The IFS dynamical core in openIFS

A hands-on introduction to Numerical Weather Prediction Models

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Michail Diamantakis

michail.diamantakis@ecmwf.int

Talk Outline

- Equation sets, grids, and dynamical core overview
- Motivation, historical context for the introduction of semi-implicit, semi-Lagrangian methods
- Fundamental algorithms and their limitations
- The pros and cons of the IFS formulation:
  - conservation aspects and errors in IFS and how we deal with them
- Atlas, Atlas multiple grids and applications on advection

The ECMWF hydrostatic global operational model equation set

$$\frac{D\mathbf{V}_h}{Dt} + f\mathbf{k}\times\mathbf{V}_h + \nabla_h\Phi + R_d T_v \nabla_h \ln p = P_{\mathrm{v}}$$

$$\frac{DT}{Dt} - \frac{\kappa T_v \omega}{(1+(\delta-1)q)\,p} = P_{\mathrm{T}}$$

$$\frac{Dq_x}{Dt} = P_{\mathrm{q}_x}$$

$$\frac{\partial}{\partial t}\left(\frac{\partial p}{\partial \eta}\right) + \nabla_h \cdot \left(\mathbf{V}_h \frac{\partial p}{\partial \eta}\right) + \frac{\partial}{\partial \eta}\left(\dot{\eta}\frac{\partial p}{\partial \eta}\right) = 0$$

$$\Phi = \Phi_s - \int_1^{\eta} R_d T_v \frac{\partial}{\partial \eta}(\ln p)\, d\eta$$

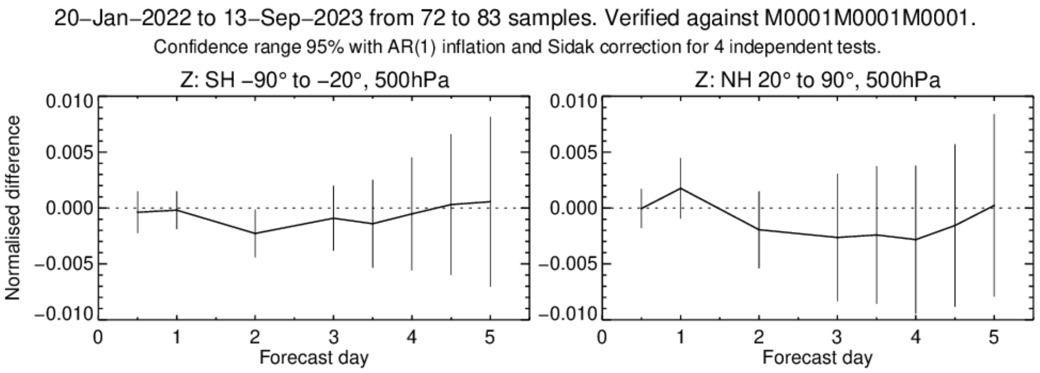
η : hybrid pressure based vertical coordinate
$\mathbf{V_h}$: horizontal momentum
T: temperature
T_v: virtual temperature (used as spectral variable)
q_x: specific humidity, specific ratios for cloud fields and other tracers x, $\delta = c_{pv}/c_{pd}$
Φ: geopotential
p : pressure
$\omega = dp/dt$: diagnostic vertical velocity
P: physics forcing terms

Continuity equation in terms of full (moist) pressure: the model conserves the total (rather than dry) atmospheric mass.

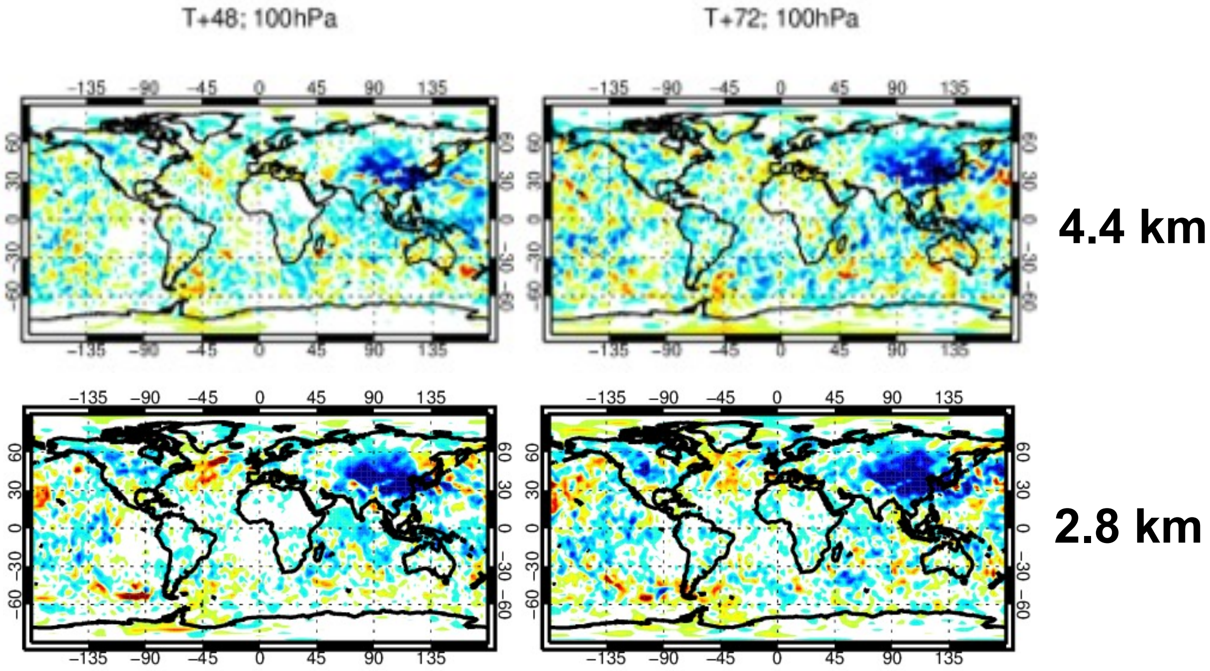
- Primitive equation hydrostatic
- A **non-hydrostatic** option is available **for research** purposes but not used operationally or in openIFS
- Spectral Transform with spherical harmonics basis
- Cubic spline Finite Elements in the vertical
- Timestepping: semi-Lagrangian semi-implicit

Non-hydrostatic versus Hydrostatic IFS systematic comparisons

- **Is the hydrostatic assumption in IFS valid at 3-10km grid spacing?**
- **Consider that its effective resolution is 4-6 times higher**



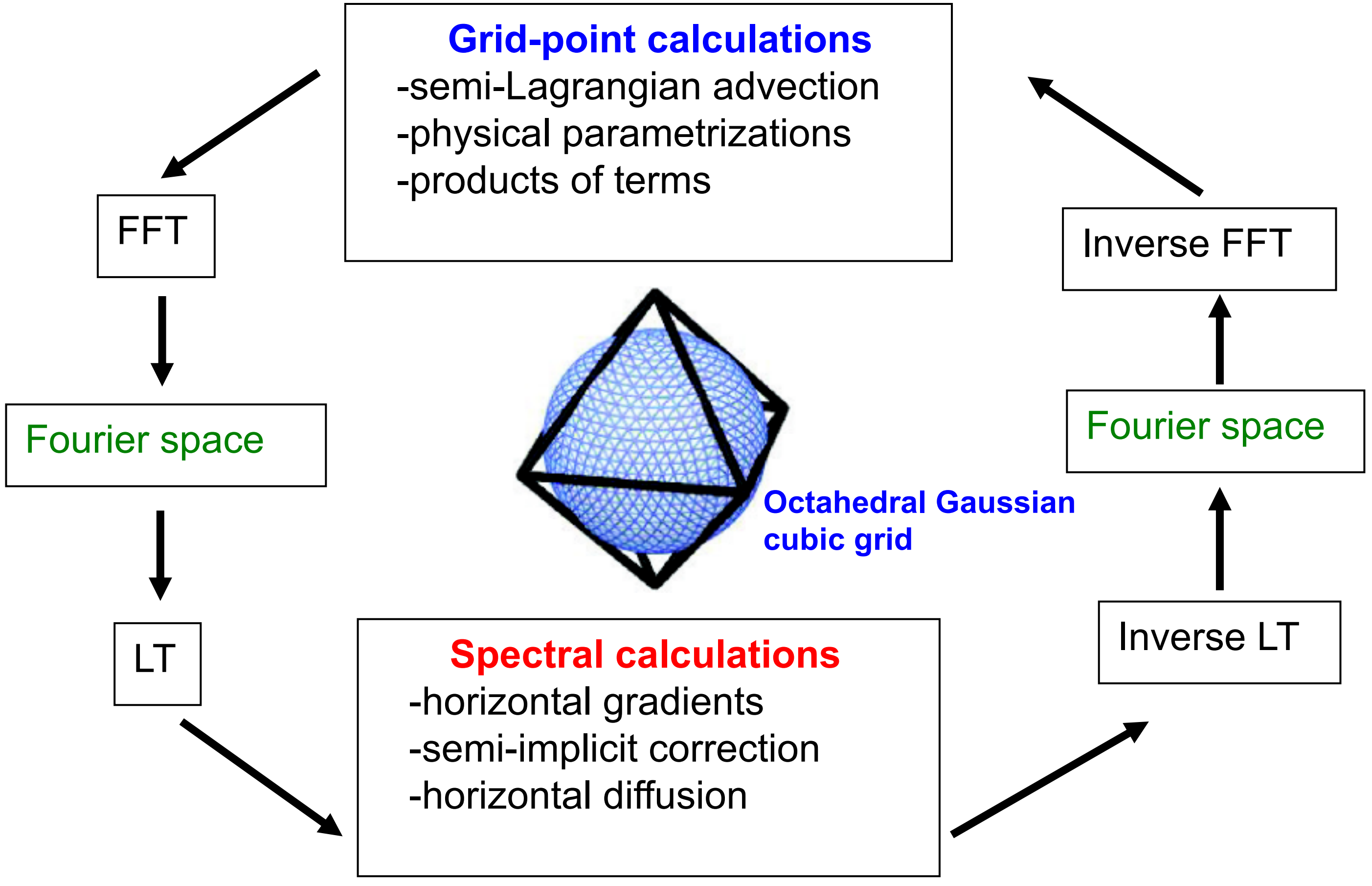
Combined winter-summer headline 500 hPa RMSE score difference (NH versus H control) at 2.8km resolution



NH-H: **deep blue** 10% **reduction of vector wind RMSE –** signal at **2.8km** only slightly stronger than 4.4km

- Two-season **systematic** and **fair** comparison: like-to-like comparisons with same numerics at 4.4km and 2.8km
- **Differences only** seen in **winter** over **Himalaya in the stratosphere**
- **Neutral** in the summer (including TC predictions)
- **Up to 2.8km resolution: little difference to justify use of the much more expensive non-hydrostatic option**
- Research experiments at 1.4km case studies show more significant differences

Solving the equations: spectral transform semi-implicit semi-Langrangian (SISL) method



FFT: Fast Fourier Transform, LT: Legendre Transform

Vertical discretization

- Hybrid pressure based vertical coordinate η(p)
- 8th order Finite Element discretization based on cubic spline basis functions
  - Accurate vertical integrals with benefits seen mostly in the stratosphere
  - More accurate vertical velocity

Cycle 48r1 scheme upgrade based on Vivoda et al, 10.1175/MWR-D-18-0043.1:

- Unified for hydrostatic and non-hydrostatic model
- Better for single precision (SP) – IFS runs SP forecasts from cycle 47r2

Spectral transforms on spherical harmonics

Spectral coefficient

longitude

latitude

Spherical harmonics

$$f(\lambda,\phi) = \sum_{m=-\infty}^{\infty} \sum_{n=|m|}^{\infty} f_n^m \, Y_n^m(\lambda,\phi), \qquad Y_n^m(\lambda,\phi) = P_n^m(\sin\phi)\, e^{im\lambda}$$

