Lateral boundary conditions for meso-scale models: some suggestions.

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1. Introduction.

Rather than summarise my research on lateral boundaries since the last All-Staff-Meeting I will instead make some comments and suggestions which are relevant for the present and future treatment of the lateral boundaries. There are three reasons for this. (a) Per has just published HIRLAM technical report 62, which describes the latest position of that research. (b) A number of HIRLAM members are using nested systems with small inner areas. (c) An objective of the HIRLAM plan is to develop an operational meso-scale model, presumably in a 'highly nested' set-up, with a small inner area.

2. Boundary update frequency.

The increased use of nested systems in which the innermost area may be quite small has brought additional urgency to the question: how often should the lateral boundaries be refreshed? If this area is small enough for a rapidly moving meteorological feature to cross it during the forecast period the forecast error in the verification area will be dominated by the errors coming from the inflow boundary after a short time.

In such a scenario, if we do not wish to be faced with the embarrassment of the coarser mesh 'host' model forecast being obviously superior to that of the nested finer mesh 'guest' model a requirement is that the guest area boundary be refreshed at every time step of the host model. Then the boundary forcing will be accurate to $O(\Delta t^h)$; (the superscript h indicates the host model).

Termonia (2003) gives a nice illustration of the problem. He describes ALADIN-Belgium's failure to capture the severity of the 'Christmas Storm' of 26 Dec., 1999 because the lateral boundaries were not being refreshed often enough. The ALADIN-Belgium nested model has 97 × 97 grid points covering the area shown in figure 1. The lateral boundary fields are refreshed every 3 hours using data supplied by Météo France. That the 3 hour refreshment interval is going to cause problems can be inferred from figures 1 and 2, which display the host fields on the guest area at 03 UTC and 06 UTC. At 03 UTC the storm is almost completely outside the area. At 06 UTC the storm is almost completely inside the area. Because the 'relaxation zone' is 8 points wide, the lateral boundary conditions of the guest model will contain some hint that a rapidly moving storm has, in reality, passed into the area. However, the low pressure will never be as deep on the guest model boundary or in its relaxation zone as it is in the host model. The consequences for the subsequent evolution of the forecast are dramatic, as can be seen by comparing figure 3, which displays the Météo France host model forecast on the Belgian area, with figure 4, which displays the the ALADIN-Belgium forecast valid at the same time. The most obvious difference is the failure to capture the very strong winds at the back of the main low pressure area. There is an additional area of concern: the guest model has generated what seems to be a spurious front stretching out to the west and south of the main depression. It looks as if a spurious secondary wave depression is developing on it. (A peripheral remark: this extraneous low has interesting implications for regional climate modelling).

Termonia (2003) points out that reducing the boundary refreshment interval to 1 hour improves the agreement between the host and guest forecasts significantly; see figure 5. The spurious low has been eliminated and the depth of the main low has been improved. Nevertheless, the key element in the forecast, the very strong gradient at the back of the low is still not as well captured as it should be. From a mathematical point of view true accuracy can only be achieved with the guest area boundary being refreshed at every time step of the host model. From an operational point of view, where compromises are necessary, the boundaries should be updated as often as is possible, and sensitivity studies should be embarked on so that it is clear what are the consequences of the various compromises being made with regard to area size, grid refinement, and boundary update frequency. (A rare event such as the one described in this section will have very little impact on the error statistics. Thus 'parallel runs' over a period including this storm could still show that the fine mesh forecast was superior to the coarse mesh forecast, on average).

In a central-forecasting-office environment a model that is inferior in a dramatic forecasting situation, such as devastating storm, becomes totally discredited even if it is superior in more routine forecasting situations. As was pointed out during the discussion session, an even more serious consequence could be the following. If such a storm occurred over the North Sea and the inner nested model were connected to a storm surge model, which, in turn, prompted various automated emergency-response actions, (or in this case, non-actions) the consequences could be, in fact, life-threatening.

Thus, it is important to make the correct decisions with regard to successive nesting. If, because of computer constraints, for example, the boundaries cannot be refreshed with sufficient frequency to maintain the same accuracy as that of the host model in such important forecasting situations, then the boundaries should be placed far enough away that a rapidly moving depression cannot reach the verification area during the forecast.

