Tracer transport in the Unified Model

Nigel Wood, Dynamics Research

The plan of attack!

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

Unified Model

Brown et al. (2013)

- Operational forecasts
  - Mesoscale (resolution approx. 4km, 1.5km)
  - Global scale (resolution approx. 17km)

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

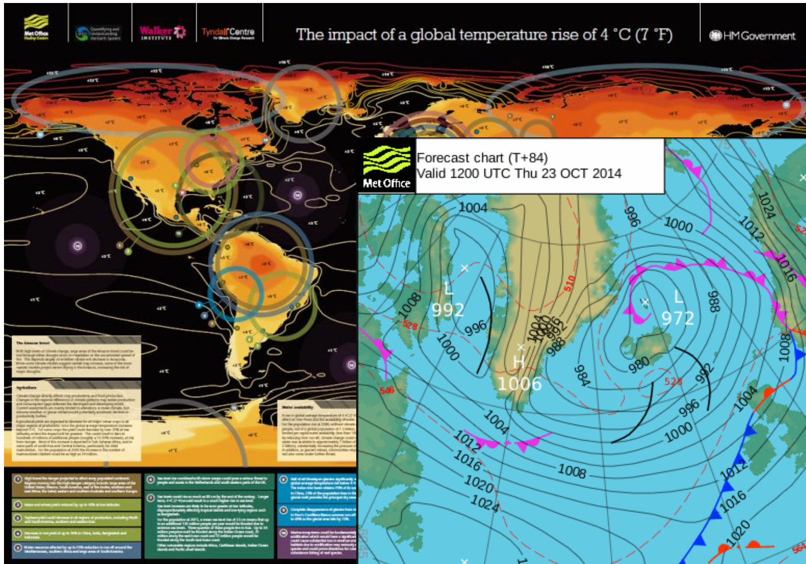
- Seasonal predictions
  - Resolution approx. 60km

- Research mode
  - Resolution 1km - 10m

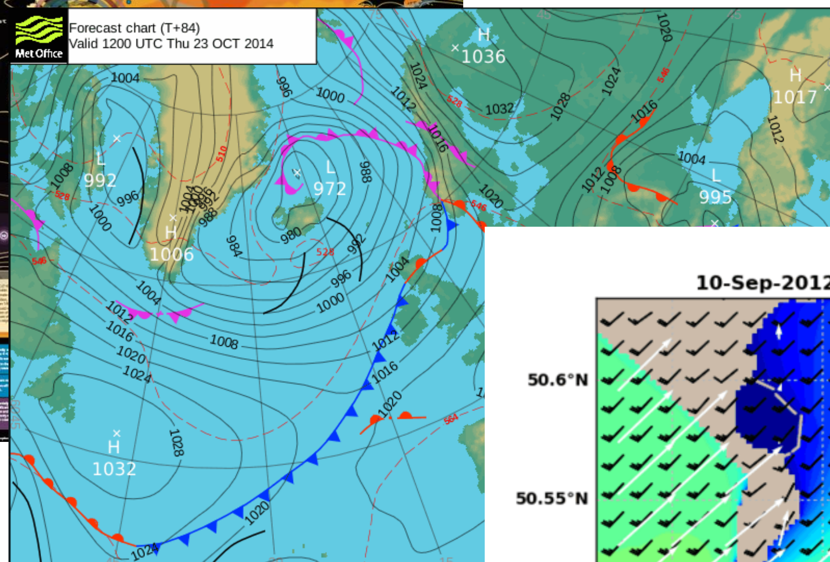
> 20 years old

The consequence of unification

300 km

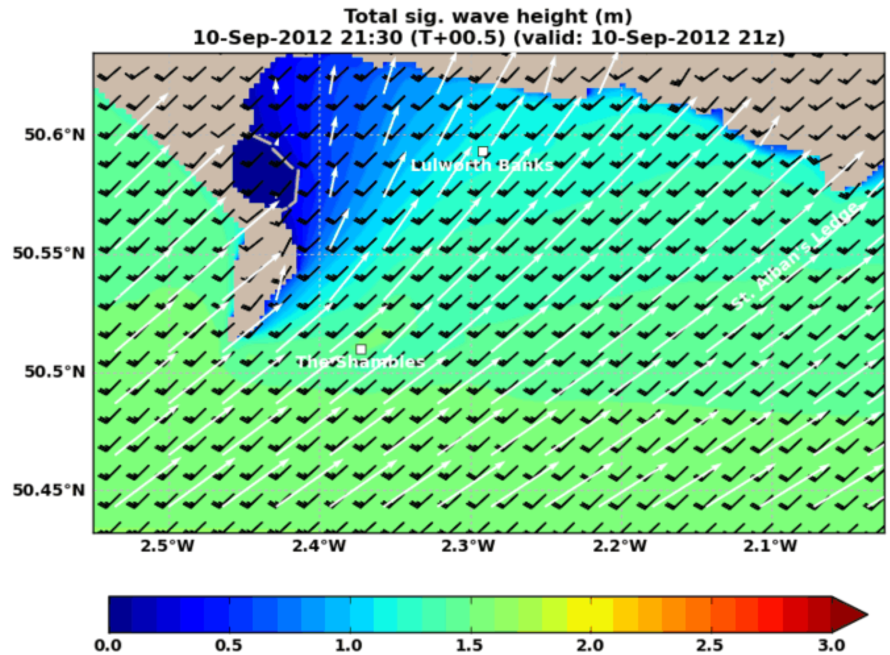


30 km

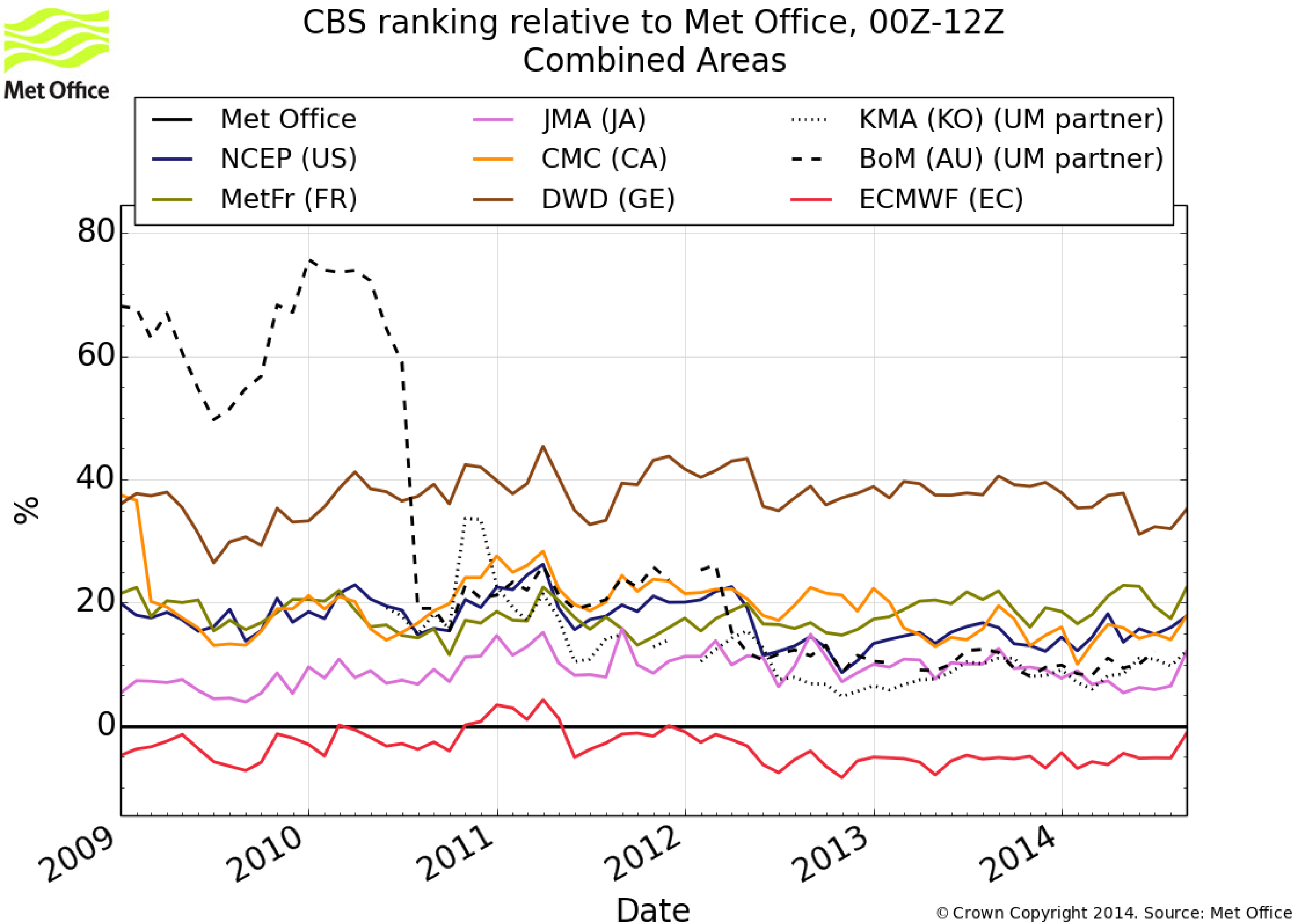


A factor of 1000 between these

300 m



…the same scheme has to continue to work


Met Office
CBS ranking relative to Met Office, 00Z-12Z
Combined Areas
Met Office
NCEP (US)
MetFr (FR)
JMA (JA)
CMC (CA)
DWD (GE)
KMA (KO) (UM partner)
BoM (AU) (UM partner)
ECMWF (EC)
%
80
60
40
20
0
2009
2010
2011
2012
2013
2014
Date

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:

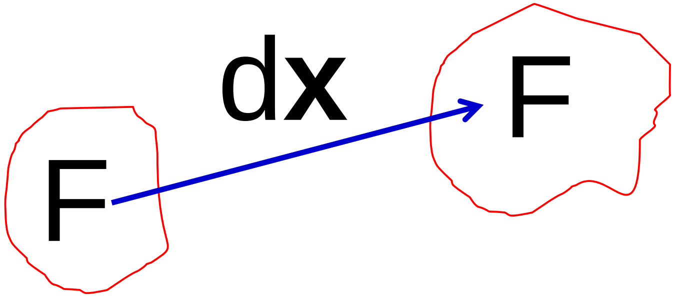
$$\frac{\partial m_X}{\partial t} + \boldsymbol{U} \cdot \nabla m_X = 0$$ Eulerian form

$$\frac{D m_X}{D t} = 0$$ 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

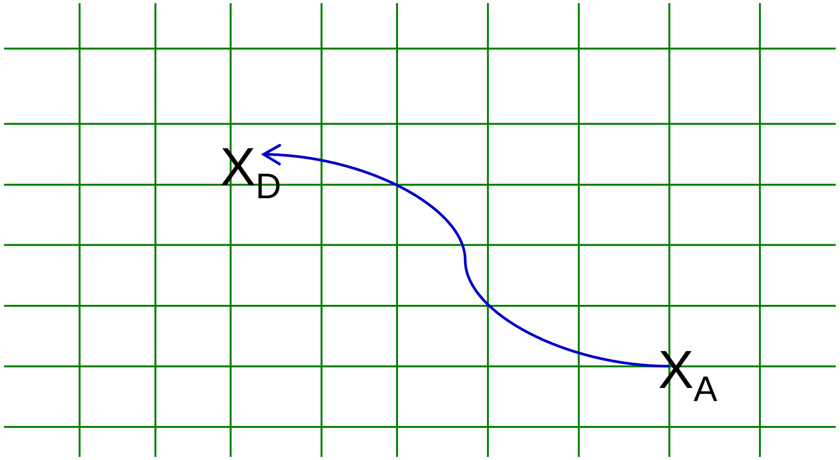


- F(**x**+d**x**,t+dt) = F(**x**,t) where d**x**/dt=**U**

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



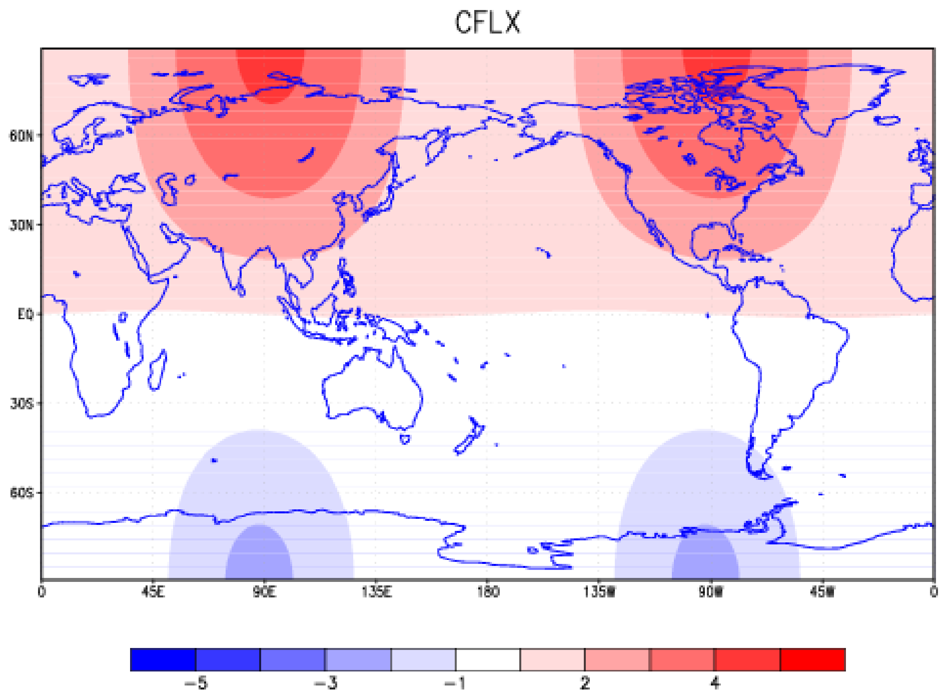
- Arrival point, X_A , always a grid point
- Departure point, X_D, in general anywhere
- Two steps:
  - Evaluate trajectory, i.e. where X_D is relative to X_A
  - Evaluate transported field at X_D

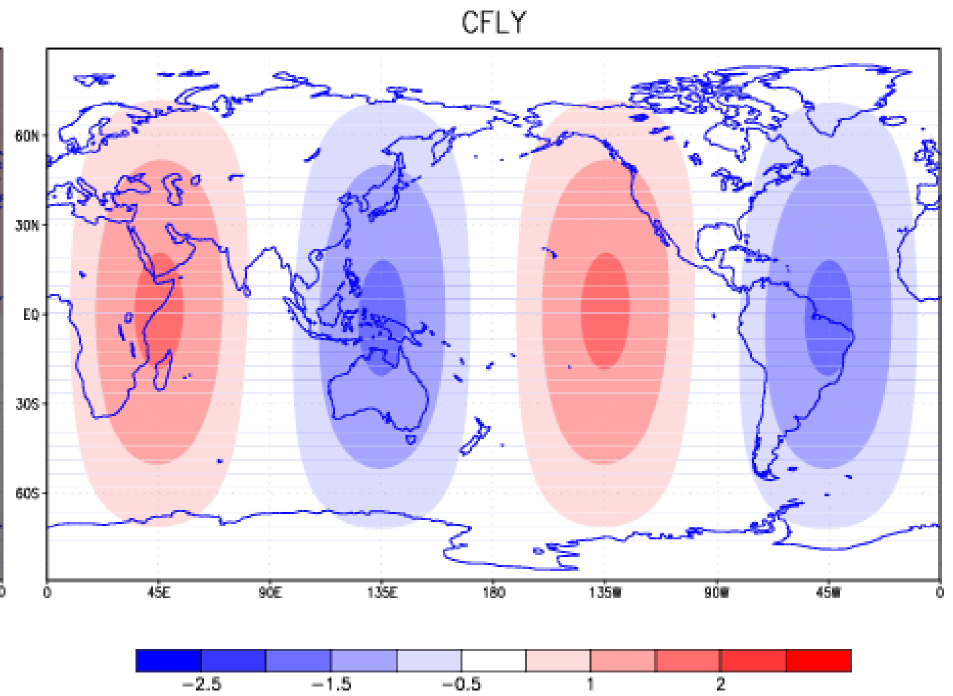
Staniforth and Côté (1991)

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 time scale d**U**/d**X**, not numerical time scale UdX
  - Particularly beneficial in large scale flows (cf. jets)
  - And in polar regions (operationally, polar dX=35 m, dt = 7.5 mins, and CFL = 1 for U=8 **cm**/s!)

An example

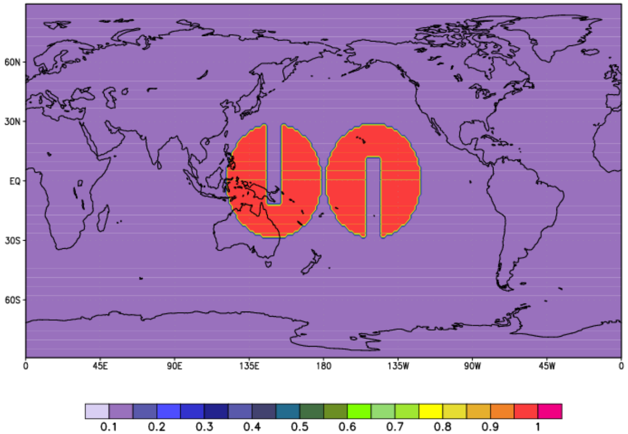


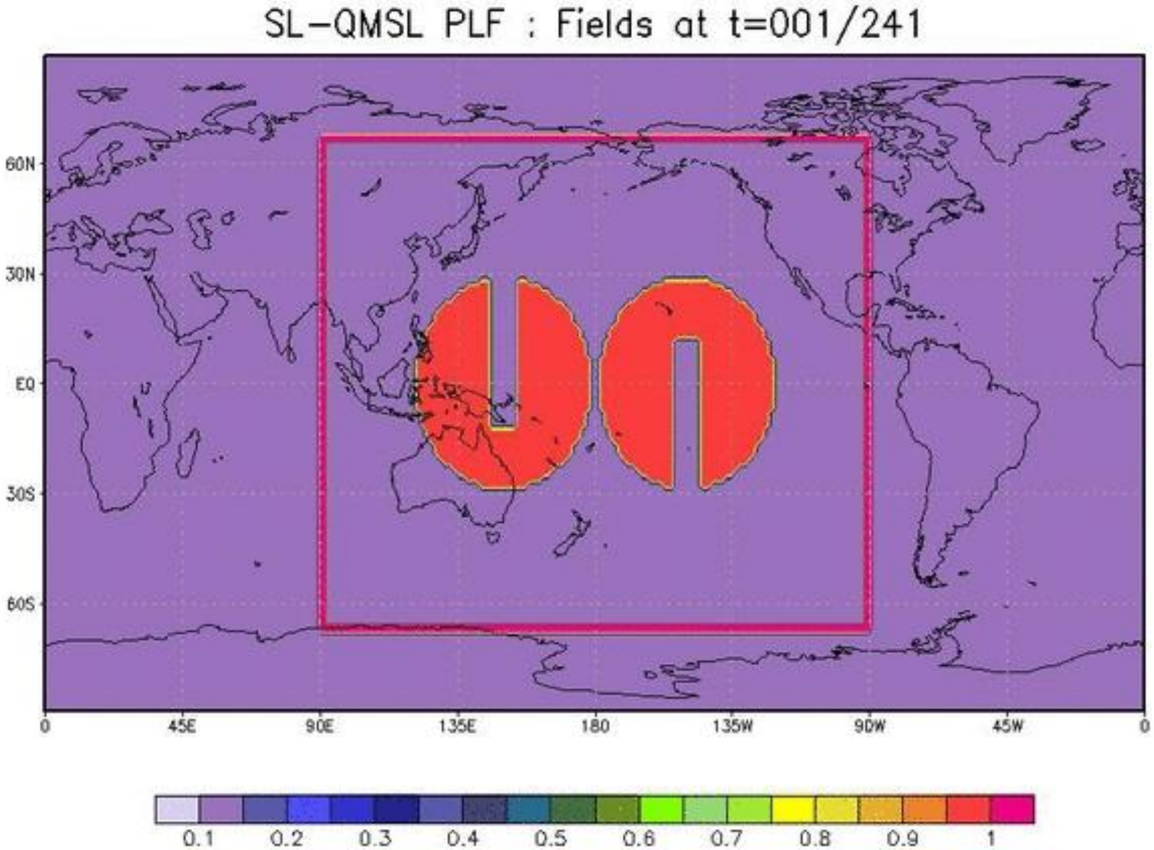


Kohei Aranami (MetO/JMA)

