Numerics developments at ECMWF

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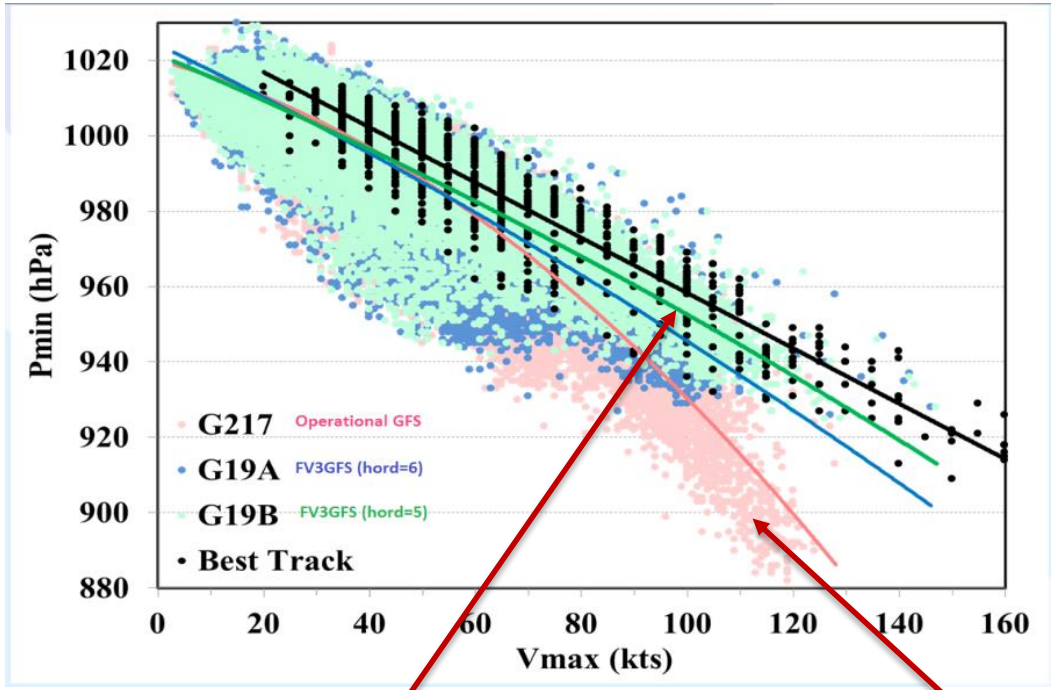
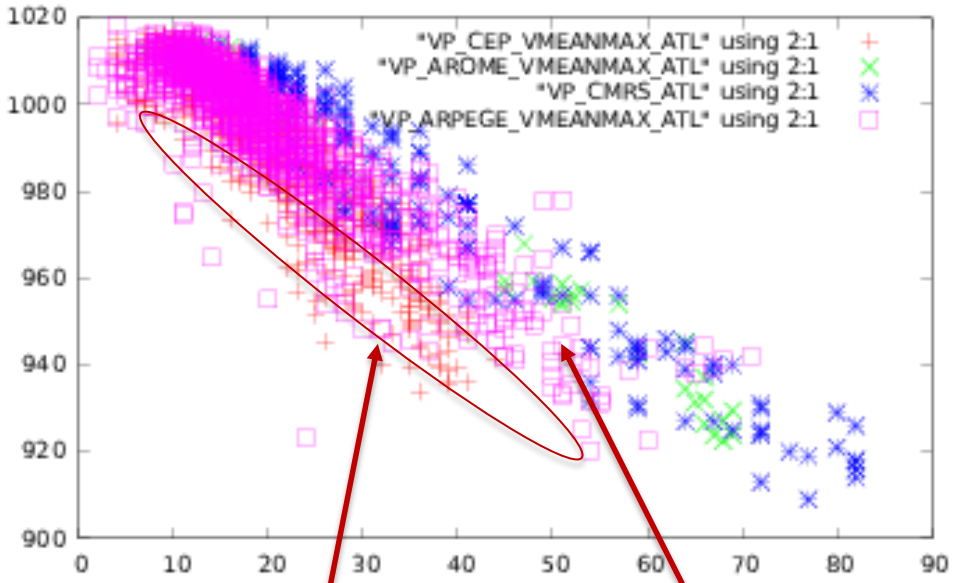
European Centre for Medium-Range Weather Forecasts (ECMWF)

Key points

- Sfc wind pressure relationship
- Stratosphere resolution dependence
- Vertical resolution vs higher order interpolations and higher order numerics
- Storm-scale horizontal resolutions
- FV vs spectral dynamical core
- Conservative FV vs semi-Lagrangian local higher order (DG)

Tropical cyclones:
10m wind - pressure relationship FV3, ARPEGE, IFS in Atlantic Basin





FV3

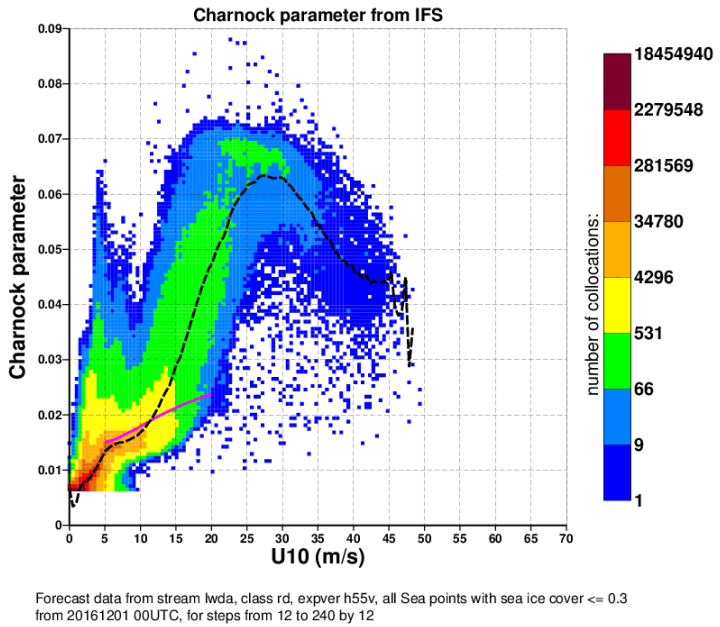
GFS

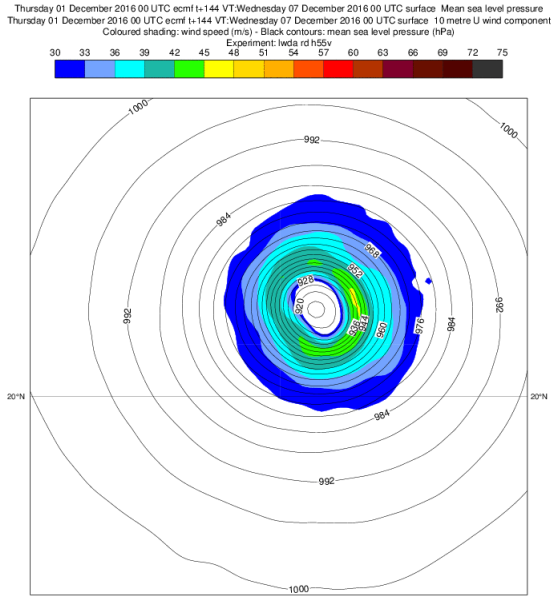
IFS

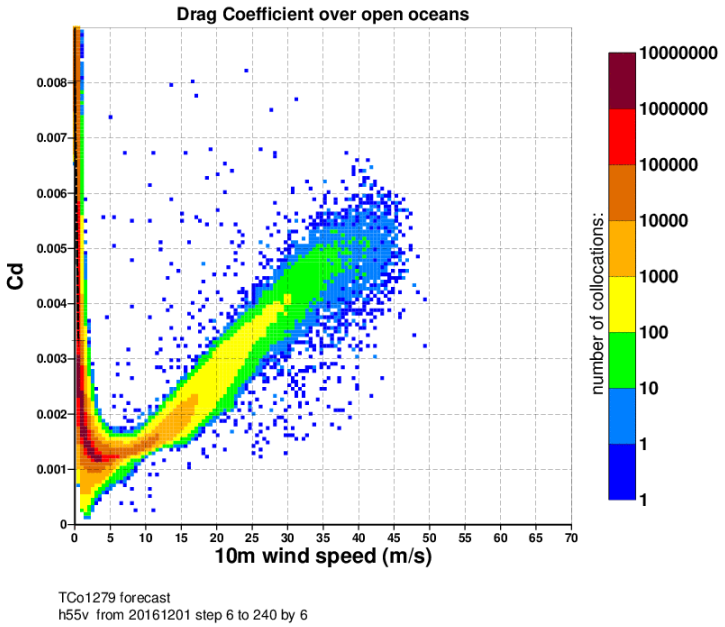
Arpege

Dynamical core or physics ?

