A Massively-Parallel Framework for Finite-Volume Simulation of Global Atmospheric Dynamics

Willem Deconinck [1]   Mats Hamrud [1]   Piotr K. Smolarkiewicz [1]
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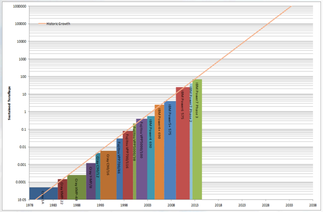
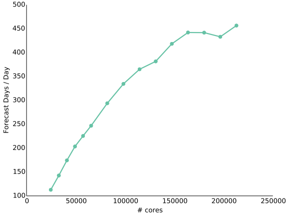
2014 PDEs Workshop

T3999 ∼5km global resolution spectral transform model IFS operational in ∼2024 scales well into petascale





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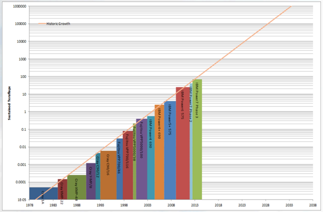

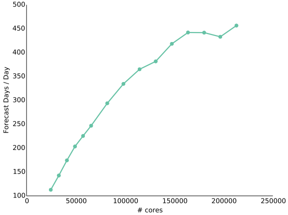

Beyond exascale (∼2030, at T7999): gridpoint method with local communication

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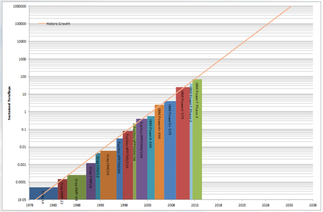

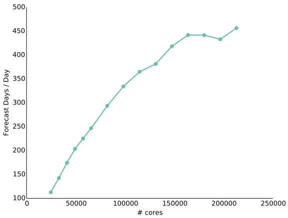

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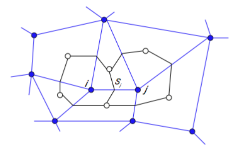

MPDATA

- horizontally unstructured
- vertically structured
- lon-lat domain
- 2^{nd} order in time and space

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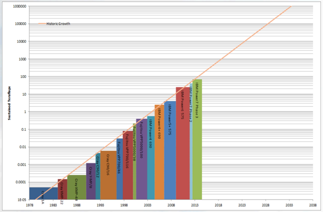

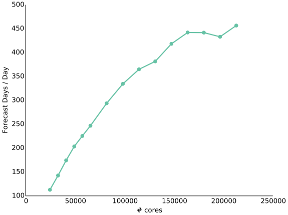

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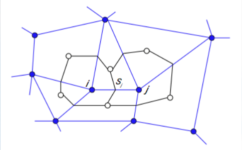

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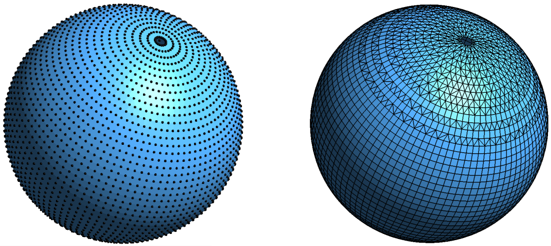

Evolutionary introduction into IFS

Developments and Results

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Development of flexible dynamic data structure

- Object Oriented C++ design with Fortran interface
- MPI / Halo-exchanges
- interpolation, mesh-generation, product delivery

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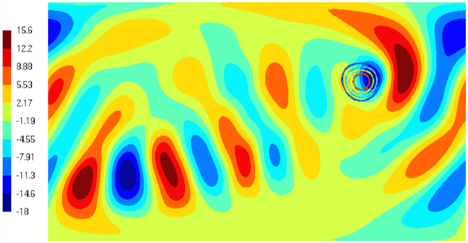

Orographic zonal flow, meridional velocity

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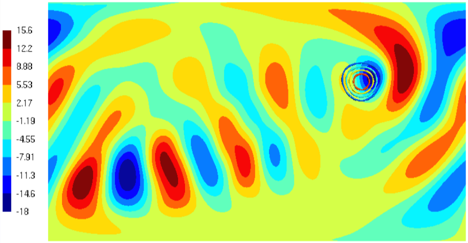

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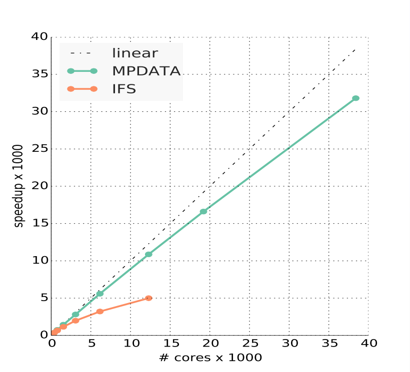

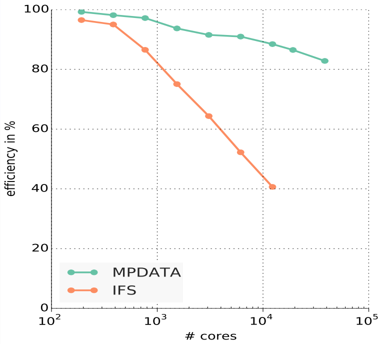

T2047 (∼10km) with 137 isentrope levels – scaling to 40000 cores

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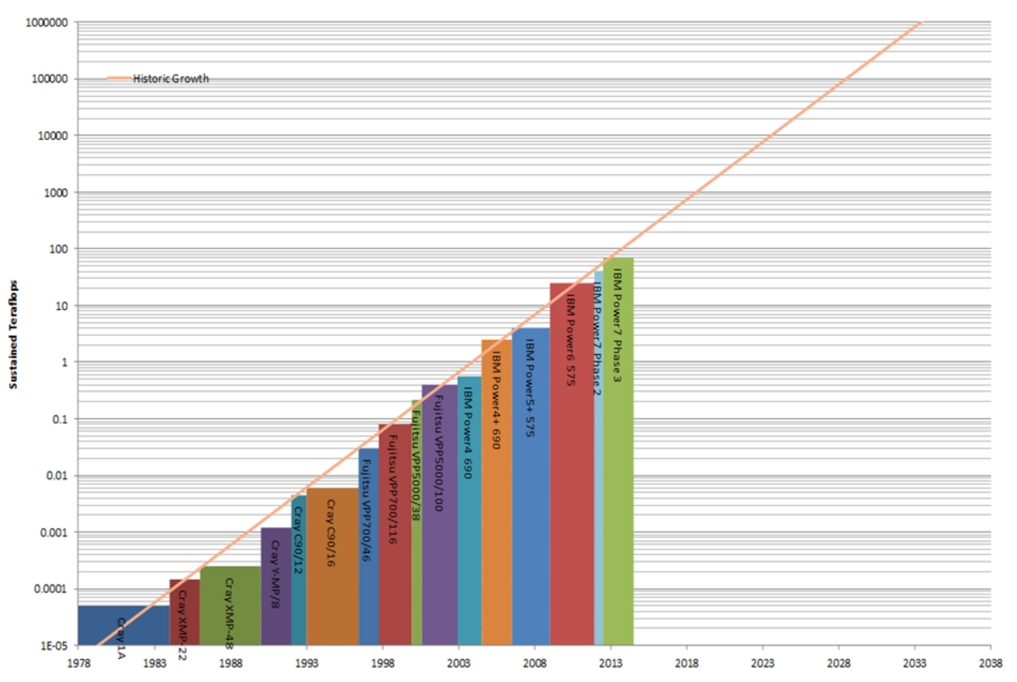
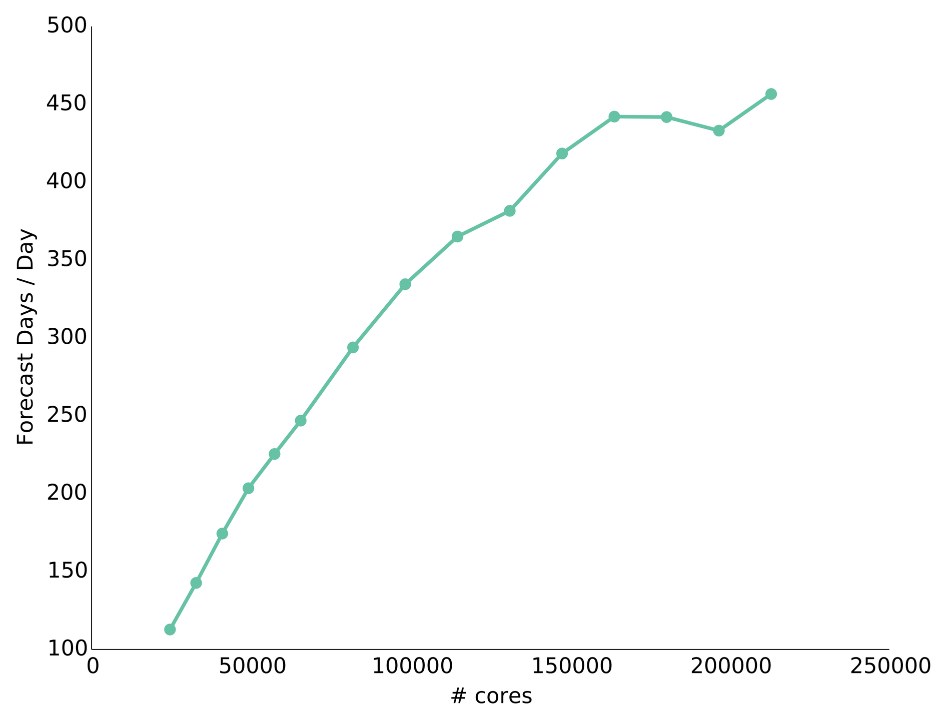
Scalability of Current IFS Dynamical Core