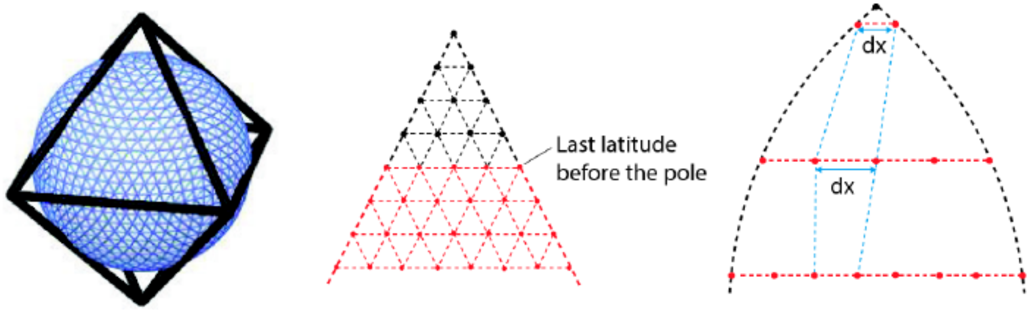
m: zonal wavenumber
n: total wavenumber

Associated Legendre Polynomials (normalised)

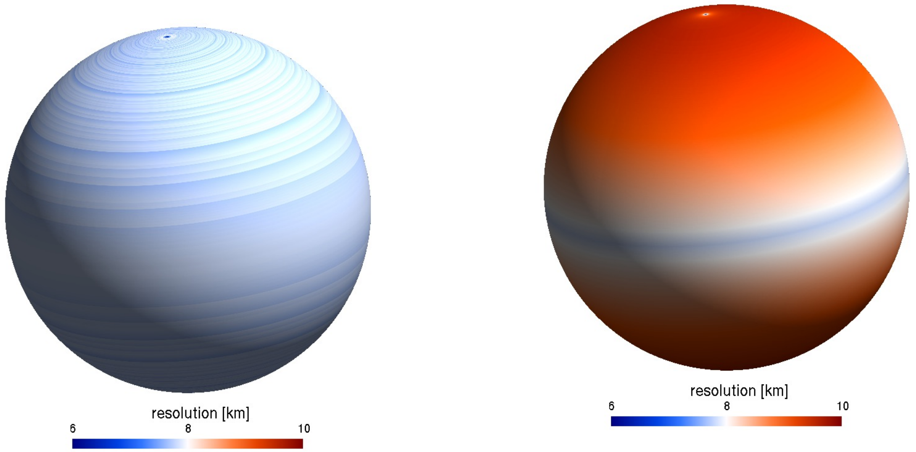
- **We can compute derivatives without approximations using analytical formulae**
- **The common "pole singularity" problem is overcome**
- **Spherical harmonics are the eigenfunctions of the Laplace operator: in time-stepping the derived "Helmholtz equation" can be decoupled and solved by a very cheap & simple diagonal solver**

- **Advancements in algorithms, hardware and software have enabled us to keep running efficiently the spectral transform method at ever increasing resolutions**
- **ecTrans: a multi-node GPU enabled spectral transform library**

The octahedral grid: accurate, efficient and scalable



Collignon projection on the sphere: *Nlati* = 4 × *i* + 16, *i* = 1, . . . ,*N*

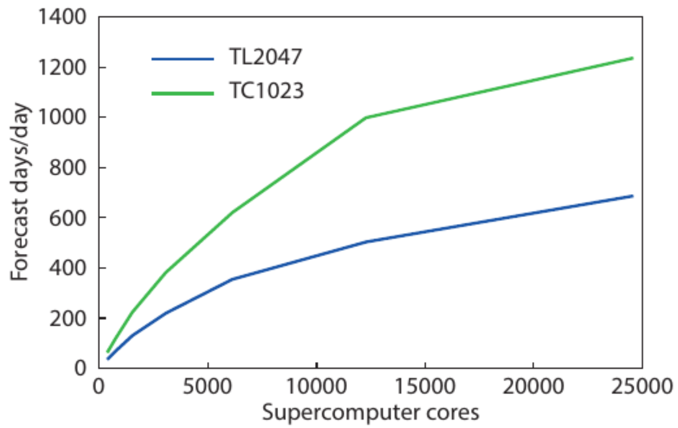


Latitudinal variation of resolution for standard cubic grid and octahedral cubic grid

Reference: "A new grid for the IFS" ECMWF newsletter 146, Winter 2015-2016, Malardel et al

Benefits of cubic octahedral grid compared with old linear grid:

- More accurate representation of fine scales at same spectral truncation
- Improved total mass conservation
- Improved efficiency and scalability
- Improved filtering effects: reduced diffusion (spectral viscosity) + no anti-aliasing filter



Cubic versus linear grid run at the same gridpoint resolution

Cubic grid achieves 2× more forecast-days-per-day than linear grid as core count increases

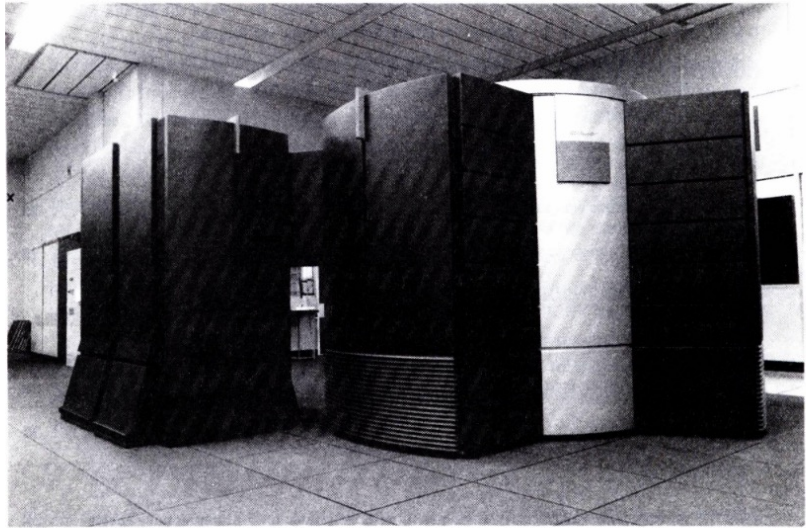
Time-stepping: semi-implicit, semi-Lagrangian (SISL) technique

Semi-Lagrangian (SL) semi-implicit (SI) technique is ideal for global NWP: stable efficient and accurate integration of the governing equations

- ❑ Unconditionally stable SL advection scheme with small phase speed errors and little numerical dispersion
  - ✓ No CFL restriction in timestep: large timesteps can be used without accuracy penalty ☺
  - ✓ Multi-tracer efficient
- ❑ Unconditionally stable SI time stepping for the integration of fast dynamical processes
  - ✓ No timestep restriction from the integration of "fast forcing" terms (gravity wave and acoustic terms in non-hydrostatic models)
  - ✓ 2nd order accuracy

History of SISL method at ECMWF

- 1991: IFS was a **spectral semi-implicit** Eulerian model on a full Gaussian grid at T106 horizontal resolution and 19 levels
  - An increase to T231 L31 resolution was planned
  - This upgrade required at least 12 x available CPU power
  - Funding was available for 4 x CPU increase …
- Upgrade was made possible by introducing:
  - A **semi-Lagrangian**, **semi-implicit** scheme on a **reduced Gaussian** grid
  - The new model was 6 x faster!



CRAY Y-MP/8: first HPC to run spectral SISL operationally (1992)
Source: ECMWF newsletter 60, Dec 1992

ATOS HPC at Bologna data centre (2022)

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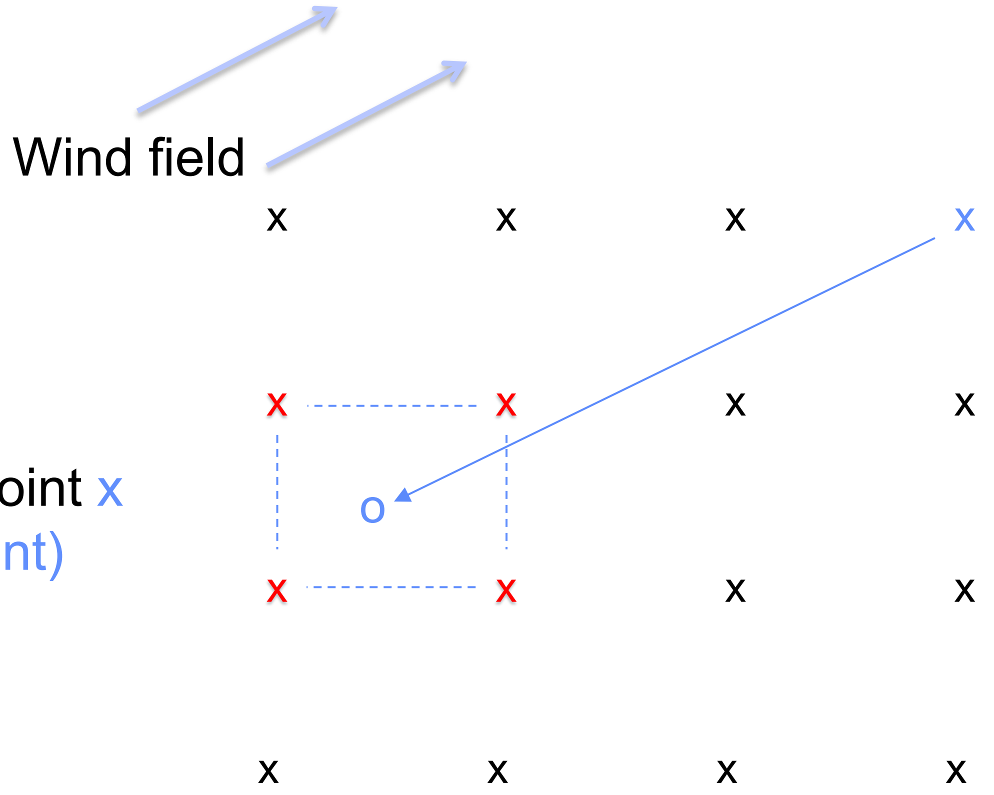
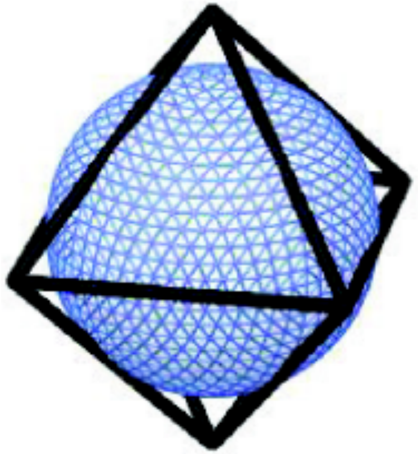
Semi-Lagrangian advection in a picture

SL is a numerical technique for solving advection type PDEs which applies *Lagrangian* type of calculations on grid-point models



o: origin of grid point x
(departure point)



A semi-Lagrangian trajectory (departure point) needs to be traced back for each grid-point of the Gaussian grid

