The ICON project: development of a unified model using triangular geodesic grids
ICON: ICOsahedral grid, Nonhdyrostatic unified (NWP+ climate+chemistry) model

- **ICON development team:**

- **Discussions and/or joint work:** N. Botta, F. Giraldo, J. Klemp, R. Klein, D. LeRoux, D. Randall, T. Ringler, H. Tomita
Outline

• Overview of the ICON development project and of the project goals

• Model equations and discretization approach

• Preliminary results of a shallow water model

• Vertical discretization

• Outlook on future work
Desired features for a new model

• **Unique framework** for **large/small scale, lower/upper atmospheric dynamics**

• **Consistency** between **conservative discrete tracer advection and continuity equation**

• **Mass conservative local grid refinement approach without spurious interface effects:** building block for a **multiscale model**
Concept of discretization approach

• Achieve the same **accuracy** and **efficiency** of advanced NWP models…

• …but preserve some **discrete** equivalents of **global** invariants relevant to geophysical flow…

• …and narrow the **gap** with Computational Fluid Dynamics (CFD) models.
Nonhydrostatic, compressible flow

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \]

\[ \frac{\partial \mathbf{u}}{\partial t} + \eta \times \mathbf{u} = -\nabla K - \frac{1}{\rho} \nabla p - \nabla \Phi \]

\[ \frac{\partial (\rho \varepsilon)}{\partial t} + \nabla \cdot [(\rho \varepsilon + p) \mathbf{u}] = -\nabla \cdot \mathbf{R} \]
Shallow water flow

\[
\frac{\partial h}{\partial t} + \nabla \cdot (Hu) = 0
\]

\[
\frac{\partial u}{\partial t} + (\zeta + f)k \times u + \nabla (gh + K) = 0
\]

\[
\frac{\partial (cH)}{\partial t} + \nabla \cdot (cHu) = 0
\]
Geodesic icosahedral grids

- Solve the pole problem
- Special case of Delaunay triangulation
- Local grid refinement
- Multiscale modelling
Data structures for grid representation

Indirect addressing that preserves data locality

Parallelization: horizontal data decomposition
Consistent fluxes at coarse/fine interface

Spatial discretization

- Finite volume discretization with **triangular** control volumes:
  - triangular C grid

- Delaunay Voronoi property
Spatial discretization, properties

• Vorticity at triangle vertices: discrete Helmholtz decomposition (Nicolaides 1992)

• No spurious vorticity production

• Raviart Thomas reconstruction of velocity, average onto edge for tangential component

\[ u(x) = u_0 + \alpha x \]
Discrete shallow water system

\[
\frac{\partial h_i}{\partial t} = - \sum_{l \in \mathcal{C}(i)} u_l H_l \sigma_{i,l}
\]

\[
\frac{\partial u_l}{\partial t} = - (\zeta + f)_l v_l - \delta_v (K + gh)_l
\]

\[
\frac{\partial (c_i H_i)}{\partial t} = - \sum_{l \in \mathcal{C}(i)} c_i u_l H_l \sigma_{i,l}
\]
Discrete wave dispersion analysis

• Stationary geostrophic solution, no spurious pressure modes

• Two physical gravity wave modes

• Two spurious gravity wave modes: frequencies always higher than physical ones
Dispersion plot, physical mode

- Less good wavenumber space than quad C
- Zero group velocity at high wavenumbers
Discrete global invariants

• Mass conservation, **consistent** discretizations of continuity equation and tracer transport

• Potential vorticity conservation, no spurious vorticity production

• Potential **enstrophy** conserving variant, energy conserving variant: **Sadourny JAS 1975**
Random initial data, f plane

Relative vorticity after 1000 days integration with random initial data (numerical test carried out by Todd Ringler, CSU)
Semi-implicit time discretization

\[ u_{l}^{n+1} = u_{l}^{n} - \Delta t (\zeta^{n+1/2} + f)_{l} v_{l}^{n+1/2} \]

\[ - \Delta t \delta_{v} (\tilde{K}^{n+1/2} + gh^{n+1/2})_{l} \]

\[ h_{i}^{n+1} = h_{i}^{n} - \Delta t \sum_{l \in C(i)} u_{l}^{n+1/2} H_{l}^{n} \sigma_{i,l} \]
Idealized vortex, day 2

Maximum resolution 40 km

Maximum gravity wave Courant number 7

(dt=900 s)
Rossby Haurwitz wave, day 10
Flow over a mountain, day 10
Flow over a mountain: relative vorticity, day 10

Colour shading: ICON model results
Black contours: NCAR reference spectral model
Height field error at day 15

\[ dx \approx 120 \text{ km}, \ dt = 900 \text{ s} \]

\[ dx \approx 60 \text{ km}, \ dt = 90 \text{ s} \]
Error at day 15, convergence test

TEST CASE 5. L2 NORM AT DAY 15. NCAR SSWM T213/dt=90s as reference. NCAR SSWM: T42, T63, T106 and T170; ICON: refinement levels 4 to 8, optimized grids;

*black dashed line: reference as in NCAR Tech Notes: T213/dt=560s
“Shallowness is the greatest vice”

Oscar Wilde
Options for vertical discretization

- **Hybrid pressure** vertical coordinate + new horizontal discretization: preliminary 3D hydrostatic ICON model

- **Terrain following** normalized height coordinate + new horizontal discretization: *first choice* for operational nonhydrostatic model

Nonhydrostatic coastal modelling

• Results: G. Lang, Bundesanstalt für Wasserbau, Germany
• Numerical model: Casulli and Walters, IJNMF, 2000
Cut cells + RBF interpolation

Terrain following model (LM)  Cut cell nonhydrostatic dynamical core (ARPA Bologna)
Computational advantages of cut cells

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<th>COMM time solver</th>
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Simulations run by D. Cesari (ARPA Bologna)
Future work

• Shallow water model on locally refined grids: optimized data structure and parallelization

• Hydrostatic, 3D model on locally refined grids

• Coupling to existing MPI-M/DWD physics packages, impact of spurious modes on simulations with full physics

• Sensitivity of results to local refinement