High Resolution Tests of the (IFS)/ARPEGE/ALADIN Dynamics Using a Quasi Academic Case

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1. Introduction

The ALADIN model is a limited area version of the French NWP global model ARPEGE, the latter having been developed in the framework of a common R & D venture between ECMWF and Météo-France. Hence, the global model exists in a single piece of code on both sides of La Manche, (Courtier et al., 1991). The global model is exploited by ECMWF at a uniform resolution under the acronym IFS and by Météo-France in its variable mesh (stretched) version under the acronym ARPEGE. Like its global brother, ALADIN has been developed thanks to an intensive international collaboration, involving nowadays 14 countries (ALADIN International Team, 1997). As one can quite easily figure out, the mission of each piece in this huge NWP jigsaw (IFS/ARPEGE/ALADIN) is different: while IFS in its deterministic version addresses scales (cut-off wave lengths) down to about 125 km, ARPEGE locally goes below 60 km thanks to the stretched grid and ALADIN applications reach scales around 20 km (the horizontal grid-size of the highest resolution operational applications being around 7 km, at the edge of a safe use of the hydrostatic assumption). It has to be mentioned here that ALADIN has been built under the general IFS/ARPEGE constraints, the most important ones being generality, flexibility and modularity. Thus ALADIN is different from the global version only where it is really necessary, e.g. treatment of the lateral boundaries, etc.; more details can be found in Geleyn (1998). Thanks to this property, ALADIN is an excellent vehicle to permanently test and validate at very high resolution the current choices made in the two global operational versions of the dynamics.

As already mentioned, there are a few operational versions of ALADIN using a horizontal grid-size shorter than 10 km. Though the NWP performance of these applications is quite good, operational experience reveals some problems probably related to the forcing due to sharp orography, like occurrences of unrealistic precipitation belts, for example. However, it is quite difficult to diagnose the causes (and find the cure) of such problems in case of a complex model working on real data. Therefore it is vital to complete the operational framework real data experiments by other types of tests. These tests may be using also real data, but completed with a lot of measurements coming from targeted field campaigns (e.g. Intensive Observation Period (IOP) cases from mountain campaigns like PYREX'90 or MAP'99), which are not available in day to day NWP practice. Beside, there is a family of so-called academic type of experiments, where the solution may be even known analytically, or simulated by an exact mathematical model. However, one has to bear in mind that good results of a scheme obtained in the academic type of tests represents a sort of necessary, but not sufficient condition of success in 3D complex conditions. That is why it is interesting to design some kind of pseudo-academic tests, in order to fill a gap between purely academic and real complex conditions. One of such pseudo-academic tests is the so-called "SCANIA" experiment proposed by Smolarkiewicz (personal communication), allowing to study the forcing induced by a complex orography (Scandinavian peninsula) in otherwise idealized conditions where orography is the only forcing. Of course, there is no exact analytical solution to compare the results with; however, one can still judge the physical realism of model's simulations. Since it would be quite impossible to set-up such an experiment in global versions of IFS/ARPEGE, Cullen (personal communication) proposed to perform SCANIA experiments with the ALADIN model, allowing to test the basis of IFS/ARPEGE dynamics thanks to the compatibility between the three parts of the same "gallery" of models. The SCANIA experiments with ALADIN represent the core of the present workshop contribution abstract.

2. Operational characteristics of IFS and ARPEGE/ALADIN and pending questions

Here we shall concentrate only on the dynamics of the models, since the experiment is run without any diabatic forcing, neither with any parameterization of sub-grid scale processes, except horizontal diffusion to damp the small scale noise. All the operational configurations use the Hydrostatic Primitive Equations (HPE) as governing equations, cast in the terrain-following hybrid coordinate of Simmons and Burridge (1981). In the horizontal, spherical coordinates are used in global versions while Cartesian plane coordinates are used in ALADIN. All those versions are spectral, but owing to its geometry ALADIN uses bi-Fourier series instead of the spherical harmonics. One of the special features of ALADIN is the so-called biperiodicisation of the fields to treat the lateral boundary problem in a spectral way, following Machenhauer and Haugen (1987).

All operational versions use a two-time-level semi-Lagrangian semi-implicit marching scheme of second order accuracy in space and time, which is a very efficient scheme, allowing relatively long time-steps with respect to explicit schemes. However, the semi-Lagrangian scheme has got a known problem to describe well the orographic forcing, e.g. the resonance problem outlined by Coiffier et al. (1987) linked to the propagation of internal gravity waves studied by Laprise and Héreil (1996). Of course, the operational models do employ treatments of this problem conform to the currently best known performances, mainly based on the averaged Eulerian treatment of orography (Ritchie and Tanguay, 1996). Another question associated both with the semi-Lagrangian and spectral methods is the use of either of the so-called quadratic and linear grids. The use of the quadratic grid avoids aliasing due to quadratic terms appearing in particular in the Eulerian treatment of advection (the spectrum is truncated at one third of the number of points on the collocation grid). The main quadratic terms are not present when using the semi-Lagrangian advection scheme, hence the maximum allowed number of waves of one half of the number of points grid may be employed (linear grid). At this point we start to get nuances, sometimes quite subtle, between options used in IFS and ARPEGE/ALADIN operational applications. For example, IFS uses the maximum truncation (linear grid) for all spectral variables but orography, which is smoothed, while both in ARPEGE and ALADIN still the quadratic grid is employed with an unsmoothed orography. The other differences (mainly in the horizontal diffusion) shall be discussed below in the paragraph on the tested configurations.

3. Set-up of the experiment

SCANIA experimental conditions were prescribed by Smolarkiewicz (personal communication) and they are as follows: the atmosphere is dry, inviscid, in hydrostatic equilibrium, its static stability is given by a constant Brunt-Väisälä frequency $N = 0.01$. There is a constant reference flow of *20 m/s* from the "north-west" (with components u = and v = on the Cartesian plane), hence blowing in the perpendicular direction to the main mountain ridge. This main flow is in geostrophic equilibrium with a constant Coriolis parameter $f = 0.0001$. The model domain is square in the horizontal, *2000 km* large, with *201 x 201* grid points and a grid-mesh of *10 km*. In the vertical, there are *91* levels, regularly spaced in *z* by *300 m*, the top of the domain being at *27 km*. Further, there are reference values of temperature and density prescribed in the middle of the domain at the "sea" level: $T_0 = \theta_0 = 300\,K$ and $\rho_0 = 1\,kg/m^3$.

All these experimental conditions were adapted to the ALADIN geometry. In the horizontal, the domain was extended to 216 x 216 points because of fields' biperiodicisation and FFT transforms, the artificial zone being a belt of 15 points on each domain's side. In the vertical, the exercise is more delicate, since the terrain-following coordinate may respect the regular *z* spacing only approximately. Therefore the hybrid coordinate η was first built in a single column in the middle of the domain by defining the half-levels to be regularly spaced in *z* (geopotential Φ) with $\Phi_s = 0$ at the bottom. The half-level pressures were computed using the hydrostatic equation and a temperature profile given by the constant Brunt-Väisälä frequency and finally the hybrid coordinate coefficients were specified. Since at the top of the experimental domain the value of pressure was still quite far from a zero value, we added eight purely pressure levels to ensure a smoother transition to zero pressure at the top of the model (zero top pressure together with rather p regular level spacing in the stratosphere is a commonly used NWP setting). Therefore the additional pressure levels avoid wave's reflection due to the otherwise brutal change of the pressure thickness between the first and second model layers in the case of 91 levels. It should also be mentioned here, that in the NWP setting the horizontal diffusion coefficient is growing towards the top of the model (proportionally to the inverse of pressure) in order to act a bit like a sponge layer in order to also diminish wave reflection from the top.

Once the hybrid coordinate is specified, the initial conditions of the prognostic variables (wind components, temperature and surface pressure) need to be prepared. While the wind initial condition is trivial (constant values on the whole of the model atmosphere), temperature and surface pressure must fulfill the above mentioned constraints:

- geostrophic equilibrium:

$$\left.\frac{\partial p}{\partial x}\right|_{\Phi=cst} = \rho f v, \quad \left.\frac{\partial p}{\partial y}\right|_{\Phi=cst} = -\rho f u$$

- hydrostatic equilibrium:

$$\frac{\partial p}{\partial \Phi} = -\rho$$

hence pressure is a function of (x,y,Φ) in the form:

$$p(x,y,\Phi) = p(\Phi + f u y - f v x) \quad (1)$$

- constant Brunt-Väisälä frequency N:

$$\frac{N^2}{g^2} = \frac{\partial \ln \theta}{\partial \Phi}$$

We will use the following notations:

$$\kappa = \frac{R}{c_p}, \quad \tilde{\Phi} = \frac{g^2}{N^2}, \quad \tilde{T} = \frac{\tilde{\Phi}}{c_p}$$

and the values prescribed at the middle of the domain (point $(0,0,0)$) shall be denoted by index "$_0$": T_0, p_0, ρ_0, θ_0. For $(x,y) = (0,0)$ we may easily write:

$$T = \left(T_0 - \tilde{T}\right)\exp\left(\frac{\Phi}{\tilde{\Phi}}\right) + \tilde{T}, \quad \theta = T_0 \exp\left(\frac{\Phi}{\tilde{\Phi}}\right) \quad \textit{and} \quad p = p_0\left[\left(1 - \frac{\tilde{T}}{T_0}\right) + \frac{\tilde{T}}{T_0}\exp\left(-\frac{\Phi}{\tilde{\Phi}}\right)\right]^{1/\kappa}$$

When combined with the geostrophic constraint (1), we obtain pressure as function of (x,y,Φ):

$$p(x,y,\Phi) = p_0\left[\left(1 - \frac{\tilde{T}}{T_0}\right) + \frac{\tilde{T}}{T_0}\exp\left(-\frac{\Phi + f u y - f v x}{\tilde{\Phi}}\right)\right]^{1/\kappa} \quad (2)$$

Similarly we obtain expressions for temperature and potential temperature:

$$T(x,y,\Phi)=\tilde{T}+\left(T_0-\tilde{T}\right)\exp\left(\frac{\Phi+f\,u\,y-f\,v\,x}{\tilde{\Phi}}\right)$$

$$\theta(x,y,\Phi)=T_0\exp\left(\frac{\Phi+f\,u\,y-f\,v\,x}{\tilde{\Phi}}\right)$$

Equation (2) can be inverted for computing geopotential from known pressure. This is important in the practical setup of the temperature field at hybrid levels. It should be noted that under these conditions there is no baroclinic forcing (the thermal wind is zero).

In practice, the surface pressure p_s is specified at the orography level Φ_s using equation (2). Knowing the hybrid coordinate coefficients, all half-level pressures are computed:

$$p=A(\eta)+B(\eta)\,p_s$$

From the known pressures the geopotential heights are specified using the inverse of equation (2). Finally, full-level temperatures are computed from the discrete form of the hydrostatic equation. Once the fields are specified in the classical model domain, they are horizontally extended to fulfill the bi-periodic condition and then spectrally fitted.

The initial conditions prepared by the procedure described above serve also as lateral boundary conditions within the integration (time constant lateral forcing). It should be noted that the coupling at the lateral boundaries is based on a Davies-Kallberg scheme. It would have probably been better to use an open boundary method in the SCANIA experiments, however this is not applicable together with the biperiodicisation technique.

The very first experiment was launched up to ten days in order to see at which stage a quasi-stationary solution is reached, using just the operational adiabatic settings. With help of the so-called "spectral norms" (sum of squares of spectral coefficients) of the evolution we could decide that the quasi-stationary solution is safely reached after 4 and a half day of forecast (108 hours). To still improve the system, we applied a digital filter initialization (DFI) forward run (so-called "launching" DFI technique), starting from +96h and providing a new "initial" state at +108h, thus diminishing the remaining small oscillations. The filtered state was then used to start just 24h long forecasts to test a selected group of experiments, lowering the CPU cost of these tests. However, when the orographic forcing changed (e.g. linear grid) the basic 96h and DFI runs were first redone.