The SL solution of the advection equation

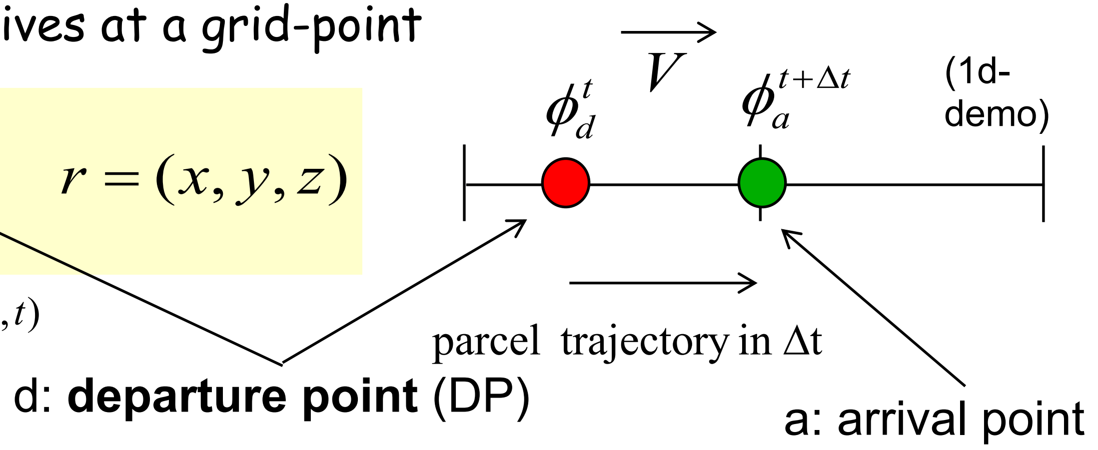
Start with the simple passive tracer advection equation (constant wind):

$$\frac{D\phi}{Dt} \equiv \frac{\partial \phi}{\partial t} + V \cdot \nabla \phi = 0, \qquad V = (u, v, w)$$

At time t parcel is at d and at t +Δt arrives at a grid-point

$$\int_{(r_d,t)}^{(r_a,t+\Delta t)} \frac{D\varphi}{Dt} Dt = 0 \Rightarrow \varphi_a^{t+\Delta t} = \varphi_d^t, \qquad r = (x, y, z)$$

This is the known result: $\varphi(r, t+\Delta t) = \varphi(r - \Delta t V, t)$



- Solution at t+Δt is obtained by finding the DP location and interpolating the available (defined at time t) grid-point ϕ values at the DP
- Eulerian advection term $V \cdot \nabla \phi$ is not explicitly computed – it is absorbed by the Lagrangian derivative (advection problem is reduced to interpolation)

Computing the departure points in real atmospheric flows: SETTLS

Consider that air parcels move in time in straight line trajectories. Perform a 2nd order Taylor expansion of an arrival (grid) point to its departure point:

Stable Extrapolation Two Time Level Scheme (Hortal, QJRMS 2002)

$$r_a(t+\Delta t) = r_d(t) + \Delta t \cdot \left(\frac{Dr}{Dt}\right)_d^t + \frac{\Delta t^2}{2} \cdot \left(\frac{D^2 r}{Dt^2}\right)_{AV}$$

AV: average value along SL trajectory

$$\left(\frac{Dr}{Dt}\right)_d^t = V_d(t), \qquad \left(\frac{D^2 r}{Dt^2}\right)_{AV} = \left(\frac{DV}{Dt}\right)_{AV} \approx \frac{V_a(t) - V_d(t-\Delta t)}{\Delta t}$$

Hence,

$$r_a(t+\Delta t) \approx r_d(t) + \frac{\Delta t}{2} \cdot \left(V_a(t) + \{2V(t) - V(t-\Delta t)\}_d\right)$$

DP can be computed by iterative sequence based on above SETTLS formula :

$$r_d^{(k)} = r_a - \frac{\Delta t}{2} \cdot \left(V_a(t) + \{2V(t) - V(t-\Delta t)\}\Big|_{r_d^{(k-1)}}\right) \quad k = 1, 2, \ldots K$$

$r_d^{(0)}$ =initial guess

Interpolate at $r_d^{(k-1)}$

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Departure point iterations convergence

- SETTLS scheme for computing the departure point is iterative

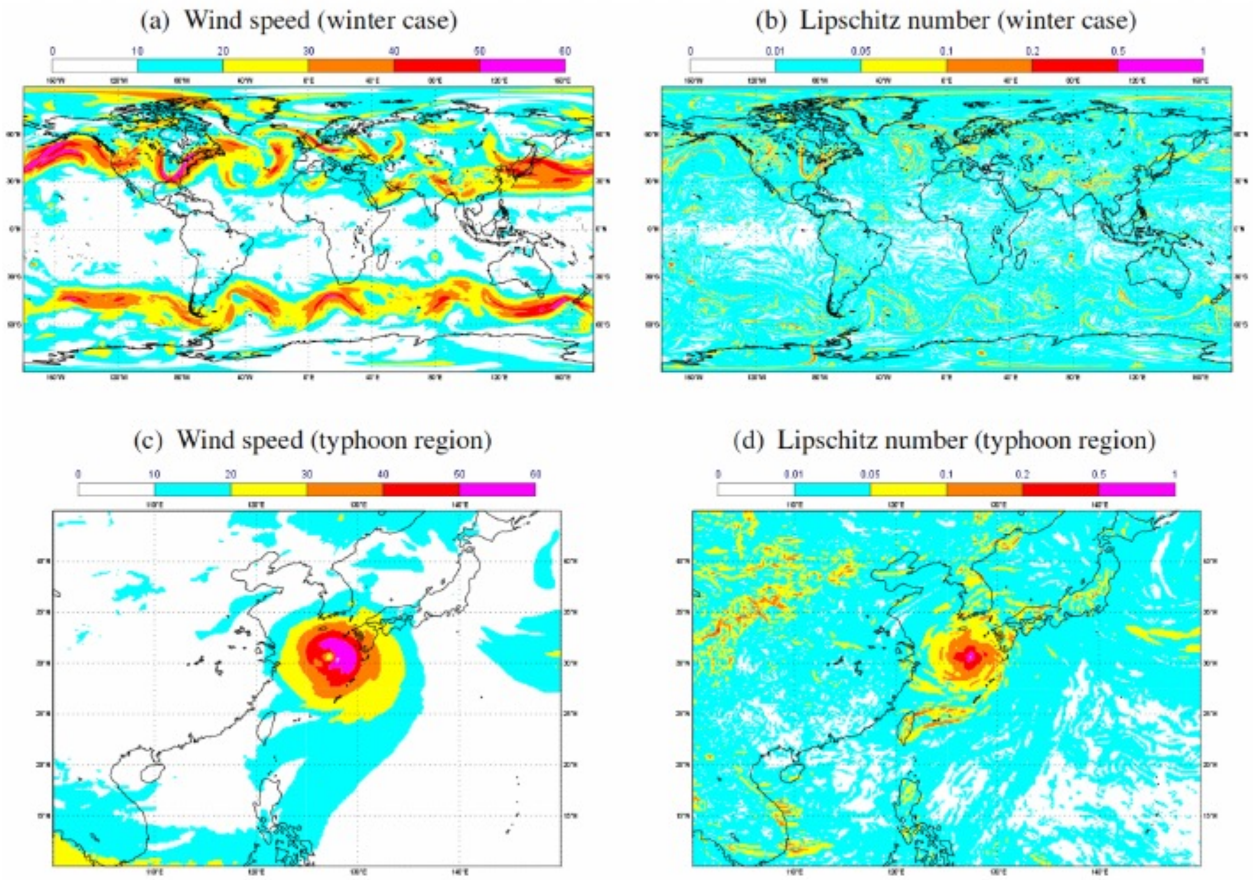
- Its convergence depends on Lipschitz number magnitude. Let $\mathbf{r_D}^{[v]}$ an estimate of the departure point D at iteration number *v.* Then:

$$\|\mathbf{r_D}^{[\nu]} - \mathbf{r_D}^{[\nu-1]}\| \leq L\|\mathbf{r_D}^{[\nu-1]} - \mathbf{r_D}^{[\nu-2]}\|, \quad \nu = 2, 3 \ldots, \nu_{max}$$

$$L \equiv \Delta t \|\frac{\partial \mathbf{V}}{\partial \mathbf{r}}\| \qquad \text{Lipschitz (deformational Courant) number}$$

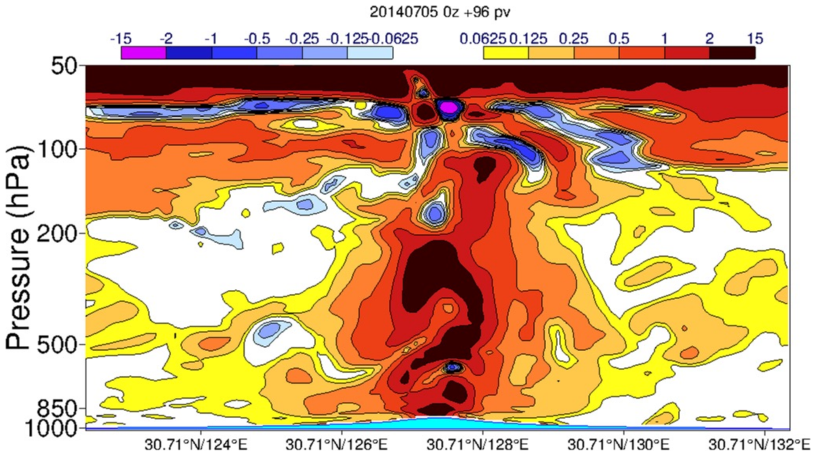
- $L < 1$ is a sufficient condition for convergence
- L is an upper bound of the rate of convergence

Lipschitz numbers in IFS forecasts

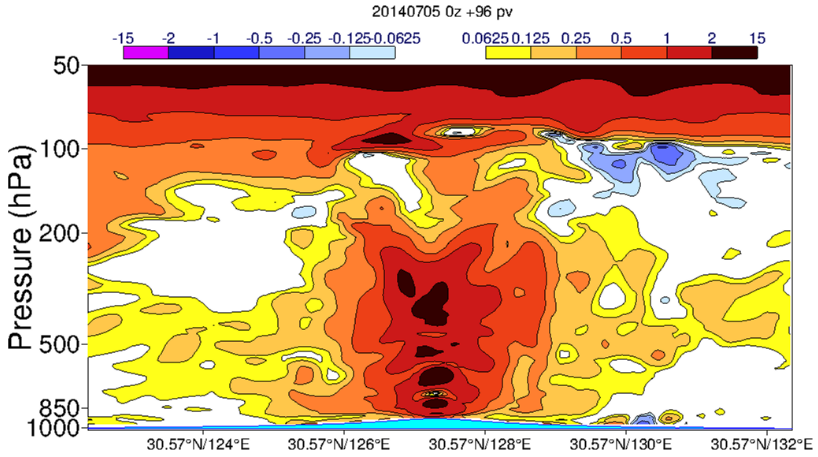


(a), (b): 00UTC 10 January 2014, t+48hrs fc at 500hPa. (c), (d): 00UTC 5 July 2014 t+96 hrs fc at 850hPa

Side-effects of non-converging DP iterations

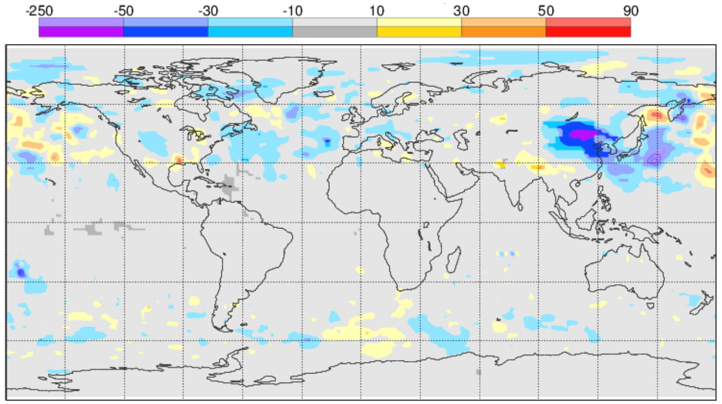


DP iterations haven't converged: **3 –iterations** with **old scheme**



DP iterations have converged: **5-iterations** with **old scheme** or **3-iterations** with **new scheme**

