TESTING OF THE NON-HYDROSTATIC MODEL LM (LOKAL MODELL) ON THE ROMANIAN TERRITORY

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Abstract: The nonhydrostatic model LM was tested for two horizontal resolutions, of 14 km and of 2.8 km, for 2-5 November 2004 and January 2005. The results have been analyzed, at 14 km resolution, by comparison with the hydrostatic model HRM at the same resolution and with observed data from 16 stations. At 2.8 km, the model outputs have been compared with hourly data from the measurement campaign on 2-5 November 2004 at Baia Mare. The model accurately describes the interaction of non-hydrostatic processes with large-scale processes. The analysis of results shows an improvement of the model forecast accuracy, especially for precipitation.

Key words: non-hydrostatic, high-resolution, limited-area model

1. INTRODUCTION

Most of the current numerical weather prediction models operate on hydrostatic scales of motion with a grid spacing of about 10 km and thus lack the spatial resolution required to explicitly capture some small-scale severe weather events. By employing a 1 to 3 km grid spacing, it is expected that deep moist convection and the associated feedback mechanism to the larger scales of motion can be solved explicitly. In addition, the impact of topography on the organization of penetrative convection, e.g. by channeling effects, is represented much more realistically in high resolution nonhydrostatic forecast models.

The nonhydrostatic Lokal Modell (LM) has been developed in its basic version at Deutscher Wetterdienst (DWD), Germany, the subsequent developments being organized within COSMO (Consortium for Small Scale Modelling). It has been designed for meso-β and meso-γ scales where nonhydrostatic effects begin to play an essential role in the evolution of the atmospheric flows. But the physical representation still needs fine tuning of the involved parameters in order to obtain a better forecast on the desired domain. Also the optimum combination of numerical schemes available at different horizontal scales needs to be found.

The LM model has been used in a series of experiments on the Romanian territory at two horizontal resolutions, 14 km and 2.8 km, in order to test its ability to simulate the medium and small scale phenomena and to highlight the improvements in the numerical prediction of near-surface weather conditions that it can provide. A short description of the model is given in section 2 and the experiment settings are presented in section 3. The model results from experiments at the resolution of 14 km are...
compared with the results of the hydrostatic model HRM (High resolution Regional Model). The two models were integrated on the same domain and at the same resolutions and the results of simulations are verified against synoptic data from 16 meteorological stations. The verification method is similar to the operational verification procedure used by the National Meteorological Administration (NMA) Bucharest for products provided to users in the aeronautical field. For the resolution of 2.8 km, the results are qualitatively compared with observed data from a measuring campaign on 2-5 November 2004 at Baia Mare. The analysis of results is presented in section 4.

2. DESCRIPTION OF THE MODELS

The Lokal Modell is a limited-area atmospheric prediction model, based on the nonhydrostatic, full compressible hydro-thermodynamical equation in advection form. The model equations are formulated in rotated geographical coordinates, using an Arakawa C-grid, and a generalized terrain-following height coordinates, with a Lorenz vertical grid staggering. The time integration is done using a second-order leapfrog HE-VI (horizontally explicit, vertically implicit) time-split integration scheme, including extensions proposed by Skamarock and Klemp (1992). There are also available options for a two-time level second order Runge-Kutta split explicit scheme (Wicker and Skamarock, 1998) and for a three time-level 3-d implicit scheme (Thomas et al., 2000). For the numerical smoothing a 4th-order linear horizontal diffusion scheme with monotonic orographic limiter is used (Doms, 2001).

The LM radiative transfer package is based on the δ-two stream radiation scheme introduced by Ritter and Geleyn (1992) for short and longwave fluxes, with full cloud-radiation feedback. It employs eight spectral intervals and incorporates the effects of scattering, absorption and emission by cloud droplets, aerosols and gases (H₂O, CO₂, O₂, O₃, N₂O, CH₄) in each part of the spectrum.

