Current state of the Finite-Volume Module of IFS at ECMWF

Christian Kühnlein, Sylvie Malardel, Piotr Smolarkiewicz, Nils Wedi

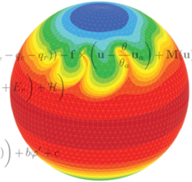
$$\frac{\partial \mathcal{G}\rho}{\partial t} + \nabla\cdot(\mathbf{v}\mathcal{G}\rho) = 0$$

$$\frac{\partial \mathcal{G}\rho\mathbf{u}}{\partial t} + \nabla\cdot(\mathbf{v}\mathcal{G}\rho\mathbf{u}) = \mathcal{G}\rho\left(-\Theta_d\widetilde{\mathbf{G}}\nabla\varphi' - \frac{\mathbf{g}}{\theta_a}(\theta' + \theta_a(\epsilon q'_v - q_c - q_r)) - \mathbf{f}\times\left(\mathbf{u} - \frac{\theta}{\theta_a}\mathbf{u}_a\right) + \mathbf{M}(\mathbf{u}) + \mathbf{D}\right)$$

$$\frac{\partial \mathcal{G}\rho\theta'}{\partial t} + \nabla\cdot(\mathbf{v}\mathcal{G}\rho\theta') = \mathcal{G}\rho\left(-\widetilde{\mathbf{G}}^T\mathbf{u}\cdot\nabla\theta_a - \frac{L}{c_p\pi}\left(\frac{\Delta q_{vs}}{\Delta t} + E_r\right) + \mathcal{H}\right)$$

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

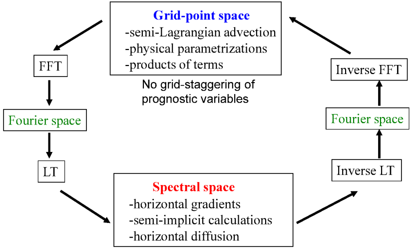
$$\frac{\partial \mathcal{G}\rho\varphi'}{\partial t} + \nabla\cdot(\mathbf{v}\mathcal{G}\rho\varphi') = \mathcal{G}\rho\sum_{\ell=1}^{3}\left(\frac{a_\ell}{\zeta_\ell}\nabla\cdot\zeta_\ell(\check{\mathbf{v}} - \widetilde{\mathbf{G}}^T\mathbf{C}\nabla\varphi')\right) + b\varphi' + c$$

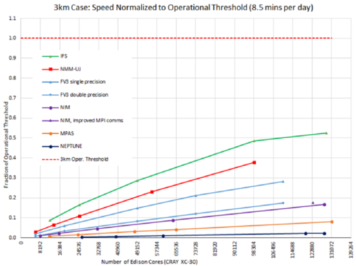


ECMWF

Operational configuration of the Integrated Forecasting System at ECMWF

Schematic of spectral-transform method in IFS



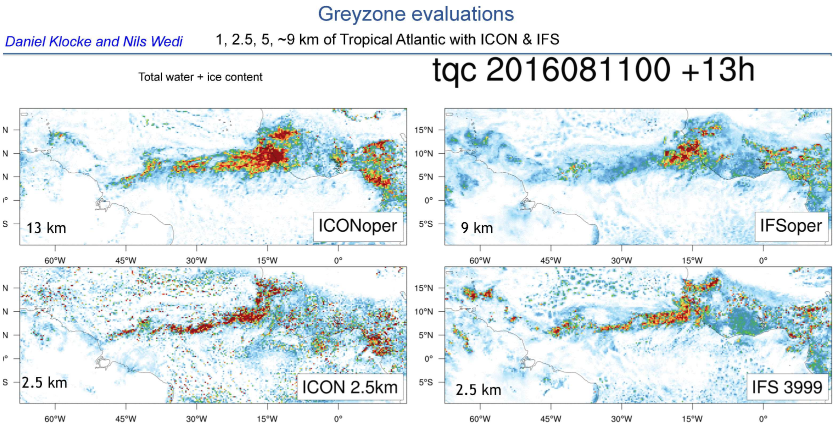


Current operational configuration of the Integrated Forecasting System (IFS) at the European Centre for Medium-Range Weather Forecasting:

