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Sensitivity of limited area model data assimilation to lateral boundary condition fields

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ABSTRACT

Experiments with a limited area model forecasting system have been carried out to show the importance of accurate lateral boundary conditions, also during data assimilation forecast cycles. Advection of observed information from data-dense areas to data-sparse areas is an important process in any data assimilation, and for limited area assimilation, this process should also work properly across the lateral boundaries. A case study including a rapid cyclogenesis in the vicinity of Iceland is used to illustrate the deterioration of forecast quality as a result of too old forecast boundaries during data assimilation.

1. Introduction

The idea of limited area modelling (LAM) is to apply a high-resolution forecast model over a spatially limited area using time-dependent lateral boundary conditions provided by, e.g., a global coarse mesh forecast model. Operational practises differ significantly between weather services applying limited area models. Some services, like the Direction de la Meteorologie Nationale (DMN) in France, are applying a very high resolution model on a rather small forecasting area while compensating the limitations of the area by using the best possible lateral boundary conditions, generated by a global forecast model starting from the same initial time as the limited area forecast.

Smaller weather services, however, do not generally have the resources to run their own global forecast model and they mostly have to rely on boundary values received from outside. The timeliness of the global forecast production and data transmission delays do not generally permit the smaller weather services to run their limited area forecasts with such "fresh" boundary condition fields as DMN in France. As an example, the weather services of Denmark, Finland and Sweden are using 12 GMT ECMWF forecasts as boundary conditions for their operational LAM runs. Due to the intentional late cut-off time for observations and the subsequently delayed forecast production at ECMWF, the forecast length of available boundary values may be up to 30 h (for 18 GMT) at the initial time of the operational LAM forecast runs. This means that the 00 GMT analysis first guess field will be a 36-h forecast close to the lateral boundaries. Since forecast domain boundaries are partly placed on the border of large data-sparse areas inside the forecast domains, this practise of using too old forecast boundary values may have a seriously negative impact also on the LAM analysis fields. Instead of advecting observed information from data-rich to data-sparse areas during the data assimilation, old forecast boundary values are advected into the forecast domain and due to the lack of observed information in data-sparse areas, the corresponding forecast errors are not corrected for.

This paper discusses an example of this negative effect of boundary values on the data assimilation and the forecast. The example is taken from pre-operational tests of the high-resolution limited area model (HIRLAM) forecasting system, which is being developed by a common Nordic/Dutch research group.

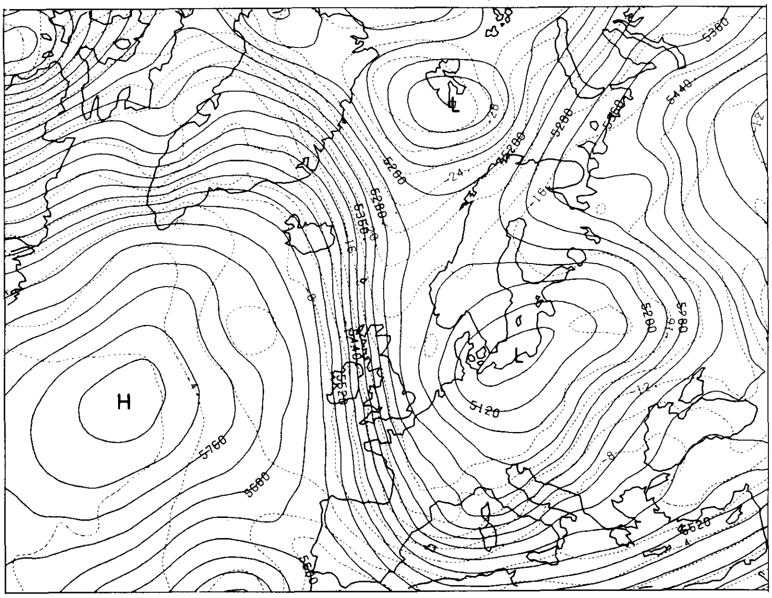

Fig. 1. Analysis of 500 hPa geopotential height and 1000/500 hPa layer mean temperature valid at 00 GMT, 1 March 1988.

