A non hydrostatic global spectral model with height based vertical coordinate: formulation and results

Juan Simarro
AEMET Agencia Estatal de Meteorología, Spain

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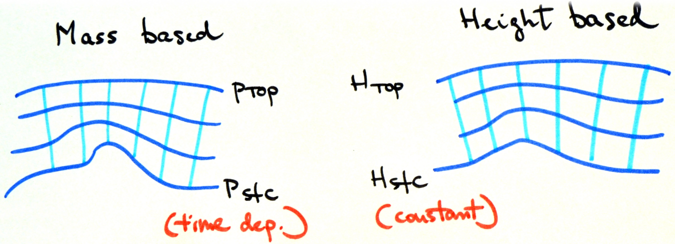
A Hirlam Dynamics Project

- The objective was to develop a VFE (Vertical Finite Element) scheme for the HARMONIE model
- Due to unsolvable problems in the first proposal, after some time it changed
  - from mass based to height based vertical coordinate
  - from VFE to High Order VFD (Vertical Finite Differences)
- Then we developed and tested a global version, which does not have the problem of the lateral boundary conditions
- Final results are for a global spectral model with High Order VFD using height based vertical coordinate
- The project has finished at this point

Spectral vs. Grid point

- Inherits many of the spectral method pros and cons
- Pros
  - Accurate horizontal spatial discretization
  - Efficient semi-implicit and semi-Lagrangian methods which allow big time steps
  - Exact 3D semi-implicit solver
- Cons
  - Cost of the spectral transformations
  - Low scalability
  - Poor conservative properties
  - Time stepping is at most second order

Mass vs. Height based vertical coordinates



- Integral and diff. operators
- Constraints
- X term in the 3D divergence
- Lower BC
- SHB stability

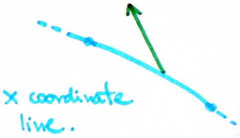
- Only diff. operators
- No constraints
- Conservative 3D divergence
- Simple BC : $w = 0$
- Small Semi-implicit decentering ($\epsilon \sim 0.05$)

Model equations

- The model simulates fully compressible non-hydrostatic air flows on a rotating dry atmosphere
- Prognostic variables are contravariant velocity components, logarithm of temperature and logarithm of pressure

Covariant vs. Contravariant basis

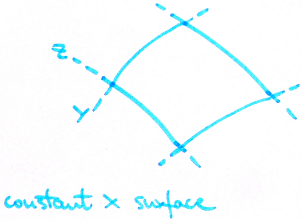
Given the vector field $\vec{a}$



$$\int \vec{a} \cdot d\vec{l} \stackrel{2^d}{\approx} a_x \, \delta x$$

↑ covariant component

Related to circulation, vorticity, momentum eq.

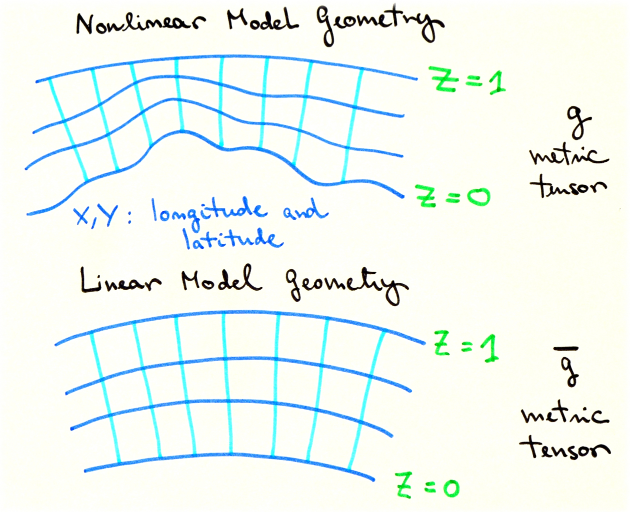


$$\int \vec{a} \cdot d\vec{s} \stackrel{2^d}{\approx} a^x \, |g|^{\frac{1}{2}} \, \delta y \, \delta z$$

↑ contravariant component

Related to flux, conservation, continuity eq.

