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Tracer transport in the Unified Model

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The plan of attack

- The Unified Model
- Some notation and nomenclature
- The semi-Lagrangian scheme
- ENDGame
- Does it matter?
- SLICE – recovering conservation
- Conservation in LAMs
- GungHo!
- Bibliography
- Transport options in ROSE

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THE UNIFIED MODEL

Unified Model

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Brown et al. (2013)

- Operational forecasts
  - ➢ Mesoscale (resolution approx. 1.5km)
  - ➢ Global scale (resolution approx. 10km)

- Global and regional climate predictions
  - ➢ Resolution around 120km
  - ➢ Run for 10-100-… years

- Seasonal predictions
  - ➢ Resolution approx. 60km

- Research mode
  - ➢ Resolution 1km - 10m

> 25 years old

The consequence of unification

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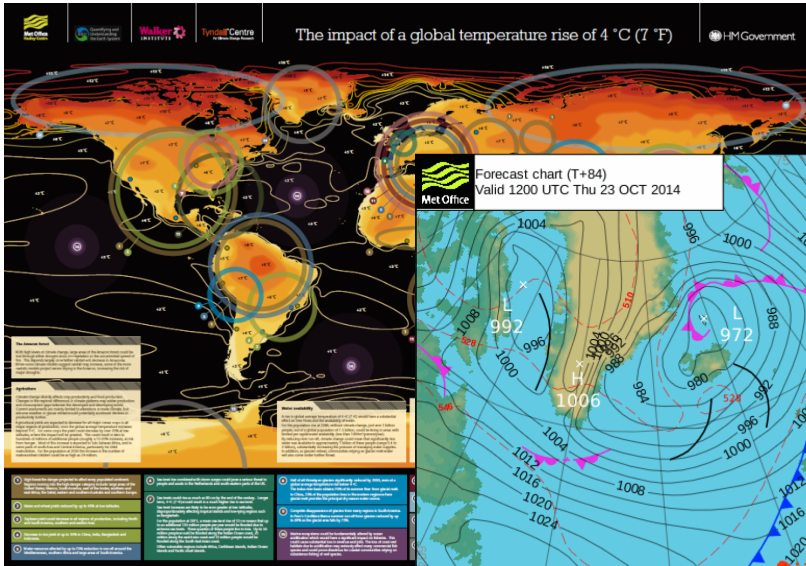
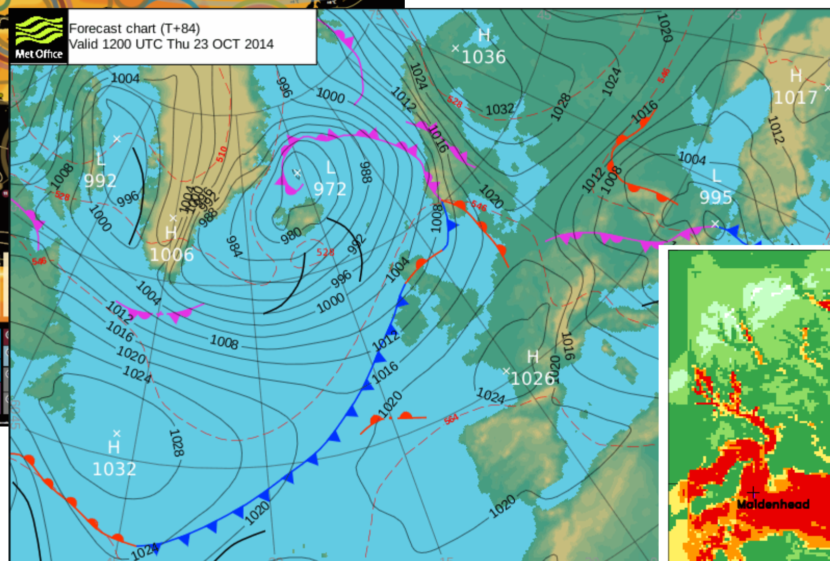
300 km

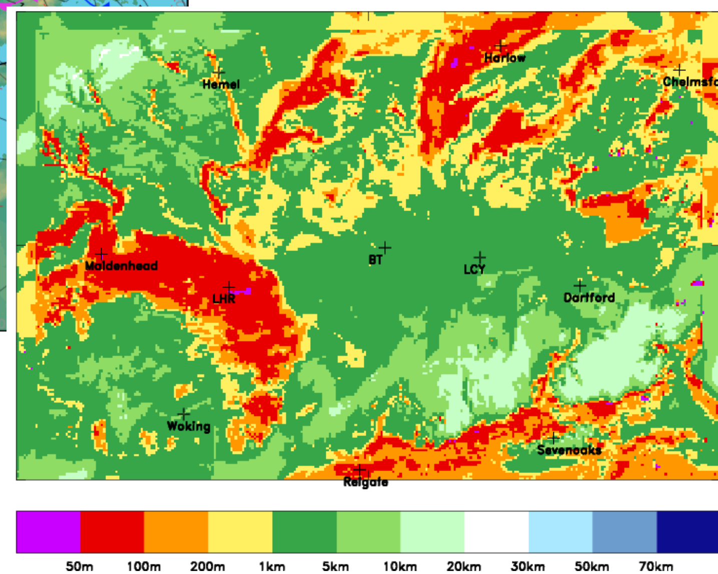


30 km



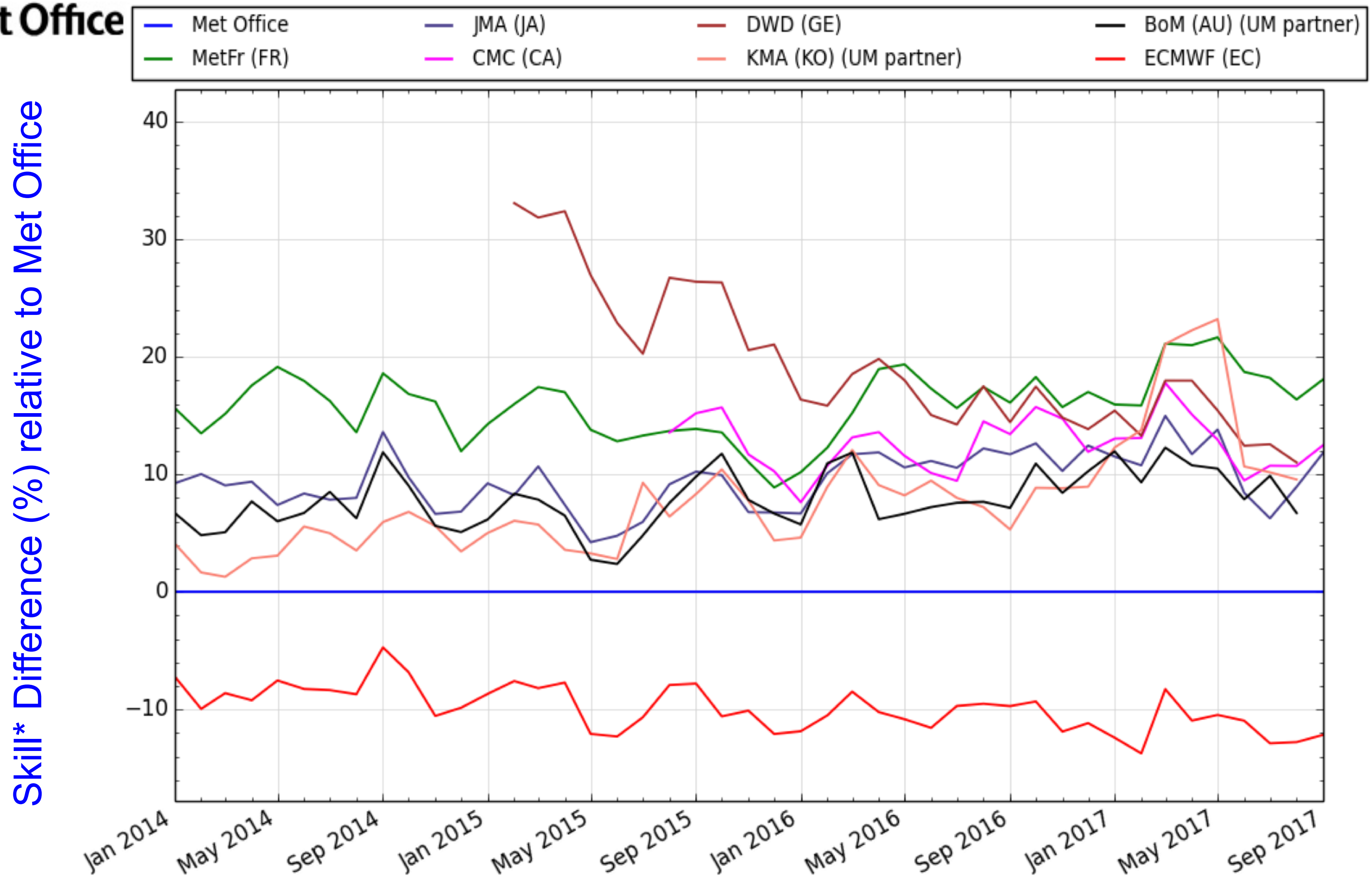
A factor of 1000 between these

300 m



…the same scheme has to continue to work

Global model cf. other centres



* Parameters: PMSL, 500hPA GPH, 250hPa/850hPA Winds; Range: T+24 to T+120

NOTATION AND NOMENCLATURE

Notation

- Let ρ_X denote the ***density***, ***concentration***, or ***mass per unit volume*** of species X
- Let ρ_d denote the density of ***dry air***
- Then $m_X = \rho_X/\rho_d$ is the ***mixing ratio*** of species X
- By definition $m_d = 1$

