Kilometric-scale non-hydrostatic dynamical core studies for the AROME project

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Abstract

The development of an operational NWP facility starts with the choice of a dynamical core, which has to be non-hydrostatic if one aims at horizontal scales of the order of one kilometre. To that end, a well-documented case of intense lee-waves has been simulated using vertical-plane versions of three models: ALADIN-NH, Méso-NH and HIRLAM-NH, using horizontal resolutions of 500 m and 2 km. The models have been assessed in terms of their qualitative and quantitative realism : as well as numerical stability, behaviour with long timesteps and sensitivity to details of the experimental setup.

It turns out that Méso-NH and ALADIN-NH have comparable degrees of realism when short timesteps are used. The semi-implicit semi-Lagrangian scheme of ALADIN-NH allows fourfold longer timesteps with no noticeable impact on the simulation quality.

1. Introduction: the AROME project

AROME (Applications of Research to Operations at MesoscalE) is a CNRM initiative to provide Météo-France with a data assimilation and numerical prediction facility around 2008, that resolves convective systems over mainland France. This requires the development of a state-of-the-art non-hydrostatic model at 2 to 3 km resolution. The model shall include detailed parameterisations of continental surfaces (through interfacing with an external soil and hydrology model around the ISBA scheme), of cloud microphysics and subgrid turbulence. Data assimilation will rely on a 3d variational algorithm that handles geostationary radiances, radar reflectivities, and conventional mesoscale networks.

Such a system is going to be numerically expensive. Degrading its resolution is not an option, as it would impede the description of convective cells. The first implementation of the model will be on a small domain for short-range prediction of locally-forced phenomena such as deep convection (squalls, intense precipitation, thunderstorms) and local low-level features (actual weather and fog). The numerical cost will be driven by the model timestep, which may be constrained by the dynamical core's stability and accuracy. The choice of a dynamical core has consequences on the whole forecasting system software, in particular on technical maintenance and physics/dynamics coupling. AROME will require a dynamical core that supports long timesteps for NWP applications. In addition, AROME must be suited for more fundamental research activities where physical accuracy is more important than numerical efficiency, usually for runs at very high resolution on tiny domains.

Several non-hydrostatic dynamical cores can be considered, among which Méso-NH, the anelastic research model used at CNRM and Toulouse University (Lafore et al. 1998), and ALADIN-NH, a compressible prototype version of ALADIN /ARPEGE /IFS (Bubnová et al. 1995) which is still being improved. It is instructive to compare oneself with other models such as HIRLAM-NH, an anelastic prototype suggested as a replacement for the operational HIRLAM community model (Rõõm 2001, Rõõm and Männik 2001, Männik and Rõõm 2002). A comparison with the Unified Model of the British Met'Office is under way (documentation available from Nigel Wood, *nigel.wood@metoffice.com*).

Dynamical core intercomparison requires the examination of relevant test cases, for which the correct result is known. Ideally one would like a deep convection case for AROME, unfortunately the appropriate physical parameterisations are not available in a consistent form in all models. An orographic lee-waves case has been chosen instead. It features intense waves with non-hydrostatic effects and strong vertical velocities that are akin to convective circulations.

2. The trapped lee-waves test case

This is a low-level trapped lee-waves case which has been observed in nature (Shutts and Broad 1993) and studied by Nance and Durran (1998) who explained the underlying mechanisms and published an idealised simulation which we will use as a reference. Shortly put, a strong enough (about 40 m/s) high-level jet will interact with a small analytical mountain (600 m high) under well-chosen stability conditions (4 layers of uniform Brunt-Vaisala frequencies) to produce two wave-trains. One propagates upwards, the other one remains trapped in lower layers with an horizontal wavelength around 8 km and vertical velocities up to 8 m/s at 3000 m height. This behaviour is confirmed by mathematical analysis. The wave-trains interact nonlinearly to create quasi-periodic phase oscillations downstream. This case seems to contain the main dynamical aspects needed for explicit convective cell simulation. It is sensitive to resonance and propagation properties of gravity waves over long distances, which makes it a stringent test.