Model coordinates and domain

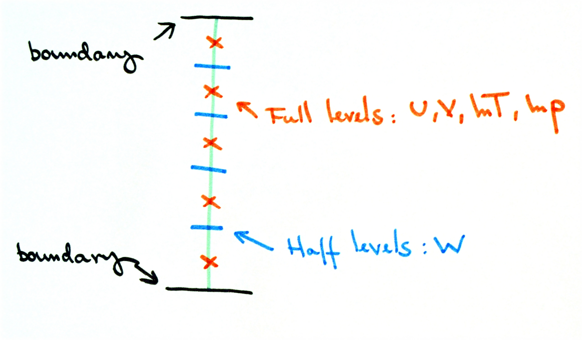


Model coordinates and domain

- Cartesian coordinates fixed to the Earth (x, y, z) are transformed into model coordinates (X, Y, Z) being X and Y the geographical longitude and latitude and Z the terrain-following vertical coordinate
- The relationship between both coordinates is analytical and constant in time
- Surface $Z = 0$ is the bottom boundary or Earth surface whereas surface $Z = 1$ is a rigid spherical surface which represents the top of the atmosphere
- metric tensor is calculated in the model coordinates to find differential operators like divergence, gradient and convariant derivative

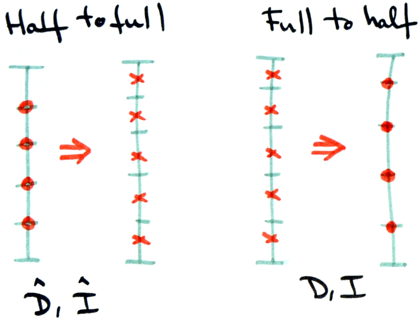
Vertical discretization

- Here a High Order VFD version is presented in 2D planar and 3D spherical geometries
- The prognostic variables are all in N full levels except the contravariant vertical velocity which is in $N-1$ half levels plus two boundary levels where it is zero



Vertical discretization

- Vertical derivative and vertical interpolation operators
- If the input field is given in half levels the result is in full levels and viceversa
- The operators take into account whether the field is supposed to be zero or not at the boundaries
- The stencil of the operators depends on the order

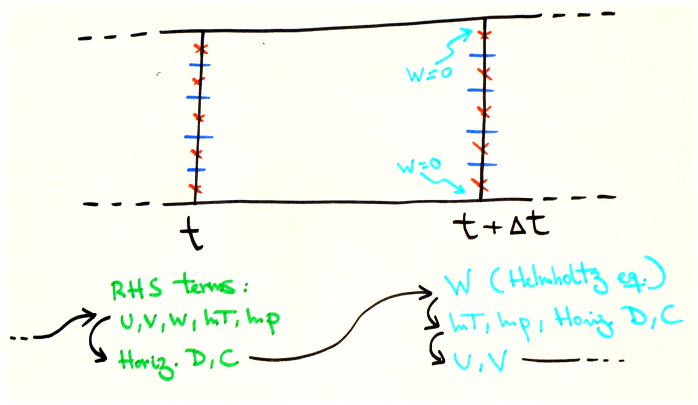


Semi-implicit time discretization

- The semi-implicit formulation follows closely the formulation used in ALADIN with the mass-based vertical coordinate
- The equations are linearized around an isothermal hydrostatic balanced atmosphere at rest with flat orography
- It is found a structure equation for finding the value of the contravariant vertical velocity at the next time step

