A finite-volume module for the IFS

Christian Kühnlein, Piotr Smolarkiewicz, Willem Deconinck, Mats Hamrud, George Mozdzynski, Joanna Szmelter, Nils Wedi

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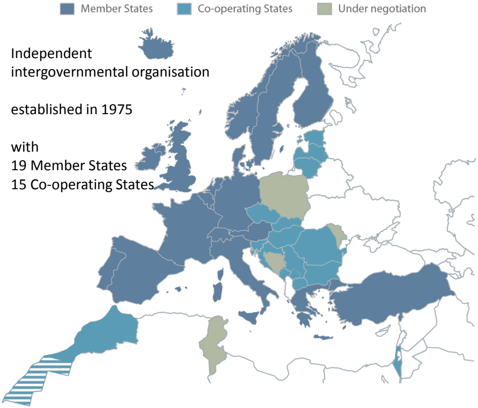
European Centre for Medium-Range Weather Forecasts



Independent intergovernmental organisation

established in 1975

with
19 Member States
15 Co-operating States

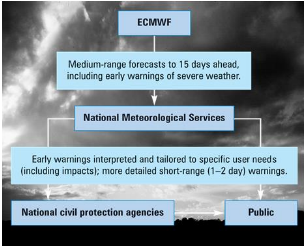
ECMWF is based in Reading (∼50 km west of London), United Kingdom

ECMWF's core mission is to:

→ produce global medium-range numerical weather forecasts and monitor the earth-system;

→ carry out scientific research to improve forecast skill;

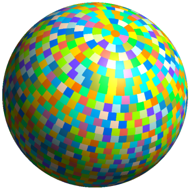
→ maintain an archive of meteorological data.



Operational configuration of IFS at ECMWF

Current operational configuration of the Integrated Forecasting System (IFS):

- hydrostatic primitive equations (nonhydrostatic option available; see Benard et al. 2014)
- hybrid $\eta - p$ vertical coordinate (Simmons and Burridge, 1982)
- spherical harmonics discretisation in horizontal (Wedi et al., 2013)
- finite-element discretisation in vertical (Untch and Hortal, 2004)
- semi-implicit semi-Lagrangian (SISL) integration scheme (Temperton et al. 2001, Diamantakis 2014)
- cubic-octahedral ("T_{co}") grid (Wedi, 2014, Malardel et al. 2016, Smolarkiewicz et al. 2016)
- HRES: $T_{co}1279$ (O1280) with $\Delta_h \sim 9\,\mathrm{km}$ and 137 vertical levels
- ENS (1+50 perturbed members): $T_{co}639$ (O640) with $\Delta_h \sim 16\,\mathrm{km}$ and 91 vertical levels



IFS parallel decomposition with 1600 MPI tasks

→ in the near future, spectral approach (as in IFS) is assumed to remain highly competitive in terms of time-to-solution

→ however, uncertainties concerning global data-rich communications with spectral approach in terms of future HPC architectures

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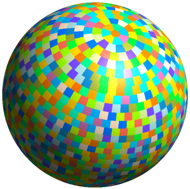

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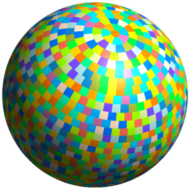

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Finite-volume module (FVM) for the IFS

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⇒ PantaRhei project at ECMWF: prepare the mathematical-numerical technology for future cloud-permitting earth-system models

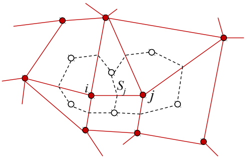
Enhance/complement IFS with a finite-volume module (FVM) that introduces:

- → numerical methods operating on compact stencils and using nearest-neighbour communications with thin halos
- → all-scale nonhydrostatic governing equations
- → local and global conservation
- → flexible meshes
- → robustness and accuracy with regard to complex, steep orography

ECMWF

FVM formulation – key features

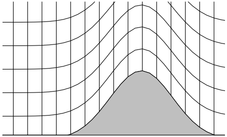
- fully compressible Euler equations in geospherical coordinates
- generalised height-based terrain-following vertical coordinate
- fully unstructured median-dual finite-volume discretisation in horizontal (Szmelter and Smolarkiewicz 2010)
- structured finite-difference discretisation in vertical
- all prognostic variables are co-located
- two-time-level semi-implicit integration scheme with 3d implicit acoustic, buoyant and rotational modes (Smolarkiewicz, Kühnlein, Wedi JCP 2014)
- preconditioned generalised conjugate residual iterative solver for elliptic problems arising in semi-implicit integration schemes
- Eulerian advection with non-oscillatory MPDATA scheme (Smolarkiewicz and Szmelter 2005)
- octahedral reduced Gaussian grid (FVM formulation not restricted to this grid!)



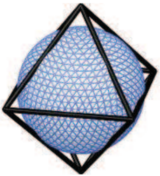
median-dual finite-volume approach

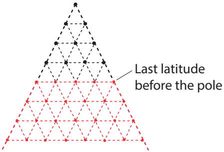
$$\int_\Omega \nabla\cdot\mathbf{A} = \int_{\partial\Omega} \mathbf{A}\cdot\mathbf{n} = \frac{1}{\mathcal{V}_i}\sum_{j=1}^{l(i)} A_j^{\perp} S_j$$

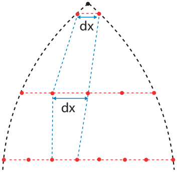
dual volume: $\mathcal{V}_i$, face area: S_j

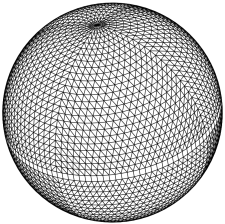


Octahedral reduced Gaussian grid









- suitable for spherical harmonics transforms applied in spectral IFS
  - $\rightarrow$ Gaussian latitudes $\Rightarrow$ Legendre transforms
  - $\rightarrow$ nodes on latitudes according octahedral rule (see above) $\Rightarrow$ Fourier transforms
- quasi-uniform resolution over the sphere
- FVM develops median-dual mesh around nodes of octahedral grid
- spectral IFS and FVM can operate on same horizontal grid

$\rightarrow$ Malardel et al. ECMWF Newsletter 2016, Smolarkiewicz et al. JCP 2016

$\rightarrow$ operational at ECMWF with HRES and ENS since March 2016

- FVM formulation is not restricted to this grid
- FVM relies on Atlas framework (developed at ECMWF) for parallel data structures and mesh generator

FVM moist compressible Euler equations

$$\frac{\partial \mathcal{G}\rho}{\partial t} + \nabla \cdot (\mathbf{v}\mathcal{G}\rho) = 0$$

$$\frac{\partial \rho\mathcal{G}\mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{v}\rho\mathcal{G}\mathbf{u}) = \rho\mathcal{G}\left(-\Theta_d \widetilde{\mathbf{G}}\nabla\varphi' - \frac{\mathbf{g}}{\theta_a}\left(\theta' + \theta_a(\varepsilon q_v' - q_c - q_p)\right) - \mathbf{f}\times(\mathbf{u} - \Upsilon_C \mathbf{u}_a) + \mathbf{M}\right)$$

$$\frac{\partial \rho\mathcal{G}\theta'}{\partial t} + \nabla \cdot (\mathbf{v}\rho\mathcal{G}\,\theta') = \rho\mathcal{G}\left(-\widetilde{\mathbf{G}}^T\mathbf{u}\cdot\nabla\theta_a - \frac{L\,\theta}{c_p T}(C_d + E_p) + \mathcal{H}\right)$$

$$\varphi' = c_p\theta_0\left[\left(\frac{R_d}{p_0}\rho\theta(1 + q_v/\epsilon)\right)^{R_d/c_v} - \pi_a\right]$$

$$\frac{\partial \rho\mathcal{G}q_v}{\partial t} + \nabla \cdot (\mathbf{v}\rho\mathcal{G}q_v) = \rho\mathcal{G}\left(-C_d - E_p + D_{q_v}\right)$$

$$\frac{\partial \rho\mathcal{G}q_c}{\partial t} + \nabla \cdot (\mathbf{v}\rho\mathcal{G}q_c) = \rho\mathcal{G}\left(C_d - A_p - C_p + D_{q_c}\right)$$

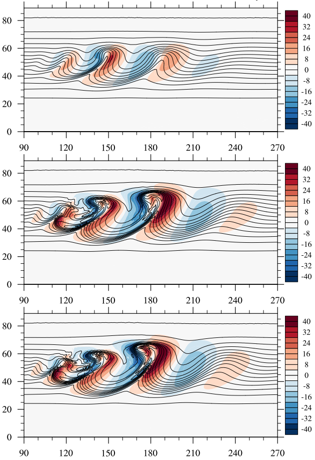
$$\frac{\partial \rho\mathcal{G}q_p}{\partial t} + \nabla \cdot (\mathbf{v}\rho\mathcal{G}q_p) = \rho\mathcal{G}\left(A_p + C_p + E_p + D_{q_p}\right) - \nabla\cdot(\mathbf{v}_p\rho\mathcal{G}q_p)$$

with:

$$\Theta_d := \frac{\theta\,(1 + q_v/\epsilon)}{\theta_0\,(1 + q_t)} \equiv \frac{\theta_d}{\theta_0} \qquad \Upsilon_C \equiv \frac{\theta}{\theta_a} \qquad \epsilon := \frac{R_d}{R_v} \qquad \varepsilon = 1/\epsilon - 1 \qquad \mathbf{v} = \widetilde{\mathbf{G}}^T\mathbf{u}$$