3. Reducing the noise in the boundary fields.

In an operational context the fields from the host area coarse integration are available only intermittently to the guest model: the fields from the coarse mesh integration are supplied to the guest model boundaries at intervals which are multiples of the time step: at times $m\Delta t, 2m\Delta t, 3m\Delta t$, and so on. In the HIRLAM model the following linear interpolation is performed to generate these fields at each time step, $n\Delta t$, between time steps $pm\Delta t$ and $(p+1)m\Delta t$.

$$\psi[(n+pm)\Delta t] = \psi[pm\Delta t] + \frac{n}{m}\{\psi[(p+1)m\Delta t] - \psi[pm\Delta t]\} \tag{2.1}$$

If, for instance, the time step $\Delta t = 10$min, and the refreshment interval is 3h then $m = 18$. Although this interpolation is 'smooth' between refreshment times the second derivatives in time of the fields will be infinite every m time steps; see figure 6. Thus, balance between the fields will be non-existent. Replacing Eq. (2.1) with a cubic spline interpolation involving the full forecast interval is ideally suited to smoothing away this difficulty.

Another potential source of noise is the spatial interpolation of the coarse mesh host fields to the fine mesh grid. For instance, a bi-linear interpolation in the horizontal can totally destroy the balance between the fields. See Kållberg (1977) for further discussion. McDonald (2002) found that a bi-cubic spline interpolation improved the balance of the interpolated fields significantly, without being totally satisfactory. He also showed that making the boundary fields more balanced did improve the forecast for a nested shallow water system.

To introduce interpolations in space and time which maintain the meteorological balance of the host model fields as well as possible is, of course, a serious technical challenge. Nevertheless, it is almost certainly one that must be faced in the context of 'meso-scale modelling', where it seems to be assumed, if I understand the HIRLAM plan correctly, that the forecast area will be small in the sense that boundary information will be having an impact on the forecast in the 'verification area'.

4. Checking the boundary relaxation coefficients.

The present choice of lateral boundary zone width and relaxation coefficients are based on practical tests JanErik Haugen and I performed on a 150km grid with large time steps; McDonald and Haugen (1992). Both may need tuning for a finer mesh and smaller time steps. The main priorities of the relaxation scheme are to damp the gravity waves as much as possible, while allowing the meteorological waves to enter the integration area, and our present choices still do this. Nevertheless, some sensitivity experiments on a 'meso-scale' sized area (1000km $\times$ 1000km) and (40 level, 5km) grid, say, would be a good idea, particularly in light of the points raised in sections 1 and 2 above.

There is ongoing research on tuning the relaxation scheme; see, for example, Marbaix et al. (2003) and the references therein. If the sensitivity experiments suggested in the previous paragraph show that our present choices of relaxation coefficients are not working well they make an interesting recommendation: rely mainly or solely on relaxation diffusion, defined by the term multiplied by D in the following relaxation formula for the $y = 0$ boundary:

$$\frac{\partial \psi(x,t)}{\partial t} = -N(x)[\psi(x,t) - \psi^h(x,t)] + D(x)\nabla^2[\psi(x,t) - \psi^h(x,t)] \tag{3.1}$$

where ψ is any of the model variables which is being relaxed toward the externally supplied host model value of the same field (designated by the superscript h) . N(x) is the Newtonian relaxation coefficient and D(x) is the diffusive relaxation coefficient. The reference HIRLAM, of course, uses 'Newtonian relaxation' and thus $D = 0$. Note that the diffusion is applied to the difference between the host and guest model fields and thus has no impact if they are equal.

Acknowledgment. Thanks to Piet Termonia for kindly supplying me with figures 1-5.

5. References.

Kållberg, Per, 1977: Test of a lateral boundary relaxation scheme in a barotropic model. *ECMWF research department internal report no.* **3** , 21pp.

Marbaix, P., Galleé, H., Brasseur, O. and J-P. van Ypersele 2003: Lateral boundary conditions in regional climate models: a detailed study of the relaxation procedure. *Monthly Weather Review,* **131**, 462-479.