Conservative form

Densities/concentrations transported according to:

$$\frac{\partial \rho_X}{\partial t} + \nabla \cdot (\boldsymbol{U} \rho_X) = 0$$

Eulerian flux form

$$\frac{D}{Dt}\left(\int_V \rho_X \, dV \right) = 0$$

Lagrangian form (V=air parcel)

Advective form

Mixing ratios/parcel labels (e.g. age of air, mass of air parcel) are transported according to:

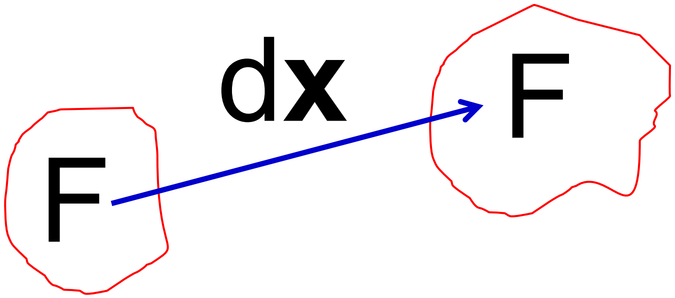
$$\frac{\partial m_X}{\partial t} + \boldsymbol{U} \cdot \nabla m_X = 0$$ Eulerian form

$$\frac{Dm_X}{Dt} = 0$$ Lagrangian form

THE SEMI-LAGRANGIAN SCHEME

From nature to a computer

- DF/Dt=0 a natural form
- Integrate along the path a fluid parcel follows

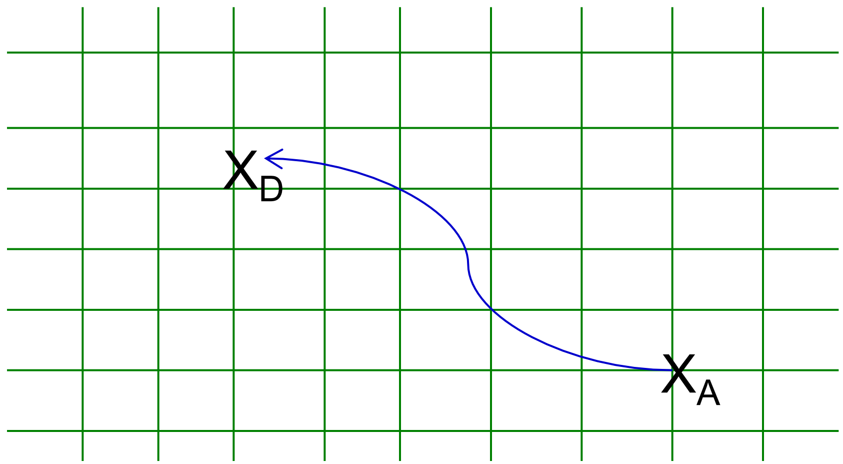


- F(**x**+d**x**,t+dt) = F(**x**,t) where d**x**/dt=**U**

Lagrangian & semi-Lagrangian

- Lagrangian model simply tracks air parcels
- This is the basis of the NAME model for plumes etc
- But, generally end up with very inhomogeneous distribution, requires interpolation/aggregation to where need answer
- Semi-Lagrangian schemes try to maintain the benefits of Lagrangian approach but on Eulerian grid

Semi-Lagrangian



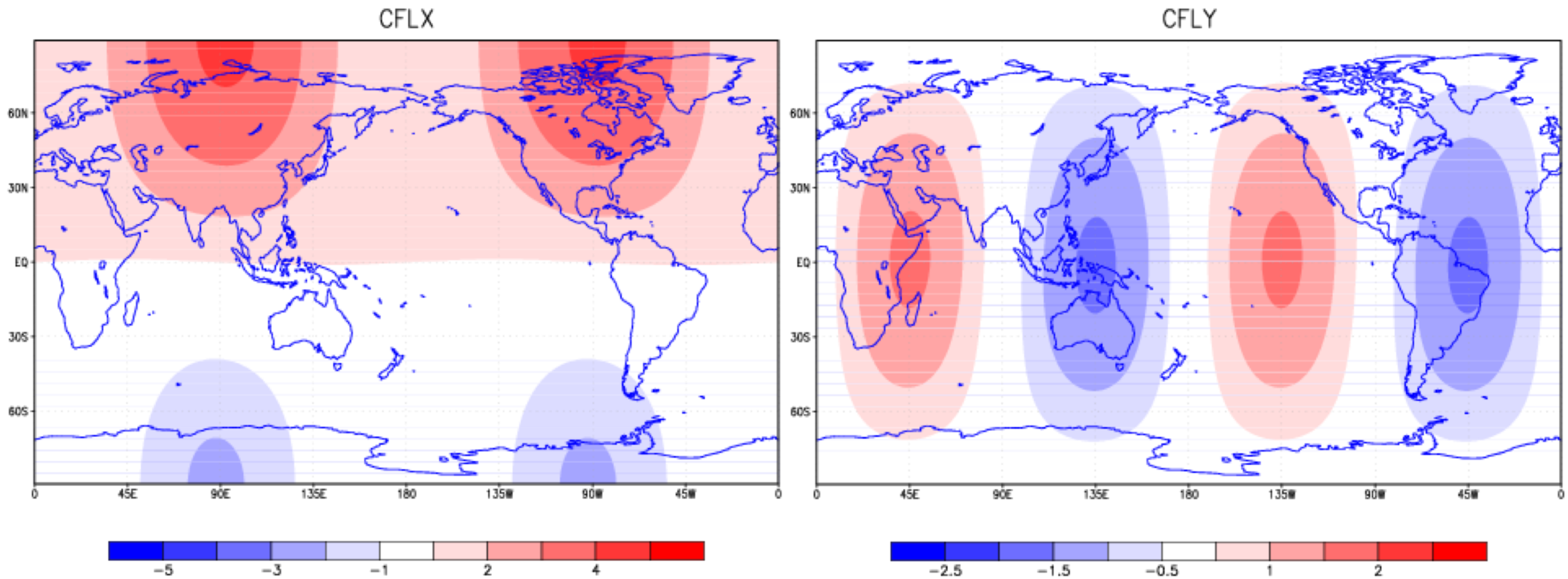
- Arrival point, X_A , always a grid point
- Departure point, X_D, in general anywhere
- Two steps:
  - Evaluate trajectory, i.e. where X_D is relative to X_A
  - Evaluate transported field at X_D

Staniforth and Côté (1991)

Benefits

- Excellent dispersion
  - ➢Captures well the speed of propagation of waves
  - ➢Key for good weather prediction
- Appropriate level of scale selective damping
- Excellent stability
  - ➢Depends on physical (inverse) time scale d**U**/d**X**, not numerical (inverse) time scale **U**/Δ**X**
  - ➢Particularly beneficial in large scale flows (cf. jets)
  - ➢And in polar regions (operationally, polar ΔX=12 m, dt = 4 mins, and CFL = 1 for U=5 **cm**/s!)

