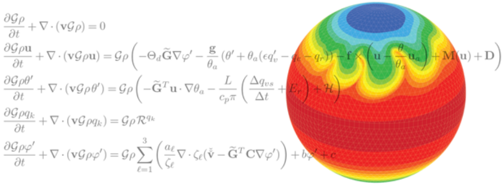
Simulating all-scale global weather with the Finite-Volume Module of IFS

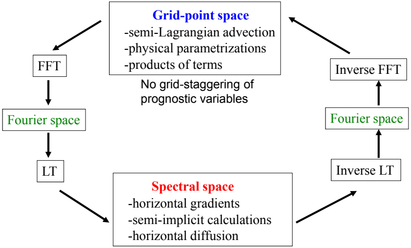
Christian Kühnlein, Sylvie Malardel, Piotr Smolarkiewicz, Nils Wedi

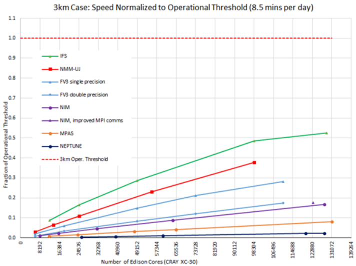


ECMWF

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 $\Delta_h \approx 16$ km and 91 vertical levels

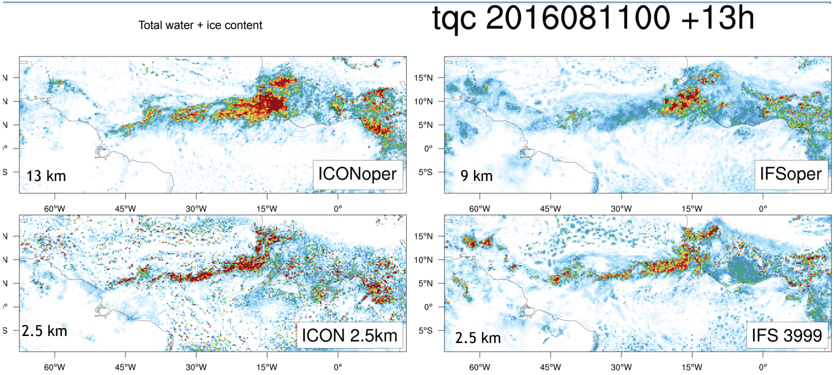
$\Rightarrow$ ECMWF strategy for the year 2025 targets to run ENS with TCo1999 with $\Delta_h \approx 5$ km

Quasi-hydrostatic versus nonhydrostatic dynamics

Greyzone evaluations

Daniel Klocke and Nils Wedi 1, 2.5, 5, ~9 km of Tropical Atlantic with ICON & IFS

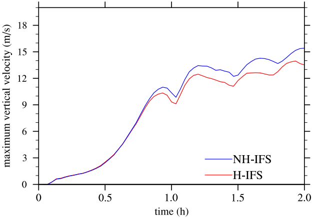
Total water + ice content



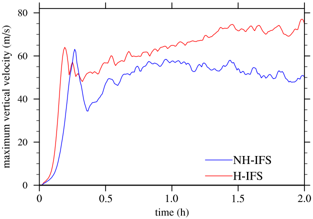
Quasi-hydrostatic versus nonhydrostatic dynamics

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?

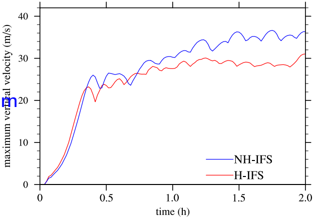
$\Delta_h = 5$ km



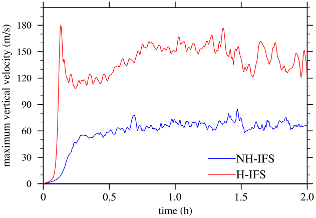
$\Delta_h = 1.25$ km



$\Delta_h = 2.5$ km



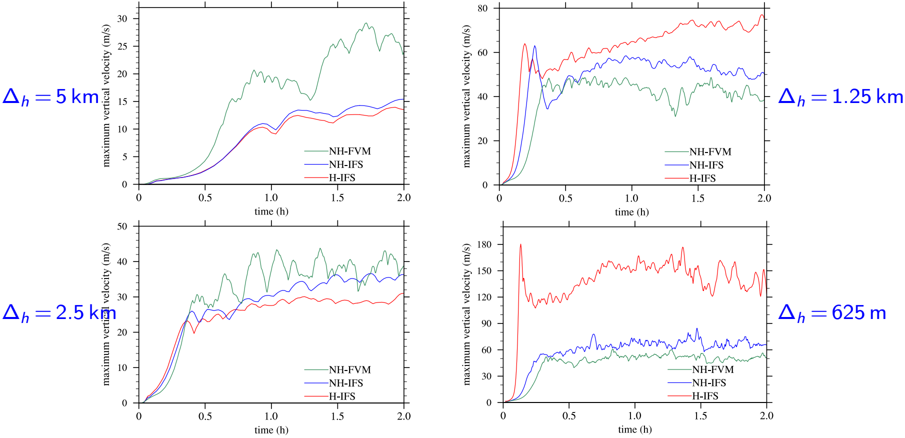
$\Delta_h = 625$ m



→ 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)

Quasi-hydrostatic versus nonhydrostatic dynamics

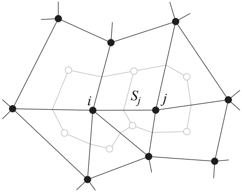
Idealized convective storm (Klemp et al. 2015) on a small planet (1/25 reduced) with H and NH formulation of IFS and NH-FVM:



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

Finite-Volume Module (FVM) of IFS—key formulation features

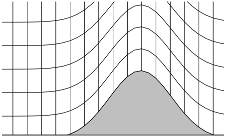
- deep-atmosphere nonhydrostatic Euler equations in geospherical framework (Szmelter and Smolarkiewicz 2010; Smolarkiewicz et al. 2016; Smolarkiewicz, Kühnlein, Grabowski 2017; Kühnlein, Malardel, Smolarkiewicz *in prep.*)
- flexible height-based terrain-following vertical coordinate
- hybrid of horizontally-unstructured 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 JCP 2014)
- 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)
- non-oscillatory finite-volume MPDATA scheme (Smolarkiewicz and Szmelter 2005; Kühnlein and Smolarkiewicz 2017)
- octahedral reduced Gaussian grid, but the FVM formulation not restricted to this (Szmelter and Smolarkiewicz 2016)
- optional moving mesh capability (as in Kühnlein, Smolarkiewicz, Dörnbrack 2012)



median-dual finite-volume approach

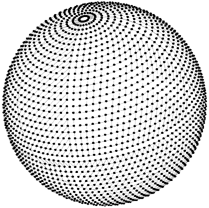
$$\int_{\Omega} \nabla \cdot \mathbf{A} = \int_{\partial\Omega} \mathbf{A} \cdot \mathbf{n} = \frac{1}{\mathcal{V}_i} \sum_{j=1}^{l(i)} A_j^{\perp} S_j$$

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

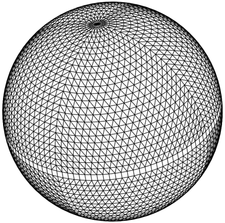


terrain-following coordinate

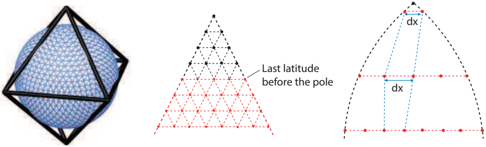
Octahedral reduced Gaussian grid



Nodes of octahedral grid 'O24'



Primary mesh about nodes of octahedral grid in 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
- 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. JCP 2016

→ 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)

Flux-form moist compressible Euler equations in generalised curvilinear coordinates (Smolarkiewicz, Kühnlein, Grabowski 2017; Kühnlein, Malardel, Smolarkiewicz *in prep.*):

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

$$\frac{\partial \mathcal{G}\rho_d \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{v}\mathcal{G}\rho_d \mathbf{u}) = \mathcal{G}\rho_d \left[-\theta_\rho \widetilde{\mathbf{G}} \nabla \varphi' + \mathbf{g}\mathcal{B} - \mathbf{f} \times \left(\mathbf{u} - \frac{\theta_\rho}{\theta_{\rho a}} \mathbf{u}_a \right) + \mathcal{M}' + \boldsymbol{\mathcal{D}} + \boldsymbol{P}^{\mathbf{u}} \right] \ ,$$

$$\frac{\partial \mathcal{G}\rho_d \theta'}{\partial t} + \nabla \cdot \left(\mathbf{v}\mathcal{G}\rho_d \, \theta' \right) = \mathcal{G}\rho_d \left[-\widetilde{\mathbf{G}}^T \mathbf{u} \cdot \nabla \theta_a + \mathcal{H} + P^{\theta'} \right] \ ,$$

$$\frac{\partial \mathcal{G}\rho_d r_k}{\partial t} + \nabla \cdot (\mathbf{v}\mathcal{G}\rho_d \, r_k) = \mathcal{G}\rho_d \left[\mathcal{D}^{r_k} + P^{r_k} \right] \qquad \text{where} \quad r_k = r_v, r_c, r_r, r_i, r_s \ ,$$

$$\varphi' = c_{pd} \left[\left(\frac{R_d}{p_0} \rho_d \, \theta \, (1 + r_v/\varepsilon) \right)^{R_d/c_{vd}} - \pi_a \right] \ ,$$

with:

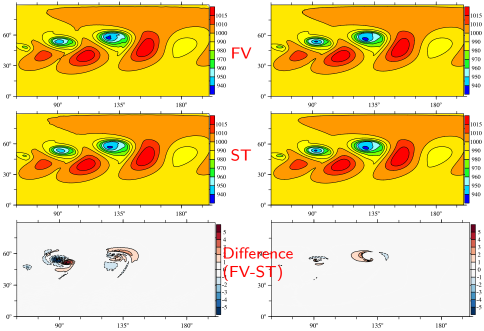
$$\mathbf{v} = \widetilde{\mathbf{G}}^T \mathbf{u} \ , \qquad \theta_\rho = \frac{\theta \, (1 + r_v/\varepsilon)}{(1 + r_t)} \ , \qquad \varepsilon = \frac{R_d}{R_v} \ , \qquad \theta' = \theta - \theta_a \ ,$$

$$\mathcal{B} = 1 - \frac{\theta_\rho}{\theta_{\rho a}} = 1 - \frac{\eta_{\theta_\rho}}{\theta_{\rho a}} \left(\theta_a + \theta' \right) \ , \qquad \eta_{\theta_\rho} \equiv \frac{1 + r_v/\varepsilon}{1 + r_t} \ , \qquad r_t = \sum_k r_k$$

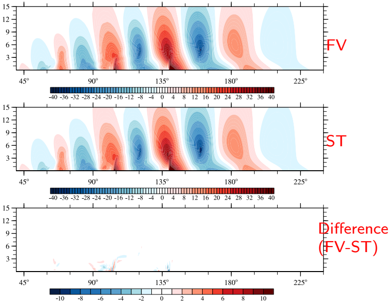
Dry baroclinic instability (Ullrich et al. 2014) with FVM and spectral-transform IFS (ST):

Surface pressure (hPa) at day 10

O160/TCo159, $\Delta_h \approx 62$ km   O640/TCo639, $\Delta_h \approx 16$ km



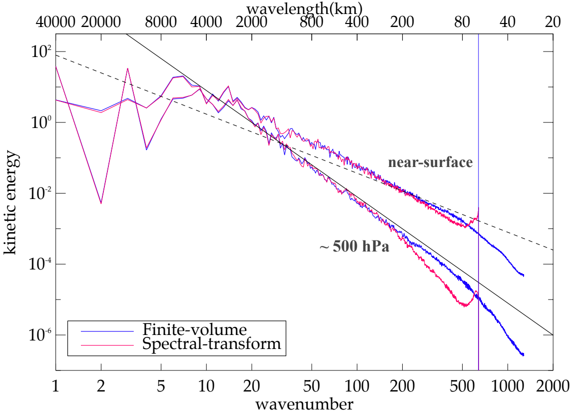
V@53N O640/TCo639, $\Delta_h \approx 16$ km, day 10