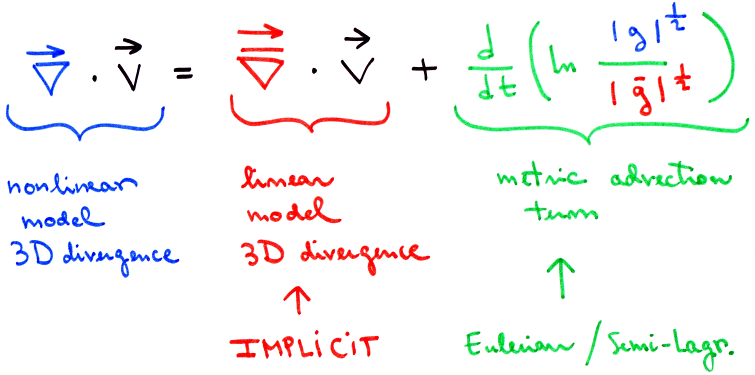
Semi-implicit time discretization

- There is no boundaries conditions at next time step between unknown horizontal velocity and vertical velocity at: $W = 0$ at any time
- Horizontal divergence and curl operators decouple horizontal momentum equations, similar to Temperton (1991)

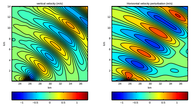


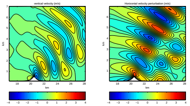
Semi-implicit time discretization

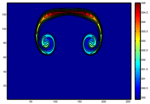
- Divergence in the non linear model is expressed as the sum of the divergence in the linear model plus a geometric constant in time advection term

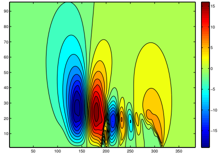


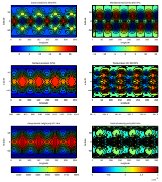
Next section some 2D and 3D tests

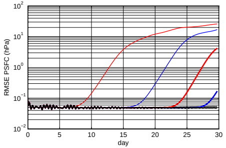


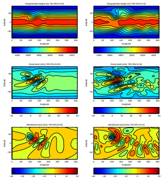


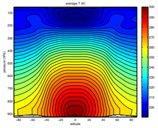


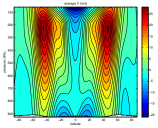












2D Tests

Linear non-hydrostatic flow (Bubnová et al. 1995)

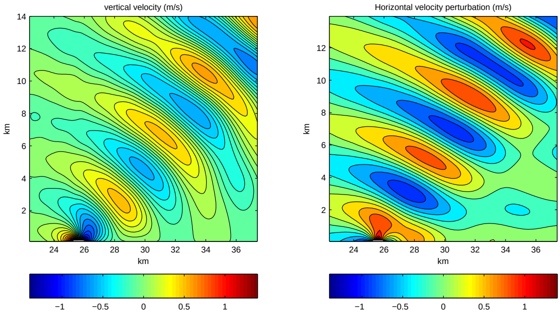


Figure: Vertical and horizontal velocities

2D Tests

Non-linear non-hydrostatic flow (Bubnová et al. 1995)

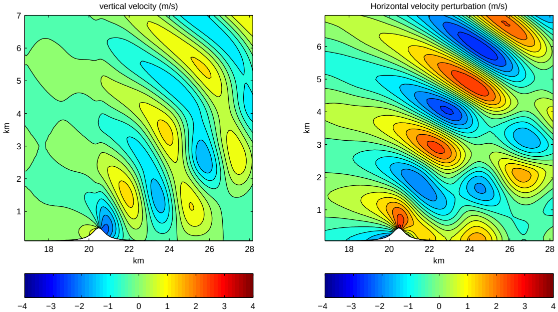


Figure: Vertical and horizontal velocities

2D Tests

Warm bubble (Janjic et al. 2001)

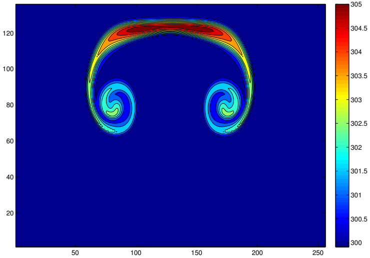


Figure: Potential temperature

Cold bubble (Straka et al. 1993)