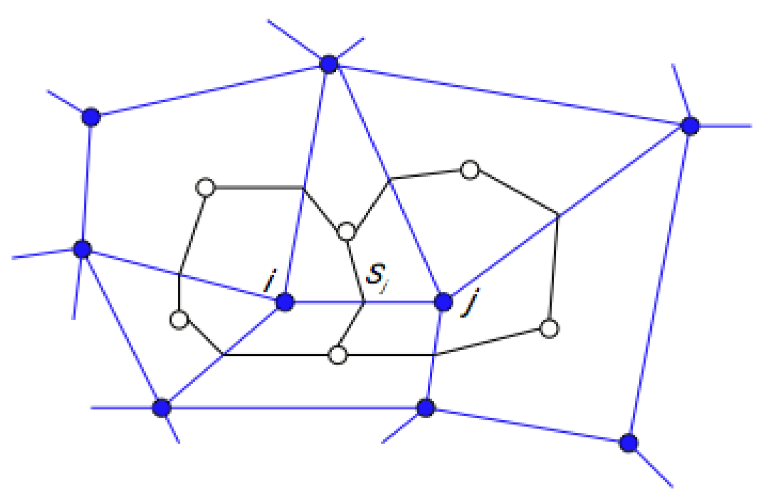
5km horizontal resolution with 137 levels



- We will reach Exa-scale in ∼2030
- Spectral Transform Method does not scale to Exa-scale because of global communications
- Semi-Lagrangian time-stepping implementation is non-conservative

Alternative Dynamical Core: Unstructured Edge-based Finite Volume MPDATA

- Non-oscillatory forward-in-time scheme, capable of accomodating a wide range of scales and conservation problems
- Unstructured prismatic meshes allow irregular spatial resolution and enhancement of polar regions.
- Formulation for time-dependent non-orthogonal curvilinear coordinates on the manifold.

