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Assimilation of radar data in the mesoscale NWP-model of DWD

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Abstract. In the area of mesoscale modelling at DWD a very high resolution model for very short term numerical weather prediction (NWP) based on the existing non-hydrostatic limited area model Lokal-Modell (LM) is under development. In addition to the assimilation of conventional data, high-resolution precipitation data derived from radar networks are introduced in the Nudging-type assimilation of the LM. 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. Basic investigations of the LHN algorithm have been carried out in a case study of a convective situation. The results from these investigations show that precipitation patterns are introduced in the assimilation runs in good agreement, both in position and amplitude, with those observed by radar. During free forecast the influence of the assimilation of radar derived precipitation rates lasts for several hours.

1 Introduction

In the matter of mesoscale modelling at DWD a very high resolution model for very short term numerical weather prediction based on the existing non-hydrostatic limited area model Lokal-Modell (LM, Doms and Schättler (1999)) is under development. It is intended to run this LMK ("LM Kürzestfrist", German: LM for very short term prediction) every 3 h with a forecasting range of 18 h. This version of LM should be run with a horizontal mesh size of 2–3 km and 50 vertical levels on a domain of 1300 km × 1300 km covering Germany. One of the main purposes of this new model is to provide the hydrological models of flood forecasting systems with input data with a high update rate. Especially to improve the quantitative precipitation forecasting (QPF), work has to be done in the area of data assimilation. In addition to the use of conventional data, such as surface, radiosonde, aircraft and wind profiler measurements, high-resolution precipitation data derived from radar networks are introduced in the Nudging-type assimilation of the LM(K). During the last years different methods, including variational as well as Nudging-type schemes, have been developed for the assimilation of precipitation data (Alberoni et al., 2001). In the framework of the project RADVOR-OP funded by a working group of the hydrological authorities of the German federal states the use of radar data in the assimilation scheme of the LMK will be made operational. The assimilation scheme of LM(K) is based on the Nudging. One main feature of this 4D method is that the prognostic variables of the model are relaxed towards the observations during a characteristic time frame. An advantage of this scheme is the possibility to use asynoptic observation data for the assimilation as well. Nudging works in that way, that a relaxation term is added to the prognostic model equations, so that the temporal development of an arbitrary prognostic variable $\Psi(\boldsymbol{r}, t)$ reads as

$$\frac{\partial}{\partial t}\Psi(\boldsymbol{r}, t) = F\left(\Psi(\boldsymbol{r}, t)\right) + G_\Psi \cdot \sum_{k_{obs}} W_k(\boldsymbol{r}, t) \cdot \left[\Psi_k^{obs} - \Psi(\boldsymbol{r}, t)\right]. \qquad (1)$$

In Eq. (1) F represents the complete model dynamics and physical parameterisations. The second addend on the right hand side of Eq. (1) is the relaxation term (i.e. the stimulation caused by observation increments). Ψ_k^{obs} is the k-th observation, which influences the value of Ψ at gridpoint $\boldsymbol{r}$ at time t. W_k is the appropriate observation-dependent weight and G_Ψ the so called Nudging coefficient. By choice of the value for G_Ψ it is guaranteed that in practical applications the Nudging term should and usually does remain smaller than the largest term of the dynamics. This situation is related to the basic idea of the method that the model fields are to be relaxed towards the observed values without significantly disturbing the dynamic balance of the model (Schraff and Hess, 2002). An disadvantage of this assimilation scheme is, that all observation data have to be transformed into one or several prognostic model variables.