For determining grid-scale clouds and precipitation, the cloud water condensation and evaporation are computed by the saturation adjustment process: if a grid box becomes supersaturated during a time step, the temperature and the concentrations of water vapor and cloud water are isobarically adjusted to a saturated state, taking into account the latent heat. If cloud water is present in spite of subsaturation, it is evaporated until either no cloud water remains or saturation is achieved. The saturation is water saturation, as cloud ice is not dealt with. Precipitation formation is treated by a bulk microphysics parameterization including water vapor, cloud water, rain and snow with column equilibrium for the precipitating phases. Also, options for a bulk scheme including cloud ice and for 3-d precipitation transport are available. The subgrid scale cloudiness is interpreted by an empirical function depending on the relative humidity and height. Corresponding cloud water content is also quantified.

There are two available schemes for moist convection treatment: the mass-flux convection scheme (Tiedtke, 1989) with equilibrium closure based on moisture convergence, and a Kain-Fritsch (1993) convection scheme with non-equilibrium CAPE-type closure. At very fine horizontal resolutions, convection is treated explicitly.

The vertical turbulent transport between the atmospheric layers is treated using a 2nd order turbulent closure with a prognostic equation for the turbulent
kinetic energy (TKE). Compared to the former parameterization scheme which is based on diagnostic second order K-closure, this has the advantage of containing additional terms that describe more physical processes (i.e. subgrid-scale condensation, thermal circulation, vertical entrainment), which affect the evolution of TKE in time.

Turbulent transport through the transfer layer between the rigid surface of the earth and the lowest atmospheric main level is parameterized using a scheme based also on the prognostic TKE equation, which does not use empirical profile functions, as it is done in the former scheme (Louis, 1979). The transfer layer consists of two parts, a roughness layer and a Prandtl layer above it. Different interpolation formulae for the turbulent velocity scale in both layers are used and a laminar sub-layer is considered, just above the rigid surface, where only laminar diffusion takes place. This transfer scheme leads to significantly improved mean profiles of the 2m-temperature and especially the 2m-dewpoint temperature, with realistic amplitudes of the diurnal cycle.

The soil processes are treated using soil model TERRA (Schrodin et al., 1995), which provides the surface temperature and the specific humidity at the ground. The ground temperature is calculated by the equation of heat conduction, which is solved in an optimized two-layer model using the extended force-restore method (Jacobsen and Heise, 1982). The soil water content is predicted for two, three or more layers by the Richards equation. Evaporation from bare land surfaces together with transpiration by plants are derived as functions of water content and – only for transpiration – of radiation and ambient temperature. Most parameters of the soil model (heat capacity, water storage capacity, etc) strongly depend on soil texture. Five different types are distinguished: sand, sandy loam, loam, loamy clay and clay. Additionally, three special soil types are considered: ice, rock and peat. Hydrological processes in the ground are not considered for ice and rock. However, potential evaporation is assumed to occur over ice, where the soil water content remains unchanged.

There is also available a new multilayer soil and vegetation model-TERRA_LM (Doms and Schattler, 2001), where the effect of freezing/melting of soil water/ice is included, the process of snow melting is changed and a time-dependent snow albedo is introduced. The new multi-layer concept avoids the dependence of layer thickness on soil type. Additionally it avoids the use of different layer structures for the thermal and the hydrological sections of the model.

The equations for the hydrostatic model HRM (High resolution Regional Model) are formulated in a rotated latitude/longitude grid using a hybrid vertical coordinate (Majewski, 2005). A split semi-implicit time-stepping scheme, according to (Burridge, 1975) is used for time integration and a linear 4th order horizontal diffusion scheme, with a slope correction for temperature is used for numerical smoothing. Some of the physical parameterizations of HRM are the same as in LM: the radiative transfer scheme, the mass-flux convection scheme after Tiedtke (1989), the soil model TERRA, while others are the same as in former schemes employed in LM: similarity theory-based surface transfer scheme (Louis, 1979), level-2 scheme (Mellor and Yamada, 1974) of vertical diffusion in the atmosphere.

3. EXPERIMENT DESIGN

The LM model has been tested for two horizontal resolutions. At the resolution of
14 km, the domain size is approximately 1000 x 900 km, with 35 vertical layers, and covers the Romanian territory (fig. 1a). The domain used for the resolution of 2.8 km is 100x100 km in size, with 50 vertical layers and it is centered on Baia Mare (fig. 1b).

The global model GME outputs, at 40 km resolution and interpolated on the model grid, were used as driving fields, with a frequency of updating the lateral boundary conditions of 3 hours, using a one-way nesting, Davies-type lateral boundary formulation. The terrain

Fig. 1. Topography of the integration domains: a) for LM and HRM models, 14 km horizontal resolution; b) for LM model, 2.8 km horizontal resolution. Units are m. Contour intervals are 200m for a) and 100m for b).
and surface data, containing all the external parameters needed by the LM and HRM models, were available for each model resolution. The initial and boundary conditions for experiments at 2.8 km are interpolated from LM outputs at 14 km. All experiments have been carried out on a Linux cluster.

The simulation periods are January 2005 and 2-5 November 2004, for the resolution of 14 km, and 2-5 November 2004 for the resolution of 2.8 km. In all experiments 24h forecasts were provided.

The results of LM integration at the resolution of 14 km are analyzed by comparison with HRM, integrated at the same resolution and on the same domain. Also, a statistical verification of the results from both models against synoptic data was done. The verification method applied follows the requests of specific users in the aeronautical field and also the standards applied operationally at NMA. The 16 meteorological stations (table 1) are located on Romanian airports and the parameters considered for verification are the following: sea level pressure (SLP), air temperature at 2m (T2m), wind speed at 10m and precipitation cumulated in intervals of 6h. In order to obtain the forecast of parameters for all considered stations, the method of the closest neighboring grid point has been used.

For the first three parameters the following verification measures have been used: mean error, standard deviation (STD) and mean square root error (RMSE). The precipitation model forecasts have been analyzed using the following scores: frequency bias, false alarm ratio (FAR), probability of detection (POD), percent correct (PC), true skill score (TSS), threat score (critical success index, (TS). Frequency bias measures the model’s ability to forecast events at the same frequency as found in the sample, disregarding forecast accuracy. False Alarm Ratio is calculated as a ratio between the number of an event’s non-occurrences and the total number of that event’s forecasts, being therefore sensitive to false predictions of the event, not to missed events. Probability of Detection is a score that measures the ability to forecast correctly a certain category, thus being sensitive to missed events, not to

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false alarms, and in an ideal situation it has the value of one. Percent Correct is a measure of forecast accuracy, calculated as the ratio between the number of correct forecasts and the total number of forecasts, expressed in percentages. A more complete indicator is the True Skill Score, that uses all the relevant information contained in the observation and forecast, allowing an estimation of the probability that the observation/forecast association is real and its value is in the fixed range $-1$ to $+1$. The last score used for the verification of precipitation is Threat Score, which is a measure of relative accuracy and has the advantage that it is sensitive to both false alarms and missed events (Stanski et al., 1989).

For the resolution of 2.8 km, the results from LM integration are analyzed only by comparison with the observation data obtained during the measurement campaign on 2-5 November 2004 at Baia Mare. The campaign was realized within the project AIRFORALL (Air Pollution Forecasting, Alert and Monitoring System on Short Time Scale, at local and regional scale, in unfavorable meteorological and topographic conditions). The purpose of the campaign was to make meteorological and pollution measurements in some locations from Baia Mare and its surroundings, in order to validate the numerical forecast databases of both meteorological fields and pollution levels. There were eight fixed measurement points during the campaign: four manual measurements and four automatic stations. The principal reason in choosing the measurement points was the representativeness for local topography processes at fine scale and as a mean of the grid-size mesh of the model used in the project (about 3 km). The following meteorological parameters were measured: wind direction and intensity at 2m (or 30m for some automatic stations); air temperature at 2m; relative humidity at 2m; atmospheric surface pressure; global radiation (only for automatic stations); net radiation (only for automatic stations). A meteorological database was created, with a frequency of one hour, for each day of the campaign.