4. Choice of tested configurations

As mentioned above, the very basic experiment was launched with the ALADIN type of operational settings corresponding to the horizontal grid size of *10 km*: two-time-level semi-Lagrangian (2TLSL) semi-implicit scheme using a time-step of 450s, Ritchie-Tanguay method and spatio-temporal de-centering of the scheme to treat the resonance problem, horizontal diffusion with divergence damping (the diffusion coefficient is five times stronger for divergence than for vorticity), quadratic grid. Beside this basic test, we examined four main group of modifications:

- Linear vs. quadratic grid related tests: (i) semi-linear grid (i.e. 2.5 intermediate ratio), (ii) linear grid and (iii) linear grid with smoother orography, the latter being rather close to the operational choice made in IFS.

- Time-stepping related tests: (i) three-time level (leap-frog) semi-Lagrangian (3TLSL) semi-implicit scheme (time-step of 225s), (ii) leap-frog Eulerian semi-implicit scheme (time-step of 75s) and (iii) leap-frog Eulerian explicit scheme (time-step of 12s).
- Orographic resonance related test: (i) application or not of the Ritchie-Tanguay method, (ii) its combination with divergence damping or not, (iii) combinations of the first two options with pseudo-second order decentering of the scheme or not.
- Horizontal diffusion related tests: (i) divergence damping (to use or not a stronger horizontal diffusion coefficient for divergence than for vorticity and temperature -"not" being the operational choice in IFS-), (ii) dependency of the horizontal diffusion coefficient on the inverse of pressure (to use or not stronger diffusion towards the top of the model), (iii) order of the diffusion (∇^6, ∇^4 and ∇^2) and (iv) overall tuning of the levels of diffusion.

Whenever relevant, combined tests were done; for example we tested the orographic resonance options using the linear grid in order to have the most severe conditions for the orographic forcing.

Within the 2TLSL scheme we also tested the available options for the extrapolation of the trajectory wind and of the non-linear terms to the time level $t + 1/2\, \Delta\, t$. However, since the solution is quasi-stationary, there was no real impact of these options on the SCANIA test, though we know that there is a lot of sensitivity in real situations, like it was for the "Baltic Jet" case (Mc Donald, 1998). At least we can draw a small conclusion that the real case type of instability related to the extrapolations to the time level $t + 1/2\, \Delta\, t$ is not directly linked to the orographic forcing. We obtained no real response either when testing the interpolation operators' options (quasi-monotonous versus purely polynomial form), the number of iterations when computing the trajectory (2 iterations vs. 3 iterations) and the semi-Lagrangian way to determine the η coordinate of full-levels to compute integrals of the continuity equation (either there is a regular spacing of levels or an intermediate coordinate is determined by the *A* and *B* coefficients of the hybrid coordinate).

5. Discussion of the results

Here we shall concentrate only on the experiments which brought some interesting results. The first group of tests was devoted to the question whether to use linear or quadratic grids.

The use of the quadratic grid (operational option in ARPEGE/ALADIN) brings a quite smoother solution, perhaps suitable for purposes of NWP, especially for the interaction with the physics. When using the linear grid, the solution reproduces quite well the results of Smolarkiewicz (personal communication) with finite differencing; on the other hand the solution starts to be noisy and it oscillates more around the stationary solution. When using the semi-linear grid, the results remain closer to the quadratic grid solution than to the linear grid one. Therefore there is probably not much interest in using the semi-linear grid. On the other hand, there is quite an interesting combination: use of the linear grid for all spectral fields except the orography, which remains smooth just like in the case of the quadratic grid. In this case the solution becomes more intense but it keeps stability and smoothness. This combination of linear grid with smoother orography is close to the operational choice made in IFS, though the way to smooth the orography is not exactly the same. In our experiment we took the orography field truncated according to the quadratic grid choice and we refitted it using the linear grid value of the spectral truncation (a necessity in the bi-periodic setting of ALADIN). These results are outlined on Figure 1.

Within the second group of tests on time-stepping, we validated the use of the 2TLSL scheme with the "*10 km* grid-size operational" time-step of 450s compared to the results obtained with the Eulerian semi-implicit integration using the "explicit scheme" length of time-step of 12s. There is hardly any difference, except that the 2TLSL solution is a bit smoother. There is neither any structural differences in the solution between the semi-implicit and explicit Eulerian schemes (using the same length of the time-step), but the explicit scheme solution is this time a lot more noisy.

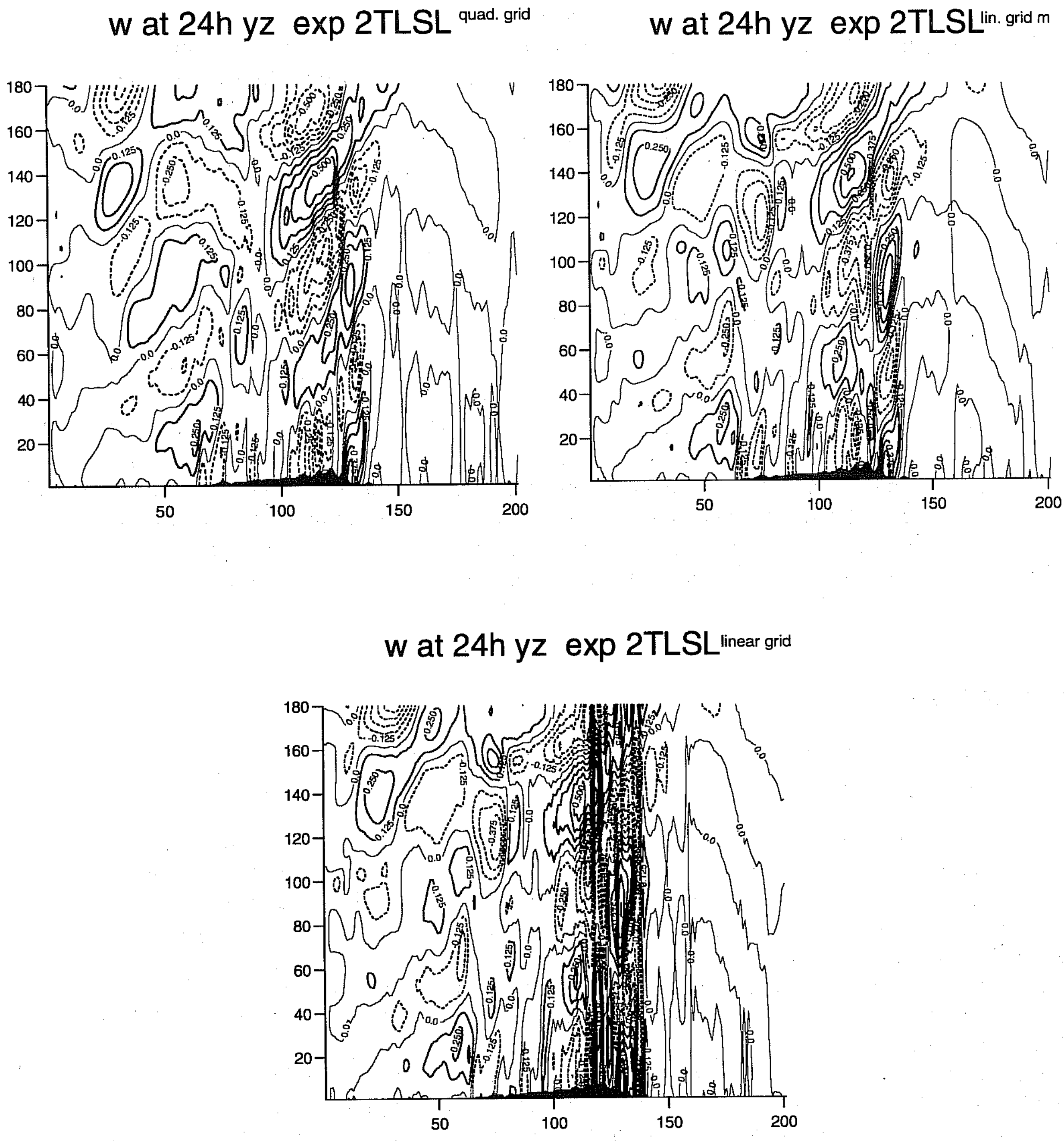

Fig. 1: Vertical velocity w $[m/s]$ y-z cross-section in the middle of the domain. The wind is blowing (quasi-orthogonally to the main ridge) at 45 degree from the right and towards the reader. The quadratic grid solution is on the upper left picture, the linear grid one using smoothed orography is on the upper right picture and the purely linear grid solution is on the bottom picture.

The third interesting problem was the one of the orographic resonance. We tested all possible combinations of the Ritchie-Tanguay method, divergence damping and spatio-temporal decentering (pseudo-second order one). The Ritchie-Tanguay method is the most efficient one to substantially reduce the orographic resonance. Beside, the most interesting combination was that of the Ritchie-Tanguay method with the divergence damping, where the divergence damping still helps to control the noise associated with the remaining resonance without affecting the underlying solution, see Figure 2. This result confirms the validity of the choice made in ARPEGE/ALADIN. On the other hand the spatio-temporal decentering (recently abandoned in IFS but still used in ARPEGE/ALADIN) had no impact. We even tested the older form of the first-order accurate decentering in the 3TLSL scheme, and this decentering showed spurious effects on the solution (damping and deformation).

Concerning the horizontal diffusion tests, we verified our operational set-up regarding the order and intensity of the horizontal diffusion as well as the tuning of the divergence damping. The operational model uses the ∇^4 diffusion order, which proved to be the best option for the SCANIA case as well (the ∇^6 order leaves still some noise while the ∇^2 order is too strong and damps the whole solution). For the intensity, we tested three times weaker and three times stronger coefficients. Here again, the operationally used values seem to be optimal: a weaker intensity allows some wavy patterns also outside the mountain area, while a stronger intensity causes appearance of "pseudo-aliasing" noise. Finally, we tested the divergence damping by using a stronger diffusion coefficient for divergence than for vorticity, the ratio varying from 1 (no divergence damping) to 9 (the operational ratio value is 5). The results show that the divergence damping has a beneficial impact (ratio 1 test gives worse results) but it should be used with moderation (ratio 9 is too much). It is difficult to choose just one optimal ratio value, however the operational value of 5 seems to be reasonable and, if anything, just slightly underestimated. Another, quite logical result, was obtained when keeping the horizontal diffusion coefficient constant along the vertical (no additional damping towards the top of the model). In that case a quite noisy pattern occurred in the upper part of the domain, due to wave reflection. This result simply confirms that the problem of wave reflection from the top of the model has to be treated. Of course, it gets worse with finer resolution and sharper orography.

6. Conclusion

The pseudo-academic SCANIA test is quite a useful tool to study the choices made in the model dynamics regarding their responses to a complex orographic forcing. A set of various experiments has been done with the NWP model ALADIN, a limited area version of the ARPEGE/IFS global model. It was found that the currently used operational options in the dynamics provide quite reasonable results, especially regarding the use of the two-time-level semi-Lagrangian semi-implicit scheme with the quite daring ALADIN "operational" length of the time-step for the grid size of *10 km* and regarding the empirically tuned horizontal diffusion scheme. The other two interesting results concern the necessary use of divergence damping together with the Ritchie-Tanguay averaged Eulerian treatment of orography in order to diminish the spurious resonance effects caused by the high resolution orographic forcing and the synergy of the combination between the linear grid and a smoother orography field. The SCANIA tool may be used, of course, to test a variety of other options, should they be sensitive to the stationary orographic forcing.

As specific outcome it seems that the IFS team should have a further look at horizontal diffusion and that the ARPEGE/ALADIN team should revisit the linear grid problematic. Otherwise there is every reason to be confident in the future of the chosen methods for the HPE stationary dynamics. Further work concentrating on the high resolution issues raised by the operational use of ALADIN should hence concentrate on rapidly changing situations, on the interaction between physics and dynamics inside a model time step and on the evolution towards the full Navier-Stokes equations (relaxation of the thin layer hypothesis, elastic dynamics). For the latter point, SCANIA tests with the fully compressible version of ALADIN (Bubnová et al., 1995) are scheduled for the near future.

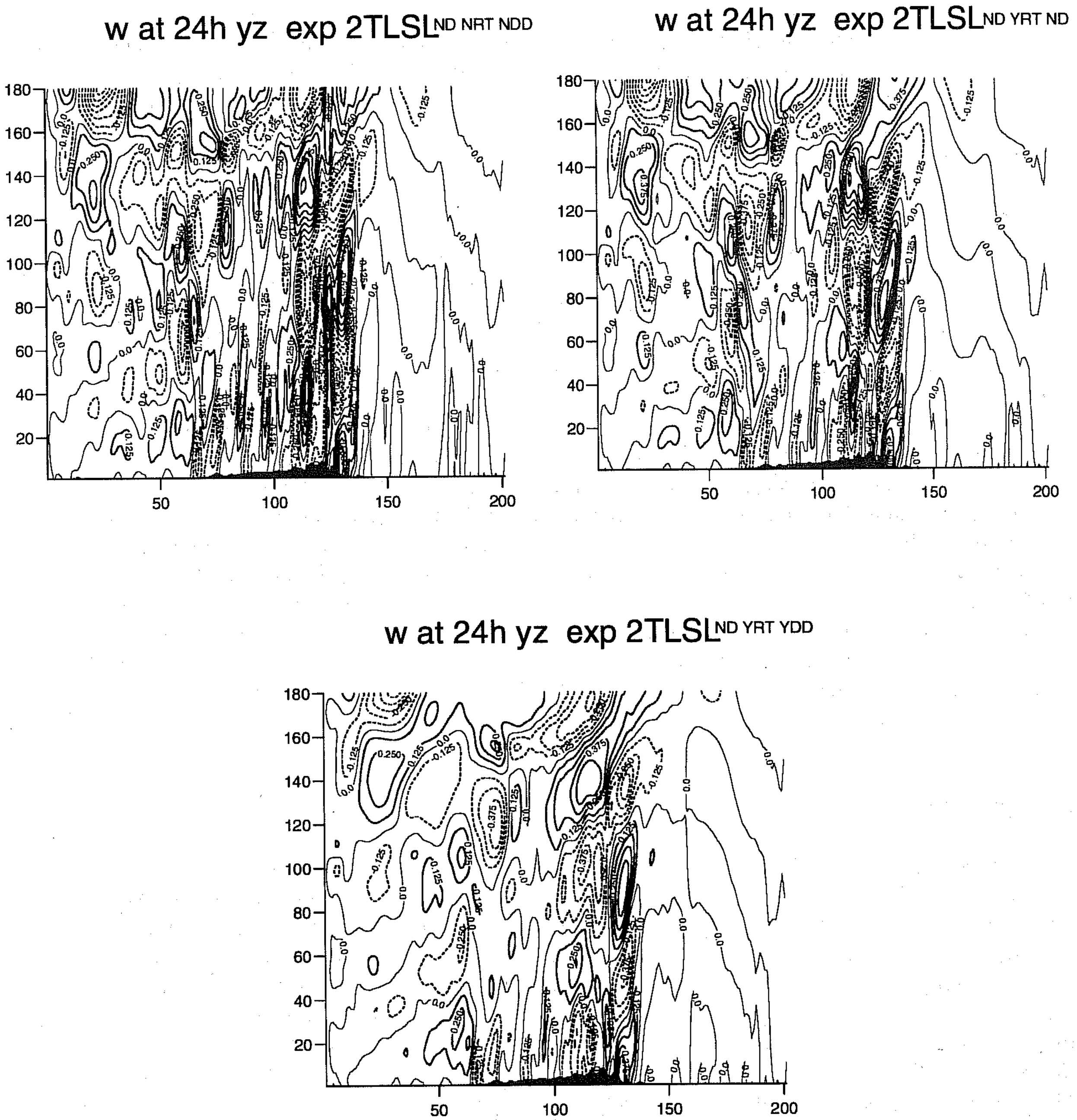

Fig. 2: Vertical velocity w $[m/s]$ y-z cross-section like on Figure 1. There is a solution without using any orographic resonance treatment on the upper left picture: no decentering (ND), no Ritchie-Tanguay method (NRT) and no divergence damping (NDD). On the upper right picture the test uses just the Ritchie-Tanguay method (YRT). On the bottom picture the results are from the test using both Ritchie-Tanguay method (YRT) and divergence damping (YDD). The reference experiment using all the three treatments is on the upper right picture of Figure 1 (hardly differing from the bottom picture here).

7. References

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