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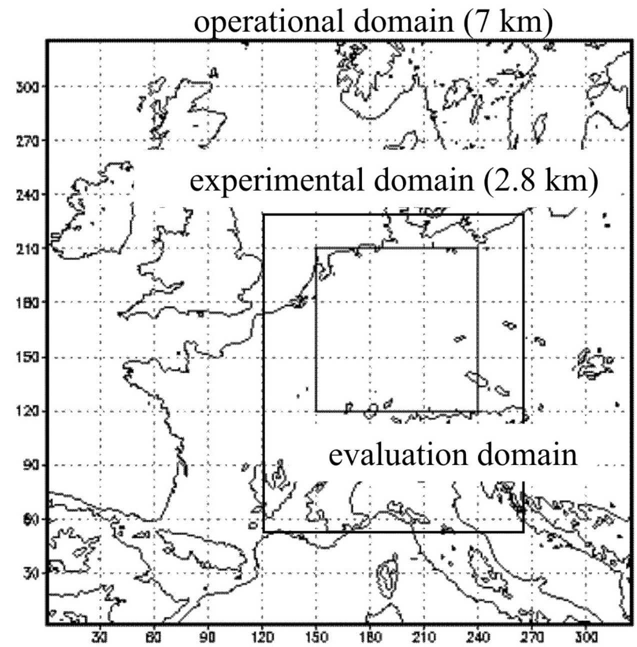

Fig. 1. Domains of interest.

2 Theory and Implementation

Contemplating an utilisation of radar reflectivities in the LM(K), it has to be stated, that a direct assimilation of both radar reflectivities and precipitation rates is not possible, because both quantities are no prognostic variables of the LM(K). Even a future prognostic treatment of precipitation in the LM(K) would not allow a reasonable direct assimilation of precipitation rates, because there is only a small feedback from the precipitation rate to model dynamics and physics. But these two components of the model are essential for the development of precipitation. Attempts have to be done in order to assimilate radar information into the model by the use of any other prognostic variables (e.g. temperature, specific humidity or components of the wind vector). Thus a relation between precipitation rate and prognostic model variables is needed. Concepts basing on processes, normally present in the context of precipitation, are desired. One special process connected with the formation of precipitation is the condensation of water vapour, which itself is directly linked to the release of latent heat. Originally, most condensation processes must be considered as the formation of cloud droplets, but this is only a preliminary stage of the precipitation forming. Nevertheless it is possible to influence the model dynamics and consequently the formation of precipitation by adjusting the model-generated latent heat release. The diabatic heating rates, which are related to phase changes of water, are tuned in that way, that the model simulates the observed precipitation rates. This is realized by adding temperature increments to the 3D temperature field. This method is called "Latent Heat Nudging" (e.g. Wang and Warner, 1988). A basic assumption to be considered when using the LHN algorithm is, that the vertical integrated rate of latent heat release is proportional to the precipitation rate. This assumption can be made, because raining clouds do not store more and more cloud liquid water in the course of time. It can be supposed that there is a balance between cloud forming (condensation) and cloud dissolving (precipitation) processes.

The attempt to correct these processes in the model is the addition of a LHN temperature increment to the equation describing the temperature tendency:

$$\frac{\partial T}{\partial t} = F(T) + \frac{\partial T_{Nudging}}{\partial t} + \frac{\partial T_{LHN}}{\partial t}. \tag{2}$$

According to the general Nudging Eq. (1), Eq. (2) describes the evolution of the temperature with time. The original prognostic model equation for T is expanded by an addend caused by the conventional Nudging and by a contribution due to the LHN. The LHN scheme implemented in the LM(K) is based on the algorithm described in Jones and Macpherson (1997). Their algorithm has been operationally and successfully used at the UK MetOffice since April 1996 (Macpherson, 2001).

An inaccuracy of the above mentioned assumption - proportion between vertical integrated rate of latent heat release and precipitation rate- is the fact that only the horizontal but not the vertical distribution of the rate of latent heat release can be derived from the 2D field of observed precipitation. Thus the model-generated rates of latent heat release are read as vertical profiles from the 3D model field and are afterwards scaled. An alternative could be the use of idealised profiles of latent heat release.

The contributions to the model-generated rate of latent heat release come from the cloud scheme, the parameterisation for grid-scale rain, the Nudging scheme (for conventional data) and if necessary from the convective parameterisation scheme. Because explicit simulation of convection is one aim of the development of the very high resolution model LMK at DWD, the convective parameterisation scheme has been switched off also for the experiments concerning Latent Heat Nudging.