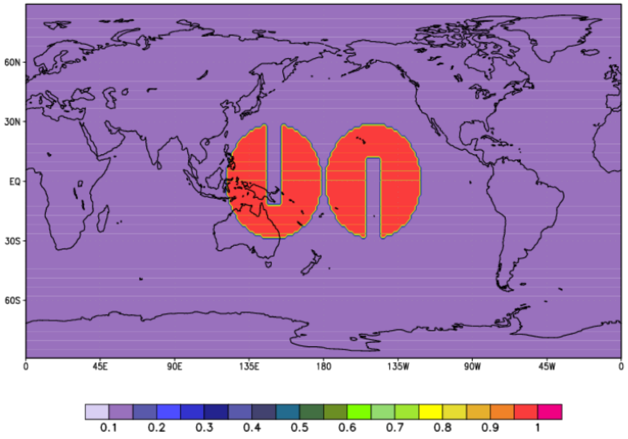
An example

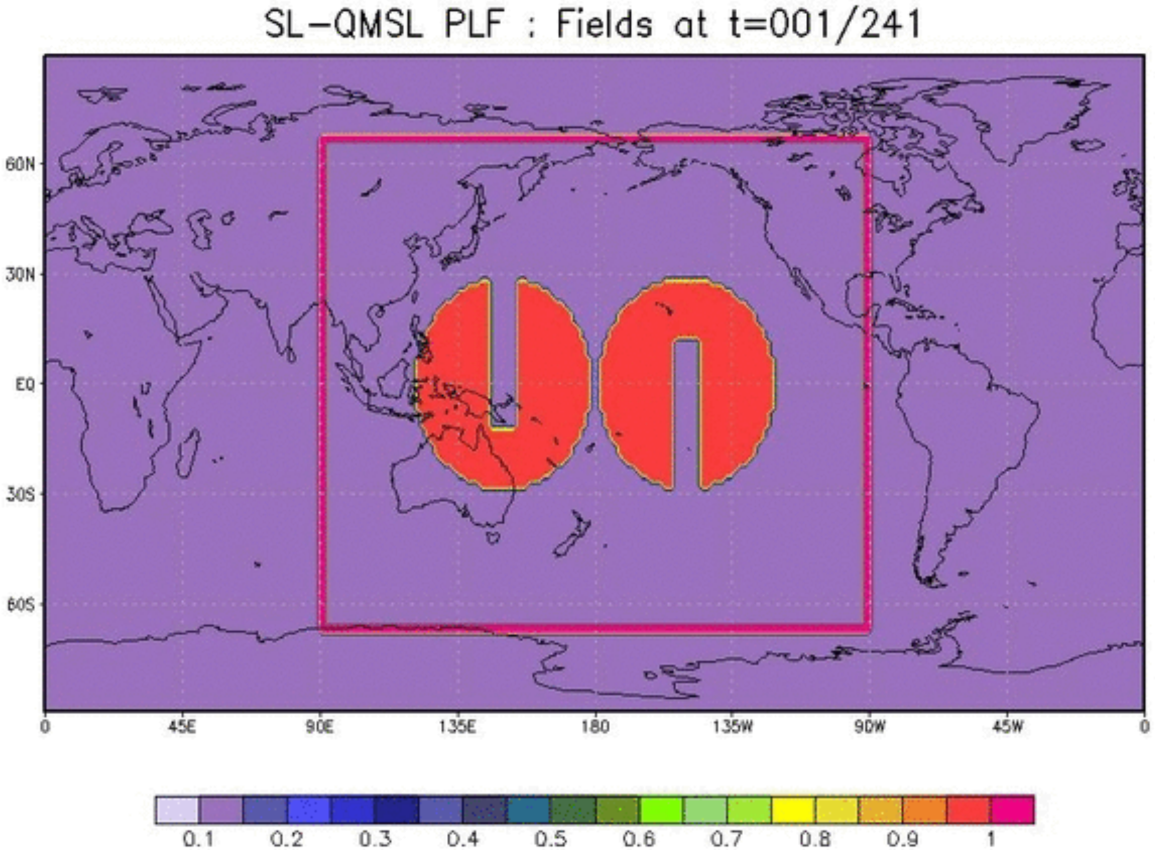


Kohei Aranami (MetO/JMA)

Slotted cylinder test case

Initial Conditions

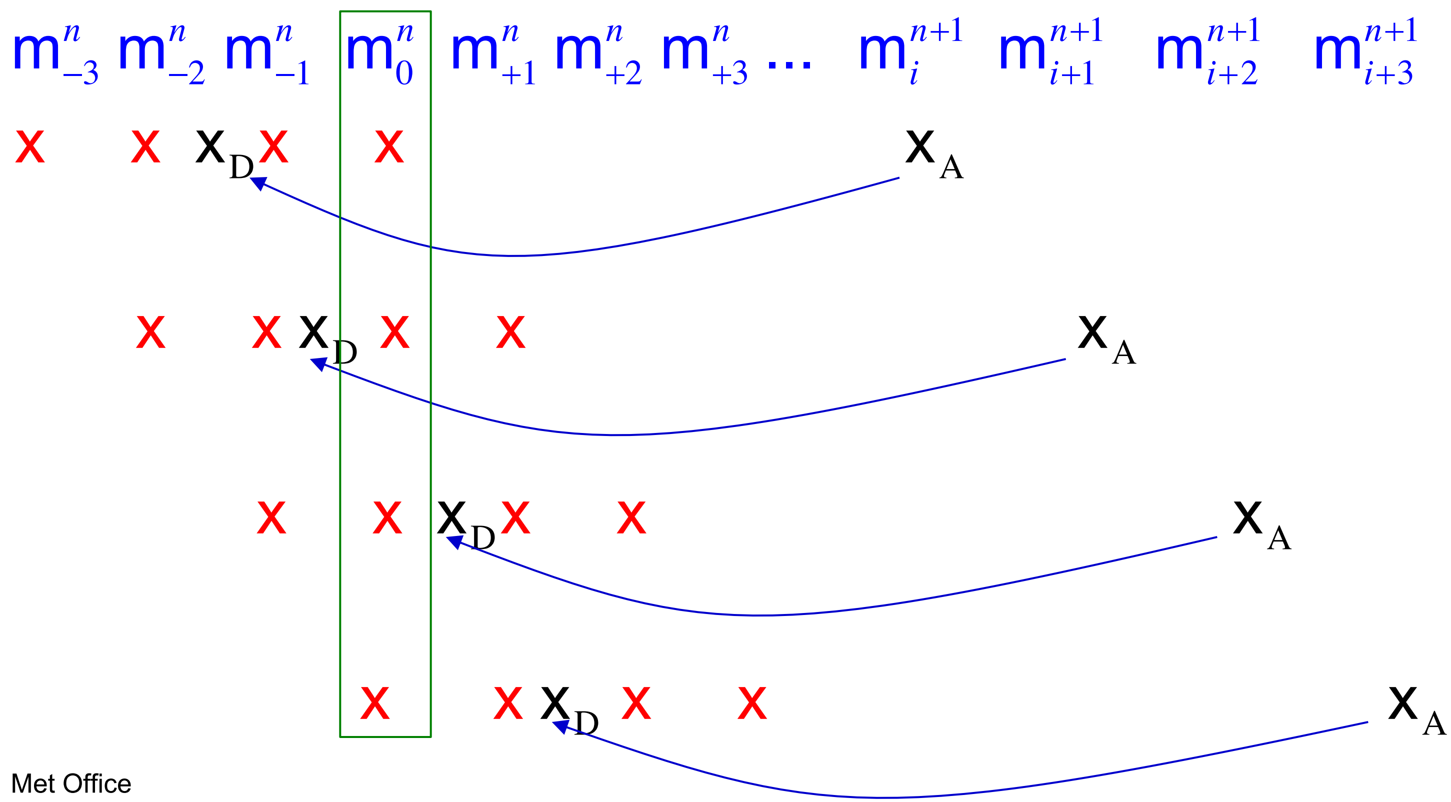




Kohei Aranami (MetO/JMA)

Disbenefits

- Lack of locality due to large time step, means departure point can be long way from arrival
- Conservation - consider cubic interpolation:



Conservation

- Even in case of interpolating mass (so don't have to worry about density variations and non-uniform grid spacing), require:

$$\sum_i \mathrm{m}_i^n = \sum_i \mathrm{m}_i^{n+1} = \sum_i \left(a_j \mathrm{m}_{j(i)-2}^n + b_j \mathrm{m}_{j(i)-1}^n + c_j \mathrm{m}_{j(i)}^n + d_j \mathrm{m}_{j(i)+1}^n \right)$$

- For this to hold independent of mass distribution

$$\left(a_{i+2} + b_{i+1} + c_i + d_{i-1} \right) \mathrm{m}_i^n = \mathrm{m}_i^n$$

which is only true if wind is uniform

- [Cf. $a_i + b_i + c_i + d_i = 1$]

ENDGame:
Even Newer Dynamics for General atmospheric modelling of the environment

(Operational since 2014; Wood et al 2014)

Transport in ENDGame I

- Semi-Lagrangian scheme applied to all variables
- Special handling of vector aspects for wind
- Lagrangian interpolation:
  - Horizontal
    - Bi-cubic for all variables
  - Vertical
    - Cubic for wind components
    - Cubic-Hermite for potential temperature and moisture variables
    - Quintic for all other tracers

Transport in ENDGame II

- Conservation:
  - Priestley algorithm (optionally) applied to moisture and tracer variables ***and*** potential temperature

- Monotonicity:
  - Bermejo and Staniforth (optionally) applied to moisture and tracer variables ***and*** potential temperature

Dry mass conservation

- Without mass fixer relative change in total mass per time step is $O(10^{-5})$
- $\Rightarrow$ apply multiplicative fixer every time step
- Important that it preserves potential energy

- Achieved by:

$$\rho^{n+1} = \left(A + Bz\right)\rho^{*}$$

- *A* and *B* chosen such that

$$\sum \rho^{n+1} dV = \sum \rho^{n} dV$$

$$\sum \rho^{n+1} gz dV = \sum \rho^{*} gz dV$$

Priestley algorithm

- Notes that loss of conservation arises from interpolation
- Compares low-order (specifically linear) interpolation with a high-order scheme (e.g. cubic or quintic)
- Argues that where these are different is where conservation will be lost
- Therefore adjusts high-order interpolated field proportionately to that difference
- Formally non-local but attempts to localize

Priestley (1993)

Monotonicity algorithm

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- Higher-order interpolation scheme more accurate on smooth data
  - ➢Cubic Lagrange is 3rd order accurate in space
- But applied to unsmooth data it will create overshoots and undershoots
- When this occurs high-order interpolation is not appropriate or sensible
- Could reduce the order progressively
- Pragmatic: limit the interpolated value to be bounded by the 8 values surrounding departure point

Bermejo and Staniforth (1992)

DOES IT MATTER WHAT WE DO?

