The Finest Scale HIRLAM - the Tartu Model

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1 Introduction

Low resolution ($\Delta x > 10$ km) numerical models, including HIRLAM, are hydrostatic. When moving to resolutions $\Delta x < 10$ km, this assumption becomes incorrect. There exists two choices: either to initiate a new numerical model which treats NH forces properly (the DWD *Local Modell* case) or to modify the existing HS model (this case). The task we raised was to develop a NH extension to the exiting numerical model HIRLAM without abandonment of existing numerical framework and with hybrid-coordinate maintenance. This task concerned adiabatic dynamics and did not affect various physical parameterizations.

2 General and Approximate Equations

The main problem consisted in introduction of NH forces into pressure-coordinate-based primitive-equation formalism. We started from the general NH equations (GE) in isobaric coordinates, proposed in (Rõõm, 1990) and comprehensively discussed in (Rõõm, 2001).

In GE dynamics, the main NH characteristic of motion is the non-dimensional density of matter in pressure coordinates, n. This field departures a little from unity at all scales: $|n - 1| \sim 10^{-5}$ - 10^{-6} for synoptic and planetary scale, $|n - 1| \sim 10^{-3}$ - 10^{-4} for HS meso-scale, $|n - 1| \sim 10^{-2}$ for shorter NH scale, yet substantial it becomes in the last case. Various approximations of different complexity, which can be deduced from GE, using the smallness of n, *Elastic acoustically relaxed model,Miller-Pearce semi-anelastic p-coordinate model, Anelastic p-coordinate model Hydrostatic primitive-equation model.*

The domains of application of these models are described in (Rõõm & Männik, 1999), and are as presented in Fig. 1.

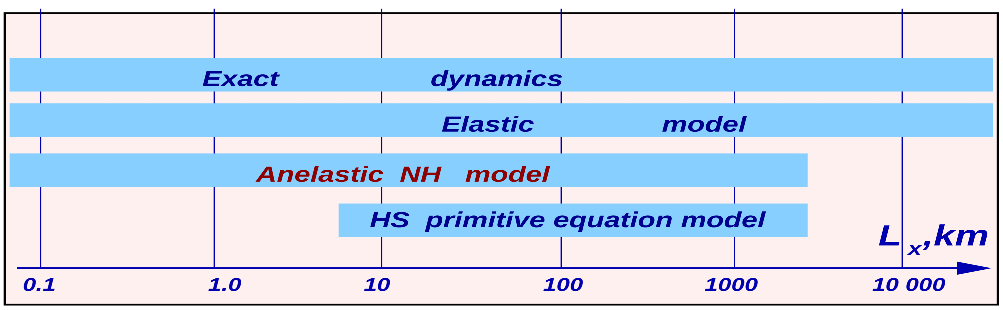


Fig. 1. Domains of applicability of different pressure-coordinate models.
L_x - *horizontal scale of the process.*

The choice was made in favor of the ANELASTIC P-COORDINATE APPROXIMATION, which coincides with HS model in the long-wave part and catches all NH effects of shorter scales. In addition, this model filters external acoustic (Lamb) waves, treating the surface pressure as the adjusted one and providing the most detailed presentation of small-scale surface pressure pattern.

3 Numerical Implementation of NH HIRLAM

Coordinate frame is the terrain following hybrid coordinate system of ECMWF origin. Spherical geometry is applied in horizontal dimensions, and the rotated spherical coordinates are used, like in the HS HIRLAM. The grid is the Staggered Arakawa C-grid.

Time integration scheme supported are the explicit leapfrog (Eulerian three-time-level scheme, *Expl. Euler*), semi-implicit leapfrog (Semi-implicit Eulerian three-time-level scheme, *SI Euler*), and semi-implicit, semi-Lagrangian two-time-level scheme (*SISL*).

Spectral smoothing is the horizontal implicit 4th order scheme and (optional) vertical explicit 4th order scheme.

Boundary conditions are the Davies' boundary relaxation scheme on lateral boundaries, surface pressure relaxation scheme on the lower boundary, and the sponge layer at the top.

Elliptic solver (ϕ-equation) to find the baric (complementary to ordinary hydrostatic) makes use of 3D orthogonal basis with boundary conditions treated as the singular boundary sources.

Physical parameterizations are the same as in hydrostatic HIRLAM (The physical tuning and updating was considered as a separate task for future, as it does not affect directly the NH updating of adiabatic dynamics).

The parallel computing environment is organized to be consistent with the Reference HS HIRLAM code.

