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Nowcasting of deep convective clouds and heavy precipitation: Comparison study between NWP model simulation and extrapolation

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ABSTRACT

An evaluation of convective cloud forecasts performed with the numerical weather prediction (NWP) model COSMO and extrapolation of cloud fields is presented using observed data derived from the geostationary satellite Meteosat Second Generation (MSG). The present study focuses on the nowcasting range (1–5 h) for five severe convective storms in their developing stage that occurred during the warm season in the years 2012–2013. Radar reflectivity and extrapolated radar reflectivity data were assimilated for at least 6 h depending on the time of occurrence of convection. Synthetic satellite imageries were calculated using radiative transfer model RTTOV v10.2, which was implemented into the COSMO model. NWP model simulations of IR10.8 μm and WV06.2 μm brightness temperatures (BTs) with a horizontal resolution of 2.8 km were interpolated into the satellite projection and objectively verified against observations using Root Mean Square Error (RMSE), correlation coefficient (CORR) and Fractions Skill Score (FSS) values. Naturally, the extrapolation of cloud fields yielded an approximately 25% lower RMSE, 20% higher CORR and 15% higher FSS at the beginning of the second forecasted hour compared to the NWP model forecasts. On the other hand, comparable scores were observed for the third hour, whereas the NWP forecasts outperformed the extrapolation by 10% for RMSE, 15% for CORR and up to 15% for FSS during the fourth forecasted hour and 15% for RMSE, 27% for CORR and up to 15% for FSS during the fifth forecasted hour. The analysis was completed by a verification of the precipitation forecasts yielding approximately 8% higher RMSE, 15% higher CORR and up to 45% higher FSS when the NWP model simulation is used compared to the extrapolation for the first hour. Both the methods yielded unsatisfactory level of precipitation forecast accuracy from the fourth forecasted hour onward.

1. Introduction

Nowcasting (i.e., very short-range forecasting) represents a powerful tool in warning the public against dangerous, high-impact weather events, including tropical cyclones, thunderstorms and tornados, which can cause flash floods, lightning strikes and destructive winds (www.wmo.int). In addition to nowcasting systems based on analogues approaches (Panziera et al., 2011; Atencia and Zawadzki, 2015), present systems for the nowcasting of processes related to convective activity can be divided in two main groups – extrapolation techniques (EXT) and numerical weather prediction (NWP) modelling.

The first group of methods is based on the extrapolation of convective cells by using either NWP model wind fields or motion fields that are derived from consecutive echoes identified by remotely sensed data (e.g., Mecklenburg et al., 2000; Novák et al., 2009; Sokol et al., 2009). The advantage of the EXT methods consists of their simplicity and short computing time. However, they do not usually simulate any development of convective processes, and only extrapolate the current state of the convective storm location into the near future. Although Germann and Zawadzki (2002) showed that large cloud systems over North America can be extrapolated for several hours, the limits of reasonable forecasts in Central Europe are only several tens of minutes.

Due to progress in computational techniques, the NWP modelling of convective storm development can be used for nowcasting (e.g., Sokol et al., 2016). The accuracy of the NWP models is limited by the horizontal resolution and applied physical parameterization. It is well known that the extrapolation methods yield more successful forecasts for the first hours than more complex NWP models (e.g., Novák et al., 2009; Mandapaka et al., 2012). However, the NWP model forecast can be significantly improved by an assimilation of the latest data derived from remote sensing measurements. The main goal of the assimilation is to improve the initialization of convective events in time and space during the NWP model integration. Both radar (e.g., reflectivity or derived Doppler velocities) and satellite (e.g., satellite-derived cloud information) data assimilations have shown a positive impact on heavy precipitation forecasts (e.g., Milan et al., 2008; Dixon et al., 2009; Sokol, 2009). In addition, the accuracy of an NWP model forecast also depends on the initial and lateral boundary conditions, which are usually taken from more global NWP models with coarser resolutions.

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Severe convective storms are directly associated with the presence of deep convective clouds and heavy precipitation, and their timely and successful forecast reduces their impact on society. Therefore, a large effort has been devoted to the research of both convective cloud forecasting (e.g., Zinner et al., 2008; Sieglaff et al., 2011) and precipitation nowcasting (e.g., Sokol and Pešice, 2012; Sokol et al., 2013; Chakraborty et al., 2016).

Total cloud coverage, including low, middle and high clouds, can be forecasted by the NWP models and compared with Satellite Application Facility in Support to Nowcasting and Very Short Range Forecasting (SAF-NWC) products focused on cloud detection and/or derived products (e.g., Derrien and Le Gléau, 2005; Bližňák and Sokol, 2012; Bližňák et al., 2014). However, for the simulation of radiation that occurs in specific parts of the electromagnetic spectrum, the radiative transfer model (RTM) needs to be implemented into the NWP models. Its advantage is that synthetic radiation can be directly compared with the radiation observed by satellites. Currently, there is a whole range of RTM codes (e.g., Evans, 1998; Mayer and Kylling, 2005; Fiorino et al., 2014, etc.), that can be applied for this task. In the 1990s, the European Centre for Medium Range Weather Forecast (ECMWF) originally developed a very fast radiative transfer model for TIROS Operational Vertical Sounder (RTTOV; Eyre, 1991; Saunders et al., 1999), which has been subsequently further developed within the EUMETSAT SAF-NWC research activities (https://nwpsaf.eu/deliverables/rtm/index.html) and employed in many studies (e.g., Keil et al., 2006; Eikenberg et al., 2015, etc.). In this paper, the RTTOV is implemented in the Consortium for Small-scale Modelling (COSMO) NWP model.