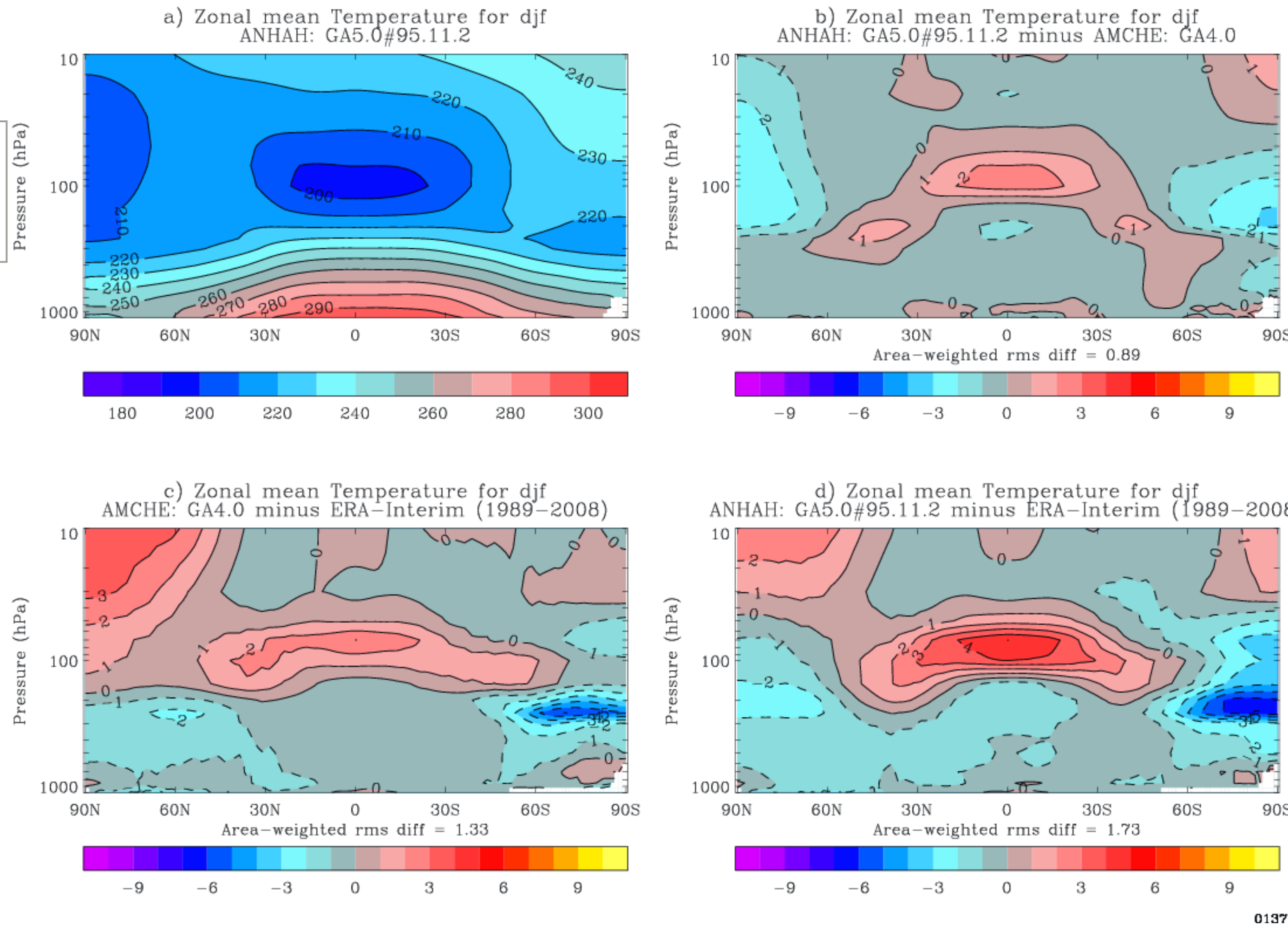
Temperature bias in 20 year AMIP run

ENDGame zonal mean temperature

EG - ND

ND - ERA

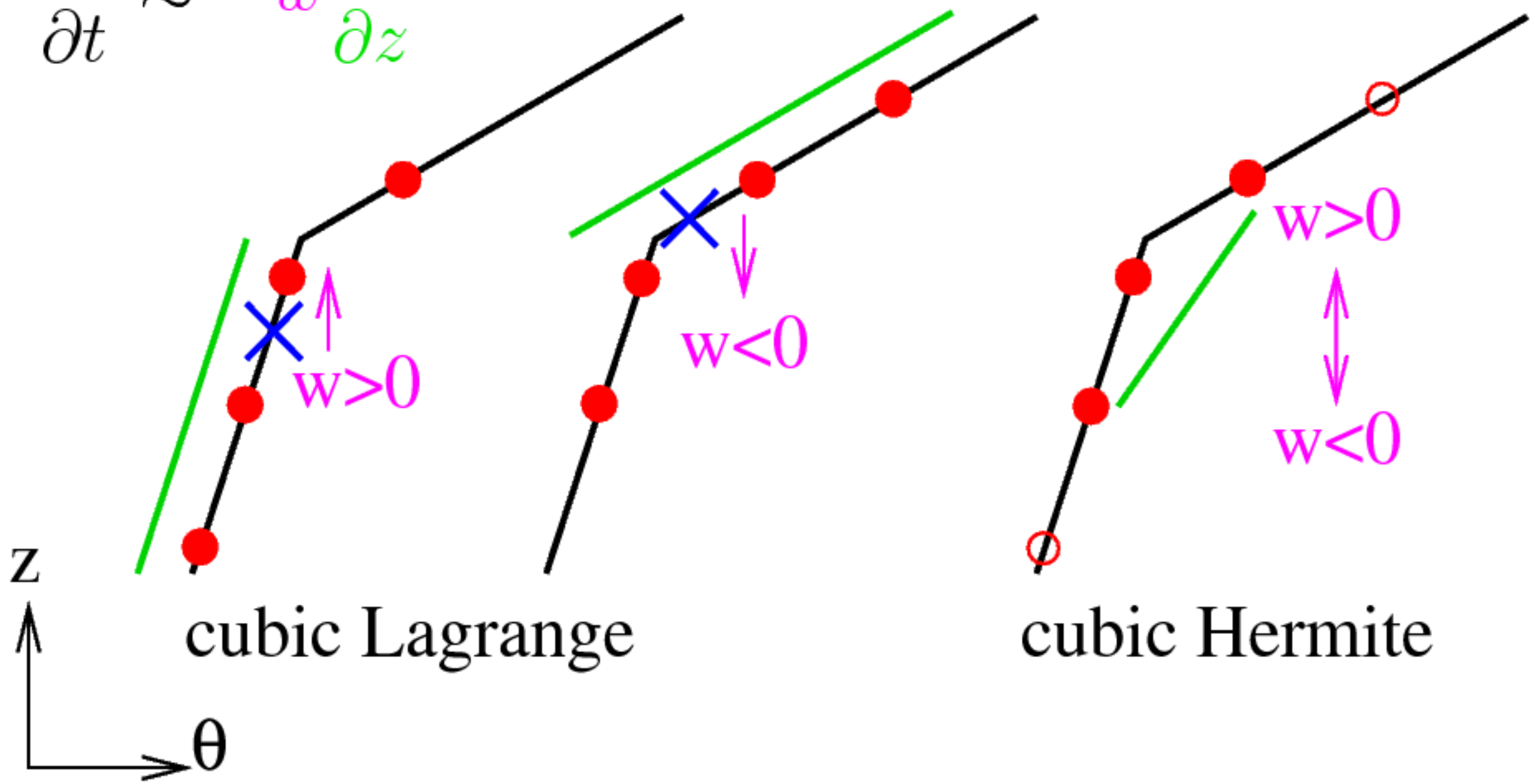
EG - ERA



(ND=New Dynamics; EG=ENDGame; ERA=ERA-Interim)

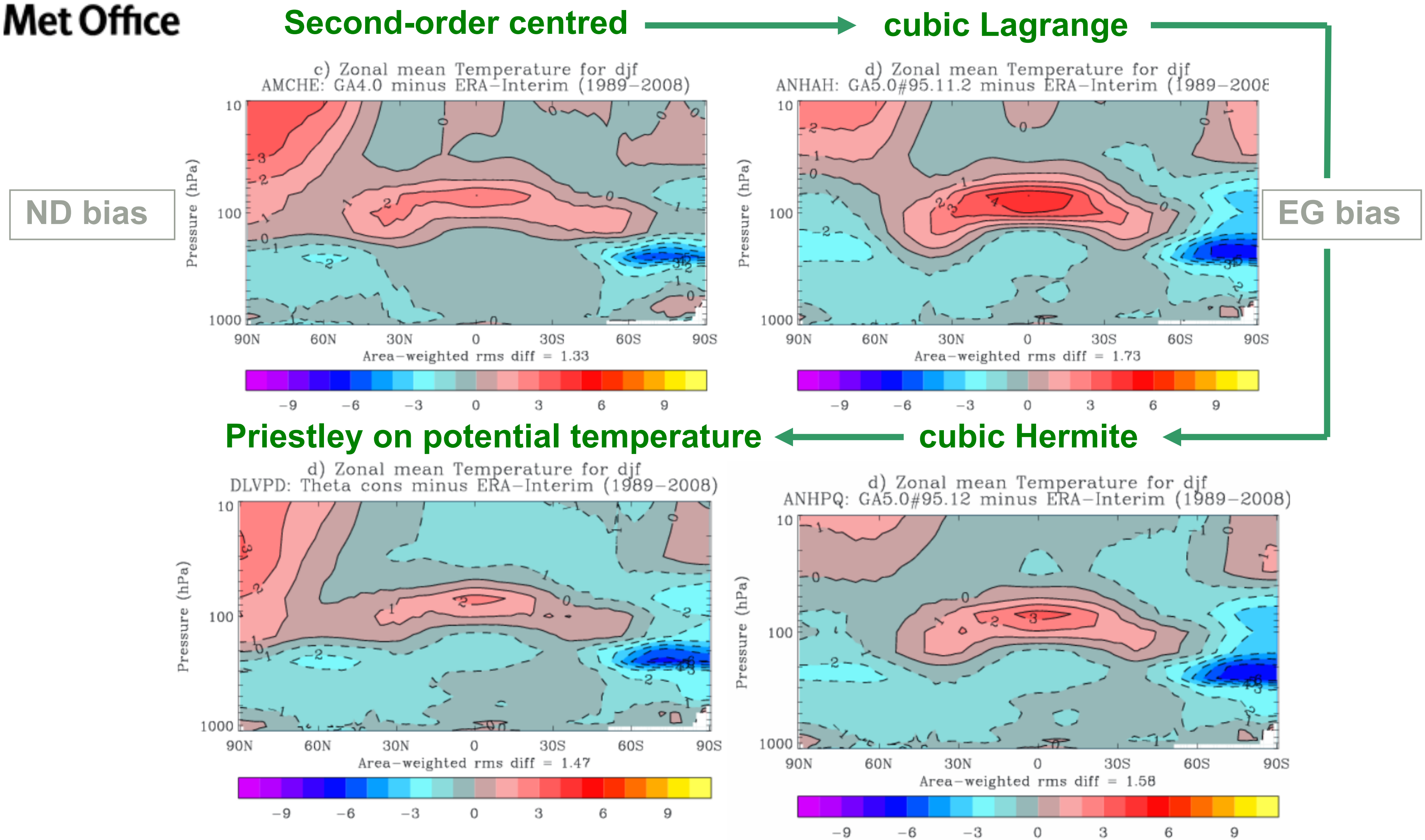
Why?

$$\frac{\partial \theta}{\partial t} \approx -w\frac{\partial \theta}{\partial z}$$



Chris Smith (Met Office)

Impact of cubic Hermite + Priestley



David Walters (Met Office)

SLICE:
SEMI-LAGRANGIAN INHERENTLY CONSERVATIVE AND EFFICIENT

RECOVERING CONSERVATION...

Conservative semi-Lagrangian

- Inherent conservation $\Rightarrow$ must use density or concentration, ρ_X
- But instead of usual Eulerian flux form

$$\frac{\partial \rho_X}{\partial t} + \nabla \cdot \left(\boldsymbol{U} \rho_X \right) = 0$$

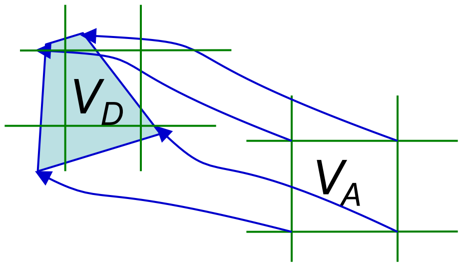
- Use Lagrangian form:

$$\frac{D}{Dt}\left(\int_V \rho_X \, dV \right) = 0$$

Conservative semi-Lagrangian

- Integrate along trajectory:

$$\int_{V_A} \rho_X^{n+1}\,dV = \int_{V_D} \rho_X^{n}\,dV$$



- Rearrange as:

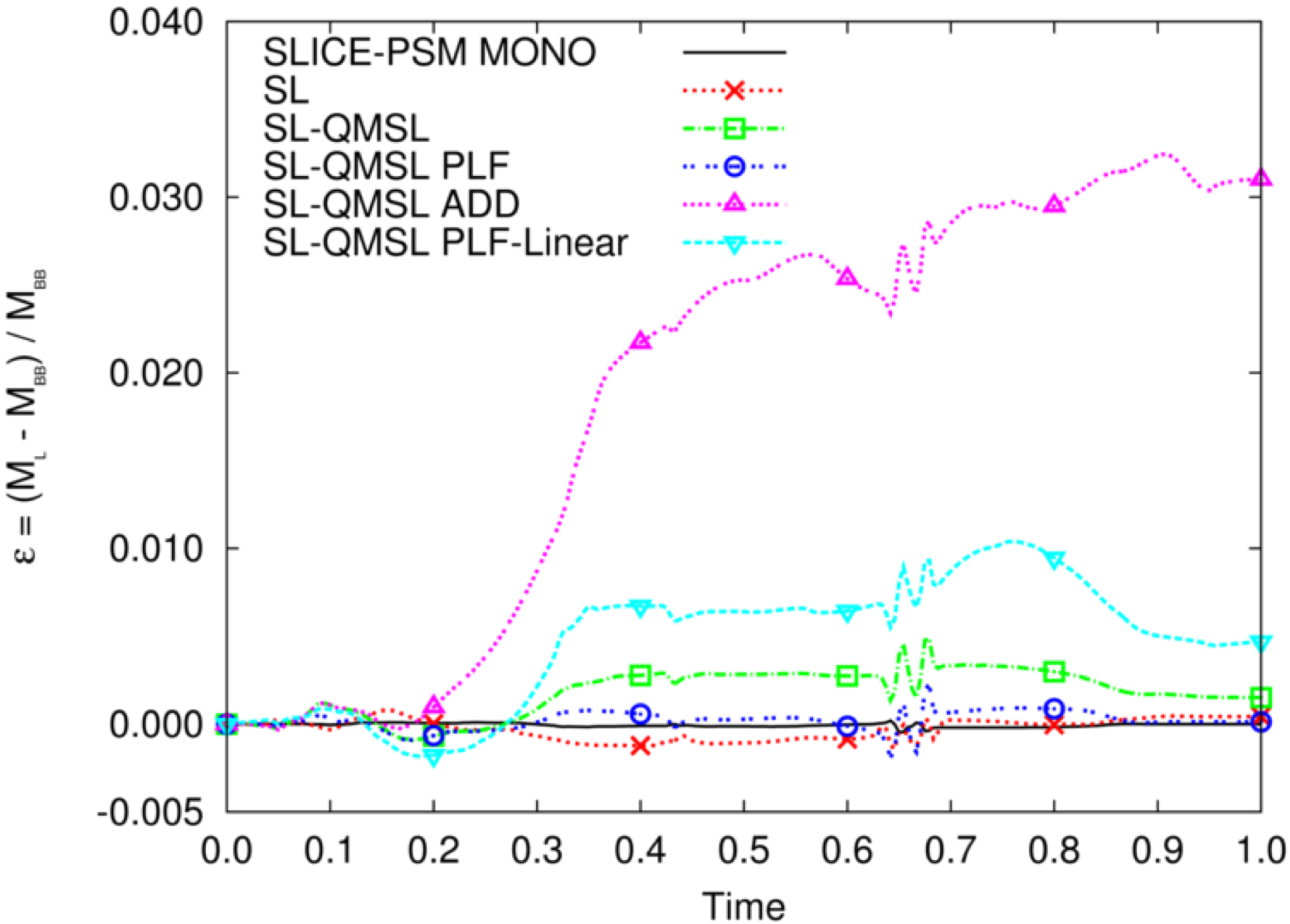
$$\rho_X^{n+1} = \frac{1}{V_A}\left(\int_{V_D} \rho_X^{n}\,dV\right)$$

Zerroukat, Wood & Staniforth (2002)

CONSERVATION IN LIMITED AREA MODELS...

