Non-hydrostatic, semi-implicit, semi-Lagrangian adiabatic core for HIRLAM

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1 Introduction

The development of the nonhydrostatic (NH), semi-implicit semi-Lagrangian (SISL) core for HIRLAM is completed in general lines. Currently (January 2005), the model is implemented with Reference HIRLAM v6.1.0 and proceeds the stage of preoperational testing at the Estonian Meteorological and Hydrological Institute (EMHI).

The NH SISL creation continued efforts of earlier NH model development in the HIRLAM framework at the Tartu University (Rõõm 2001, Männik & Rõõm 2001, Rõõm & Männik 2002).

The main goals at the NH SISL development have been:

- To bring the semi-anelastic, pressure-coordinate, NH approach to a logical and definite finish in the HIRLAM framework;
- To upgrade HIRLAM for mesoscale use, substantially enhancing the computational efficiency of the NH core, and thus making the model competitive with other mesoscale forecast models.

In the first part we will give a short description of the dynamics and numerics, employed in the model. In the second part, preliminary test results with the new core are presented and discussed.

2 Model description

2.1 Dynamics

The basic for dynamics are the semi-anelastic pressure-coordinate equations of motion and thermodynamics in Lagrangian form. In detail these equation are described in (Rõõm 2001). The only and main difference between that model and current approach is the surface pressure treatment. In the current model the surface pressure is treated as non-adjusted, satisfying the 'full' evolutional equation, which coincides with surface pressure treatment by the primitive equations. Altogether, the set of dynamical equations is factually the HS primitive equation set, updated with an additional equation for vertical acceleration (the vertical momentum equation), which includes an additional, non-hydrostatic geopotential. This additional potential is diagnosed from the condition of the non-divergence of motion in pressure-coordinates (the continuity equation, which also is the same as in the HS primitive-equation model).

2.2 Discrete model

For discretization, the hybrid coordinates of ECMWF origin are employed along with C-grid staggering. The Semi-Lagrangian (SL) trajectory calculations are applied, which factually coincide with the trajectory calculations in HS case. Thus, the existing (McDonald & Haugen 1992, McDonald 1995) routines from HS HIRLAM are possible to employ for trajectory calculations and interpolating procedures.

The two-level time stepping scheme is also appropriated from HS model.

2.3 NH-specific features

Separation of forces to the main (linear) forces and perturbation (nonlinear) part makes use of pressure(height)-dependent reference temperature $\hat{T}(p)$, Brunt-Väisälä frequency $N(p)$, and reference surface pressure $\hat{p}_s(x, y)$. To avoid fictive geopotential force generation by reference surface pressure, $\hat{p}_s(x, y)$ must be chosen from the barometric relationship in concordance with reference temperature $\hat{T}(p)$. Consequently, the real dynamic variables are represented by fluctuative parts os temperature T, and surface pressure p_s.

The use of height dependent reference fields $\hat{T}(p)$, $N(p)$ insures to the benefit of increasing the weight of linear forces, which are treated implicitly, in comparison with explicit non-linear perturbations. The aim of such increase of the linear implicit forces is to maximize the stability of the model. For instance, in the ideal case of coincidence of the actual temperature $T(x, y, p, t)$ with the reference field $\hat{T}(p)$, the perturbative, nonlinear hydrostatic pressure forcing disappears, and scheme becomes (at that instant) unconditionally stable for optionally large time steps.

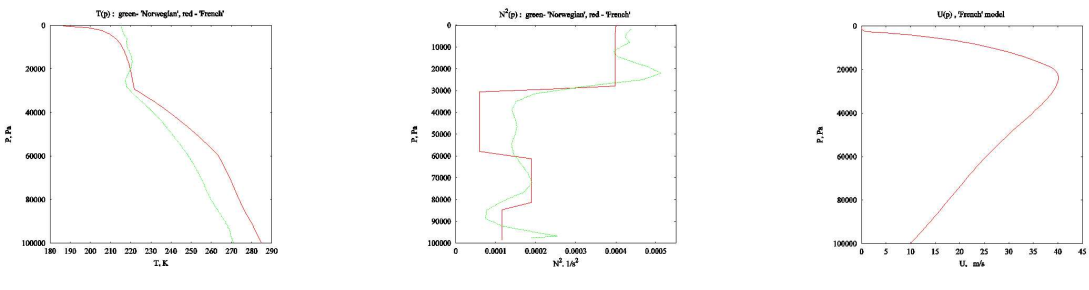

Fig. 1.