2. The HIRLAM data assimilation and forecasting system

The HIRLAM data assimilation and forecasting system consists of three major parts: the objective analysis scheme, the non-linear normal mode initialization scheme and the grid-point forecast model. The objective analysis scheme is a limited area version of the ECMWF scheme, which is based on three-dimensional multivariate optimum interpolation of forecast errors, see Lönnberg and Shaw (1987). The initialization scheme is a non-linear normal mode scheme utilizing the balance condition and iteration scheme introduced by Machenhauer (1977). In the present application, four vertical modes are initialized and only adiabatic tendencies are used.

The formulation of the HIRLAM forecast model is based on the ECMWF gridpoint LAM, as implemented by Undén (1982) at the Swedish weather service. The model is formulated in the hybrid (σ/pressure) vertical coordinate system and at present, a transformed latitude–longitude projection is used in the horizontal. A new physical parameterization package has been developed by the HIRLAM group. The model uses the simplified Davies lateral boundary relaxation scheme originally tested for the ECMWF gridpoint LAM, see Kållberg and Gibson (1977). For a detailed description of the system, reference is made to the HIRLAM Documentation Manual (Kållberg, 1989).

3. Description of data and the experiments

The HIRLAM data assimilation and forecasting system was used for extensive pre-operational experimentation from January until August 1988. One such experimentation period was started on 00 GMT 27 February 1988 with a 12-h ECMWF forecast as first guess for the HIRLAM analysis. Data assimilation, with an assimilation cycle of 6 h, was continued until 00 GMT 3 March 1988. 130×100 horizontal gridpoints with a horizontal resolution of $0.5° \times 0.5°$ were used. 16 vertical hybrid levels were used in the analysis, in the initialization as well as in the forecast model.

A rapid cyclogenesis occurred in the vicinity of Iceland on 1 March 1988. Analysis maps, describing the 500 hPa flows during the period 1–2 March 1988 are given in Figs. 1–2. For the largest horizontal scales, the flow is dominated by

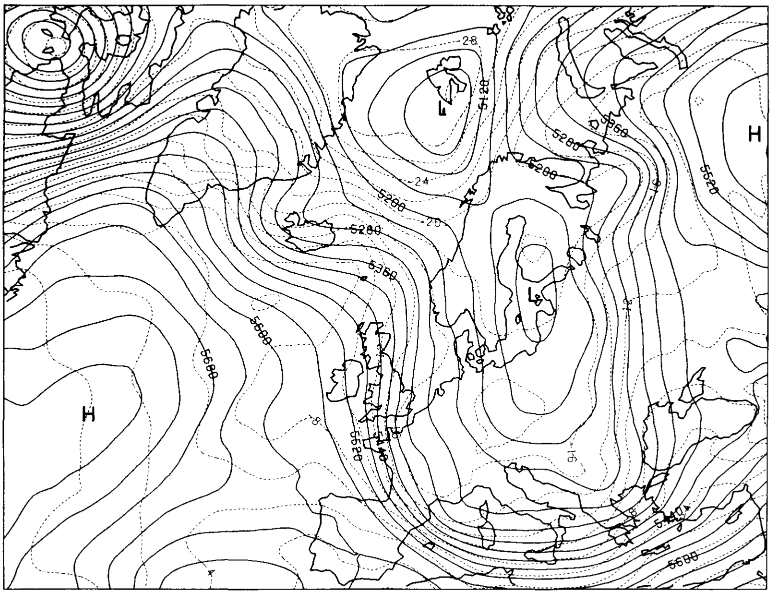

Fig. 2. Analysis of 500 hPa geopotential height and 1000/500 hPa layer mean temperature valid at 00 GMT, 2 March 1988.

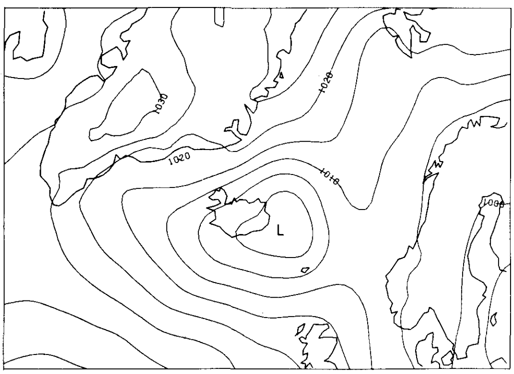

Fig. 3. Analysis of sea-level pressure valid at 00 GMT, 2 March 1988.

