Scientific strategy for the implementation of a 3D-Var data assimilation scheme for a double-nested limited area model

Steluţa Alexandru
National Institute of Meteorology and Hydrology,
97, Sos. Bucuresti-Ploiesti, 71552 Bucharest, Romania
E-mail: steluta.alexandru@meteo.inmh.ro

Scientific supervisor: András Horányi
Hungarian Meteorological Service, P.O. Box 38, H-1525 Budapest, Hungary
E-mail: horanyi.a@met.hu

Introduction

Data assimilation is an analysis technique in which the observed information is combined together with a numerical model in order to obtain as much as possible an accurate and consistent description of the atmospheric state. The data assimilation schemes take into account all available information, i.e. the observations, the background (which is a numerical forecast started at a previous time, valid at the current time, being called also *first guess*, because it is the best guess of the atmospheric state, before any observations are taken), the error statistics of these two types of information, the physical laws governing the atmospheric flow.

In the frame of numerical weather prediction (NWP), the result of data assimilation is called an atmospheric *analysis*, being the best estimate of the true state of the atmosphere at the given time and the initial conditions for the numerical forecasts. So one of the key elements of successful numerical forecasts is a good description of the initial conditions of the NWP models.

One of the modern data assimilation techniques is the variational data assimilation. This technique consists of the minimization of a cost function, which measures the distance between the analysis and all the available information used, weighted by the reliability of each of these information sources. A data assimilation system is being developed for the ALADIN/Hungary, spectral double-nested mesoscale limited area model (LAM), based on a three-dimensional variational (3D-Var) scheme (Fischer, 2002).

The purpose of the research was to find the best scientific strategy for the implementation of a 3D-Var scheme for a double-nested LAM. So at the beginning, a general evaluation has been performed in order to get an idea about the applicability of the system, and moreover to find the best possible framework for such a mesoscale data assimilation scheme. Afterwards, some interesting meteorological situations have been chosen, where on the one hand, the reference version (without data assimilation) failed to provide a good prediction and on the other hand, where the operational (reference) forecast was reasonably good. In the first case, the improvements were checked, and in the latter one, whether the new scheme is able to keep the good performance of the reference model.

General evaluation

ALADIN/Hungary is a *double-nested limited area model*, its lateral boundary conditions (LBC) being provided by another LAM, the ALADIN/LACE (Limited Area modelling in Central Europe) model, which has a bigger domain, and a lower resolution. At its turn, the ALADIN/LACE is driven by the French global model, ARPEGE. The idea of the double-nested models is to get a fine scale resolution in the area of interest, and to analyze better the physical processes from the smaller scales.

In the 3D-Var scheme for the ALADIN/Hungary model, the background information is provided through six hours forecast from the previous integration of the model. The background error statistics are computed by the NMC (National Meteorological Center, called now National Centers for Environmental Prediction) method. This method estimates the background error statistics using a set of differences between forecasts valid at the same time, but at different ranges (usually 36h - 12h differences) (Parrish and Derber, 1992). First, the NMC method was used for the global model (ARPEGE), then, it was adapted for the high-resolution limited area model (Berre, 2000). The surface and upper-air (radiosoundings) observations were taken into account in the assimilation process.

The aim of the general evaluation was to provide the best framework for the ALADIN/Hungary 3D-Var system, estimating the best choices among the several possible solutions as: what first guess to be used, what lateral boundary conditions (from the global model or from the limited area model), the optimal initialization method to be applied both in cycling and in production, the best way to incorporate the LBC (thus the information to be consistent in time or in space), etc.

As a reference for all the experiments performed with the 3D-Var scheme, the ALADIN/Hungary model was running in dynamical adaptation mode (the operational version). This means that the initial and lateral boundary conditions for the ALADIN/Hungary model are obtained through the interpolation of the analyses and forecasts of the coupling model onto the high-resolution grid (Horányi et al., 1996).

As evaluation tools, simple statistical measures (RMSE, BIAS) and diagnostic measures (time-evolution of the fields at different levels, spectral energy on ellipses for the spectral fields) have been used. For a subjective evaluation, maps with the mean sea level pressure increments and with the representation of different meteorological fields were drawn. We have to mention about the different number of observations used in the verification procedure of analyses and forecasts. Thus, at the 00 UTC and 12 UTC, around 20 radiosoundings are performed over the ALADIN/Hungary domain, while at 06 UTC and 18 UTC, only around 6. This means that the statistical scores for 06 UTC, as example, do not have the same precision, as those for 00 UTC. But even in this situation the scores give us a rough idea about how the forecast using 3D-Var scheme is behaving compared to the operational one (in dynamical adaptation).

The first basic experiments were performed for one week period (25.02.2002 - 02.03.2002), when two different coupling techniques have been tested both in cycling and in production, namely: time-consistency and space-consistency. As the name already suggested, these techniques were different in the sense that the 3D-Var analysis and the lateral boundary conditions from the coupling model, necessary for the integration of the model, have been chosen in such a way that the information provided by the files was consistent in time, or respectively in space.

The verification scores show that the 3D-Var analysis fits closer to observations, for all the fields, which was expected. After 6h forecast, the fields of the model with data assimilation is keeping from the initial improvement, but not for all levels (Figure 1). After 24h integration, the scores are the same (not shown). ***Time-consistency technique seems to give a better forecast so far***.