Examples of reference temperature profiles (a) and corresponding Brunt-Väisälä frequencies (b). The reference wind profile (c) is used for model tests with artificial orography.

The potential problem with sophistication of the main elliptic equation for NH geopotential due to the (more) complicated reference temperature distribution (common SISL approaches, including the HS SISL HIRLAM, make use of the constant reference temperature) is solved by using a special algorithm to solve this main elliptic equation.

In general, the developed NH SISL numerical algorithm is computationally (by time consumption rate per time-step) even more economic than the HS parent.

3 Testing

3.1 Model experiments

Aim of the model experiments is (1) debugging, and (2) model quality control. In the model experiments adiabatic stationary flow regimes over given orography are studied and compared to the known analytical solutions of the linearised dynamics.

As an example, in Fig. 2 the stationary flow over Agnesi ridge with half-width a_x = 3 km and maximum height h = 600 m is presented. The wind and temperature profiles are the 'French' case in Fig. 1. The grid is 276x100x100 points, horizontal resolution is 0.55 km. At such a reference state, the waves present a stationary wave-train downstream of the mountain, each wave vertically directed and penetrating the whole depth of the atmosphere. It is rather difficult to model this wave pattern correctly, the simulation quality is a good indicator of the quality of the numerical scheme. In this special case we were checking the stability of the model with respect to the time step size. In the top panel, the time step is $\Delta t = 30$ s, in the bottom panel – $\Delta t = 60$ s. The critical time step in this particular experiment is $\Delta_{cr}t = \Delta x/U_{max} = 13$ s.

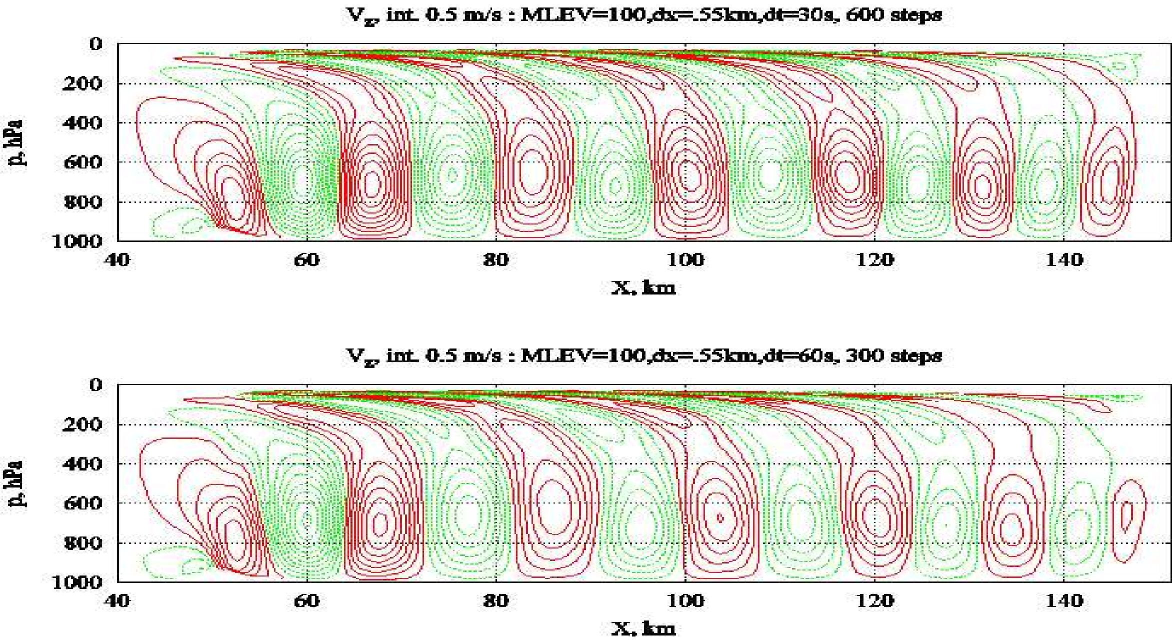

Fig. 2.