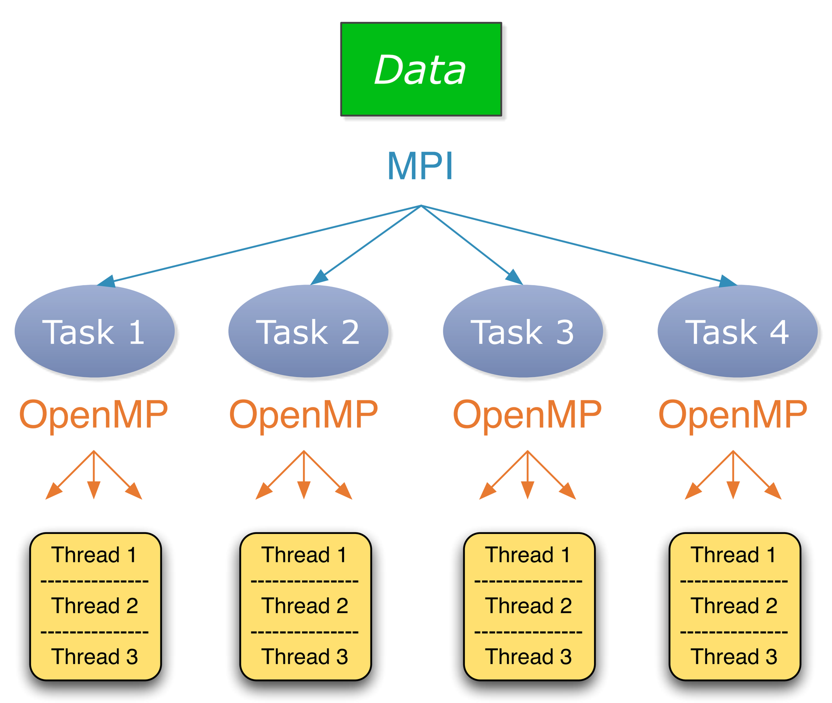


$$\frac{\partial G\psi}{\partial t} + \nabla \cdot (G\mathbf{v}^*\psi) = GR$$

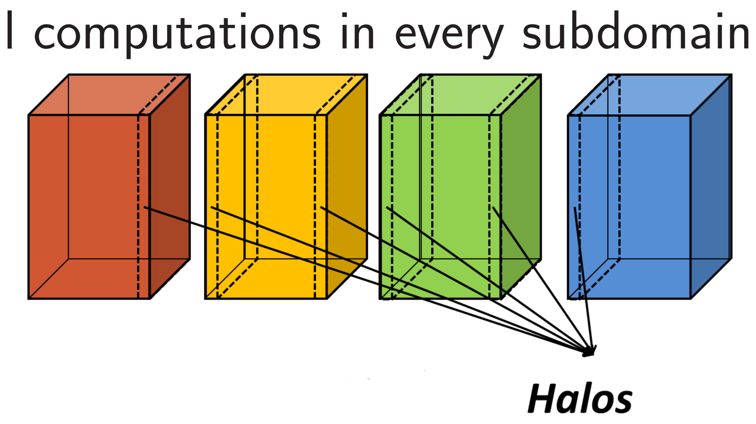
See Szmelter and Smolarkiewicz (2010, JCP), for further discussion.

