Non-hydrostatic modelling with ICON

Almut Gassmann
Max Planck Institute for Meteorology
Hamburg, Germany
ICON: tool for NWP and climate applications
Wishes for the project some years ago:

- non-hydrostatic atmospheric model
- dynamics in grid point space
- triangular grid based on the tessellation of an icosahedron
- local zooming with static grid refinement
- transport scheme: conservative, positive definite, efficient
- dynamics conserves mass, energy, potential vorticity
- physics parameterizations from COSMO, ECHAM
- coupling to ocean model, atmospheric chemistry, hydrology, and land model
- common software framework supports different models (ocean, atmosphere; grids)
- modularity, portability
- scalability and efficiency on multicore architectures

from: http://infoskript.de/uploads/pics/Wollmilchsau.jpg
Overview for patchwork talk

1. Non-hydrostatic equation set
2. C-grid discretisation on triangles and hexagons/pentagons
3. Special topics concerning discretisations
   a) SICK (Hollingsworth et al., 1983)
   b) terrain-following coordinates
   c) advection schemes
4. Physics parameterization packages
5. Grid refinement
6. Efficiency, scalability
7. Outlook
Non-hydrostatic atmospheric model - model core formulation

\[
\begin{align*}
\frac{\partial \vec{v}}{\partial t} &= - \frac{\vec{v} \times \vec{q} \vec{v}}{\rho} - \nabla (K + \Phi) - c_{pd} \theta_v \nabla \Pi \\
\frac{\partial \rho}{\partial t} &= - \nabla \cdot (\rho \vec{v}) \\
\frac{\partial \Pi}{\partial t} &= - \frac{R_d \Pi}{c_{vd} \rho \theta_v} \nabla \cdot (\theta_v (\rho \vec{v})) \\
\frac{\partial \rho \theta_v}{\partial t} &= - \nabla \cdot (\theta_v (\rho \vec{v}))
\end{align*}
\]

\(\cdot \rho \vec{v}\) (to obtain energy equ.)

\(\Pi\) = Exner pressure
\(\theta_v\) = virtual pot. temperature
\(\rho\) = density
\(v\) = 3D velocity vector
\(K\) = spec. kinetic energy
\(\Phi\) = geopotential
\(\omega_a\) = 3D abs. vorticity vector
\(R_d\) = gas constant for dry air
\(c_{vd}\) = spec. heat capacity at constant volume for dry air
\(c_{pd}\) = spec. heat capacity at constant pressure for dry air

+ Transport equations for specific moisture quantities.

**Hamiltonian description**

- discretisation of Poisson backets
- symplectic time integration

\[
\frac{\partial F}{\partial t} = \{F, H\}
\]

Almut Gassmann (MPI-M), Hans Herzog (formerly DWD)
Triangular and hexagonal C-grids

\[ \begin{align*}
    j_1 &= j \\
    j_2 &= -\frac{1}{2}j - \frac{\sqrt{3}}{2}i \\
    j_3 &= -\frac{1}{2}j + \frac{\sqrt{3}}{2}i \\
    v_1 + v_2 + v_3 &= 0
\end{align*} \]

\[ \begin{align*}
    i_1 &= i \\
    i_2 &= -\frac{1}{2}i + \frac{\sqrt{3}}{2}j \\
    i_3 &= -\frac{1}{2}i - \frac{\sqrt{3}}{2}j \\
    u_1 + u_2 + u_3 &= 0
\end{align*} \]

\[ \mathbf{v} = u \mathbf{i} + v \mathbf{j} = \frac{2}{3} \left( u_1 \mathbf{i}_1 + u_2 \mathbf{i}_2 + u_3 \mathbf{i}_3 \right) = \frac{2}{3} \left( v_1 \mathbf{j}_1 + v_2 \mathbf{j}_2 + v_3 \mathbf{j}_3 \right) \]

\[ \frac{\partial \alpha}{\partial x_1} + \frac{\partial \alpha}{\partial x_2} + \frac{\partial \alpha}{\partial x_3} = 0. \]
Checkerboard problem
Shallow water model

Fulfillment of the constraint:
No, triangular C-grid
Yes, hexagonal C-grid
with a special tangential wind reconstruction.