4 Computational Efficiency

The time-consumption rate is approximately two times the HS scheme time-consumption rate.

Maximum time-step (in seconds):

Δx, km	U, m/s	$\Delta x/U$	Expl. Euler	SI Euler	SISL
11	60	183	60	150	250
2.0	20	100	40	80	200
0.5	30	18.3	16	18	55

5 Testing

Extensive testing with model flow regimes was carried out. Some examples of modeling of stationary flow regimes over circular hill are presented in Figures 2 and 3.

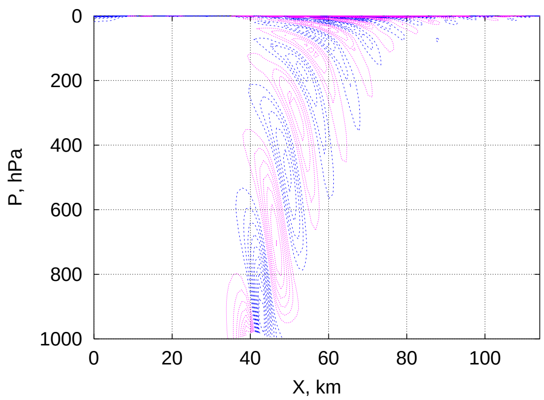


Fig. 2. Flow over circular hill. Vertical velocity distribution, contour interval 0.1 m/s. $\Delta x = \Delta y =$ 1km;
Vertical resolution: 60 level ECMWF grid.
a = 3 km, h = 200 m, $N = 0.015\ 1/s$, $U = 20$ m/s.
(Männik & Rõõm, 2001).

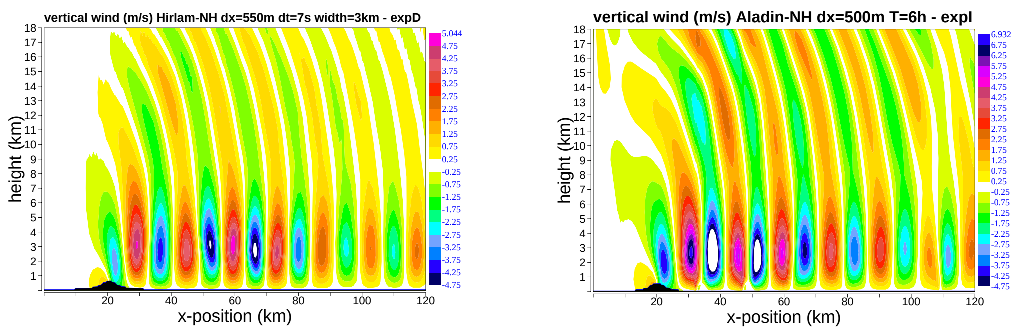
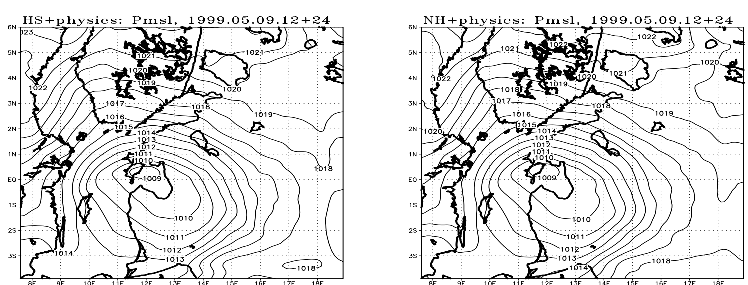


Fig. 2. Non-hydrostatic flow regimes over isolated mountain according to NH HIRLAM (left) and Aladin-NH of Meteo France (right). *a = 3 km, h = 600 m.* (Männik 2003).

Real-condition tests at 10 km resolution are presented in Figures 4 an 5.



HS model *NH model*

Fig. 4. Forecast of the cyclone evolution with HS SI and NH SI Eulerian schemes. *0.1 deg (11 km) resolution, 31 levels.*

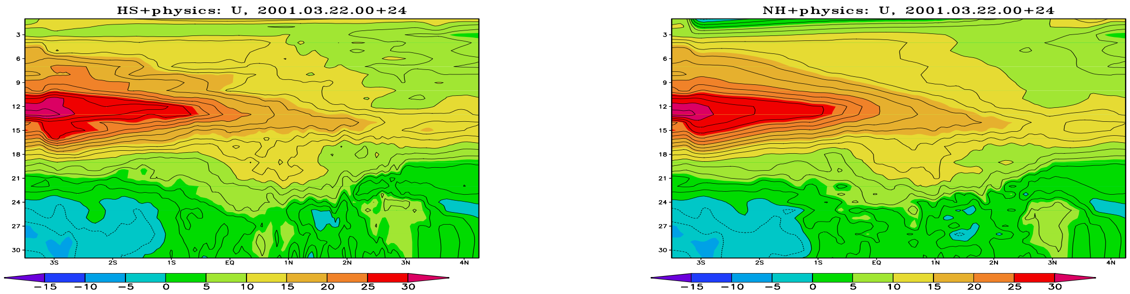
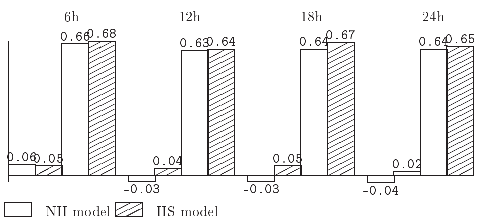
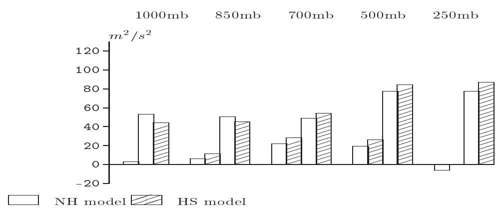


Fig. 5. Cross-section ($\lambda = 10E$) of the U-component of wind for 2001.03.22.00+24. over Norway. HS SI (left) and NH SI Eulerian schemes (right panel). *0.05 deg (5.5 km) resolution, 31 levels.*

6 Forecast Statistics

Up to date (late autumn 2003), statistics with 0.1 deg (11 km) resolution model are carried out (Männik, 2003). Results of these statistical experiments are presented in Fig. 6 for sea-level pressure, geopotential, and temperature.





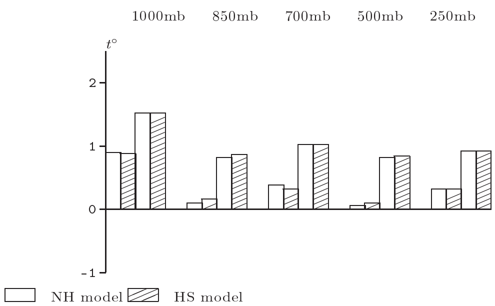


Fig. 6. Forecast statistics.
Grid 206×206*, 31 levels, 0.1 deg resolution.*
Period: 1999.08.24 - 09.04

At the 5 km resolution, the model accuracy looks quite similar. As these experiments demonstrate, the accuracy of NH model is comparable to the hydrostatic parent model at HS mesoscale resolutions.

So far we lack statistics at 1 - 3 km resolutions. Due to very small modeling domains, the standard HIRLAM verification procedures are not applicable in these cases, and new statistical testing tools must be developed which HIRLAM lacks so far.

7 Preoperational application

Currently (November 2003), with joint efforts by Finnish Meteorological Institute (FMI), Estonian Meteorological and Hydrological Institute (EMHI), and Insitute of Environmental Physics of Tartu University (TU), a preoperational

NH HIRLAM is in the stage of implementation at EMHI. Model has two resolutions and two forecast areas, as shown in Fig. 7. The coarser model, named ETA, has 0.1 deg (11 km) resolution and 40 levels in vertical. It downscales initial and boundary data from 33 km resolution FMI HIRLAM. The finer one, ETB, has resolution 3.3 km and takes its initial and boundary data from ETA model.

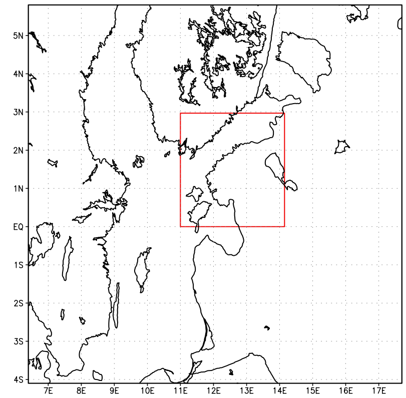


Fig 7. Forecast domains in ETA (large grid) and ETB (small box).

8 Nonhydrostatic effects

Question, at which resolution the NH effects become considerable, is relevant for NH modeling. At orographically forced flows this scale is approximately $\Delta x \sim 5$ km (as the scale of the minimal resolved orography $a \sim 2\Delta x \approx 10$ km). Orographic effects emerge in down-stream tilting of orographic waves as demonstrate Figs. 2 and 3. For flat terrain with no mountain wave excitation, the NH effects should appear in deep convection events, like the thunderstorms, if the resolution is fine enought to resolve individual convective cells.