- hydrostatic primitive equations (nonhydrostatic option available; see Benard et al. 2014)
- hybrid $\eta - p$ vertical coordinate (Simmons and Burridge, 1982)
- spherical harmonics representation 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 ("TCo") grid (Wedi, 2014, Malardel et al. 2016)
- HRES: TCo1279 (O1280) with $\Delta_h \approx 9$ km and 137 vertical levels
- ENS (1+50 perturbed members): TCo639 (O640) with $\Delta_h \approx 18$ km and 91 vertical levels

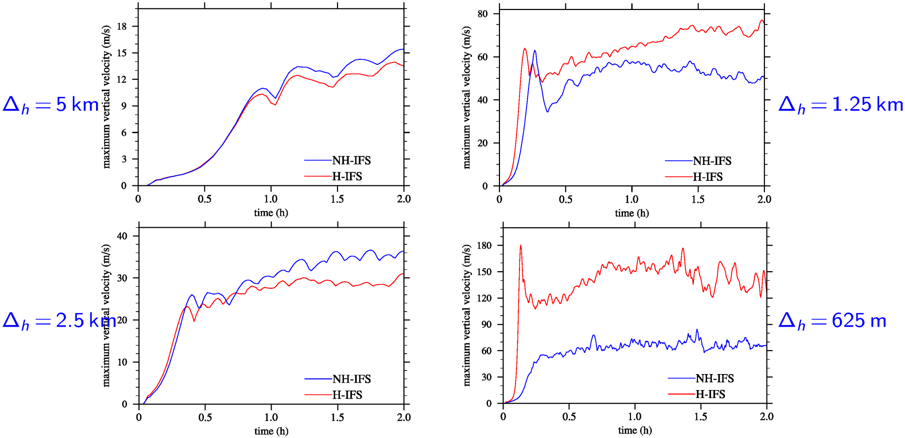
$\Rightarrow$ ECMWF strategy for the year 2025 targets to run ENS with TCo1999 with $\Delta_h \approx 5$ km

Quasi-hydrostatic versus nonhydrostatic dynamics



Quasi-hydrostatic versus nonhydrostatic dynamics

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)

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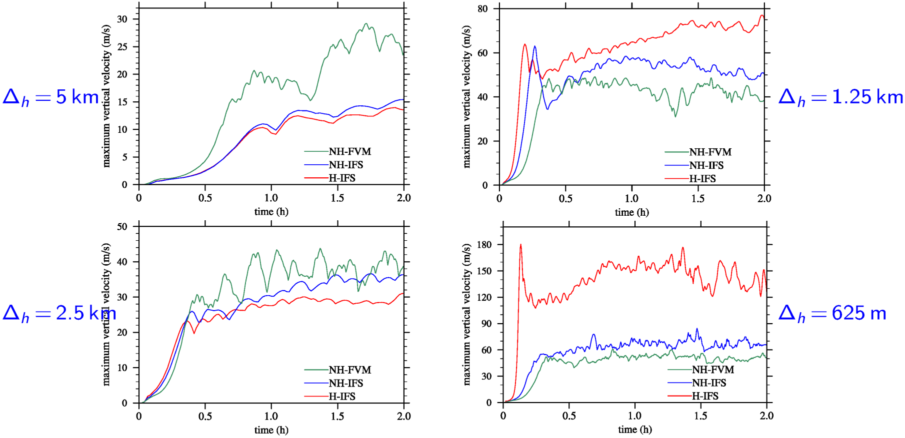
Quasi-hydrostatic versus nonhydrostatic dynamics

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



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

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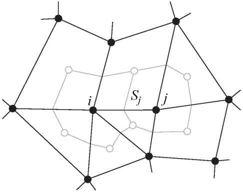
IFS-FVM—key formulation features

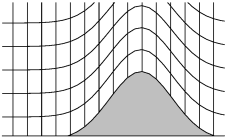
- moist-precipitating, deep-atmosphere, nonhydrostatic, fully compressible Euler equations (Smolarkiewicz, Kühnlein, Grabowski 2017; Kühnlein et al. *in prep.*)
- flexible height-based terrain-following vertical coordinate
- hybrid of horizontally-unstructured median-dual finite-volume with vertically-structured 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 2014)
- finite-volume non-oscillatory forward-in-time (NFT) MPDATA scheme (Smolarkiewicz and Szmelter 2005; Kühnlein and Smolarkiewicz 2017), dimensionally-split NFT advective transport (Kühnlein et al., *in prep.*)
- preconditioned generalised conjugate residual iterative solver for 3D elliptic problems arising in the semi-implicit integration schemes (Smolarkiewicz and Szmelter 2011 for a more recent review)
- octahedral reduced Gaussian grid, but the IFS-FVM formulation not restricted to this (Szmelter and Smolarkiewicz 2016)
- optional moving mesh capability (Kühnlein, Smolarkiewicz, Dörnbrack 2012)