a quasi-stationary cyclonic system centred over Southern Scandinavia and an anti-cyclonic area with sea-level pressures up to 1050 hPa over the Northern Atlantic and Greenland areas. Superimposed on the large-scale anti-cyclonic flow over Greenland is a smaller scale upper-air trough which is of main interest for the experiments reported here. This small-scale upper-air trough enters the HIRLAM forecasting area through the western boundary on 29 February, reaches its northernmost position over Greenland on 1 March and it is strongly amplified during its further movement towards the south-east. A strong surface cyclogenesis is associated with this amplification, and the sea-level pressure drops from 1027 hPa to 996 hPa in the area east of Iceland in less than 24 h. A surface analysis map for 00 GMT 2 March is given in Fig. 3. Several factors probably contribute to this rapid development; southward absolute vorticity advection, vorticity stretching due to the orography difference between the Greenland ice cap and the sea, in addition to baroclinic processes.

The HIRLAM pre-operational forecast did not predict this cyclogenesis particularly well compared to, e.g., the UK Met. Office operational forecast. The HIRLAM 24-h forecast map for the surface is given in Fig. 4. This HIRLAM forecast failure will be shown to be related to use of too old lateral boundary data (24-h and 36-h forecasts were used throughout).

Several experiments were carried out to check the sensitivity of the forecast quality to different boundary conditions in the data assimilation phase as well as in the forecast phase, resulting in 24-h forecasts valid at 00 GMT 2 March 1988. The only differences between the various experi-

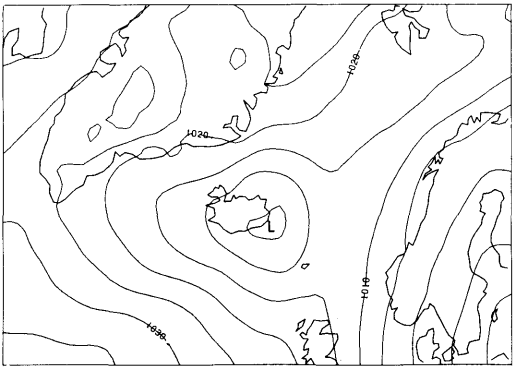

Fig. 4. HIRLAM (ETA) 24-h forecast of sea-level pressure valid at 00 GMT, 2 March 1988.

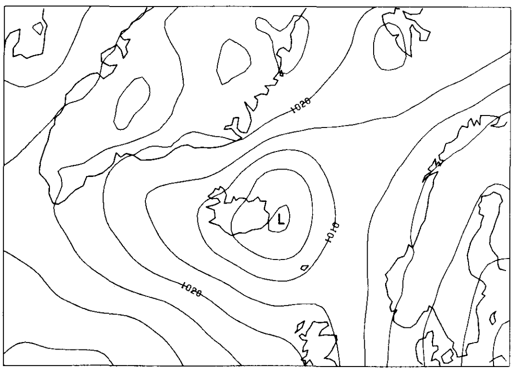

Fig. 5. HIRLAM (SUM) 24-h forecast of sea-level pressure valid at 00 GMT, 2 March 1988.

ments were the boundary data sets. Characteristics of the experiments are summarized in Table 1.

4. Impact of forecast lengths and frequency of the boundary fields

As was mentioned above, the HIRLAM pre-operational data assimilation and forecast experiment were run with forecasts as long as 36 h for the lateral boundaries during the data assimilation. In addition, the lateral boundary values were updated only twice a day; intermediate boundary fields were derived by linear interpolation in time. In the following, we will refer to this experiment with the experiment name ETA. In order to test the impact of the best available forecast boundary fields, an experiment, SFM, was carried out. The differences between the SFM and the ETA experiments are the following: (1) Boundary frequency is 4 per day instead of 2 per day. (2) 12 GMT + 6-h and 12 GMT + 12-h forecasts are used instead of 12 GMT + 36-h as boundary fields for the data assimilation forecasts starting at 12 GMT and 18 GMT. This means that more recently observed information, from outside the HIRLAM forecast area, is entered into the area through the lateral boundary conditions.

The SFM 24-h forecast (no map included) showed a significant improvement over the corresponding ETA forecast. The 500 hPa trough was more amplified, the central pressure of the surface low was 2 hPa deeper (Table 1), and the surface pressure gradients north of Iceland were stronger, all in agreement with the verification analysis.