Idealised tropical cyclone with 2-way coupled waves: CY46R1



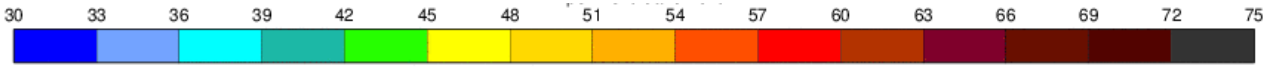




Charnock v U10

U10 and MSLP at t+144

Cd v U10



Bidlot et al

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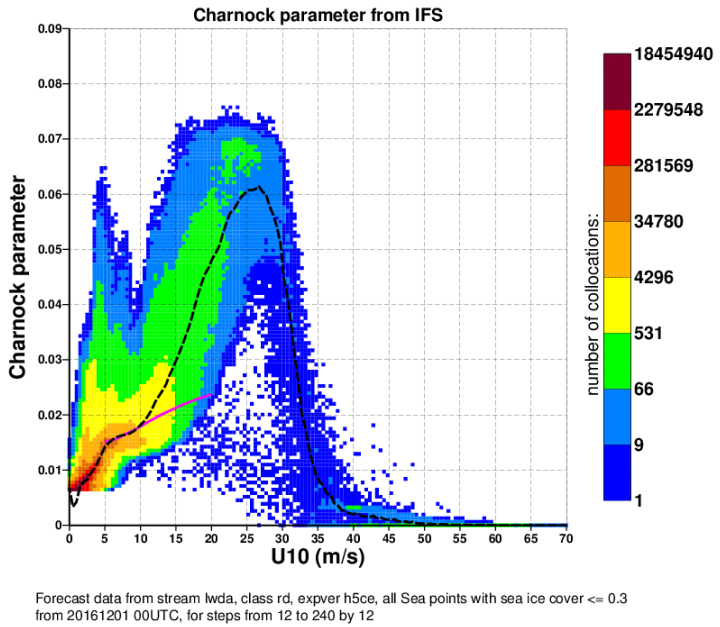
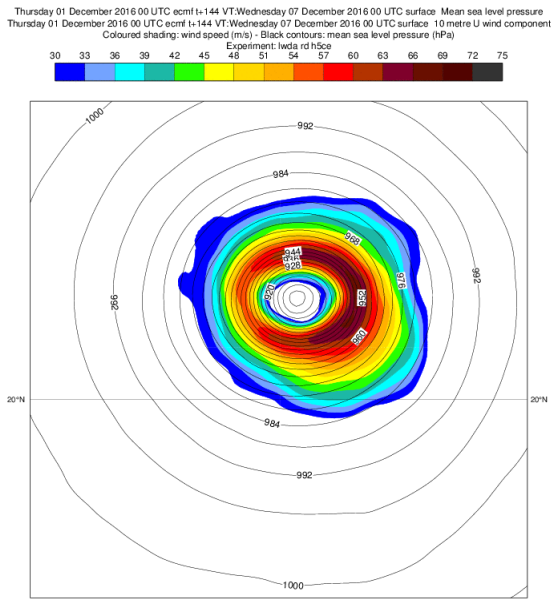
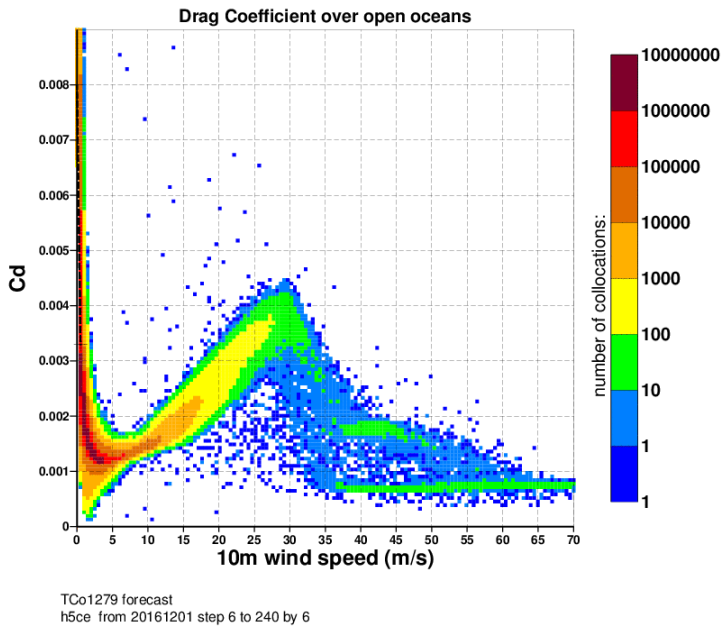
Idealised tropical cyclone with 2-way coupled waves : CY46R1 + limitation on Charnock







Charnock v U10

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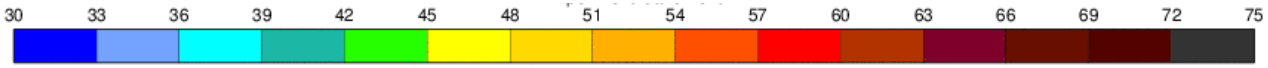


Bidlot et al

ECMWF

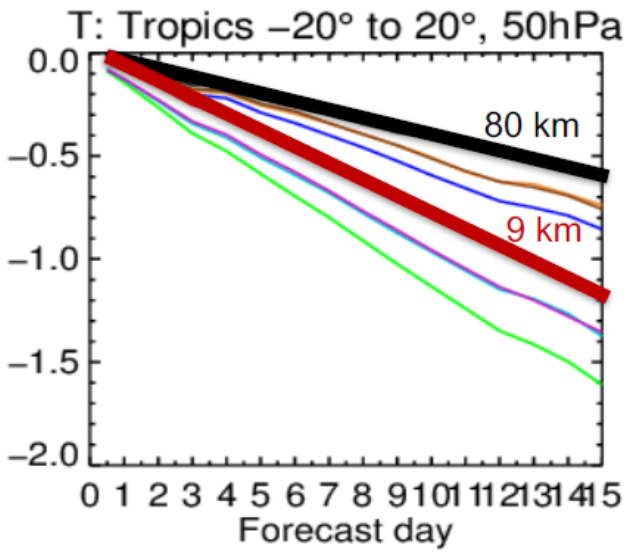
Stratosphere

Inna Polichtchouk

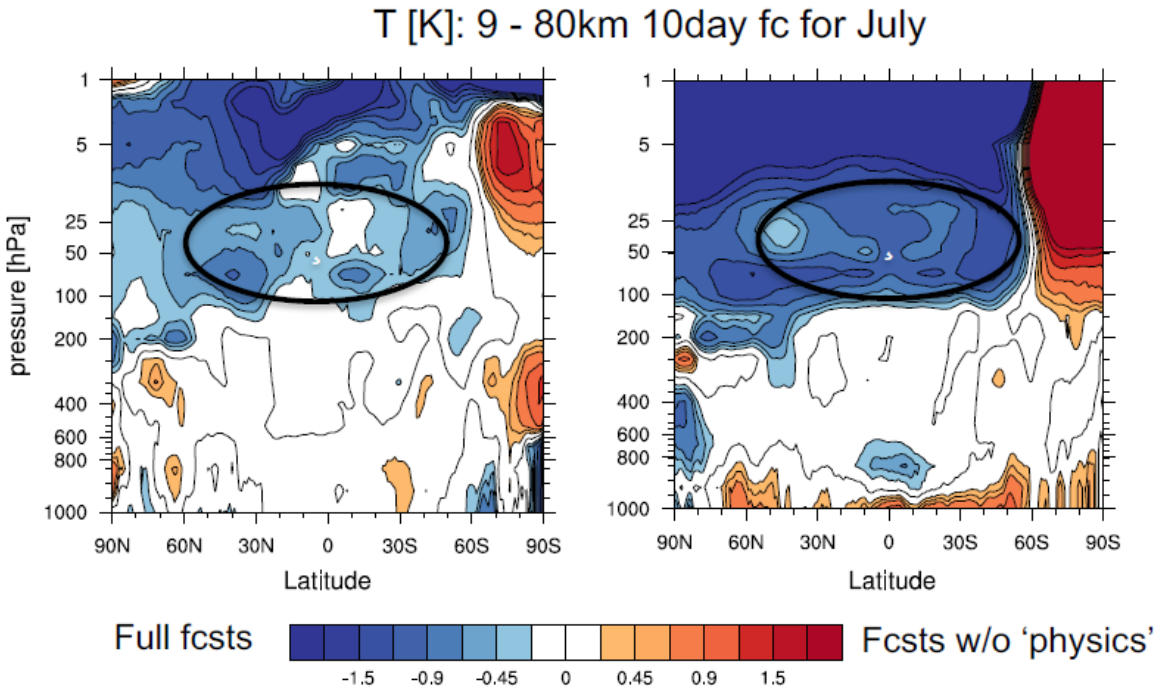
Horizontal resolution sensitivity of temperature biases

Stratosphere cools in the global mean with increase **in horizontal resolution** → biases **worse** in the lower- to mid- stratosphere with increase in horizontal resolution. Affects all forecast ranges, from medium to seasonal.

Resolved dynamics the culprit. Forecasts with no physical parametrizations, show the same horizontal resolution.



Verification against analysis

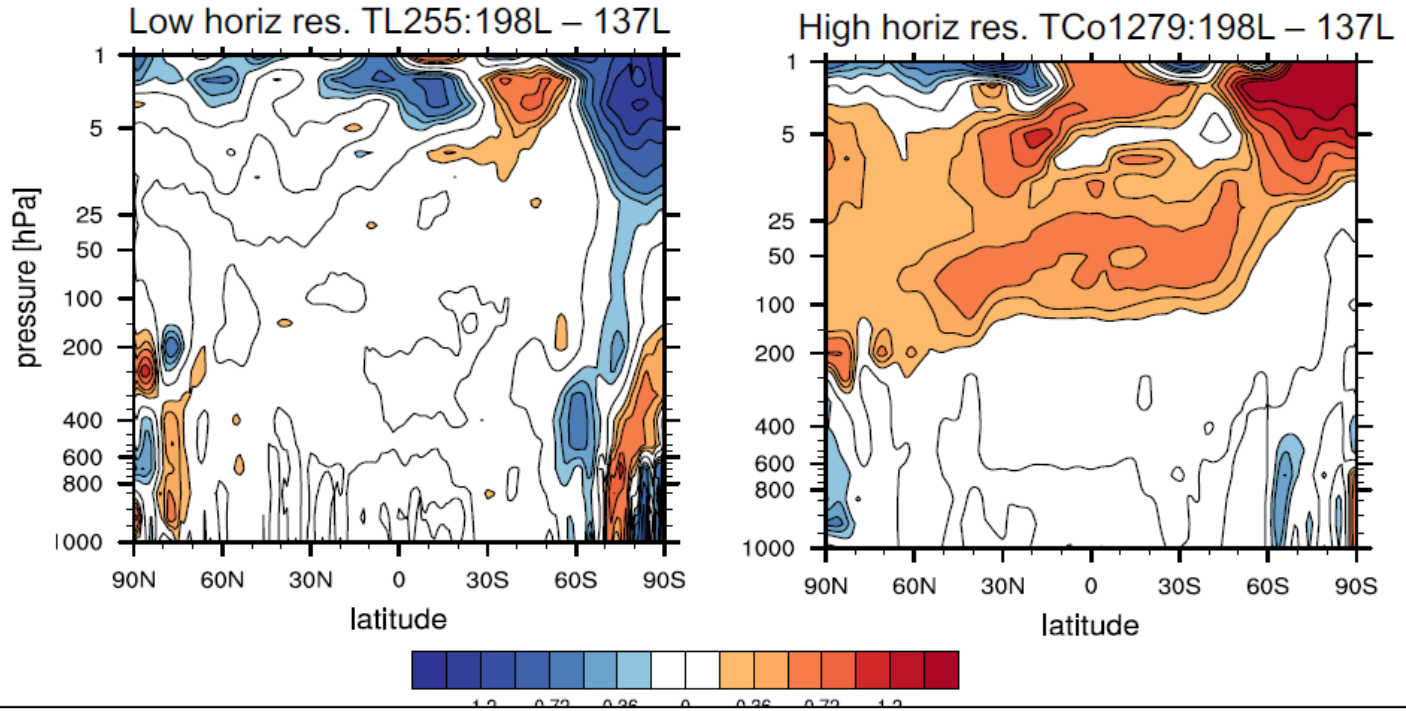


Inna Polichtchouk

Vertical resolution sensitivity of temperature

Question: Does increasing **vertical resolution** eliminate the horizontal resolution sensitivity?

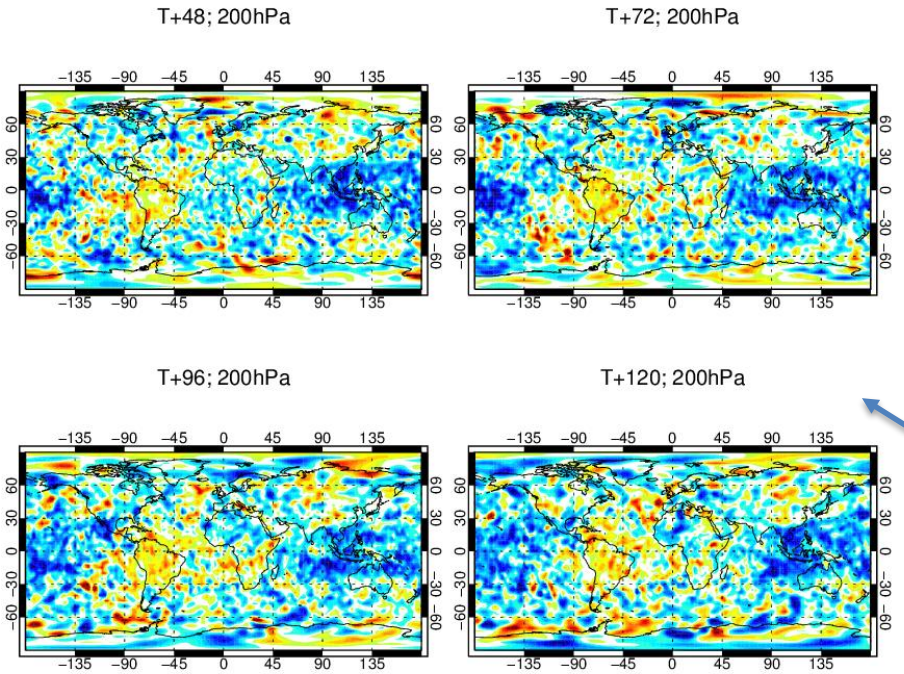
200m vertical resolution in the 150-50hPa region enough to eliminate horizontal resolution sensitivity (up to TCo1279 horizontal resolution).



High order departure point calculation scheme option for CY47R1

Available in 47r1 (implemented by F. Vana)

0	0	0	0
1/2	5/24	1/3	−1/24
1	1/6	2/3	1/6
	1/6	2/3	1/6



Lobato IIIA Runge-Kutta for DP: similar properties as Crank-Nicolson but higher order

- 4th order
- A-stable
- Symmetric
- Requires solution of two implicit stages which is done iteratively as the SETTLS scheme (more expensive)

Initialise with an explicit method and then iterate:

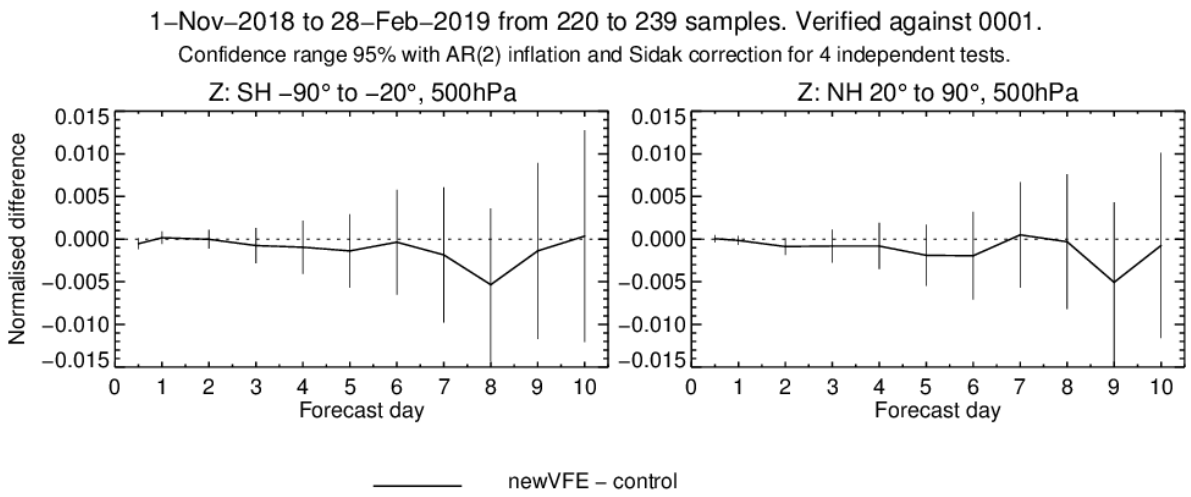
$$\mathbf{r}_M^{(l)} = \mathbf{r}_A - \frac{\Delta t}{24}\left[5\mathbf{V}^{t+\Delta t}(\mathbf{r}_A) + 8\mathbf{V}^{t+\Delta t/2}(\mathbf{r}_M^{(l-1)}) - \mathbf{V}^{t}(\mathbf{r}_D^{(l-1)})\right]$$

$$\mathbf{r}_D^{(l)} = \mathbf{r}_A - \frac{\Delta t}{6}\left[\mathbf{V}^{t+\Delta t}(\mathbf{r}_A) + 4\mathbf{V}^{t+\Delta t/2}(\mathbf{r}_M^{(l)}) + \mathbf{V}^{t}(\mathbf{r}_D^{(l-1)})\right], \qquad \ell = 1, 2, \ldots$$

- RK4 with quadratic wind interpolation (at M, D) in above iterations
- Research experiments at tco399~25km res are overall neutral but show some improvement at 200 hPa temperature
- Extra cost ~ 10% mainly due to quadratic wind interpolation

Collaboration with member states (J. Vivoda): new VFE for H/NH IFS

- *Hydrostatic-IFS: Finite Element discretization in the vertical (VFE)*
- *NH-IFS: Finite Differences discretization (applying FE to NH not straightforward due to C1 constraint)*
- *New VFE (Vivoda, Smolikova, Simarro MWR 2018) overcomes "C1 condition"restriction at the price of a small computational overhead:*
  - *A single code base for a unified H & NH version that is stable and can have order of up to 12*
  - *Remapping of integration interval in [0,1] and polynomial evaluation with use of synthetic division algorithm enables use of single precision in high order*
  - *Having the same discretization for both H and NH model will allow use of same numerics and "fair" straightforward comparisons between the two formulations*

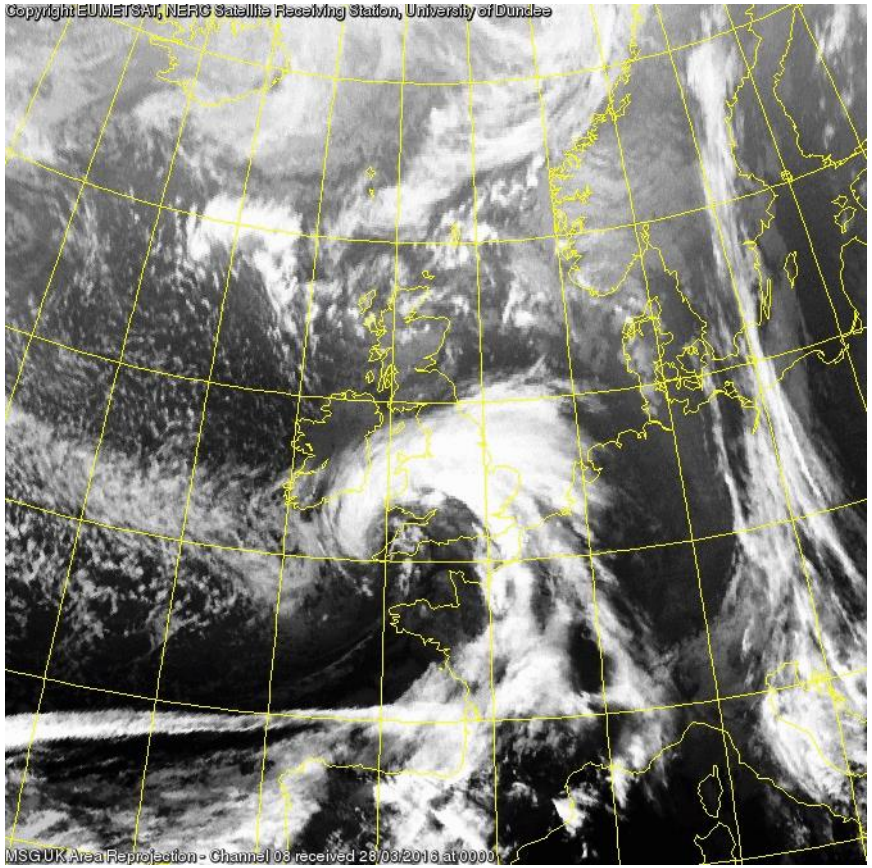


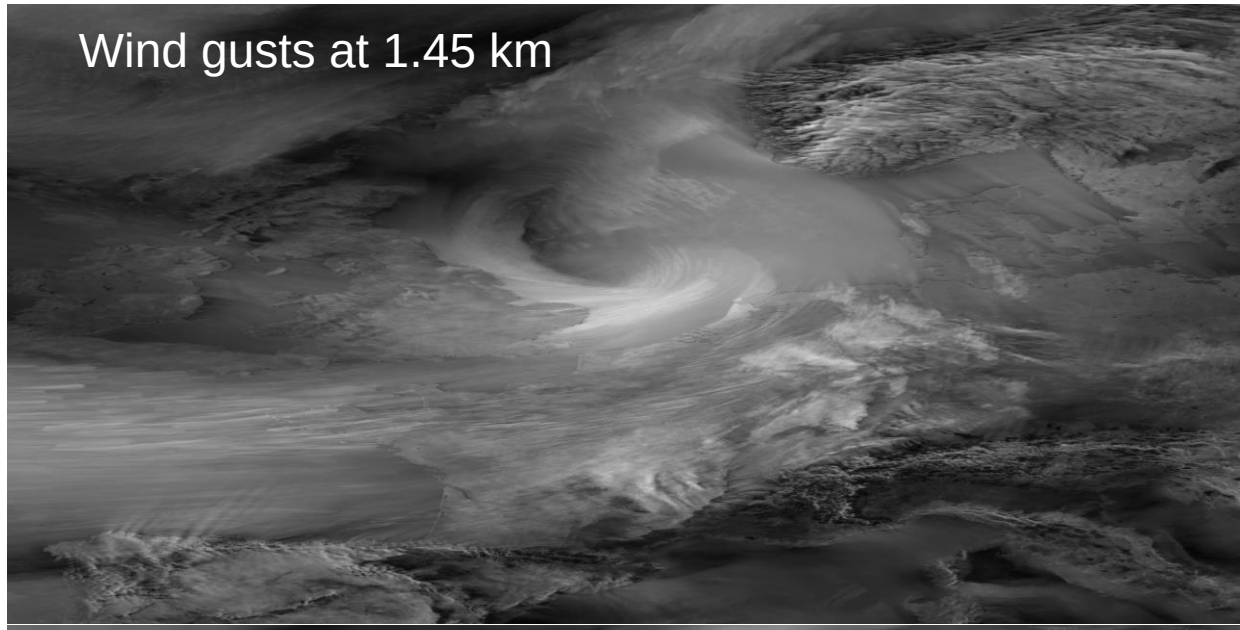
New VFE compared with current scheme in the hydrostatic model:

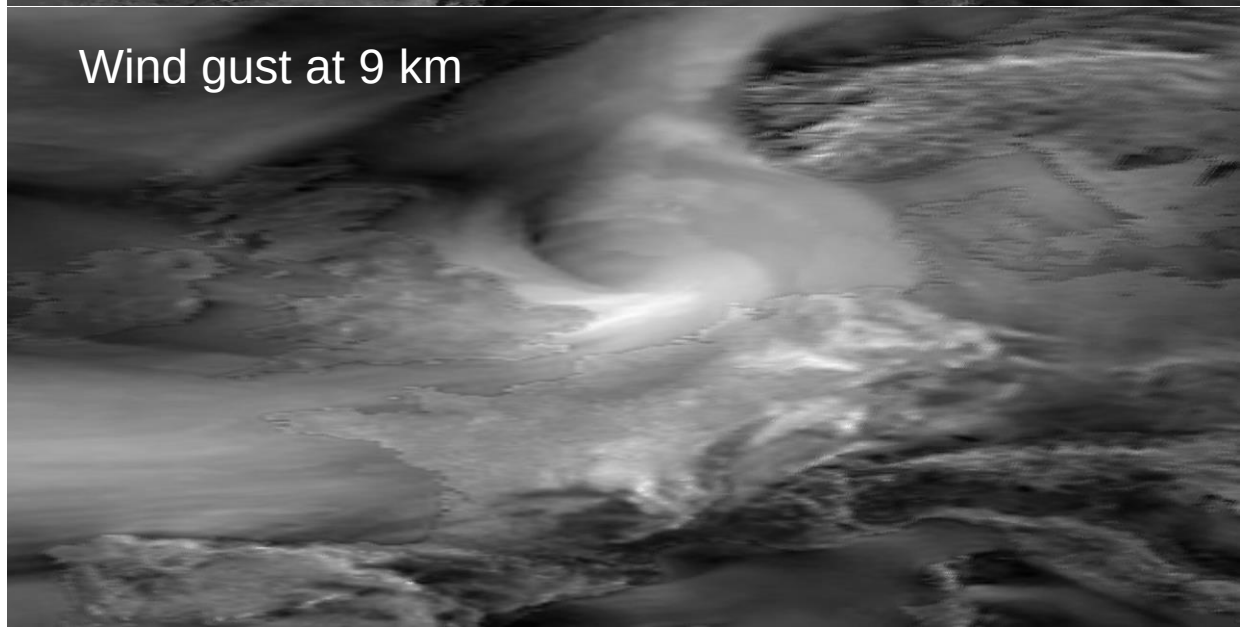
- Same cost
- Neutral scores
- High order VFE gave neutral scores
- Reduces mean temperature in upper stratosphere – improves tco399 RMSE but that depends on resolution and pre-existing biases
- New VFE could be adopted and replace current one (future work)

Improved surface boundary layer description

… wind gust details at 1.45km



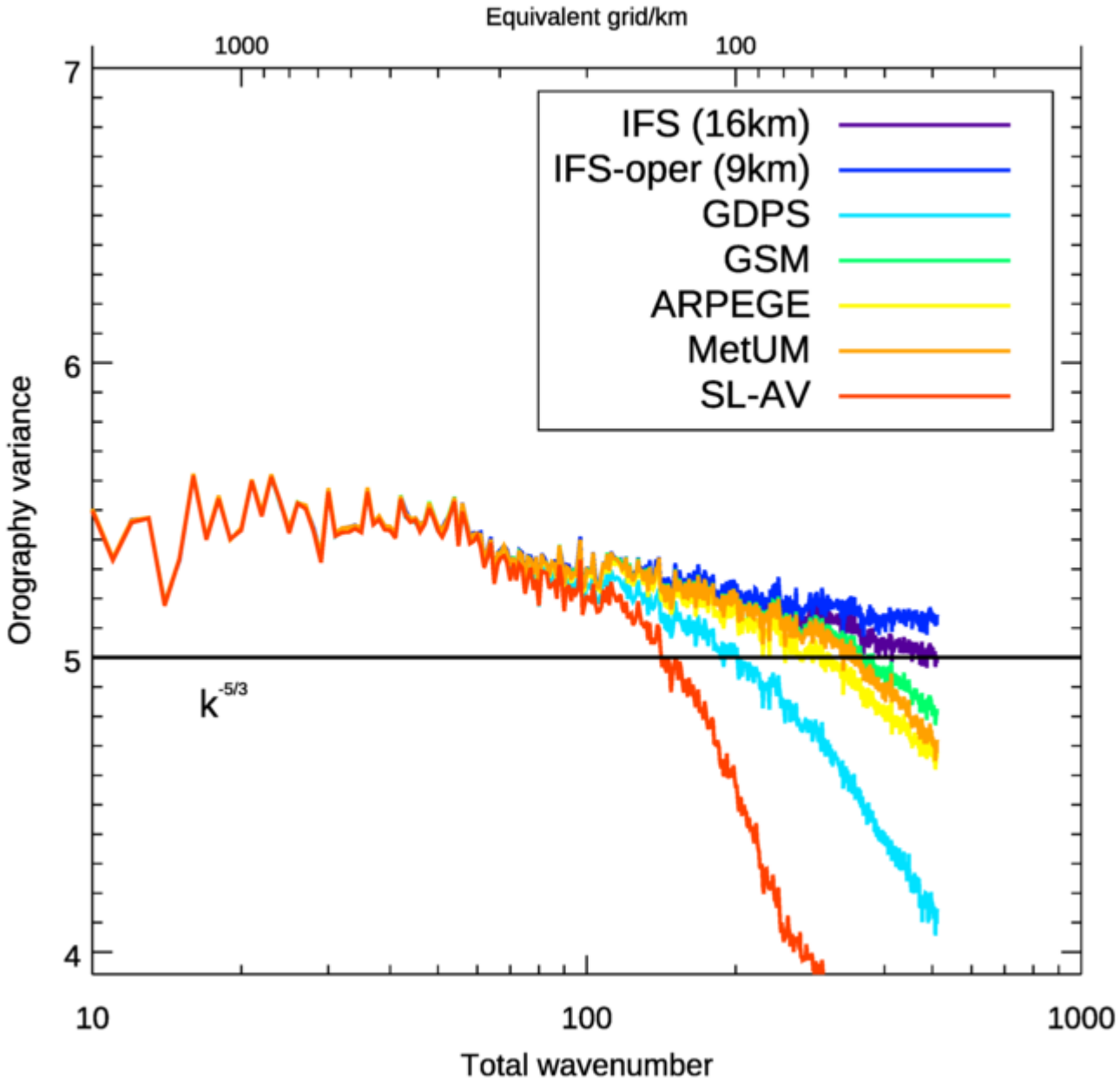




Orography representation

- Differences in orography (and associated filters applied) have a significant impact on surface stresses and circulation patterns on weather & climate models.