Vertical velocity waves (isoline interval 0.5 m/s) at stationary flow over Agnesi ridge. Top: Δt = 30 s, bottom: Δt = 60 s.

3.2 Time-step estimates

There is no strict upper limit for the accessible time-step Δt in NH SISL model. In the table, estimations of maximum reliable time-step are presented.

Max U, [m/s]	$T(p)$	Δx, [km]	$\Delta t_{Cr} = \frac{\Delta x}{U}$ [min]	Δt [min]	$\Delta t/\Delta t_{Cr}$	parcel path (max), [km]
40	const	5.5	2.3	4.6	2.0	11
55	real	5.5	1.67	4.0	2.4	13.2
40	real	2.2	0.92	2.8	3.0	6.6
42	real	0.55	0.22	1.0	4.6	2.5

As one can conclude, (1) the efficiency of the model is comparable with the HS case at low resolutions; (2) the efficiency of the model increases in terms of the ratio $\Delta t/\Delta t_{cr}$ with the resolution increase.

3.3 Real-condition experiments

The NH SISL adiabatic core was investigated in two cases: In mountainous region with resolution 5.5 km and in lowland conditions with resolution 3.3 km.

3.3.1 Norwegian experiment (mountains)

The resolution is 5.5 km, grid size is 156x156 points, 31 levels. The reference HIRLAM is v5.0.0, physics is switched on. Forecast period is 24 h, and the time step is 4 minutes.

The model check is carried out through comparison with forecast results by HS SISL model in identical conditions. As Fig. 3 demonstrates, the surface pressure of NHY model is $\sim$ 1 mb higher on the lowlands and over the sea, and $\sim$ 1 mb lower on the mountain-tops.

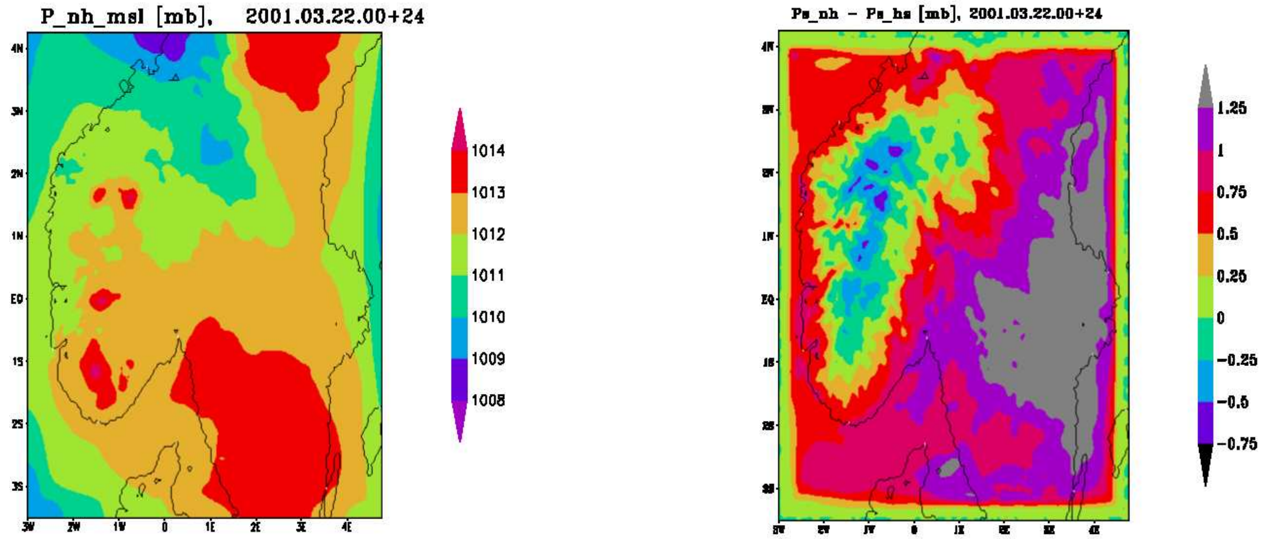

Fig. 3.

Mean sea-level surface pressure in 24 h Norwegian forecast with 5.5 km resolution and 4-minute time-step. Left: Mean sea level pressure; right: Surface pressure difference from the HS SISL results

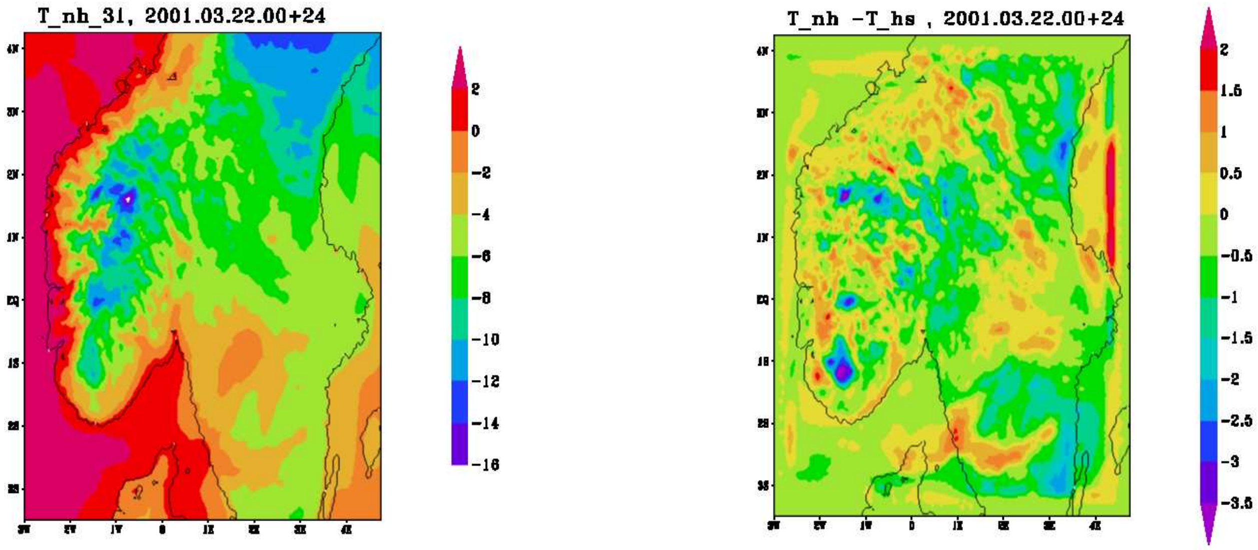

Fig. 4.

10 m temperature in 24 h Norwegian forecast with 5.5 km resolution and 4-minute time-step. Left: Temperature; right: Temperature difference from the HS SISL results

