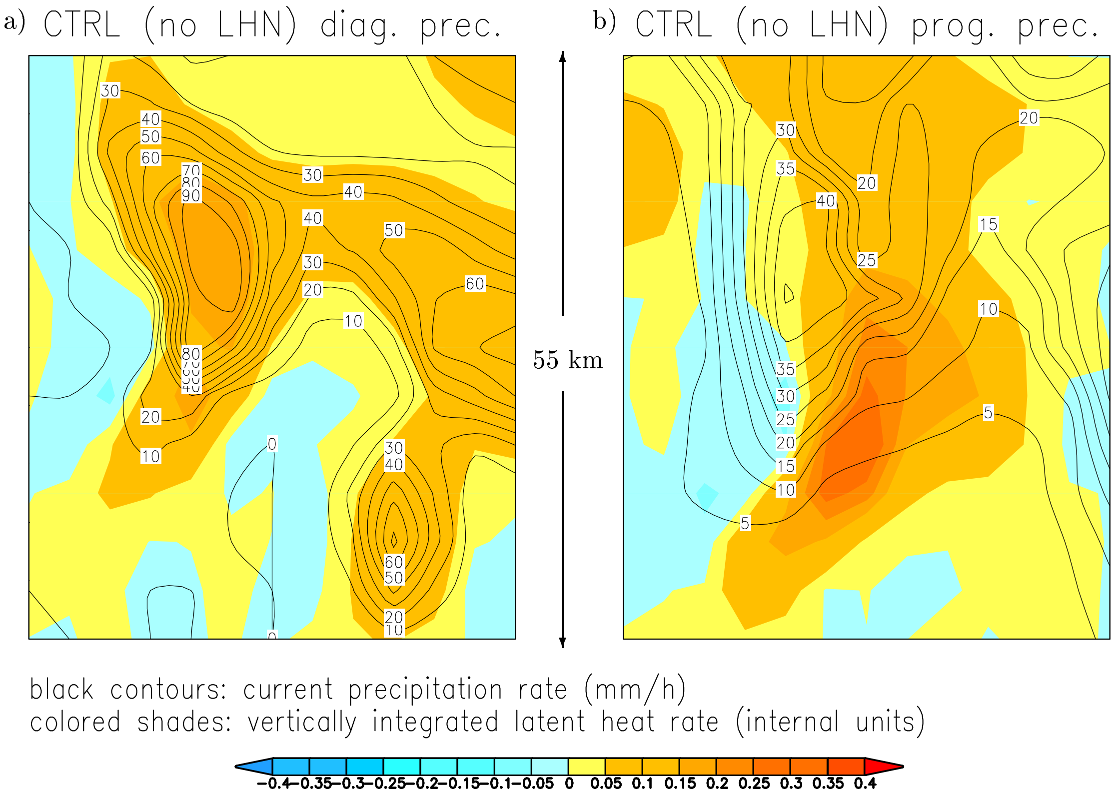

Figure 3: Horizontal fields of vertically integrated latent heat rate (shaded colours) and current precipitation rate at the ground (black contours) for a run with diagnostic precipitation (a) and prognostic precipitation (b).

flux of each preicpitation constituent. The sum of these fluxes is vertically integrated starting from a certain layer down to the ground. This top layer is defined as the layer, in which the sum of the precipitation fluxes is higher than the chosen threshold of the LHN approach (i.e. 0.1 mm/h). The given integral can be used as a reference for the LHN and has a significant benefit on the LHN results. After some tests we decided to use this integral instead of the diagnostically calculated precipitation rate.

The second challenge is found to be as the change of the spatial structure of latent heat release within the model. In contrast to the diagnostic treatment of precipitation, latent heat release is now layered more horizontally than vertically. Very high values of latent heat release will be found in the updraft regions at the leading edge of a convective cell. No precipitation will reach the ground, there. Further upstream the release of latent heat becomes weaker and the precipitation rate arises. In terms of correlation of precipitation rate and latent heat release it means that within the same vertical column there is a weak correlation at an early state of a convective cell, a higher positive correlation in the middle of its lifetime and a weak negative correlation at the end of the lifetime. This feature strongly influences the effects of LHN. To consider these influences it has to be checked, if the original LHN scheme is still consistent. Especially all the control parameters have to be recalibrated in order to take into account the higher amounts of latent heat release. One essential effect will be discussed here in more detail. Performing prognostic precipitation will get vertical columns with a certain precipitation rate at the ground but no appreciable latent heat release above it. This will take place mainly in upstream regions of a convective cell, where the cell is almost dissipated. At these locations the model generally produces negative values of latent heat release due to evaporation of precipitation. In the case, that too much precipitation is modelled at these grid points (i.e. $\alpha < 0$), the resulting temperature increment will be positive. This of course will increase the precipitation rate instead. Therefore it is necessary to assure that increments will only be inserted at the right vertical layers. At grid points, where the precipitation rate of the model has to be increased, only positive temperature increments are added and negative increments at grid points where the