The calculation of the LHN temperature increment is performed by scaling the model-generated latent heat rate with the ratio of analysed to modeled precipitation rate and subsequent subtraction of the model-generated part:

$$\Delta T_{LHN} = \left(\frac{RR_{ana}}{RR_{mod}} - 1\right) \cdot \Delta T_{LH_{mod}}. \tag{3}$$

The analysed precipitation rate is a weighted mean of observed and modeled precipitation rate:

$$RR_{ana} = w \cdot RR_{obs} + (1 - w) \cdot RR_{mod}. \tag{4}$$

Thus, at gridpoints where no radar-derived precipitation rate RR_{obs} is available ($w = 0$), the scaling factor and consequently the LHN temperature increment are zero. In order to prevent the LHN algorithm from producing too big temperature increments, both the scaling factor itself and the

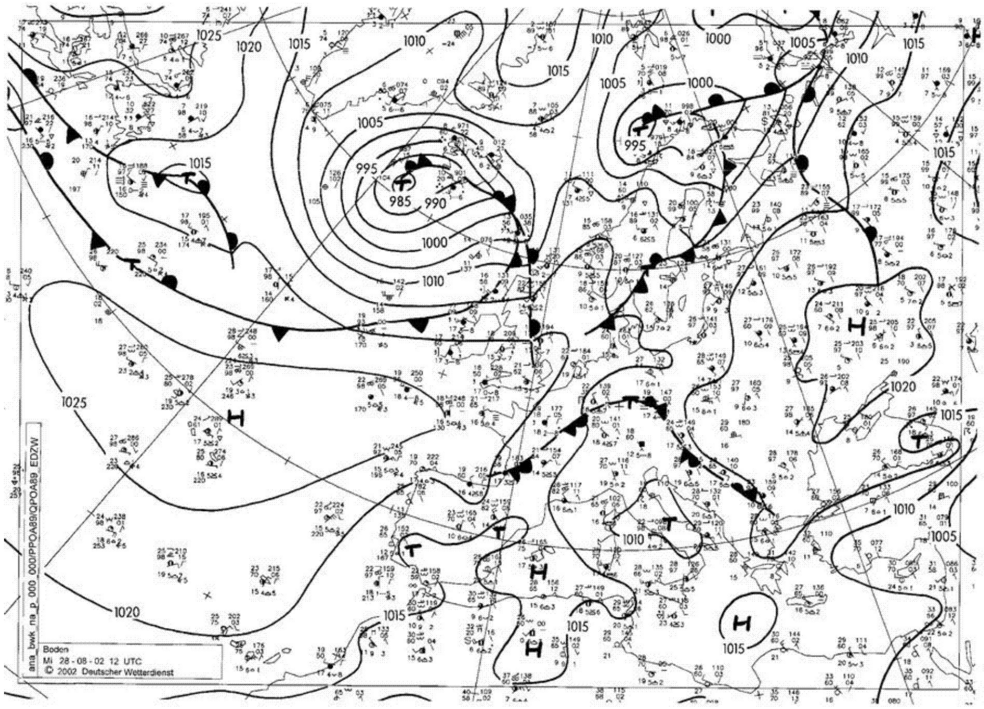

Fig. 2. Meteorological situation at August 28, 2002, 12 UTC.

temperature increments can be limited by imposing threshold values. In the case that the model is completely dry at a certain gridpoint, generally no vertical profile of latent heat release can be read from the model, because cloud forming processes and even clouds need not be present there. Thus, a gridpoint search for gridpoints with an appropriate precipitation rate and corresponding vertical profile of latent heat release can be performed as an optional feature of the LHN algorithm. The search radius is 10 gridpoints. When the gridpoint search fails, a climatological profile of latent heat release is used. Further procedures of the LHN algorithm, which can be used optionally, are:

– vertical filtering of the profile of latent heat rate

– horizontal filtering of the profile of latent heat rate

– adjustment of the vertical profile of specific humidity

Besides the tuning of the temperature profile at a certain gridpoint, the vertical profile of specific humidity at this gridpoint can be adjusted during the LHN. Depending on the sign of the temperature increment, specific humidity q is increased in order to reach a value of 100% of relative humidity (positive temperature increment) or specific humidity is decreased in order to retain relative humidity (negative temperature increment).