Triangular C-grid
Divergence field for linear geostrophic adjustment problem with poorly resolved Rossby deformation radius.

\[ \tilde{v}_1^1 + \tilde{v}_2^2 + \tilde{v}_3^3 = 0. \quad D_{l,u}^t = \pm \frac{4}{3d} (v_1 + v_2 + v_3), \quad \sum_{u \in h} D_{l,u}^t = \sum_{l \in h} D_{l,u}^t. \]

\[ \tilde{u}_1^1 + \tilde{u}_2^2 + \tilde{u}_3^3 = 0. \quad \zeta_{l,u}^t = \mp \frac{4}{3d} (u_1 + u_2 + u_3). \quad \sum_{u \in h} \zeta_{l,u}^t = \sum_{l \in h} \zeta_{l,u}^t. \]

Hexagonal C-grid

\[ \frac{\partial \alpha}{\partial x_1} + \frac{\partial \alpha}{\partial x_2} + \frac{\partial \alpha}{\partial x_3} = 0. \]
Hydrostatic dycore

An internal symmetric computational instability

A. HOLLINGSWORTH\textsuperscript{1}, P. KÅLLBERG\textsuperscript{1}, V. RENNER\textsuperscript{2} and D. M. BURRIDGE\textsuperscript{1}

\textsuperscript{1} European Centre for Medium Range Weather Forecasts, Reading. \textsuperscript{2} Deutscher Wetterdienst, Offenbach am Main, Federal Republic of Germany.

\[ -\mathbf{v} \cdot \nabla \mathbf{v} = -k \eta_z \times \varrho \mathbf{v} - \nabla K \]

Omega (Pa/s) 850hPa

Baroclinic wave test

Vorticity (1/s) 850hPa

spatial resolution $\sim 120$km, hexagonal C-grid model (triangular C-grid model has similar problems)

Almut Gassmann (MPI-M), Günther Zängl (DWD)
Correction for SICK

\[ K = \sum \frac{u_e^2}{6} \]

K: spec. kinetic energy

Omega (Pa/s)
850hPa

Baroclinic wave test (hydrostatic dycore)

Vorticity (1/s)
850hPa

Spatial resolution ~ 120km, hexagonal C-grid model (triangular C-grid model has similar solution)

Almut Gassmann (MPI-M), Günther Zängl (DWD)
Non-hydrostatic dycore
L-grid staggering + terrain-following coordinates

- *interface* levels height-centered between *main* levels
- horizontal pressure gradient:
  - Covariant velocity equations
  - Do not remove background reference profile
  - Care with lower boundary

\[
\frac{\partial u_{\text{orth}}}{\partial t} = \frac{\partial u_{\text{cov}}}{\partial t} - \frac{\partial z}{\partial x} \frac{\partial w}{\partial t}
\]

- *main* levels height-centered between *interface* levels
- horizontal pressure gradient:
  - search for neighboring point in the same height
  - reconstruct Exner function using a Taylor expansion until the second order
Acid test for terrain-following coordinates: Resting atmosphere over a high mountain

Vertical slice model

Spurious vertical velocities remain in the range of mm/s.

Errors do not spoil higher levels.

$N^2 = 10^{-4}/s^2$

35 vertical layers, $dt=6$ sec

For $a < 14$ km, the model becomes unstable.

$→$ SLEVE coordinate

$→$ Filtering of orography

Bell shaped mountain

$H_{max} = 4$ km

$h = \frac{H_{max}}{a} \left( \frac{x-x_c}{a} \right)^2 \frac{3}{2}$

explicit estimate
Tracer advection scheme according to Miura (2007)

Departure region $a_{i\epsilon}$:
approximated by rhomboidally shaped area.
Assumption: $v=\text{const}$ along a given edge

Reconstruction of $q^n(x,y)$:
SGS tracer distribution approximated by 2D polynomial.
Example: linear polynomial (in ICON up to 3rd order)

$$q^R(\bar{x} - \bar{x}_i) = q|_{\bar{x}_i} + \left( \frac{\partial q}{\partial x} \right)^n_{\bar{x}_i} (x - x_i) + \left( \frac{\partial q}{\partial y} \right)^n_{\bar{x}_i} (y - y_i)$$

Integration:
Gauss-Legendre quadrature

Daniel Reinert (DWD)
Deformational flow test case


- Time-varying, analytical flow field \( \vec{V}(\lambda, \phi, t) = \vec{v}(\lambda, \phi)\Psi(t) \)

- Tracer undergoes severe deformation during the simulation

- Flow reverses its course at half time and the tracer field returns to the initial position and shape \( \Psi(t) = \cos(\pi t/T) \)

- Test suite consists of 4 cases of initial conditions, three for non-divergent and one for divergent flows.