Massively Parallel Implementation

- Multiple levels of parallelism



- Local computations in every subdomain

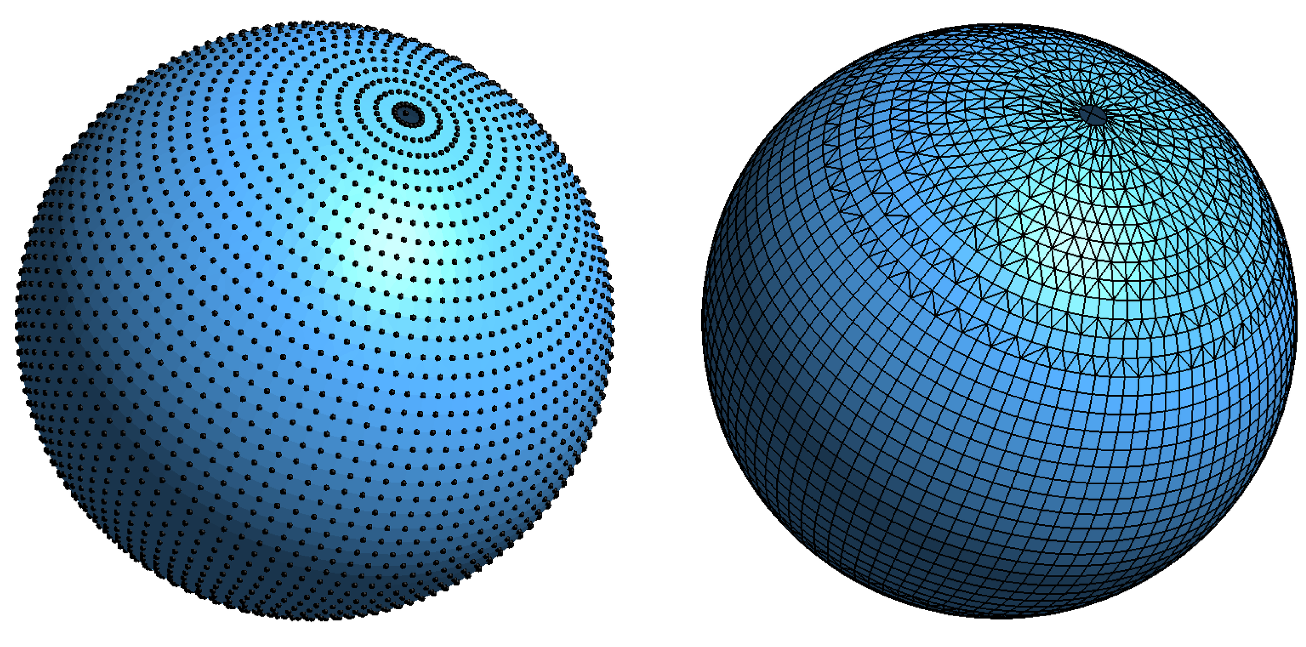


- Optimal Equal-Area Domain decomposition

- Small halo needs to be exchanged with surrounding subdomains for Distributed Memory algorithms
- Shared Memory parallelisation avoids further subdivision of subdomains
- Structured treatment of vertical direction discounts cost of horizontal indirect addressing

Evolutionary Introduction into IFS

- Construction of unstructured mesh using same data points as used by IFS' Spectral Transform Method
- Integration with ECMWF's infrastructure for archiving, post-processing, visualisation



Flexible Dynamic Framework

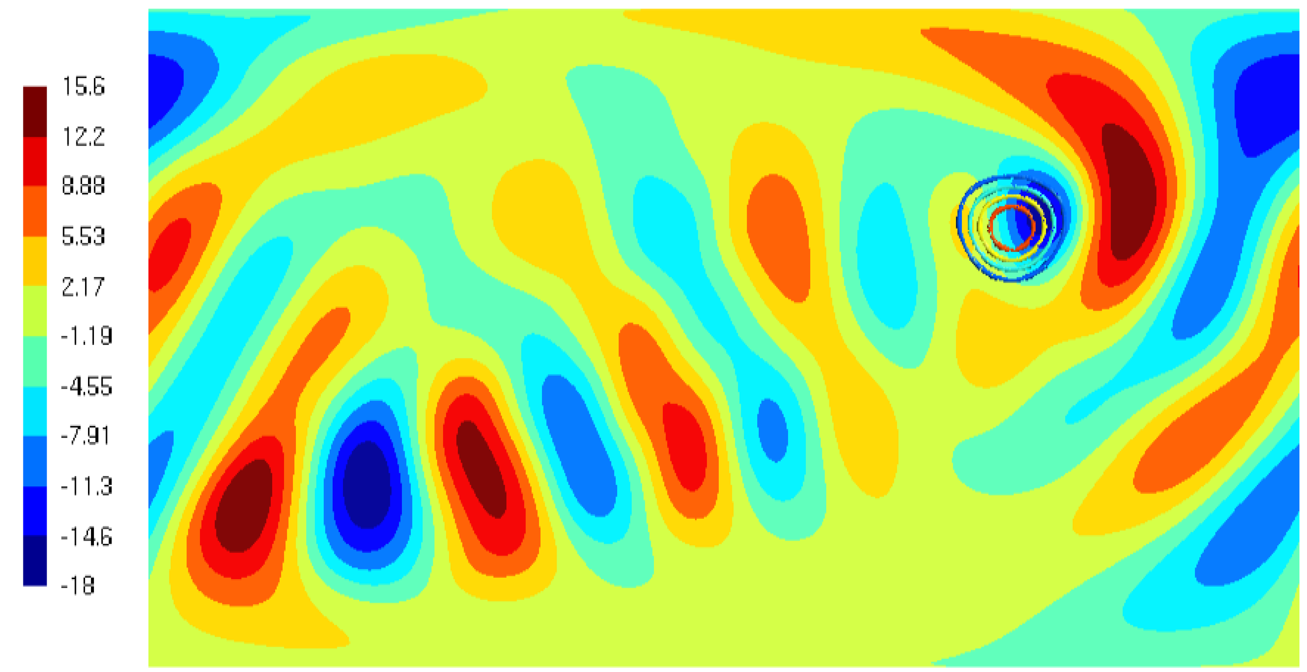
- Complex requirements for unstructured meshes
- Handling of distributed memory parallelisation
- Mesh specific routines: construction of dual mesh, periodicity, reading/writing fields, interpolation
- Multiple meshes to handle multigrid implementations
- Object Oriented Design using C++:
  - Hierarchical nesting of topological objects
  - Meshes, Field Sets, Fields
  - Multiple Halo-Exchange patterns
- Fortran Interface allows direct access to internal data