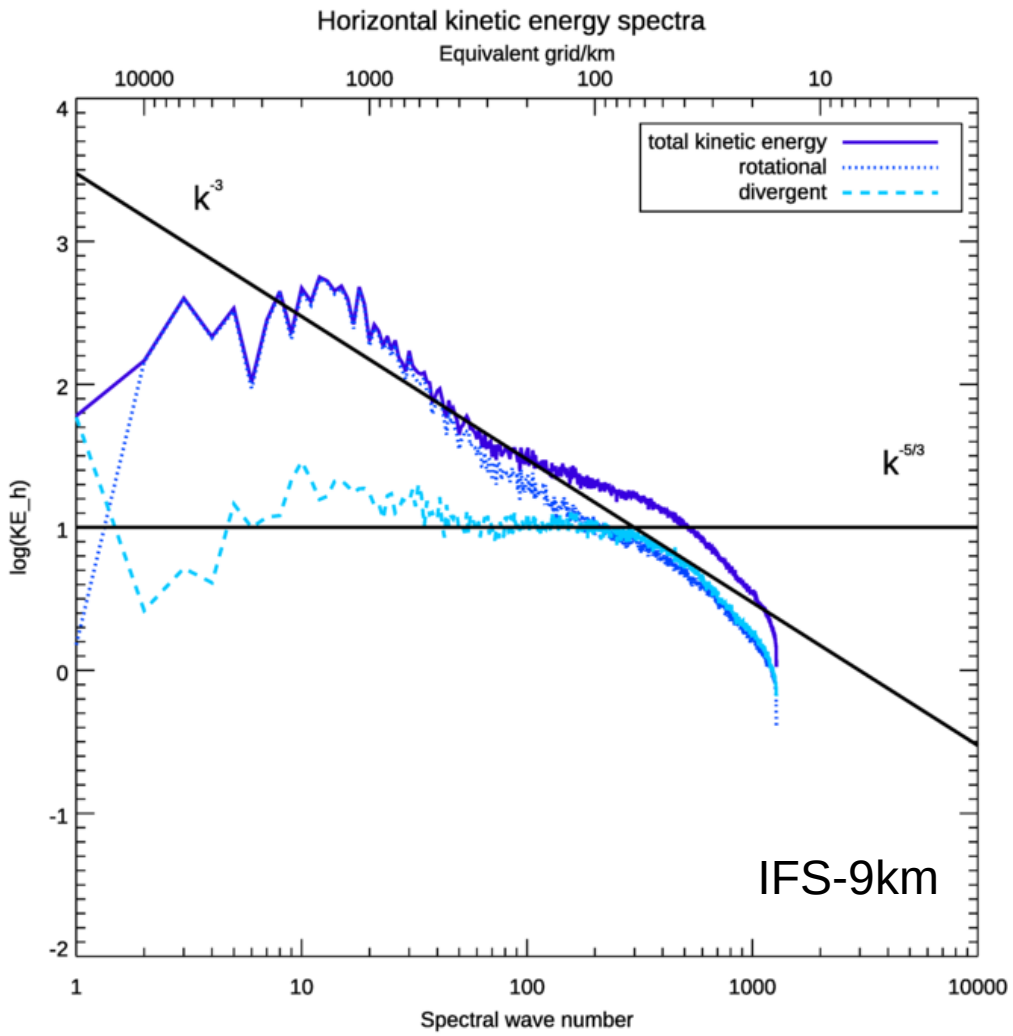
Elvidge et al 2019

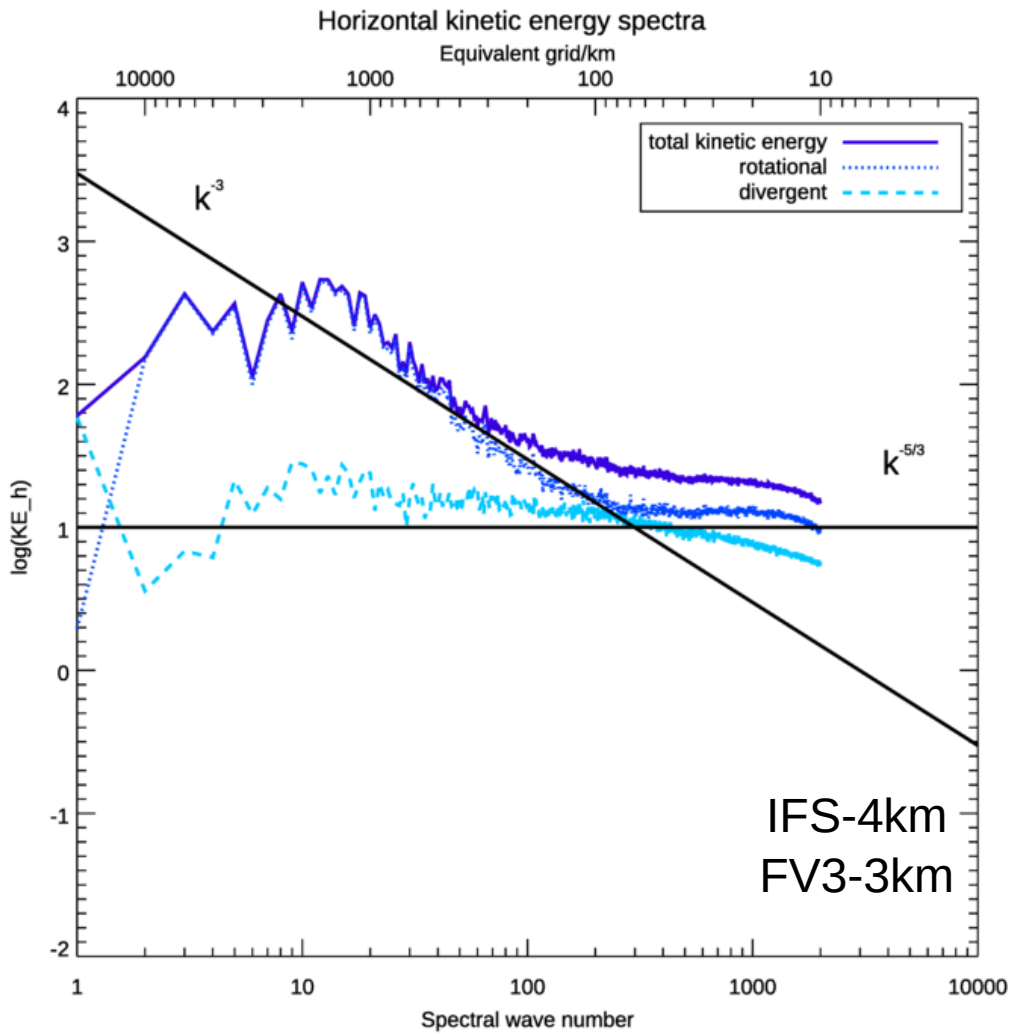


ECMWF

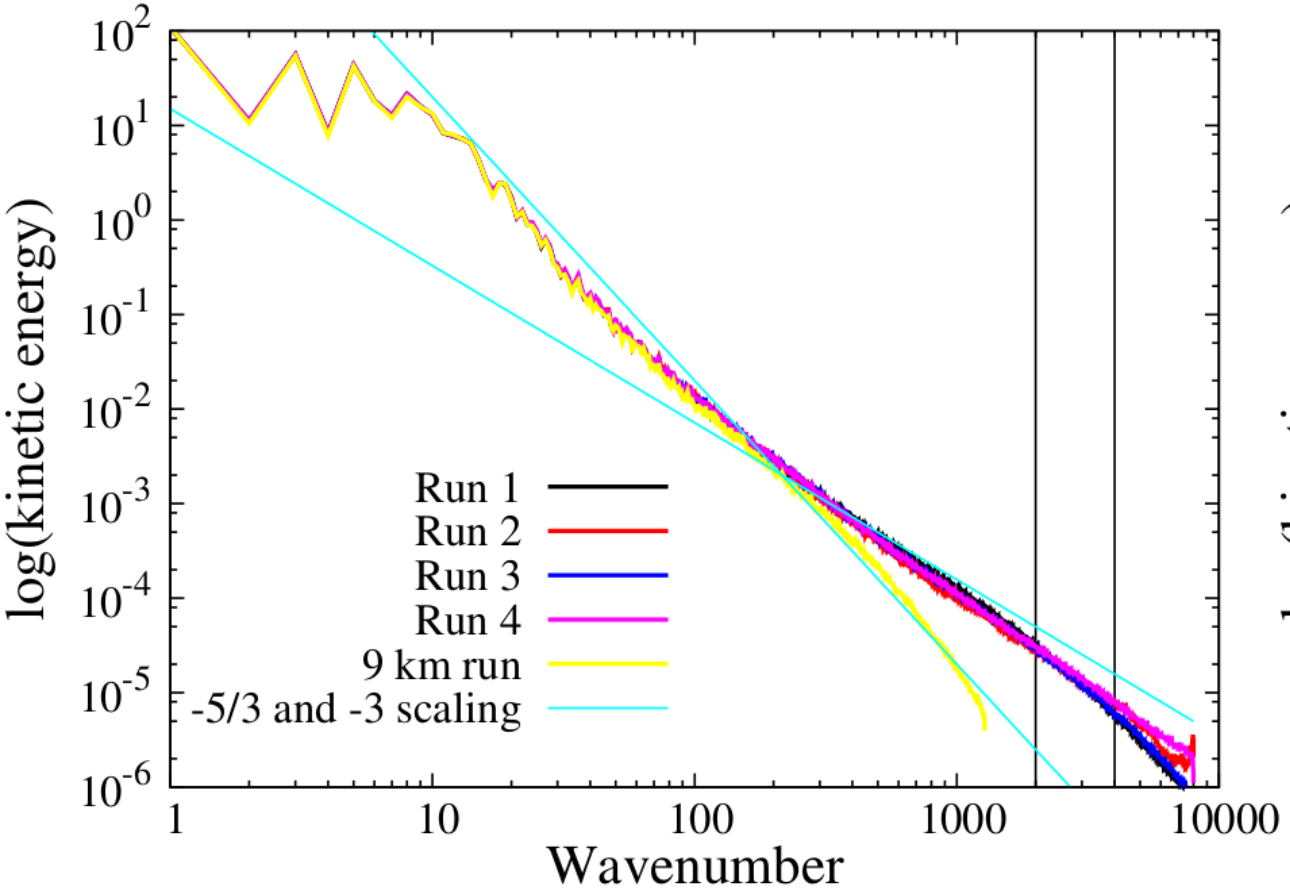
IFS vs FV3 kinetic energy spectra 200hPa

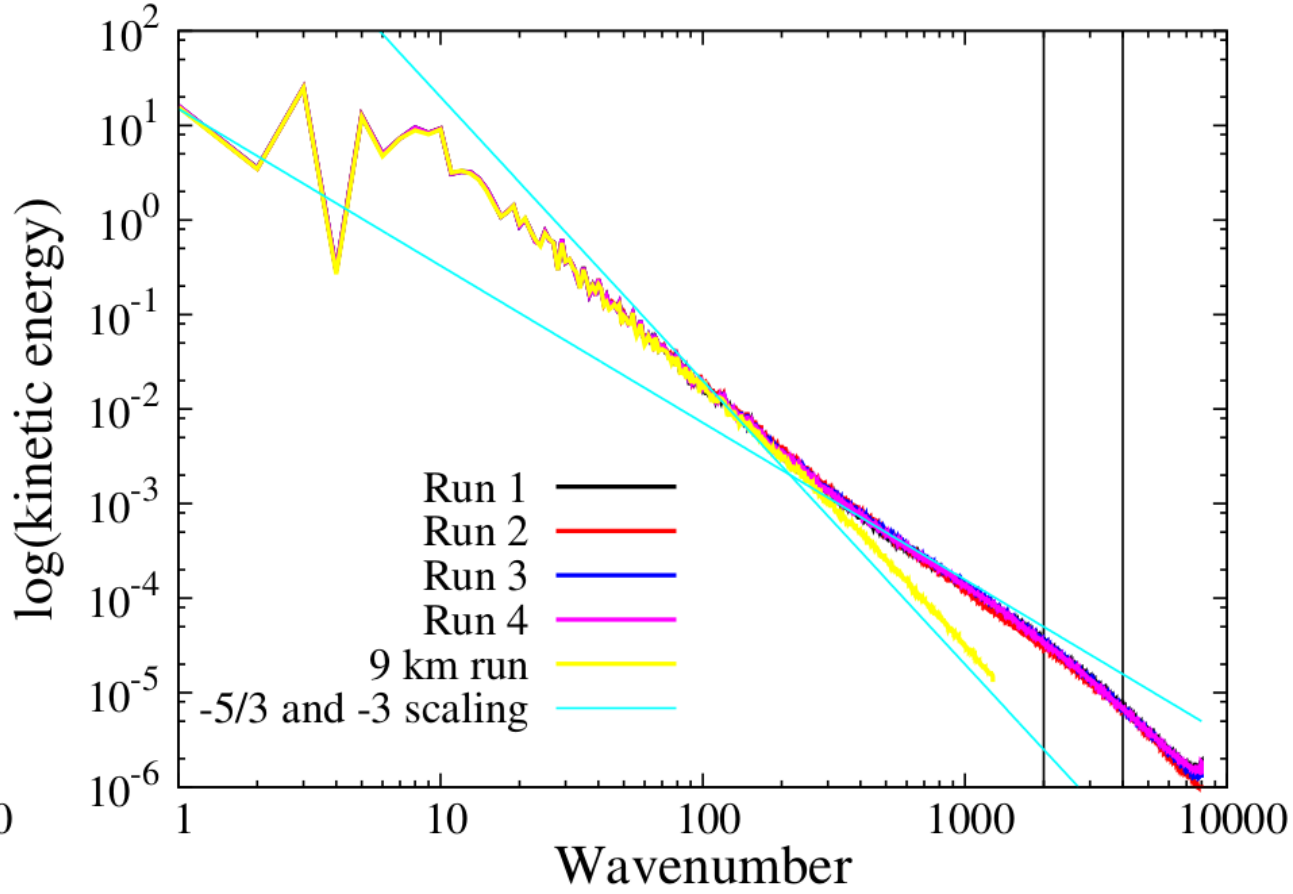
T+48h
Same initial conditions
Dyamond





Energy spectra





- The spectra @1.45 km are reasonable and show clear improvements compared to a simulations at 9 km.
- Effective resolutions is between 5 and 10 km.