Example:
Tracer field for case 1

- R3B4 (≈ 95km)
- CFL≈0.5
- flux limiter

Daniel Reinert (DWD)
Temperature advection and baroclinic wave

Non-hydrostatic hexagonal C-grid model runs without diffusion and different orders of $\theta$-advection:

- 2$^{nd}$ order
- 3$^{rd}$ order
- 4$^{th}$ order

Phase lag with respect to the finest resolution

240 km
120 km
60 km
30 km

Almut Gassmann (MPI-M)
collaboration with Bill Skamarock (NCAR)
Held Suarez test

mean climate of the last 100 days in a run of 300 days for R2B04

Maria-Pilar Ripodas (DWD)
For **aqua-planet simulations** we need additionally features for radiation:

- the diurnal cycle
- ozone climatology

**Tracer transport in both models:**
- **ECHAM:** Lin and Rood (1996) flux-form semi-Lagrangian algorithm (finite volume) with piecewise parabolic reconstruction
- **ICON**
  -- Miura scheme with linear reconstruction (that means second order)
  -- Limiter in the vertical: semi-monotonous slope limiter
  -- Limiter in the horizontal: monotonous flux limiter
### Non-hydrostatic dycore + physics parameterizations

<table>
<thead>
<tr>
<th>Physics</th>
<th>Author(s)</th>
<th>Current status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prognostic Microphysics</td>
<td>Doms et al. (2004), Seifert and Crewell (2008)</td>
<td>Tested</td>
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<tr>
<td>Including prognostic rain and snow</td>
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<tr>
<td>Saturation adjustment</td>
<td>Blahak, Seifert</td>
<td>Tested</td>
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<td>assumption of constant density</td>
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<td>Convection</td>
<td>Tiedtke-Bechtold</td>
<td>Tested</td>
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<tr>
<td>RRTM-Radiation</td>
<td>Taken from ECHAM</td>
<td>Tested</td>
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<tr>
<td>Cloud cover</td>
<td>Köhler</td>
<td>Technical and physical testing</td>
</tr>
<tr>
<td>Turbulent transfer and diffusion</td>
<td>Raschendorfer</td>
<td>Under implementation</td>
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<tr>
<td>Including prognostic TKE</td>
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</tr>
</tbody>
</table>

Kristina Fröhlich, Thorsten Reinhardt, Martin Köhler (DWD)
Non-hydrostatic dycore + physics parameterizations

Baroclinic wave experiment without turbulence parameterization

→ without radiation

← without radiation

Kristina Fröhlich, Thorsten Reinhardt, Martin Köhler (DWD)
Grid refinement

Two-way nesting -- algorithm:

• one time step in parent domain (black)
• interpolation of lateral boundary fields/tendencies
• two time steps in refined domain (red)
• feedback from the fine domain to the parent domain, overwrite the parent values

One-way nesting -- algorithm:

• feedback is turned off
• Davies nudging is performed near the nest boundaries
Grid refinement

Baroclinic wave test: QV (g/kg) at 1.8 km AGL on day 14

Günther Zängl (DWD)
Efficiency and scalability

- Radiation: 63.30%
- Other: 9.86%
- Physics: 14.82%
- Nh solver: 8.81%
- Transport: 3.21%

Graph showing speedup with respect to number of cores:
- Total
- Nh solver
- Physics
- Radiation
- Linear

Authors:
- Rainer Johanni (external)
- Leonidas Linardakis (MPI-M)
- Günther Zängl (DWD)
Outlook

Further steps for ICON

• consolidation of the code (include remaining physics)
• improvement of efficiency, data structure, IO
• data assimilation + ICON
• preoperational runs next year at DWD
• finalizing ICON grid ocean model at MPI-M
• coupled ocean/atmosphere runs by the end of next year