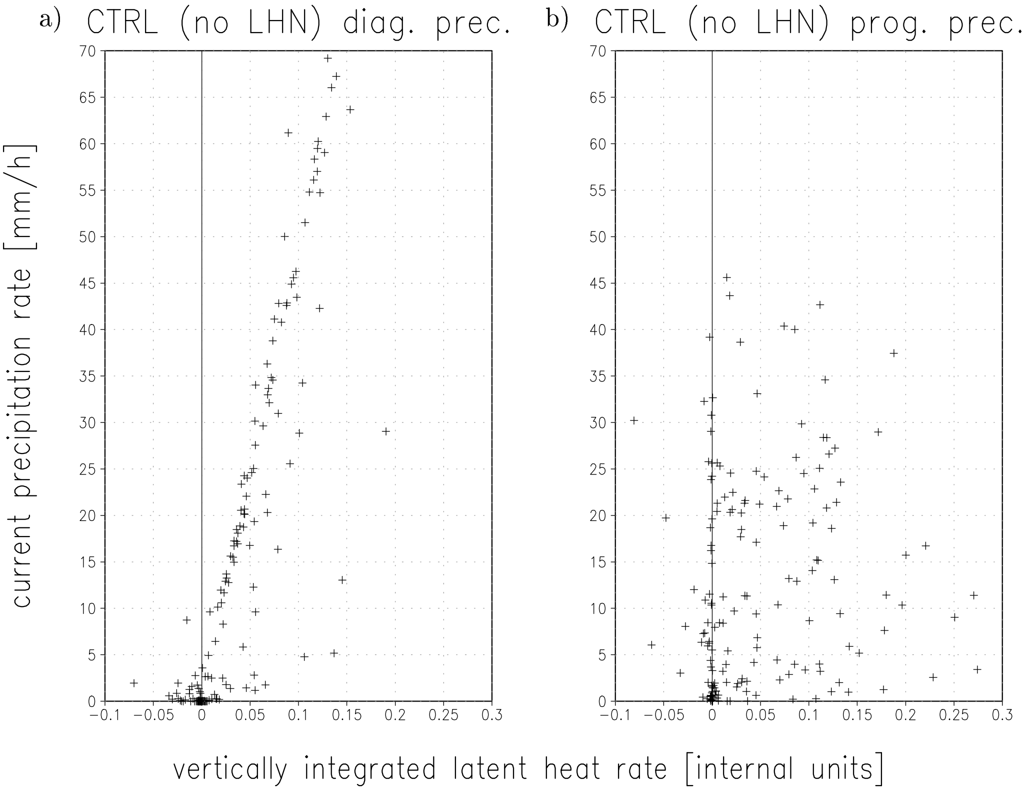

Figure 4: Scatterplots of vertically integrated latent heat rate and current precipitation rate at the ground for a run with diagnostic precipitation (a) and prognostic precipitation (b).

model produces higher amounts than the observations. This means that LHN increments are inserted only in layers with positive values of latent heat release.
One suggestion to tackle the less important spatial displacement of the precipitation constituent is to spatially smooth the fields of observed as well as modelled surface precipitation rate and the 3D field of latent heat release, in order to get a better correlation of precipitation and latent heating. Of course, this would lead to a loss of information on the grid scale.

Figure 5 shows the hourly sum of precipitation for different LHN configurations (panels c to h) in comparison with the radar observation (panel a) and a simulation without LHN at all (panel b) for the 8th July 2004 9 UTC after 6 hours of assimilation. For panel c we just used the original LHN configuration maintained in all the runs with diagnostic precipitation but used the prognostic treatment of precipitation. This implies the use of:

- an additional moisture adjustment,
- vertical filtering of the increments,
- search for nearby profiles at grid points without appreciable precipitation and
- LHN parameters as follows:
  - upper limit of the ratio is set to 3.0 (i.e. $\alpha <= 2$),
  - lower limit of the ratio 0.3 (i.e. $\alpha >= -0.7$) and
  - nudging coefficient equal 1.0.

Again, we get a strong overestimation of precipitation due to the LHN. In the simulation for panel d we just changed the upper limit of the ratio to 1.5 (i.e. $\alpha <= 0.5$). This has a distinct effect on the forecast. The overestimation is not as strong as before and the locations of the patterns fit better, as well. In the next step of development we apply the LHN increments only in certain vertical layers as mentioned above. The results look quite good, even though the precipitation is underestimated now. So far, all the LHN simulations used the delayed prognostic model precipitation as reference. Using an immediate precipitation reference yields some additional benefits, especially in position and structure of the precipitation patterns. As a matter of fact, the application of a precipitation reference

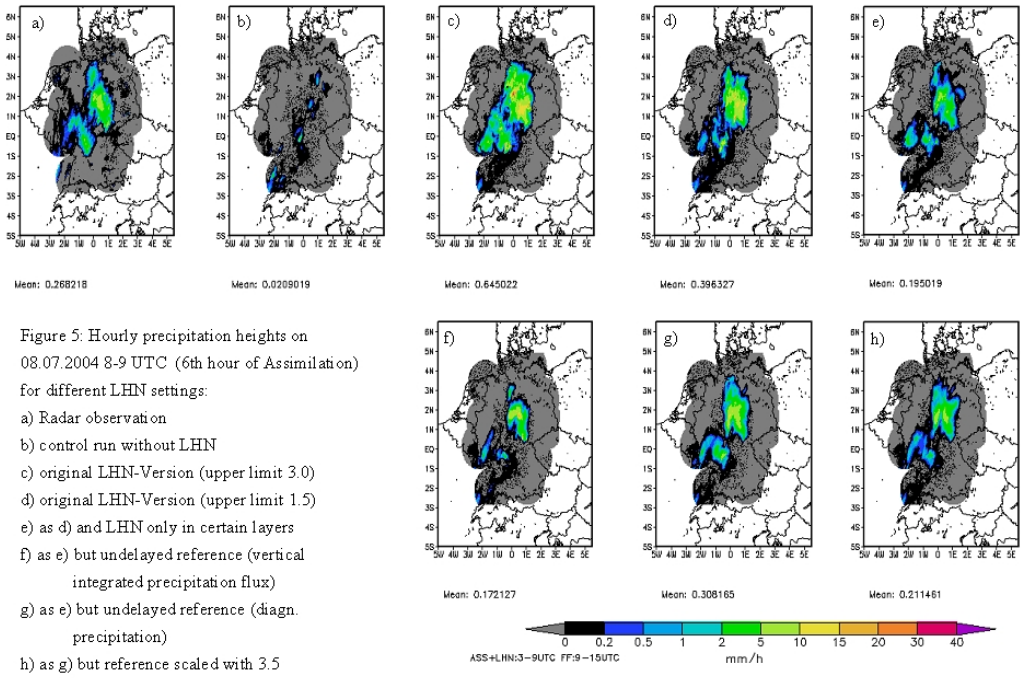

Figure 5: Hourly precipitation heights on 08.07.2004 8-9 UTC (6th hour of Assimilation) for different LHN settings:
a) Radar observation
b) control run without LHN
c) original LHN-Version (upper limit 3.0)
d) original LHN-Version (upper limit 1.5)
e) as d) and LHN only in certain layers
f) as e) but undelayed reference (vertical integrated precipitation flux)
g) as e) but undelayed reference (diagn. precipitation)
h) as g) but reference scaled with 3.5

Figure 5: Hourly precipitation on 8th July 2004 8-9 UTC (after 6 hours of assimilation) for different LHN configurations. Panels b) - h) shows the prognostic precipitation of the model

within the LHN approach is still under investigation. Nevertheless the results of newer experiments (not shown here) suggest that the vertical integrated precipitation flux appears to be more useful than the diagnostically derived precipitation rate.

4 CASE STUDY WITH LHN AND A REFERENCE PRECIPITATION

In order to test the previously mentioned adaptations to the LHN algorithm and to assess the effectiveness of LHN under the new circumstances, we carried out an assimilation cycle covering 10 days and 3 daily forecasts starting at 00, 12 and 18 UTC at each of these days. The period starting on the 7th July 2004 mainly covers convective precipitation events. For these simulations we chose the LMK configurations for the general model setup and the following adopted LHN features:

- use of a reference precipitation (vertical integrated precipitation flux),
- LHN-coefficient: 1.0, upper limit: 2, lower limit: 0.5;
- applying temperature increments only in certain layers (more or less only in clouds).

For the purpose of comparison a control experiment without LHN was made. Figure 6 shows mean Equitable Threat Scores (ETS) and mean Frequency Biases (FBI) for hourly accumulated precipitation heights for a threshold of 0.1 mm for the assimilation run and the free forecasts starting at 18 UTC. The use of the LHN algorithm leads to continuously improved analyses states during the assimilation. This is shown by the higher values of ETS in fig. 6a. This positive impact of radar data is still visible in the free forecasts for up to 7 hours (fig. 6b) on average. However, there is also a weak but persistent increase in the FBI present, which most of the time during assimilation tends towards the desired value of 1.0 (see fig. 6c). The greater values of FBI after the 8th hour of the 18 UTC forecasts (fig. 6d) points out that the performance of LHN is still improvable. But these values as well as the values in the night time hours of the assimilation run can probably be explained by a too low number of precipitation events during the hours from 0 until 6 UTC.