5. Impact of analysed boundaries with different boundary frequency

In order to test the impact of the best possible analysed boundary fields, an experiment, SUM, was run with analysed boundaries inserted with a frequency of 4 per day during the data assimilation as well as during the forecast. The SUM forecast (Fig. 5) shows significant improvements of the Icelandic cyclogenesis in addition to that obtained with the best possible ECMWF forecast

Table 1. *Characteristics of data assimilation and forecast experiments*

Experiment name	Assimilation boundaries	Forecast boundaries	Boundary updating frequency	Pressure in centre of low
ETA	forecasts ("old", see text)	forecasts	2/day	1004 hPa
SFM	forecasts ("fresh", see text)	forecasts	4/day	1002 hPa
SUM	analyses	analyses	4/day	999 hPa
SAM	analyses	analyses	2/day	1001 hPa
SUN	analyses	forecasts	4/day	1000 hPa

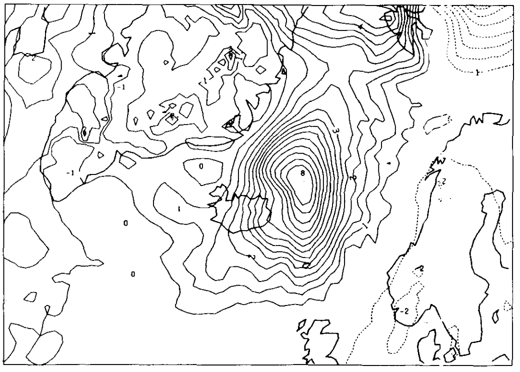

Fig. 6. Differences between the HIRLAM (ETA) and the HIRLAM (SUM) 24-h sea-level pressure forecast fields valid at 00 GMT, 2 March 1988. Contour interval 0.5 hPa.

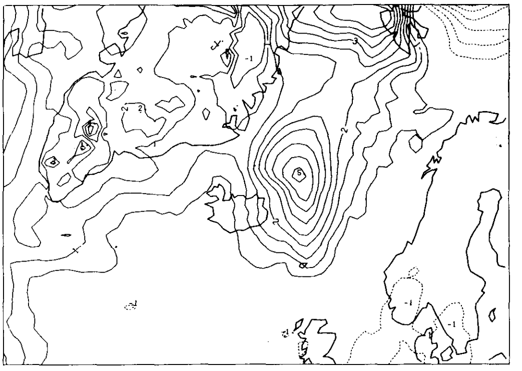

Fig. 7. Differences between the HIRLAM (SFM) and the HIRLAM (SUM) 24-h sea-level pressure forecasts fields valid at 00 GMT, 2 March 1988. Contour interval 0.5 hPa.

boundaries (experiment SFM). The forecast sea-level pressure field east and north-east of Iceland is close to the verification analysis.

A closer inspection of the ETA, SFM and SUM sea-level pressure forecasts together with the difference between the ETA and the SUM forecasts (Fig. 6) show that the improved lateral boundary fields mainly influence the rather small horizontal scale associated with the strong Icelandic cyclogenesis. Other forecast errors on larger scales not directly related to the different lateral boundaries, e.g., the errors in the filling of the Central European low pressure system, remain very similar.

In order to test the sensitivity of the data assimilation and the forecast for the lateral boundary frequency, an experiment, SAM, was run with boundary frequency 2 per day but in all other details equal to the SUM experiment with analysed boundary fields. The SAM sea-level pressure forecasts (no map included) showed a significant deterioration of the forecast quality compared to the SUM forecast, indicating the importance of increased frequency of lateral boundary fields.

6. Relative impact of analysed boundaries in the data assimilation and in the forecast

The evaluation of the SFM and the SUM experiments illustrated the impact of using analysed boundary values in the data assimilation and in the forecast. To illustrate the relative importance of analysed boundary values in each of the two phases of the forecast production, an experiment, SUN, was carried out with analysed boundaries used during the data assimilation phase but with forecast boundaries (the same as in the SFM forecast) during the forecast phase. The SUN forecast (not shown) is very similar to the SUM forecast as regards the cyclogenesis, illustrating the importance of using accurate boundary values during the data assimilation for this particular case of rapid cyclogenesis associated with a small-scale upper-air trough advected over the lateral boundary. This is also clearly confirmed by looking at the corresponding sea-level pressure forecast difference maps. The difference map between the SFM and SUM forecasts (Fig. 7) illustrates the total impact of using analysed boundaries, the difference map between the SUN and the SUM forecasts (Fig. 8) illustrates the impact of using analysed boundaries during the forecast phase, while the difference map between the SFM and SUN forecasts (Fig. 9) illustrates the impact of analysed boundaries during the data assimilation phase. It is quite clear from these forecast difference maps that analysed boundary values during the data assimilation gives the major positive contribution to the cyclogenesis, penetrating all the way into the centre of the forecast area, while the impact of analysed boundaries during the forecast phase is more restricted to areas closer to the lateral boundaries.