- **Pre cy48r1**: **5 DP iterations** needed for sufficient convergence (Diamantakis & Magnusson, MWR2016 doi:10.1175/MWR-D-15-0432.1)
- **From cy48r1:** fast convergence in **3 iterations** starting from previous timestep DPs (Diamantakis & Vana, QJRMS 2021, https://doi.org/10.1002/qj.4224)

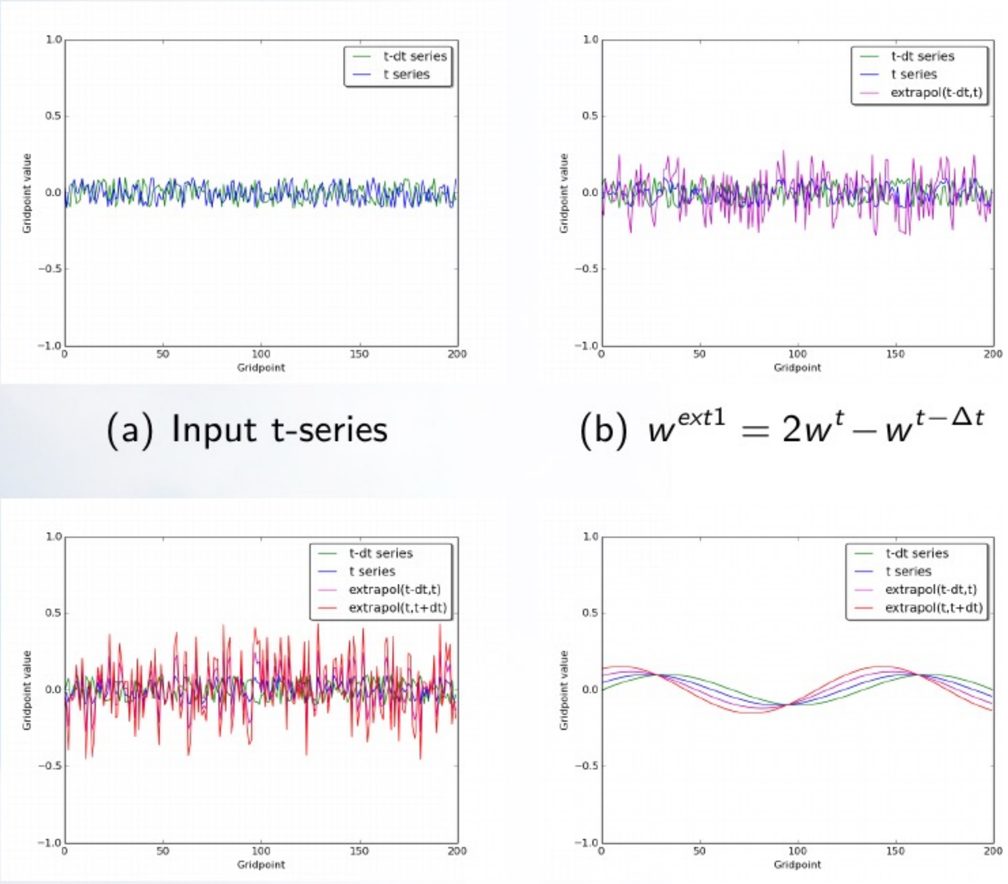


Root Mean Square Error difference for the geopotential height when DP iterations have not sufficiently converged

Special treatment for stratospheric warming predictions

- In “Sudden Stratospheric Warmings” noise is seen in upper stratosphere and model underpredicts the temperature
- Origin of noise: **vertical velocity time extrapolation** in SETTLS
- Solution: use non-extrapolating 1st order scheme for grid-points with sudden changes in vertical velocity in 2 consecutive steps

Impact of SETTLS time-extrapolation on noisy and smooth data

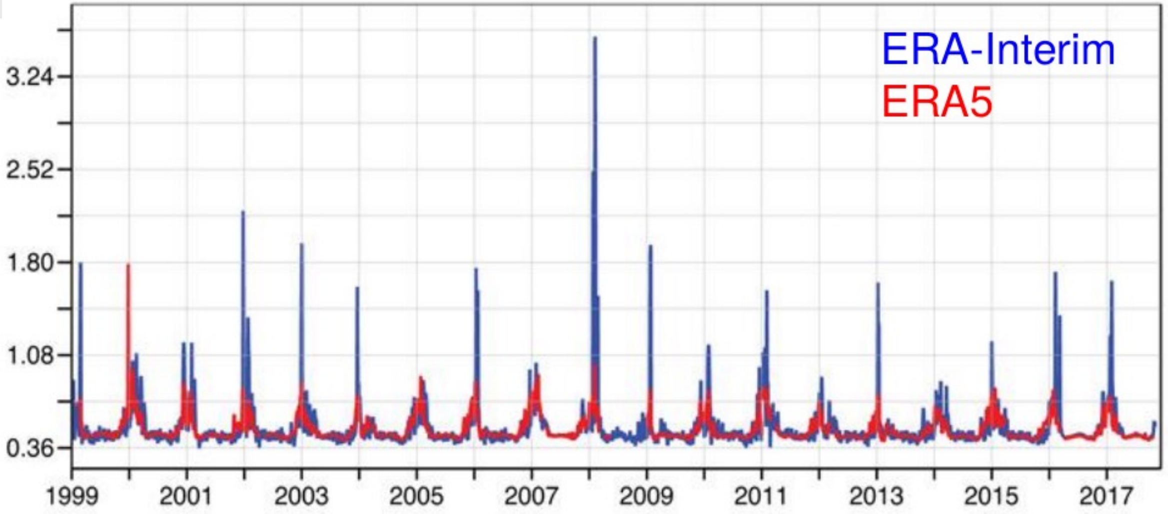


(a) Input t-series (b) $w^{ext1} = 2w^t - w^{t-\Delta t}$

(c) $w^{ext2} = 2w^{ext1} - w^t$ (d) Smooth data

Much better representation of Sudden Stratospheric Warming events, due to changes in the Semi-Langrangian scheme (*Diamantakis, 2014*)

NH winter SSWs

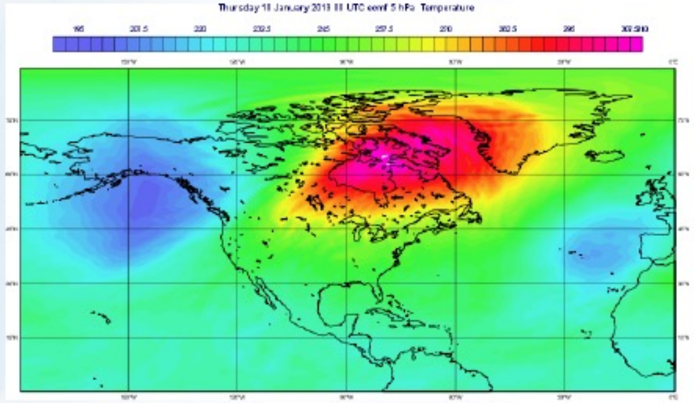


Standard deviation of MW radiances observed vs simulated temperature fields of ERA-Interim (blue) and ERA5 (red) using satellite channel (noaa15) peaking around 5hpa.

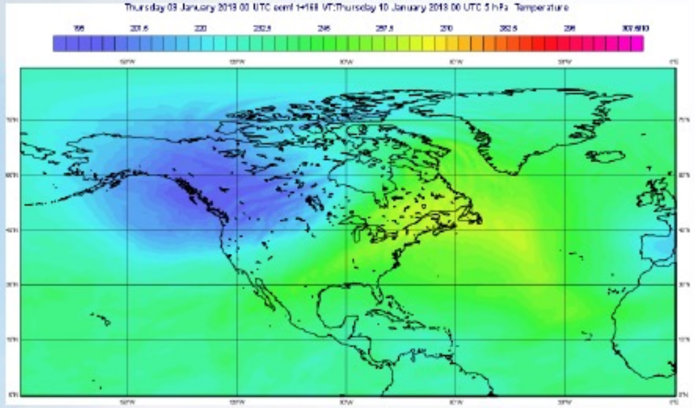
T. McNally, A. Simmons

A reference: “Improving ECMWF forecasts of sudden stratospheric warmings”, ECMWF newsletter No.141 Autumn 2014

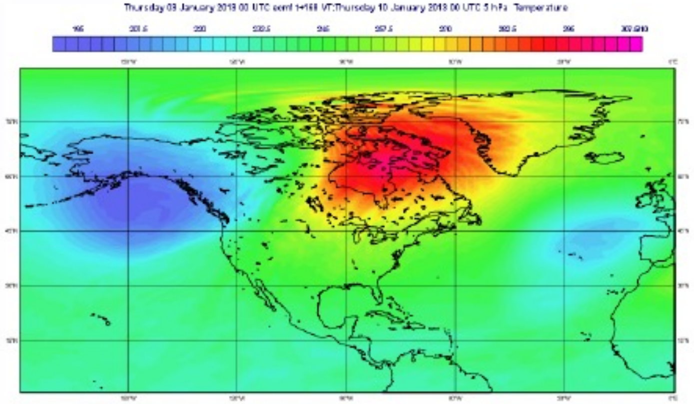
Major SSW January 2013



(a) Analysis



(b) t+7d CONTROL



(c) t+7d NEW

Old scheme (CONTROL) versus currently SETTLS scheme

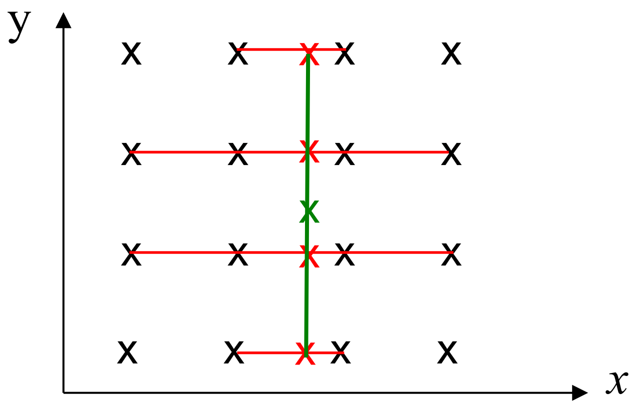
The role of interpolation in the semi-Lagrangian scheme

After computing the **departure points** we need to:

- ***Interpolate** the advected field at the **DP***
- *Interpolation must use the grid-points that lie in the neighbourhood of the DP*

ECMWF model uses quasi-monotone quasi-cubic Lagrange interpolation

Cubic Lagrange interpolation: $\phi(x) = \sum_{i=1}^{4} w_i(x)\phi_i \; , \quad w_i(x) = \dfrac{\prod_{k\neq i}^{4}(x - x_k)}{\prod_{k\neq i}^{4}(x_i - x_k)}$

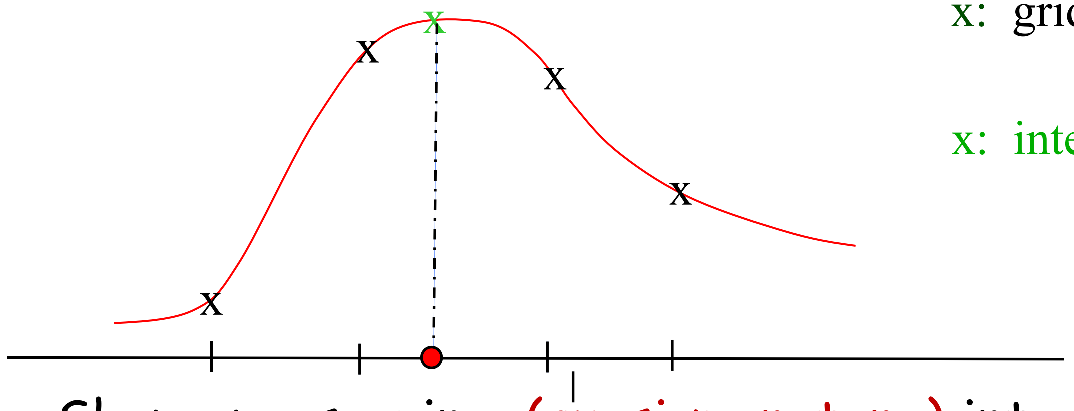


Number of 1D cubic interpolations in 2D: 5 =>3D: 21 (64pt stencil)

