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MEANDER: The objective nowcasting system of the Hungarian Meteorological Service

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Abstract—In this paper, an overview of the complex nowcasting system of the Hungarian Meteorological Service is presented. The system named MEANDER started to work as a linear extrapolation process to provide warnings on convective storms. The role of the numerical weather prediction (NWP) models have been increased by involving the Weather Research and Forecasting (WRF) Model into nowcasting procedures. In the current state, MEANDER system consists of 2 main segments: NWP and linear parts.

In the NWP segment, WRF model is used in two steps: in the first step, WRF (WRF-ALPHA) is run at a 2.5×2.5 km horizontal resolution grid, using non-hydrostatic dynamics and ECMWF model data as initial and boundary conditions. The second step is a higher resolution (1.2×1.2 km) WRF model run – named WRF-BETA –, that uses lateral conditions and first guess data coming from WRF-ALPHA outputs and assimilates radar reflectivity, satellite and surface observation data. The domain of WRF-BETA is included in the domain of WRF-ALPHA. The applied nowcasting-specific assimilation helps the model to develop significant precipitating weather systems on the right location in the right time. WRF-BETA outputs provides such background information for the nowcasting system that makes the forecast of the linear segment more exact.

In the linear part, the actual objective analysis is considered at the beginning and the NWP prediction at the end of the nowcasting period. In the meantime, linear interpolation is applied. Radar data has key role in the nowcasting procedures in the linear segment, too. There are several derived parameters that are used for calculating the SYNOP-type present weather parameter for all grid points in the analysis and for the entire forecast time.

The MEANDER system has a warning process that is able to create weather warnings for all districts of Hungary, helping decisions of forecasters.

Key-words: nowcasting, nowcasting-systems, Weather Research and Forecasting Model (WRF), storm warning

1. Introduction

The term nowcasting is related to detailed analysis of the present state of the weather and to its very short-range (only few hours)[1] forecasts. Objective methods were developed for such purposes already in the 70-s and early 80-s of the previous century (*Browning*, 1982). Originally, the nowcasting techniques focused on the forecast of thunderstorms and on the extrapolation of radar or satellite images. Mathematical methods (e.g., fuzzy-logic techniques) or conceptual models have been developed to refine the analyses of the storms motion and to assess the development of precipitation bands (*Conway* and *Labrousse*, 1997). The extrapolation-based nowcasting systems can be cell-oriented, like the system TITAN (Thunderstorm Identification, Tracking, Analysis and Nowcasting, described by *Dixon* and *Wiener*, 1993) or can use object-tracking algorithms as the system COTREC (*Li et al*., 1995; *Mecklenburg et al*., 2000) or the system TREC (*Horváth et al*., 2012). The extrapolation of radar echoes can be combined with several other kinds of observation data, parameterizations, conceptual models, thus, striving to emulate the approach of a human forecaster. An example of such (sometimes called expert) system is the NCAR Auto-Nowcaster (*Mueller et al*., 2003). Some systems have been based on stochastic approaches to decompose the precipitation field in order to create an ensemble of nowcasts for several spatial scales – e.g., the system STEPS (*Bowler et al*., 2006; *Foresti et al*., 2014).

Several studies and demonstration cases showed that the performance of extrapolation methods is strongly limited. The predictability depends on the scale and intensity of the extrapolated precipitation (e.g., *Germann* and *Zawadzki*, 2002). Refinement of the extrapolation techniques (e.g., filtering of nonpredictable scales of precipitation described by *Turner et al*., 2004) can increase the forecast lead time, but for higher intensities (occurring typically in convective environment), the forecast skills usually decrease very rapidly with time (shown e.g., by *Lee et al*., 2009). This also motivated the use of forecasts of numerical weather prediction (NWP) models in nowcasting systems, already in the 90-s of the 20th century. NWP inputs have sometimes only support role in estimating the speed and direction of the motion of precipitation cells and their development (for example, in the GANDOLF system, described by *Pierce et al*., 2000). Several nowcasting systems provide blending of the extrapolation methods with NWP data. This approach was used in the system NIMROD (Nowcasting and Initialization for Modeling Using Regional Observation Data System, described by *Golding*, 1998). Blending with NWP data is important for systems, which forecasts of temperature, wind, or other meteorological parameters generate besides

[1] At the beginning, the 0–1 or 0–2-hour period was denoted as nowcasting-range, but (perhaps as a consequence of increasing influence and use of numerical weather prediction models for nowcasting purposes) the 0–6-hour period is mentioned more often now.

precipitation nowcasts. For example, tendencies from NWP models are used in the nowcasting system INCA (Integrated Nowcasting through Comprehensive Analyses, described by *Haiden et al*., 2011).

Current efforts to improve the forecasts (mainly beyond the 0–1 h forecast range) are closely related to assimilation of all available observational data (surface, radar, satellite observations, etc.) and preparation of a three-dimensional objective analysis, which can be used as initial condition in a high-resolution NWP model run. This is the basic approach for systems such as LAPS (Local Analysis and Prediction System, introduced in *Albers et al*., 1996). The advance of the computational technology enabled frequent updates of the NWP models (so-called rapid update cycles), which can be either directly used for nowcasting purposes or for blending with extrapolation systems. Several assimilation techniques have been applied in order to improve the very short range NWP forecasts, e.g., nudging, 3DVAR, or ensemble Kalman Filter technique (an overview of these methods was given by *Sun et al*., 2014).