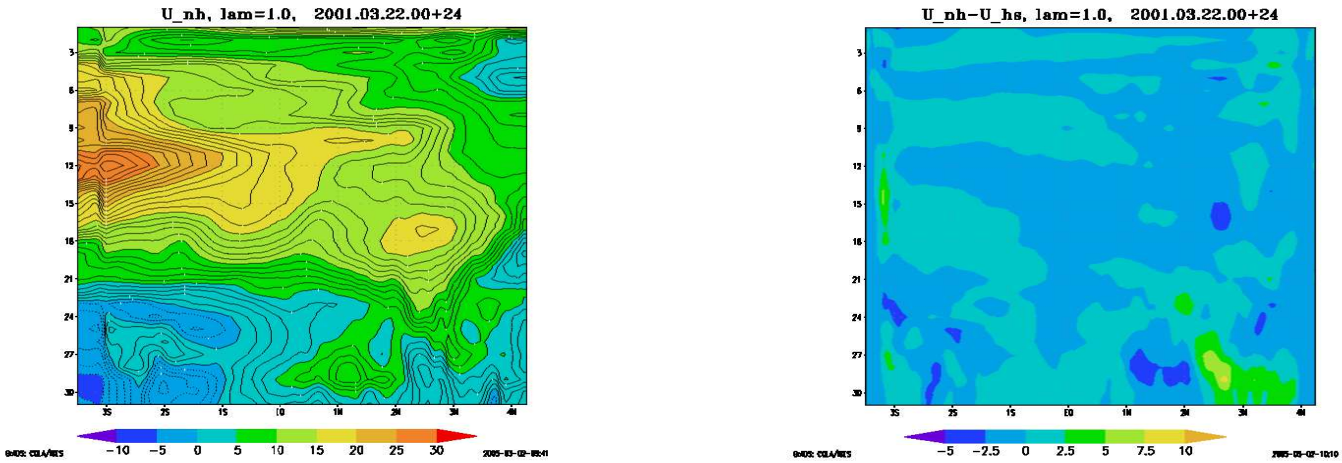

Fig. 5.

Vertical cross-section of the wind component U_x in 24 h Norwegian forecast with 5.5 km resolution and 4-minute time-step. Left: Vertical cross-section of U_x; right: Departure of U_x from the corresponding HS SISL wind

The forecasted 10-m temperature (Fig. 4) does not differ from HS SISL results more than $\sim \pm$ 0.5 C.

However, the local differences in forecasted wind fields are substantial and may reach 10 m/s by amplitude. This is explained by slightly different placement of steep local fronts of wind fields in HS and NH models.

3.3.2 Estonian B-area experiments (lowlands)

Experiments similar to the previous case, were carried out with NH SISL core, implemented with the Reference HIRLAM 6.1.0, physics included, for of 3.3 km resolution Estonian B-area. The grid in this case was 186170 points, 40 levels in vertical. The former Eulerian SI model grid was 104x100 points here. Thus, the increase in the forecast area due to implementation of SI SISL scheme is about 3.3 times. In Fig. 6, the 36 h MSL surface pressure and lowest level temperature are presented. The time-step in this experiment was 1.5 min (90 s). However, model remains stable and produces the same forecast with time step 2.5 min (150 s) also.

The differences with the HS SISL model do not exceed in the current lowland case ±0.3 mb in surface pressure, ±0.5 C in the lowest level temperature fields.

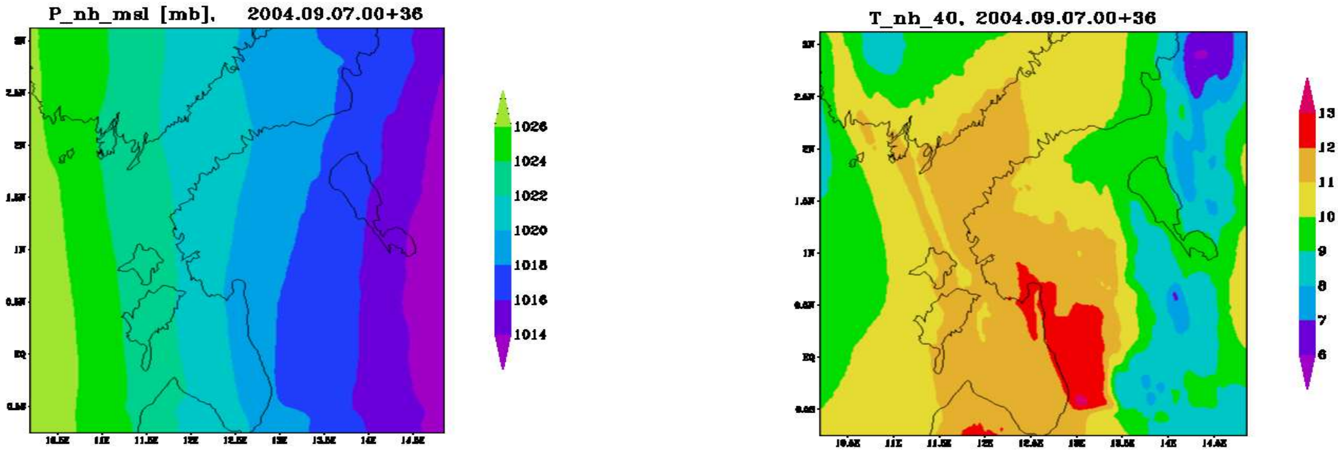

Fig. 6.