The verification of cloud forecast accuracy can sometimes be a difficult task, especially in cases when conventional observations (e.g., subjective estimations of cloud cover by observers at weather stations) are sparse or totally missing (Mittermaier, 2012; Mittermaier, 2014). On the contrary, remote sensing measurements with high spatial and temporal resolutions provide a suitable data source for cloud forecast verification. This type of data can be obtained by various methods, including aircraft observations (e.g., Ohtake et al., 2014), meteorological satellites on both polar and geostationary orbits (e.g., Otkin and Greenwald, 2008; Zingerle and Nurmi, 2008; Bikos et al., 2012; Kotarba, 2015) or cloud radar/lidar instruments installed aboard meteorological satellites (e.g., Chepfer et al., 2008; Miller et al., 2014; Jing et al., 2016).

The long-term evaluation of COSMO model forecasts of water-cycle variables (i.e., integrated water vapour, cloud base height, precipitation and brightness temperature (BT)) has already been performed over a 2-year period with several in situ and remote sensing instruments (Böhme et al., 2011). The results of simulated BTs in WV06.2 μm and IR10.8 μm channels showed very good agreement with Meteosat Second Generation (MSG) observations for the whole range of the BT spectrum and specifically for BT IR10.8 μm > 280 K (i.e., in the cloud-free regions). Argence et al. (2008) simulated and objectively evaluated a single convective event that caused heavy precipitation in north of Africa using the Méso-NH model. They compared the model simulation with Meteosat 7 measurements and showed a time evolution of the model performance with an emphasis on deep convective clouds.

A verification of the BTs that were observed by MSG and forecasted by the same model over West Africa during a 1-month period is described by Söhne et al. (2008). Compared to MSG observations, a series of daily 48-h forecasts that were made with the Méso-NH model reproduced the overall variation of the BTs in IR10.8 μm. This model captures diurnal BT cycles under conditions of clear-sky and high-cloud cover, but it misses the lowest BTs values that are associated with deep convection. Similarly, Nachamkin et al. (2009) evaluated deep cloud forecasts performed by the nonhydrostatic model COAMPS with GOES observations over the Eastern Pacific. They found that the majority of large, synoptic-scale systems were well simulated; however, the model failed to capture the variability found in the observations at smaller scales. A verification of convection-permitting ensemble forecasts illustrating the advantage of satellite observations and the model-to-satellite approach was performed by Chaboureau et al. (2012). They computed and evaluated BT fields of infrared and microwave channels for two severe storm cases that occurred over a data-sparse area of the Mediterranean region. A new verification score based on application of the pyramid matching algorithm to observed and simulated satellite imagery was used in regional ensemble forecasts calculated by the COSMO Limited-area Ensemble Prediction System (Keil and Craig, 2007).

In this paper, we use the COSMO NWP model and the RTTOV to simulate synthetic outputs of MSG-SEVIRI IR10.8 μm and WV06.2 μm channels and compare them with satellite measurements. Together with the radiances, we also evaluate precipitation forecasts using gauge-adjusted radar precipitation because cloud development and precipitation are closely related. The comparison is performed for 5 days with severe convection, which caused heavy precipitation and hail, and it is aimed at nowcasting with lead times up to 5 h. It should be stressed that the paper concentrates on evaluation of forecasts of severe convective phenomena (i.e., low BTs and heavy precipitation) produced by two nowcasting models and is focused on nowcast of mature stages of the convective storms because they represent dangerous weather event. The main goals of this paper are the following: (i) evaluate development of convective clouds and precipitation by the COSMO NWP model by various verification techniques and (ii) compare NWP model results with a simple extrapolation of the cloud and precipitation fields.

This paper is organized as follows. The NWP model and data assimilation are presented in Section 2. Section 3 describes the radar, gauge and satellite data that were used in this article. The applied verification techniques and extrapolation method are described in Section 4, and Section 5 contains our results and discussion. Finally, our conclusions, summary and outlooks for the future are detailed in Section 6.

2. NWP model

Forecasts were performed by the non-hydrostatic NWP model COSMO, version 4.18 (Steppeler et al., 2003). The original model version was complemented with an advanced two-moment cloud microphysical scheme, proposed by Seifert and Beheng (2006), with six classes of hydrometeors: rainwater, cloud water, snow, cloud ice, graupel and hail. In addition, the model code was also complemented by the assimilation of rain rates derived from radar reflectivity data based on a correction of the water vapour mixing ratio in the model and by the RTTOV model, version 10.2. The basic principle of the assimilation method is continuous change of model water vapour mixing ratio in each model integration step. If the forecasted precipitation underestimates radar derived precipitation then the model water vapour mixing ratio is increased; in an opposite case it is decreased. The changes of the model mixing ratio are performed by the nudging technique. In addition, the extrapolated radar reflectivity along Lagrangian trajectories derived from the time sequence of radar measurements is also assimilated into the model as observations in the first hour of the forecast (Sokol, 2011; Sokol and Zacharov, 2012). The model was run without the deep convection parameterization, but the shallow convection parameterization was maintained, as in Stephan et al. (2008). We used the standard model configuration and standard model parameter values that are recommended by the German Weather Service (DWD) for the application and a horizontal resolution of 2.8 km.

The model integrations, which we denote as COSMO-CZ, were calculated over the area of the Czech Republic (CR) and its close neighbourhood. Fig. 1 displays the model domain, which consists of 281 × 211 grid points with a horizontal resolution of 2.8 km and with a highlighted verification domain. The model was integrated with a time step of 30 s, and the model outputs were recorded every 15 min at the same times as the available MSG-SEVIRI data. The model run started at 0600 UTC when the convective event occurred during the afternoon (1200–1800 UTC) and at 1200 UTC when the convection occurred in the evening hours (1800 UTC onwards), Table 1. The initial