median-dual finite-volume approach

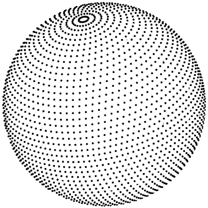
$$\int_{\Omega} \nabla \cdot \mathbf{A} = \int_{\partial\Omega} \mathbf{A} \cdot \mathbf{n} = \frac{1}{\mathcal{V}_i} \sum_{j=1}^{l(i)} A_j^{\perp} S_j$$

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

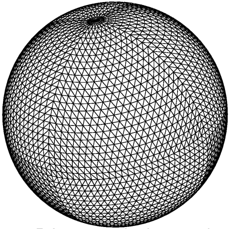


terrain-following coordinate

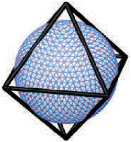
Octahedral reduced Gaussian grid

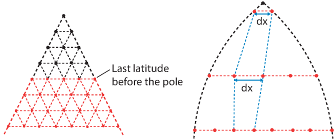


Nodes of octahedral grid 'O24'



Primary mesh about nodes of octahedral grid in IFS-FVM





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

⇒ finite-volume and spectral-transform IFS can operate on same quasi-uniform horizontal grid

→ Malardel et al. ECMWF Newsletter 2016, Smolarkiewicz et al. 2016

→ operational at ECMWF with HRES and ENS since March 2016

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

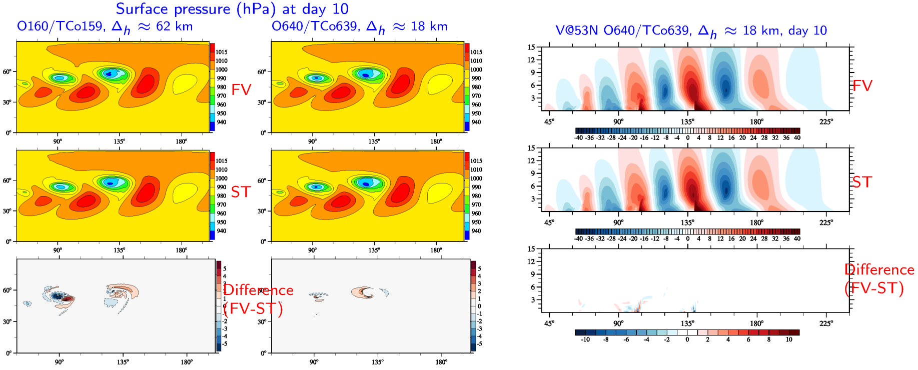
ECMWF

Main formulation features of IFS-ST and IFS-FVM

Table: Summary of the main formulation features of IFS-ST and IFS-FVM

Model aspect	IFS-ST	IFS-FVM
Equation system	hydrostatic primitive	fully compressible Euler
Prognostic variables	p_s, u, v, T_v, q_k	ρ_d, u, v, w, θ', r_k
Horizontal coordinates	λ, ϕ (lon-lat)	λ, ϕ (lon-lat)
Vertical coordinate	hybrid η-pressure	generalized height
Horizontal discretization	spectral-transform (ST)	unstructured finite-volume (FV)
Vertical discretization	structured FE	structured FD/FV
Horizontal staggering	co-located	co-located
Vertical staggering	co-located	co-located
Horizontal grid	octahedral Gaussian	octahedral Gaussian/arbitrary
Time-stepping scheme	2-TL constant-coefficient SI	2-TL SI
Advection	non-conservative SL	conservative FV Eulerian

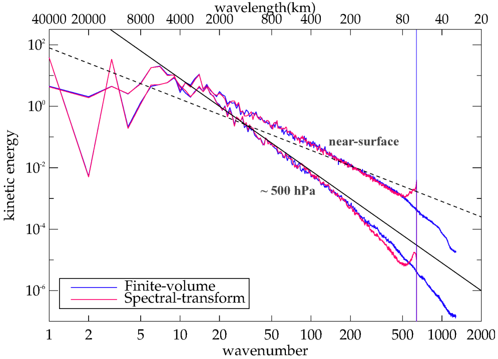
Dry baroclinic instability (Ullrich et al. 2014) using IFS-FVM and IFS-ST:



- Finite-volume solutions achieve accuracy of established spectral-transform IFS for planetary-scale baroclinic instablility

Finite-volume and spectral-transform solutions in IFS

Instantaneous kinetic energy spectra O640/TCo639 ($\Delta_h \approx 18$ km)
for baroclinic instability at day 15

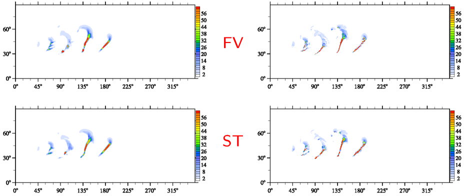


Finite-volume and spectral-transform solutions in IFS

Moist baroclinic instability using IFS-FVM and IFS-ST with parametrization for large-scale condensation and diagnostic precipitation:

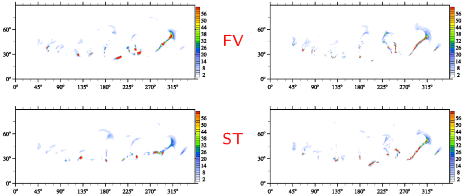
Precipitation (mm/day) at day 10

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

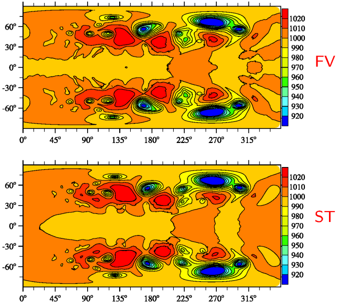


Precipitation (mm/day) at day 15

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

Finite-volume and spectral-transform solutions in IFS

Moist baroclinic instability using IFS-FVM and IFS-ST with parametrization for large-scale condensation and diagnostic precipitation:

Precipitation (mm/day) at day 10

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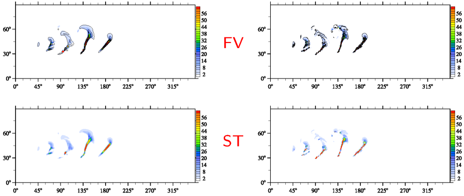

Precipitation (mm/day) at day 15

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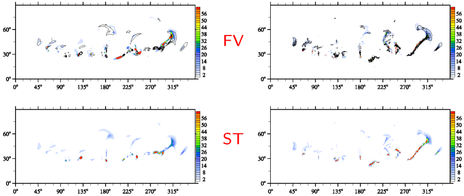
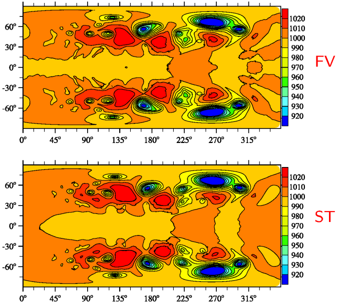


Surface pressure O640/TCo639, $\Delta_h \approx$ 18 km, day 15



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

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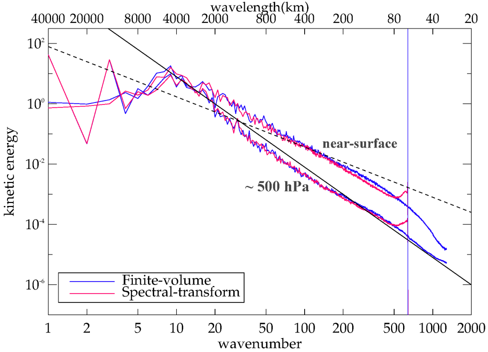
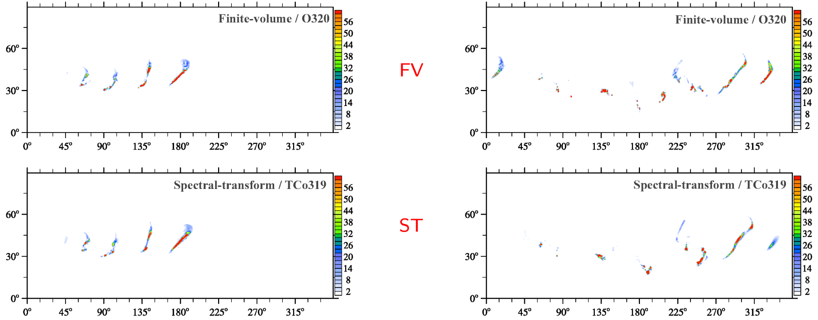
Instantaneous kinetic energy spectra O640/TCo639 ($\Delta_h \approx 18$ km)
for moist baroclinic instability at day 15