3 Preparation of Radar Data

Input data for the assimilation is the 2D field of the observed precipitation rate RR_{obs}. Starting point for the provision of the LHN scheme with radar derived precipitation rates is the international composite (PI), available at DWD. The measurements of radar reflectivities gained at each individual radar site of the German radar network and at several locations in the neighbouring countries are incorporated in this product. The local reflectivity product of the German radar network is derived from the volume scan. The data actually used are the echos next to the ground, coded in 7 reflectivity classes. The spatial resolution of the PI, which is originally delivered in polar-stereographic projection, is $4\,\text{km} \times 4\,\text{km}$. The product is available every 15 min. After a conversion of the reflectivity data into a precipitation rate by a simple Z-R-relation, an interpolation of the pixel values to the desired LM(K) grid is performed. Investigations of the LHN-algorithm by means of idealized experiments have shown, that a high update rate of radar data would lead to more realistic Nudging-analyses and subsequent forecasts (Leuenberger and Rossa, 2003). Thus and because of some other reasons, which will be mentioned below, a new radar composite basing on the DX product of DWD (spatial mesh: $1\,\text{km} \times 1^{\circ}$, time resolution 5 min) will be used as proxy data for the LHN scheme. This product will be provided by the project RADOLAN as a preliminary product of the gauge adjustment procedure, the project is dedicated to. An advantage of this product, which is derived from the precipitation scan, is the additional correction of orographic attenuation and the use of a variable Z-R-relation for the calculation of precipitation rates from echo intensities.