→ "a" subscript denotes ambient state which satisfies subset of full equations, "0" subscript refers to constant reference, all primed variables are deviations with respect to the ambient state ($\psi' = \psi - \psi_a \quad \psi = u, v, w, \theta, ..$)

Baroclinic instability (Jablonowski and Williamson, 2006) with FVM (from top: anelastic, pseudo-incompressible, compressible)



→ Generic nonhydrostatic formulation with consistent options:

- ⋆ fully compressible Euler equations (default)
- ⋆ pseudo-incompressible (Durran, JAS 1989)
- ⋆ anelastic (Lipps and Hemler, JAS 1982)

$$\frac{\partial \mathcal{G}\varrho}{\partial t} + \nabla\cdot(\mathbf{v}\mathcal{G}\varrho) = 0$$

$$\frac{\partial \mathcal{G}\varrho\mathbf{u}}{\partial t} + \nabla\cdot(\mathbf{v}\mathcal{G}\varrho\mathbf{u}) = -\mathcal{G}\varrho\left(\Theta\widetilde{\mathbf{G}}\nabla\varphi' + \mathbf{g}\Upsilon_B\frac{\theta'}{\theta_b} + \mathbf{f}\times(\mathbf{u}-\Upsilon_C\mathbf{u}_a) + \mathbf{M}\right)$$

$$\frac{\partial \mathcal{G}\varrho\theta'}{\partial t} + \nabla\cdot\left(\mathbf{v}\mathcal{G}\varrho\theta'\right) = -\mathcal{G}\varrho\left(\widetilde{\mathbf{G}}^T\mathbf{u}\cdot\nabla\theta_a\right)$$

with optional coefficients:

$$\varrho := \left[\rho(\mathbf{x},t),\ \rho_b\frac{\theta_b(z)}{\theta_0},\ \rho_b(z)\right], \quad \varphi' := \left[c_p\theta_0\pi',\ c_p\theta_0\pi',\ c_p\theta_b\pi'\right]$$

$$\Theta := \left[\frac{\theta}{\theta_0},\frac{\theta}{\theta_0},1\right],\ \Upsilon_B := \left[\frac{\theta_b(z)}{\theta_a(\mathbf{x})},\frac{\theta_b(z)}{\theta_a(\mathbf{x})},1\right],\ \Upsilon_C := \left[\frac{\theta}{\theta_a(\mathbf{x})},\frac{\theta}{\theta_a(\mathbf{x})},1\right]$$

Further reading

TECHNICAL MEMORANDUM

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The modelling infrastructure of the Integrated Forecasting System: Recent advances and future challenges

N.P. Wedi, P. Bauer, W. Deconinck, M. Diamantakis, M. Hamrud, C. Kühnlein, S. Malardel, K. Mogensen, G. Mozdzynski, P.K. Smolarkiewicz

Research Department

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A finite-volume module for simulating global all-scale atmospheric flows

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ABSTRACT

The paper documents the development of a global nonhydrostatic finite-volume module designed to enhance an established spectral-transform based numerical weather prediction (NWP) model. The module adheres to NWP standards, with formulation of the governing equations based on the classical meteorological latitude–longitude spherical framework. In the horizontal, a bespoke unstructured mesh with finite-volumes built about the reduced Gaussian grid of the existing NWP model circumvents the notorious stiffness in the polar regions of the spherical framework. All dependent variables are co-located, accommodating both spectral-transform and grid-point solutions at the same physical locations. In the vertical, a uniform finite-difference discretisation facilitates the solution of intricate elliptic problems in thin spherical shells, while the pliancy of the physical vertical coordinate is delegated to generalised continuous transformations between computational and physical space. The newly developed module assumes the compressible Euler equations as default, but includes reduced soundproof PDEs as an option. Furthermore, it employs semi-implicit forward-in-time integrators of the governing PDE systems, akin to but more general than those used in the NWP model. The module shares the equal regions parallelisation scheme with the NWP model, with multiple layers of parallelism hybridising MPI tasks and OpenMP threads. The efficacy of the developed nonhydrostatic module is illustrated with benchmarks of idealised global weather.

1. Introduction

Numerical weather prediction (NWP) has achieved high proficiency over the past 30 years. This owes much to advancements in computer hardware, observational networks and data assimilation techniques as well as numerical methods for integrating hydrostatic primitive equations (HPE). One particular numerical approach embraced widely by NWP combines semi-implicit time stepping with semi-Lagrangian advection (SISL) and with spectral-transform spatial discretisation of the governing HPE [46]. The SISL time stepping enables integrations with Courant numbers of the fluid flow and wave motions much larger than unity, whereas the spectral-transform discretisation facilitates the efficient solution of elliptic equations induced by the SISL approach. Moreover, it circumvents the computational expense of the latitude–longitude (lat–lon) co-

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