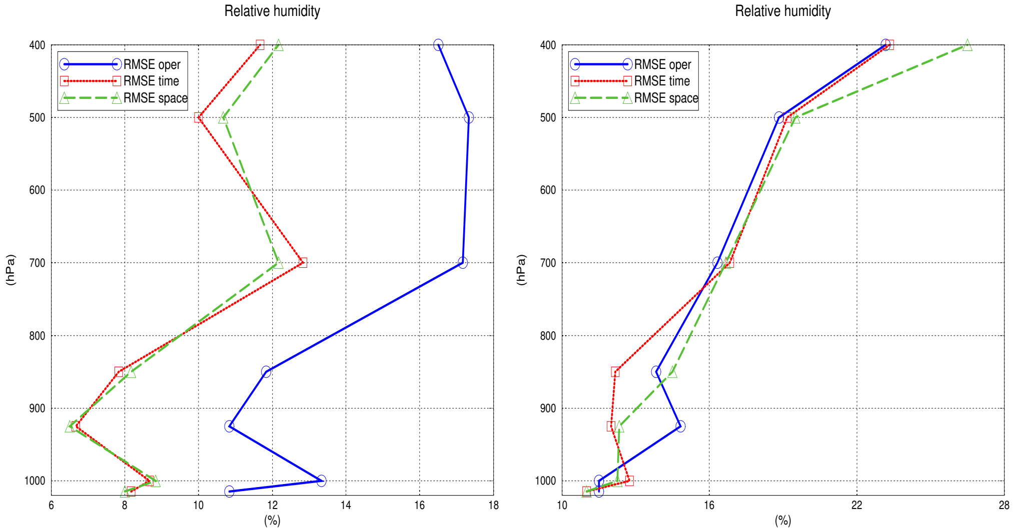

Figure 1: The vertical profile of RMSE of the operational analysis (*oper*), and using 3D-VAR scheme in time-consistency (*time*), and space-consistency (*space*), (left), and after 6h integration (right), for the period 25.02.2002 - 02.03.2002, base 00 UTC

Other basic experiments were carried out for the same period, testing different initialization methods, using time-consistency as coupling technique. The ALADIN model is using the digital filter initialization, to suppress the unrealistic high frequency gravity oscillations from the initial conditions (Lynch and Huang, 1992; Lynch et al, 1997). Another initialization method has been proposed for testing, namely the incremental digital filter initialization (IDFI), when it is assumed that the first guess is already balanced and the analysis increment (the difference between the analysis and the first guess) should be filtered.

So in turn, digital filter initialization, incremental digital filter initialization, and no initialization were applied in cycling (for the first guess). The statistical scores were very close, no matter what initialization method has been used (not shown).

In Figure 2, the noise can be seen for the first time-steps of the integration, when no initialization and IDFI were used in cycling. The curves when DFI was applied, are rather smooth. It is not an obvious conclusion which initialization method is better, especially because the RMSE scores were so close. But one can see that for some points, sometimes 6h is not enough to get a filtered forecast. It is also possible in the future to use a shorter assimilation window. So the 6h forecast has more chances to be realistic if the results from the time evolution are not so noisy. It was concluded that ***in the 3D-Var cycling, DFI is needed***.

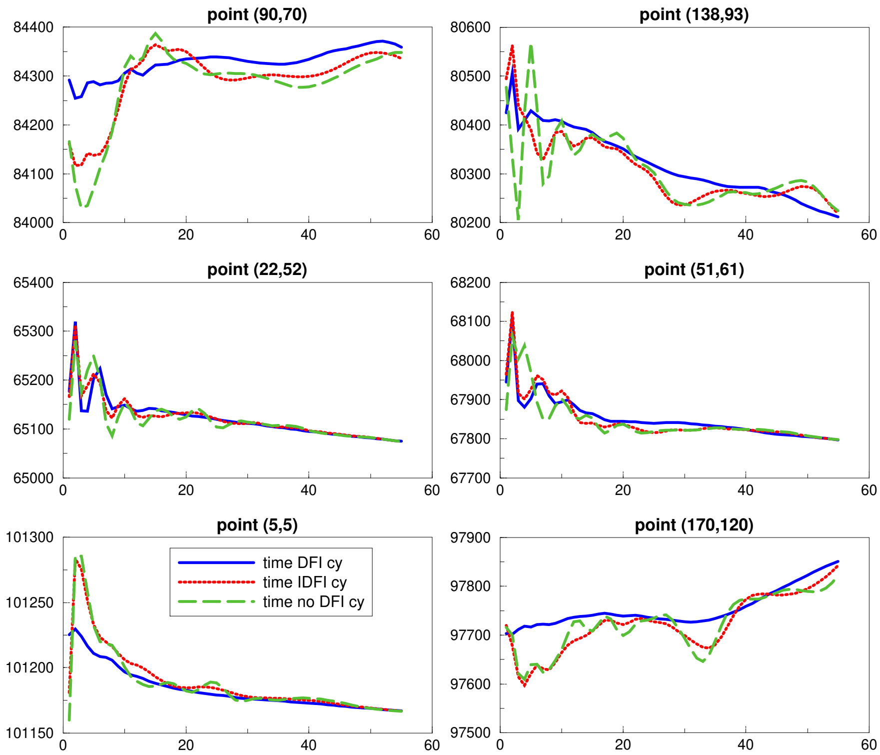

Figure 2: The time evolution of the mean sea level pressure using different initialization methods in cycling, DFI (*time DFI cy*), IDFI (*time IDFI cy*), no DFI (*time no DFI cy*), for 28.02.2002 base 00 UTC

The time evolution of the mean sea level pressure was checked during the 6h integration in production (not shown), for the operational forecast and using 3D-Var scheme with different initialization methods in cycling and in production. It seems that the fields are in balance, when DFI was used in production (for the operational model, and also with 3D-Var scheme). Without initialization, the noise appeared especially for the first time-steps. This confirms that ***digital filter initialization has to be applied also in production***. (Alexandru, 2002).