- 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 ($\Delta_h \approx 16$ km)
for baroclinic instability at day 15

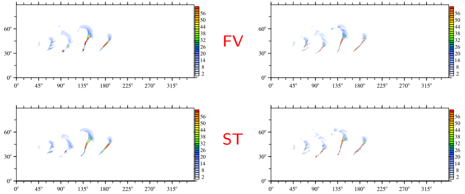


Finite-volume and spectral-transform solutions in IFS

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

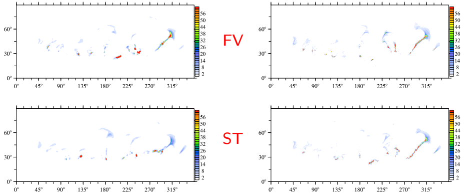
Precipitation (mm/day) at day 10

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

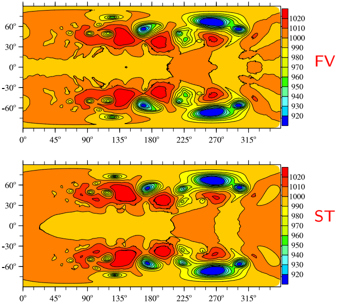


Precipitation (mm/day) at day 15

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

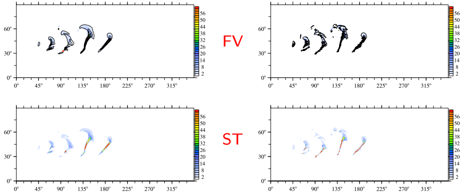


- Finite-volume solutions achieve accuracy of established spectral-transform IFS for moist flows

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

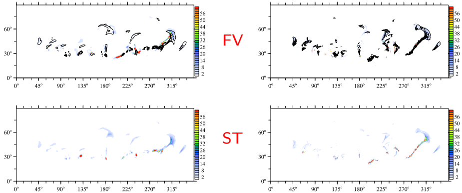
Precipitation (mm/day) at day 10

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

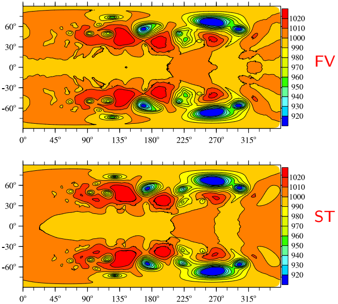


Precipitation (mm/day) at day 15

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



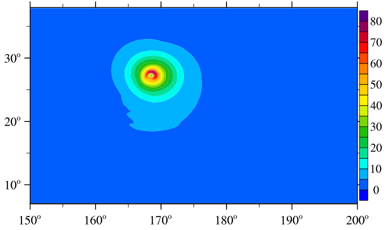
- Finite-volume solutions achieve accuracy of established spectral-transform IFS for moist flows

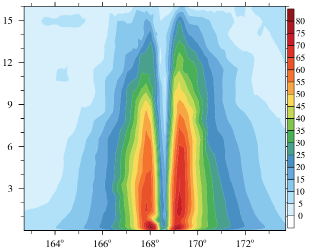
Tropical cyclone simulations with coupling to parametrisations for large-scale condensation with diagnostic rain, surface fluxes and PBL diffusion (Reed and Jablonowski 2011) on O640/L60:

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

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

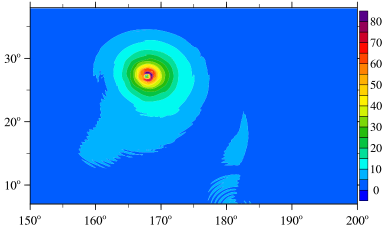
FV

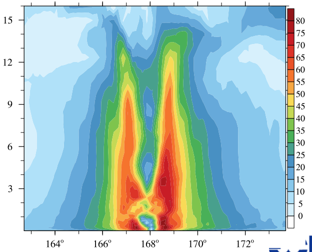




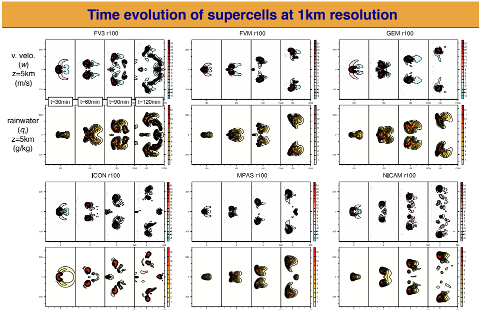
day 10

ST





Dynamical Core Model Intercomparison Project (DCMIP)