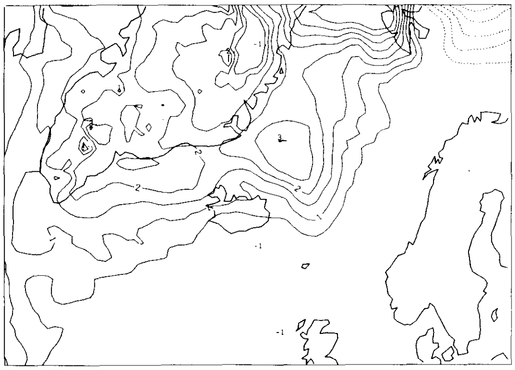

Fig. 8. Differences between the HIRLAM (SUN) and the HIRLAM (SUM) 24-h sea-level pressure forecasts fields valid at 00 GMT, 2 March 1988. Contour interval 0.5 hPa.

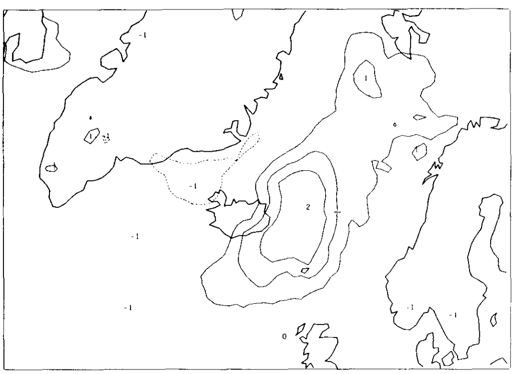

Fig. 9. Differences between the HIRLAM (SFM) and the HIRLAM (SUN) 24-h sea-level pressure forecasts fields valid at 00 GMT, 2 March 1988. Contour interval 0.5 hPa.

7. Concluding remarks

A rapid cyclogenesis has been studied by forecast sensitivity experiments using different analysis and forecast data sets to derive the lateral boundary conditions for the HIRLAM model. It is concluded that the forecast of this cyclogenesis is significantly improved by using as fresh lateral boundary fields as possible with analysed boundaries giving the best forecast results. Taking the size of the utilized forecast area into account, it was found to be of particular importance to use as good boundary data as possible during the data assimilation forecast runs preceding the one-day forecast simulating the cyclogenesis. This was so because the use of too old boundary fields, e.g., too long forecasts, during data assimilation inhibited the important process of advecting observed information from data-dense to data-sparse areas across the lateral boundary zone. In the particular case studied, a small-scale upper-air trough, later associated with the rapid cyclogenesis, moved over the western boundary of the HIRLAM forecast area into the data-sparse area between North America and Greenland during the data assimilation phase. The use of too old boundary forecast values, and also the use of too in-frequent boundary data updating, obviously damaged the structure of this upper-air trough within the boundary (relaxation) zone. Due to lack of data in the actual area, it was not possible for the analysis to restore the structure of the small-scale upper-air trough.

The importance of proper boundary values for the LAM data assimilation was somewhat of a surprise to the author. It is of course not wise to make too general conclusions from a single case study, but the author is convinced that several forecast failures by, e.g., the Swedish LAM system could be explained by experiments similar to those reported here (in case the most recent ECMWF forecast fields are not available at the SMHI, old ECMWF forecast fields up to 60-h or constant boundary fields are used over the rather small Swedish LAM area).

8. Acknowledgements

This work was carried out within the framework of the Nordic/Dutch HIRLAM-project. I am grateful to all my colleagues in the HIRLAM project for very stimulating cooperation in the development of the HIRLAM system. Per Kållberg is acknowledged for his contribution through stimulating discussions, software development and constructive comments on the manuscript.

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