The last set of basic experiments has been realized to see the implications of the double-nesting on the 3D-Var results. It was carried out for one month's period (25.02.2002 - 25.03.2002), using as lateral boundary conditions, the ALADIN/LACE and ARPEGE files (from the assimilation cycle), in space-consistency. In cycling, the 3D-Var analysis, and ALADIN/LACE, respectively ARPEGE analyses were used as LBC for the first guess. Digital filter initialization was applied both in cycling and in production.

The statistical measures showed that the analyses for relative humidity and wind, using 3D-Var scheme are better represented than the operational analysis, for all levels. The temperature and geopotential have also better scores using data assimilation, but the difference is not significant as for the previous fields (not shown).

This improvement confirms only that the analysis is closer to observations.

After 6h integration, the scores for temperature are almost neutral, with small variations near the surface. The forecast of geopotential, with data assimilation, has been improved, especially for some upper-levels. The scores of the forecast using 3D-Var scheme look slightly better than in dynamical adaptation, for zonal wind, at almost all the upper-levels, and for relative humidity, especially near the surface (Figure 3). The meridional wind is better represented by the operational model. In the picture, the fields with the largest differences are presented.

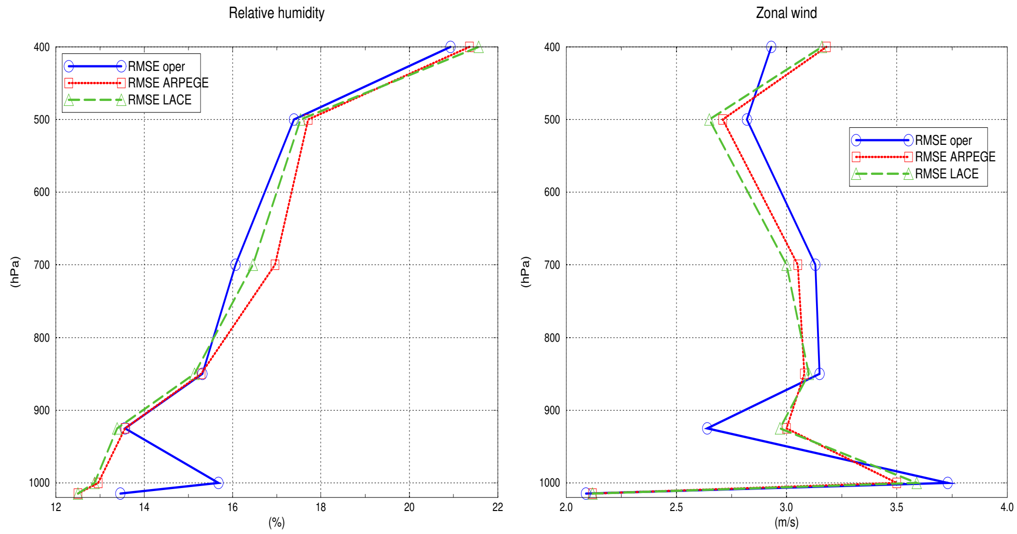

Figure 3: The vertical profile of RMSE for the operational forecast (*oper*), and using 3D-Var scheme, with ALADIN/LACE (*LACE*) and ARPEGE (*ARPEGE*) LBC, for the period 25.02.2002 - 25.03.2002, base 00 UTC

Looking on the maps with the representation of some meteorological fields, the differences for the experiments with 3D-Var scheme and different lateral boundary conditions are not visible. These last experiments emphasized that ***the choice of the LBC from ALADIN/LACE or ARPEGE models is not so important***. (Alexandru [1], 2003).

Case studies

After the best possible strategy for the ALADIN/Hungary 3D-Var system was established, some interesting meteorological situations have been selected in order to study more in detail the performance of the model using the 3D-Var scheme. For some case studies, the improvement of the forecast with data assimilation has been checked, and for others, whether the 3D-Var system is able to keep the good results of the reference version (in dynamical adaptation).

◇ The first case study (the 17-18th of July 2002)

The first case was chosen because the operational model failed to provide a good prediction. A brief description of the synoptic situation is presented below. A cyclone, coming from Northern Italy, moved to East, and remained over the Carpathian Basin, between the 18-20th of July 2002. On 18.07, large quantity of precipitation (40-70 mm/24h) has been measured over the central part of Hungary, along the Danube river (Figure 4).

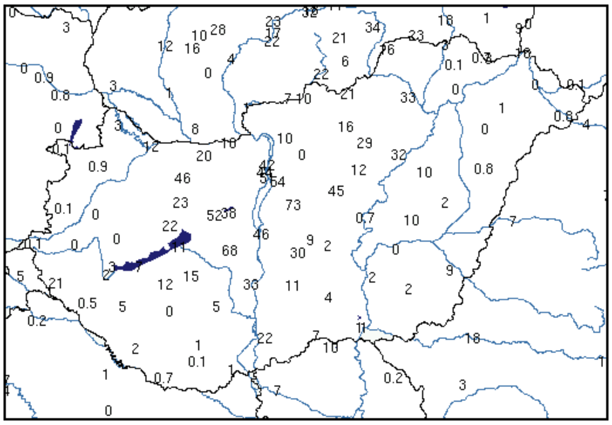

Figure 4: The quantity of precipitation (mm/24h) measured over Hungary between 18.07 06 UTC - 19.07 06 UTC

The experiments were carried out using lateral boundary conditions from the ALADIN/LACE, respectively ARPEGE models, in time-consistency, and two different sets of observations. One set contains the SYNOP and TEMP data from the Hungarian Meteorological Service (HMS), and the other one is from Météo France, zoomed over the ALADIN/Hungary domain. The last set has besides SYNOP and TEMP data, also AIREP, SATOB, PILOT observations.

The forecast of the operational model (called *"oper"*) did not give any indication about the rainfall. One can see that the quantity of predicted precipitation is very small (less than 10 mm in 24h), over almost the entire country (Figure 5).

The experiments with 3D-Var scheme gave a good forecast of the event, compared to the operational model. When LBC from ALADIN/LACE model and data from the Hungarian Meteorological Service have been used (*"3dvar"* set), the quantity of precipitation seems to be overestimated (with maximum value as 170 mm in 24h). A better forecast of the rainfall was performed by the model with 3D-Var scheme using LBC from ARPEGE and observational data from HMS (*"3dvar ARP"*), respectively with LBC from ALADIN/LACE and data from Météo France (*"3dvar TLS"*). The quantity of rainfall is closer to the real measurements (bigger than 50 mm in 24h over the Danubian Basin), and the location is well predicted.

Probably the good forecast given by the *"3dvar ARP"* set is due to the observations and moreover to the information from the ARPEGE model. In the *"3dvar TLS"* experiments, the bigger influence came from the observations (especially AIREP, SATOB), as they have been nearer to the moment of the event.

As a conclusion from this case study, we can say that the operational model, even with 6 hours before the event was not able to predict any features of the phenomenon. All the experiments with data assimilation forecasted large quantity of precipitation. Among these, the *"3dvar ARP"* set was the closest one to reality. (Alexandru [2], 2003).

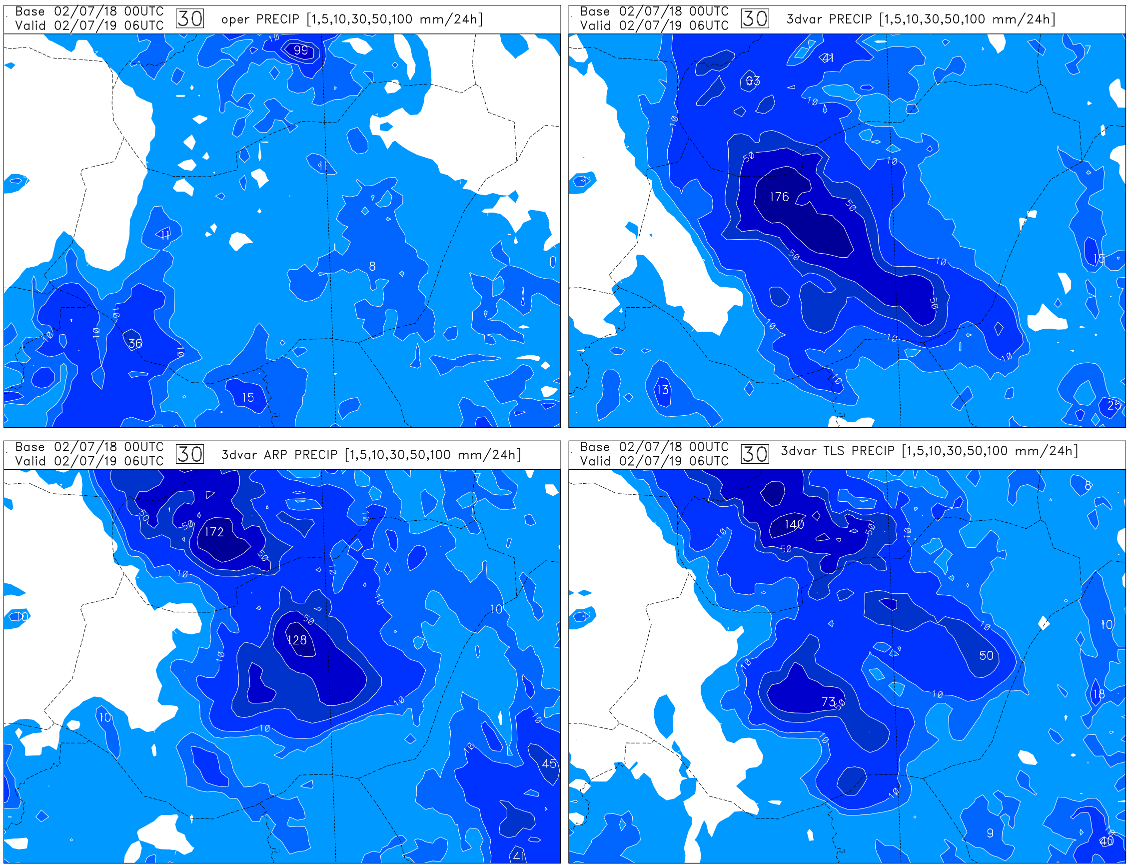

Figure 5: The quantity of precipitation (mm/24h) forecasted by the model in dynamical adaptation (*oper*) and using 3D-Var scheme with different data and LBC (*3dvar*, *3dvar ARP*, *3dvar TLS*) between 18.07 06 UTC - 19.07 06 UTC, from 18.07 00 UTC run

◇ The Czech Floods from August 2002

The operational forecast of this event was considered a success by the forecasters. So the goal was to see if the 3D-Var system is also able to have a reasonable good prediction.

In August 2002, disastrous floods hit the central Europe. The floods proceeded in two waves and were caused by intensive rain from two deep cyclones and the related frontal systems, one following the other at a very short time interval. Both moved slowly, but only the second one was remarkably well developed. The quantity of precipitation was significant in Austria, Bavaria and Bohemia, i.e. 100-150 mm in 24h, and in some places more than 300 mm (Figure 6).

The experiments with the 3D-Var scheme were carried out using the operational LBC for ALADIN/Hungary model (from ALADIN/LACE) and the SYNOP and TEMP data available at the HMS.

Both models, with and without data assimilation, succeeded to predict the slow motion of the cyclone, together with the heavy rainfall. On the 11 th of August, the cyclone moved from the northern Italy over Austria. Then, on the following day, the center of the low pressure system went over the northern part of Bohemia. On the 13 th of August, the forecasts of the models showed that the cyclone continued to move in a northeastward direction, over Poland, and began to fill.

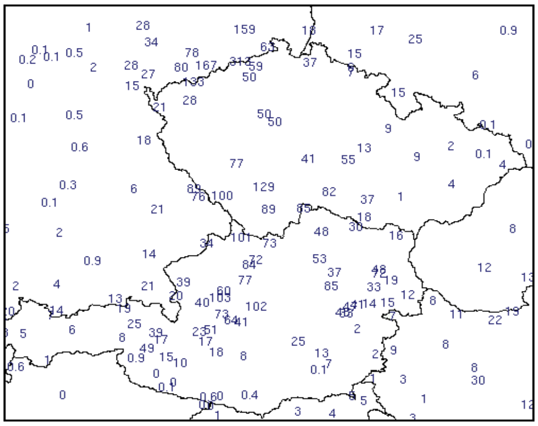

Figure 6: The quantity of precipitation (mm/24h) measured over Austria and Czech Republic, between 12.08 06 UTC - 13.08 06 UTC

Figure 7 shows the precipitation cumulated in 24h between 12.08 06 UTC and 13.08 06 UTC. In some places in Austria, the quantity of precipitation is more than 100 mm in 24h, which is a slight overestimation, compared to real measurements. But both models predicted the right place of the rainfall in Saxony, where values as 296 mm in 24h are shown. The operational forecast had the closest value to reality. But also the 3D-Var experiments predicted an important quantity in that area.

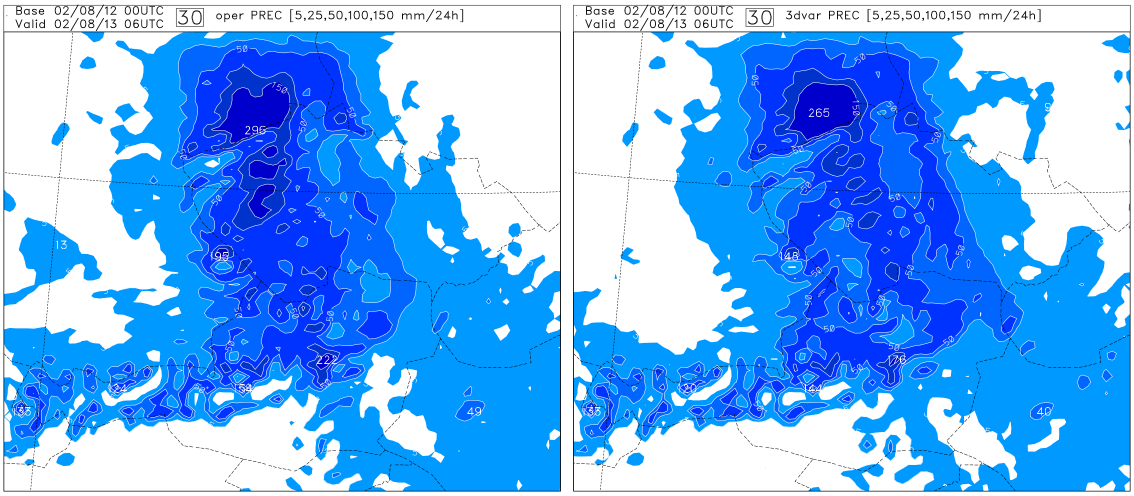

Figure 7: The quantity of precipitation (mm/24h) forecasted by the operational model (left) and using 3D-Var scheme (right), between 12.08 06 UTC - 13.08 06 UTC, from 12.08 00 UTC model run

The good forecast of the operational ALADIN/Hungary model is partly due to the good information provided through the lateral boundary conditions. Being a double-nested limited area model, it means that both ALADIN/LACE and mainly ARPEGE models had a good forecast for the floods. The global model ARPEGE is using the 4D-Var scheme (Thépaut and Courtier, 1991; Courtier et al, 1994), and more other observations are assimilated, compared to the 3D-Var scheme for ALADIN/Hungary model. So this fact explains the good performance of the global model.