Slotted cylinder test case

Initial Conditions

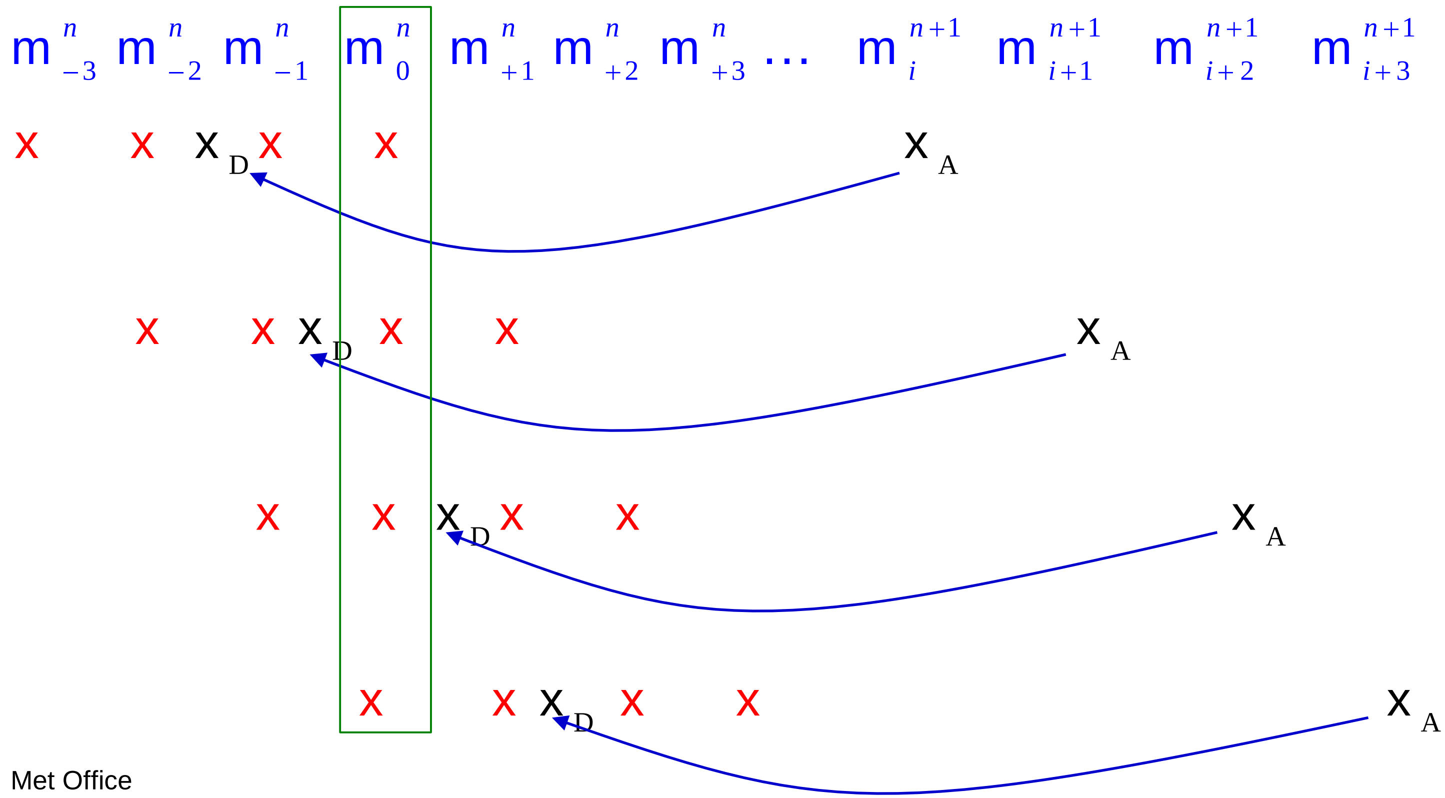




Kohei Aranami (MetO/JMA)

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:

$$\sum_i m_i^n = \sum_i m_i^{n+1} = \sum_i \left(a_j m_{j(i)-2}^n + b_j m_{j(i)-1}^n + c_j m_{j(i)}^n + d_j m_{j(i)+1}^n \right)$$

- For this to hold independent of mass distribution

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

which is only true if wind is uniform

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

New Dynamics

Transport in New Dynamics I

- Semi-Lagrangian scheme applied to:
  - All moisture variables and all tracers
  - Wind components (special handling of vector aspects)
  - Horizontal aspects of potential temperature advection
  - Nearest grid point in vertical for potential temperature
- Eulerian flux scheme used for dry density
- And Eulerian advection scheme for residual vertical advection of potential temperature

Davies et al (2005)

Transport in New Dynamics II

Met Office

- Lagrangian interpolation:
  - Bi-(quasi-)cubic in horizontal and quintic in vertical for moisture variables and all tracers
  - Tri-(quasi-)cubic for wind components
  - Bi-(quasi-)cubic for horizontal aspects of potential temperature advection
- Conservation:
  - Priestley algorithm (optionally) applied to moisture and tracer variables
- Monotonicity:
  - Bermejo and Staniforth (optionally) applied to moisture and tracer variables

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

Met Office

- 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)

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

ENDGame

Wood et al (2014)

- Motivation: New Dynamics numerically unstable
  - Mixed semi-Lagrangian/Eulerian approach unstable
  - Eulerian approach probably root cause of polar noise
  - More diffusion needed to control instabilities – impact on accuracy and scalability
  - Extrapolated winds used in departure point evaluation – unstable
  - "Non-interpolating in vertical" for potential temperature – cause of valley cooling
- ENDGame
  - Adopts iterated approach akin to Canadian GEM model
  - Model significantly more: stable, scalable and accurate

Transport in ENDGame I

- Semi-Lagrangian scheme applied to:

All variables!

Transport in ENDGame II

- 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
- 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

Met Office

- 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:

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

- *A* and *B* chosen such that

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

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

Does it matter what we do?

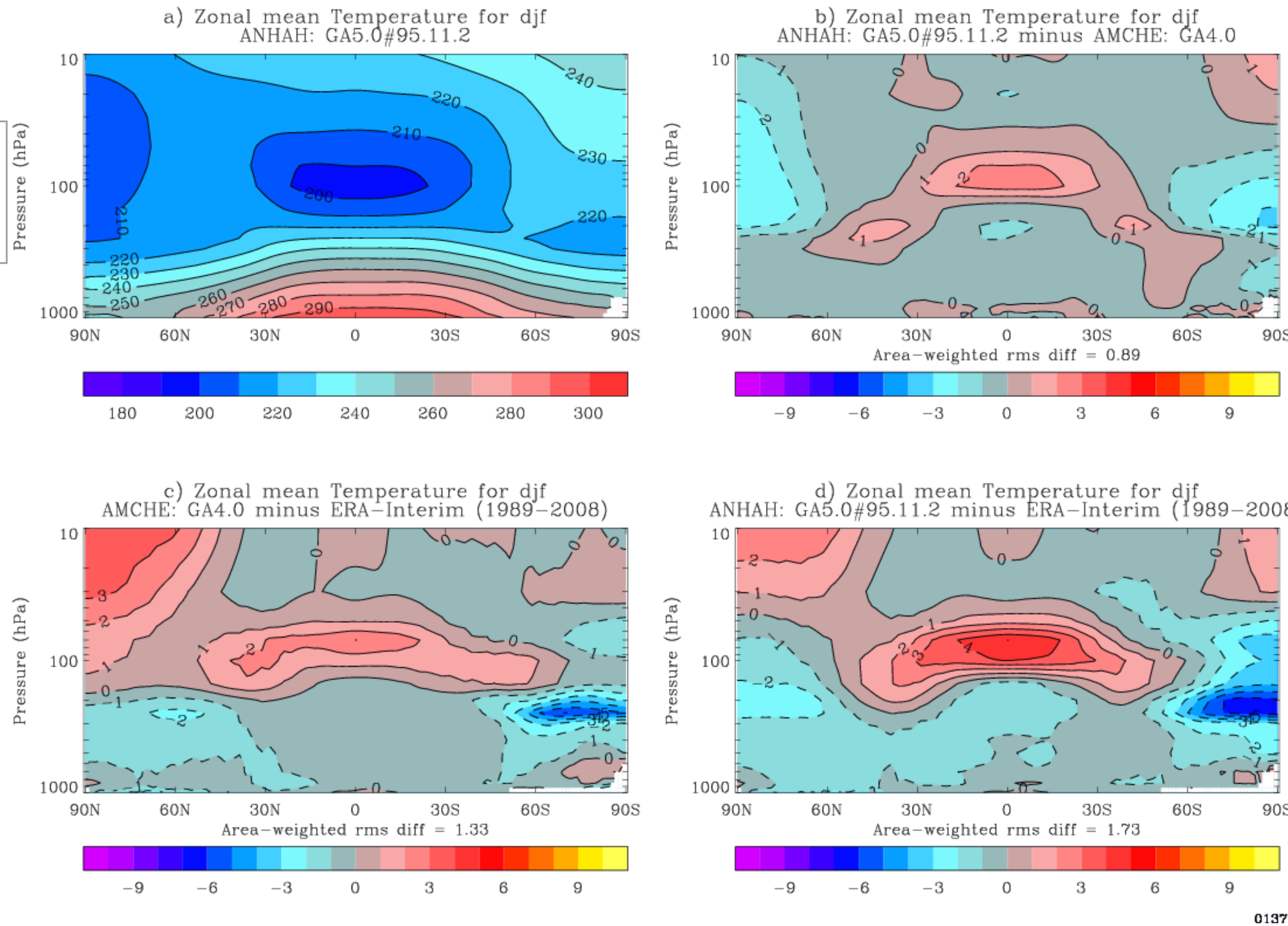
Temperature bias in 20 year AMIP run

ENDGame zonal mean temperature

EG - ND

ND - ERA

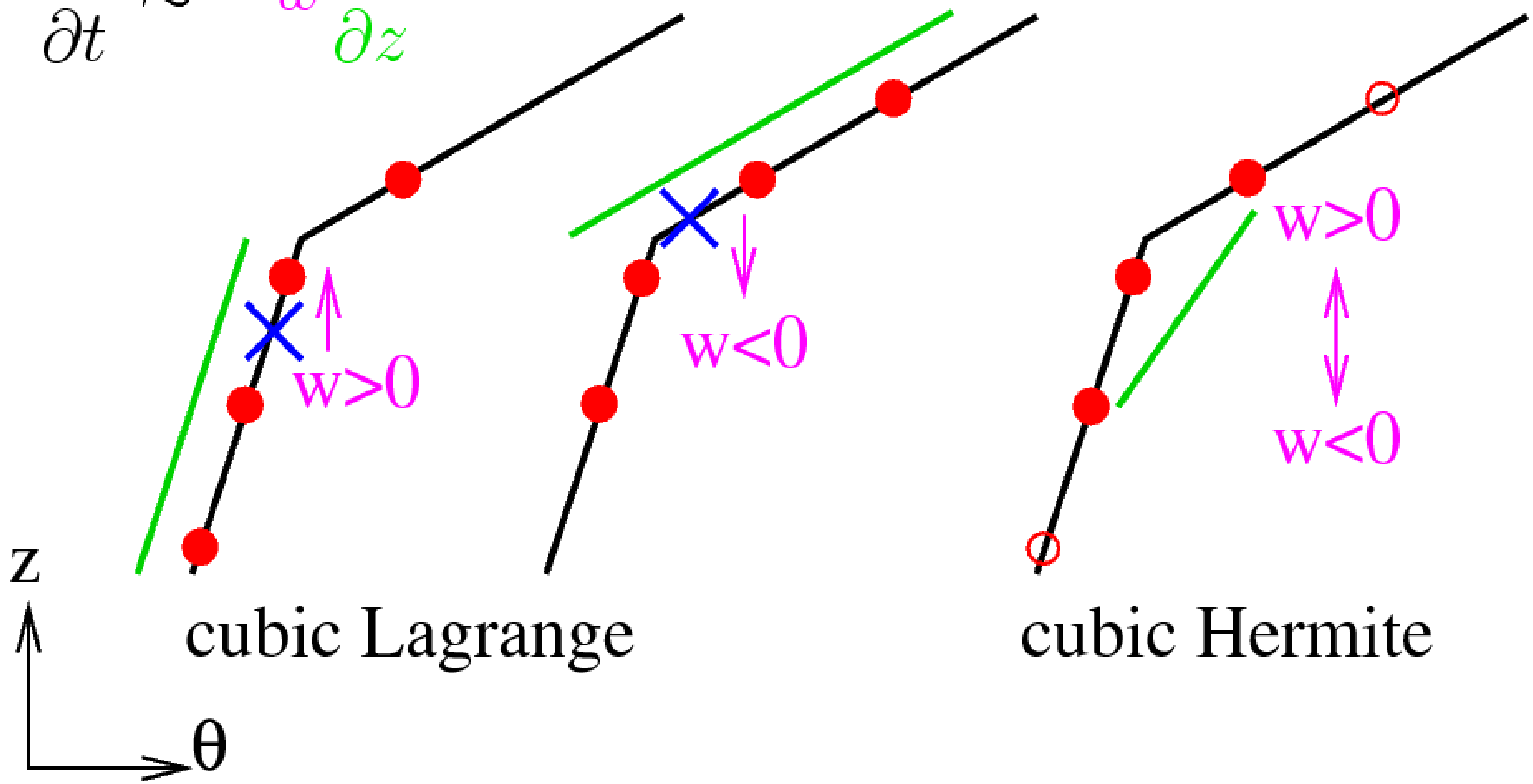
EG - ERA



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

Why?

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



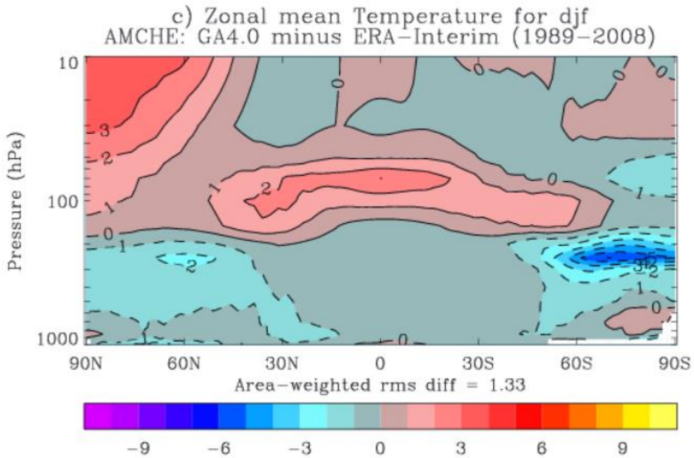
Chris Smith (Met Office)

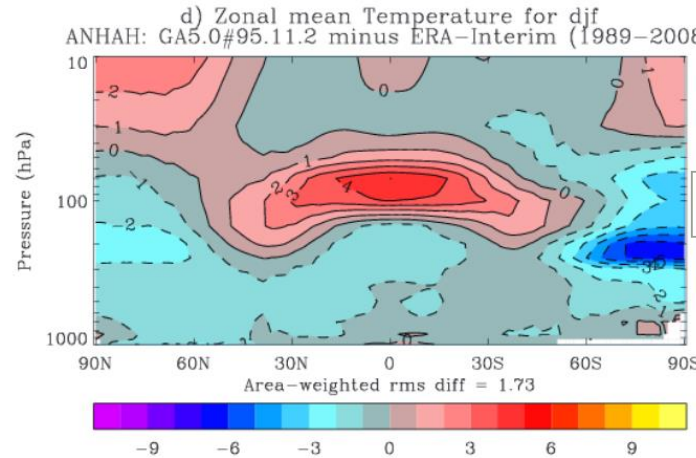
Impact of cubic Hermite + Priestley

Met Office

Second-order centred → **cubic Lagrange**

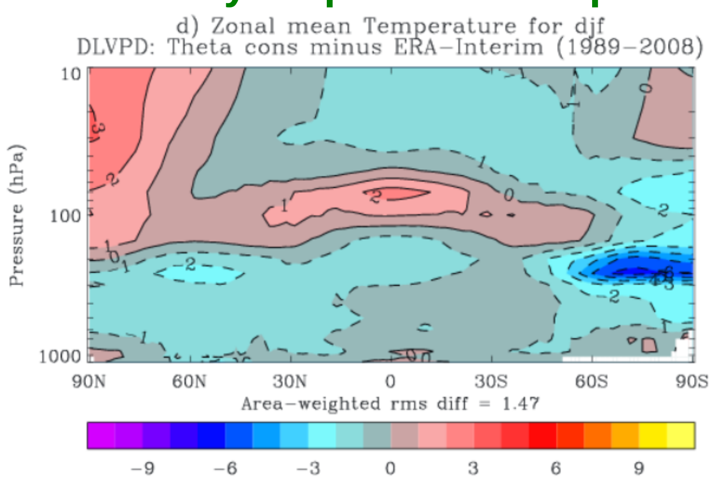
ND bias

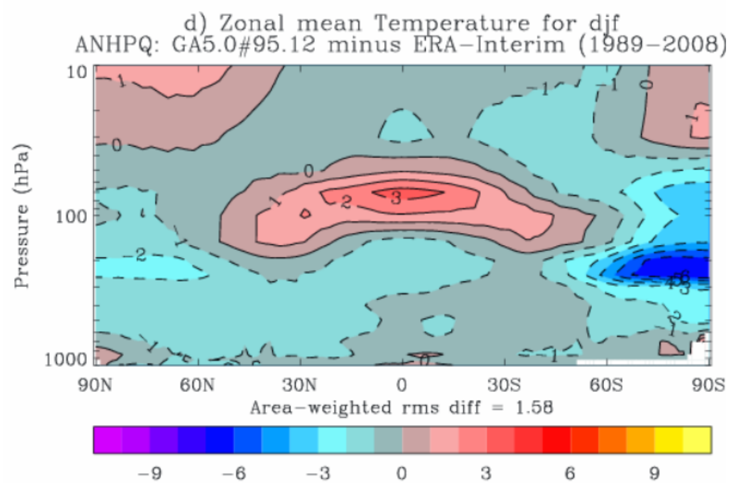




EG bias

Priestley on potential temperature ← **cubic Hermite**





David Walters (Met Office)

SLICE:
Semi-Lagrangian Inherently Conservative and Efficient

Recovering conservation...

Conservative semi-Lagrangian

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

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

- Use Lagrangian form:

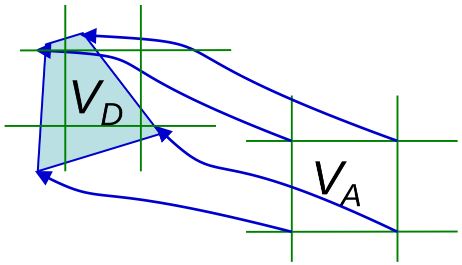
$$\frac{D}{Dt}\left(\int_V \rho_X \, dV \right) = 0$$

Zerroukat, Wood & Staniforth (2002)

Conservative semi-Lagrangian

- Integrate along trajectory:

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

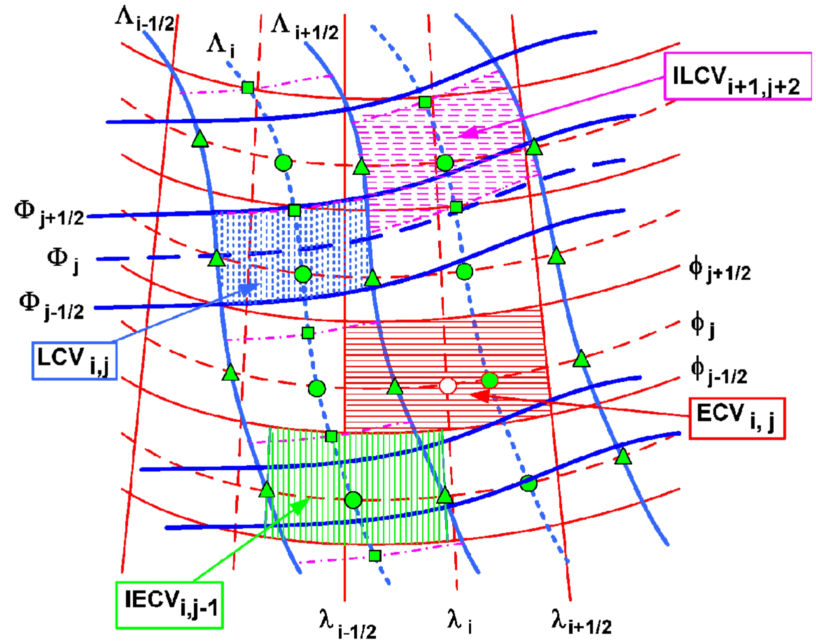


- Rearrange as:

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

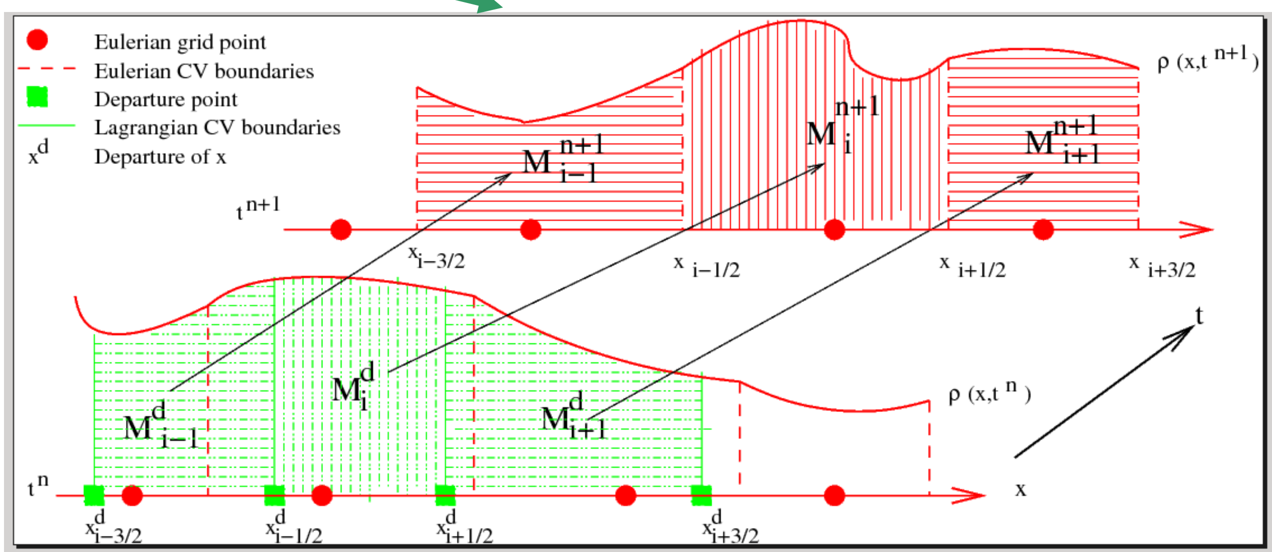
SLICE

1. Cascade 3D reconstruction into 3 x 1D reconstructions:



2. Perform 1D reconstructions

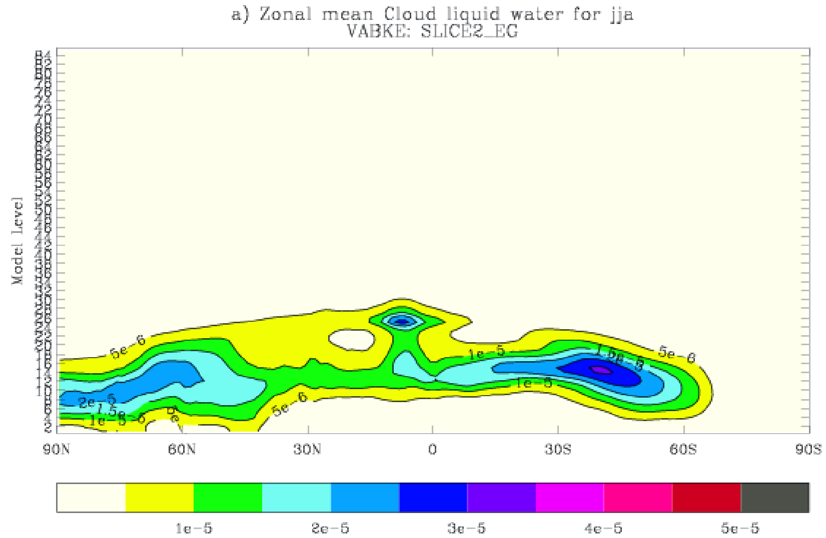
Available as branch



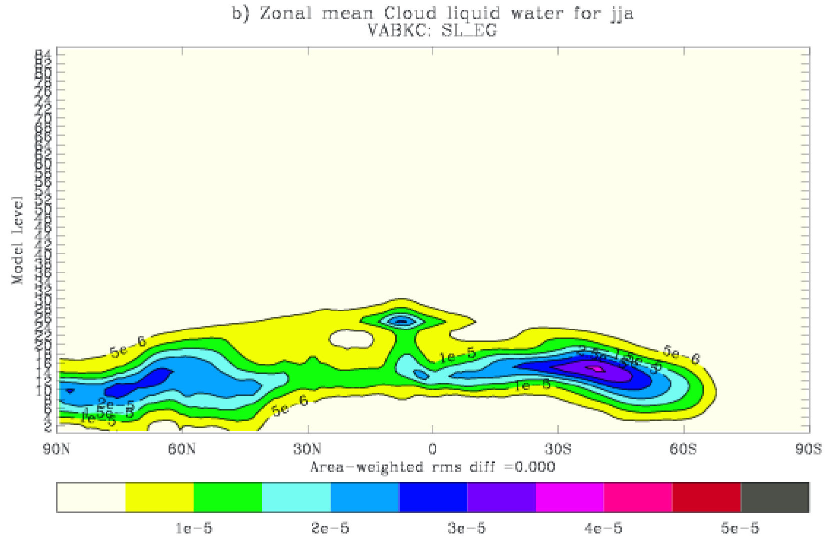
SLICE in a 20 year AMIP

Cloud liquid water

SLICE



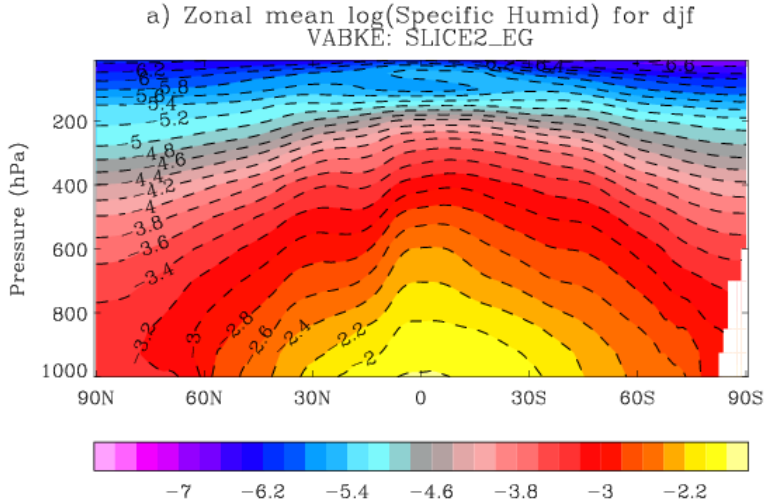
Standard SL



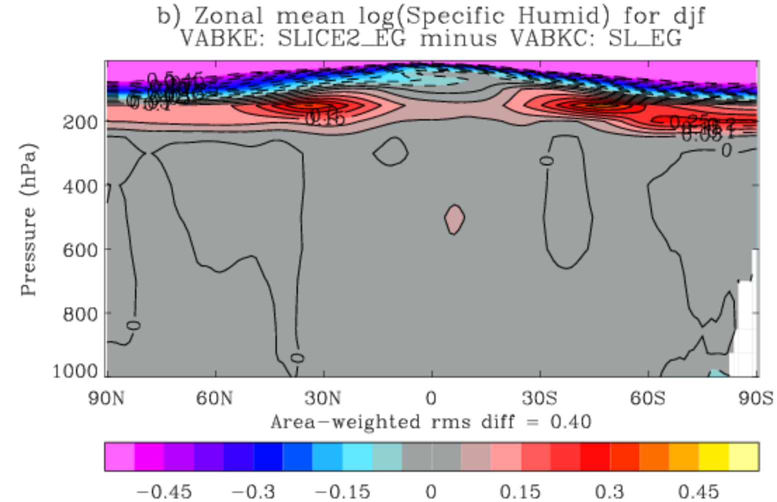
Similar level of agreement also found in chemical tracers

SLICE in a 20 year AMIP

SLICE log(q)



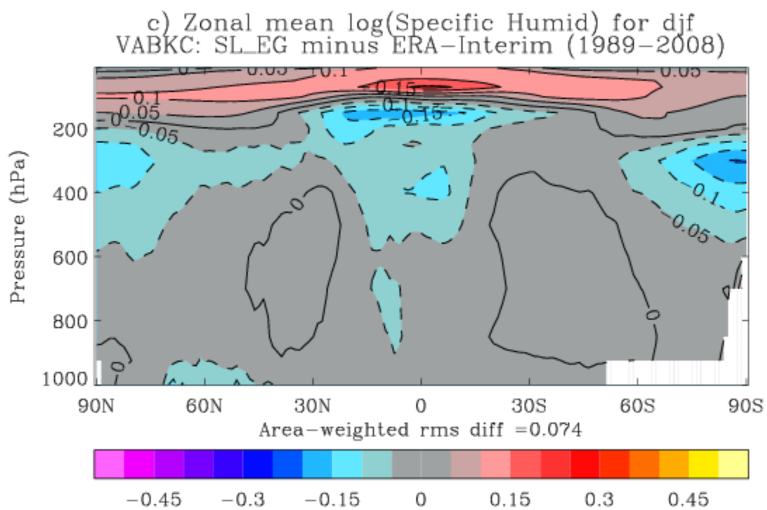
SLICE - SL



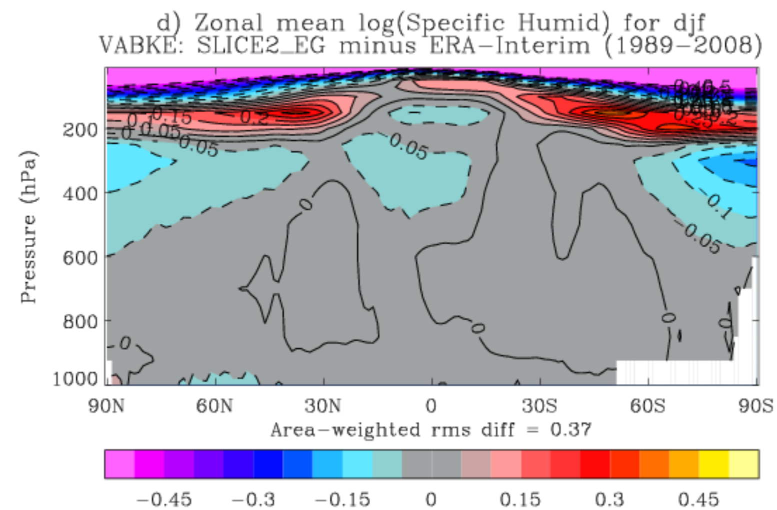
But...cross tropopause transport of moisture seems to be awry

Possibly linked to TTL warm bias issues?