McDonald, A., 2003: Transparent boundary conditions for the shallow water equations: testing in a nested environment. *Mon. Wea. Rev.,* **131**, 698-705.

McDonald, A., and J.E. Haugen, 1992: A two time level, three dimensional semi-Lagrangian and semi-implicit grid point model. *Monthly Weather Review,* **120**, 2603-2621.

Termonia, P., 2003: Monitoring and improving the the temporal interpolation of lateral boundary coupling data for limited area models. *Monthly Weather Review,* **131**, 2450-2463.

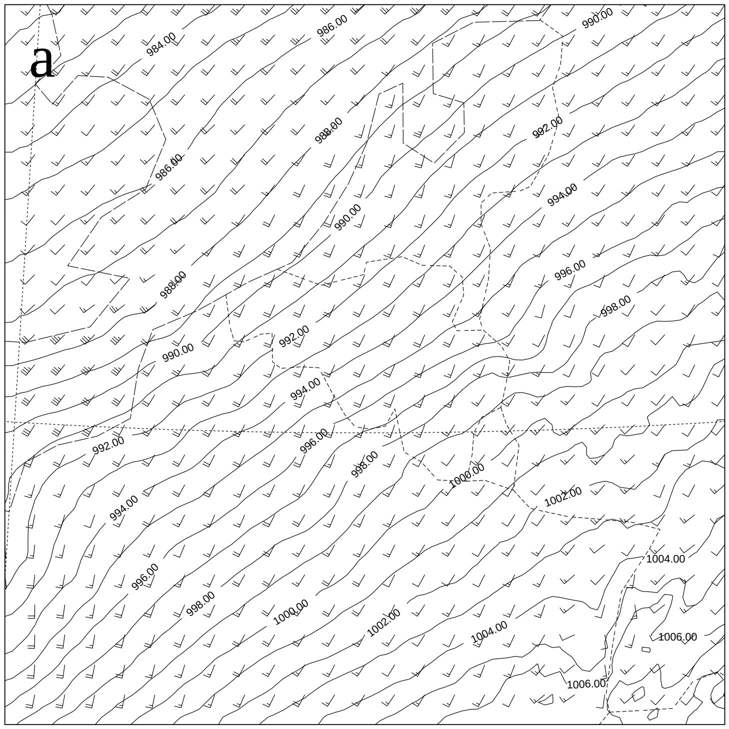

Figure 1: *The large area Météo France host model 3 hour forecast valid at 0300 UTC, 26 Dec., 1999 displayed on the ALADIN-Belgium integration area*

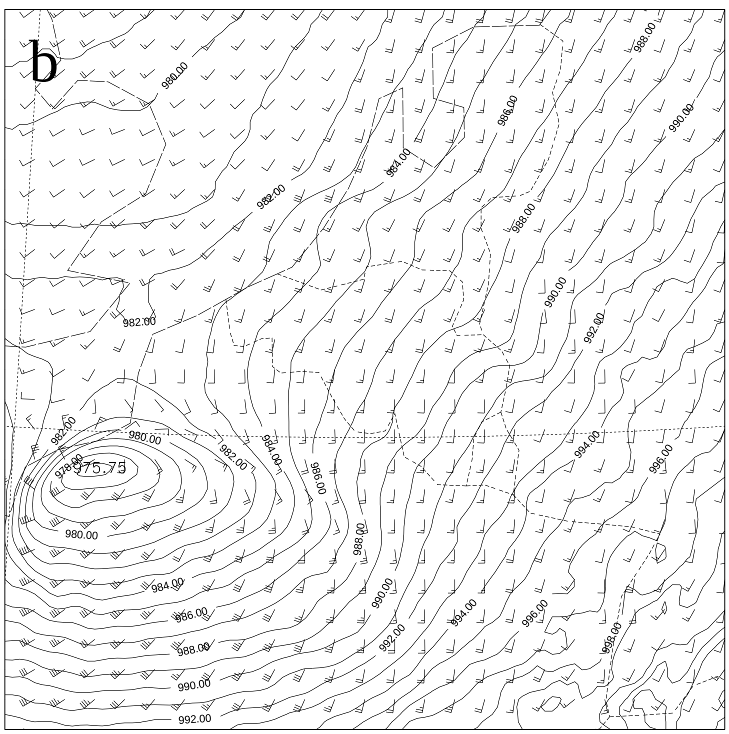

Figure 2: *The ALADIN-France 6 hour forecast valid at 0600 UTC, 26 Dec., 1999 displayed on the ALADIN-Belgium integration area*