Shallow Water Equations on the Sphere

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

$$\frac{\partial G\mathcal{Q}_x}{\partial t} + \nabla \cdot (G\mathbf{v}^*\mathcal{Q}_x) = G\left(-\frac{g}{h_x}\mathcal{D}\frac{\partial H}{\partial x} + f\mathcal{Q}_y - \frac{1}{G\mathcal{D}}\frac{\partial h_x}{\partial y}\mathcal{Q}_x\mathcal{Q}_y\right)$$

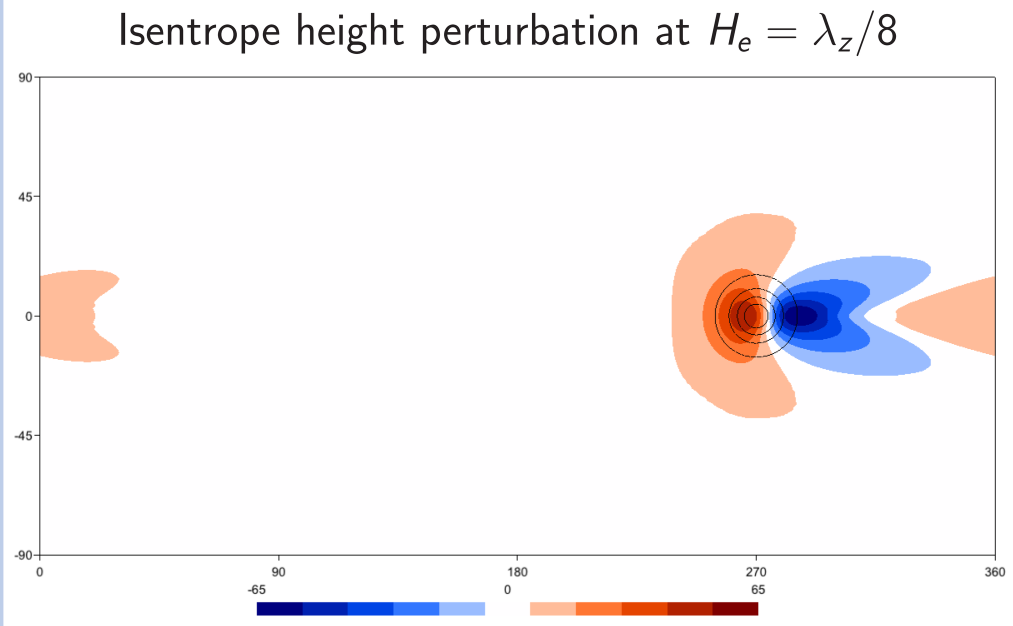
$$\frac{\partial G\mathcal{Q}_y}{\partial t} + \nabla \cdot (G\mathbf{v}^*\mathcal{Q}_y) = G\left(-\frac{g}{h_x}\mathcal{D}\frac{\partial H}{\partial x} + f\mathcal{Q}_y - \frac{1}{G\mathcal{D}}\frac{\partial h_x}{\partial y}\mathcal{Q}_x\mathcal{Q}_y\right)$$



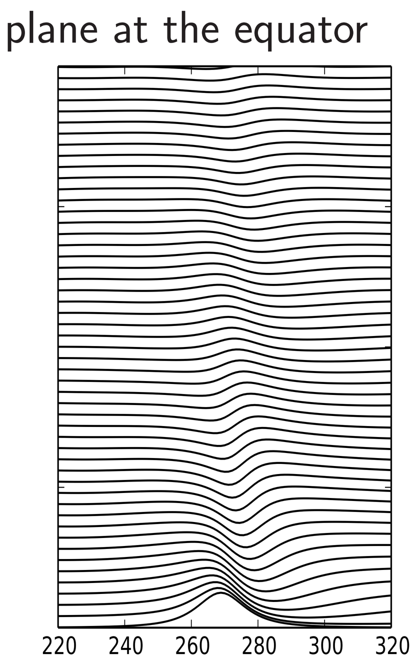
Meridional wind-component for flow over 2km mountain at mid-latitudes; result obtained using Reduced Gaussian mesh with 16km resolution.