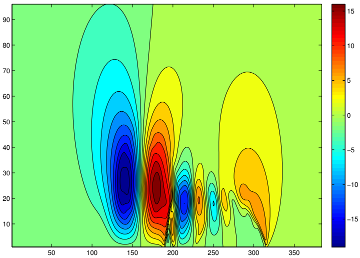


Figure: Vertical velocity

3D Tests

3D Rossby-Haurwitz wave (Jablonowski et al. 2008)

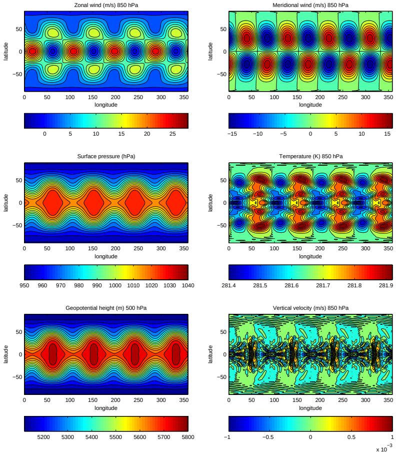


Figure: Integration at day 15.

3D Tests

Steady Jablonowski baroclinic instability rotated test: the flow should stay steady indefinitely (Jablonowski and Williamson 2006)

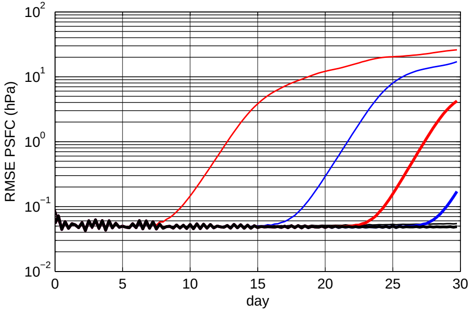


Figure: RMSE of surface pressure for rotated angles of 0° (black), 45° (red) and 90° (blue). Bold lines and thin correspond to T85 and T42 respectively

3D Tests

Mountain induced Rossby wave train: flow across a 2000 *m* height mountain (Jablonowski et al. 2008)

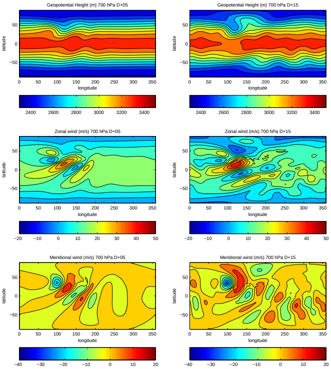


Figure: 2000 *m* mountain induced Rossby wave train at day 5 and 15: geopotential height, zonal and meridional wind at 700 *hPa*

3D Tests

Held-Suarez climate (Held and Suarez 1994)

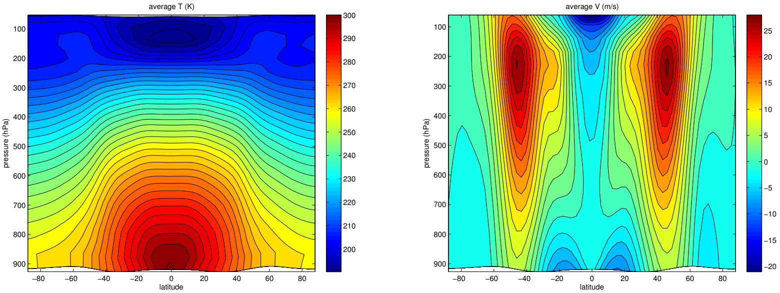
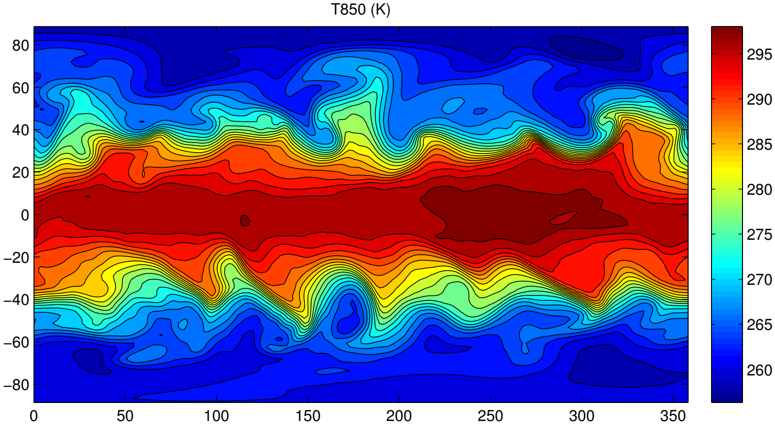