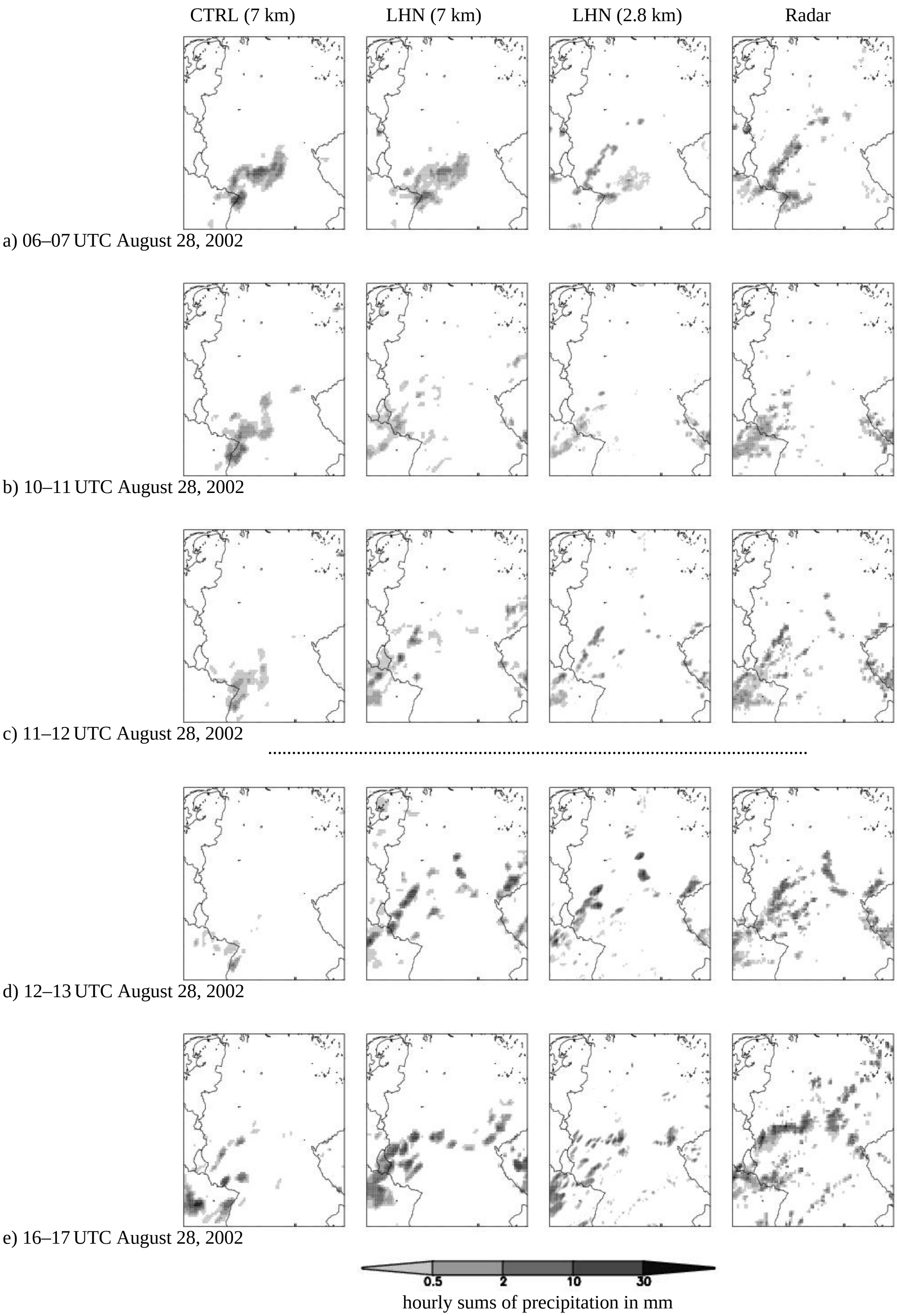

Fig. 3. Influence of the LHN on the Nudging-analysis depending on the mesh size of the LM, experimental setup: no convective parameterisation scheme, assimilation from 6–12 UTC, free forecast from 12–18 UTC, (1st column: CTRL (7 km), 2nd column: LHN (7 km), 3rd column: LHN (2.8 km), 4th column: Radar).

4 Case Study

For a selected event LM-runs on the operational domain (mesh size 7 km, 325×325 gridpoints, 35 vertical levels) and LMK-runs on an experimental domain (mesh size 2.8 km, 361×441 gridpoints, 40 vertical levels) have been carried out. Results of horizontal fields are presented on a limited evaluation domain. Figure 1 shows the geographical position of these domains. In general the convective parameterisation scheme has been switched off, in order to give the model the chance to directly simulate convection. The provisioning of the LM(K) with boundary data is done by the GME. After 6 hours of data assimilation (Nudging and Latent Heat Nudging, including humidity adjustment during the LHN) from 6–12 UTC a free forecast lasting from 12–18 UTC has been carried out.

4.1 Overview of the Meteorological Situation

At August 28, 2002 Germany was influenced by only small synoptic-scale pressure gradients. In the warm, moist and unstable air mass a development of showers and thunderstorms took place in the afternoon in the area of a quasi-stationary front, which lay over Germany. A synoptic chart of this situation is presented in Fig. 2. It was reported that heavy precipitation occured locally (e.g. 70 mm between 15.15 and 16.30 UTC in Herborn, Hesse and 85.5 mm within 4 h in Wissen, Rhineland-Palatinate).