The case can be simulated by a model with a vertical 2d-plane geometry, no humidity, and no physical parameterisations. However, enough resolution (500 m) is needed to correctly describe the waves. Thus, one needs to distinguish the purposes of 500 m experiments, for which the correct solution is known, from 2 km experiments (AROME's target resolution) which will be sensitive to the discretisation properties of each model.

All experiments have in common the initial state, which is hydrostatic and horizontally homogeneous, extrapolated upwards where needed, since the models have different tops. Orography is specified by a formula of the form $y=1/(1+x^2)$. Vertical resolution is about 200 m throughout the troposphere. The spectral ALADIN-NH resolution is identical to the gridpoint space resolution using a linear grid with no extension zone. The wind blows from left to right on the plots. Lateral boundary conditions are stationary. Downward wave reflection from the model top is prevented using an ad-hoc absorbing layer. A weak horizontal and vertical diffusion is used in most cases. Simulations are run for 6 hours : after a spin-up phase for a few minutes, wave-trains develop and propagate mainly downstream until they reach the model outflow boundary.

All plots use the same contouring (1 m/s for vertical velocity) and the same geography, the abscissa ranging from 20 km upstream of the mountain top to 1000 km downstream, the vertical coordinates is height, from zero to 10 km. Hovmöller diagrams (figs. 2 and 6) use model output every 15 mn.

3. Results at resolution 500 m

ALADIN-NH produces a wave-train (fig. 1) and a time evolution (fig. 2) consistent with Nance et Durran (1998) and with Méso-NH (fig. 3) and HIRLAM-NH (fig. 4). The main inconsistency is in HIRLAM-NH, in the downstream damping of the waves (on the right of the plot) and in the lack of phase oscillation. This may be due to the system of equations used (the Lamb wave is filtered out of HIRLAM-NH) or to excessive wave-damping in the stratosphere.

The timestep is limited to 4 s in Méso-NH and 7 s in HIRLAM-NH, by the stability of the explicit integration scheme. The ALADIN-NH timestep is 10 s. The vertical velocity maxima are somewhat dissymmetric in ALADIN-NH because the model is resolving part of the low-level boundary layer turbulence in the most dynamically unstable areas. The Méso-NH run is affected on the right by some wave-interaction with the boundary of the simulation domain.

4. Results at resolution 2 km

At this resolution it would not make sense to use the same mountain as Nance and Durran (1998) because it would be too narrow (6 km width) to be properly resolved. A wider mountain (12 km) is used here, which is going to alter the phase of the waves, but hardly their wavelength or amplitude.

ALADIN-NH exhibits a damped wave-train (fig. 5) with little phase oscillation (fig. 6), although the simulation remains qualitatively correct with still intense vertical velocities. The downstream damping is due to the lack of horizontal resolution. The Méso-NH (fig. 7) and HIRLAM-NH (fig. 8) behaviour is similar with some alteration. Méso-NH has the strongest vertical velocities with grid-scale ("2Δx") features that do not exist at 500 m resolution. HIRLAM-NH has the weakest waves with a strong damping, whereas ALADIN-NH has the most realistic wave-train far downstream of the mountain.

The timesteps are 16 s for Méso-NH, 20 s for HIRLAM-NH, 30 s for ALADIN-NH.

A rigorous assessment of the 2 km resolution runs raises the question of the reference, since the orography is not the same as the one in section 3. Tracking down resolution problems requires reference runs at 500 m resolution with the 12 km mountain. These runs are not available for HIRLAM-NH. The 500 m Méso-NH and ALADIN-NH runs are (as in section 3) in nearly perfect agreement with the same vertical velocities within 5 %. The exception is the first updraught which is 12 % stronger in Méso-NH. When moving to 2 km resolution, Méso-NH strongly reduces the vertical velocities except in the first updraught, and shifts the wave-train phase upstream by almost π. ALADIN-NH reduces its velocities by a similar amount but shifts the wave-train phase downstream by $\pi/2$ or so. This explains the strong phase-inconsistency between the two models at 2 km resolution.