LAM Conservation (budget)

- SL alone good
- Monotonicity messes this up
- Conservation recovers accuracy
- And gives exact budget



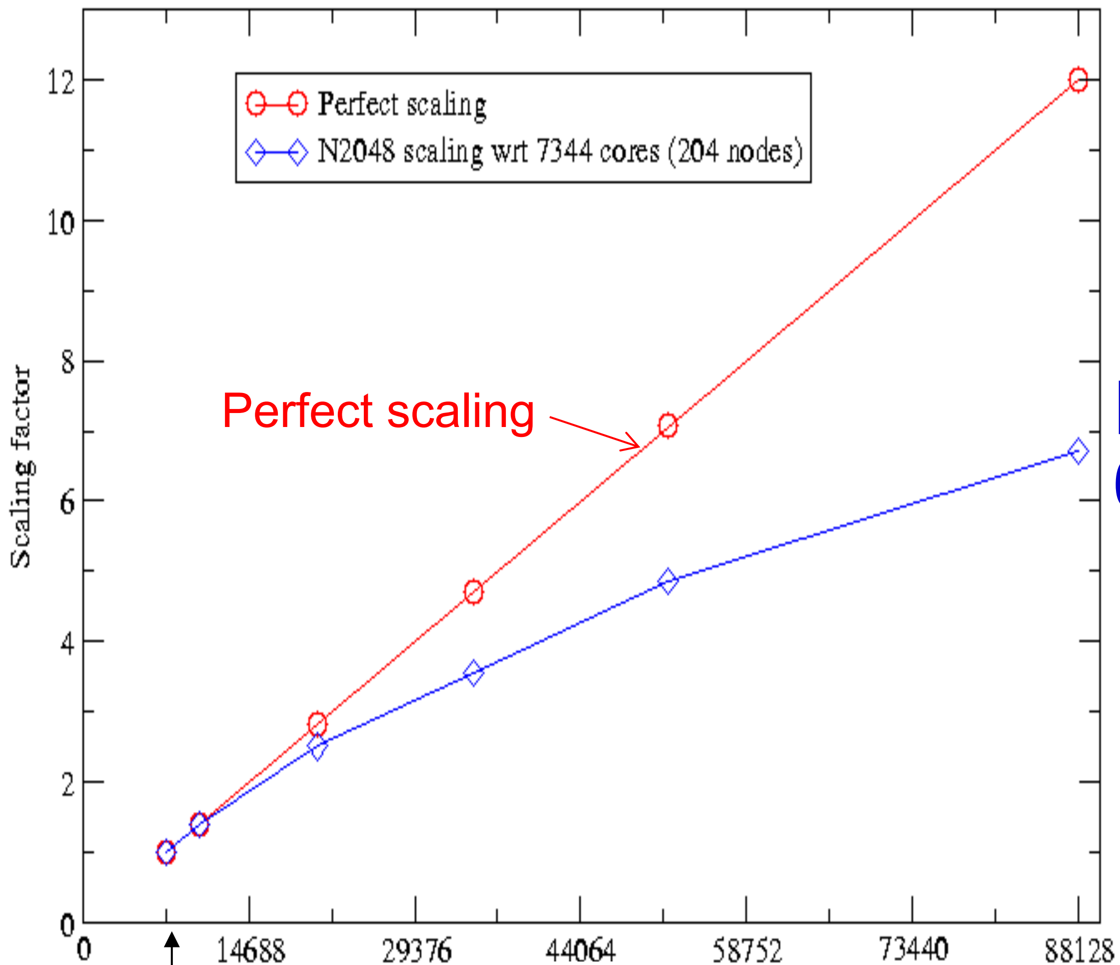
PLF: Aranami, Davies and Wood (2014)

ZLF: Zerroukat & Shipway (2017)

GUNGHO INTO THE FUTURE!

Scalability

T_{7344}/T_N



ENDGame
6.5 km global

7344 cores

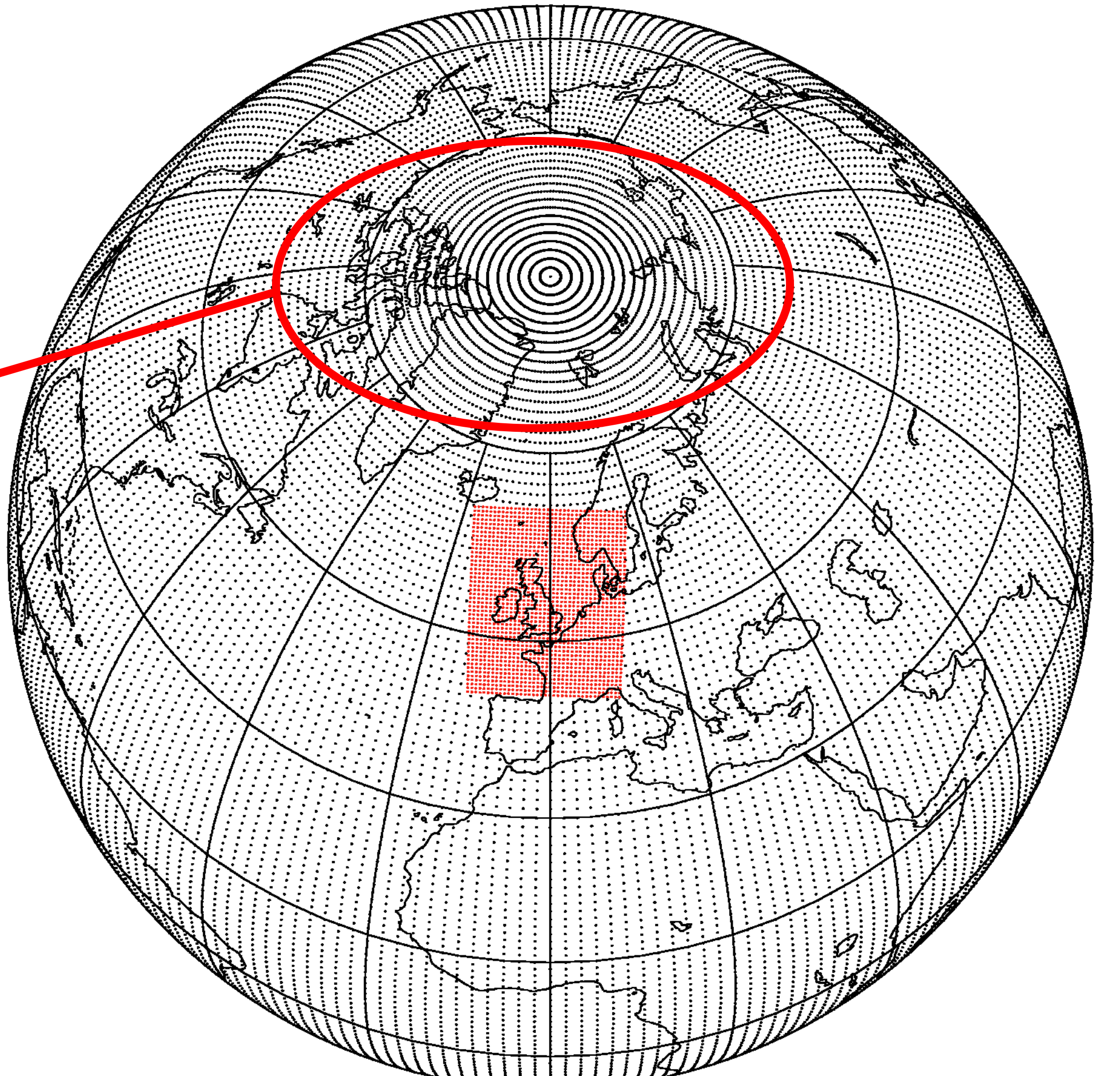
Cores

(1 node=36 cores)

Paul Selwood & Andy Malcolm (Met Office)

The finger of blame…

- At 17km resolution, grid spacing near poles = 35m
- At 10km spacing = 12m
- At 1km reduces to 12 **cm**!



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GungHo!

Globally

Uniform

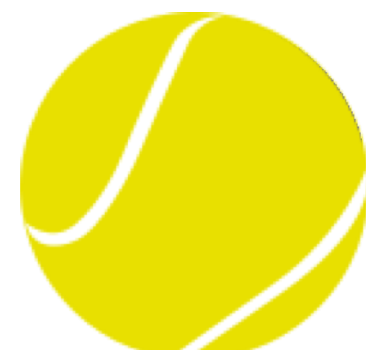
Next

Generation

Highly

Optimized

工合



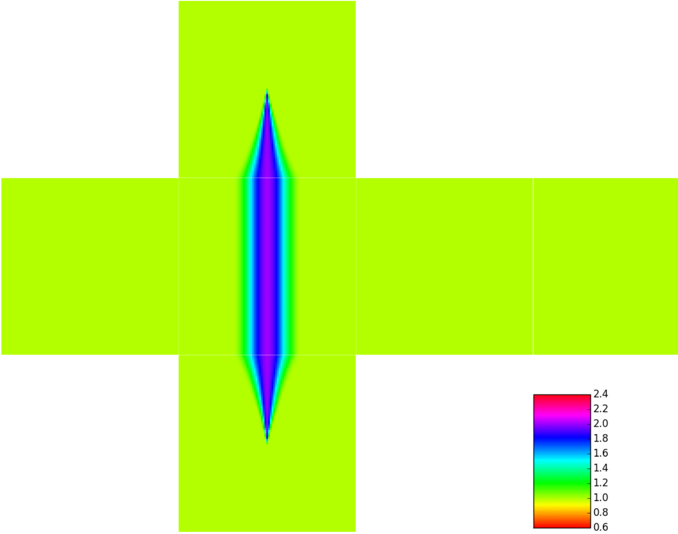
NERC SCIENCE OF THE ENVIRONMENT

Science & Technology Facilities Council

"Working together harmoniously"