Mean sea-level surface pressure (left) and lowest level temperature (right) 36 h forecasts in Estonian B-area domain.

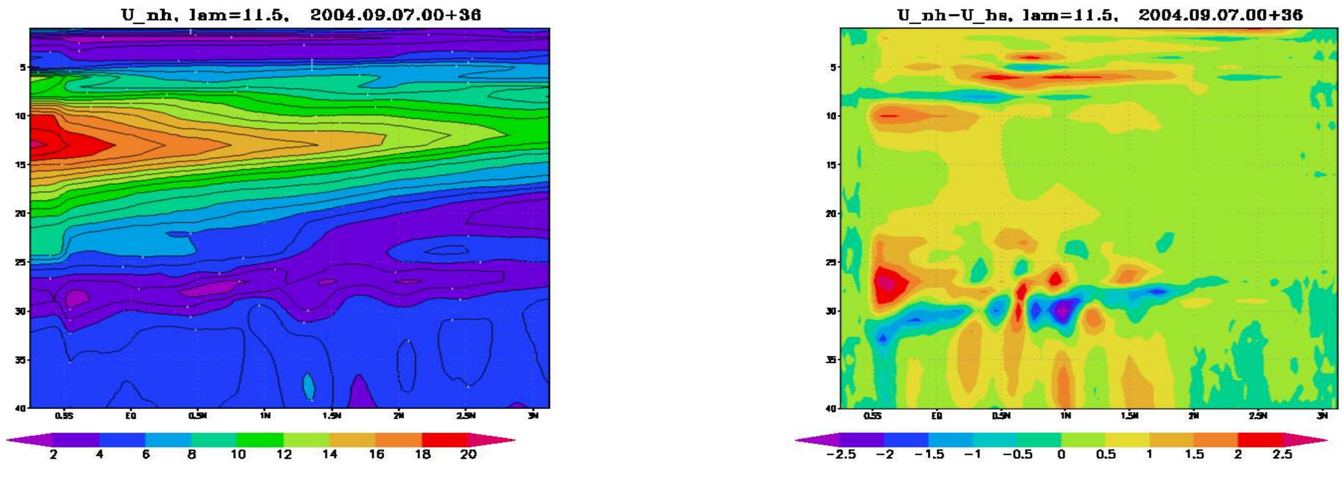

Fig. 7.

Vertical cross-section of the wind component U_x in 36 h Estonian B-area forecast with 3.3 km resolution and 1.5-minute time-step. Left: Vertical cross-section of U_x; Right: Departure of U_x from the corresponding HS SISL wind

4 Conclusions

We consider the NH SISL development as the completed task:

- The stability and the time step characteristics of the new model are reasonable.
- Comparison with theoretical results (mountain flows), as well as with other models (NH Euler, HS SISL) shows that NH SISL is reliable and ready for applications.
- The computational efficiency increase is substantial.

Currently, the NH SISL is implemented as the adiabatic core in Estonian B-area (3.3 km resolution, grid 186x170, 40 levels, physics of HIRLAM 6.1.0) and the statistical testing is activated. As the experimentation experience reveals, the NH-specific effect is moderate at these resolutions for the given physical paramterization and lowlands condition. More NH behavior will be expected at higher resolutions (0.5 - 1km, 100 levels) with explicit moist convection physics and complex orography. NH SISL will be a suitable tool for physics development (complex terrain, boundary layer, moist convection) at these very high spatial resolutions.

5 References

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