5. Additional tests

The sensitivity to the timestep and time-stepping scheme was investigated in ALADIN-NH. The simulations are unchanged when using a shorter timestep, or an explicit Eulerian scheme, or an older ("*d3*") version of the semi-implicit scheme. In this paper the most recent two-time-level semi-implicit semi-Lagrangian scheme was used ("SISL2TL *d4*"). This version allows timesteps up to 15 s and 60 s for the 500 m and 2 km runs, respectively, with no visible degradation of the fields. Timesteps of 20 s and 90 s, respectively, produce qualitatively satisfactory runs with some deformations (phase shifting and sparse occurrences of numerical noise). In summary one concludes that the ALADIN-NH dynamics allows four times longer timesteps than the explicit Eulerian limit values that apply to Méso-NH.

The stratospheric part of the simulations is sensitive to vertical resolution, to the upward extrapolation of the Nance and Durran (1998) profiles, to the functional form and strength of the top absorbent. Precise tuning is required to suppress downward wave-reflection, although it does not affect the waves at low levels.

A fraction of the waves propagates upstream. Downstream, waves start interacting with the model boundaries near the end of the runs. Sensitivity studies to the horizontal domain size and to the position of the mountain indicate that lateral boundary conditions do not affect the trapped lee-waves that appear on the plots.

Tests at 1 km and 1.5 km resolution show that the impact of degrading the horizontal resolution is progressive.

The application of horizontal numerical diffusion is necessary to prevent numerical noise at the scales of the model grid, in explicit runs as well as ALADIN-NH SISL2TL runs with very long timesteps. The trapped lee-waves are not sensitive to the strength of this diffusion.

Vertical diffusion has an impact near the surface under the crests of the trapped lee-waves. It represents the mixing effect of unresolved turbulence. It affects the wave-phase in runs with the wide (12 km) mountain. Since vertical diffusion schemes are very different between ALADIN-NH and Méso-NH, one cannot tell whether this would be enough to explain their phase inconsistencies.

The phase inconsistencies at 2 km resolution are sensitive to other details of the experimental framework e.g. the mountain height or the definition of the vertical profile of the large-scale atmosphere : changes of the order of precision of meteorological observations are enough to compensate for the phase differences. This high sensitivity seems to be linked to a mechanism of hydraulic jump formation (rotor), as depicted by Doyle and Durran (2002) who find a similar sensitivity of orographic waves to surface friction of mountain height. Hence the mechanism for the 2 km phase inconsistencies seems to be the interaction between a physical bifurcation and minor discretisation differences between Méso-NH and ALADIN-NH.

6. Conclusions

The intercomparison of ALADIN-NH and Méso-NH dynamical parts was carried out in a dry, non-hydrostatic test case with little sensitivity to physics, which requires a 500 m horizontal resolution to be accurately resolved. The conclusion is that both models produce realistic simulations when similar timesteps are used. With a 2 km resolution, which is on the border of resolving the considered phenomenon, results are degraded in a similar fashion in both models, with some differences in details that do not place any model clearly above the other. HIRLAM-NH produces heavily damped features which lack the unstationary component of the reference simulation. One notes that ALADIN-NH allows a fourfold increase in timestep size over Méso-NH, with no visible degradation in physical accuracy.

The results are liable to revision in the future, as the three models are still evolving. They shall be extended to three-dimensional runs. They are not necessarily representative of the quality of the full models, with physical parameterisations, physics-dynamics coupling, and unstationary lateral boundary conditions. It is possible that the maximum admissible timesteps will be limited by the physics, such as the cloud microphysics.

At this stage one can only conclude that the ALADIN-NH dynamics offer the best prospects for operational use in the AROME project thanks to its good behaviour with long timesteps, which should make the AROME model as economical as possible.

7. Acknowledgements

Philippe Bougeault masterminded this study. Large parts of the ALADIN-NH code were developed by Radmila Brozková, Jean-François Geleyn and Gwenaëlle Hello among others, and more recently, Jan Masek, Petra Smoliková and Jozef Vivoda. Thanks to Isabelle Mallet for their work on Méso-NH and to Aarne Männik (Tartu University, Estonia) for running the HIRLAM-NH tests.

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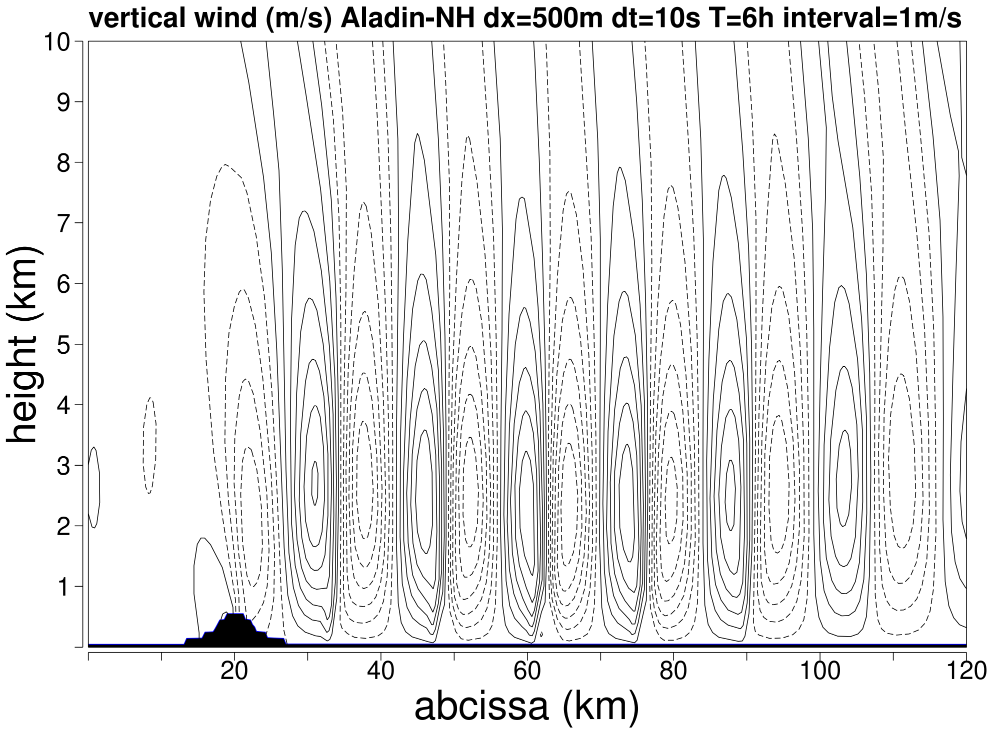

Figure 1 : ALADIN-NH vertical velocities at 500 m horizontal resolution. Contour spacing is every 1 m/s with a contour at 0.5 m/s. Downward velocities are dashed. The orography is in black at the bottom of the plot.

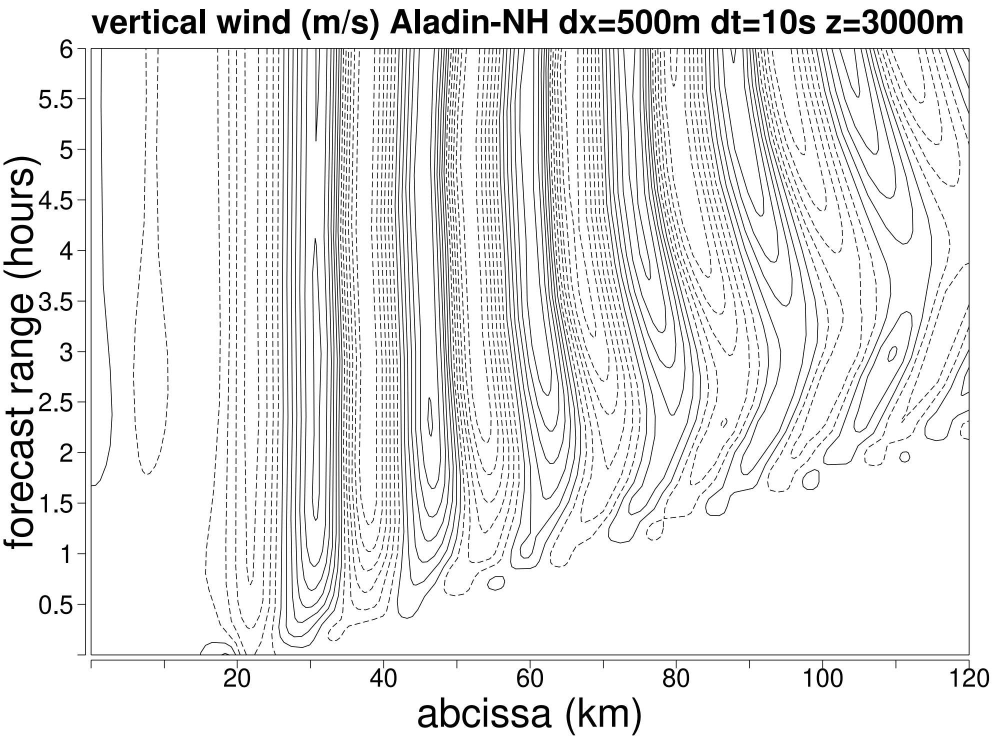

Figure 2 : Time evolution of 500 m resolution ALADIN-NH vertical velocities, at height 3000 m.

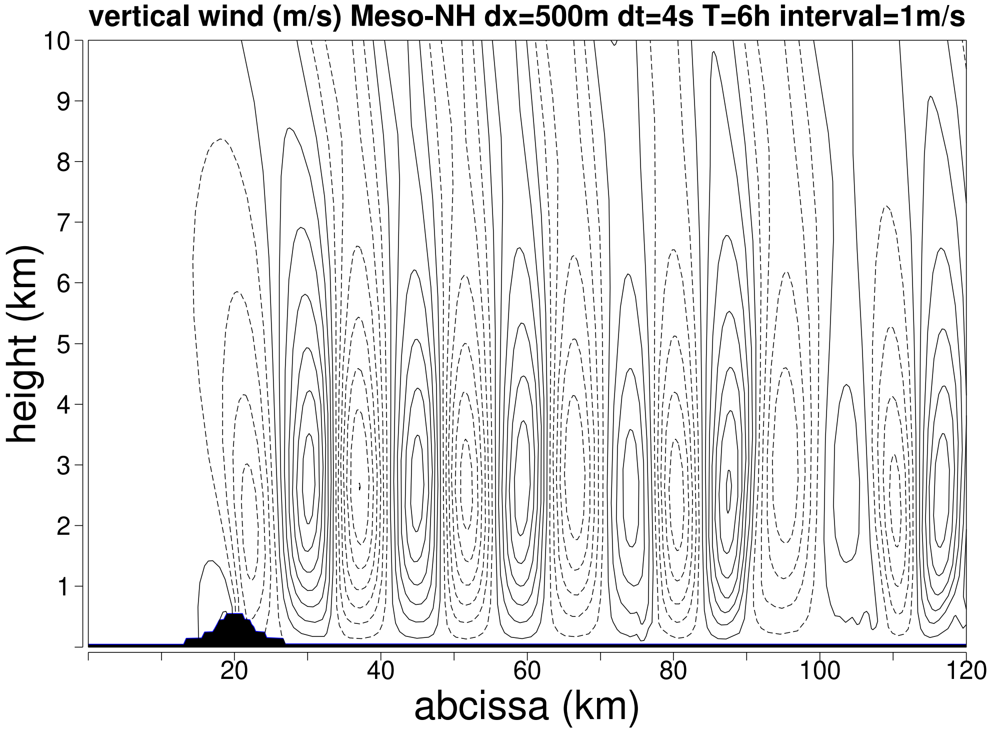

Figure 3 : As in fig. 1, using Méso-NH at 500 m resolution.

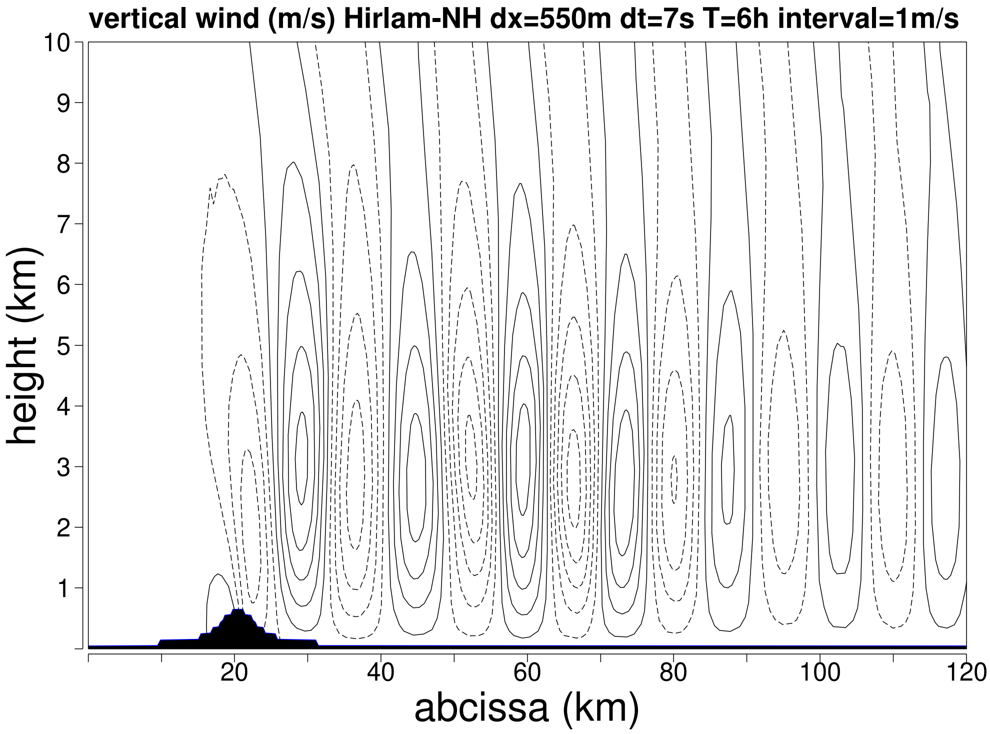

Figure 4 : As in fig. 1, using HIRLAM-NH at 550 m resolution.

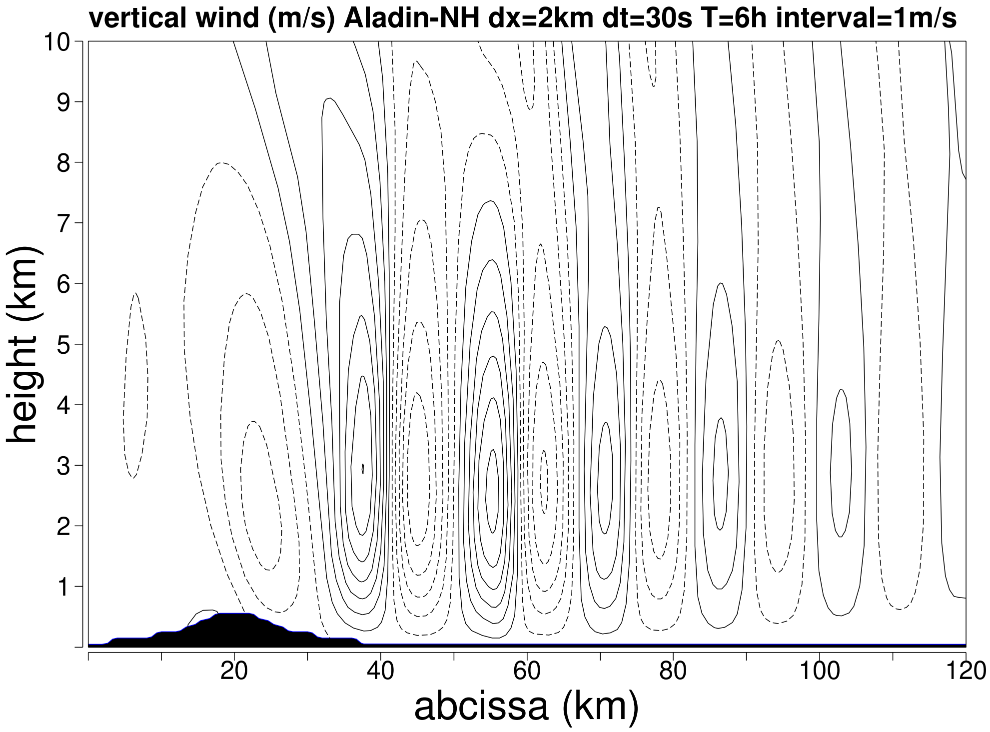

Figure 5 : As in fig. 1, using ALADIN-NH at 2 km horizontal resolution.

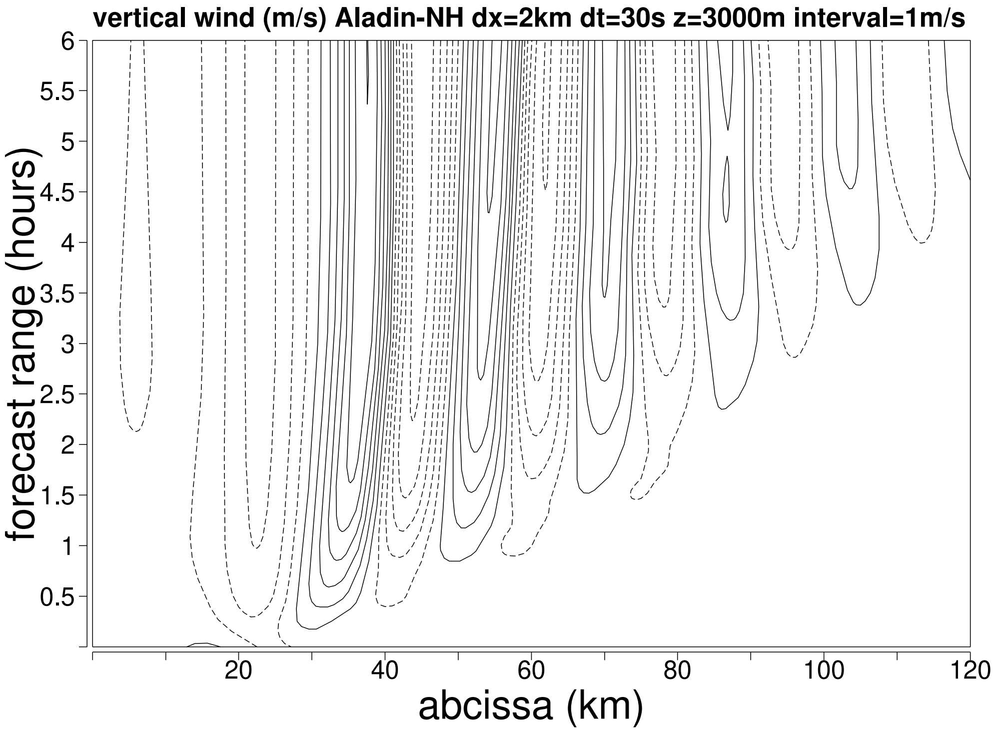

Figure 6 : As in fig. 2, at 2 km horizontal resolution.

