Numerical weather prediction and HIRLAM programme

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Contents

- Introduction to numerical weather prediction and HIRLAM
- Primitive equations
- Hybrid coordinates
- Discretization
- Data assimilation
- Boundary conditions
- Future of HIRLAM
Numerical weather prediction (NWP)

- National meteorological services are required to provide short and medium range weather forecasts
- Global models use whole Earth, resolution 20-40 km
- Limited area models: smaller scale, global models as boundaries
- Modern forecasts done with numerical weather prediction models
NWP model

- Atmospheric model
  - Model dynamics
    - Primitive equations, boundary conditions
  - Parameterization
    - Sub-scale phenomena, complex physical processes

- Data assimilation
  - Observations
  - Initial conditions
HIRLAM program

- European collaboration on High Resolution Limited Area Modelling
- String of projects since 1985, current HIRLAM-A set in motion 2006
- FMI a member since the beginning
- Used in routine weather forecasting at FMI
- Other applications include
  - oceanographics, aviation, wave and storm forecasts, road condition and air quality prediction, atmospheric research...
Primitive equations

- Govern the atmosphere
- Based on conservation laws of mass, momentum, energy and moisture
- Wind forecast equation
  - Time changes in W-E and S-N wind components: Advection, turbulence, Coriolis force, surface friction…
- Continuity equation
  - Vertical motion, velocity in hydrostatic + acceleration in non-hydrostatic
Primitive equations (cont’d)

- Moisture forecast equation
  - Evaporation of liquid, condensation etc
- Temperature forecast equation
  - Evaporation of liquid, condensation etc
- Hydrostatic equation
  - Height field for wind forecast equations
- Chemistry and molecular processes excluded
- Wind, temperature + moisture = prognostic
- Continuity + hydrostatic = diagnostic
HIRLAM primitive equations

- Hydrostatic kernel in operational model
  - Balance between the weight of the atmosphere and vertical pressure gradient force
- Convection parameterized
  - Changes in temperature and moisture due non-hydrostatic processes statistical
- Continuity equation stationary, but air compressible: air density prognostic variable
HIRLAM coordinate system: horizontal

- Limited area model = no need to deal with singular poles
- Horizontal domain described in spherical coordinates \( \{\lambda, \theta\} \)
  
  \[ dX = a \cos \theta \, d\lambda \]
  
  \[ dY = a \, d\theta \]

  \( a \) = radius of Earth
HIRLAM coordinate system: vertical

- Hybrid coordinate $\eta$ defined via mapping:
  \[ p_{k+1/2} = A_{k+1/2}(\eta) + B_{k+1/2}(\eta) p_0 \]
- $p_0$ given background pressure
- Discrete scalar fields defined at full levels $k = 1, \ldots, N$
- Pressure and vertical velocity defined at half levels $k = \frac{1}{2}, \ldots, N-\frac{1}{2}$
Examples of curvilinear hybrid coordinates

- **Velocity**

\[
\left( \cos \theta \frac{dx}{dt}, \frac{dy}{dt}, \frac{d\eta}{dt} \right)
\]

- **Continuity equation**

\[
\left( \frac{d_H}{dt} + D \right) \frac{\partial p}{\partial \eta} + \frac{\partial}{\partial \eta} \left( \eta \frac{\partial p}{\partial \eta} \right) = 0
\]

\[
\frac{d_H}{dt} = \frac{\partial}{\partial t} + \bar{v}_H \cdot \nabla_H, \quad D = \nabla_H \cdot \bar{v}_H
\]
Discretization

- Semi-Lagrangian discretization scheme
  - Arriving trajectories coincide with grid points
  - As parcels move, they are no longer uniformly distributed
  - Departure points do not coincide → determined by interpolation
- Semi-implicit time-stepping
Discretization (cont’d)

- Arakawa C-grid
- Spatial derivatives by second-order finite difference
- Operational grid spacing typically about 2.5 - 10 km
- Meso-γ-scale – version with 1 km resolution under development
Data assimilation

- Links real weather and model forecast via minimum error analysis
- Two set of information needed to generate a forecast
  - A set of recently collected observations
  - A prior forecast estimate valid at the time of observations = ‘background’
- Background: humidity, temperature, winds etc. at regular set of grid points
Data assimilation (cont’d)

- Accuracy depends on availability of observations → satellites
- Procedure is repeated in cycles
  - Observations & background → a short term forecast aka now-cast
  - Now-cast becomes new background
  - New observations are collected
  - New now-cast
- Several methods exist
Optimum Interpolation (OI)

- Operational HIRLAM uses OI upper-air analysis
- Minimum variance scheme
  - Weighted average of observation is taken over its impact area
  - Weighting based on closeness to studied location in space and time and reliability of observation

\[ a_k = b_k + \sum_{i=1}^{N} w_{ki} (y_i - b_i) \]
3D-VAR and 4D-VAR

- OI is stationary → methods taking into account prevailing winds under development
- Variational assimilation: observation operator algorithms applied to model state to predict observations
- Developed for spectral HIRLAM
- Incremental state model formulation: observation increment = difference between observations and forecast
4D-VAR: increment state model formulation
4D-VAR

¢ Based on minimization of cost-function
  \[ J = J_b + J_o + J_c \]
¢ \( J_b \) = distance between analysis and background
¢ \( J_o \) = distance between analysis and observations
¢ \( J_c \) = balance constraint
¢ Best forecast is model state which corresponds to minimum cost function
¢ Not yet operational!
HIRLAM boundary conditions

- Domain bordered by Earth surface, space, and global model
- Lateral boundaries prescribed by global host model → all variables prescribed → over-specified!
- Boundary value fields provided by European centre for medium-range weather forecast 4 times a day
- Guest model and host model evolve independently → sharp differences may arise → relaxation scheme
HIRLAM boundary conditions (cont’d)

- Guest model (HIRLAM) fields are relaxed in a relaxation area
  \( \phi_i = (1 - \alpha_i)\phi^G_i + \alpha_i\phi^H_i \)
- Relaxation zone width and weights user defined, default \( n = 10 \) and
  \[ \alpha_i = \frac{1}{2} \left( 1 + \cos \frac{\pi(i - 1)}{n} \right) \]
- Upper boundary condition \( \frac{d\eta}{dt} = 0 \)
- No physical basis, may cause standing waves near upper boundary region
HIRLAM future

‡ Highest priority non-hydrostatic mesoscale models
  ‡ Hydrostatic assumption not valid with finer grids
  ‡ Physics schemes, parameterization
‡ Shorter time-scale
‡ Smaller grid spacing
  ‡ Observation grid mismatch
‡ Coupling mechanisms to e.g. biosphere and chemistry