Despite of advances in NWP techniques, it is recognized that the role of the conceptual models and forecasters in nowcasting is still important as shown during the WMO demonstration projects for Sidney and Beijing Olympic games (*Ebert et al*. 2004, *Wilson et al*., 2010).

At the Hungarian Meteorological Service (OMSZ), subjective methods to forecast thunderstorm activities have been developed since the 1960-s based on surface and sounding data (*Bodolai*, 1954; *Götz* and *Bodolainé*, 1963a, 1963b, *Bodolainé et al.,* 1967). These studies were concentrating on prefrontal squall lines and severe thunderstorms. Methods were developed and applied to evaluate remote sensing data and introduce that information into weather warning (*Bodolainé*, 1980*; Boncz et al.,* 1987; *Bodolainé* and *Tänczer,* 1991; *Putsay et al*., 2009). Because of the geographical environment, the Carpathian Basin is inherently susceptible to floods, and conceptual models were created to understand and recognize weather patterns responsible for local and regional scale floods (*Bodolainé* and *Homokiné*, 1984; *Bonta* and *Takács,* 1988; *Bodolainé* and *Tänczer*, 2003). Appearance of more accurate radar data and increasing number of automated weather stations created the need for developing objective nowcasting system MEANDER (mesoscale analysis, nowcasting and decision routines) that was introduced to operational service in the year of 2003 (*Horváth* and *Geresdi*, 2003). The first version of MEANDER was based on simple extrapolation of radar data. Later, using blending technique with NWP data, MM5 (*Dudhia*, 1993) model was applied as the background NWP tool. The analyses of MEANDER were also tested as input for the MM5 model (*Horváth*, 2005). In the last few years, several modifications and upgrades were done on the MEANDER system. In this paper the recent state of the nowcasting system of the Hungarian Meteorological Service is presented.

2. Development of the MEANDER system

Earlier versions of the nowcasting system used by the Hungarian Meteorological Service were linear extrapolation based procedures, and they focused on severe thunderstorms nowcast. For this reason, MEANDER considered radar-measured heavy precipitation echoes and these echoes were extrapolated using a constant motion vector field. Motion vectors were calculated from a background hydrostatic numerical model, taken the closest forecast time step to the actual time. For the motion vector calculation, density and wind component values of vertical model levels were applied. The calculation based on the idea, that thunderstorm cells are massive objects and their movement is determined by conditions in the surrounding vertical layers of the atmosphere (*Fig. 1*). The speed of the cloud is $\vec{V}^c$ and the mass of the cloud is represented by the sum of **n** vertical layers with each layer with ρ_i. The ***I*** momentum of the cloud can be written as

$$I = \sum_{i=1}^{n} \rho_i \vec{V}^c .$$

The momentum of the cloud supposed to be equal to the sum of its environment momentum, thus

$$\sum_{i=1}^{n} \rho_i \vec{V}^c = \sum_{i=1}^{n} \rho_i \vec{v}_i^e ,$$

where $\vec{v}_i^e$ represents the environment wind on the ith vertical level (taken from NWP). The above equation provides the cloud motion vector:

$$\vec{V}^c = \frac{\sum_{i=1}^{n} \rho_i \vec{v}_i^e}{\sum_{i=1}^{n} \rho_i} .$$

The above calculated motion vector is useful for thunderstorms, but for stratiform precipitation it didn’t work properly (*Horváth* and *Geresdi*, 2003).

Objective analysis of earlier MEANDER versions was based mainly on observations. The spatial and temporal resolution of available NWP was not high enough for effective use in meso-scale. Increase in density of surface observations enabled production of higher resolution surface analyses, but that was not physically consistent with higher level model data.

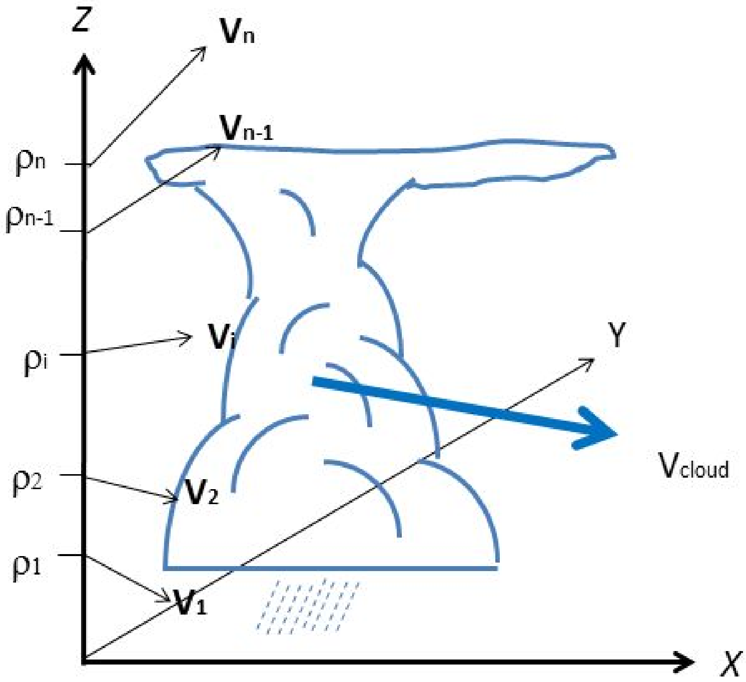

Fig. 1. Calculation of motion vectors for convective clouds. On the vertical axis ρi and ***Vi*** represents the vertical profiles of density and wind of the environment, ***Vcloud*** represents the cloud motion vector.