Moist-precipitating baroclinic instability using IFS-FVM and IFS-ST with IFS cloud parametrization:

Precipitation (mm/day) at day 10
O320/TCo319, $\Delta_h \approx 36$ km

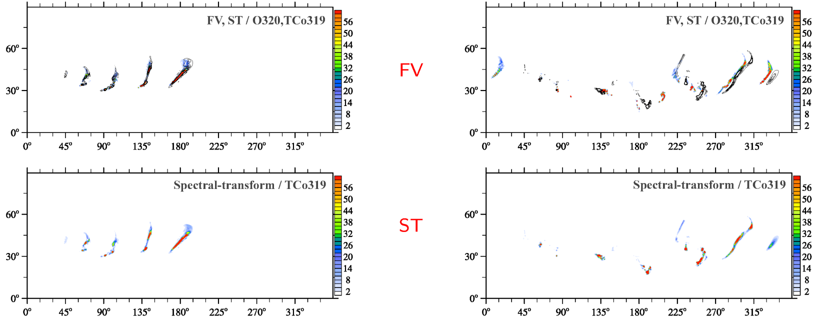
Precipitation (mm/day) at day 15
O320/TCo319, $\Delta_h \approx 36$ km



Moist-precipitating baroclinic instability using IFS-FVM and IFS-ST with IFS cloud parametrization:

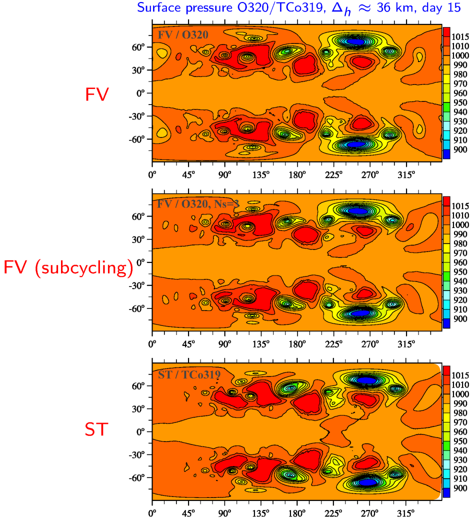
Precipitation (mm/day) at day 10
O320/TCo319, $\Delta_h \approx 36$ km

Precipitation (mm/day) at day 15
O320/TCo319, $\Delta_h \approx 36$ km



Finite-volume and spectral-transform solutions in IFS

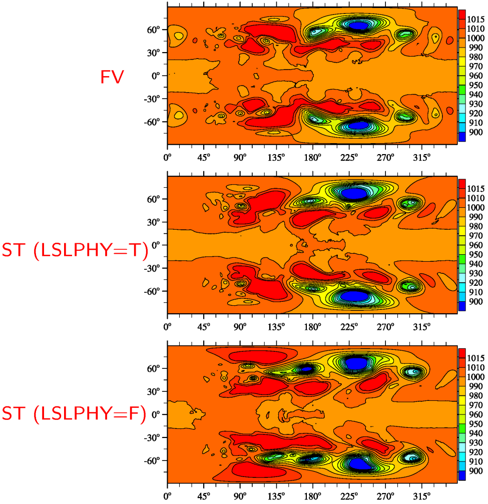
Moist-precipitating baroclinic instability using IFS-FVM and IFS-ST with IFS cloud parametrization:



Finite-volume and spectral-transform solutions in IFS

Moist-precipitating baroclinic instability using IFS-FVM and IFS-ST with IFS cloud and convection parametrization:

Surface pressure O320/TCo319, $\Delta_h \approx$ 36 km, day 15



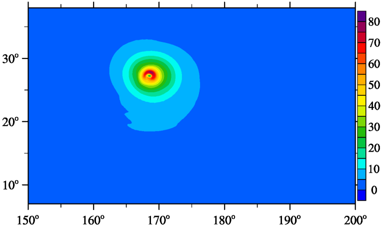
Tropical cyclone simulations with FV and ST approaches in IFS

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:

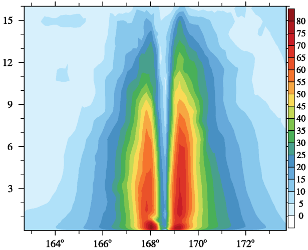
Wind speed (m/s) in horizontal section at z ≈ 1 km:

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

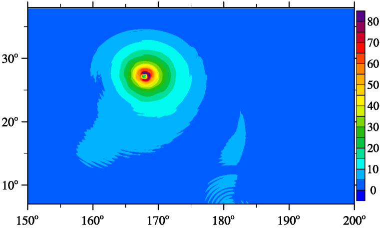
FV

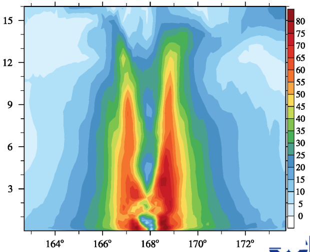


day 10



ST





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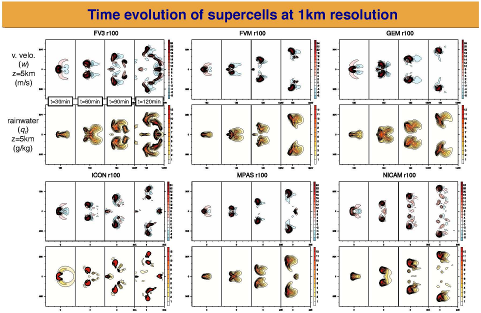
Dynamical Core Model Intercomparison Project (DCMIP)



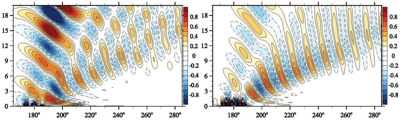
Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2017-108
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 6 June 2017

Geoscientific Model Development Discussions

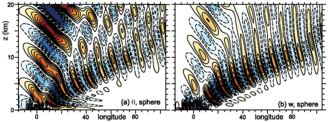
DCMIP2016: A Review of Non-hydrostatic Dynamical Core Design and Intercomparison of Participating Models

Paul A. Ullrich[1], Christiane Jablonowski[2], James Kent[3], Peter H. Lauritzen[4], Ramachandran Nair[4], Kevin A. Reed[5], Colin M. Zarzycki[4], David M. Hall[6], Don Dazlich[7], Ross Heikes[7], Celal Konor[7], David Randall[7], Thomas Dubos[8], Yann Meurdesoif[8], Xi Chen[9], Lucas Harris[9], Christian Kühnlein[10], Vivian Lee[11], Abdessamad Qaddouri[11], Claude Girard[11], Marco Giorgetta[12], Daniel Reinert[13], Joseph Klemp[4], Sang-Hun Park[4], William Skamarock[4], Hiroaki Miura[14], Tomoki Ohno[14], Ryuji Yoshida[15], Robert Walko[16], Alex Reinecke[17], and Kevin Viner[17]

IFS-FVM and MPAS results for stratified flow past Schär mountain on a reduced-radius planet after 2 h
(left: potential temperature perturbation θ' [K], right: vertical velocity w [m/s], lon-height section at lat=0)



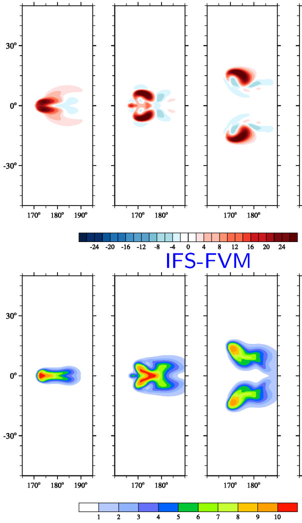
IFS-FVM

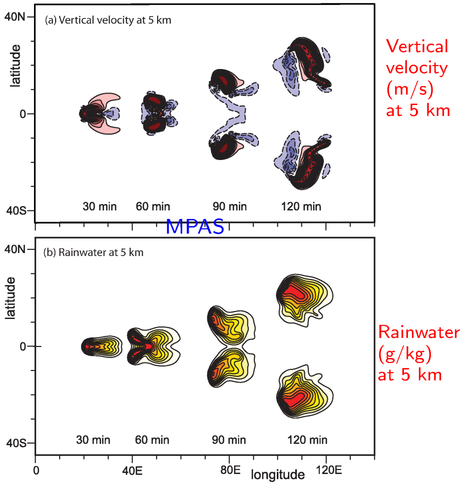


MPAS

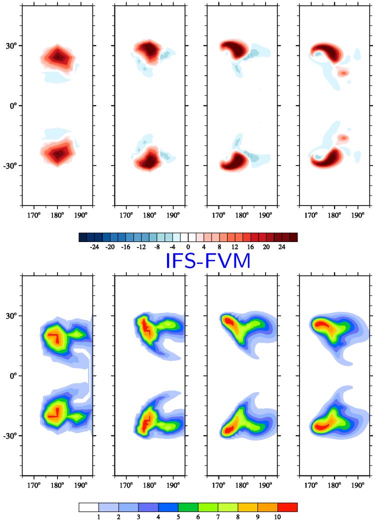
Mesoscale convective storm on reduced-size planet

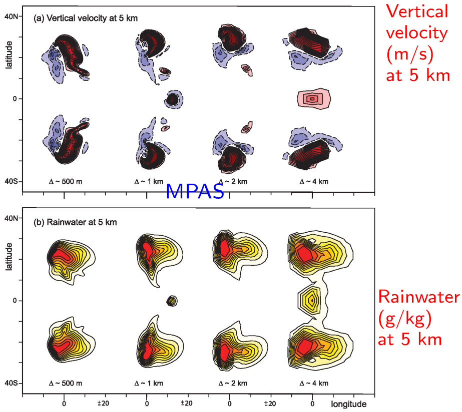
Supercell evolution (0.5, 1, 1.5, 2h) with IFS-FVM (left) and MPAS (right) at ≈ 0.5 km grid spacing (cf. Klemp et al. 2015):





Supercell for grid spacings (4, 2, 1, 0.5 km) with IFS-FVM (left) and MPAS (right) after 2 h of simulation (cf. Klemp et al. 2015):





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Some relevant references

Further reading:

- Kühnlein C., P. K. Smolarkiewicz, A. Dörnbrack, Modelling atmospheric flows with adaptive moving meshes., J. Comput. Phys., 2012.
- Szmelter J., P. K. Smolarkiewicz P.K, An edge-based unstructured mesh discretisation in a geospherical framework., J. Comput. Phys., 2010.
- Smolarkiewicz P.K., C. Kühnlein, N. P. Wedi, A discrete framework for consistent integrations of soundproof and compressible PDEs of atmospheric dynamics., J. Comput. Phys., 2014.
- Smolarkiewicz P.K., W. Deconinck, M. Hamrud, C. Kühnlein, G. Modzinski, J. Szmelter, N. P. Wedi, A finite-volume module for simulating global all-scale atmospheric flows., J. Comput. Phys., 2016.
- Kühnlein C., Smolarkiewicz P.K., An unstructured-mesh finite-volume MPDATA for compressible atmospheric dynamics., J. Comput. Phys., 2017.
- Smolarkiewicz P.K., C. Kühnlein, W. W. Grabowski, A finite-volume module for cloud-resolving simulations of global all-scale atmospheric flows., J. Comput. Phys., 2017.
- Deconinck W., P. Bauer, M. Diamantakis, M. Hamrud, C. Kühnlein, G. Mengaldo, P. Marciel, T. Quintino, B. Raoult, P. K. Smolarkiewicz, N. P. Wedi, *Atlas*: The ECMWF framework to flexible numerical weather and climate modelling., https://doi.org/10.1016/j.cpc.2017.07.006, 2017.
- Waruszewski M., C. Kühnlein, H. Pawlowska, P. K. Smolarkiewicz, MPDATA: Third-order accuracy for arbitrary flows, *in press, JCP.*
- Smolarkiewicz P.K., C. Kühnlein, N. P. Wedi, Perturbation equations for all-scale atmospheric dynamics., *submitted to J. Comput. Phys.*
- Kühnlein C., S. Malardel, Smolarkiewicz P.K., et al., Finite-volume and spectral-transform formulations of IFS, *in preparation for GMD*
- Kühnlein C., R. Klein, Smolarkiewicz P.K., Splitting of advection in an all-scale atmospheric model, *in preparation for MWR*