To save computations: use *cubic interpolation only for nearest neighbour rows and linear interpolationfor remaining rows. "quasi-cubic interpolation": 3*cubic+2*linear interpolations in 2D 7*cubic+10*linear in 3D* (32 pt stencil)

Shape-preserving (locally monotonic) interpolation

- Creation of "artificial" maxima /minima

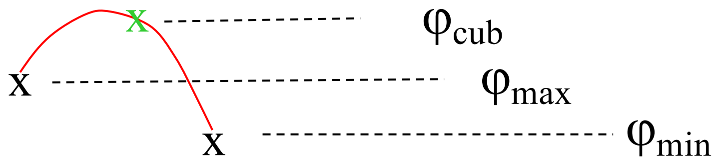


x: grid point values

x: interpolated value

- Shape-preserving (quasi-monotone) interpolation

  - Quasi-monotone cubic interpolation: $\varphi_{qm} = \max(\varphi_{\min}, \min(\varphi_{\max}, \varphi_{cub}))$



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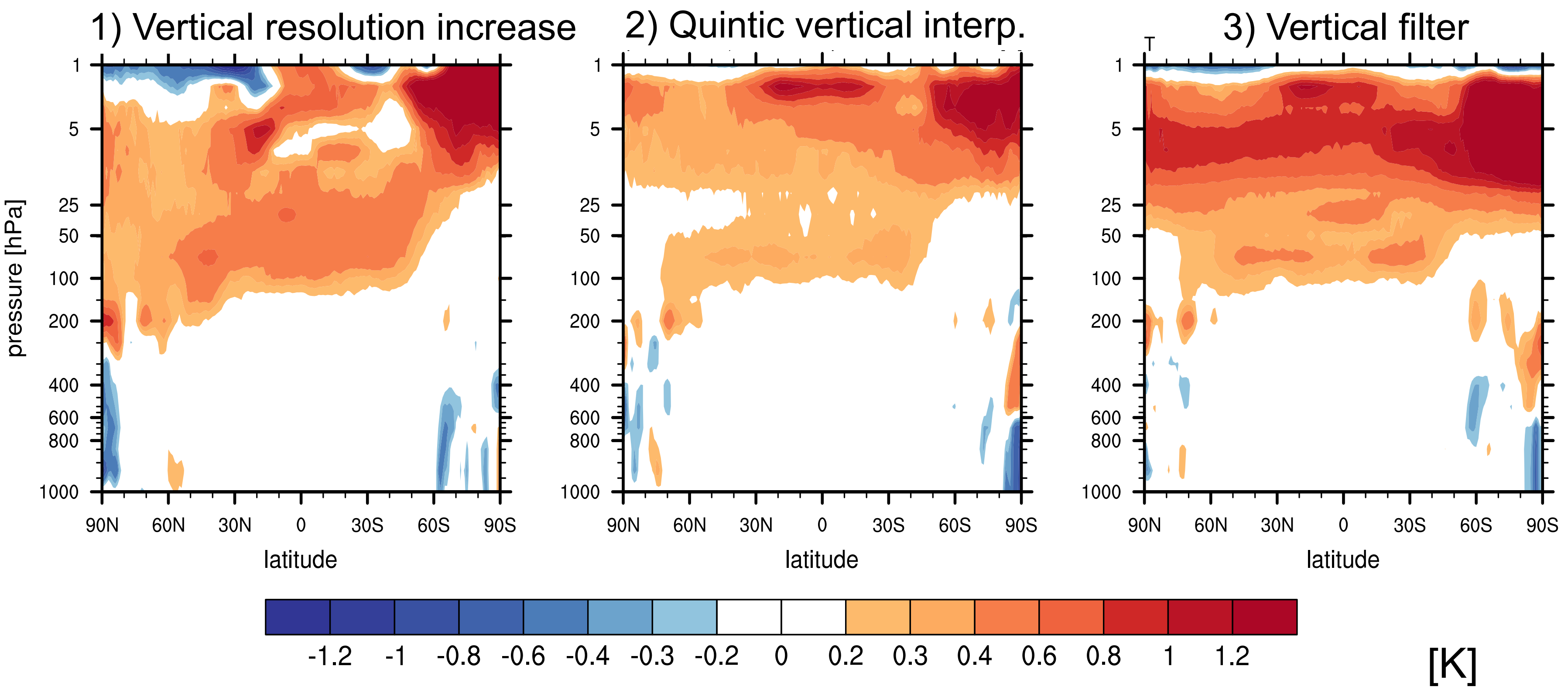
Reducing stratospheric T-bias

Spurious $2\Delta z$ noise due to **inadequate vertical-to-horizontal resolution aspect ratio** spuriously **cools** the stratosphere at high horizontal resolution.

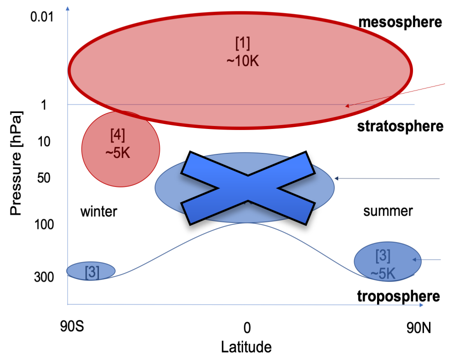
Solutions:

1) increase **vertical resolution** (ENS in 47r3); Expensive!
2) use **quintic** vertical interpolation on T & q in the semi-Lagrangian advection (47r1)
3) **filter $2\Delta z$** noise in T in the semi-Lagrangian advection (SLVF filter by F. Vana, 48r1)

ECMWF newsletter 163, spring 2020 Policthchouk et al



T response from CTRL.



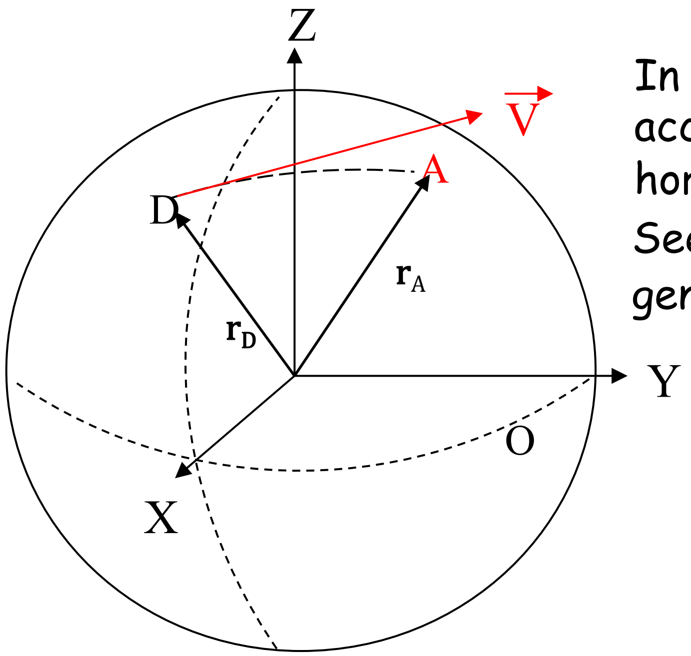
Also thinner sponge layer (above 0.78hPa) from cycle 48r1 (work by I. Polichtchouk)

SL advection on the sphere in cycle 48r1+

To compute DP on the sphere:

1. Transform horizontal velocities (u,v) in a geocentric Cartesian system (X, Y, Z)
2. Apply SETTLS algorithm to compute $r_d = (X_d, Y_d, Z_d, \eta_d)$
3. Compute lon/lat of DP from (X_d, Y_d, Z_d) ⟶ $\lambda_d = ATAN2(Y_d, X_d)$, $\theta_d = \arcsin \frac{Z_d}{\sqrt{X_d^2 + Y_d^2 + Z_d^2}}$

Details of the implementation on the IFS terrain following coordinate in: Diamantakis & Vana QJRMS 2021 10.1002/qj.4224.



In **SL transport**, **vector** quantities **transported** from **D** to **A must be rotated** to account for curvature effects: multiply with a "rotation matrix" R the interpolated horizontal wind vector at D

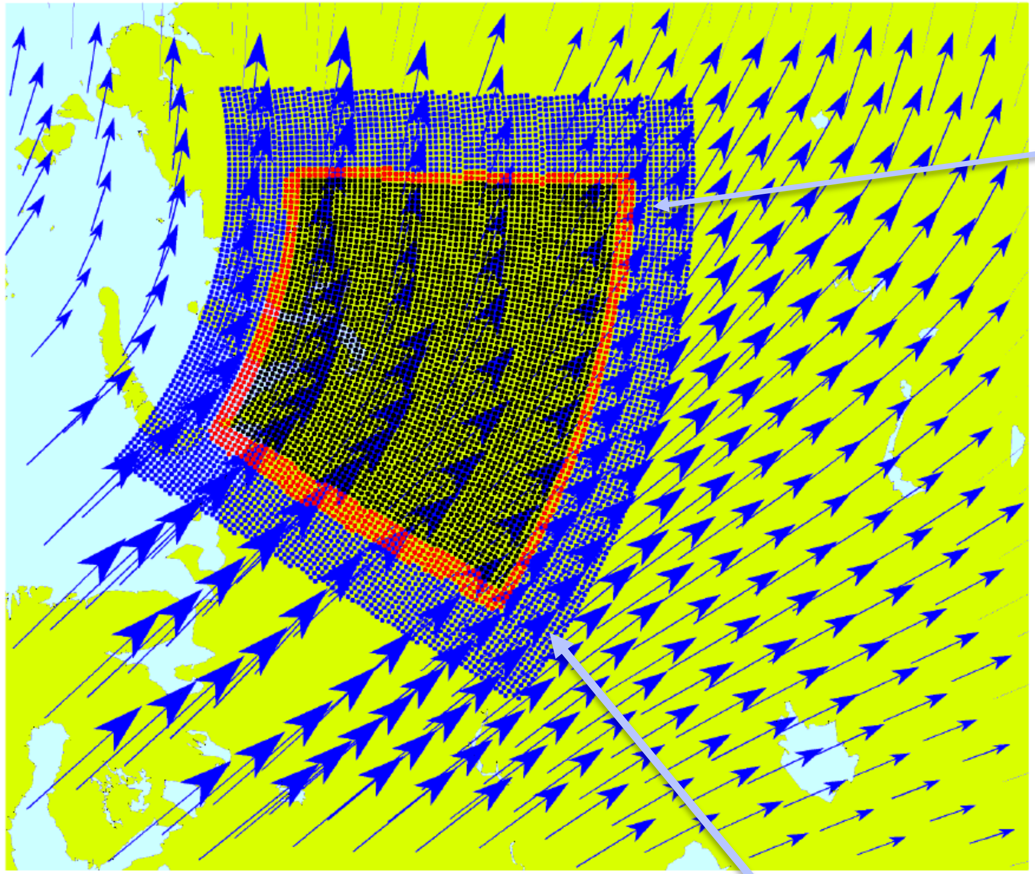
See Temperton et al QJRMS 2001, Staniforth et al QJRMS 2010 (provides general formula independent of φ=angle $\widehat{DOA}$ between position vectors **r**$_A$ and **r**$_D$)

$$\begin{pmatrix} u_A \\ v_A \end{pmatrix} = \underbrace{\begin{pmatrix} p & q \\ -q & p \end{pmatrix}}_{R(V_D):\,rotation\ matrix} \begin{pmatrix} u_D \\ v_D \end{pmatrix}, \quad q = \frac{(\sin\theta_A + \sin\theta_D)\sin(\lambda_A - \lambda_D)}{1+\cos\varphi}$$

$$p = \frac{\cos\theta_A \cos\theta_D + (1 + \sin\theta_A \sin\theta_D)\cos(\lambda_A - \lambda_D)}{1+\cos\varphi}$$