Figure: Held-Suarez test. Mean temperature (K) and mean meridional velocity (m/s) for a 800 days experiment at T42 and 20 vertical levels

3D Tests

A Held-Suarez planet day (T63)



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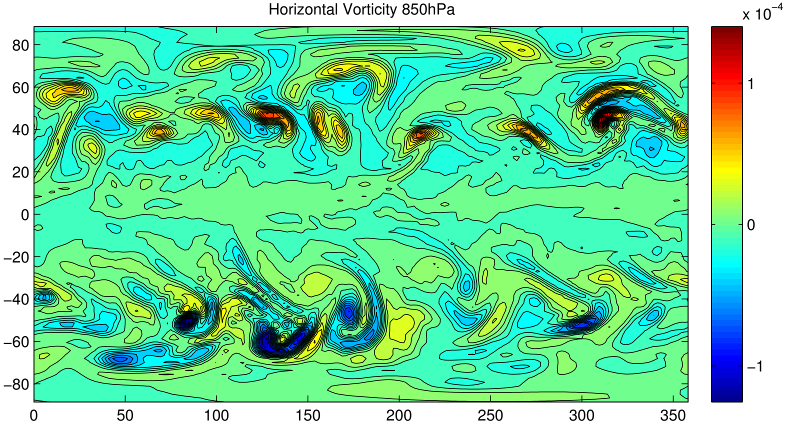

3D Tests

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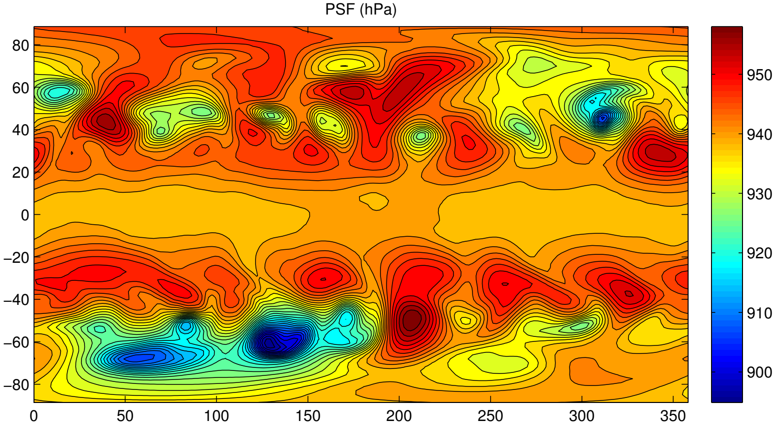

Main conclusions of the project

- Implementation of published 2D and 3D tests: good results in both non-hydrostatic and hydrostatic regimes
- Contravariant velocity: allows simple boundary conditions and compact or conservative expression of the velocity divergence: this result can be applied to grid point models as well
- Steep orography and stability: High Order VFD is competitive with respect other models, it is not the case of the VFE version, which is less stable
- Mentioned Pros and Cons of the spectral method in high resolution modelling
- Mentioned Pros and Cons of mass and height based vertical coordinates
- Results are good and the scheme seems to be suitable for another global spectral non-hydrostatic model

Thank you for your attention

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Mediterranean Sea from Castelldefels (Spain)