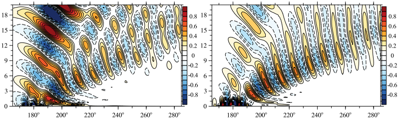
Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2017-108
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 6 June 2017

Geoscientific Model Development Discussions
EGU

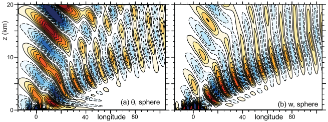
DCMIP2016: A Review of Non-hydrostatic Dynamical Core Design and Intercomparison of Participating Models

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]

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)



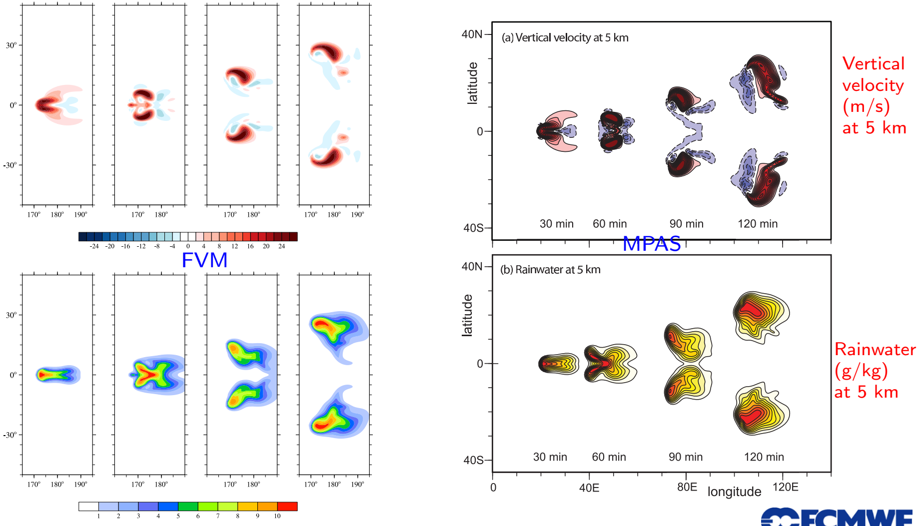
FVM



MPAS

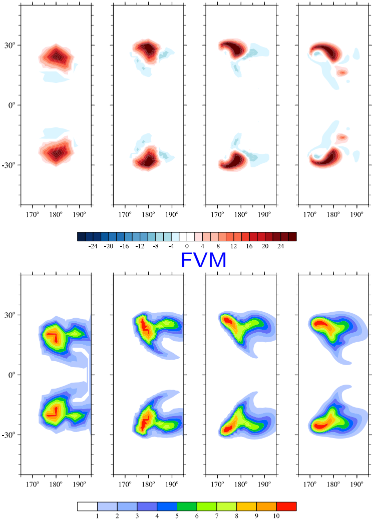
Mesoscale convective storm on reduced-size planet

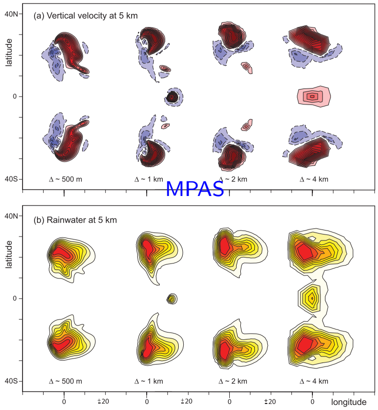
Supercell evolution (0.5, 1, 1.5, 2h) with FVM (left) and MPAS (right) at ≈ 0.5 km grid spacing (cf. Klemp et al. 2015):



Mesoscale convective storm on reduced-size planet

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





Vertical velocity (m/s) at 5 km

Rainwater (g/kg) at 5 km

Some relevant references

Further reading:

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