4. RESULTS

a) LM simulations for the horizontal resolution of 14 km

In the following, some examples of comparisons between the LM model and the HRM model, for November 2, 2004 are presented. The meteorological situation of this date was characterized by a quite high temperature over the country for this period, with a maximum of 23.3 $^\circ$C measured at Baia Mare, low wind and light, sparse precipitation.

The spatial distribution of 2m-temperature difference between the two models, LM and HRM is shown in figure 2. It can be seen that the representation of nonhydrostatic effects in LM leads to a higher forecast accuracy (of the forecast) for this parameter in regions where the nonhydrostatic processes dominate the minimum represented scale (e.g. intra-Carpathian region). Deviations of T2m values up to 2-3 degrees in comparison with the measured data, for this situation, are observed.

Figure 3 shows the vectorial difference in the wind field superimposed on sea level pressure difference between the two models, LM and HRM, and in figure 4 the plots for vertical velocities at levels of 850 hPa and 1000 hPa are presented. SLP in LM is lower in regions affected by vertical mass transport (south-western, northern part of the country, figure 4b) and interactions of non-hydrostatic processes with large scale processes. The non-hydrostatic tendency in vertical velocity gives a higher accuracy of wind speed at 10m in comparison with the HRM results,
although still overestimated. Differences in SLP are up to 2 hPa in an interval of 24h, generally lower for LM if compared with the measured data for this simulation period, and the wind speed correction is up to 3 m/s for this case.

Looking at the total precipitation in 24h (fig. 5 a, b), a significant reduction
both in quantity and spatial distribution of precipitation in LM simulations can be noted, but this parameter is still significantly overestimated. A statistical verification of both models against synoptic data has also been done for January 2005. The scores for 2m-temperature, sea level pressure and

![Fig. 4](image1.png)

Fig. 4. Vertical velocity (Pa/s) for 02.11.2004, 24 h anticipation, in: a) HRM, at level of 850 hPa; b) LM, at level 850 hPa; c) HRM, at level 1000 hPa; d) LM, at level 1000 hPa. Contour interval is 0.02 Pa/s.

![Fig. 5](image2.png)

Fig. 5. Total precipitation in 24h interval for 02.11.2004, at 14 km resolution: a) for HRM; b) for LM. Units are mm/day.
wind speed at 10m have been computed for each station and each anticipation (6h, 12h, 18h and 24h). Figures 6-9 show a monthly synthesis of forecast accuracy for the two models, performed for the 16 stations and two anticipations (18h and 24h) allowing the possibility to follow the evolution of forecast quality between anticipations and between stations.

Analyzing the plots in figure 6 (a-c), an improvement in the forecast quality of the LM model in comparison with the HRM model can be observed. There is also a similitude in the evolution of the two models’ forecast, since both models underestimate the forecast value of SLP, as shown by the negative bias for all stations but Bucuresti-Baneasa (fig. 6a). For most stations, the mean error is less then 2 mb, excepting Caransebes station, where it doubles for both models. The plot for standard deviation (fig. 5b) shows an almost uniform distribution of the forecast-observation differences around the mean error, for both models and for all anticipations. It can be seen that for the anticipation of 18h the standard deviation has a maximum value of 6, but for the anticipation of 24h the variance doubles and the maximum is now of 19.

If for SLP the mean errors are systematically negative, in the case of 2m-temperature (fig. 7, a-c) the deviation sign differs between stations. The bias is in the order ±1.5 °C for both models and both anticipations, excepting again Caransebes station, where the mean error is about -3 °C. The STD values show that the spread of the instantaneous error is different between stations and also between models: for LM, the STD is less then 8, for the anticipation of 18h, and has a maximum of 12 for the anticipation of 24h, while for HRM there are stations where STD is higher then 20, showing a high frequency of the cases when the instantaneous error is far from the mean.

For wind speed at 10m, the errors were computed only for those cases when the observed values were at least 4 m/s. This
condition is similar to the standard used in the NMA’s operational verification of this parameter, where the winds with speed less than this threshold are not subject to statistical verification. Figures 8 (a, b) indicate a quite good forecast accuracy of both models for this parameter for certain stations (i.e. Timisoara and Bucuresti-Baneasa), where STD is less than 2, for both models, but there are also stations (i.e. Cluj and Tulcea) where high values of the scores (STD about 4, RMSE about 3) were obtained.

For precipitation, the verification procedure is applied for the Producing/NonProducing category and there is no reference to the forecasted/observed quantity of precipitation. From the analysis of the scores computed for this...
parameter (fig. 9 a-f), it can be seen that the hydrostatic model HRM overestimates the producing of precipitation, therefore having a quite high probability of detection. In the LM case, the high PC values of the forecast, in agreement with the low FAR, emphasize a better forecast quality of this model in comparison with the HRM forecast.

The statistical evaluation of the LM and HRM models for these four parameters emphasizes a better quality of the LM forecast. However, these are preliminary conclusions as the sample data set is too short and a more detailed analysis is necessary for cases when significant errors were obtained.

Fig. 9. Scores for precipitation cumulated for 6h interval, for January 2005: a) frequency bias; b) percent correct; c) probability of detection; d) false alarm ratio; e) true skill score; f) threat score.
b) LM simulations for the horizontal resolution of 2.8km

The results of a qualitative comparison between the LM model simulations at 2.8 km resolution and the measured data are presented below, for 3 November 2004. The meteorological situation of this date was characterized, as well as in the previous day, by a quite high air temperature, with a maximum of 22 °C at Baia Mare. There was light precipitation on large areas in the south of the country, but no precipitation in the Baia Mare region.

For the considered date, the local sub-diurnal cycle of 2m-temperature is accurately reproduced at fine resolution as well as in the simulation at 14 km (fig.10), but the values for both resolutions are systematically underestimated.

![Fig. 10. Diurnal variation of 2m-temperature (°C) at Baia Mare, for 03.11. 2004; blue –observation; red- LM at 2.8 km resolution; green- LM at 14 km resolution.](image)

The local rotation of wind vector, for wind at 10m (fig. 11a-d) is well represented at this resolution and it is in good agreement with hourly measured data. This feature is also present in LM simulations at 14 km resolution, but less emphasized and it does not appear in the hydrostatic model HRM.

The absolute values of forecast surface fields show a systematic difference when compared with observations, which suggests that a fine tuning of the parameters in physical representations (e.g. roughness length) could significantly improve the quantitative forecast of these fields.

5. CONCLUSIONS

The nonhydrostatic LM model has been tested for two horizontal resolutions: of 14 km and of 2.8 km on domains covering the Romanian territory and, respectively, centered on Baia Mare.

The comparison with the hydrostatic model HRM at 14 km resolution shows that the nonhydrostatic processes considered in LM, as well as the improved parameterizations and numerical schemes, lead to a higher forecast accuracy of the analyzed parameters (SLP, 2m-temperature, wind speed at 10m, precipitation). This is also found in the results of both models’ statistical evaluation against the synoptic data from 16 stations. By analyzing these scores, it can be seen that the LM model shows an improvement of forecast quality in comparison with the HRM forecast for all considered parameters and all anticipations. However, for both models the forecast quality is diminished for long-range anticipations. It should be noted that, as the mean values were computed for a short dataset, of only 30 days, the results of models’ statistical evaluation should not be generalized. Especially for precipitation, the scores should be computed for a longer period of time, analysis for 3-months or even 1-year intervals being more relevant.

Apart from these improvements, there is also a substantial reduction of the computational time for LM model (ca. 20 minutes for 24 h forecast) in comparison with HRM model (about 50 minutes for 24h forecast), for the domain and resolution considered in this study.
At fine resolution, the model accurately reproduces the local sub-diurnal cycle of 2m-temperature and the rotation of wind, but the values of forecast surface fields present systematic differences when compared with the analyzed period observations, suggesting again the necessity of fine tuning on the considered domain.

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