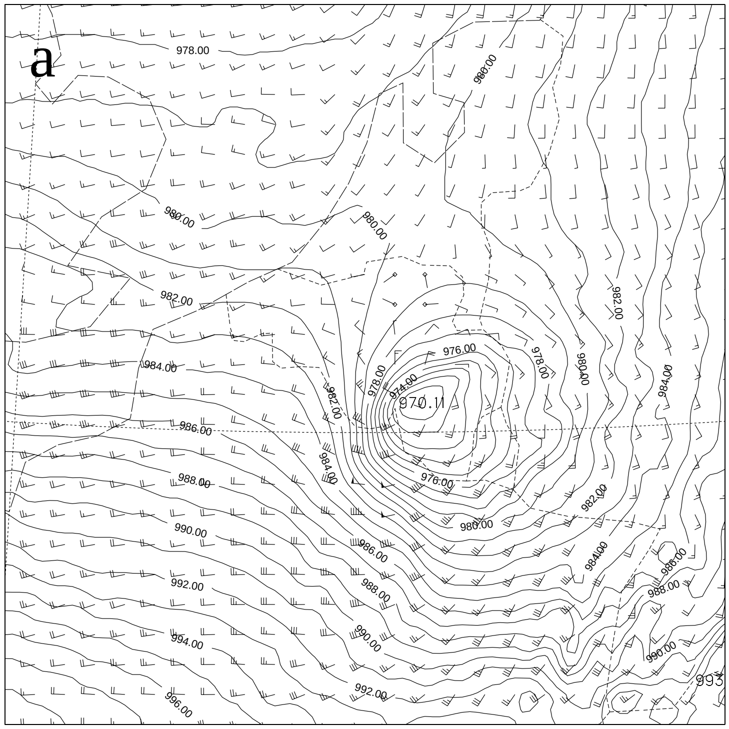

Figure 3: *The ALADIN-France 9 hour forecast valid at 0900 UTC, 26 Dec., 1999 displayed on the ALADIN-Belgium integration area*

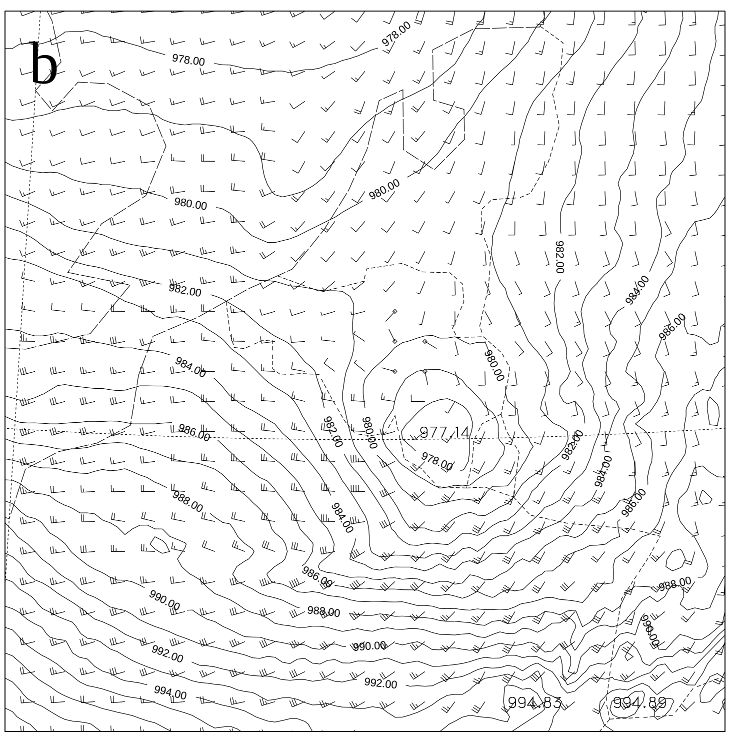

Figure 4: *The ALADIN-Belgium 9 hour forecast valid at 0900 UTC, 26 Dec., 1999 which used a 3 hour refreshment interval for the boundaries.*

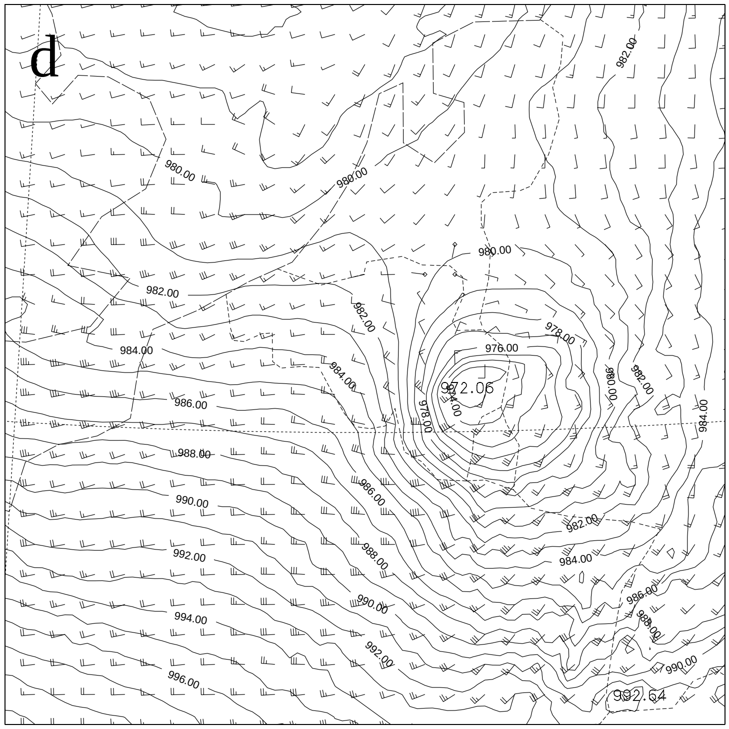

Figure 5: *The ALADIN-Belgium 9 hour forecast valid at 0900 UTC, 26 Dec., 1999 which used a 1 hour refreshment interval for the boundaries.*

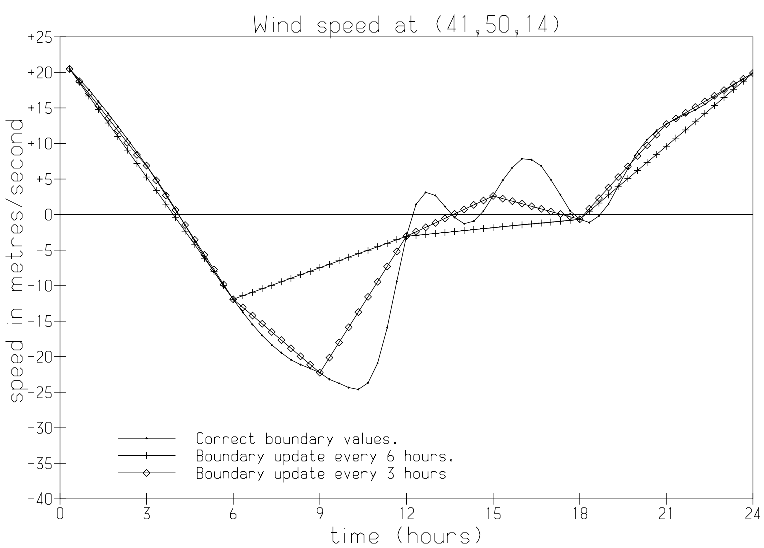

Figure 6: *Plot of the grid-point value at level 14 of the eastward component of the wind produced by the semi-Lagrangian integration of a primitive equation model with a 55km mesh size in the horizontal an 16 levels in the vertical is shown by the dots. If this were the host model supplying these winds as boundary values to a finer mesh model, then the '+'s show the boundary values which would actually be used, assuming a 6h refreshment cycle from the host model. The diamonds illustrate a 3h refreshment period.*