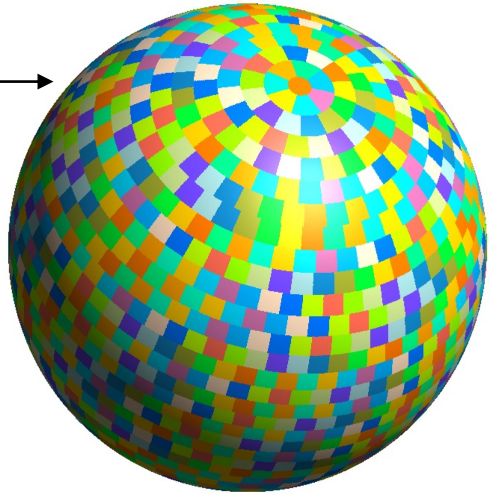
Parallel implementation of advection

Interpolation at the DP near the edges of MPI domains requires data from neighbouring domain



Blue: Halo region

Equal region domain decomposition + MPI and openMP parallel



Halo width for MPI assumes a maximum wind speed larger than the ones observed in the atmosphere e.g. 250m/s

Two levels of communication:

- Entire wind halo filled for the DP iterations
- When the DP is known then only a smaller sub-region around the DP needs to be filled
- No need to fetch data from remote processors at the expense of extra memory use

Combining SL with SI to solve prognostic equations

- A nonlinear system of m-prognostic equations must be solved:

$$\frac{DX}{Dt} = M(X), \quad X = (X_1, X_2, \ldots, X_m)$$

e.g. X=(u,v,T,p,q,…)

- Integrate along SL trajectory using 2nd order semi-implicit Crank-Nicolson scheme:

$$X^{t+\Delta t} - X_d^t = \int_t^{t+\Delta t} M(X)dt \Rightarrow X^{t+\Delta t} - X_d^t = \frac{\Delta t}{2}\left(M_d^t + M^{t+\Delta t}\right)$$

Convention: when no subscript then the variable "sits" at an arrival (grid) point

- An isothermal reference profile is used to linearise terms in M which are responsible for fast wave propagation.

$$\Re = M - L$$

R: nonlinear residual terms; these are changing slowly and can be integrated explicitly

L:"Fast linearized" (e.g. GW) terms. These should be integrated implicitly to permit stable long timesteps

IFS-SISL for NWP prognostic equations

Splitting in fast linear and slow nonlinear residual terms the two-time-level, 2nd order IFS discretization (Temperton et al, QJRMS 2001):

$$\frac{X^{t+\Delta t} - X_d^t}{\Delta t} = \frac{1}{2}\left(L_d^t + L^{t+\Delta t}\right) + \frac{1}{2}\overbrace{\left(\Re_d^{t+\Delta t/2} + \Re^{t+\Delta t/2}\right)}^{\text{time-extrapolated nonlinear res}}$$

terms interpolated at the DP

The time-extrapolated non-linear residual of the right hand-side is at a trajectory mid-point and can be approximated by the 2nd order SETTLS expansion:

$$\Re_M^{t+\Delta t/2} = \Re_d^t + \frac{\Delta t}{2}\left(\frac{d\Re}{dt}\right)_{AV} \approx \Re_d^t + \frac{\Delta t}{2}\frac{\Re^t - \Re_d^{t-\Delta t}}{\Delta t}$$

Re-arranging terms, yields the familiar SETTLS formula resulting in a 2nd order discretization scheme

$$\frac{X^{t+\Delta t} - X_d^t}{\Delta t} = \frac{1}{2}\left(L_d^t + L^{t+\Delta t}\right) + \Re_M^{t+\Delta t/2}, \qquad \Re_M^{t+\Delta t/2} = \frac{1}{2}\left(\Re^t + \left\{2\Re^t - \Re^{t-\Delta t}\right\}_d\right)$$

all right-hand side terms are given

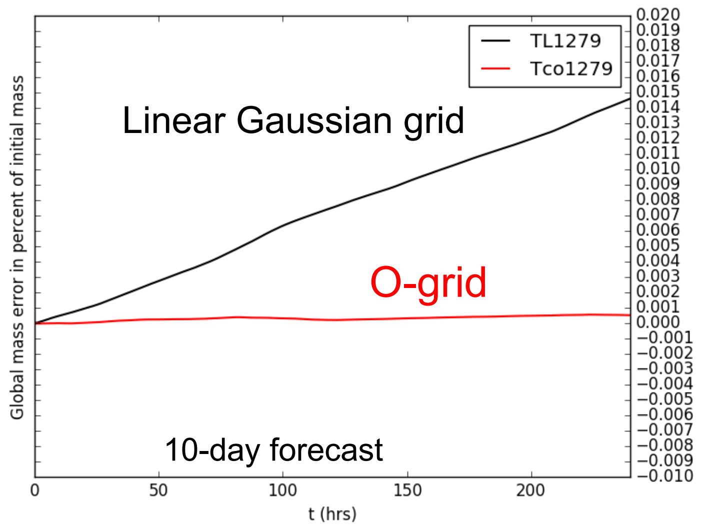
Helmholtz equation

- Through elimination of variables, previous discretized system is reduced to a single Helmholtz elliptic equation **in terms of horizontal wind** divergence
- Helmholtz equation is solved in spectral space at the end of each timestep
- Constant in time reference profiles ⟹ constant coefficient **Helmholtz equation**
- **Using spherical Harmonics properties Helmholtz equation can be solved very cheaply with a direct diagonal solver (or 5-diagonal when Coriolis terms are implicit)**
  - Having a cheap Helmholtz solver + being able to use large Δt (due to unconditional stability and good dispersion properties of SISL) contributes to high computational efficiency
- Remaining prognostic variables are computed with back substitution

Mass conservation in semi-Lagrangian advection

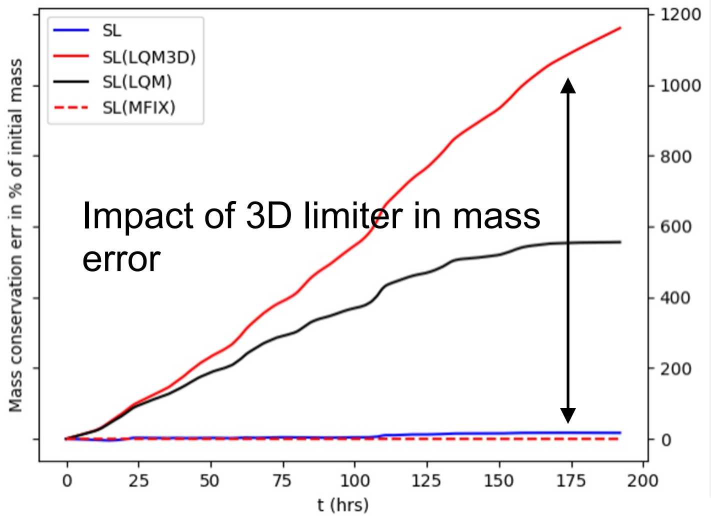
Mass conservation: important for **composition forecasts, long range, climate, high-resolution forecasts**

- Semi-Lagrangian time-stepping does not conserve mass, energy, momentum
- **Why?** Continuity expressed in non-conservation form + numerical errors (interpolation, etc)
  - Small conservation error for smooth tracers and total air mass
  - Large for localised tracers with large gradients
  - Monotone interpolation limiters amplify greatly cons errors
  - Orography amplifies conservation errors
  - Interaction with boundary conditions amplifies cons errors: much larger near the surface
    - COMAD interpolation available in openIFS (Malardel and Ricard QJRMS, 2014) improves conservation of tracers near the surface



Mass errors as percent of initial mass

With O-grid **total air** mass conservation error is very small in double precision



Case study:
Idealised discontinuous tracer 4x5 degrees rectangle placed on the near surface level :

- Large mass conservation error growth in time
- Monotone limiter greatly amplifies mass con errors but needed …

IFS mass fixers

- **A simple mass fixer (rescaling) is applied on surface pressure field to keep air mass constant in time**
- **A more sophisticated tracer mass fixer is applied on water tracers, GHG gases, aerosols**
  - **The tracer mass fixer used is a locally weighted scheme (ECMWF TM 819, 2017 Diamantakis & Agusti-Panareda, scheme based on Bermejo & Conde MWR 2002) which gives more skilful tracer concentration predictions apart of correcting their global mass error**

Corrected tracer mixing ratio

$$\phi_{jk} = \phi_{jk}^{adv} - \lambda w_{jk}, \quad \lambda = \frac{\delta M}{\underbrace{\sum_j A_j \sum_k w_{jk} \frac{\Delta p_{jk}^{adv}}{g}}_{\text{mass integral}}}, \quad \delta M = M\left(\phi_\chi^{adv}\right) - M\left(\phi_\chi^{n}\right)$$

Tracer mixing ratio after advection

Lagrange multiplier

M total mass for tracer ϕ

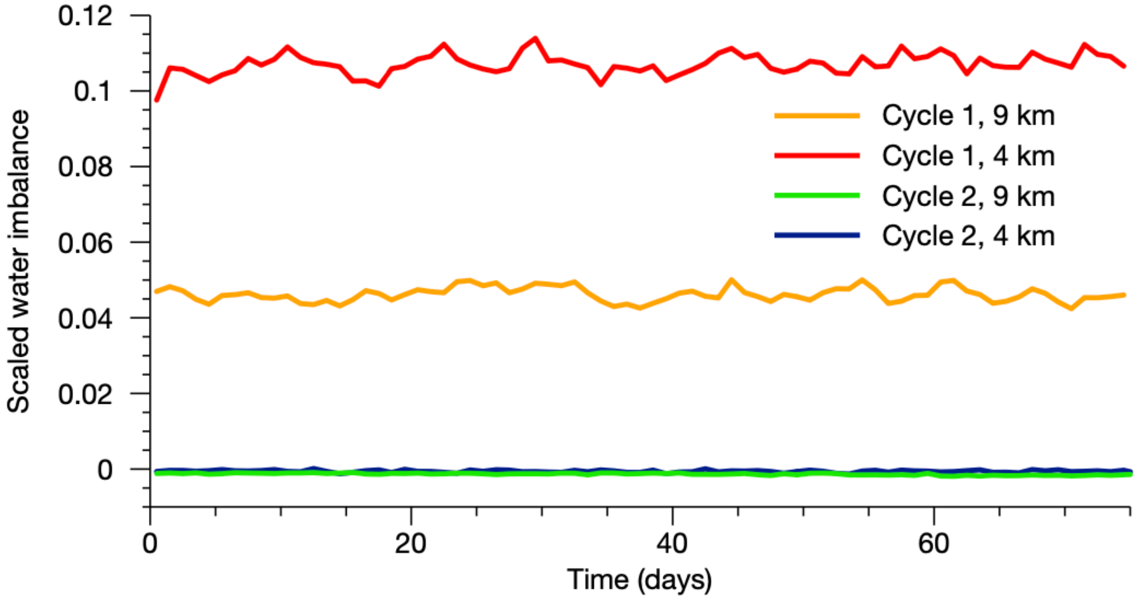
δM: mass conservation error in a timestep after SL advection

w_{jk} is a weight that depends on the sign of δM, it is proportional to the interpolation truncation error and the mass content of grid-box that corresponds to jk