SL – ERA Interim



SLICE – ERA Interim

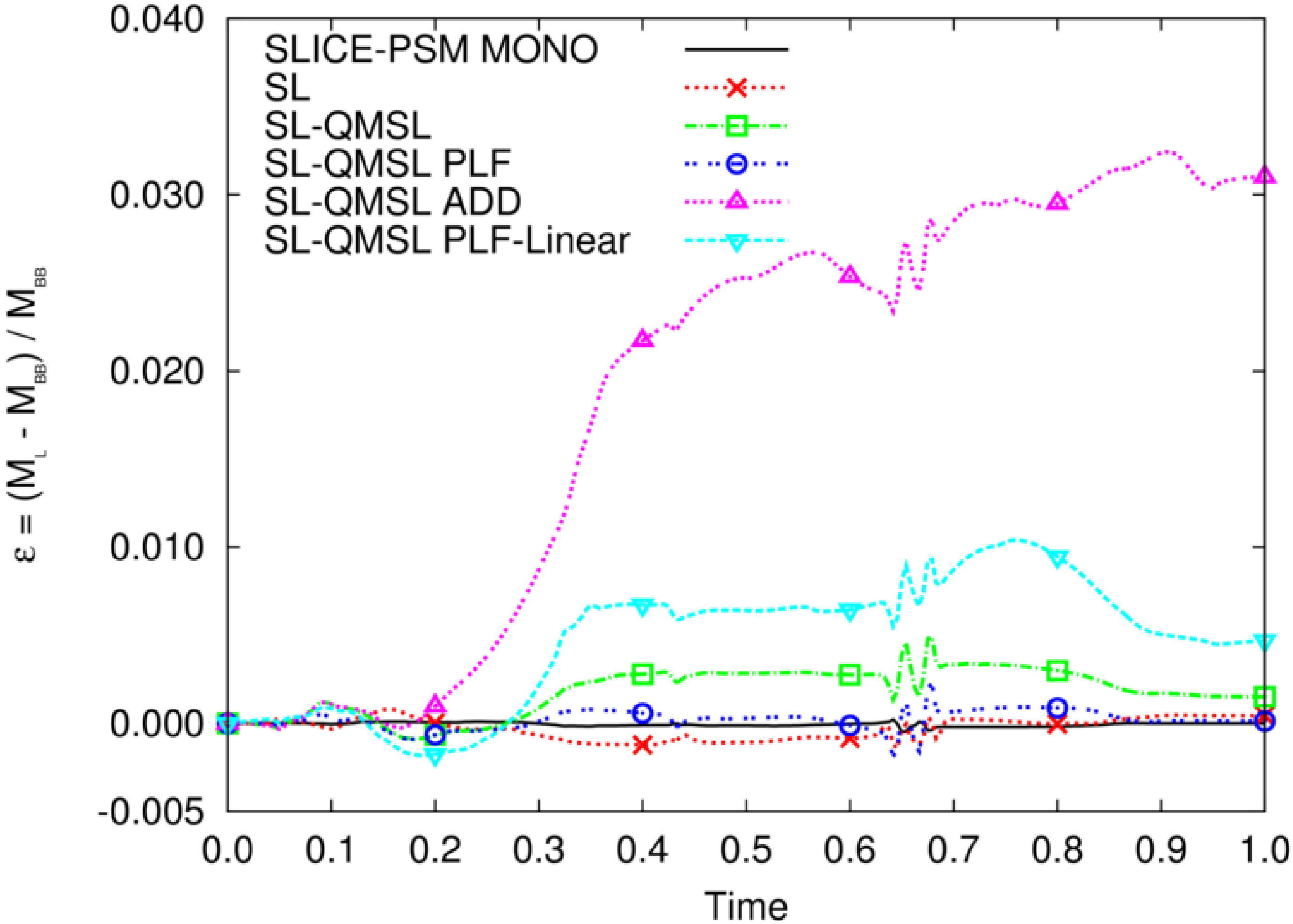


0180

Conservation in Limited Area Models...

LAM Conservation (budget)

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



Aranami, Davies and Wood (2014)

Qtidy – an alternative

- Noting that monotonicity has greatest impact:

1. Switch off monotonicity
2. Use quintic Lagrange interpolation in ***all*** directions
3. Tidy any negative condensed moisture variables by absorbing negative values directly into local vapour field
4. Adjust potential temperature for phase change

- Could be used together with LAM conservation

Paul Field (Met Office)

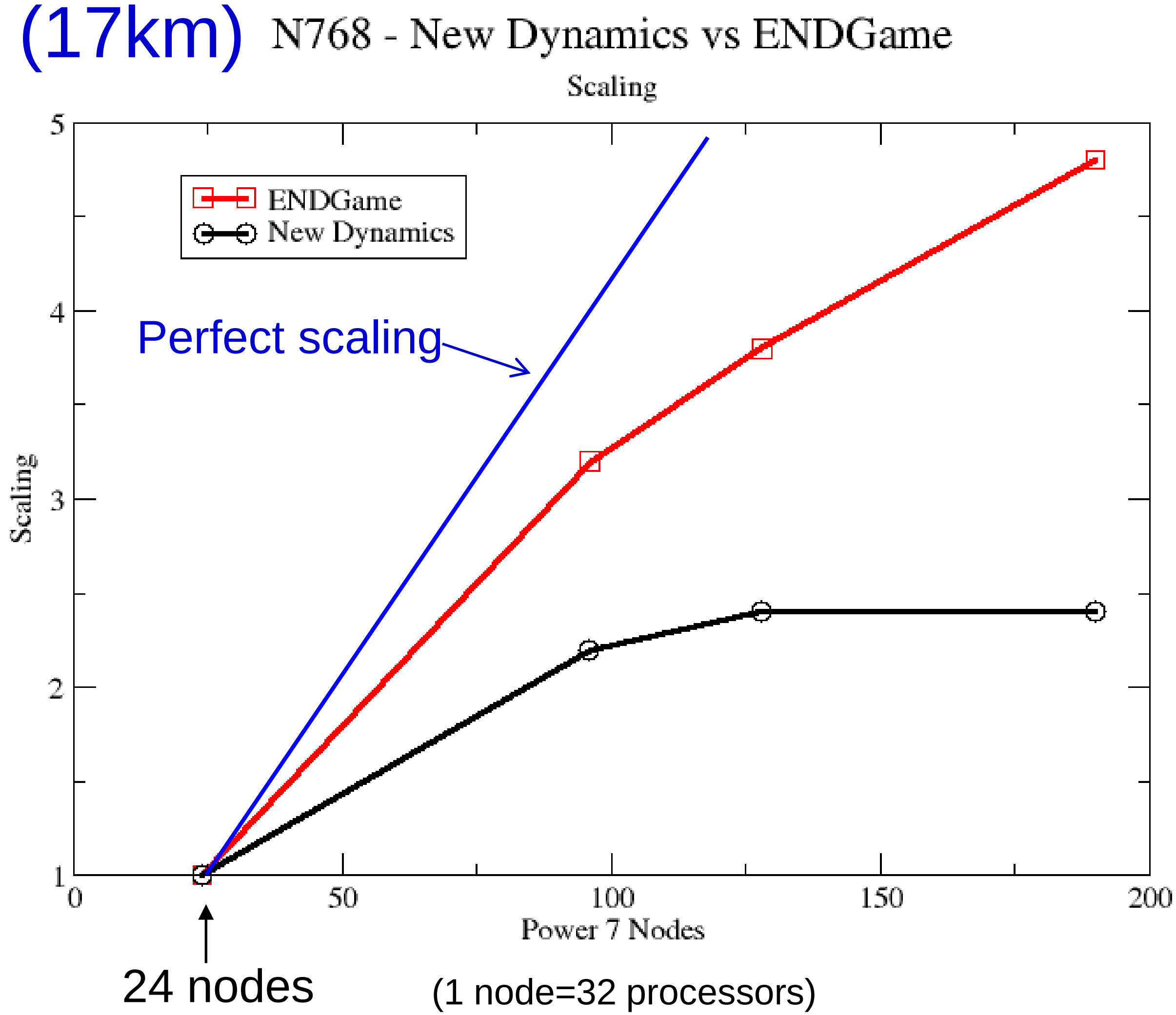
Met Office

GungHo into the future!

Scalability

(17km)

T_{24}/T_N

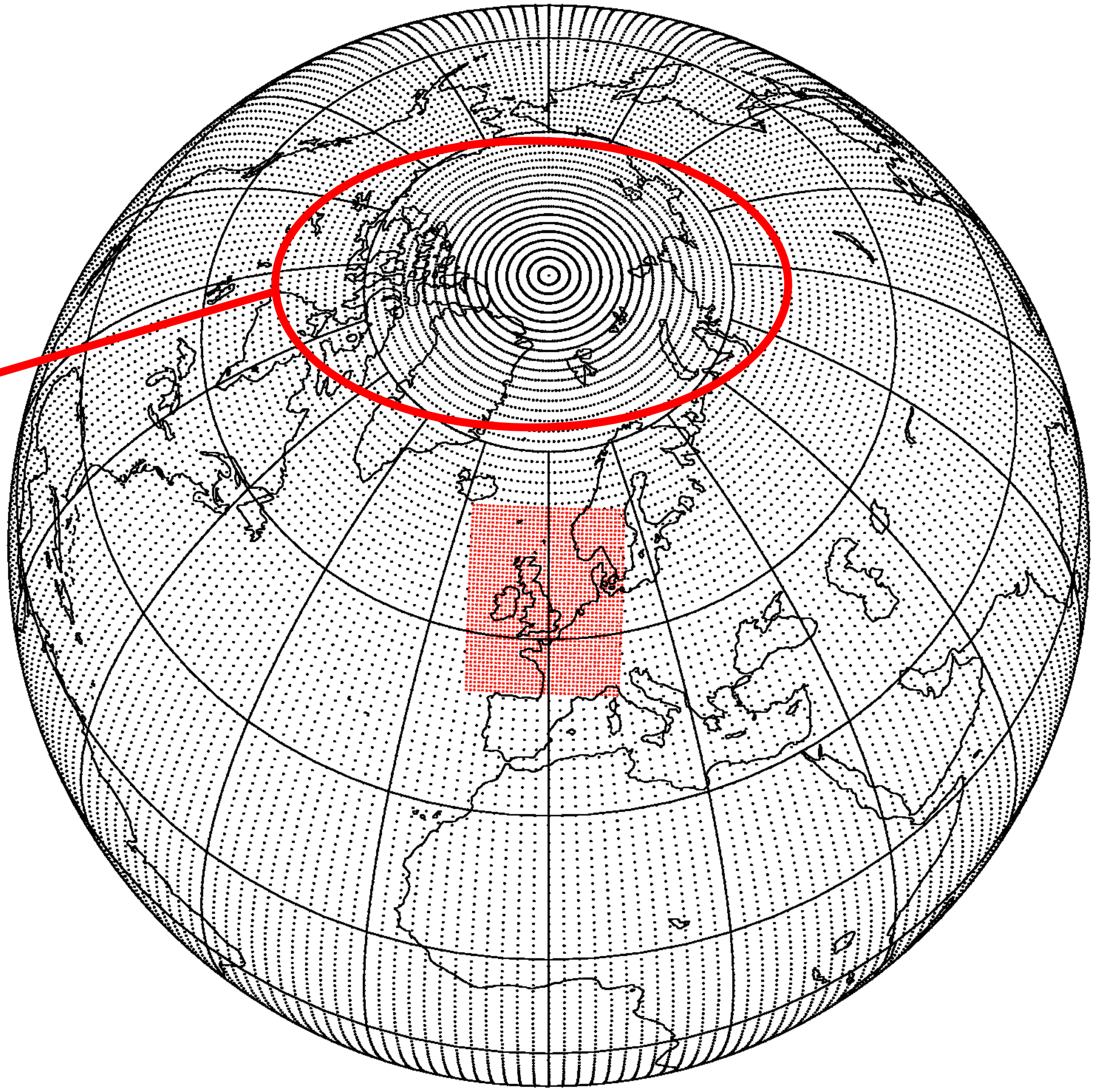


(1 node=32 processors)

Andy Malcolm (Met Office)

The finger of blame…

- At 25km resolution, grid spacing near poles = 75m
- At 17km resolution, grid spacing near poles = 35m
- At 10km reduces to 12m!