Installation of non-hydrostatic MM5 model allowed to use the blending technique for nowcasting: linear interpolation was applied instead of linear extrapolation. The system interpolated between the objective analysis at the beginning and the numerical forecast at the end of a nowcasting period (*Horváth*, 2005). The objective analysis used not only observation but, in addition, MM5 outputs as first guess information, and four dimensional data assimilation technique were applied to enhance the analysis (*Stauffer* and *Seaman*, 1990).

Motion vectors for radar echo replacement were also calculated from MM5 upper level wind data. Operational usage of high resolution satellite data also helped to improve the nowcasting, especially the cloud type and overcast part (*Putsay et al.*, 2010). Later versions of MEANDER considered not only convective but stratiform precipitation, too. A decision procedure determined that a precipitating system was stratiform or convective. For startiform systems, the average wind vector between 1000–4000 m proved to be the best parameter as motion vector.

The third generation of the MEANDER system is more NWP-based. The initial conditions provided by background NWP model are modified with respect to certain significant, observed meteorological objects, using conceptual models. For example: radar detected thunderstorms are included in the initial model field in such a way, that convergence and divergence in the wind field and anomaly in the temperature and humidity field are placed to the appropriate location. These impacts allow the model (or at least give it a chance) to develop significant objects on the right location in the right time. The presently applied WRF model (*Skamarock et al.*, 2005) is able to manage these dynamically not balanced modification of first guess fields and, as it is shown later, WRF is able to provide corrected background data for the nowcasting system. Below, the currently used 3rd generation MEANDER system is presented.

3. Two-layer NWP background of the nowcasting system

The basic input data for the NWP segment of nowcasting are ECMWF deterministic model forecasts. Model level ECMWF data provide boundary conditions and first guess information for the non-hydrostatic WRF model. The WRF domain covers the Carpathian Basin with a 2.5×2.5 km horizontal resolution grid. This model version named WRF-ALPHA runs with 6-hour frequency and has 36-hour forecasting range. In addition to ECMWF data, surface and upper air measurements are also involved into initial conditions using WRF data assimilation tools (*Skamarock et al.*, 2005). WRF-ALPHA also uses special input coming from a stand-alone soil model that calculates soil humidity and soil temperatures on 4 soil layers. The soil model is based on the NOAH model (*Chen* and *Dudhia*, 2001), and it receives meteorological input data from MEANDER analysis (for example precipitation) and from previous WRF model run (surface fluxes, etc.). Calculated soil data are updated 4 times a day. The sensitivity of deep convection to soil condition of the Carpathian Basin was described by *Ács et al.*, 2010, and this sensitivity justifies special care of soil input data.

The second part of the NWP segment is based on a higher resolution WRF model run (1.2×1.2 km). In this model, named WRF-BETA, measured data have got higher role. First guess data originating from WRF-ALPHA input, observed temperature, humidity and wind data are assimilated using nudging facility of WRF. Two hours of nudging period are applied, i.e., the –2, –1, and 0-hour analyses are used (0 hours means the last time when analysis is available). Not only weather station data, but remote sensing information are also involved in the analyses. Especially at cases of thunderstorms, radar reflectivity can be involved into the analyses using conceptual models.

Thunderstorms can be identified by radar reflectivity in such a way, that ellipses are assigned to locations where radar reflectivity is higher than a threshold value (45 dBz). The ellipses procedure was developed in the TITAN method (*Dixon* and *Wiener*, 1993) and was applied – among of others – for nowcasting related research (*Horváth at al.*, 2008; 2012). On locations where thunderstorms are detected, the analysis field is modified by the conceptual model as described below.

The model is based on the idea that a thunderstorm has an updraft and a downdraft channel. In the updraft channel, there is a positive temperature and humidity anomaly and there is significant convergence of the wind field at lower layers. The other pole of the thunderstorm is the downdraft channel where deficit in the absolute humidity (mixing ratio of water vapor) and divergence at lower layers can be found. The fuel of this "two-pole engine" is the humidity. Normally, the moisture is available from the basic analysis field, but the objective analysis is not necessary exact concerning the humidity analysis. To supply the thunderstorm with humidity in its initial phase, a humidity reservoir is added to the model with positive humidity anomaly and slight convergence at the lower layers (*Fig. 2*). The temperature profile of the updraft channel is calculated in such a way that equivalent potential temperature (EPT) is considered to be constant (*Fig. 3*), and EPT is calculated from the near surface layers supposing saturated air. In this way, the updraft channel of the thunderstorm appears as wet and warm bubbles in the analysis field (*Horváth*, 2006). The wind field is modified in lower layers (~lower 1000 m) to be convergent with respect to the center of the updraft channel. On the bottom of the downdraft channel the wind is divergent, blowing out of the center of the downdraft channel, and there is a weak depression in the field of absolute humidity. In the humidity reservoir, there is a weak horizontal flow in the direction of dual channels. The modification made by the conceptual model is added to the field of the objective analysis. Several numerical experiments were made to set parameters for the conceptual models. Experiments show that relatively little perturbation of humidity and wind values are enough for the conceptual model for triggering thunderstorms (*Fig. 4*). WRF model is tolerant of conceptual model made perturbations, and this triggering procedure helps to develop thunderstorms on proper place in proper time. The life time of triggered thunderstorm is more than 2 hours at about 70% of investigated cases. Sometimes the initial thunderstorms dissipated, but they made neighboring groups of incorrectly forecasted thunderstorms weaker or disappear.