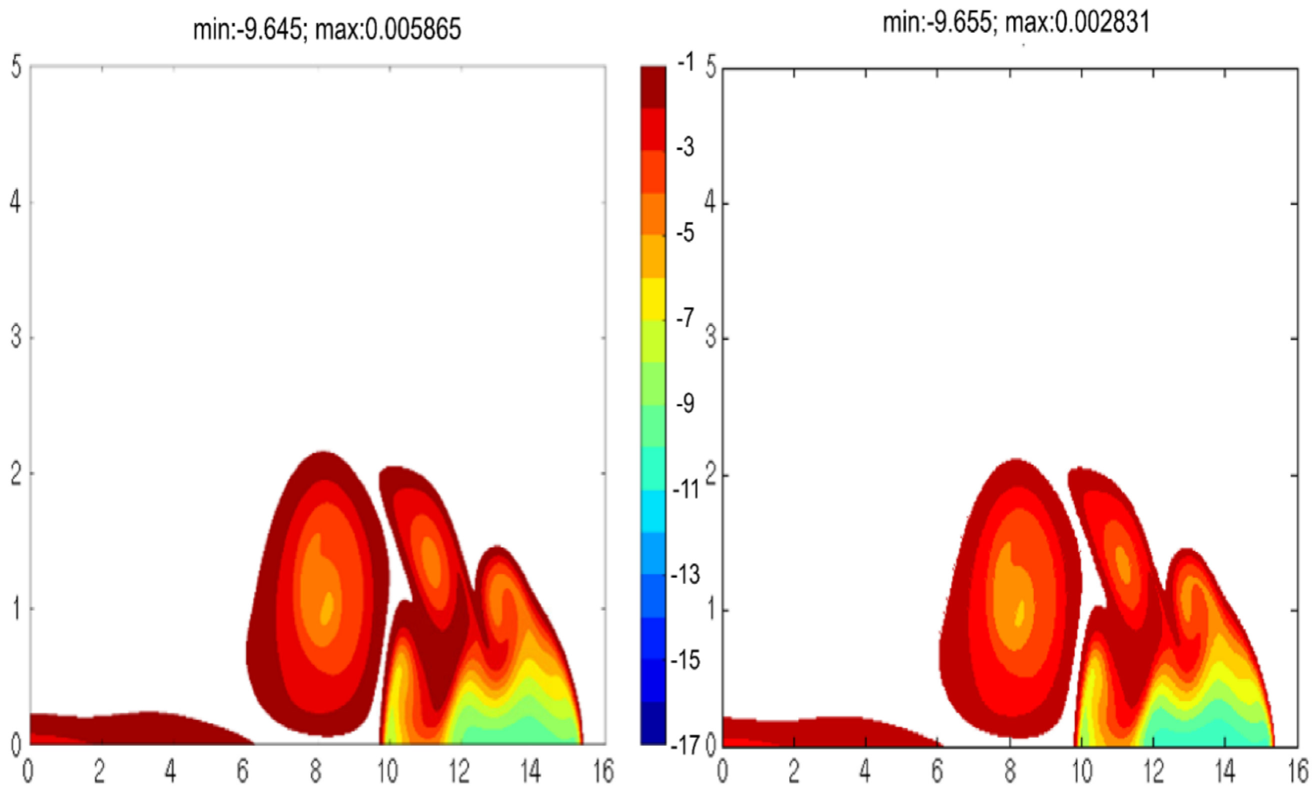
Where are we?

- Cubed-sphere is principal contender
- But grid non-orthogonal
- To maintain same accuracy using mixed finite-element spatial discretization...
- ...coupled with an ***Eulerian flux form*** transport scheme (either finite element or finite volume)
- Redesigning Unified Model
  - ➢F2003
  - ➢Separation of concerns - PSyKAl
- Targeting mid-2020's



Straka cold bubble

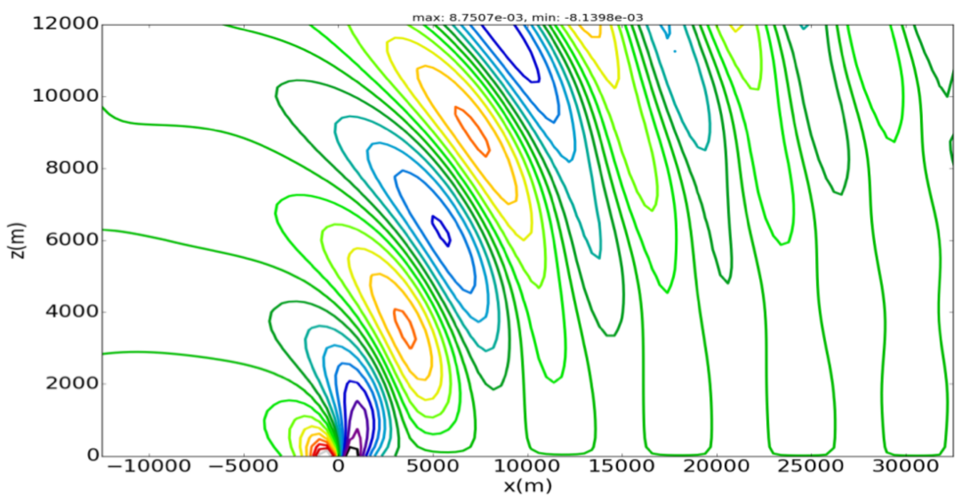
Low Order Mixed FEM; GH = 50 m; EG = 50 m