GungHo!

Globally

Uniform

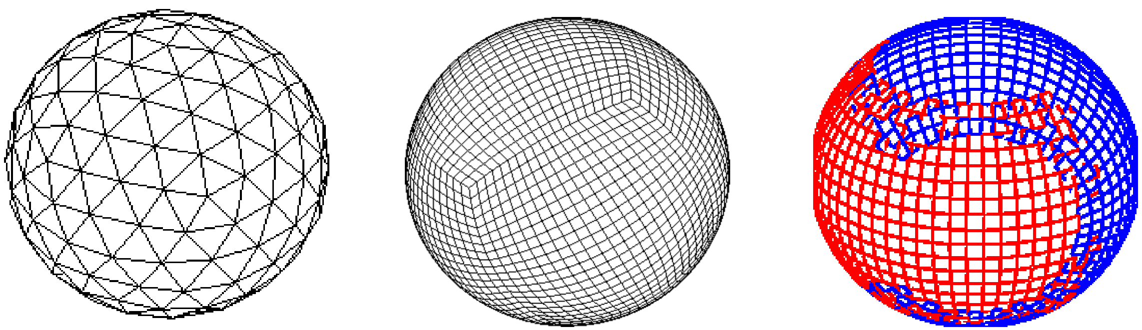
Next

Generation

Highly

Optimized

工合



“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 early 2020's

Thank you!

Questions?

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

Bibliography

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5. Davies, T., Cullen, M., Malcolm, A., Mawson, M., Staniforth, A., White, A. & Wood, N. (2005) , A new dynamical core for the Met Office's global and regional modelling of the atmosphere, *Q. J. R. Meteorol.Soc.* **131**, 1759–1782.
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10. Zerroukat, M., Wood, N. & Staniforth, A. (2002) , SLICE: A Semi-Lagrangian Inherently Conserving and Efficient scheme for transport problems, *Q. J. R. Meteorol. Soc.* **128**, 2801–2820.

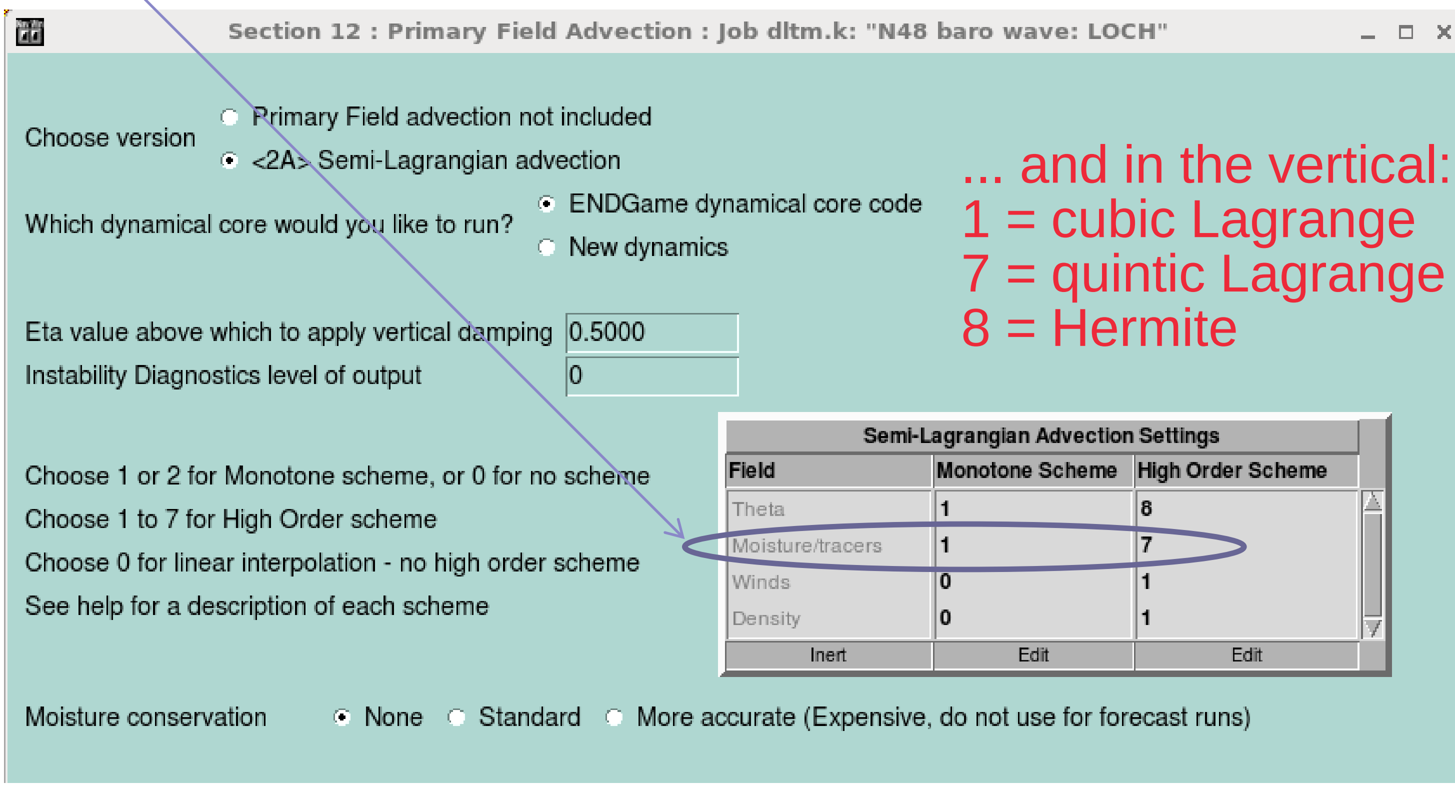
Tracer transport options in UMUI and Rose

with thanks to Chris Smith

Interpolation options in UMUI: Vn ≤ 8.6

Moisture and tracers treated in the same way

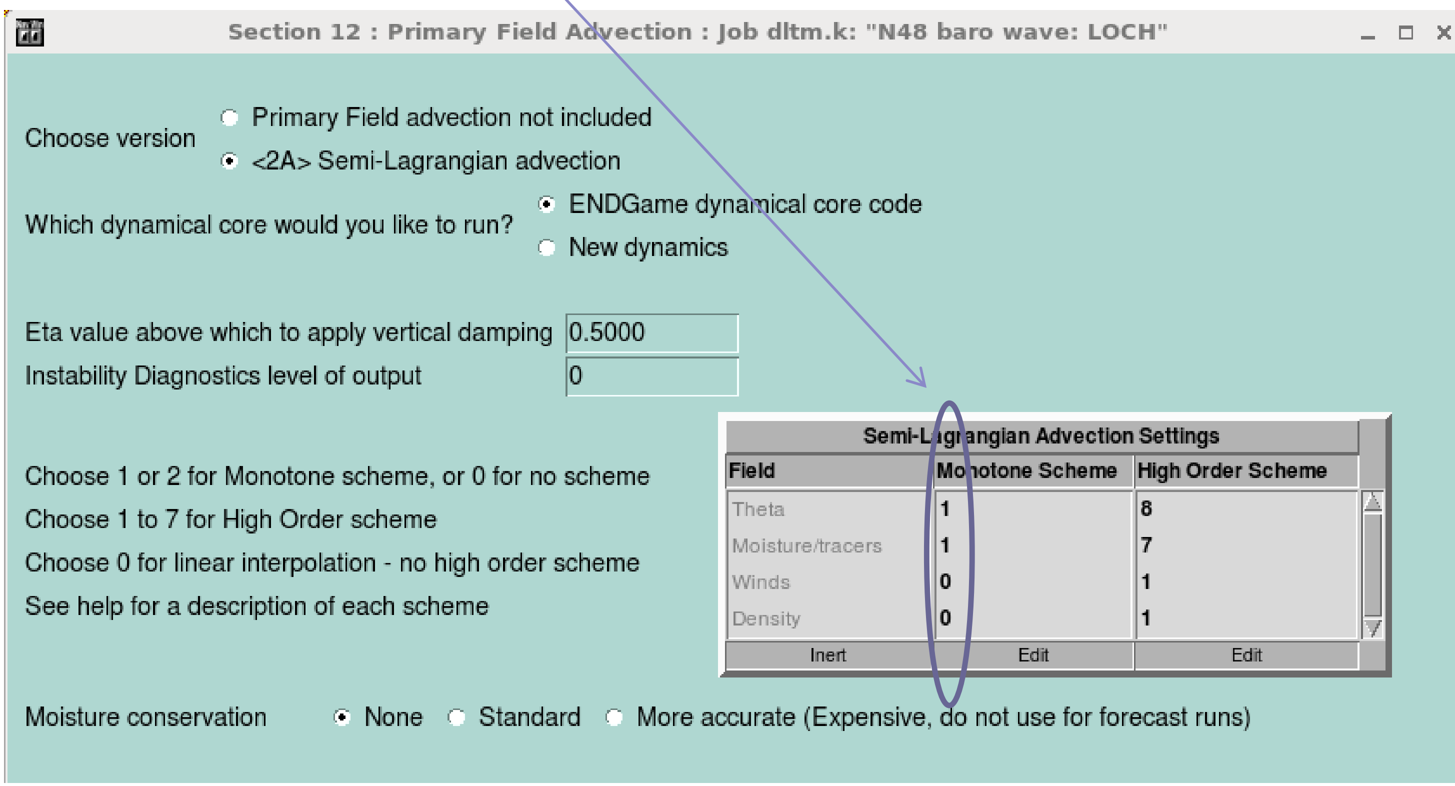
High Order Scheme:
0 = tri-linear
>0 = bi-cubic in horizontal ...



