Assimilation of extrapolated radar reflectivity into a NWP model and its impact on a very-short range precipitation forecast

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1. Introduction

Severe convective storms occur frequently in central Europe during summer. Most of these storms produce high rainfall rates, but their impact on the environment is negligible. Some storms, however, are accompanied by torrential rains that can accidentally cause local flash floods, which significantly impact inhabitants. It is very difficult to forecast the development of such events and their locations.

Recent high-resolution NWP models are supposed to be able to directly simulate at least the larger-scale elements of organized convection without using convective parameterization. The NWP models must include assimilation of the latest data, especially those data that contain information on convective processes in the atmosphere (e.g., radar, satellite, and lightning observations), to have a chance to forecast rapidly developing convective storms. The data assimilation not only adds the current data into the NWP model, but should also initialize convective-scale events. Number of papers from the last decade show that the assimilation of radar data (reflectivity or derived Doppler velocities) into a NWP model can significantly improve precipitation forecasts for the next several hours (e.g., Macpherson, 2001; Tong and Xue, 2005; Leuenberger and Rosa, 2007; Milan et al., 2008; Stephan et al., 2008; Dixon et al., 2009; Sokol, 2009; Sugimoto et al., 2009; Zhang, 2009). Although the positive effect of the assimilation usually disappears within a few hours, the improvement is useful for nowcasting of precipitation. Forecasts of such models, however, are time-consuming; therefore, they are not commonly used operationally for forecasts with lead times of one to three hours. However, with increasing computer power, one can expect that such models will substitute currently employed nowcasting models in the foreseeable future.

This paper deals with the nowcasting of convective precipitation, and it proposes a method assimilating observed and extrapolated radar reflectivity.

2. NWP model

The COSMO NWP model, version 4.8, was applied. This is a non-hydrostatic, compressible model formulated in advection form. The numerical solution uses a two-level integration scheme based on the Runge–Kutta method (Doms and Schaettler, 2002; Steppeler et al., 2003). The model was integrated in the area shown in Fig. 1 with a horizontal resolution of 2.8 km and with 50 vertical levels. The model time step was 30 s. The model was run without the parameterization of deep convection. The parameterization of shallow convection was included. The precipitation processes made use of five classes of hydrometeors (rain water, cloud water, snow, ice, and graupel).

The initial and lateral boundary conditions were derived from the prognostic fields of the COSMO-EU model, which started integration at 0000 UTC. This model is operated by the German Weather Service. The horizontal resolution of the COSMO-EU model is about 7 km. The boundary data were obtained by the linear interpolation of prognostic data, which were available at each hour of the integration time.

3. Assimilated data and assimilation method

Radar reflectivity fields at 2 km above sea level (CAPPI 2 km), which are the standard operational products of the Czech Hydrometeorological Institute (CHMI), were assimilated into the model. The CHMI operates two C-band radars at the Skalky and Brdy sites (Novak, 2007; Fig. 1). The measurements are available with a horizontal resolution of 1 km by 1 km with a temporal resolution of 10 min. The measured data were checked and controlled to minimise ground clutter and anomalous propagation artefacts. Ground clutters were removed using the Doppler filter, and vertical profiles of reflectivity were corrected using the method described by Novak and Kracmar (2002). Radar composites were composed from data of both radars, with the maximum value applied to overlapping coverage areas.

Optimal locations of radar sites with respect to topography ensure that there is no significant terrain blockage of radar echo in the reflectivity products. The elevation of the lowest radar beam is less than 1500 m for pixels in the Czech Republic (CR). The quality of the CHMI radar data is comparable to other data from European radar
networks (Michelson et al., 2004).

From the reflectivity measurements \((Z, \text{dBZ})\) at CAPPI level 2 km, rain rates \((R, \text{mm/h})\) were calculated using the \(Z\–R\) relationship

\[
Z = 200R^{0.6}
\]  

(1)

where two corrections were applied: (i) to eliminate weak non-precipitation echoes, \(R\) is set to 0 mm/h for \(Z<7\) dBZ; and (ii) to reduce overestimation caused by hail, \(R\) is set to \(R = 99.85\) mm/h for \(Z > 55\) dBZ. The rain rates were assimilated into the model (see Section 4). For verification purposes, hourly precipitation fields were calculated using a merging procedure that combines radar-derived precipitation with hourly gauge measurements applied by the CHMI (Salek et al., 2004).

Radar reflectivity was extrapolated using a method of Lagrangian persistence. Assuming the motion field is constant in time, the extrapolated values were obtained going backward along the trajectories of the motion field, which is derived from two consecutive radar measurements using the COTREC method (Novak et al., 2009). The two latest radar scans in the assimilation window were used. Trajectories were calculated with the same time step as the COSMO model, i.e., \(\Delta t = 30\) s. This procedure of forecasting radar reflectivity is very fast, and it has negligible impact on the model’s time consumption.

The assimilation technique is based on a water vapour correction (WVC) method (Falkovich et al. 2000; Sokol and Rezacova, 2009; Sokol, 2009). This method consists of adding or removing water vapour into or from the model’s water vapour mixing ratio, \(q_v\). Oversaturation or undersaturation, which can follow corrections for water vapour, result in the release or absorption of heat, which invokes changes in the model’s temperature. This mechanism is similar to the latent heat nudging method, which is the standard option of the COSMO NWP model (Stephan et al., 2008).

The WVC method corrects model \(q_v\) according to the difference \((D)\) between the model \((R_{\text{mod}})\) and the observed rain rates \((R_{\text{obs}})\):

\[
D = q(R_{\text{obs}}) - q(R_{\text{mod}})
\]

(2)

where

\[
q(R) = \frac{70.2026 \times 10^4}{\rho} R^{0.9143}
\]

(3)

and \(\rho\) denotes the air density \((\text{kg m}^{-3})\). The formula (3) results from an empirical relationship employed by Hagen and Yuter (2003). If \(D > 0\) in (2), the model underestimates observed precipitation, and \(q_v\) is increased at each model level \((k)\) by \(\text{DIF}\):

\[
q_{v,k}^{\text{new}} = q_{v,k} + \text{DIF}
\]

(4)

where

\[
\text{DIF} = \text{MIN}(w(z_k) \alpha D, \delta)
\]

(5)

and

\[
\delta = \text{MAX}(\varepsilon_+ + q_{v,k}(T_k) - q_{v,k,0})
\]

(6)

Here, \(\alpha\) and \(\varepsilon_+\) are constants, \(q_{v,k}\) is the water vapour mixing ratio at the \(k\)th model level, and \(q_{v,k,0}\) is the saturation value of \(q_v\) at the temperature at level \(k\) \((T_k)\). The weighting function \(w\) depends on the height \(z_k\) (in m), which is the height of the \(k\)th model level above sea level at the grid point, where the assimilation is performed. Function \(w\) is defined by the following relations:

\[
w(z_k) = 0 \quad \text{for } z_k \leq 1000, \quad \text{(7a)}
\]

\[
w(z_k) = (z_k - 1000) / 500 \quad \text{for } 1000 < z_k \leq 1500, \quad \text{(7b)}
\]

\[
w(z_k) = 1 \quad \text{for } 1500 < z_k \leq 5000, \quad \text{(7c)}
\]

\[
w(z_k) = 1 - (z_k - 5000) / 5000 \quad \text{for } 5000 < z_k \leq 8000, \quad \text{(7d)}
\]

\[
w(z_k) = 0 \quad \text{for } z_k > 8000. \quad \text{(7e)}
\]

If \(D < 0\), then \(q_v\) is decreased by \(\text{DIF}\):

\[
q_{v,k}^{\text{new}} = q_{v,k} - \text{DIF}
\]

(8)
4. Evaluation of precipitation forecasts using the observed and extrapolated radar reflectivity

The impact of the assimilation of observed and extrapolated radar reflectivity was evaluated for nine convective events that occurred in June and July 2009. The common feature of these events is that convective storms developed in the afternoon and evening. They caused local heavy precipitation with high rain rates. Several storms were followed by local flash floods. The driving model, COSMO-EU, as well as ALADIN NWP model operated by the CHMI in all cases forecasted possibility of convective storms but large majority of the forecasts were inaccurate in space and in values of forecasted storms.

The evaluation of precipitation forecasts by COSMO-CZ stems from a comparison of the forecasts with observations both by eye and by objective verification using the Fractions Skill Score (FSS; Roberts and Lean, 2008). The FSS compares the fractional coverage in forecasts with the fractional coverage derived from observations over different-sized neighbourhoods (squares). The fractional coverage is determined as the number of points that have values exceeding a given threshold. Therefore, the FSS depends on the size of the squares and on the threshold values used to calculate the fractional coverage. The values of the FSS range from 0 (completely wrong forecast) and 1 (perfect forecast). A FSS value, which is considered to indicate a reasonably skilful forecast, is $FSS_{uni} = 0.5 + f_o/2$, where $f_o$ is the fraction of observed grid points exceeding the given threshold in the evaluated domain. The $FSS_{uni}$ represents the FSS that would be obtained at the grid scale from a forecast with $f_o$ at every grid point (uniform FSS; Roberts and Lean, 2008). In the case of convective events, like those used in this study, the mean precipitation over the model domain is very low. If the threshold is sufficiently high, then $f_o$ is close to 0, and consequently, the $FSS_{uni}$ is close to 0.5. Therefore $FSS=0.5$ was used to indicate a reasonably skilful model forecast.

4.1 Organization of tests

Basic information about evaluated forecasts is given in Table 1. Altogether we evaluated 45 calculations and for each of them we evaluated hourly precipitation forecasts for lead times from 1 to 4 hours. Longer forecasts are not influenced by the initial conditions (assimilation) and depend only on lateral boundary conditions. Schematic representation of the forecasts is shown in Fig. 2.

4.2 Evaluation by eye

All forecasts obtained by COSMO-CZ without assimilation (COS), with the assimilation of only radar reflectivity (COBS) and with the assimilation of both observed and extrapolated radar reflectivity (CEXT) were subjectively evaluated. As COS forecasts were apparently less accurate than forecasts by COBS and CEXT in most cases, they are not discussed in the following text.

It is worth mentioning that the evaluation results by eye and FSS are similar in most cases because high values of FSS correspond to subjectively good forecasts and vice versa. The difference may appear when FSS significantly depends on the threshold values.

The subjective evaluation has showed that CEXT yields significantly better forecasts than COBS and the biggest improvements occur in 2nd and 3rd forecasting hours. Cases when COBS provide more accurate forecasts than
CEXT are very rare. Fig. 3 and 4 shows two examples of forecasts.

Table 1. List of forecasted and evaluated events

<table>
<thead>
<tr>
<th>Date</th>
<th>Beginning of the integration [UTC]</th>
<th>Beginning of the forecast [UTC]</th>
<th>CAPE [J/kg]</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 June, 2010</td>
<td>09</td>
<td>12, 13, 14, 15, 16</td>
<td>5</td>
<td>Frontal convection</td>
</tr>
<tr>
<td>25 June, 2010</td>
<td>09</td>
<td>12, 13, 14, 15, 16</td>
<td>1320</td>
<td>Convection</td>
</tr>
<tr>
<td>26 June, 2010</td>
<td>09</td>
<td>12, 13, 14, 15, 16</td>
<td>1549</td>
<td>Convection</td>
</tr>
<tr>
<td>29 June, 2010</td>
<td>09</td>
<td>12, 13, 14, 15, 16</td>
<td>1307</td>
<td>Frontal convection</td>
</tr>
<tr>
<td>30 June, 2010</td>
<td>09</td>
<td>12, 13, 14, 15, 16</td>
<td>2070</td>
<td>Convection</td>
</tr>
<tr>
<td>1 July, 2010</td>
<td>09</td>
<td>12, 13, 14, 15, 16</td>
<td>2505</td>
<td>Convection</td>
</tr>
<tr>
<td>2 July, 2010</td>
<td>09</td>
<td>12, 13, 14, 15, 16</td>
<td>2405</td>
<td>Convection</td>
</tr>
<tr>
<td>3 July, 2010</td>
<td>09</td>
<td>12, 13, 14, 15, 16</td>
<td>3365</td>
<td>Convection</td>
</tr>
<tr>
<td>4 July, 2010</td>
<td>09</td>
<td>12, 13, 14, 15, 16</td>
<td>2461</td>
<td>Convection</td>
</tr>
</tbody>
</table>

FIG. 2 Schematic representation of the forecasts. Model starts integration at 09 UTC and radar data are assimilated within assimilation windows (green stripe). Two types of data assimilation (CEXT, COBS) are applied. In case of COBS only observed data are assimilated (green stripe) and the biginning of the red stripe corresponds to the beginning of the forecast. In case of CEXT, in addition to the observed data, also extrapolated data from the interval denoted by the label EXT are assimilated.

FIG. 3. Observed and forecasted 1-h precipitation totals for 29 June 2009, and for 1st, 2nd and 3rd hour. Forecast started at 15 UTC.
4.3 Evaluation by FSS

The accuracy of the forecasts was objectively evaluated by FSS for the threshold of 5 mm/h (see Section 4) and for elementary areas (EA) from 1 to 101 grid cells. Size of the cell is 2.8 km by 2.8 km. This evaluation using FSS agreed with the subjective evaluation given in Section 4.2. As follows from Figs. 5 and 6 for all beginnings of forecasts COBS is less accurate than CEXT on average. CEXT reaches the largest improvement of FSS for 2nd and 3rd lead hours. On the other hand the FSS values rapidly decrease for 4th and 5th hour which is related to the fact that the assimilation has little impact on the model forecasts for such long periods.
FIG. 6. Mean differences of FSS between forecasts by CEXT and COBS starting at 12, 13, ..., 16 UTC in dependence on lead times. The mean differences are shown for four selected days by colour curves (see Legend). The black line depicts the mean difference over all forecasts.

5. Conclusions

We demonstrated that a simple extrapolation technique can be used as a source of valuable data for assimilation. Assimilating extrapolated radar reflectivity data evidently improved precipitation forecast. The largest improvement was achieved for the 2nd lead hour but also for the 1st and 3rd hours the improvement was not negligible. For larger lead times we also found some improvement but the accuracy of the forecasts is low in general.

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References


