3.1 OpenIFS: Dynamical Core

Hydrostatic and non-hydrostatic dynamics

Hydrostatic equilibrium describes the atmospheric state in which the upward directed pressure gradient force (the decrease of pressure with height) is balanced by the downward-directed gravitational pull of the Earth. On average the Earth’s atmosphere is always close to hydrostatic equilibrium. This has been used to approximate the Euler equations underlying weather prediction models and successfully applied in NWP and climate prediction. Non-hydrostatic dynamical effects start to become important below horizontal scales of about 10km.

The ECMWF IFS model uses a hydrostatic dynamical core for all forecasts.

Dynamical core

The dynamical core of IFS is hydrostatic, two-time-level, semi-implicit, semi-Lagrangian and applies spectral transforms between grid-point space (where the physical parametrizations and advection are calculated) and spectral space. In the vertical the model is discretised using a finite-element scheme. A reduced Gaussian grid is used in the horizontal.

The evolution equations of the IFS are a terrain following mass-based vertical coordinate (Simmons and Burridge, 1981), solving the hydrostatic, shallow-atmosphere equations (Ritchie et al., 1995). The solution procedure uses the spectral transform method. The first spectral transform model was introduced into operations at ECMWF in April 1983. Spectral transforms on the sphere involve discrete spherical harmonics transformations between physical (gridpoint) space and spectral (spherical-harmonics) space. This technique has been successfully combined with semi-implicit time stepping (Robert et al., 1972), where the resulting Helmholtz problem is solved in spectral space, and the unconditional stability of semi-Lagrangian (SL) advection (Temperton et al., 2001), where the only limiting factor on the time step is the magnitude of local truncation errors.

The IFS also has extra configurations available for research experiments that are not used operationally. An example is the dry Eulerian dynamics used for low resolution testing.

The horizontal resolution of IFS has approximately doubled every 8 years, with approximately 9km global grid resolution (and an effective resolution of ~36km) in 2016.

Spectral representation

The IFS uses a spectral transform method to solve numerically the equations governing the spatial and temporal evolution of the atmosphere. The idea is to fit a discrete representation of a field on a grid by a continuous function. This is achieved by expressing the function as a truncated series of spherical harmonics:

\[
A(\lambda, \mu, \eta, t) = \sum_{l=0}^{T} \sum_{m=-l}^{l} \psi_{lm}(\eta, t) Y_{lm}(\lambda, \mu) = \sum_{l=0}^{T} \sum_{m=-l}^{l} \psi_{lm}(\eta, t) P_{l}^{m}(\mu) e^{im\lambda}
\]

where \(\lambda\) and \(\mu\) are the longitude and latitude of the grid point, \(T\) is the spectral truncation number and \(Y_{lm}\) are the spherical harmonic functions which are products of the associated Legendre polynomials, \(P_{l}^{m}\), and the Fourier functions, \(e^{im\lambda}\).

The spectral coefficients \(\psi_{lm}\) are computed from the discrete values known at each point of a Gaussian grid on the sphere by

- a Fast Fourier Transform in the zonal direction followed by
- a slow/fast Legendre transform in the meridional direction.

At each time step in the IFS:

- derivatives, semi-implicit correction and horizontal diffusion are computed in spectral space;
- explicit dynamics, semi-Lagrangian advection and physical parametrizations are computed in grid point space.

The representation in grid point space is on the Gaussian grid. The grid point resolution is determined by the spectral truncation number, \(T\).
Linear, quadratic and cubic grids

The relationship between the spectral resolution, governed by the truncation number $T$, and the grid resolution depends on the number of grid points at which the shortest wavelength field is represented. For a grid with $2N$ points between the poles (so $4N$ grid points in total around the globe) the relationship is:

- **linear grid:** the shortest wavelength is represented by 2 grid points $4N \approx 2(T_L + 1)$
- **quadratic grid:** the shortest wavelength is represented by 3 grid points $4N \approx 3(T_Q + 1)$
- **cubic grid:** the shortest wavelength is represented by 4 grid points $4N \approx 4(T_C + 1)$

Until the implementation of IFS cycle 18r5 on 1 April 1998, the IFS used a quadratic grid. The introduction of the two-time level semi-Lagrangian numerical scheme at IFS cycle 18r5 made possible the use of a linear Gaussian grid reflected by the $T_L$ notation. The linear grid has been used since then, up to IFS cycle 41r1. For the planned resolution upgrade, the cubic representation is used with the notation $T_C$ used to indicate the spectral truncation.

Keeping the spectral truncation constant but increasing the number of grid points used to represent the shortest wavelength increases the effective grid point resolution.

This allows for a more accurate representation of diabatic forcings and advection, which is then controlled through truncation in spectral space. In addition the cubic grid has no aliasing, less numerical diffusion and provides more realistic surface fields. It also substantially improves mass conservation.

References

The IFS hydrostatic dynamical core is described in more detail in the following references: