Increasing Horizontal Resolution in Global NWP and Climate Simulations

Illusion or Panacea?

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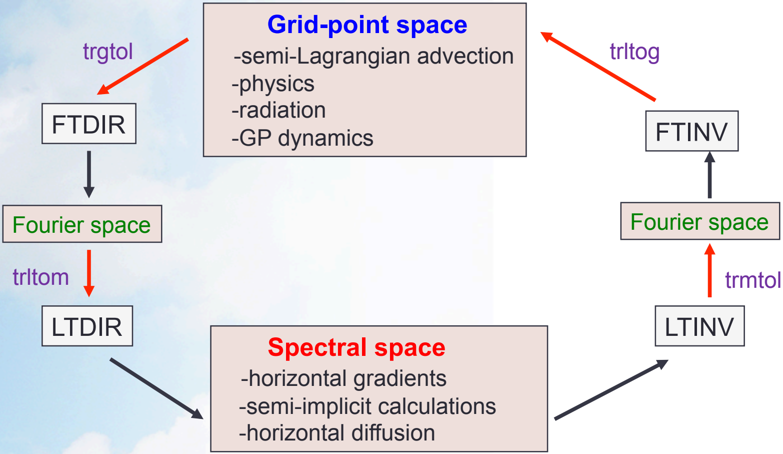
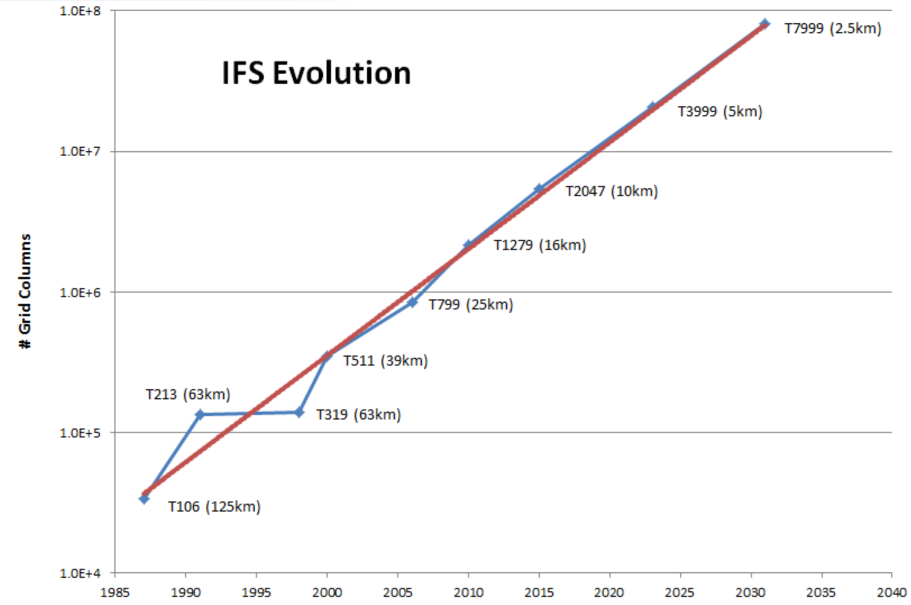
- Medium-Range ~10 days ahead
- IFS: Global NWP model
- 1279 spectral wave lengths
  ~16km horizontal resolution
- 137 levels vertically
- Run model in less than 1 hour
- 51 ensemble forecasts for confidence interval

- double resolution every 8 years
- by 2015: ~10km horizontal resolution

Spectral Transform Model



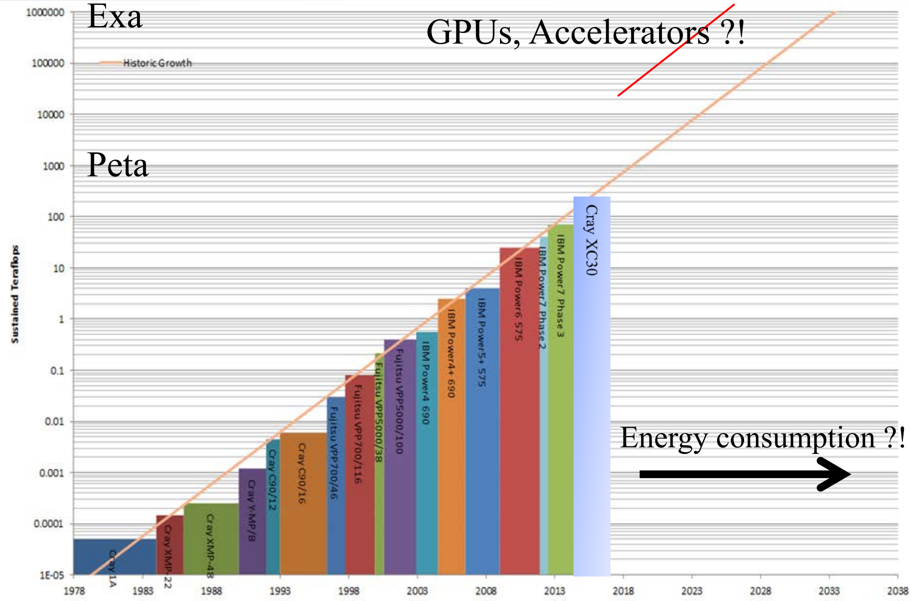


IFS Evolution
Grid Columns
1.0E+8
1.0E+7
1.0E+6
1.0E+5
1.0E+4
1985
1990
1995
2000
2005
2010
2015
2020
2025
2030
2035
2040
T7999 (2.5km)
T3999 (5km)
T2047 (10km)
T1279 (16km)
T799 (25km)
T511 (39km)
T213 (63km)
T319 (63km)
T106 (125km)

IFS model resolution	Envisaged Operational Implementation	Grid point spacing (km)	Time-step (seconds)	Estimated number of cores[1]
T1279 H[2]	2013 (L137)	16	600	2K
T2047 H	2014-2015	10	450	6K
T3999 NH[3]	2023-2024	5	240	80K
T7999 NH	2031-2032	2.5	30-120	1-4M

1 – a gross estimate for the number of 'IBM Power7' equivalent cores needed to achieve a 10 day model forecast in under 1 hour (~240 FD/D), system size would normally be ~10 times this number.
2 – Hydrostatic Dynamics
3 – Non-Hydrostatic Dynamics

Still feasible to obtain Exaflop?



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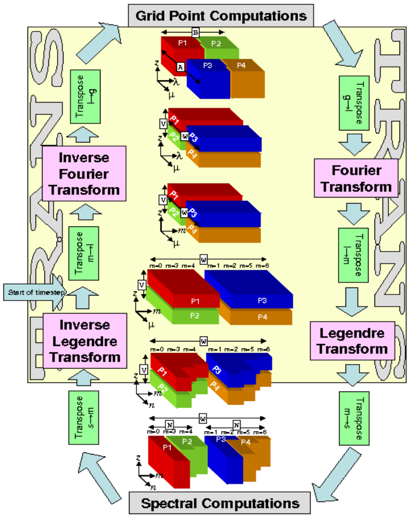
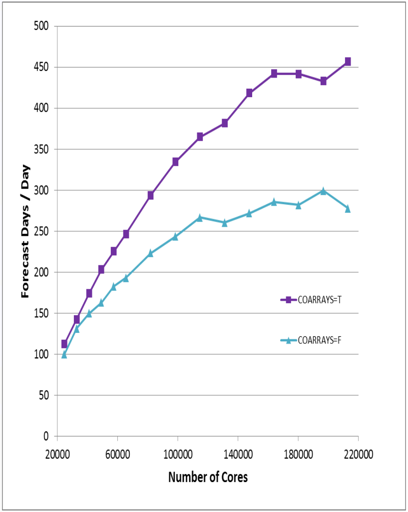
How does IFS scale?

Time step flow



T3999 L137 performance



Overlapping communication and computations helps!

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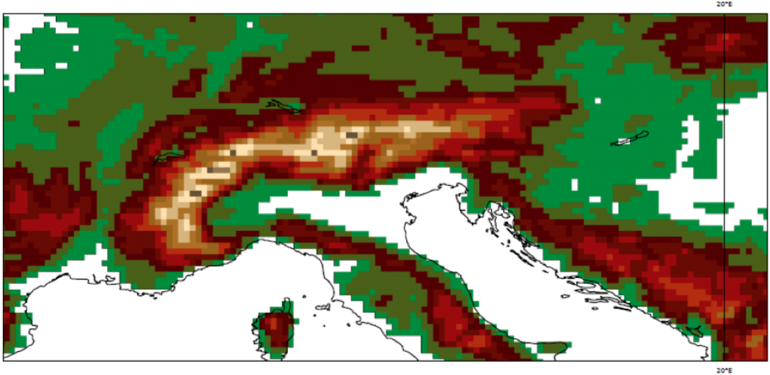
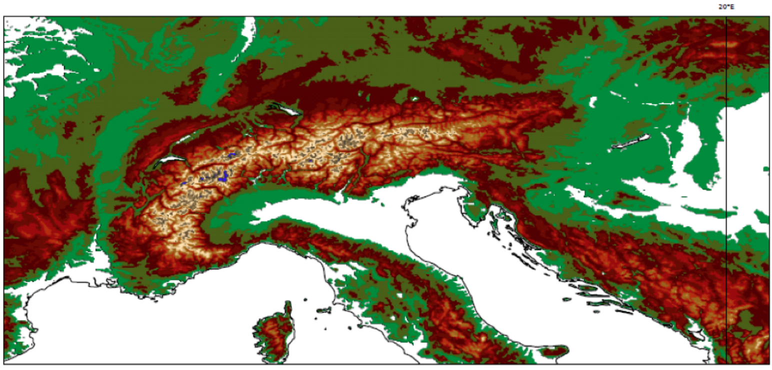
Orography – T1279 (16km)



Alps

Orography – T7999 (2.5km)



Alps

Concurrence of events

Increased Resolution

- Resolved convection
- Non-hydrostatic effects
- Less predictable scales

Not necessarily improved forecasts

Assess and Quantify Forecast uncertainty

- Estimation of initial state
- Imperfect model assumptions

Novel Computer Architectures

- Energy efficient Massively parallel computing
- Accelerator technology (GPU, coprocessors, ...)
- Disruptive software developments

Rethink modelling strategy

We need deeper understanding of multi-scale interactions at ultra-high *global* resolution

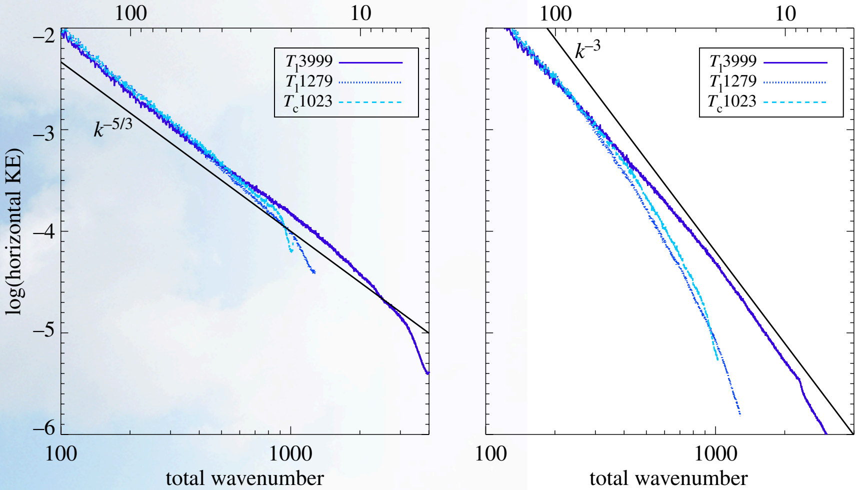
- Effective resolution compared to observations: 6 to 8 Δx

Increase gridpoint resolution, without increasing spectral resolution

- Truncating spectral wave numbers
  $\equiv$ filtering poorly resolved waves
- Dramatically cheaper spectral transforms.
- Controlled aliasing errors

How does this trade-off influence the effective resolution and scores?

1. Decrease spectral resolution with constant grid-point resolution:
   $\rightarrow$ Neutral or Improved scores
2. Increase grid-point resolution with constant spectral resolution:
   $\rightarrow$ Significant improvement



Comparison of global spectra after 5 days of simulation for the resolutions T_c1023 and T_l1279 at the lowest model level ∼10 m height (left) and at a mid-tropospheric model level ∼500 hPa (right)

T_l (linear grid) : 2N + 1 points
T_c (cubic grid) : 4N + 1 points

Explanation

Similar to Large Eddy Simulation with Explicit Filter

- Dynamics are computed with truncated (filtered) more accurately resolved fields.
- Aliasing errors are controlled
- Physical parametrizations are computed relatively more accurately.
- Semi-Lagrangian time-stepping grid-point interpolation is more acccurate.

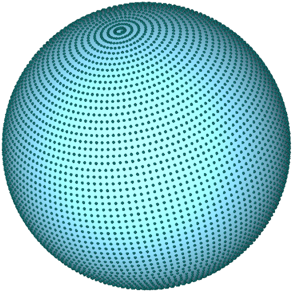
Further possible improvements with technology to compute local gridpoint derivatives

- Opening avenues for improved physical parameterisations and local turbulence closures
- Conservative transport of passive tracers

Grid-point derivatives for Reduced Gaussian Grid?