Satellite data also can be used for WRF-BETA initial data by EUMETSAT provided SAFNWC information (*Derrien* and *Le Gléau*, 2005). Cloud mask and cloud type information allow to recognize opaque and thick cloudiness. Considering the mean value of cloud water mixing ratio (CLW) coming from WRF-ALPHA, it is possible to assign CLW values for cloudy areas. WRF-BETA accepts CLW as initial data and involving CLW does not increase numerical instability during the model run (numerical experiments were made to involve rain water into initial condition, but this input parameter increased the instability). Case studies showed that involving CLW has some positive influence on cloudiness, but improvement of this procedure is still under way.

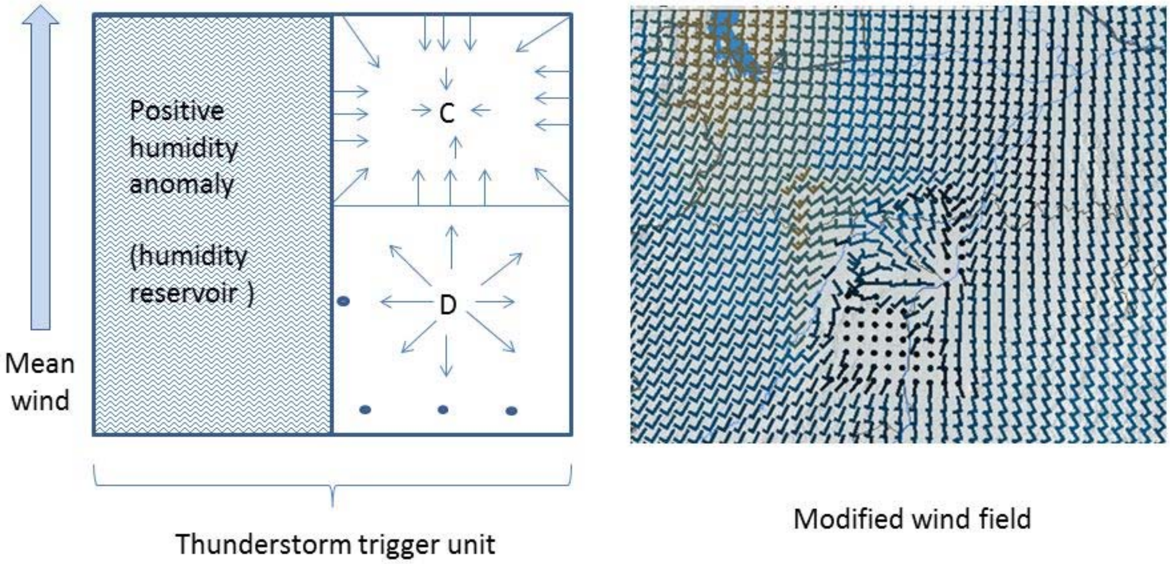

Fig. 2. The structure of a convective trigger unit (left) and the perturbed low level wind field (right). In the trigger unit, the square denoted by C represents the convergence in the updraft channel and letter D represents the divergence in downdraft channel. The right rectangle represents the humidity reservoir where is extra humidity added relative to the first guess to supply convection.

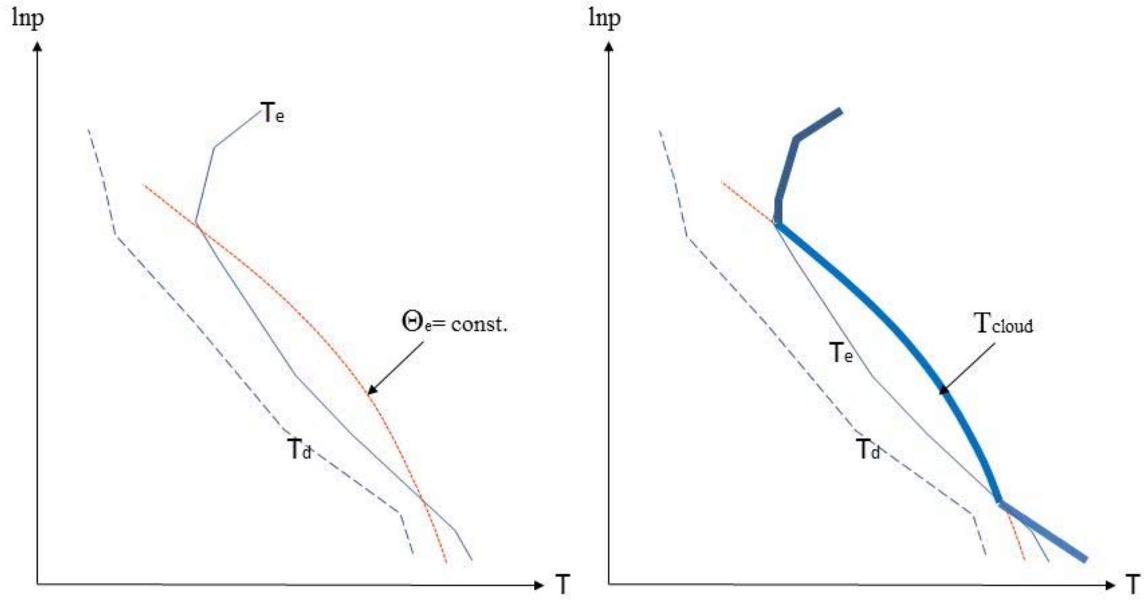

Fig. 3. Modification of the vertical temperature profile in the updraft channel of the triggering unit. In the original profile (left): T_e and T_d represents the temperature and dew point profiles of the first guess and θ_e shows the constant equivalent potential temperature (EPT) calculated from the lower 1000 m. The modified profile (right) is represented by the thick line.

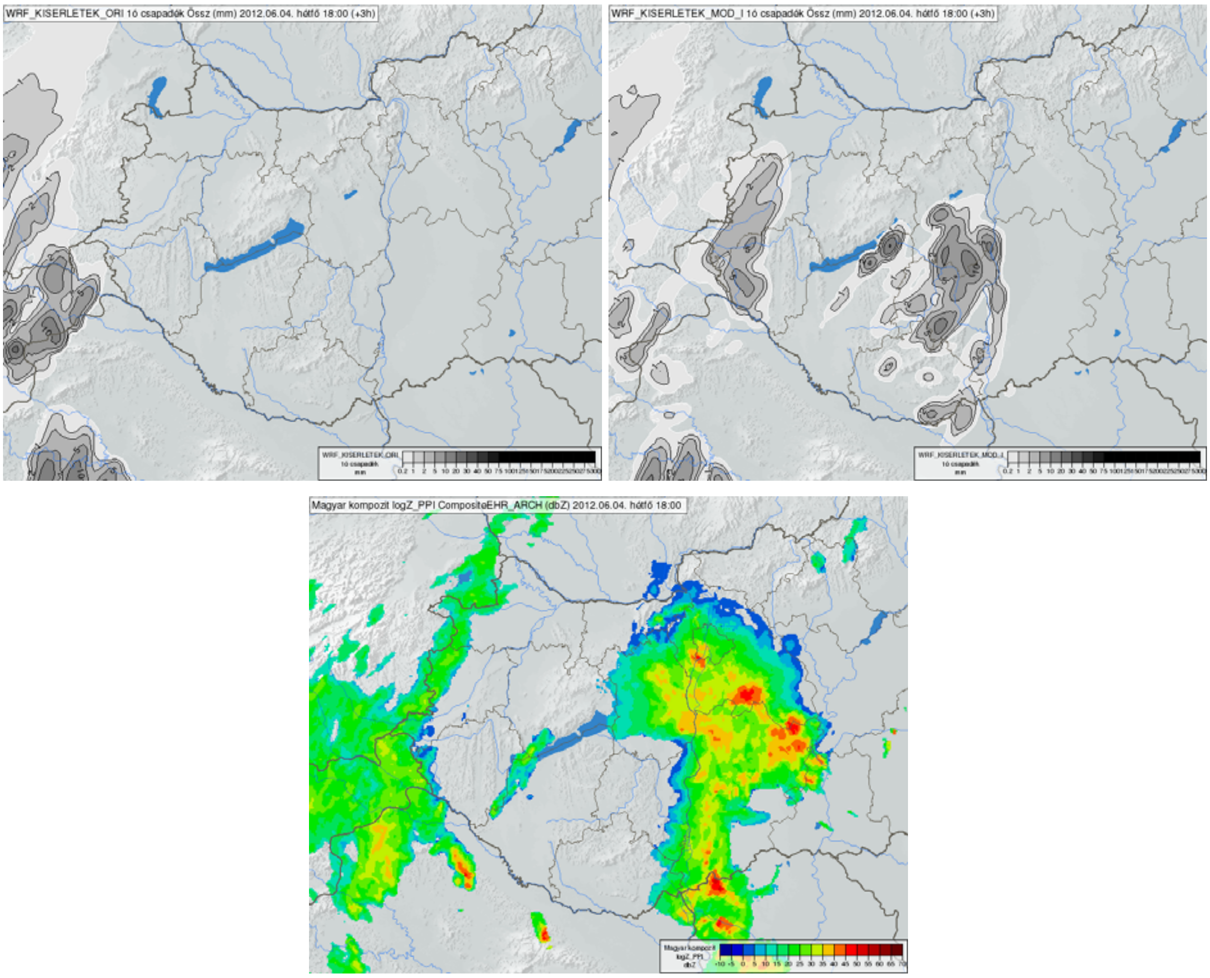

Fig. 4. 1-hour accumulated precipitation of +3-hour forecast of the WRF model at reference (upper left) and triggered forecasts (upper right) and the measured radar reflectivity (lower image). The model start time is 15:00 UTC June 4, 2012, the radar reflectivity image time is 18:00 UTC June 4, 2012. The triggered model run produced more realistic result than the reference run.

There are some derived parameters calculated as first guess data for nowcasting applications. The visibility for all grid points is computed from the lowest model level using mixing ratio of water vapor, cloud water, rain water, cloud ice, and snow (*Kunkel*, 1984). Radar motion vectors are calculated separately for convective and stratiform precipitating systems as described above.

In an ideal case, WRF-BETA should always be run when new observations are available. Because of limited computer power, WRF-BETA runs in every third hours providing NWP output for the nowcasting system for the next 8 hours with 15 minutes output frequency.

4. The linear segment of the nowcasting system

The linear segment of the MEANDER system consists of two parts: an objective analysis and a linear forecast. The objective analysis uses the coincidental WRF-BETA forecast, measured surface data, radar data, and satellite information. The grid of the objective analyses is the same as the WRF-BETA grid (1.2×1.2 km). During the objective analysis, derived parameters are also calculated, and finally, for all grid points, synoptic-type present weather code values (snow, rain, thunderstorm, etc.) are assigned. The frequency of the objective analysis is 10 minutes. From all objective analyses, a linear forecast is made for 3 hours ahead and updated in every 10 minutes.

The analysis segment uses WRF-BETA outputs as first guess data. For basic parameters, differences between observed and first guess values are calculated at all observation points. These differences are interpolated to all grid points using biharmonic spline procedure (BHS). Input for BHS are (1) coordinates of observation points, (2) coordinates of grid points of the objective analysis, (3) difference values between grid point and observation point data at the observation point. Outputs of BHS are interpolated differences at all grid points of the objective analysis. Finally, first guess data are corrected by the interpolated values at grid points.

In order to decrease representation error, grid points of first guess data are considered in the circle of radius *R* around an observation point. Differences between observation value and first guess values are calculated, and that grid point is chosen where the difference is the smallest. This minimum value is considered as the difference between first guess and observation as input (3) for BHS at the given observation. Coordinates of the observation point are taken to be equivalent to the coordinate of the chosen grid point as input (1) for BHS. This "wobbling observation" procedure proved to be useful on those locations, where the gradient of the considered parameter is large, for example at lake or sea side observation points or hilly regions. In practice, *R* is chosen 4 km for flat regions, and 5 km for hilly regions and lake side stations.

Radar data for the nowcasting system are from the Hungarian composite radar images that are created from 3 Doppler radars of the Hungarian Meteorological Service in every 5 minutes. The spatial resolution of radar information has the same order than the nowcasting grid has, so transformation of radar reflectivity data to the nowcasting grid does not cause distortion or data loss. Satellite data can also be projected to the nowcasting grid. Applied satellite data are NWCSAF products such as cloud cover, cloud type, cloud top temperature (*Derrien* and *Le Gléau*, 2013). When radar and satellite data are on the common platform of the nowcasting grid, a process compares them and eliminates large radar errors. This procedure (not detailed here) is important because of large number of commercial electromagnetic devices (for example WIFI devices) that make artificial noise and sometimes remain in the reflectivity field despite filtering procedures of the radar facility.

The linear forecasting segment of the nowcasting system is based on the blending technique for basic parameters such as pressure, humidity, wind, and temperature. At the beginning of the 3-hour-long nowcasting period, the objective analysis is considered, and at the end there is an actual WRF-BETA forecasted data field. In the meantime, linear interpolation is applied (*Fig. 5*). Radar echoes can be advected using motion vector fields. (Motion vector fields, coming from WRF-BETA, are not permanent fields, but they are changing during the forecast time, so forecasted radar echoes are moving along fractionally linear paths.) The forecast of precipitating clouds allows the calculation of integrated precipitation using Marshal-Palmer form between radar reflectivity and rain intensity (*Marshal* and *Palmer*, 1948). In this procedure, the amount of precipitation is computed up to 3 hours, using 1 minute time step.

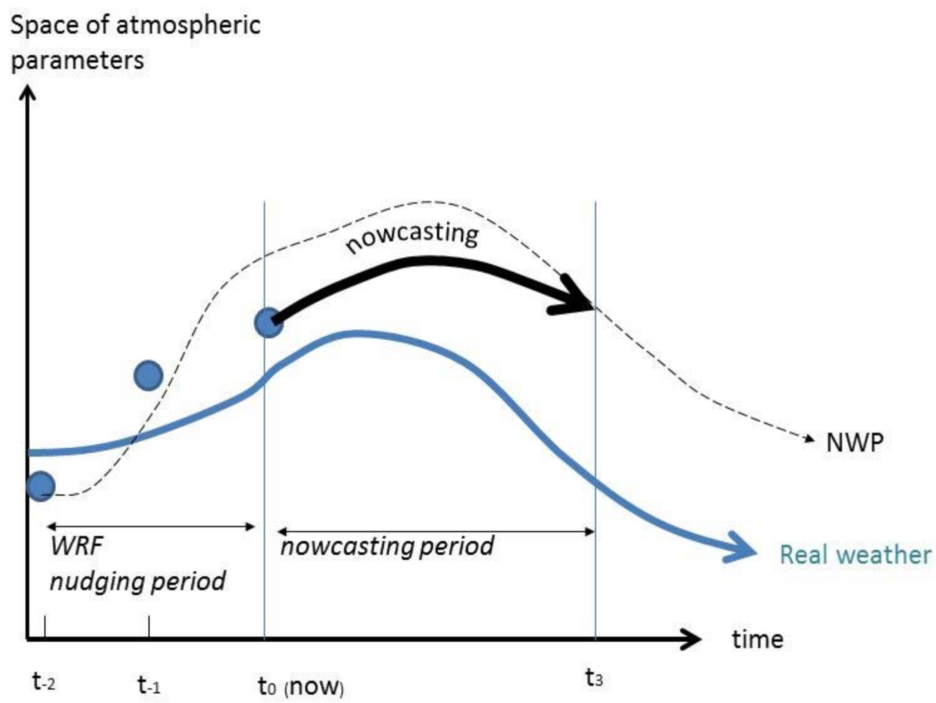

Fig. 5. Theoretical background of MEANDER system. Along the vertical axis the atmospheric parameters, on the horizontal axis the time are labeled. The continuous line represents the trajectory of the real weather, dashed line shows NWP forecast, circles represents objective analysis. The thicker solid line shows the nowcasting.