Correction computed by the mass fixer is the solution of a constrained optimization problem that ensures that its global norm is minimized subject to the constraint that global mass remains constant

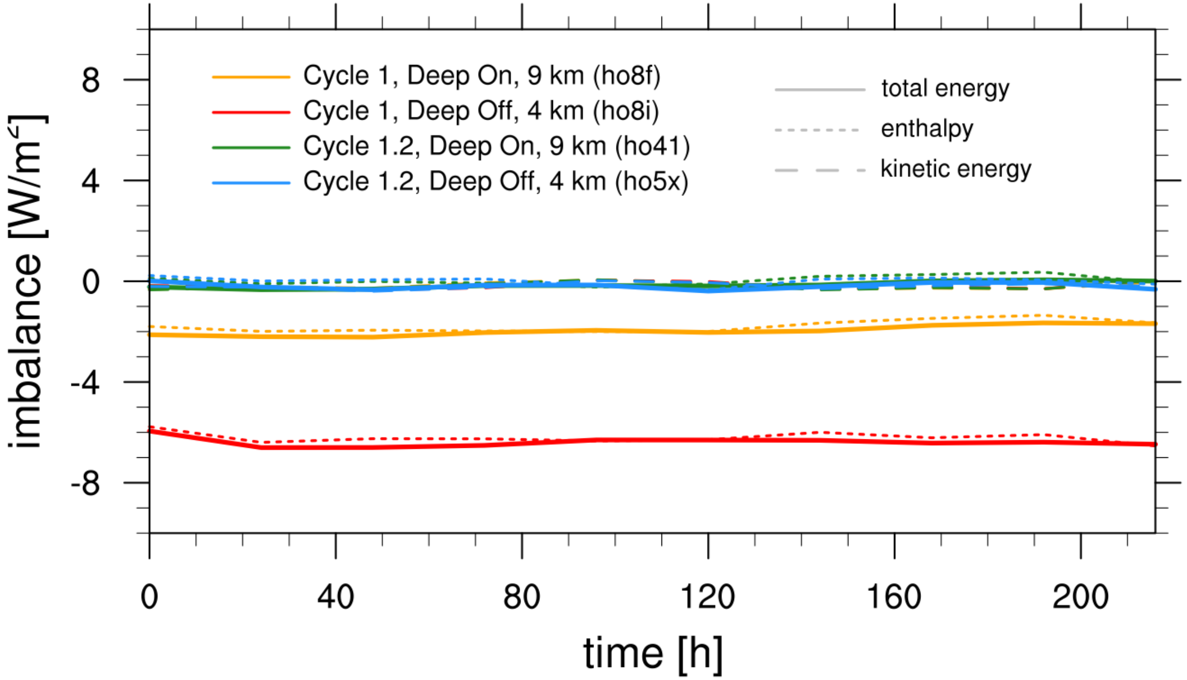
Fixing water leakage in IFS

Mass fixer on moist tracers (humidity, clouds): improvement in precipitation scores and overall skill of ENS forecasts



Total water conservation error as a fraction of total precipitation in long integrations

- 10% surplus is reduced to nearly 0% with tracer mass fixer



Total Energy leakage reduction with fixer:
2 W/m2 -> -0.15 (deep conv on)
6 W/m2 -> -0.32 (deep conv off)

Reference: ECMWF newsletter 172, p14

Plots and diagnostics by Tobias Becker from **nextGEMS project** runs

CATRINE = Carbon Atmospheric Tracer Research to Improve Numerical schemes and Evaluation

Funded by the European Union

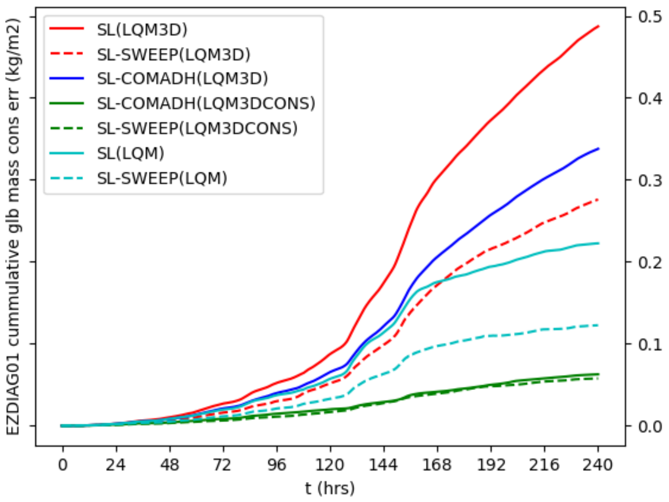
CATRINE
Carbon Atmospheric Tracer Research to Improve Numerics and Evaluation

- 3-year HE project from 01-01-24 supporting CO2MVS (inversions of greenhouse gases) - ECMWF coordinator (A. Agusti-Panareda + M.D.)
- CATRINE WP1: **focus** on **numerical schemes**
  - Development of case studies & diagnostics to understand origin & evolution of mass conservation errors in SL advection
  - Design / implementation of improved algorithms and analysis of their impact on conservation & transport accuracy

Project deliverable reports with detailed information on SL advection transport scheme evaluation and improvements:

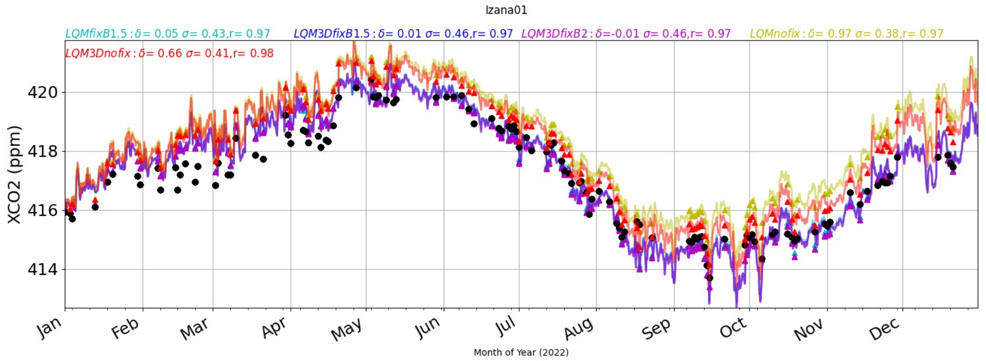
https://www.catrine-project.eu/sites/default/files/2025-04/CATRINE-D1-1-V1.1.pdf

https://www.catrine-project.eu/sites/default/files/2025-06/CATRINE-D1-2-V1.0.pdf



Advection case study: tracer emitted from a single-point source

Reduction of mass conservation error (kg/m²) accumulation from CATRINE developments. Max reduction of conservation error ~ O(10).



Simulated time-series of CO_2 concentration versus observations at Izana site using optimized fluxes

Impact of enforcing conservation through mass fixer.

Conservation improves CO_2 simulation accuracy. Mass fixer (purple, blue) compared to run without mass fixer (yellow, red)

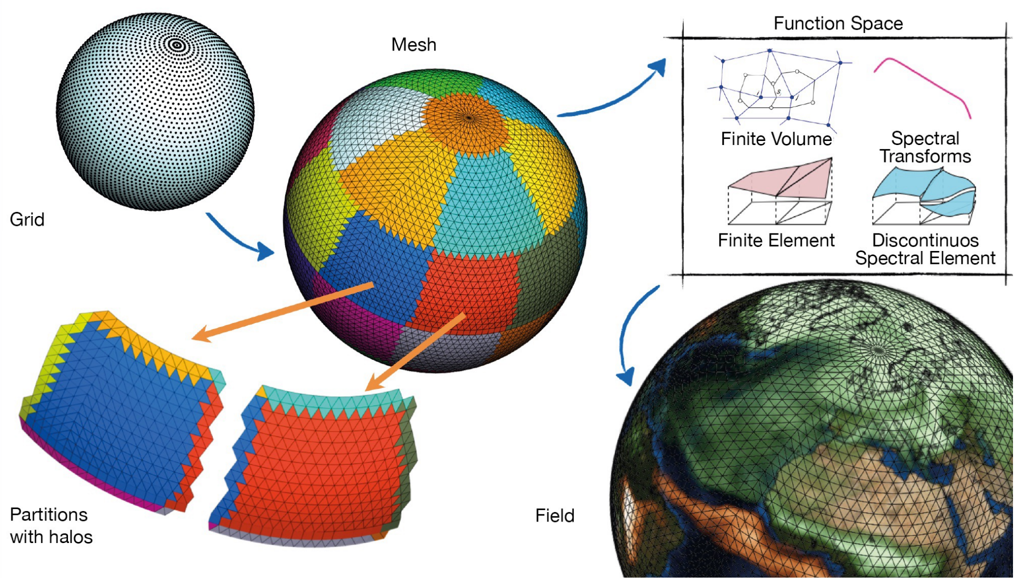
Atlas: a library for NWP and Climate modelling

Atlas (Deconinck et al, Computer Phys Coms 2017) : *A library for NWP and Climate*

Open source code: https://github.com/ecmwf/atlas

Documentation: https://sites.ecmwf.int/docs/atlas/

- C++ or Fortran interface
- Grid/mesh generation capabilities with parallelization (faster)
  - structured grids
  - unstructured hybrid meshes
- Mathematical operators for NWP & climate in HPC environment
- Parallel data structures and algorithms for mesh-to-mesh interpolation
- Flexible memory management and CPU-GPU offloading capabilities
  - Capabilities to couple models (e.g. ocean & atmos)
  - Capabilities parametrizations with the dynamics (e.g. radiation, cloud scheme)
- Can facilitate porting of alternative transport schemes for tracers in a non-disruptive way




```
grid = atlas_Grid("O1280") ! Create O1280 octahedral Gaussian grid
meshgenerator = atlas_MeshGenerator("structured")
mesh = meshgenerator%generate(grid)   ! Generate mesh from grid
method = atlas_fvm_Method(mesh)       ! Setup finite volume method
nabla  = atlas_Nabla(method)          ! Create FVM nabla operator
call nabla%gradient(scalarfield, gradientfield) !

Compute  gradient
```