The accurate information from the lateral boundary conditions, together with the assimilation of more SYNOP observations, helped the model with 3D-Var scheme to obtain a good prediction of the event. So it has been shown that the 3D-Var system do not deteriorate the good performance of the reference model. (Alexandru [3], 2003).

⋄ **The third case study (the 4*th* of August 2002)**

Another case, when the operational model (in dynamical adaptation) has not been able to predict an important quantity of precipitation over Hungary was selected to be studied using the 3D-Var scheme.

On the 4*th* of August 2002, a low pressure system dominated over the central-eastern part of Europe. In altitude the ridge of the anticyclone from North-Africa was extended. In the western part of Hungary, the temperatures were in the morning around 23 °C, increasing till 30 °C, at noon. The air was very humid. A cold front was moving through Austria and Hungary. Advancing, the cold air moved the humid air upward, determining an instability line, along which the turbulence is severe, rain showers and thunderstorms occur. Such instability line has been developed in the north-western part of Hungary, causing an intensive rainfall. Thus, in less than six hours, the quantity of precipitation reached a maximum of 65 mm.

The 3D-Var experiments have been carried out using the lateral boundary conditions from the ALADIN/LACE model, and as observations, SYNOP and TEMP data from the Hungarian Meteorological Service.

The forecasts from the 04.08 00 UTC and 06 UTC runs showed that both models, with and without data assimilation, did not predict the rainfall, neither at the right moment, nor later. It means that the information coming from the observations did not bring any indication about the future development of the instability line.

The 04.08 12 UTC run brought the main difference in the forecasts of the two models. The operational model predicted fair weather, without any precipitation. Comparing to reality, one can say that for this particular period of time, the operational model has a good forecast, the rainfall happening earlier than this model run. But in the same time, it is a failure, not predicting the precipitation at the right moment, either later. Being a local phenomenon which has developed very fast, it was not forecasted by the coupling model. So no information about it came through the lateral boundary conditions from the ALADIN/LACE to ALADIN/Hungary model. Instead, the experiments using 3D-Var scheme forecasted a huge quantity of precipitation (more than 100 mm), but with six hours delay. On the one hand, this represents a misforecast, but on the other hand, the rainfall was still predicted (Figure 8).

Other experiments were performed using only SYNOP or TEMP data, in order to see what observations could have influenced so much the precipitation forecast. Thus it was found that the model using the 3D-Var scheme and only TEMP data, did not predict any rainfall, which means that all the information about it came from the surface observations. Indeed, assimilating only SYNOP data, the quantity of precipitation is significant (not shown).

So the information from the observations (from 04.08 at 12 UTC) reproduced the state of the atmosphere, with high humidity. Thus the analysis of the model caught the end of the storm. Because any other information from the lateral boundary

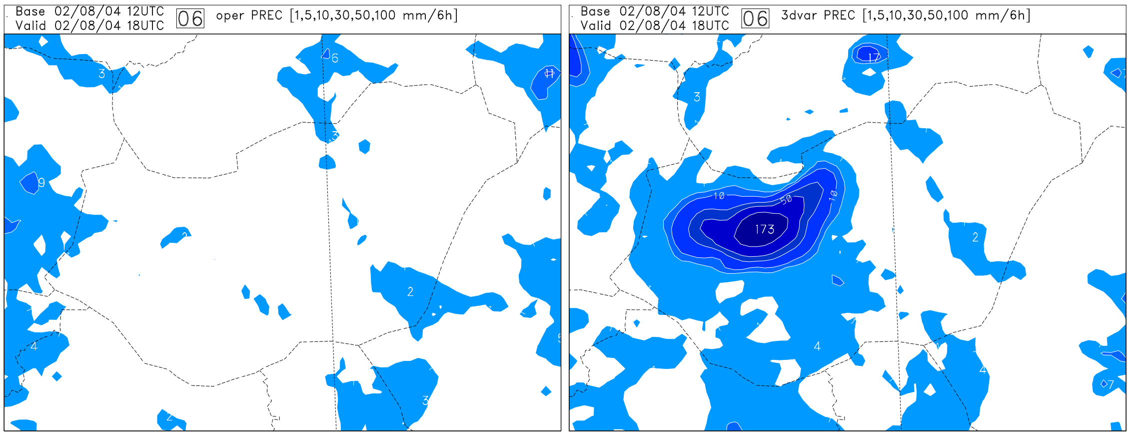

Figure 8: The quantity of precipitation (mm/6h) forecasted by the operational model (*oper*) and using 3D-Var scheme (*3dvar*), between 04.08 12 UTC - 18 UTC, from 04.08 12 UTC model run

conditions or from the first guess did not give any indication about an existing storm, the model "said" that it is the beginning. So, one can say that the model using 3D-Var scheme had good initial conditions, but it was beyond its capacity to predict such a rainstorm. (Alexandru [4], 2003).