5 SUMMARY AND OUTPUT

Applying a conventional Latent Heat Nudging scheme in combination with a prognostic treatment of precipitation did not work well, and in

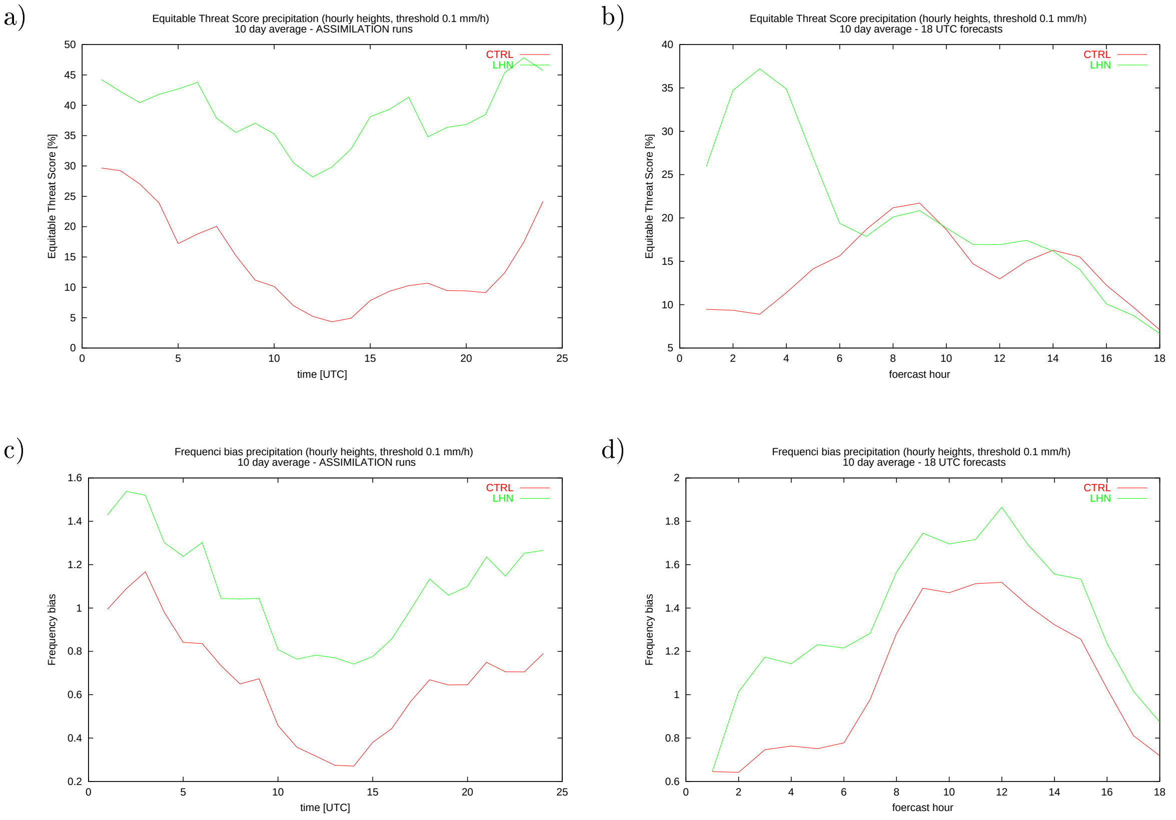

Figure 6: Mean Equitable Threat Scores and Mean Frequency Biases for hourly Precipitation heights (threshold 0.1 mm) for assimilation runs (a) and (c) and for 18 UTC forecasts (b) and (d). The Mean scores were obtained by averaging over a 10 day period.

particular resulted in an overestimation of precipitation during the assimilation. Investigations revealed that this is mainly because of two properties of the 'prognostic precipitation' scheme which tend to violate the proportionality between vertically integrated latent heat release and surface precipitation that is assumed in the LHN approach. Firstly, precipitation needs a certain time to reach the ground, and secondly, the areas with largest precipitation flux are displaced from the regions with strongest latent heating. fter adapting the LHN scheme appropriately, the model is again able to simulate the precipitation patterns in good agreement with radar observations. Moreover, in the free forecast, the skill scores of simulations with the adapted scheme become even better than for simulations with the former diagnostic treatment of precipitation. With respect to a 10 day simulation period in summer 2004, we can observe a benefit of LHN up to several hours within the free forecast. Further adaptations and tuning of the LHN scheme are possible and could lead to further improvements , as for instance spatial smoothing of precipitation fields and fields of latent heat release. In addition, simulations over longer periods in summer and winter are necessary, to decide on the operational use of the LHN approach.

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