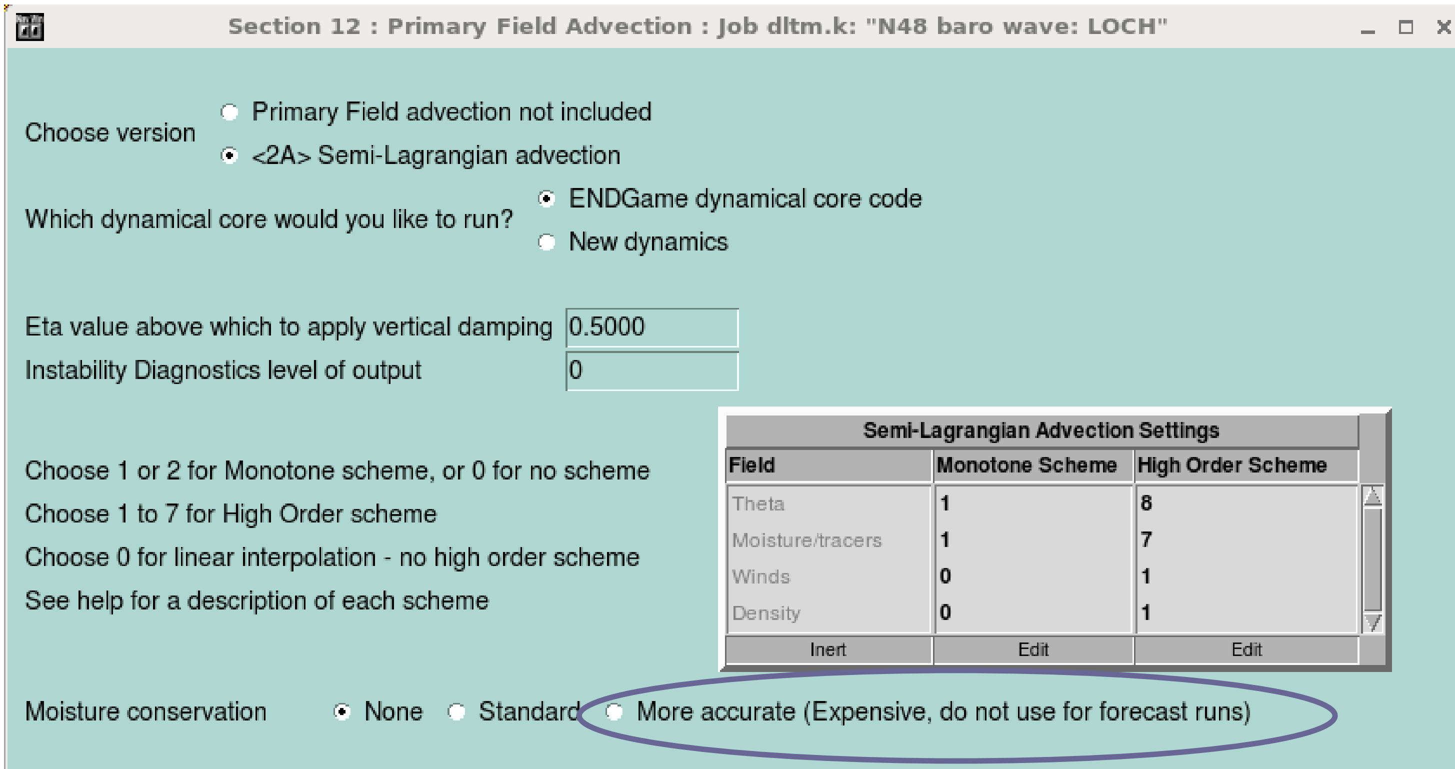
... and in the vertical:
1 = cubic Lagrange
7 = quintic Lagrange
8 = Hermite

Monotonicity options in UMUI: Vn ≤ 8.6

1 = monotone clipping
0 = non-monotone (if high order)



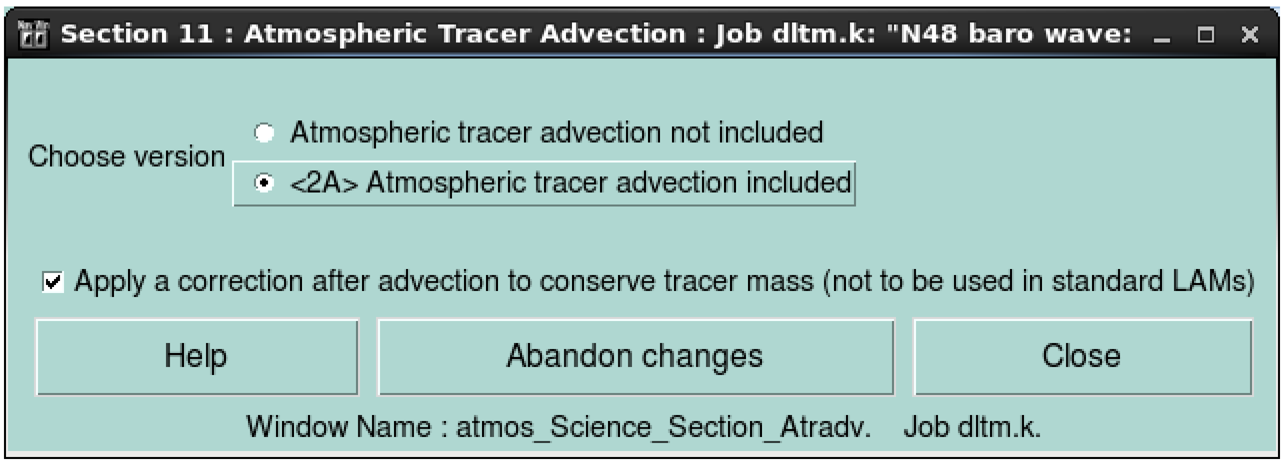
Conservation options in UMUI: vn ≤ 8.6



New Dynamics only

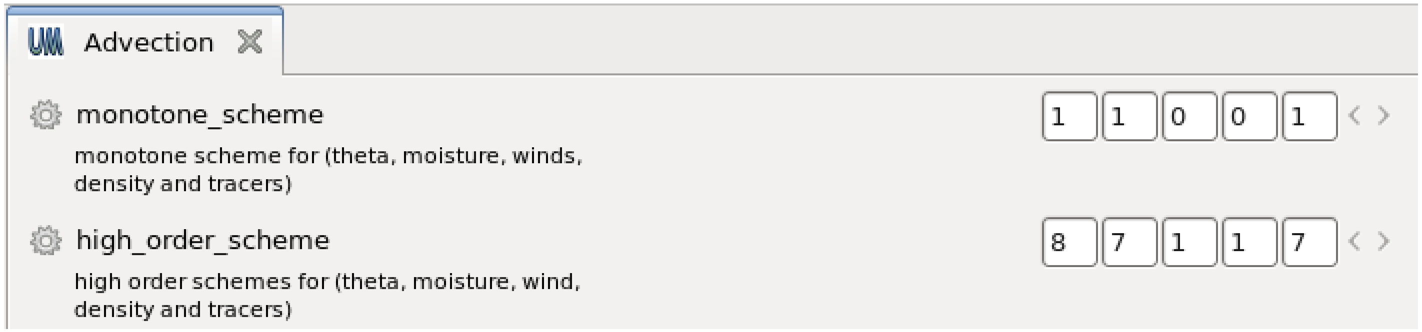
Tracer conservation in UMUI: vn ≤ 8.6

Just two clicks in the Section 11 panel:



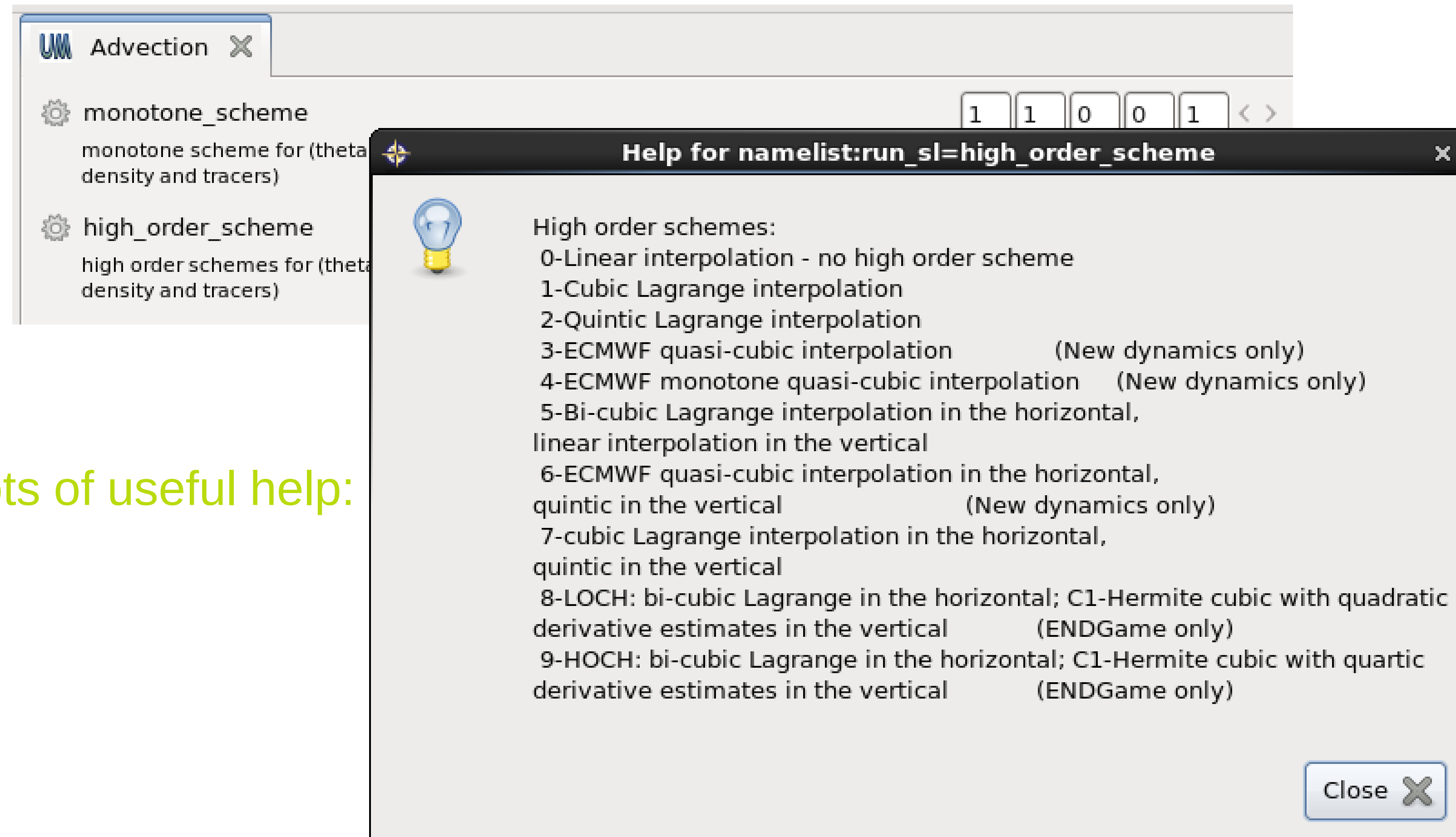
Interpolation options in Rose: vn ≥ 10.1

Now separate options for moisture and tracers:



Interpolation options in Rose: Vn ≥ 10.1

And lots of useful help:



Conservation options in Rose: vn ≥ 10.1

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