Derived parameters can be calculated at any time step of the nowcasting period. Among these parameters the precipitation phase, which frequently changes in wintertime, is especially important in the Carpathian Basin. There is a method developed by Geresdi (*Geresdi* and *Horváth*, 2000) to calculate the phase of precipitation applying cloud physics. The 1D cloud model is applied to calculate the cloud top, maximum updraft, and hailstone size of a potential thunderstorm (*Geresdi et al*., 2004). The TREC method that was developed by the remote sensing division of the Hungarian Meteorological Service is also applied for the nowcasting system for 1 hour accumulated precipitation estimation (*Horváth et al*., 2012). The radar based process considers previous radar reflectivity images and calculates a motion vector field taking correlations between two images. Motion vectors are applied to interpolate radar images with 1 minute temporal resolution in such a way, that radar echoes are replaced by motion vectors. Using these interpolated reflectivity images (and calculated precipitation intensity from that), the accumulated precipitation can be computed. A procedure calculates thunderstorm-associated maximum wind gust using the maximum radar reflectivity and the maximum cloud top height of cumulonimbus cells (*Bartha*, 1994). The convective wind field of a stormy day is shown in *Fig. 6*. Non-convective wind gusts are also computed from WRF-BETA, and this parameter is included in the objective analysis. During the forecast, it is blended with NWP data similarly to other basic parameters. The final result of derived parameters calculating procedure is "present weather" code values for all grid points. This parameter is depicted in similar way as the observed present weather parameters from WMO-SYNOP code.

Warning segment of the nowcasting system is designed to issue weather warning for the next 3 hours using the actual analysis and nowcasted present weather parameters. There are 3 warning levels, and the actual level is clearly defined by the previously calculated present weather code. (For example, there are three kinds of present weather code for thunderstorm in MEANDER: thunderstorm – first level; severe thunderstorm – second level; extreme thunderstorm – third warning level). There are 175 districts in Hungary, and the warning system generates individual weather warnings for those districts where it is justified by calculated present weather parameters. In the practice the forecaster on duty receives automatically generated warning maps on a special graphical user interface, and he or she can accept or interactively modify proposed information. Actual weather warnings appear on the warning page of the Hungarian Meteorological Service (http://met.hu/idojaras/veszelyjelzes/riasztas/). The flow chart of the nowcasting system is presented in *Fig. 7*.

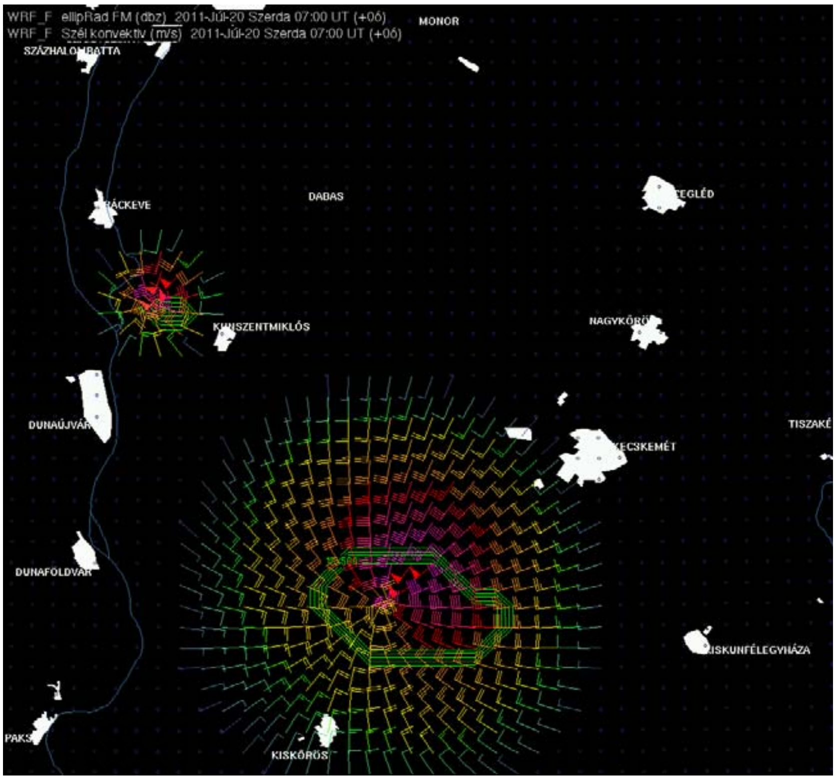

Fig. 6. Calculated convective wind field and thunderstorm contour lines on east of Danube at 07:00 UTC, July 20, 2011. That was a severe convective storm case caused serious damages near Kecskemét.