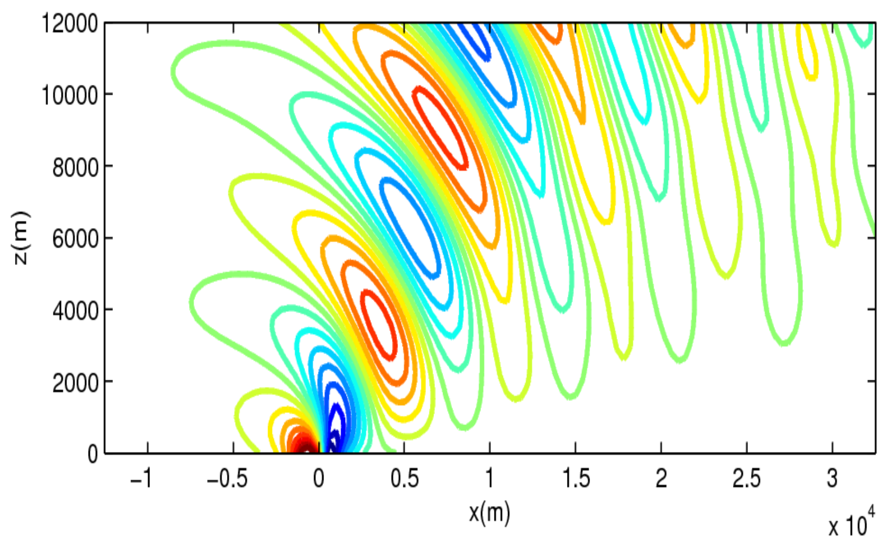
GungHo ENDGame

Orographic gravity waves

Low-order Mixed FEM; stratified flow over a small hill; uniform Cartesian domain



GungHo

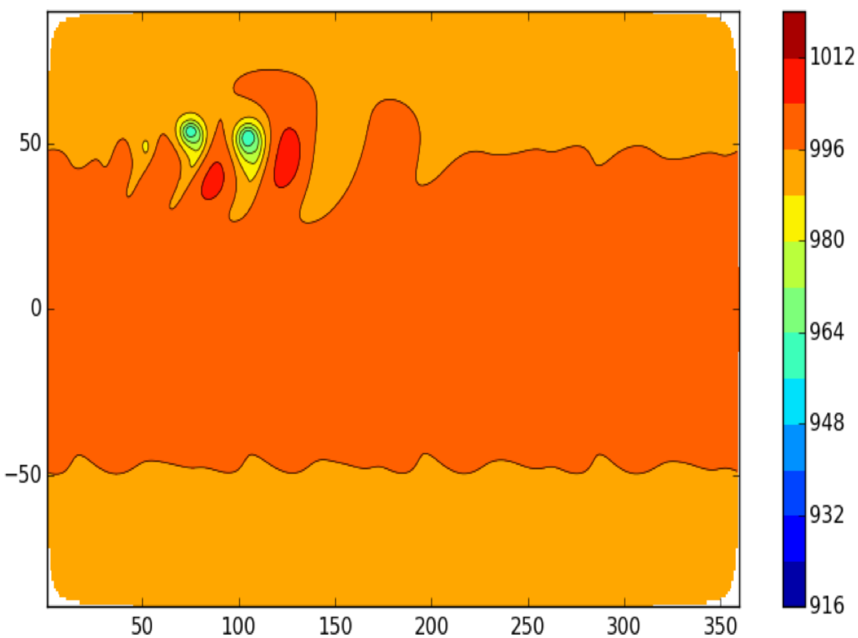


ENDGame

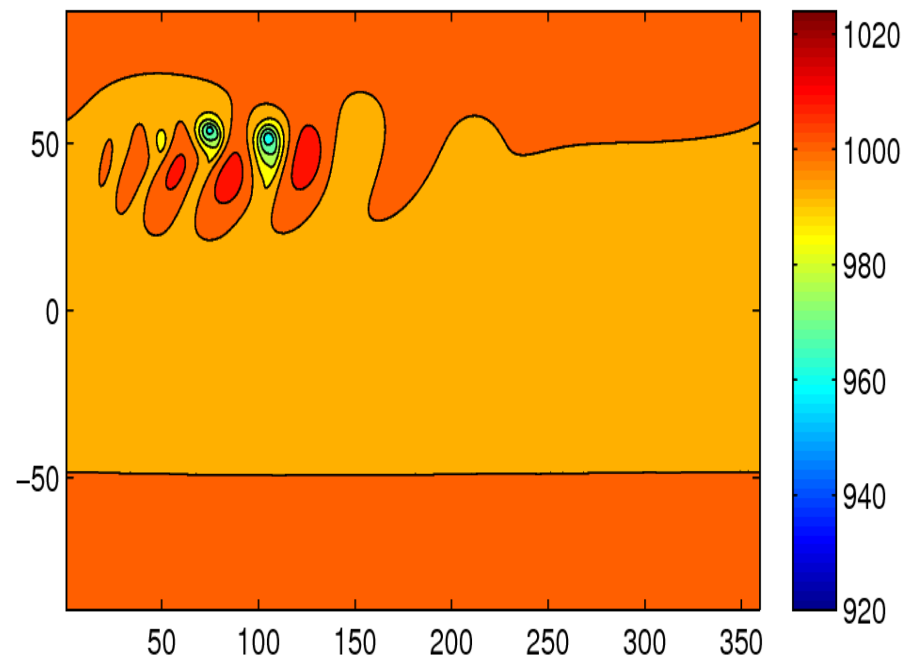
Baroclinic wave

Low Order Mixed FEM; GH = C96 ~ 1 degree; EG = 1 degree

Day 8 surface pressure



GungHo



ENDGame

Thank you!

Questions?

See extra slides for Bibliography and How to select options in UM

Bibliography

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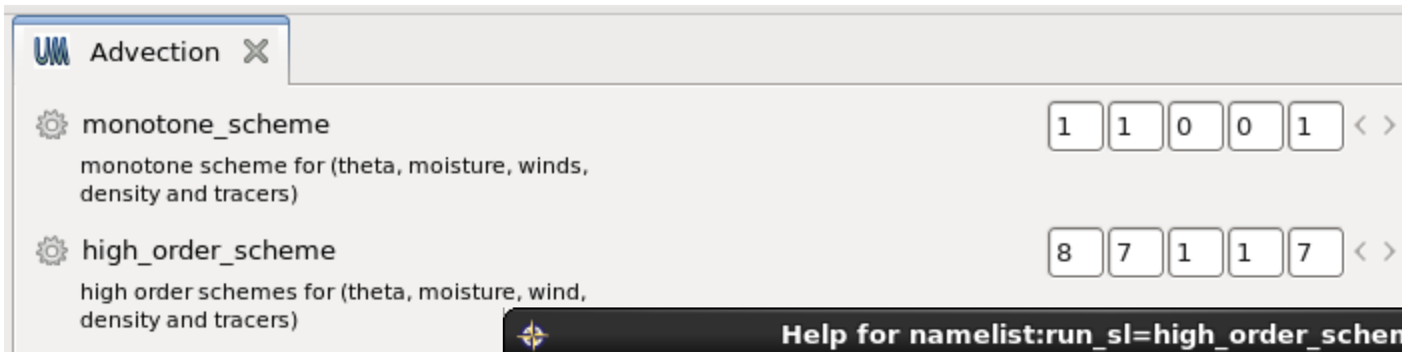
8. Zerroukat, M. And Shipway, B. (2017) , ZLF (Zero Lateral Flux): A simple mass conservation method for semi-Lagrangian based limited area models, Submitted to *Q. J. R. Meteorol. Soc.*

TRACER TRANSPORT OPTIONS IN ROSE

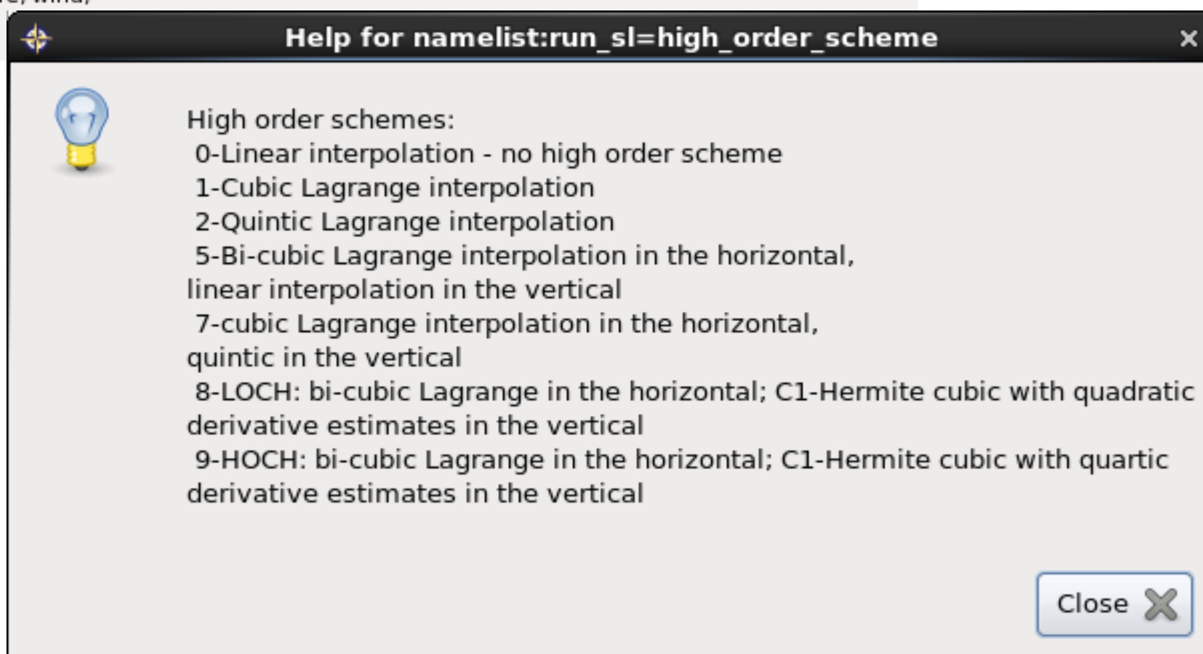
with thanks to Chris Smith

Interpolation options in Rose: vn ≥ 10.6

Separate options for moisture and tracers ...

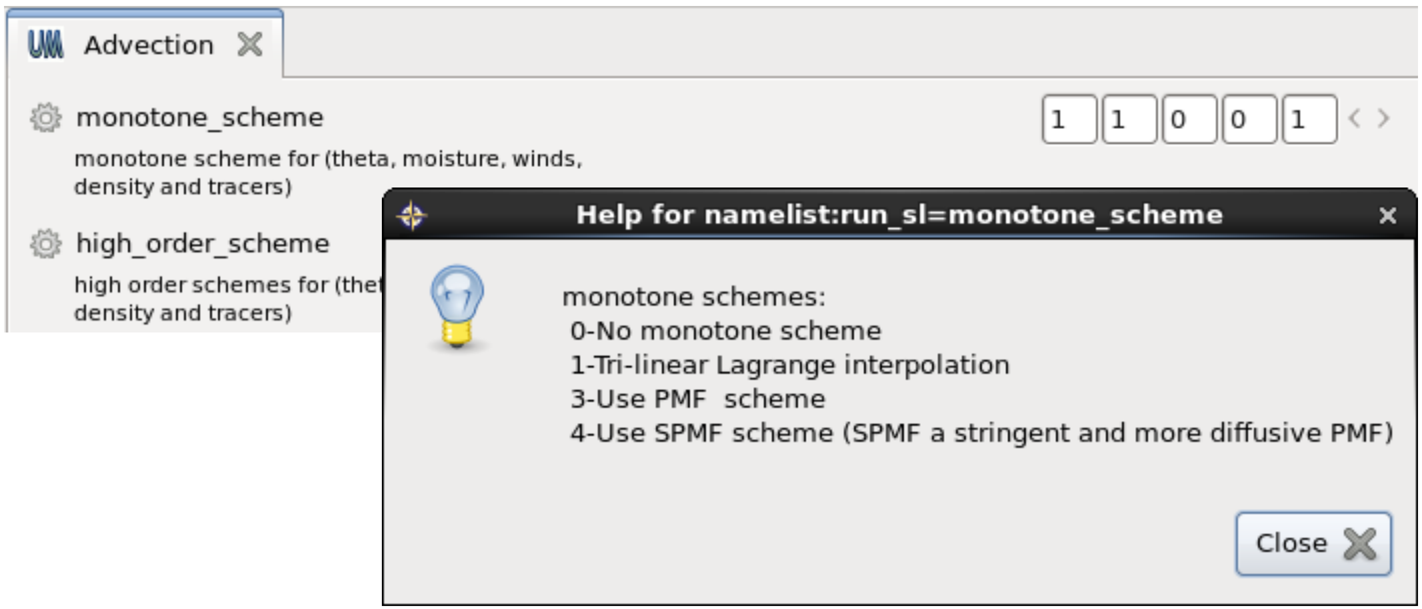


... with range of interpolation schemes



Interpolation options in Rose: vn ≥ 10.6

... and new options for monotonicity



Conservation options in Rose: vn ≥ 10.1

Tracer conservation now has the option to use the Priestley (1993) algorithm: