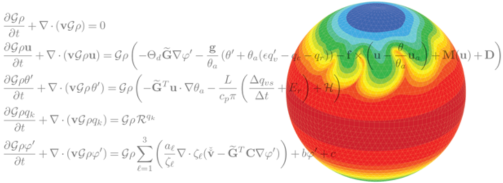
Simulation in the greyzone with the Finite-Volume Module of the IFS

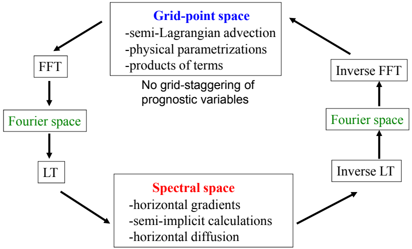
Christian Kühnlein, Sylvie Malardel, Piotr Smolarkiewicz
ECMWF colleagues and ESCAPE partners

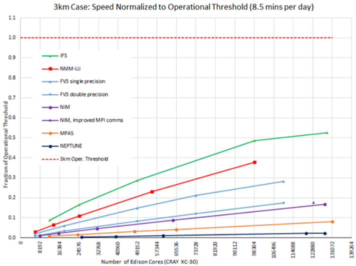


ECMWF

Operational configuration of the Integrated Forecasting System at ECMWF

Schematic of spectral-transform method in IFS

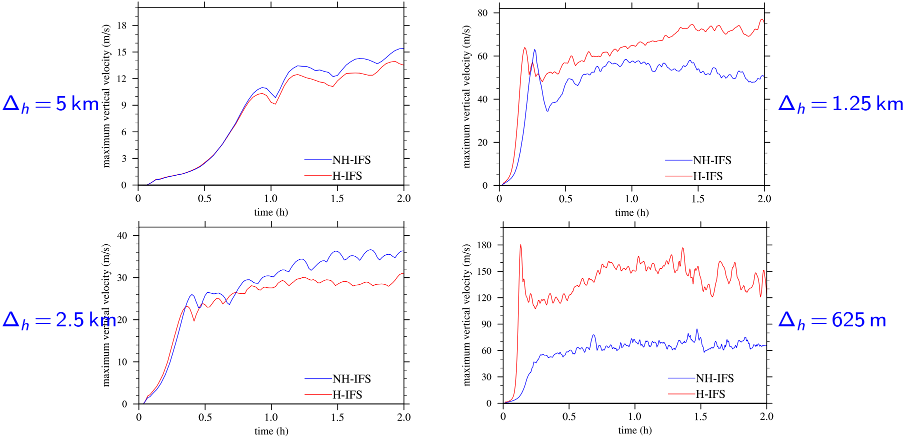




Current operational configuration of the IFS:

- hydrostatic primitive equations (nonhydrostatic option available; see Benard et al. 2014)
- hybrid $\eta - p$ terrain-following vertical coordinate (Simmons and Burridge, 1982)
- semi-implicit semi-Lagrangian (SISL) integration scheme (Temperton et al. 2001, Diamantakis 2014) $\rightarrow$ permits long time steps!
- cubic-octahedral ("TCo") grid (Wedi, 2014, Malardel et al. 2016)
- HRES: TCo1279 (O1280) with $\Delta_h \sim 9$ km and 137 vertical levels
- ENS (1+50 perturbed members): TCo639 (O640) with $\Delta_h \sim 18$ km and 91 vertical levels

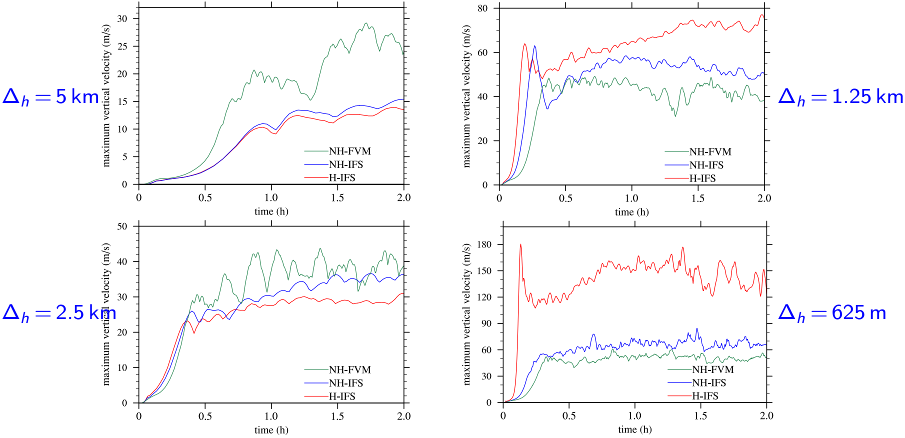
Idealized convective storm (Klemp et al. 2015) on a small planet (1/25 reduced) with H and NH formulation of IFS: From what horizontal grid spacing Δ_h appear significant differences?



→ H-IFS and NH-IFS use Forbes et al. 2011 microphysics and similar numerical configurations, in particlar TCo grid, FD in vertical, ICI, no explicit diffusion, no convection scheme)

Nonhydrostatic dynamics

Idealized convective storm (Klemp et al. 2015) on a small planet (1/25 reduced) with H and NH formulation of IFS and NH-FVM:

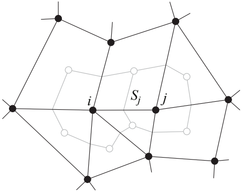


→NH-FVM uses smaller time steps and different microphysics parametrisation!

FVM formulation – key features

Finite-Volume Module of the IFS:

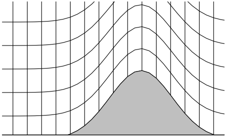
- deep-atmosphere nonhydrostatic Euler equations in geospherical framework (Szmelter and Smolarkiewicz 2010; Smolarkiewicz et al. 2016; Smolarkiewicz, Kühnlein, Grabowski 2017; Kühnlein, Malardel, Smolarkiewicz *in prep.*)
- generalised height-based terrain-following vertical coordinate
- hybrid of horizontally-unstructured median-dual finite-volume with vertically-structured finite-difference/finite-volume discretisation (Szmelter and Smolarkiewicz 2010; Smolarkiewicz et al. 2016)
- 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)
- non-oscillatory finite-volume Eulerian MPDATA scheme (Smolarkiewicz and Szmelter 2005; Kühnlein and Smolarkiewicz 2017; Kühnlein, Klein, Smolarkiewicz *in prep.*)



median-dual finite-volume approach

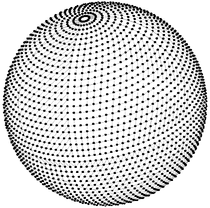
$$\int_\Omega \nabla\cdot\mathbf{A} = \int_{\partial\Omega} \mathbf{A}\cdot\mathbf{n} = \frac{1}{\mathcal{V}_i}\sum_{j=1}^{l(i)} A_j^{\perp} S_j$$

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

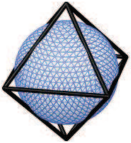


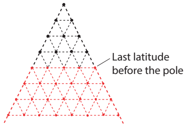
terrain-following coordinate

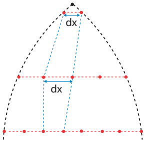
Octahedral reduced Gaussian grid



Nodes of octahedral grid 'O24'







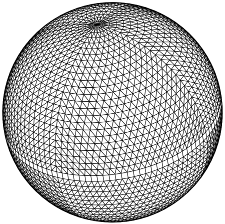
- octahedral reduced Gaussian grid (*octahedral grid* of size OX)
- suitable for spherical harmonics transforms applied in spectral IFS
  - $\rightarrow$ Gaussian latitudes $\Rightarrow$ Legendre transforms
  - $\rightarrow$ equidistant distribution of nodes along latitudes following octahedral rule $\Rightarrow$ Fourier transforms
- FVM develops median-dual mesh around nodes of octahedral grid

$\Rightarrow$ finite-volume and spectral-transform IFS can operate on same quasi-uniform 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

- Mesh generator and parallel data structures for FVM provided by ECMWF's Atlas framework (Deconinck et al. 2017)



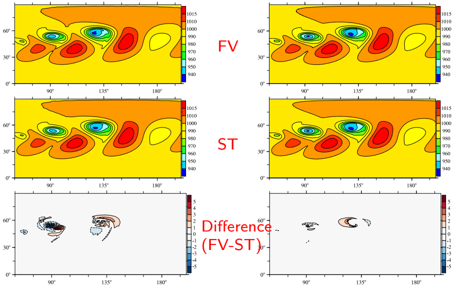
Primary mesh about nodes of octahedral grid in FVM

Finite-volume and spectral-transform solutions in IFS

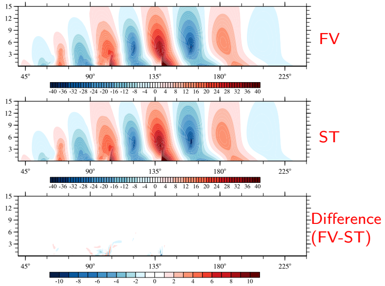
Dry baroclinic instability (Ullrich et al. 2014) with FVM and spectral-transform IFS (ST):

Surface pressure (hPa) at day 10

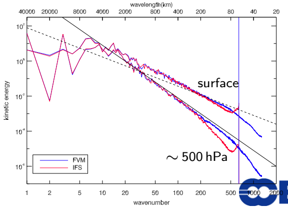
O160/TCo159, $\Delta_h \approx 62$ km O640/TCo639, $\Delta_h \approx 18$ km



V@53N O640/TCo639, $\Delta_h \approx 18$ km, day 10



Kinetic energy spectra O640/TCo639 ($\Delta_h \approx 18$ km), day 15

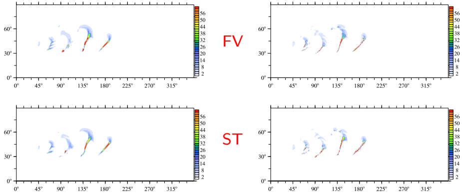


- Finite-volume solutions achieve accuracy of established spectral-transform IFS
- Nonoscillatory finite-volume MPDATA advection scheme features implicit regularisation at the grid scale

Moist baroclinic instability with FVM and spectral-transform IFS (ST) with large-scale condensation and diagnostic precipitation:

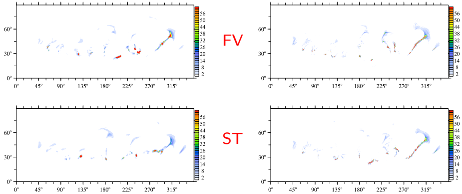
Precipitation (mm/day) at day 10

O160/TCo159, $\Delta_h \approx 62$ km   O640/TCo639, $\Delta_h \approx 18$ km

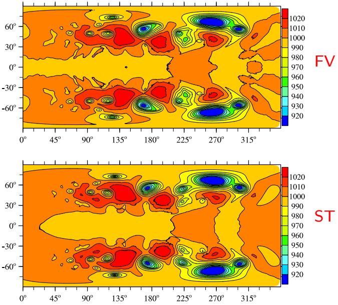


Precipitation (mm/day) at day 15

O160/TCo159, $\Delta_h \approx 62$ km   O640/TCo639, $\Delta_h \approx 18$ km



Surface pressure O640/TCo639, $\Delta_h \approx 18$ km, day 15

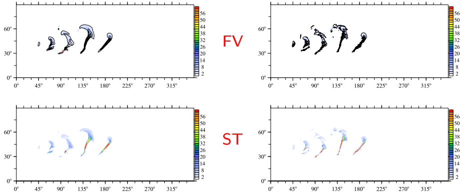


- Finite-volume solutions achieve accuracy of established spectral-transform IFS for moist flows

Moist baroclinic instability with FVM and spectral-transform IFS (ST) with large-scale condensation and diagnostic precipitation:

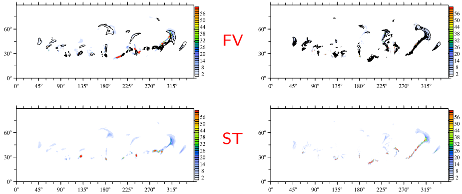
Precipitation (mm/day) at day 10

O160/TCo159, $\Delta_h \approx 62$ km — O640/TCo639, $\Delta_h \approx 18$ km

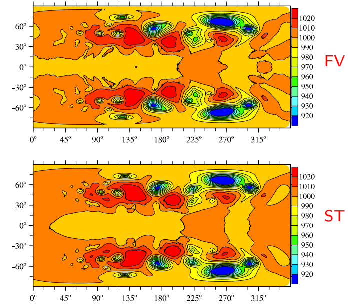


Precipitation (mm/day) at day 15

O160/TCo159, $\Delta_h \approx 62$ km — O640/TCo639, $\Delta_h \approx 18$ km

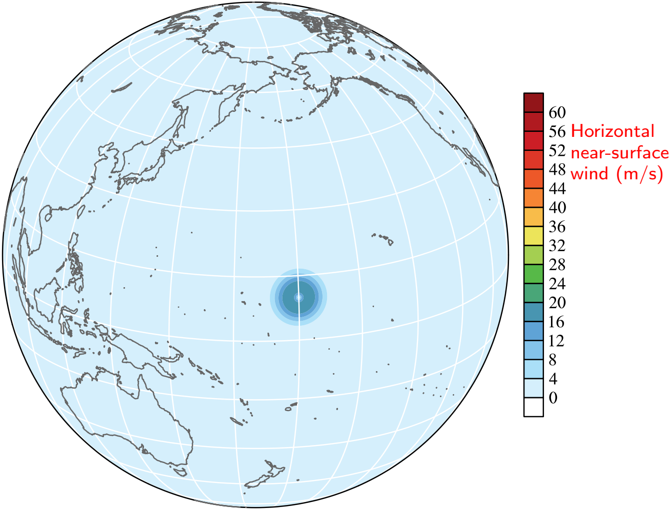


Surface pressure O640/TCo639, $\Delta_h \approx 18$ km, day 15



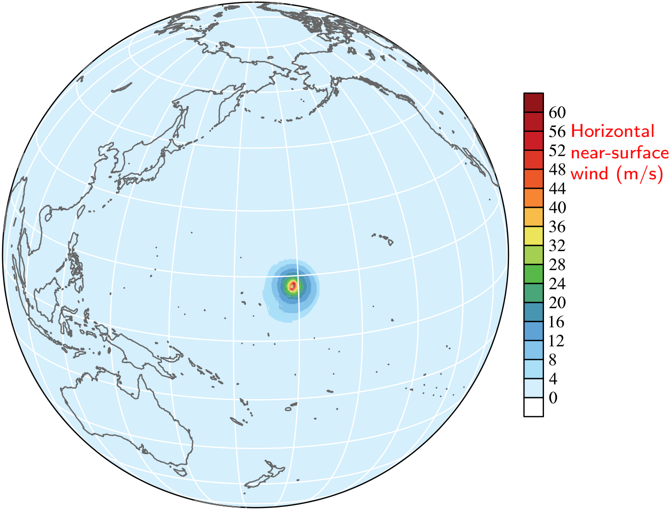
- Finite-volume solutions achieve accuracy of established spectral-transform IFS for moist flows

Tropical cyclone simulations



Tropical cyclone simulations (over 10 days) on aqua-planet with parametrisations for large-scale condensation with diagnostic rain, surface fluxes and PBL diffusion (Reed and Jablonowski 2011)

Tropical cyclone simulations



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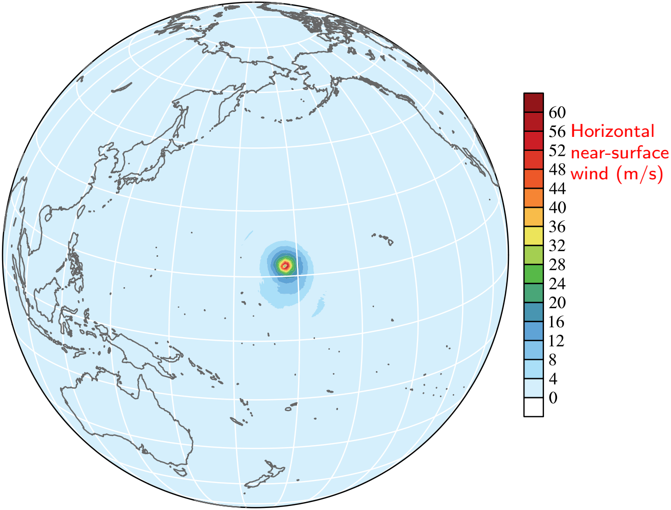