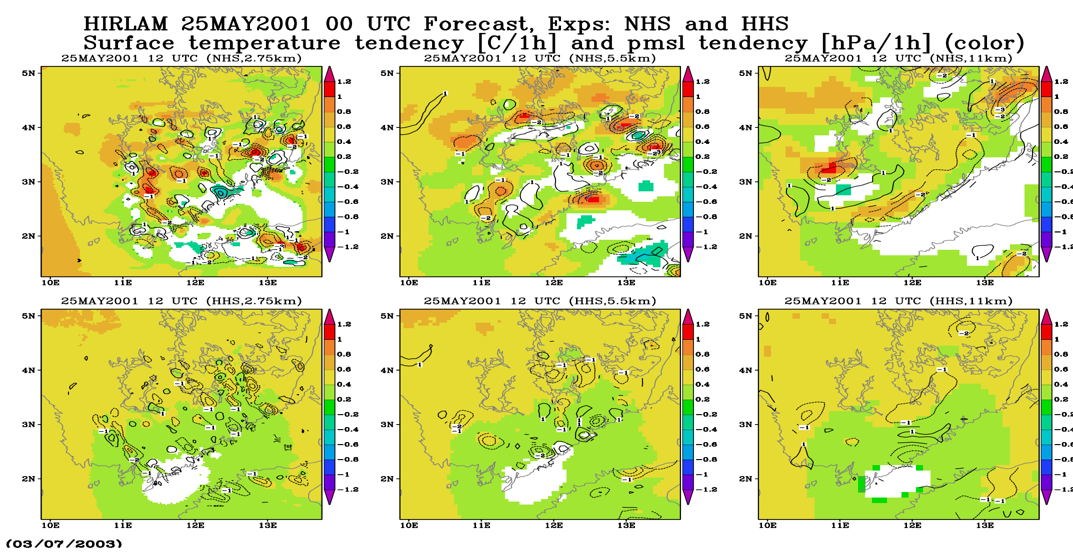


Fig. 8. Surface temperature and pressure fluctuation pattern, modeled with NH (top panels) and HS HIRLAM (bottom) for 2.75 (left), 5.5 (centre), and 11 km (right) resolution cases. *(With due reference to Sami Niemela)*

The oserved short-scale surface temperature and pressure fluctuations are

$$T_s' \sim 3 \text{ K}, \quad p_s' \sim 0.1 - 0.3 \text{ hPa}.$$

Convection modeling with both HS and NH HIRLAM at 2.75, 5.5 and 11 km resolution was lately carried out by Sami Niemela, Helsinki University (personal communication). As these experiments demonstrate (Fig. 8), both the HS and NH models get the near–surface temperature fluctuations properly, but only the NH model can catch the associated surface pressure fluctuations with correct amplitudes at 2.75 km resolution, and with somewhat reduced amplitudes at 5.5 km resolution. These examples demonstrate that the resolving power (resolution of relevant physical effects) of the NH HIRLAM with respect to the presentation of fine-scale surface pressure fluctuations is high.

9 References

Rõõm, 1990: General equations of atmospheric dynamics in isobaric coordinates, Izvestia, Atmospheric and Oceanic Physics, 26,1: 9 - 14.

Rõõm, R., 2001: Nonhydrostatic adiabatic kernel for HIRLAM. Part I: Fundamentals of nonhydrostatic dynamics in pressure-related coordinates. Hirlam Technical Report No 48, 25 p.

Männik, A., Rõõm, R., 2001: Nonhydrostatic adiabatic kernel for HIRLAM. Part II: Anelastic, hybrid-coordinate, explicit-Eulerian model. Hirlam Technical Report No 49, 53 p.

Rõõm, R., Männik, A., 2002: Nonhydrostatic adiabatic kernel for HIRLAM. Part III: Semi-implicit Eulerian scheme. Hirlam Technical Report No 55, 29 p.

Rõõm R., A. Männik , 1999: Responses of different nonhydrostatic, pressure-coordinate models to orographic forcing. J. Atm. Sci., v. 56, No 15, 2553 - 2570.

Männik, A., 2003: Implementation and validation of the nonhydrostatic adiabatic core of the numerical weather prediction model HIRLAM, Dissertationes Geophysicales Universitatis Tartuensis, Tartu Ülikool, TÜ Kirjastus, 2003.