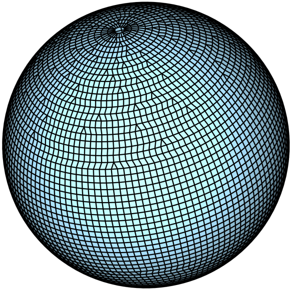
Reduced Gaussian Grid

- Uniform distribution in zonal direction
- Gaussian distribution in meridional direction
- Progressively reduce number points towards poles



Cannot be used for Finite Difference schemes directly.

- Create unstructured mesh about Reduced Gaussian Grid points
- Discretize using element-based or edge-based methods



Atlas project

A parallel, flexible and dynamic data structure framework

- Both structured and unstructured meshes
- Object-Oriented design in C++ with Fortran 2003 interface
- A new basis for development of alternative scalable dynamical cores
  $\rightarrow$ Compact stencil space discretisation
  $\rightarrow$ Nearest neighbour communication

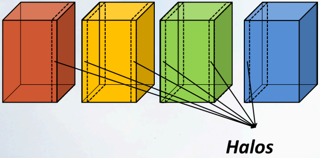
Noteworthy capabilities

- mesh generation / mesh reading / mesh writing / interpolation
- Input/Output of fields
- Parallelisation (halo-exchange, gather, distribute)
  - Domain decomposition algorithm
  - Halo construction algorithm

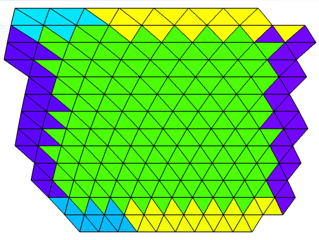
Atlas project

Parallelisation

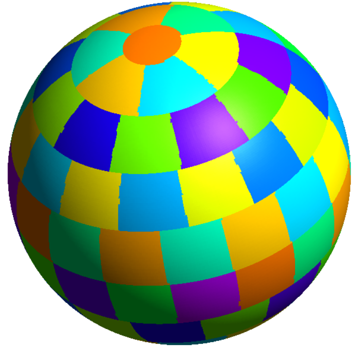
- Local computations in every subdomain



- Halo computation algorithm



- Optimal Equal-Area Domain decomposition



PantaRhei project

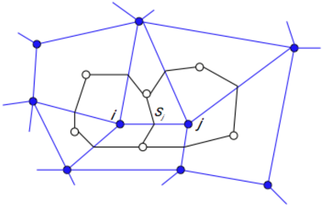
- Fortran 2003 project
- Built on Atlas framework
- Unstructured Edge-based Finite Volume scheme
  → MPDATA advection – explicit
  → Elliptic solver – implicit forcing
- Hydrostatic equations
  → 2D: Shallow Water Equations
  → 3D: Isentropic / Isopycnic coordinates
- Non-hydrostatic equations (3D)
  → Anelastic
  → Pseudo-Incompressible
- Structured treatment of vertical direction
- Hybrid MPI / OpenMP parallelisation

MPDATA – Szmelter and Smolarkiewicz (2010, JCP)

Multidimensional Positive Definite Advection Transport Algorithm

$$\frac{\partial \psi}{\partial t} + \frac{\partial}{\partial x}(u\psi) = \frac{\partial}{\partial x}\left(K\frac{\partial \psi}{\partial x}\right) \quad \text{with} \quad K = \frac{(\delta x)^2}{2\,\delta t}(|U| - U^2)$$

- 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.



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

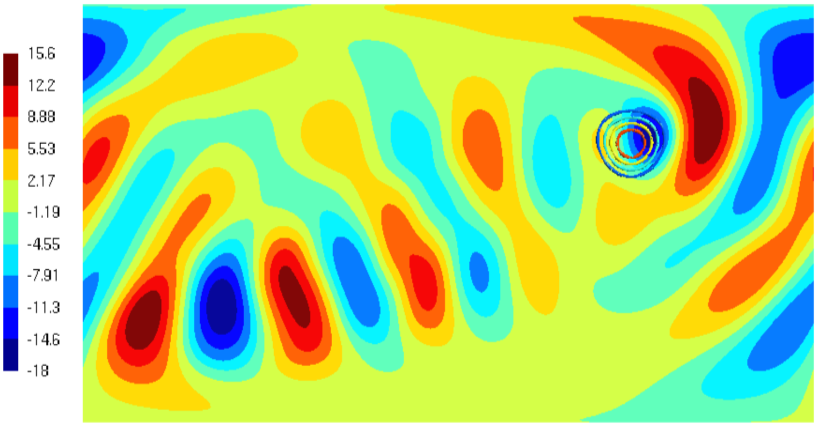
Shallow Water Equations on the Sphere

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

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

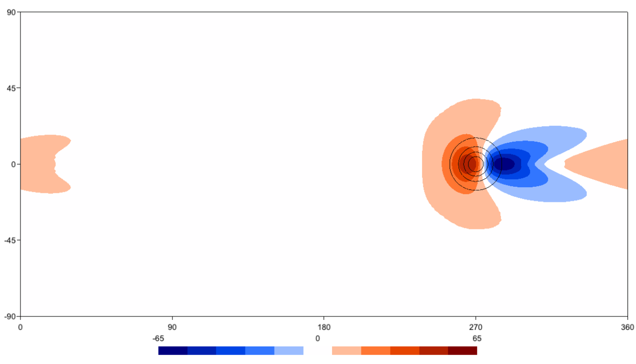
$$\frac{\partial G\mathcal{Q}_y}{\partial t} + \nabla \cdot (G\mathbf{v}^*\mathcal{Q}_y) = G\left(-\frac{g}{h_x}\mathcal{D}\frac{\partial H}{\partial x} + f\mathcal{Q}_y - \frac{1}{G\mathcal{D}}\frac{\partial h_x}{\partial y}\mathcal{Q}_x\mathcal{Q}_y\right)$$

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

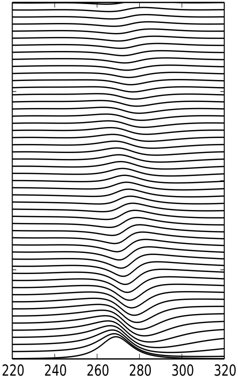


3D Hydrostatic Equations in Isentropic Coordinates

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

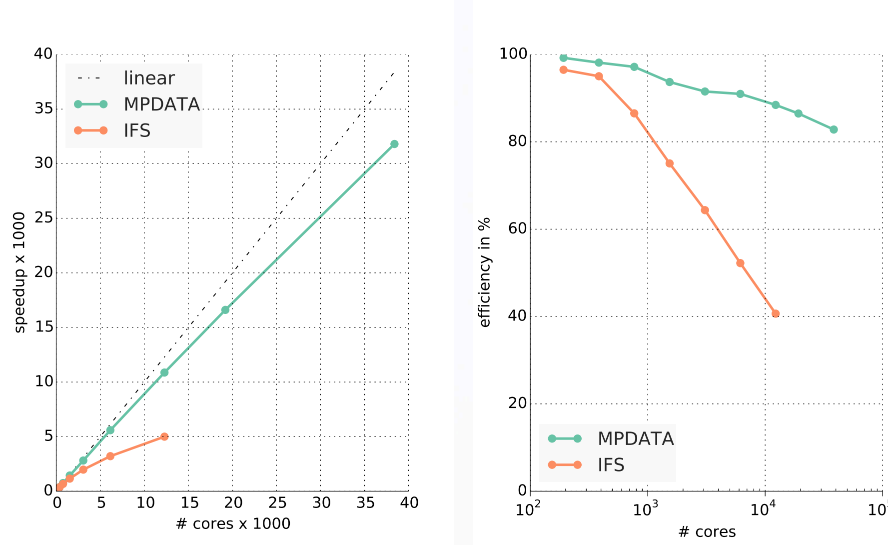


Isentropes in a vertical plane at the equator



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

Parallel Scaling results – Dynamics only!



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

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Conclusions

- Horizontal resolution increases in NWP and climate prediction are likely to continue to provide improvements in forecast quality and offer new opportunities for uncertainty estimation.
- Blunt increases are not a panacea without adjusting the numerical techniques applied and are likely to be unaffordable or, worse, they may not lead to the desired improvements.
- Alternative dynamical cores based on nearest-neighbour communication might provide answers to scalability issues involved with spectral transformations
- Preliminary work on an MPDATA based dynamical core on unstructured meshes has started, showing promising results
- Using unstructured mesh with same gridpoints as the spectral model provides evolutionary aspect with a hybrid spectral/gridpoint model.

Thank you for your attention!

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