4.2 Influence of the LHN on the nudging-analysis depending on the mesh size of the LM

In this paragraph three Nudging-analyses, one without LHN and two with different mesh sizes (7 km, 35 vertical levels and 2.8 km, 40 vertical levels respectively) are compared with radar derived precipitation rates. The 2.8 km run (LMK) was started at 21 UTC one day before by interpolating the analysis of the 7 km run (LM) to the finer mesh. Afterwards 9 hours of conventional Nudging were carried out in both suites independently. This is the reason for the distinct differences between the 7 km and 2.8 km run in the first hour (6–7 UTC) of Nudging and LHN, as can be seen in Fig. 3a. In this case the simulation on the finer grid contains less erroneous precipitation as the corresponding run on the 7 km grid. Thus the LHN algorithm must not remove much misplaced precipitation from the run but mainly must insert precipitation at points where the model does not simulate precipitation so far. In the first hour of LHN this works much better on the finer grid than on the operational one. Throughout the next two hours the assimilation of observed precipitation rates turns out well in both LHN runs. In contrast to these LHN suites the control run shows a more extended area of precipitation, which is shifted moreover to the southeast. After that the convection weakens over a wide range (except Bavarian forest). Figure 3b shows that this happens in accordance with the Radar observations. But the convergence line remains in the Radar as well as in the LHN assimilation runs. During the last hour of assimilation from 11 to 12 UTC a revival of the convection can be observed in the Radar and in the LHN runs respectively but not in the control run. The assimilation of small convection cells e.g. in the Thuringian forest naturally works better in the 2.8 km run than in the 7 km one. All in all, the LHN experiments show precipitation patterns which fit much better to the corresponding radar derived observations than the control experiment without LHN. This good agreement is shown in Fig. 3c. At the beginning of the free forecast the convective cells are strongly intensifying in both LHN runs. Figure 3d displays that the simulated intensities of precipitation reach maxima, which are clearly above the corresponding observations. At the same time the convective cells remain strongly limited in their horizontal extension. At this stage the control run shows a further weakening of precipitation in contrast with the radar measurements. Later on inaccuracies occur in the correct position and intensity of single convection cells. An interesting aspect is the occurence of small convective cells over the mountain ranges of Swabian and Franconian Alb between 16 and 17 UTC, as demonstrated in Fig. 3e. Besides the radar only the 2.8 km run shows these structures.

4.3 Sensitivity of LHN concerning humidity adjustment

Two LMK runs have been carried out on the experimental domain (mesh size 2.8 km), one run with humidity adjustment during the LHN, the other one without. After three hours of Nudging and simultaneous LHN both runs already show a good correspondence between their precipitation patterns and the distribution given by the radar observations, as one can see in Fig. 4a. While the position of the precipitation maxima is assimilated quite well, there are problems in areas with low precipitation rates. Especially the assimilation run without humidity adjustment still depicts areas with weak precipitation between 8 and 9 UTC, which already have been misplaced in the analysis at 6 UTC (compare to Fig. 3a) and could not be dried up completely throughout the following three hours. After another three hours of assimilation, i.e. within the last hour of Nudging and LHN, the position of the convergence line over the western part of Germany is reproduced well by both assimilation runs. At a first glance the precipitation patterns of the two assimilation runs, presented in Fig. 4b, do not seem to differ much. Figure 4c zooms in the area of Thuringian forest and in the mountains of “Erz- and Fichtelgebirge”. It can be seen, that the assimilation of the developing thunderstorms works better in the case of additional humidity adjustment. After three hours of free forecast, again the run with humidity adjustment during the LHN shows more realistic precipitation patterns than the corresponding run without humidity adjustment. From Fig. 4d we can derive that this is especially true when concerning the intensity but less in case of the position of the maxima of the predicted precipitation fields. Both simulations have in common, that the horizontal extension of precipitation patterns is much smaller than in the corresponding radar observations. The total amount of precipitation

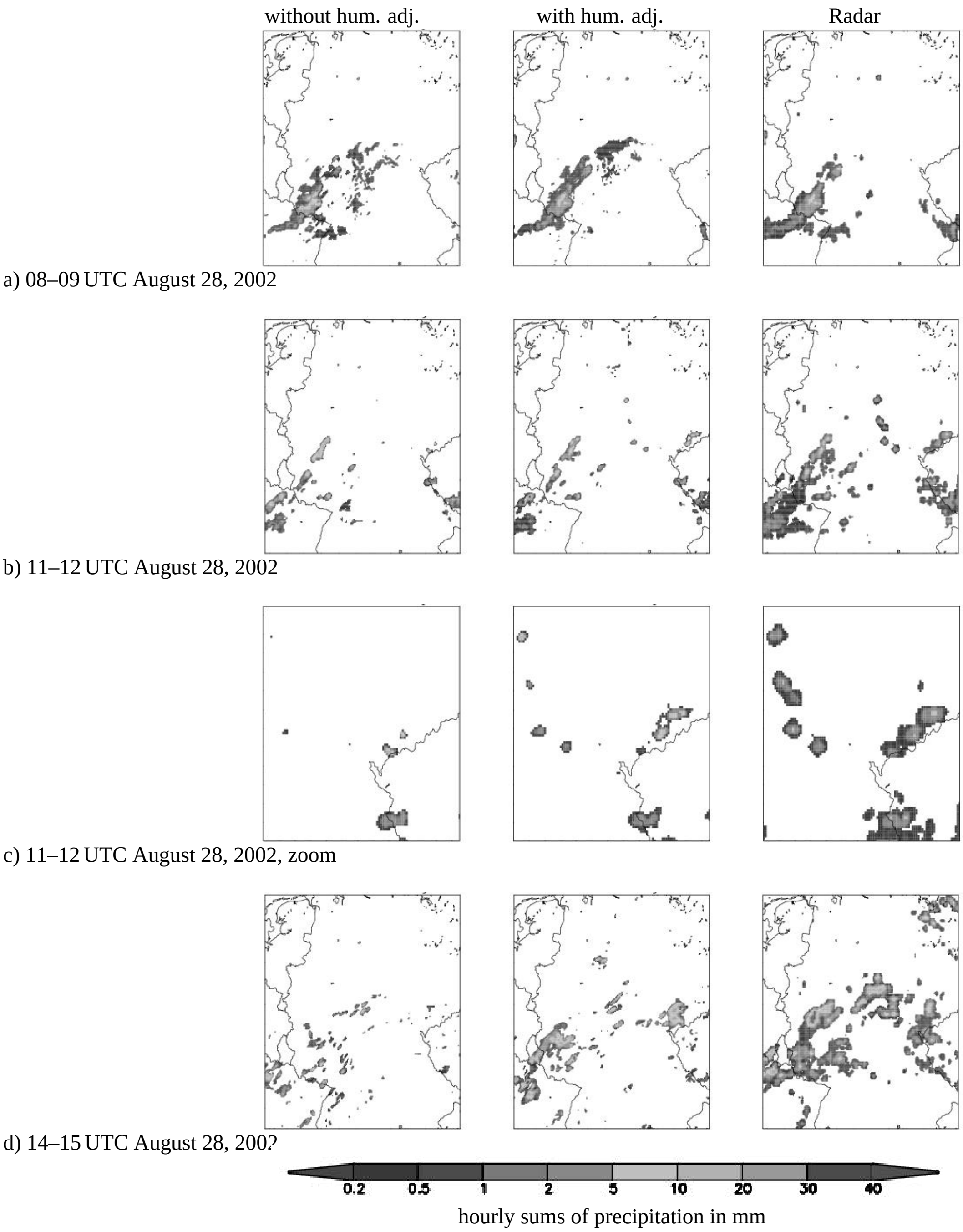

Fig. 4. Sensitivity of LHN concerning humidity adjustment, experimental setup: no convective parameterisation scheme, assimilation from 6–12 UTC, free forecast from 12–18 UTC, (1st column: without humidity adjustment, 2nd column: with humidity adjustment, 3rd column: Radar).

(integrated over the evaluation domain) is too small in the forecasts compared to the radar observations.

5 Conclusions

Incorporating the LHN-algorithm in the Nudging-type assimilation scheme of the LM(K) allows to assimilate the radar-derived precipitation rates during the assimilation runs very well. Experiments have shown that the explicit simulation of convection leads to more realistic results than model runs with parameterized convection. Using a finer grid within the simulation shows a potential for further improvements of the quantitative precipitation forecast. An additional humidity adjustment during the LHN results in a more exact analysis of the atmospheric state and in more realistic free forecasts. However, the positive impact of the radar data decreases rapidly during the free forecast. In order to understand this, more investigations of the 3D model state are carried out. The main focus is on the interactions between the process of LHN and the model dynamics.

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