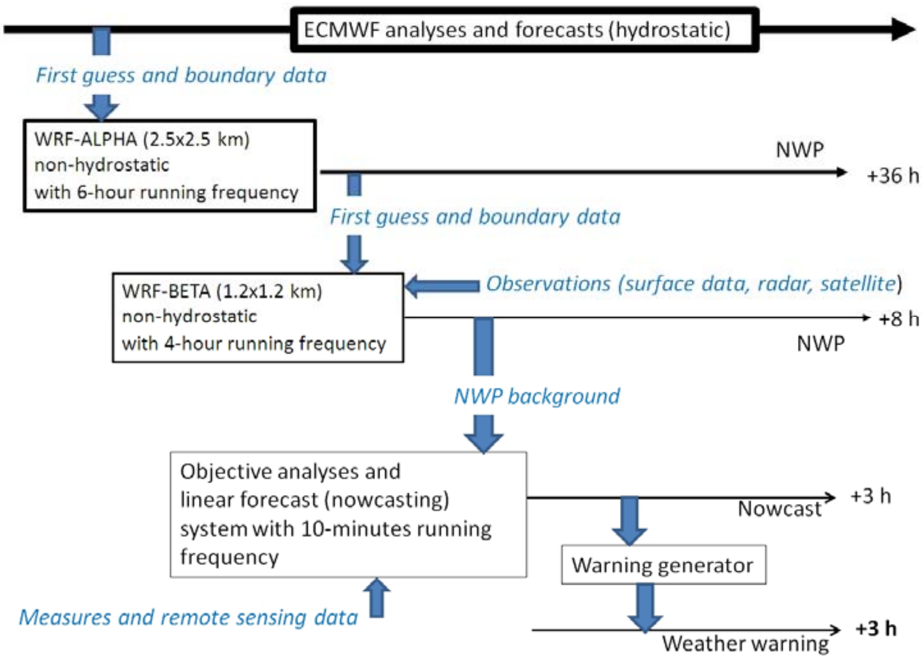

Fig. 7. Flow chart of the MEANDER system.

5. *Evaluation and experiences*

Concerning NWP (WRF-BETA) background, many case studies have been done to analyze the impact of radar assimilation made by the conceptual thunderstorm model. In about 70% of cases, the conceptual model has unambiguous positive impact up to 5 hours forecast. This way of introducing thunderstorm is safe, no significant gravity waves or other side effects were experienced. The limitation of the conceptual model is that it cannot be applied before first radar signs of thunderstorms appear. Currently used computer resources do not allow to run numerical models exactly in the same time when thunderstorms appear. The ideal solution would be a flexible NWP model run: WRF-BETA should run any time when the weather condition justifies that.

The nowcasting of the linear segment for basic parameters is verified by comparison of the analyses with earlier issued nowcasting at all grid points. Verification shows that basic parameters have relative small errors for the first 2 hours. The RMSE for temperature is above 0.5 ˚C, for pressure 0.1 hPa, for relative humidity 10%, and for wind speed 1.6 m/s. The precipitation forecast is highly dependent on the precipitation type. The forecast of stratiform precipitation is significantly better than forecast of convective precipitation (93% vs. 72%). There are problems with the verification of the derived parameters. For parameters like present weather, it is problematic to compare analysis fields with forecasts, because present weather itself is a derived parameter at the analysis time, too. Therefore, present weathers like freezing rain, severe thunderstorms can be verified via case studies, where inherently subjective visual observations are collected posteriorly. Case studies show that the most sensitive parameter is the precipitation phase and phase related present weather, especially freezing rain. Also, there is high spatial variability concerning visibility parameters. Most "nowcastable" significant present weathers are associated with stratiform precipitation like summer rain or winter snow. Severe convective storms and multicell thunderstorms can also be relative properly forecasted, especially when they are in developing phase and the advection is more decisive than developing. In the linear segment, the thunderstorm development has not been solved yet, the blending technique of radar observed cell transition to NWP simulated cell is still under development. The precipitation-associated parameters show significantly growing errors after 2 hours, hence in operational public usage only this forecast range is considered.

Evaluation of the warning segment shows better results than point-to-point comparison above. A district contains several grid points and the chance that weather objects hits at least a grid point in a district is definitely larger. Considering significant weather events, there is overestimation of weather warning for freezing rain and slight overestimation of severe convective events for 2 hours.

6. Summary

The MEANDER nowcasting system takes advantages of high resolution numerical modeling and very short range linear extrapolation. The hydrostatic ECMWF data are downscaled (in both time and space) to the resolution of the nowcasting system in two steps. During the first phase, the applied WRF (WRF-ALPHA) creates high resolution non-hydrostatic forecast 4 times a day. The WRF-ALPHA outputs are first guess and lateral condition data for a higher resolution WRF-BETA that produces forecast for the nowcasting domain with 1.2×1.2 km horizontal resolution. WRF-BETA uses nearly all available remote sensing and measured data and provides first guess information for the linear segment.

The linear segment uses observations for making analysis, which is the first pillar of the linear nowcasting. The second pillar is the WRF-BETA forecast that is considered at the end of the 3-hour-long nowcasting period. Radar located precipitating systems are moved in the linear segment using motion vector fields, calculated from WRF-BETA forecast. Derived parameters are computed during the linear segment, and finally, present weather values are assigned to all grid points. Finally, the warning segments are used to issue weather warnings for 175 districts of Hungary. The linear segment runs every 10 minutes, 24 hours a day.

Verifications and experiments show that the MEANDER system in the present stage provides usable forecast and warnings for the next 2 hours. Developing nowcasting-oriented assimilation techniques and more frequent model runs may help to extend this range in the near future.

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