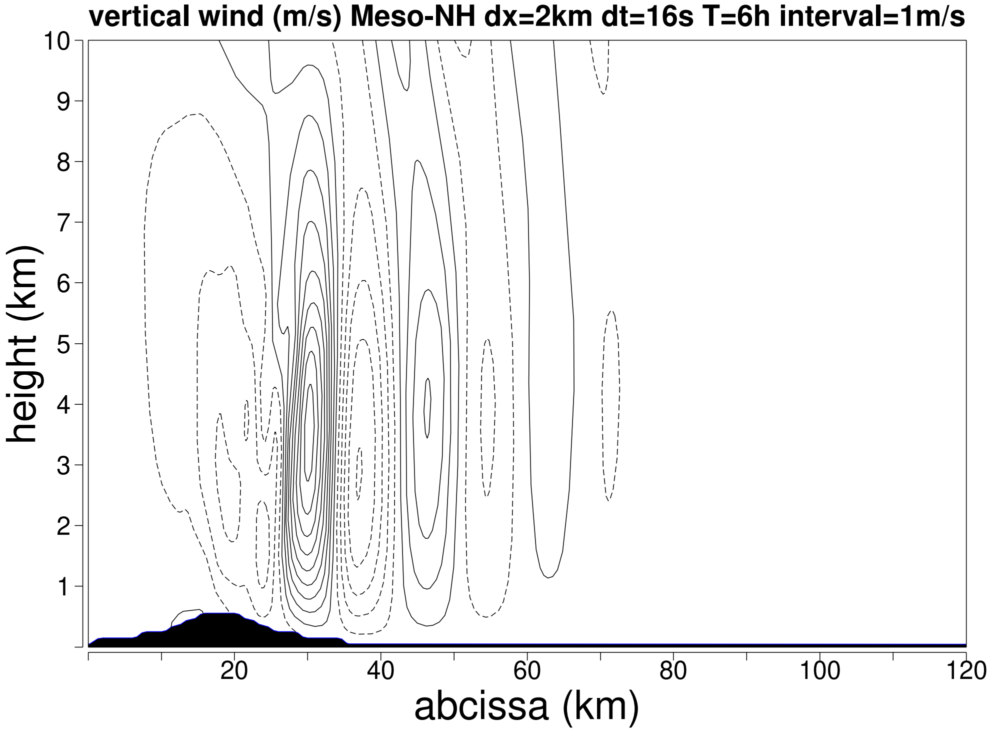

Figure 7 : As in fig. 1, using 2 km Méso-NH.

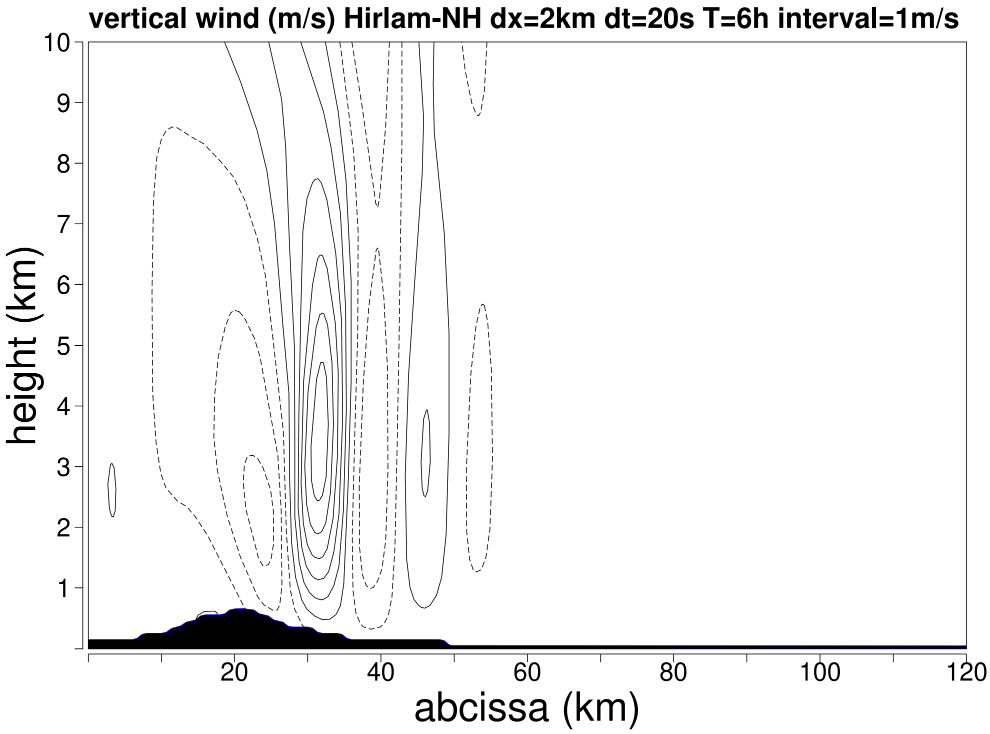

Figure 8 : As in fig. 1, using 2 km HIRLAM-NH.