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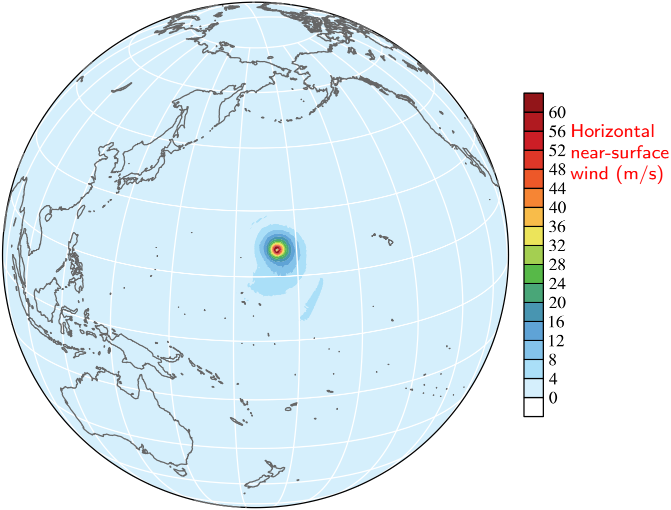
Tropical cyclone simulations



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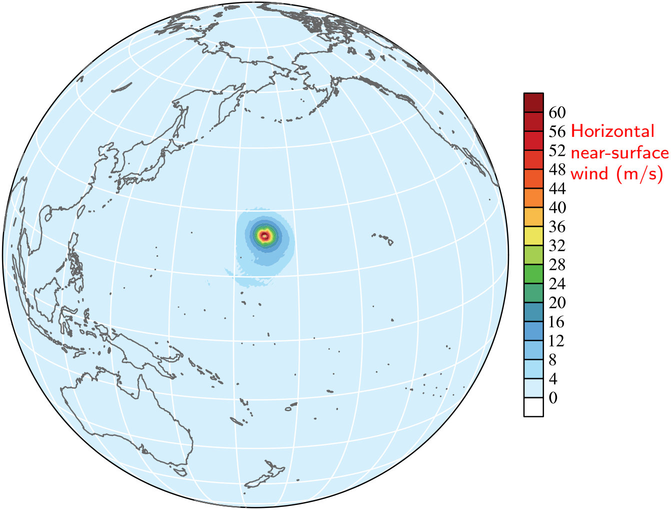

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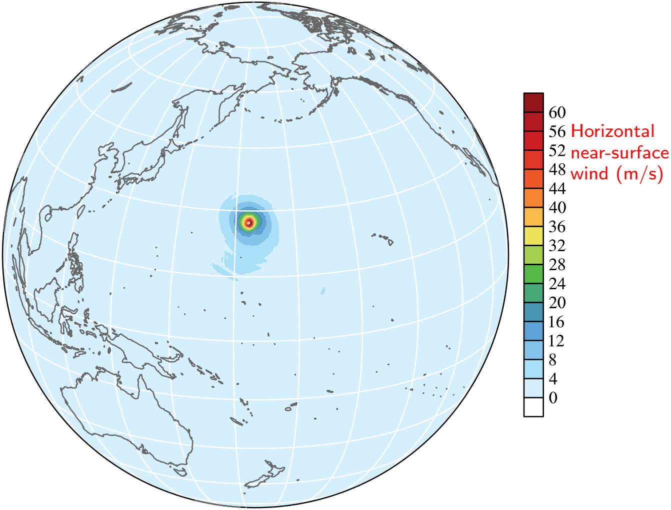
Tropical cyclone simulations