⋄ The "inversion" case (the 27th of December 2002)

Since the first three cases happened in the summertime, it was decided to choose also some "winter" cases. So the forecasters proposed a case when a strong temperature inversion occurred in the north-western part of Hungary, on the 27th of December 2002, at noon. In the previous days to this inversion, an anticyclone was extended over Hungary, so the air was very cold and dry. A warm advection from the Mediterranean Sea replaced the cold air in the altitude, causing a temperature contrast around 8 °C, between the 980 hPa and 850 hPa levels.

The 3D-Var experiments were performed using the observations available at HMS (SYNOP, TEMP) and the lateral boundary conditions provided by the global model ARPEGE.

With more than 12 hours before the event, both models (in dynamical adaptation and using the 3D-Var scheme) had a similar forecast, predicting a temperature inversion, in that region, but not so strong (around 4 °C). The main difference appeared in the analysis from 27.12 12 UTC run, when the operational model was very close to reality. The inversion can be seen also in the analysis of the model with 3D-Var scheme (Figure 9), only that the variation of the temperature in altitude is smaller.

At first sight, these results appeared as being "strange", mainly because the idea of data assimilation procedure is to improve the analysis, and in this case it seems that it was getting worse. So the temperature field of the different information used in the integration of the model (the first guess, the 3D-Var analysis, the lateral boundary condition, the analysis after the digital filter initialization has been applied) was investigated. It was discovered that the temperature forecast from the first guess was farther than reality. The 3D-Var scheme succeeded to bring the analysis closer to observations, but not as much as the operational analysis was. The

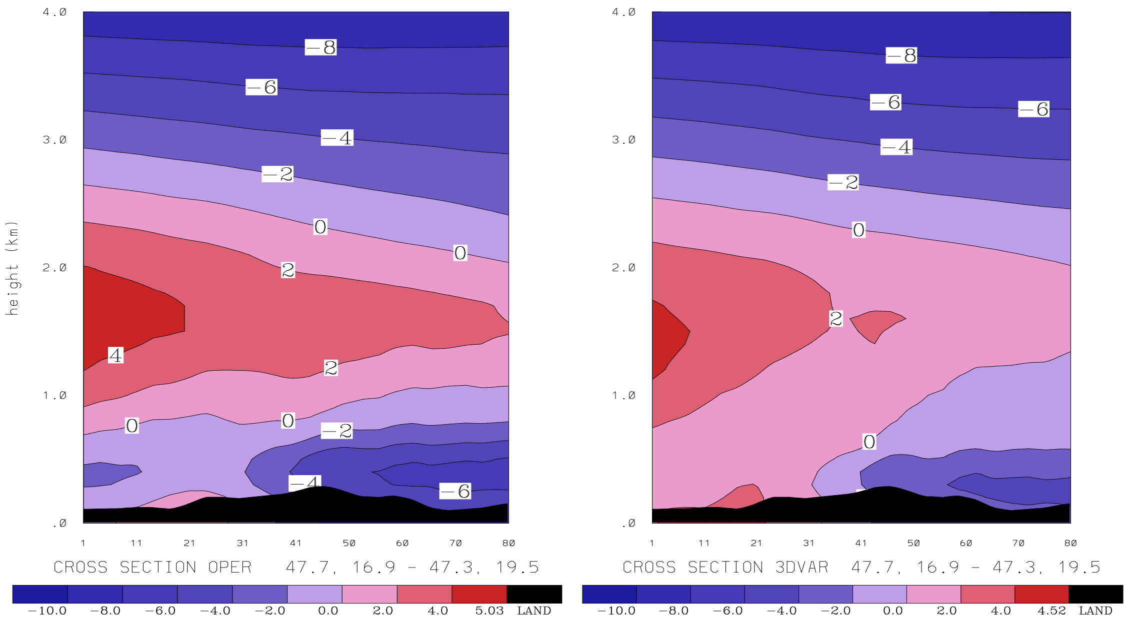

Figure 9: The vertical cross-sections of the temperature field, through Hungary, from the operational analysis (left) and using 3D-Var scheme (right), from 27.12 12 UTC run

model in dynamical adaptation had more accurate information contained in the initial condition, from the global model. After the digital filter initialization has been applied, the analysis of the model using the 3D-Var scheme was getting farther from the observations (not shown).

Other experiments have been performed in order to check the reasons for the misforecast of the model using the 3D-Var scheme. First, it was tested whether or not the information from the observations was sufficient. So the observations used for the 4D-Var cycling in the ARPEGE model (from Météo-France), which include SYNOP, AIREP, SATOB, TEMP and PILOT measurements, were assimilated. The temperature field from the analysis is looking almost the same as with the data from HMS, which means that the reason of the bad analysis is not the amount of the observations in the region.

Then, another experiment has been realized, using the first guess from the ARPEGE model (the 6h forecast from the 27.12 06 UTC run), instead of that one of the ALADIN/Hungary 3D-Var system. The results showed an improved analysis, almost similar with the one of the operational analysis. So it seems that for this case, the global model was able to predict a better first guess than the limited area model. This is probably due to the advantage of the 4D-Var scheme to use the observations at the "correct time".

So this case study showed that the data assimilation procedure worked properly, but due to the fact that the information from the first guess was too far from observations, the model could not obtain a better result. This means that further it should be investigated which part of the physics of the limited area model has to be improved, in order not to lose already after 6h integration, the good features introduced by the 3D-Var procedure.

◇ **The "snow" case (the 7^{th} of January 2003)**

Another chosen "winter" case is from the 7^{th} of January 2003, when a significant amount of snow fell over Hungary. The synoptic situation can be described by a high-pressure zone placed in the northern part of Europe, and by cyclones moving over the Mediterranean Sea, in the south. So Hungary was at the edge between the two weather systems. As an effect of the air with two contrasting characteristics there were sharp differences in the temperature and intensive frontal zone over the Carpathian Basin, causing snowfall all over the country on the 7^{th} of January (Figure 10).

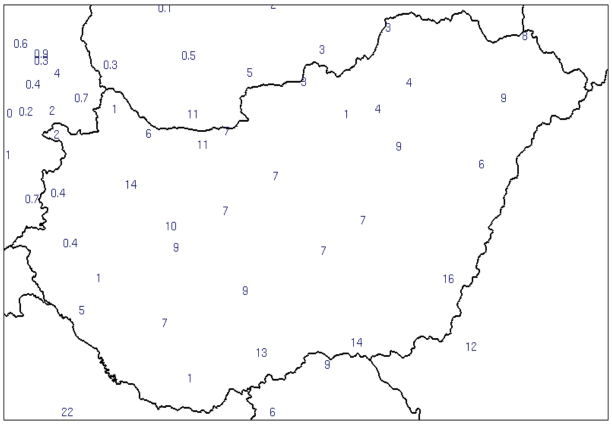

Figure 10: The quantity of precipitation (mm/12h) measured over Hungary, between 07.01 06 UTC - 07.01 18 UTC

The forecasts of different experiments, with and without data assimilation, have been examined. The area of high humidity is covering the entire country (not shown). The air has an ascending motion, especially in the south-eastern part of Hungary (also not shown), where the quantity of precipitation is significant. Comparing with the real measurements, one can say that both models predicted the same pattern of the areas where the precipitation is expected (Figure 11). Only that there is an overestimation of the maximum of precipitation fell in the northern part of Serbia and also the area in the north-western part of Hungary predicted by the models as being covered with snow, is smaller than in reality.

Considering the limitations of the models in defining the precise location of precipitation, these forecasts showed the possibility of the occurrence of snowfall almost over the entire country. The good prediction of the model running in dynamical adaptation is partly due to the accurate information provided by the global model through the initial and lateral boundary conditions. For the model using the 3D-Var scheme, both the information from the observations and from the lateral boundary conditions "played" an important part in the forecasting of the snowfall.

Conclusions

In the present paper, the research work on the 3D-Var scheme for the double-nested limited area model, ALADIN/Hungary, is described. The experiments were realized in two parts. At the beginning, a general evaluation was carried out, in order to get a rough idea about the applicability of the ALADIN 3D-Var system. Then,

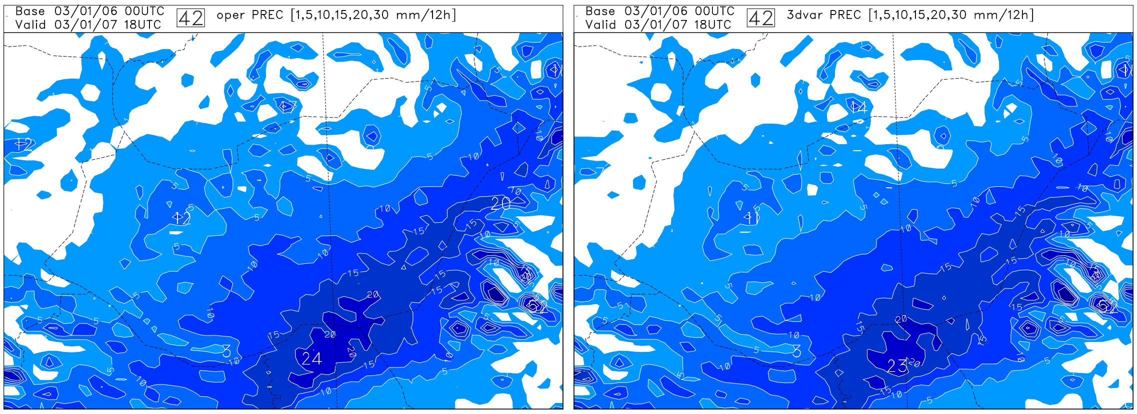

Figure 11: The quantity of precipitation (mm/12h) forecasted by the operational model (left) and using 3D-Var scheme (right), between 07.01 06 UTC - 07.01 18 UTC, from 06.01 00 UTC run

some case studies have been investigated, to study the scheme in more detail.

It was concluded that for the 3D-Var scheme for the ALADIN/Hungary model the optimal choices are as follows: digital filter initialization to be applied in cycling and production, lateral boundary conditions to come from the same integration of the model (thus the information to be consistent in time), and the choice of the LBC from the global or limited area model is not so important.

The case studies showed the good performance of the scheme, but also some limitations. So the assimilation of surface data together with the radiosoundings observations is necessary. The information from the lateral boundary conditions is also important to be accurate, in order to obtain a good short-range forecast. For some situations, the amount of applied data was proven to be too poor for providing a good forecast. So more other types of observations is indicated to be used in the future.

So far, we could conclude that the present framework of the ALADIN/Hungary 3D-Var system is appropriate to obtain a good forecast. But the scheme is still the "subject" of improvements. In the future, it is planed to try to test other background error statistics, the explicit blending technique.

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