Cycle 48r1 Atlas capabilities: advection on multiple grids

Demo: O3 advected at 32km grid forced by winds from a 18km grid

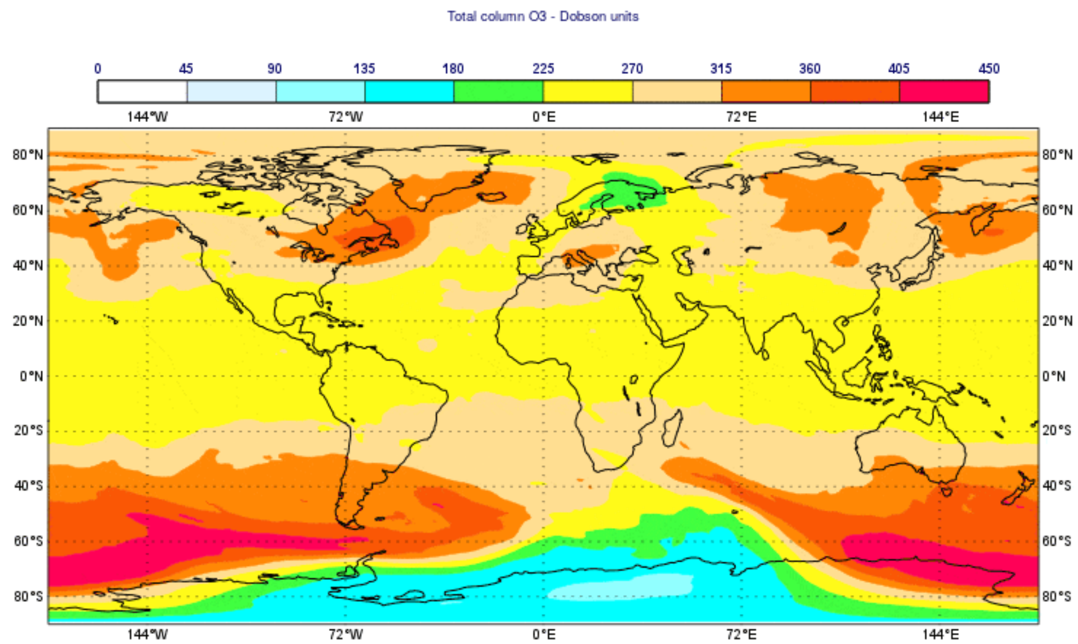
Semi Lagrangian advection step

t^{n}

t^{n+1}

REMAP

Pressure
Wind
Tracer



REMAP

Tracer

t^{n}

Time-stepping in coarse mesh

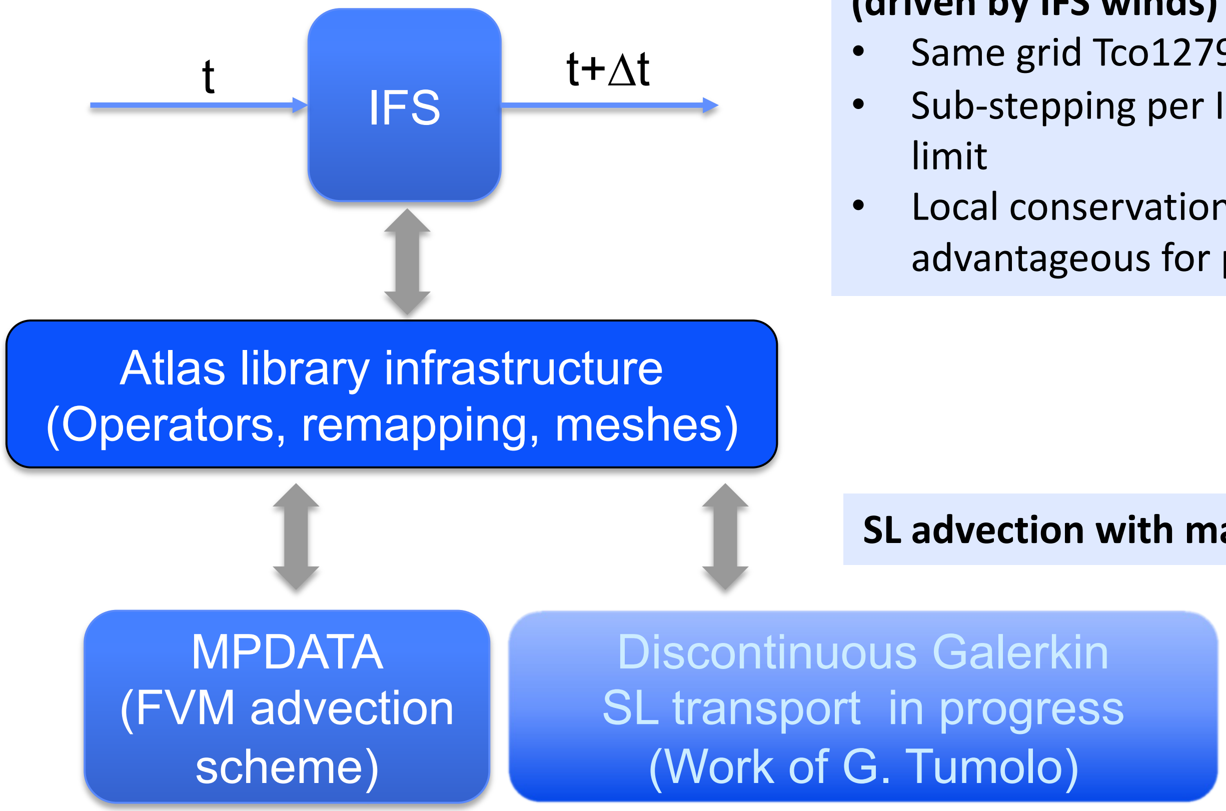
t^{n+1}

Remapping using linear interpolation (cubic also available)

Thanks to W. Deconinck for ppt schematic

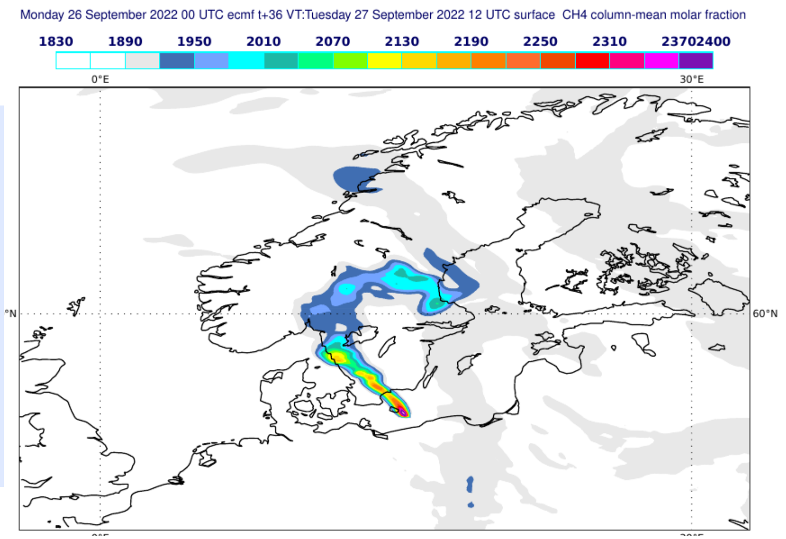
Example: plug-in MPDATA advection into IFS with Atlas MGRIDS

Nordstream gas leak simulation case study (9km)

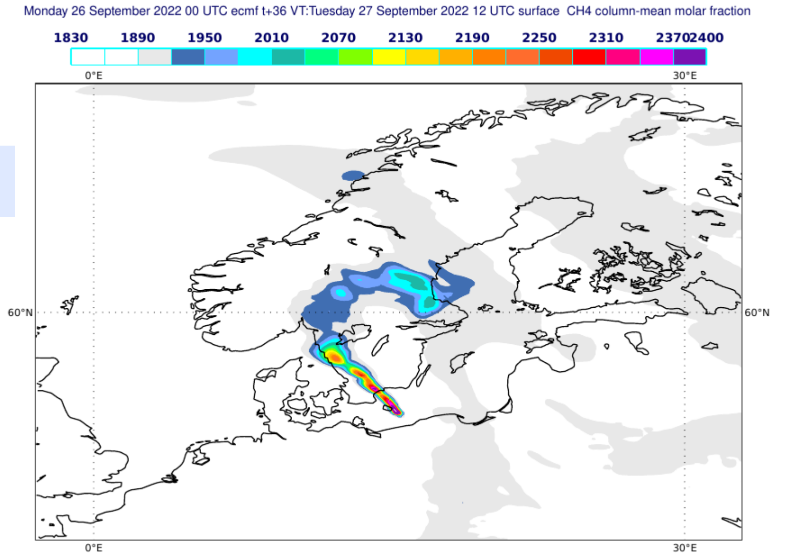


MPDATA simulation using Atlas MGRIDS (driven by IFS winds)

- Same grid Tco1279L137
- Sub-stepping per IFS step due to CFL limit
- Local conservation of MPDATA can be advantageous for plumes



SL advection with mass fixer



Work in progress in the dynamical core

IFS relies on an efficient and accurate dynamical core that is constantly improved

Current plans:

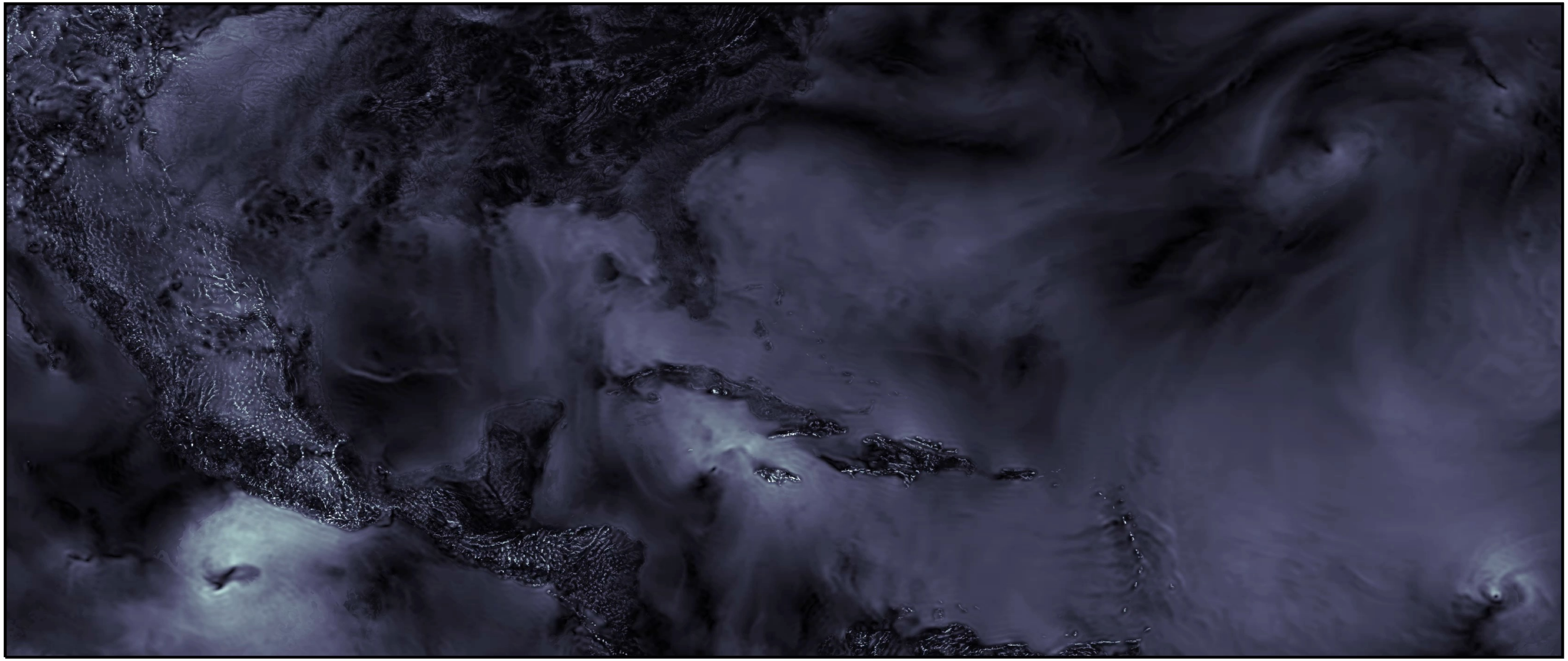
- New **faster** but **equally (or more) accurate interpolation** scheme **SWEEP** for s**emi-Lagrangian** advection in progress
- Work on dry mass conserving forms of continuity equation with potential benefits
  - Improvement of intense precipitation systems
  - Improvement in the representation of tracers in CAMS
- Overall work to improve further tracer transport of the IFS (conservation properties, accuracy)

Long term plans: PMAP (Portable Model for multi-scale Atmospheric Predictions)

- Global and Regional model (PMAP-LES) written in Python Gt4Py
- Performance portable (CPU/GPU seamless execution)
- Inherently conserving and stable at very steep orographic slopes – PMAP-LES tested down to O(10) m resolution

Thank you for your attention!

IFS demo: Hurricane Ida simulation (10m wind gust) at 1.4km simulation by Inna Polichtchouk (INCITE 2022 project)



ECMWF