Dueben et al, 2019

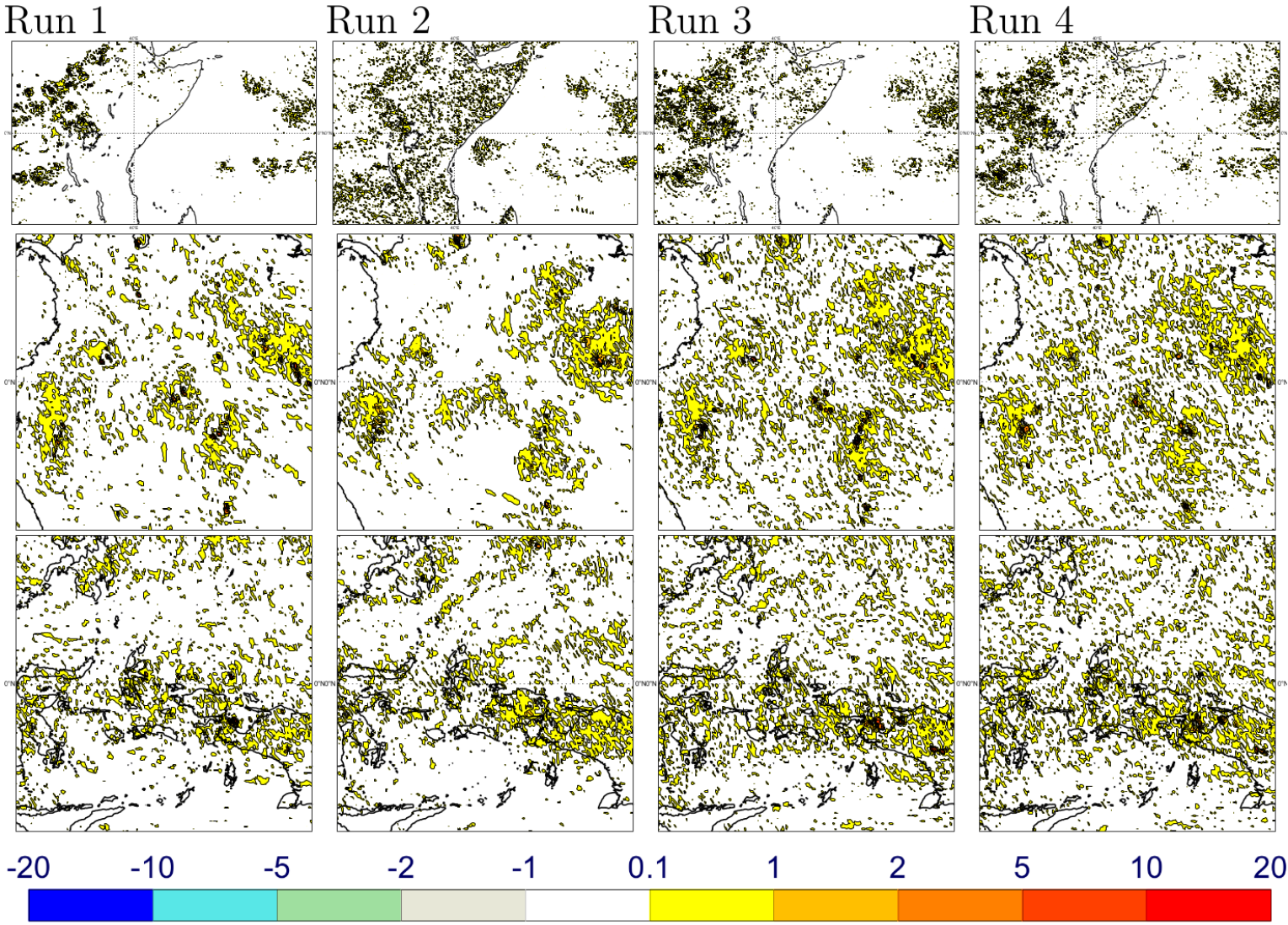
Vertical velocity [m/s]

Run 1: H, 120s, 0PC; **Run 2:** NH, 120s, 1PC; **Run 3:** H, 30s, 2PC; **Run 4:** NH, 30s, 2PC

- Run 1 shows the smallest area with strong convection
- Run 1 and 2 are similar
- Run 3 and 4 are similar

-> small differences between H and NH

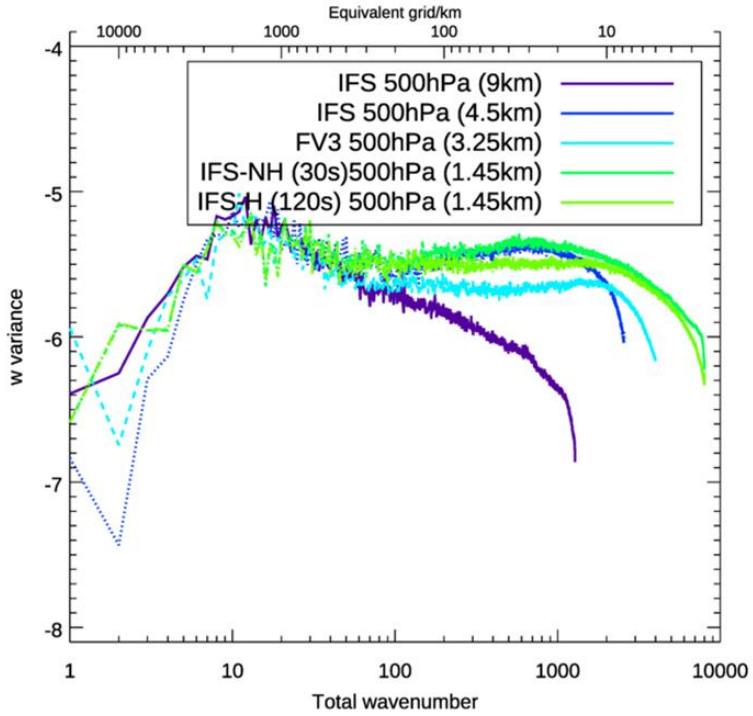
-> large differences as Function of time step choice



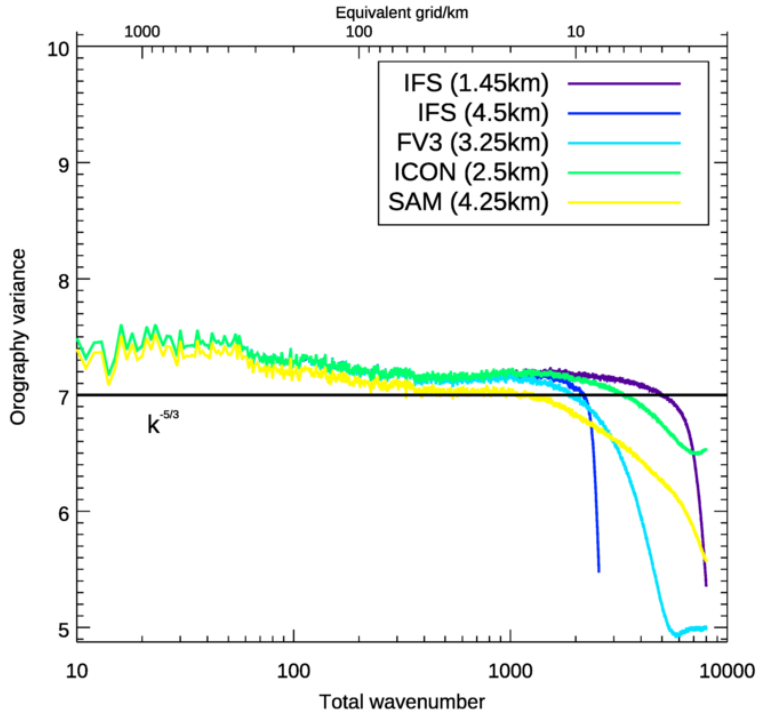
Dueben et al, 2019

Dyamond Project – storm-scale resolving simulations

Vertical velocity



Orographic variance

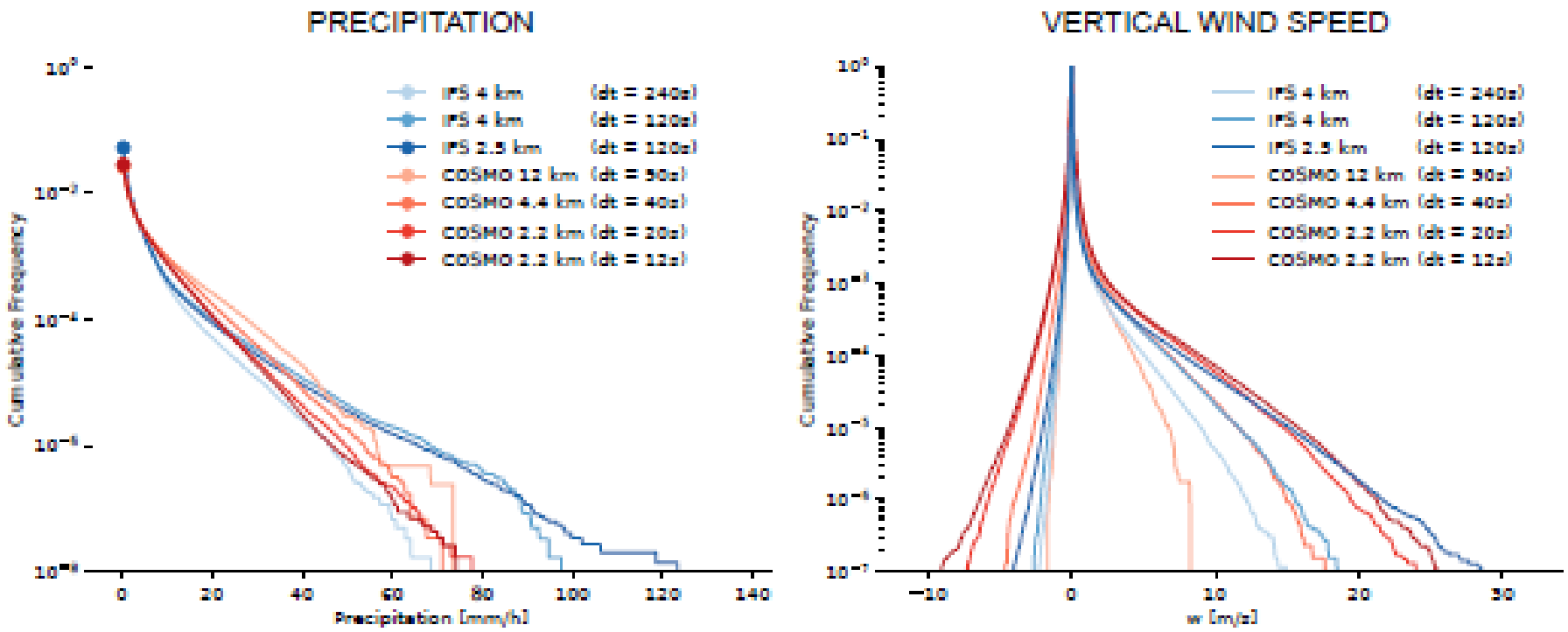


The ESiWACE project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 675191.

esiwace
CENTRE OF EXCELLENCE IN SIMULATION OF WEATHER AND CLIMATE IN EUROPE

Cumulative frequency plots of precipitation and vertical wind speed at 500 hPa based on hourly output from 2 days

Grey zone of convection



Christian Zeman (ETH) et al, 2019

Main findings:

- IFS shows considerably more light precipitation than COSMO.
- Precipitation and updraft velocities change drastically when the timestep is halved in IFS.
- COSMO produces similar updraft but much higher downdraft velocities than IFS.

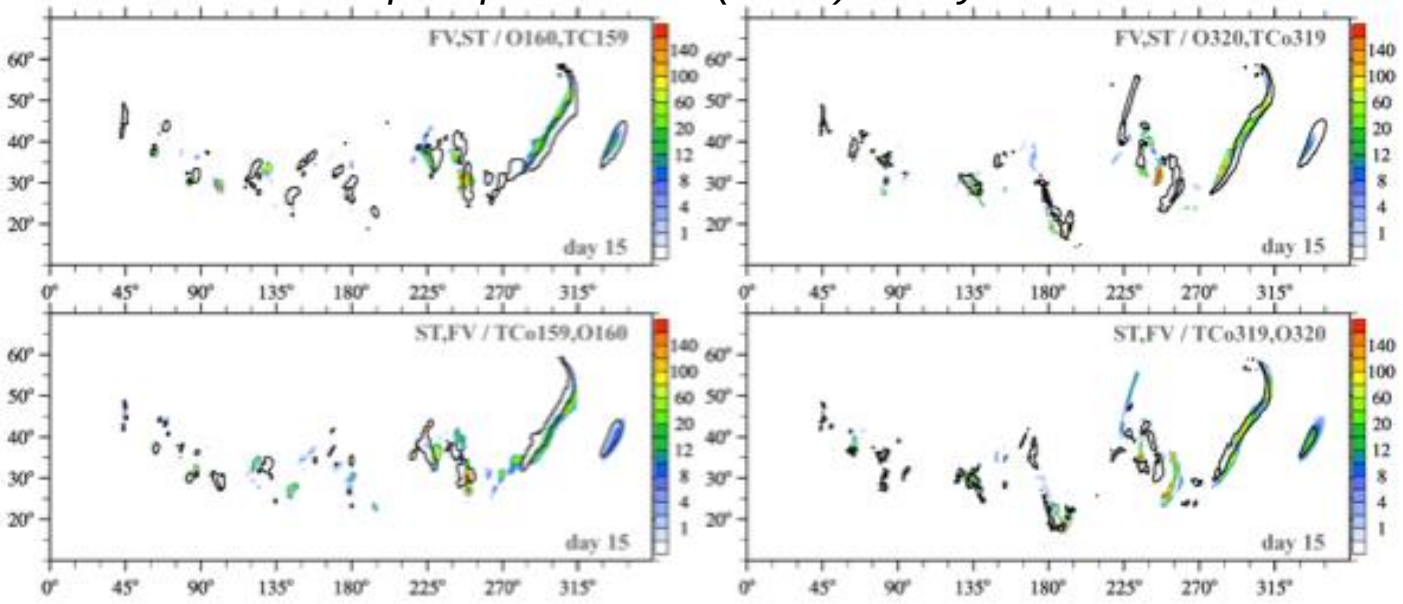
IFS dynamical core options

Model aspect	IFS-FVM	IFS-ST	IFS-ST (NH option)
Equation system	fully compressible	hydrostatic primitive	fully compressible
Prognostic variables	$\rho_d, u, v, w, \theta', \varphi', r_v, r_l, r_r, r_i, r_s$	$\ln p_s, u, v, T_v, q_v, q_l, q_r, q_i, q_s$	$\ln \pi_s, u, v, d_4, T_v, \hat{q}, q_v, q_l, q_r, q_i, q_s$
Horizontal coordinates	λ, ϕ (lon–lat)	λ, ϕ (lon–lat)	λ, ϕ (lon–lat)
Vertical coordinate	generalized height	hybrid sigma–pressure	hybrid sigma–pressure
Horizontal discretization	unstructured finite volume (FV)	spectral transform (ST)	spectral transform (ST)
Vertical discretization	structured FD–FV	structured FE	structured FD or FE
Horizontal staggering	co-located	co-located	co-located
Vertical staggering	co-located	co-located	co-located, Lorenz
Horizontal grid	octahedral Gaussian or arbitrary	octahedral Gaussian	octahedral Gaussian
Time stepping scheme	2-TL SI	2-TL constant-coefficient SI	2-TL constant-coefficient SI with ICI
Advection	conservative FV Eulerian	non-conservative SL	non-conservative SL

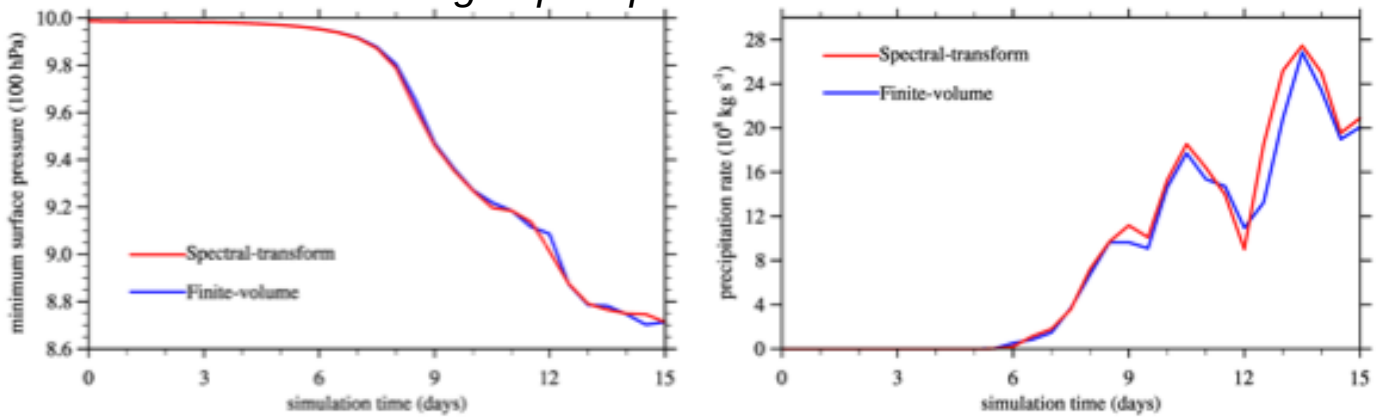
(Kühnlein et al, 2019)

IFS-FVM (finite-volume) comparison to hydrostatic IFS-ST: moist-precipitating dynamics and coupling to IFS physics parametrisations

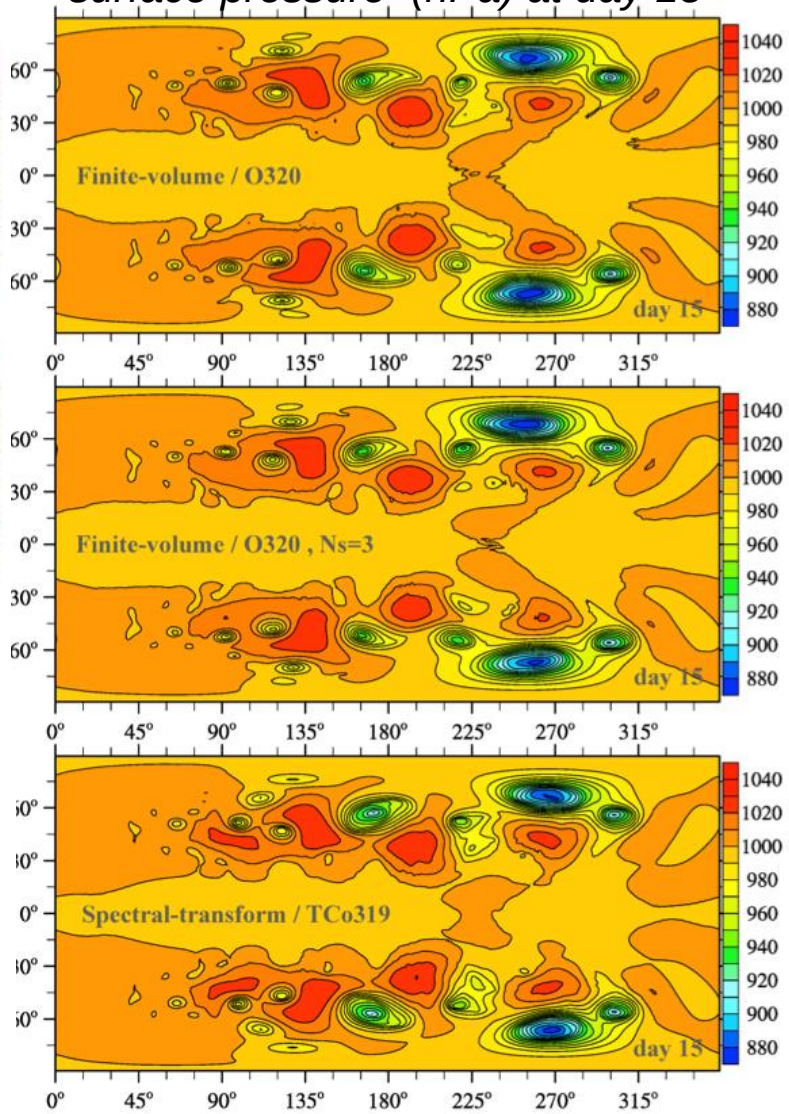
precipitation rate (mm/h) at day 15



Area-averaged precipitation rate with simulation time



surface pressure (hPa) at day 15



(Kühnlein et al, 2019)

Generalised perturbation equations for all scale atmospheric dynamics

Smolarkiewicz, Kühnlein & Wedi, JCP (2019).

Defining perturbations $\Psi'(\mathbf{x},t) := \Psi(\mathbf{x},t) - \Psi_a(\mathbf{x},t)$ for dependent variables $\Psi(\mathbf{x},t)$ about an arbitrary "ambient" state $\Psi_a(\mathbf{x},t)$ that satisfies the governing equations leads to (e.g.)

$$\frac{d\theta'}{dt} = -\mathbf{v}' \cdot \nabla\theta_a + \mathcal{H}' \ ,$$

$$\frac{d\mathbf{u}'}{dt} = -\mathbf{v}' \cdot \nabla\mathbf{u}_a - \frac{\theta}{\theta_0}\widetilde{\mathbf{G}}\nabla\phi' - \frac{\theta'}{\theta_0}\widetilde{\mathbf{G}}\nabla\phi_a - \mathbf{f}\times\mathbf{u}' + \boldsymbol{\mathcal{M}}'(\mathbf{u},\mathbf{u}_a) + \boldsymbol{\mathcal{D}}'(\mathbf{u},\mathbf{u}_a)$$

GBIS

where:

$$\widetilde{\mathbf{G}}\nabla\phi_a = \frac{\theta_0}{\theta_a}\left(\mathbf{g} - \mathbf{f}\times\mathbf{u}_a + \boldsymbol{\mathcal{M}}(\mathbf{u}_a) + \boldsymbol{\mathcal{D}}(\mathbf{u}_a) - \frac{d_a\mathbf{u}_a}{dt}\right)$$

$$\mathcal{H}' = \mathcal{H} - \mathcal{H}_a \ ,$$

$$\mathbf{v}' = \widetilde{\mathbf{G}}^T\mathbf{u}' \ ,$$

$$\boldsymbol{\mathcal{M}}'(\mathbf{u},\mathbf{u}_a) = \boldsymbol{\mathcal{M}}(\mathbf{u}' + \mathbf{u}_a) - \boldsymbol{\mathcal{M}}(\mathbf{u}_a) \ ,$$

$$\boldsymbol{\mathcal{D}}'(\mathbf{u},\mathbf{u}_a) = \boldsymbol{\mathcal{D}}(\mathbf{u}' + \mathbf{u}_a) - \boldsymbol{\mathcal{D}}(\mathbf{u}_a) \ , \qquad \boldsymbol{\mathcal{D}}' = \boldsymbol{\mathcal{D}}(\mathbf{u}')$$

for flow independent viscosity

REF used in the Kühnlein et al. GMD (2019) comparisons of IFS-FVM & IFS-ST (baroclinic instability test case without initial perturbations)

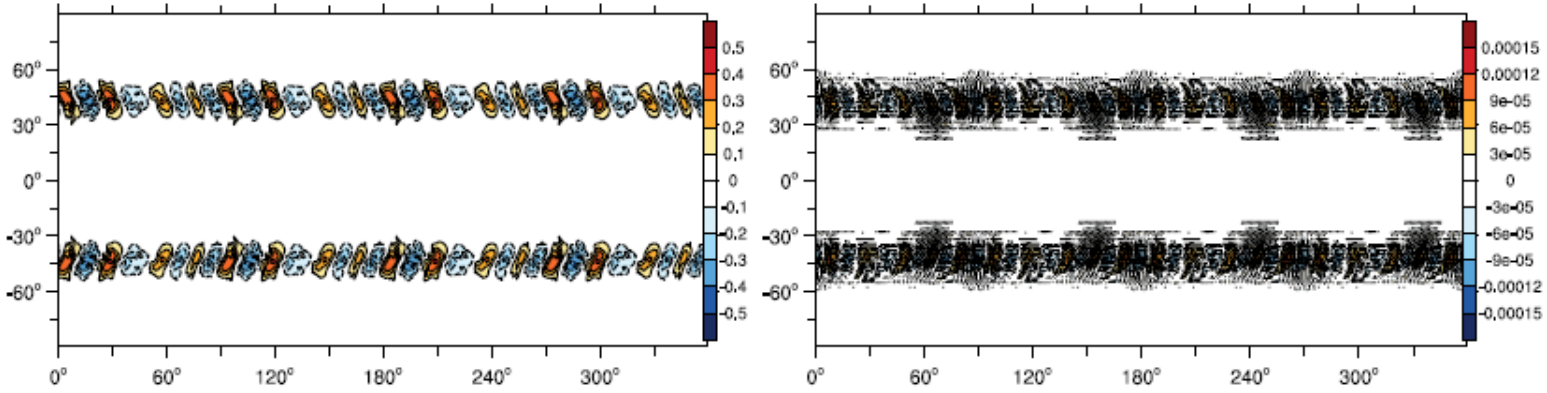


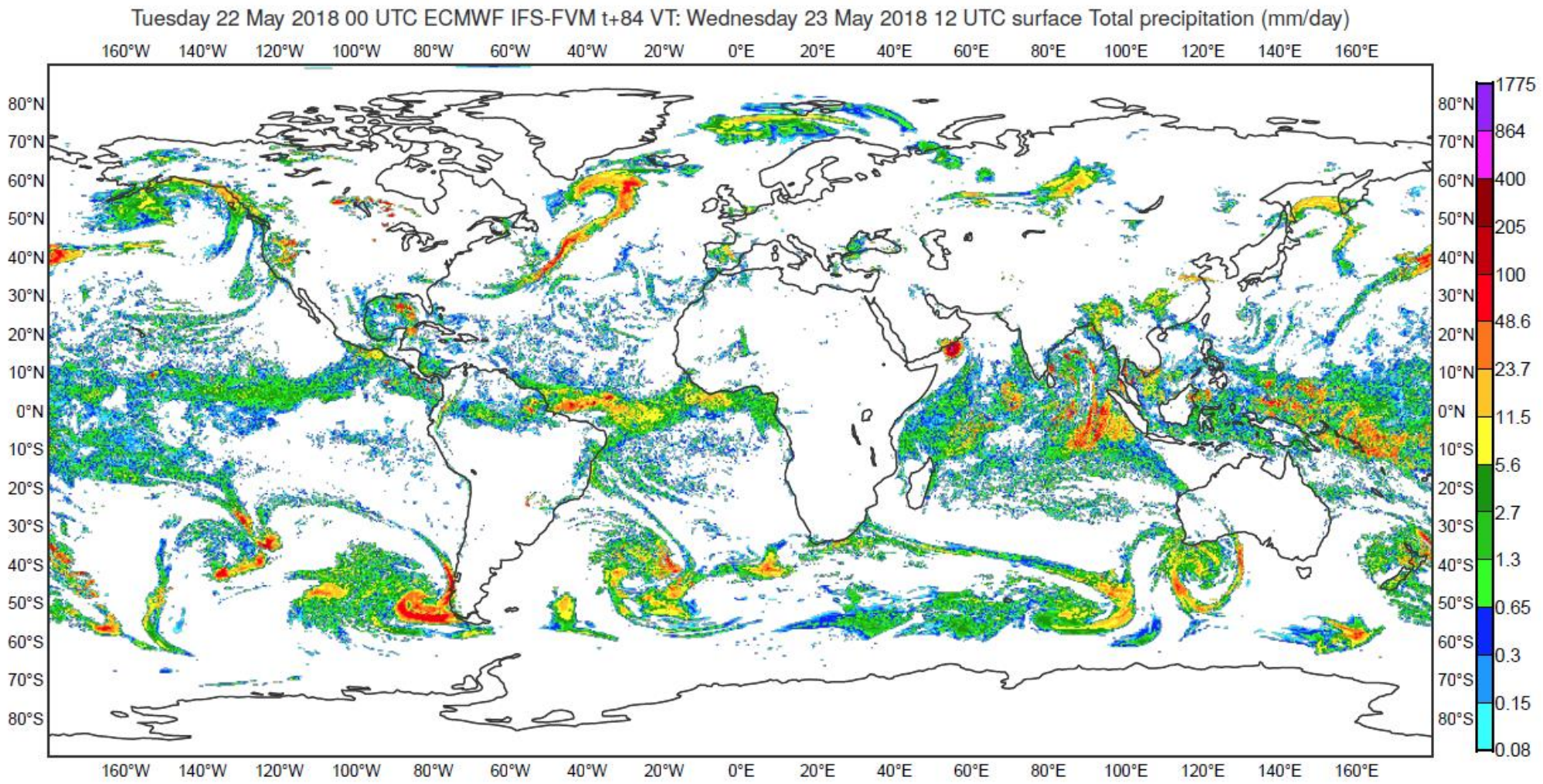
Fig. 2. The 18 days surface θ' REF (left) and GBIS (right) solutions on the O180 grid without the initial perturbation.

The corresponding O640 (~18km) mesh results (average; standard deviation) are

REF: $(2.2 \times 10^{-4}; 2.4 \times 10^{-2})$ GBIS: $(2.7 \times 10^{-11}; 7.4 \times 10^{-6})$

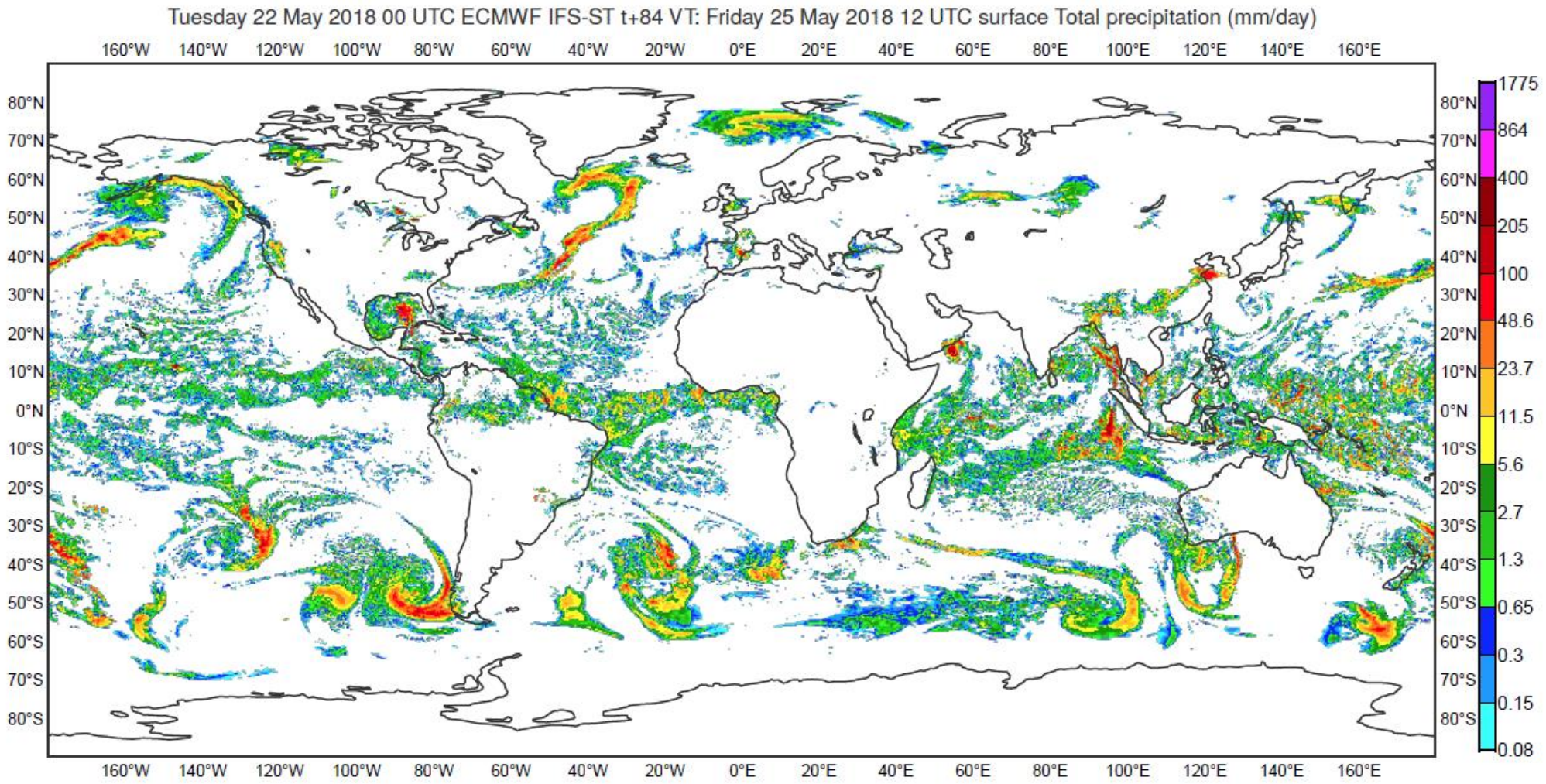
IFS-FVM

Total (instantaneous) precipitation rate, full ECMWF physics (except radiation) on the same TCo639 (~18km) grid after 3.5 days



IFS-ST

Total (instantaneous) precipitation rate, full ECMWF physics (except radiation) on the same TCo639 (~18km) grid after 3.5 days



Funded by the European Union

- Hardware is evolving fast, new approaches might be needed:
  - IFS is already very **high order** but is **not local**
  - FVM is **very local** but **not high order**

G. Tumolo,
L. Bonaventura, T. Benacchio,
W. Deconinck, A. Mueller

- The SL-DG approach combines high order accuracy and long time steps of IFS with locality of FVM. Combination with SI-DG treatment of fast waves terms.
- Design and implementation of the core structure of SISL-DG included so far
  - PANTHER - a parallel p-adaptive 3D DG library including DG operators on the sphere relevant for SI and SL techniques
  - 3D Eulerian DG (*EU*-DG) transport dwarf (flux form & advective form)
  - 3D SL-DG transport dwarf (advective form, based on Atlas)
- First Results:
  - ✓ Using tensor product of modal basis on quad elements extruded in vertical columns, one sided communications
  - ✓ EU-DG shows the best scaling but suffers from severe stability limitations
  - ✓ SL-DG unconditional stability + combination with SI-DG stencil seems promising

Additional slides