Tropical cyclone simulations (over 10 days) on aqua-planet with parametrisations for large-scale condensation with diagnostic rain, surface fluxes and PBL diffusion (Reed and Jablonowski 2011)

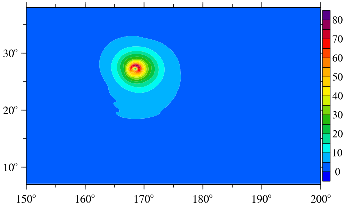
Tropical cyclone simulations with FV and ST approaches in IFS

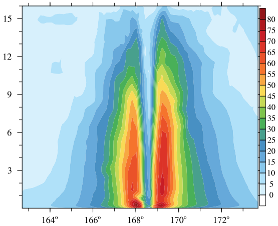
Tropical cyclone simulations with coupling to parametrisations for large-scale condensation with diagnostic rain, surface fluxes and PBL diffusion (Reed and Jablonowski 2011) on O640/L60:

Wind speed (m/s) in horizontal section at z $\approx$ 1 km:

Wind speed (m/s) in zonal-height section:

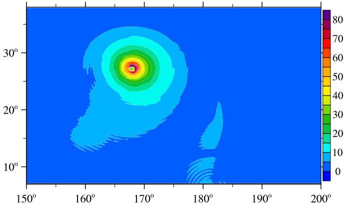
FV

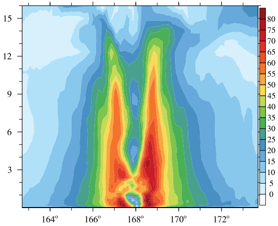




day 10

ST

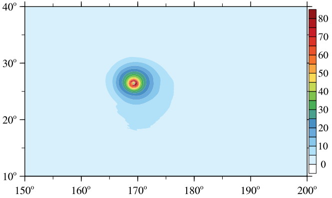




Higher resolution with FVM

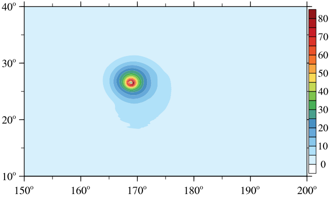
FVM, O1280(9km)/L60

Wind speed (m/s) in horizontal section at z ≈ 1 km:

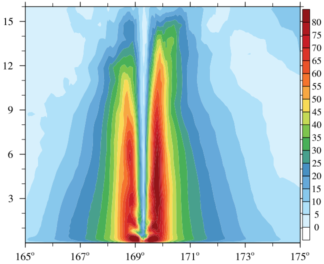


FVM, O1600(6.5km)/L60

Wind speed (m/s) in horizontal section at z ≈ 1 km:

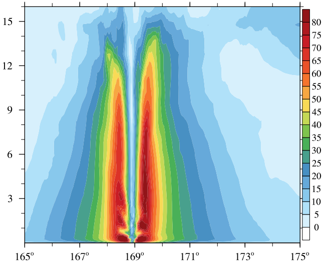


Wind speed (m/s) in zonal-height section:



day 10

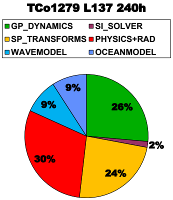
Wind speed (m/s) in zonal-height section:

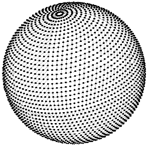


→ Driven by numerical and computational advancements, globally high resolutions are becoming standard in FVM

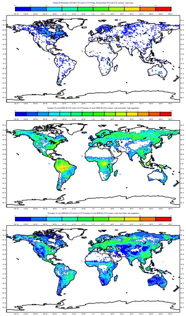
Coupling FVM to IFS physics parametrisations

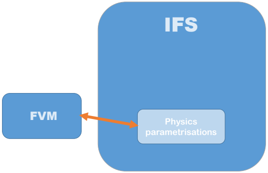
Where is the time spent in IFS?





⇒ FVM can simply maintain IFS surface fields due to similar horizontal grids

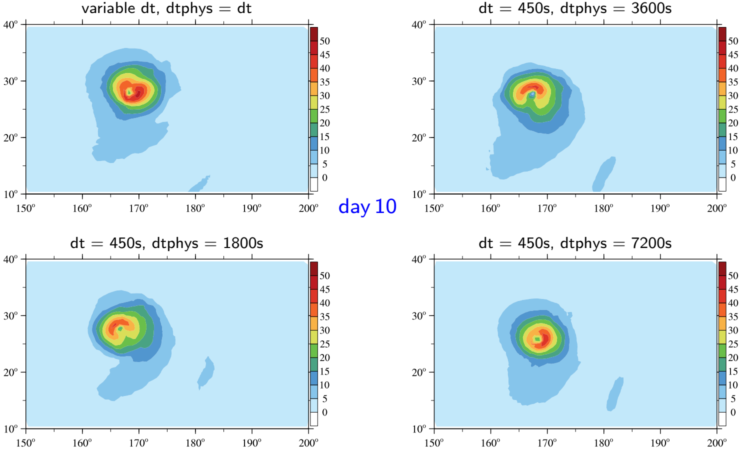




⇒ Keep IFS physics parametrisations (mostly) unchanged, and couple to FVM by means of its own flexible interface

- FVM uses octahedral grid and non-staggered variable arrangement in horizontal, like in IFS
- FVM uses height-based versus pressure-based vertical coordinate
- FVM uses smaller (and optionally variable) time steps

Tropical cyclone simulations with coupling to parametrisations for large-scale condensation with diagnostic rain, surface fluxes and PBL diffusion (Reed and Jablonowski 2011) on O160/L60:



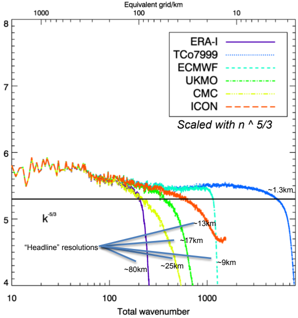
Wind speed (m/s) in horizontal section at z ≈ 1 km

Steep and complex orography

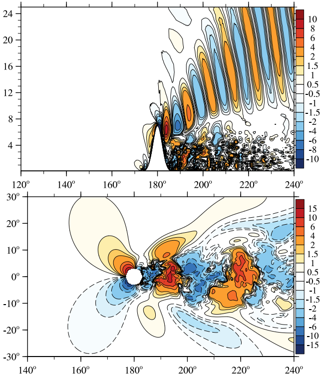
Estimates of maximum slopes of IFS global mean orography:

Grid	Δ_h	max. slope
O1280	9 km	9°
O1600	6.5 km	10°
O2000	5 km	17°
O4000	2.5 km	30°
O8000	1.25 km	$> 50^\circ$
O16000	0.625 km	$> 70^\circ$

Orography spectra at various NWP centres

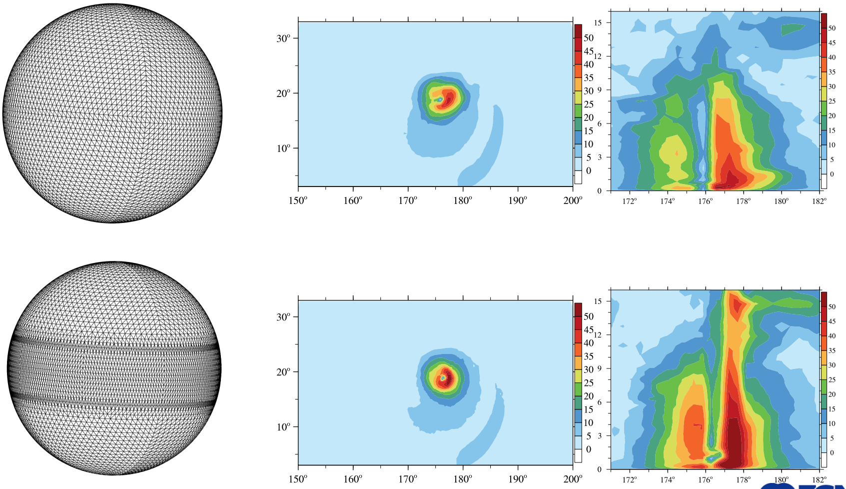


FVM simulation of stratified flow past steep orography with maximum slope $\sim 70^\circ$ on a reduced-radius planet after 2 h (vertical wind (m/s), meridional wind (m/s) in lon-height section at lat=0, lon-lat section at z=2 km), cf. Zängl et al. QJ 2015.



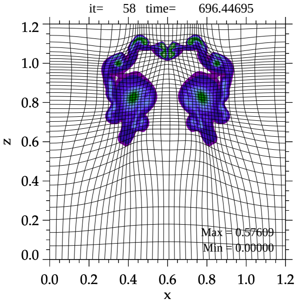
Variable resolution and adaptive meshes

Tropical cyclone simulations with FVM at uniform (upper row) and variable resolution (lower row) meshes (primary mesh, wind speed in m/s in at $z \approx 1\,\mathrm{km}$, wind speed in zonal-height section):



Variable resolution and adaptive meshes

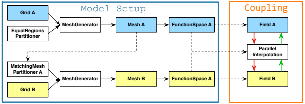
Rising thermal simulation with adaptive moving meshes



- FVM/Atlas will provide support for variable resolution by changing the mesh in computational space
- FVM optionally offers moving mesh adaptation via continuous mappings in physical space
- Variable resolution and mesh adaptivity in the horizontal and/or vertical can permit to better/explicitly resolve processes in fine regions but may require parametrisation in coarse regions
- Needs criteria where to put finer resolution
- Generally very little experience with variable resolution and mesh adaptivity in global NWP

Outlook: multi-grid approaches for dynamics and physics

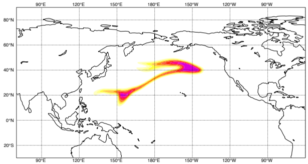
ECMWF's Atlas library (Deconinck et al. 2017) will provide multi-grid capabilities



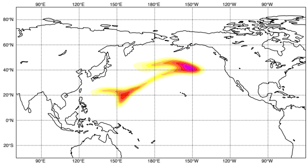

```
grid_A          = atlas_Grid("O1280")
partitioner_A   = atlas_EqualRegionsPartitioner()
mesh_A          = meshgenerator % generate(grid_A, partitioner_A)
fs_A            = atlas_functionspace_NodeColumns(mesh_A)

grid_B          = atlas_Grid("O640")
partitioner_B   = atlas_MatchingMeshPartitioner(mesh_A)
mesh_B          = meshgenerator%generate(grid_B, partitioner_B)
fs_B            = atlas_functionspace_NodeColumns(mesh_B)

interpolation_AB = atlas_Interpolation(type="finite-element",
                                        source=fs_A, target=fs_B)
```

Proof-of-concept: SL tracer advection on coarsened mesh (M. Diamantakis, W. Deconinck)

Run with original grid spacing $\Delta_h = 125$ km



Run with coarsened grid spacing $\Delta_h = 210$ km, but using advective velocities from high resolution



- experimentation with multigrid capabilities provided by Atlas (e.g. tracer advection on coarser grid)
- radiation is already run at coarser spatial (and temporal) resolution in IFS but using different technique
- flexible future framework to study systematically running (some) physics parametrisations at coarser/finer spatial resolution than dynamics

Outlook and conclusions

⇒ FVM, an ongoing development at ECMWF, complements the established spectral-transform IFS with novel capabilities

- → nonhydrostatic governing equations
- → flux-form nonoscillatory advective transport
- → robustness wrt steep orography
- → variable resolution and adaptive meshes

- From which Δ_h do nonhydrostatic effects become important? Experimentation with IFS so far indicates that $\Delta_h = 2.5$ km could still employ hydrostatic primitive equations for medium-range weather forecasting
- variable resolution can be a way forward, if we find criteria where to refine and physics parametrisations scale-aware
- multigrid capability using Atlas will permit to systematically investigate physics parameterisations to be run on coarser/same/finer grid wrt to dynamics
- FVM interface to IFS physics parametrisations is under development, and the model is progressing towards realistic medium-range NWP forecasts

References related to FVM

Further reading:

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