Non-hydrostatic modelling with HARMONIE

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1. Introduction

The HARMONIE model is the tool for cooperation between the consortia HIRLAM and ALADIN. It is the limited area version of the IFS/ARPEGE system in which several physics parameterization packages have been implemented.

These physics packages, apart from the possibility of using ECMWF physics, are called ALADIN (for synoptic scale resolutions), ALARO (for the “grey zone” resolutions) and AROME (for convection permitting scales).

2. Future model configurations

A joint HIRLAM-ALADIN brainstorming workshop was called in May 2010 to discuss about possible future model configurations. Representatives from the UKMO, COSMO and ECMWF participated in the workshop.

The main aim of the workshop was to discuss whether the spectral semi-implicit semi-Lagrangian version of the HARMONIE model could be maintained in the short to medium term, when the computers probably will have a much larger number of processors than they have nowadays.

The workshop didn’t arrive to a definitive conclusion but it was the first step in the process to prepare for possible drastic changes in the architecture of computers.

A report was produced after the workshop by a group of four people from the management groups of both HIRLAM and ALADIN in which the main recommendation was to keep a watchful eye on the computer market and to collaborate with ECMWF in the adaptation of the model algorithms to the changes in computer architectures.

3. Behaviour of deep convection using AROME

The stated targeted resolution of HARMONIE to implement as operational forecast model at the meteorological institutes of the members of HIRLAM-A is 2.5 km. At this resolution the dynamics should represent, at least in a great part, the deep convection and therefore a physics parameterization package like AROME, which do not include the parameterization of deep convection, should be usable.

Several experiments have been performed using the HARMONIE model at 2.5 km resolution with the AROME physical parameterization package.

Using the values of horizontal diffusion and size of the time step which should have been used in the hydrostatic version of the model at this resolution, resulted in the appearance of grid-point storms with an unphysical looking outflow in the lower levels of the model ("fireworks"). There was also a lack of organization between the individual cells, which were too small in size.

Increasing the resolution to 1 km and 0.5 km resulted in a further decrease of the size of the convection cells, with the maximum intensity of precipitation not changing very much and with a too early onset of the precipitation.

If the spectral (linear) horizontal diffusion was increased, the onset of convection was delayed but the outflow became larger.

In the HARMONIE model (as well as in the IFS) there is the possibility of applying a "semi-Lagrangian horizontal diffusion" (SLHD). This possibility takes advantage of the semi-Lagrangian horizontal stencil of points used by the interpolation for semi-Lagrangian advection, to apply locally a smoother in grid-point space. The application of SLHD to some hydrometeors (rain, graupel, …) resulted in a decrease of the intensity of the grid-point storms in both the amount of rain and the strength of the "fireworks".

The impact of microphysics has been also studied. Several experiments were run with a modification to the amount of evaporation, a change in the falling speed of the hydrometeors or eliminating some of the hydrometeors like the graupel. A large sensitivity was found to these changes which sometimes used unphysical values of the parameterization parameters.

These experiments led to the recommendation of a setup which included a small value of the linear (spectral) horizontal diffusion (the same for all the fields to which it is applied), SLHD applied to hydrometeors (but not to humidity itself), and considered the convenience of applying some sort of parameterization of deep convection, which should decrease its influence when the resolution increases.

4. Implementation of a finite-element discretization in the vertical in the non-hydrostatic version of HARMONIE

In the application of the semi-implicit method to the non-hydrostatic version of the HARMONIE model, the process of elimination of equations to arrive at a single Helmholtz equation needs some relationships (constraints) between the vertical operators used in the equations. These constraints determine the finite difference discretization used at present but they are difficult to fulfil with a finite-element discretization.

One possibility to overcome these limitations could be to use a different set of prognostic variables, chosen so that there is no vertical integral operator. Having only derivatives in the vertical, the constraints needed to be able to eliminate equations to arrive at a single Helmholtz equation is easier to fulfil with finite elements.

Several combinations of prognostic variables were considered but in all of them the non-linear model was found to be unstable in the presence of orography, when the stability analysis was applied following the method of Simmons, Hoskins and Burridge (SHB).

The main instability cause was the so-called X-term, which is a term in the three-dimensional divergence, appearing because the coordinate system in the vertical is time-dependent.

An alternative to be considered was then to replace the vertical coordinate, making it time independent. Hybrid vertical coordinates based on geometrical height have been used successfully before in non-hydrostatic modelling. On the other hand, covariant variables for the wind components and their corresponding covariant derivatives make the expression of the three-dimensional divergence simpler, without the presence of the non-linear term (the X-term) which makes the model unstable in the presence of orography.

A vertical slab model was coded using this vertical coordinate. The set of prognostic variables used is:

Covariant velocities (“horizontal” and “vertical”)

Ln(Temperature)

Ln(Pressure)

The Helmholtz equation to be solved includes only the “vertical laplacian” vertical operator.

Helmholtz: $$\left(I-\beta^2 c_*^2\left(\nabla^2+L_z\right)-\beta^4 c_*^2 N_*^2 \nabla^2\right)W_{n+1}=RHS$$

Where vertical Laplacian:

$$L_Z=\frac{1}{H_*^2}\left(\frac{H_*}{H_T}\partial_Z\cdot\frac{H_*}{H_T}\hat{\partial}_Z+\frac{H_*}{H_T}\hat{\partial}_z\right)$$

$$c_*^2\equiv R_d T^*\frac{C_{pd}}{C_{vd}};\quad H_*=\frac{R_d T^*}{g};\quad N_*^2=\frac{g^2}{C_{pd}T^*}$$

This operator, computed with the finite-element technique, has real negative eigenvalues for all the tested distribution of vertical levels and therefore the linearized model is stable. An SBH stability analysis for the three-time-level scheme shows amplification factors smaller than 1.01 in the non-linear model for temperatures in the range 0.5xT^* → 2.xT^* where T^* is the semi-implicit reference temperature.

The prognostic variable in the Helmholtz equation is the covariant vertical velocity, whose boundary value at the surface and at the top of the model is zero. It turns out that including this boundary condition on the basis functions for the finite-element scheme (operator) is important to make the eigenvalues of the vertical laplacian operator real and negative.

Several tests from the literature have been run with the slab model, using both finite differences and finite elements in the vertical discretization and both Eulerian and semi-Lagrangian advection. All of them gave stable integrations and the vertical finite element version was more accurate than the finite differences version.

The test run were

- Two-layer atmosphere. Flow over a bell-shaped mountain with two different atmospheric stabilities. Good agreement was found with the linear analytical solution.
- Warm bouble test: good agreement with other published results
- -Linear and non-linear hydrostatic waves
- Linear and non-linear non-hydrostatic waves
- Propagation of acoustic waves

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5. References:

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