3D Hydrostatic Equations in Isentropic Coordinates

Froude Number = 2, Zontal wind U = 10 m/s, Brunt-Väisälä frequency = 0.04
Isentrope height perturbation at $H_e = \lambda_z/8$

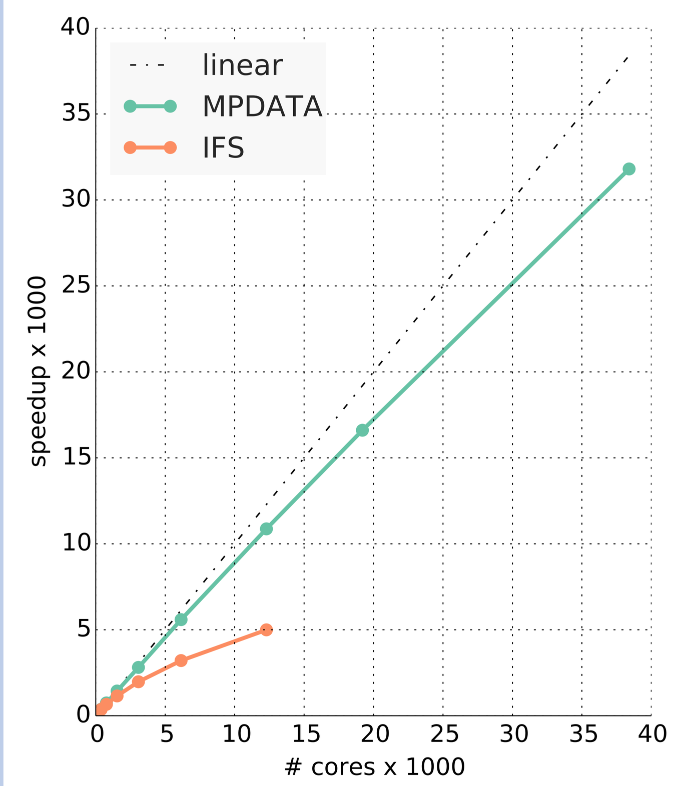


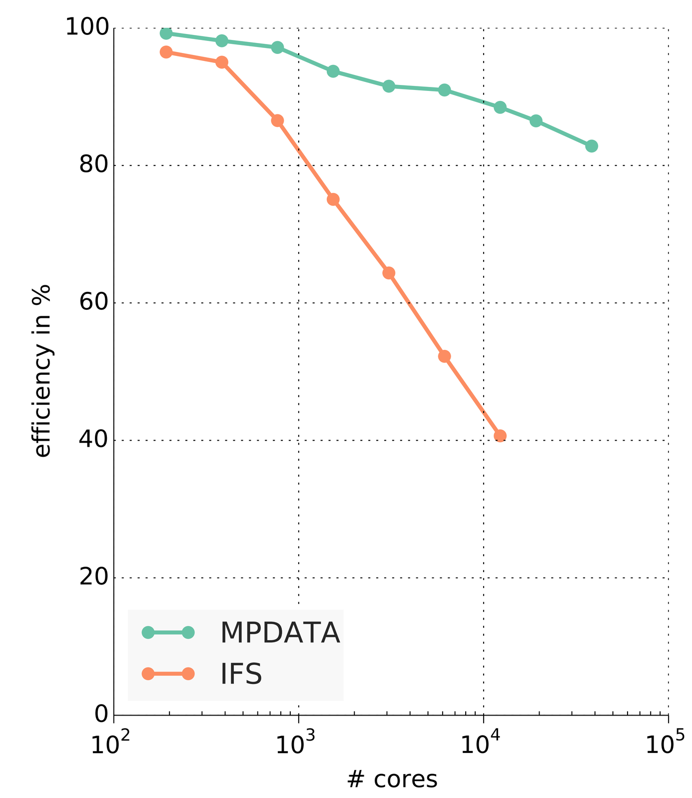
Isentropes in a vertical plane at the equator



Result obtained using Reduced Gaussian mesh with 1km horizontal resolution, and 40m vertical resolution on a small planet with radius 64km.

Parallel Scaling results





Scaling results obtained with 10km Reduced Gaussian mesh and 137 Levels.

Acknowledgements

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