GungHo!

A new dynamical core for the Unified Model

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Outline

- The Unified Model
- The driver for change & GungHo!
- From GungHo! to not so gungho
- Summary

Unified Model

Met Office

Unified Model (UM) in that *single* model for:

- Operational forecasts at
  - Mesoscale (resolution approx. 4.4km, 1.5km)
  - Global scale (resolution approx. 25km)
- Global and regional climate predictions (resolution around 100km, run for 10-100-… years)
- Seasonal predictions
- + Research mode (1km - 10m) and single column model
- >20 years old

Met Office

The governing equations

$$\frac{D_r u}{Dt} - \frac{uv\tan\phi}{r} - 2\Omega\sin\phi v + \frac{c_{pd}\theta_v}{r\cos\phi}\frac{\partial\Pi}{\partial\lambda} = \boxed{-\left(\frac{uw}{r} + 2\Omega\cos\phi w\right)} + S^u$$

$$\frac{D_r v}{Dt} + \frac{u^2\tan\phi}{r} + 2\Omega\sin\phi u + \frac{c_{pd}\theta}{r}\frac{\partial\Pi}{\partial\phi} = \boxed{-\left(\frac{vw}{r}\right)} + S^v$$

$$\left\{\frac{D_r w}{Dt}\right\} + c_{pd}\theta_v\frac{\partial\Pi}{\partial r} + \underbrace{\frac{\partial\Phi}{\partial r}}_{\approx g} = \boxed{\frac{\left(u^2+v^2\right)}{r} + 2\Omega\cos\phi u + S^w}$$

$$\frac{D_r}{Dt}\left(\rho_y r^2\cos\phi\right) + \rho_y r^2\cos\phi\left(\frac{\partial}{\partial\lambda}\left[\frac{u}{r\cos\phi}\right] + \frac{\partial}{\partial\phi}\left[\frac{v}{r}\right] + \frac{\partial w}{\partial r}\right) = 0$$

$$\frac{D_r\theta}{Dt} = S^\theta$$

Approximate equation sets

	Deep	Shallow (r → a, neglect boxed terms)
Non-hydrostatic	Complete equations	Non-hydrostatic shallow
Hydrostatic (neglect *Dw/Dt*)	Quasi-hydrostatic	Hydrostatic primitive

A little history…

Year	Equation Set	Levels	ΔX (km)	Notes
1959	Quasi-Geostrophic	2	320	
1965	“	3	300	
1972	Shallow Hydrostatic	10	300	
1982	“	15	150	Global
1991	Unified Model Deep, Quasi-Hydrostatic	20	90	1st Global deep model
2002	Deep, Non-Hydrostatic (“New Dynamics”)	38/50/70/85	60/40/25	1st Global deep NH model

2000-	The Joy – 500 pages of New Dynamics
2002	ENDGame research starts
2014?	ENDGame operational…

The driver for change…

Computational performance critical

Global 25km model (current resolution):

- Forecast to: 7 days 3 hours
- Timestep: = 10mins $\Rightarrow$ 1026 time steps
- Resolution 1024 × 768 × 70 = 55M grid points

To run in 60 minute slot, including output

The consequence…

Global 17km model (upgrade next year?):

Timestep = 6 mins

Resolution = 1536 × 1152 × 70 = 124M points

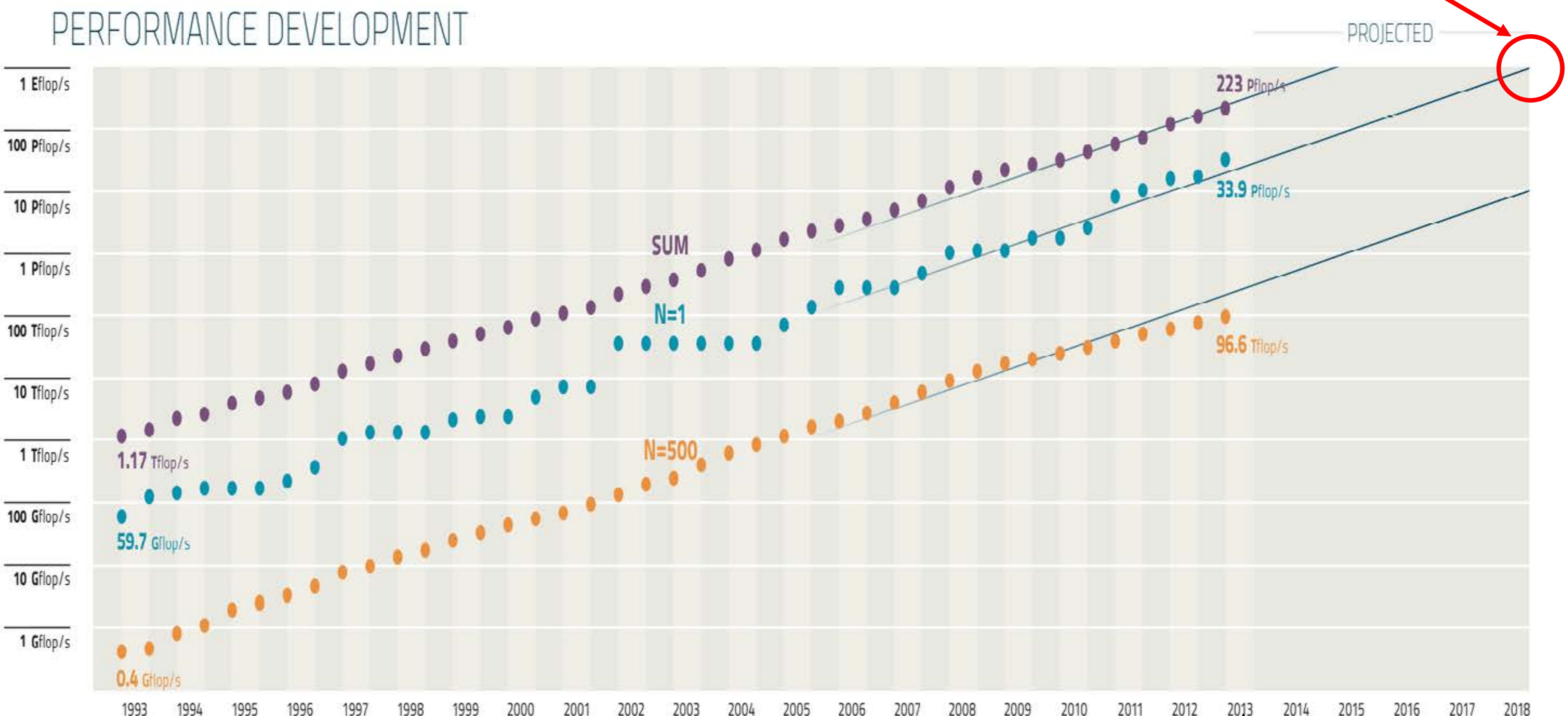
⇒ Increase by factor of nearly 4

But time slot unchanged

⇒ Algorithmic + code *efficiency* is critical

Top500 projections

100M cores?



(Top500.org)

2013

2018

Top500 #1 Cores

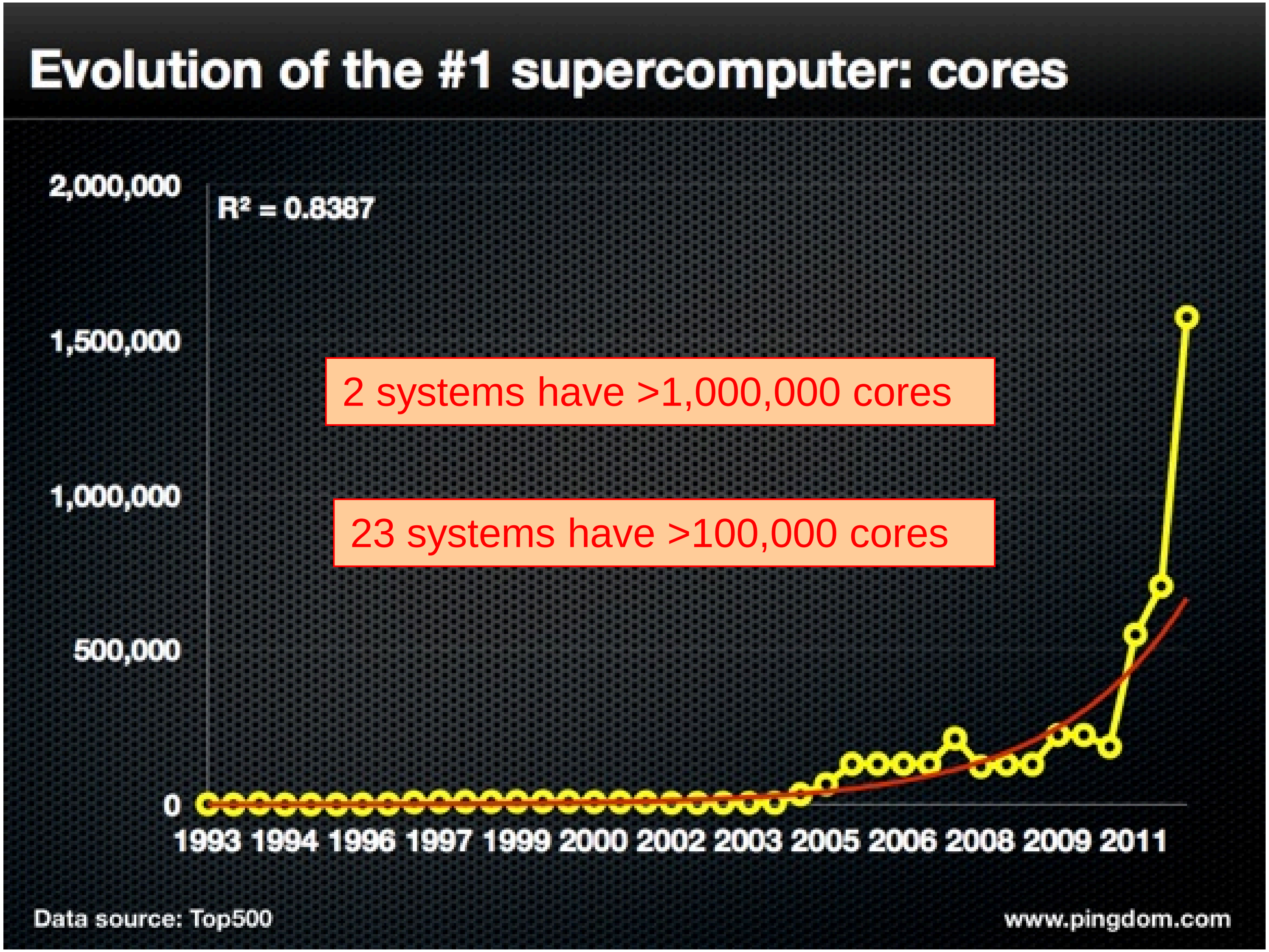
<u>ECMWF</u>

25K cores #44

<u>MetO</u>

18K cores #57

15K cores #70

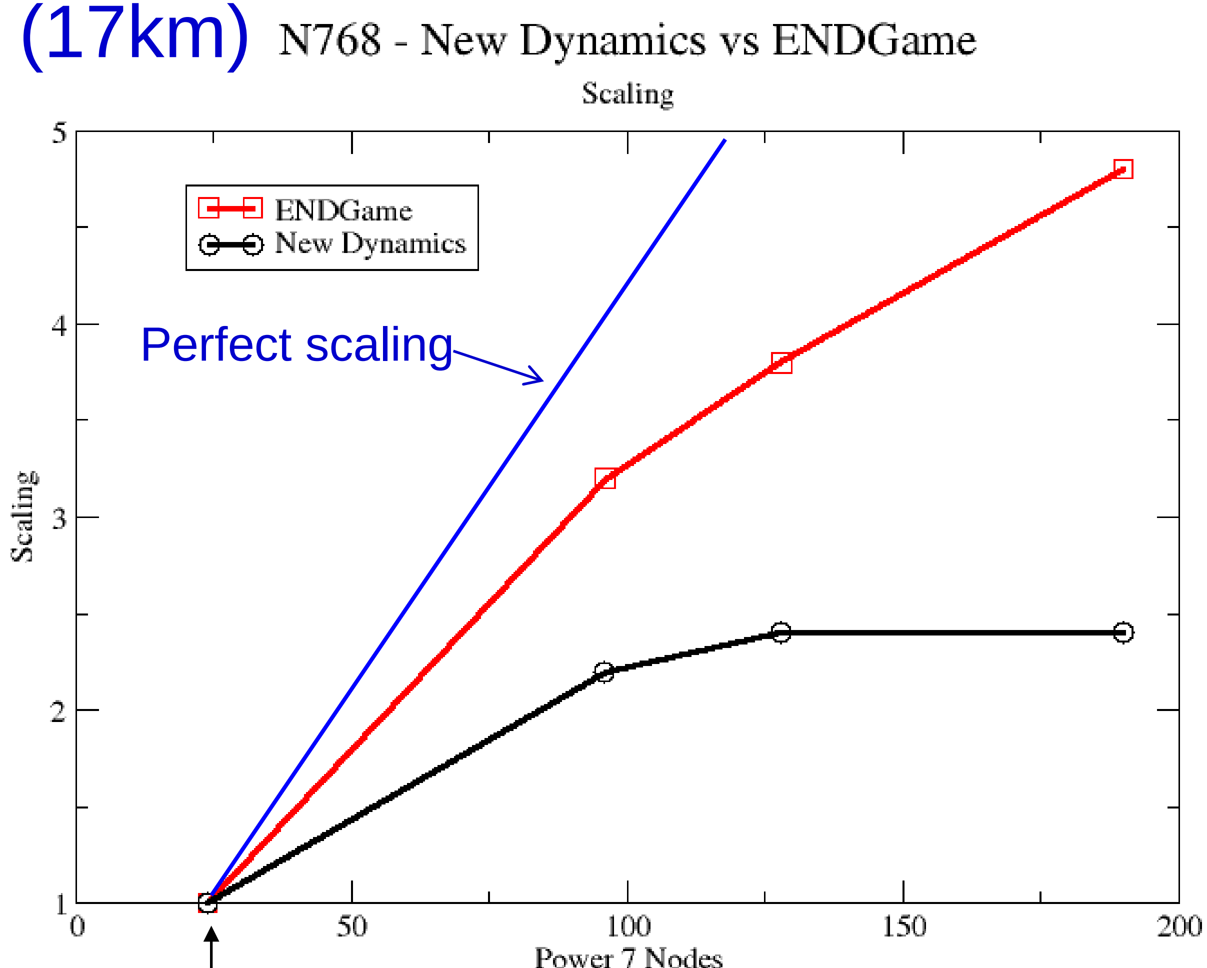


⇒ Algorithmic + code *scalability* is critical

Scalability

(17km)

T_{24}/T_N

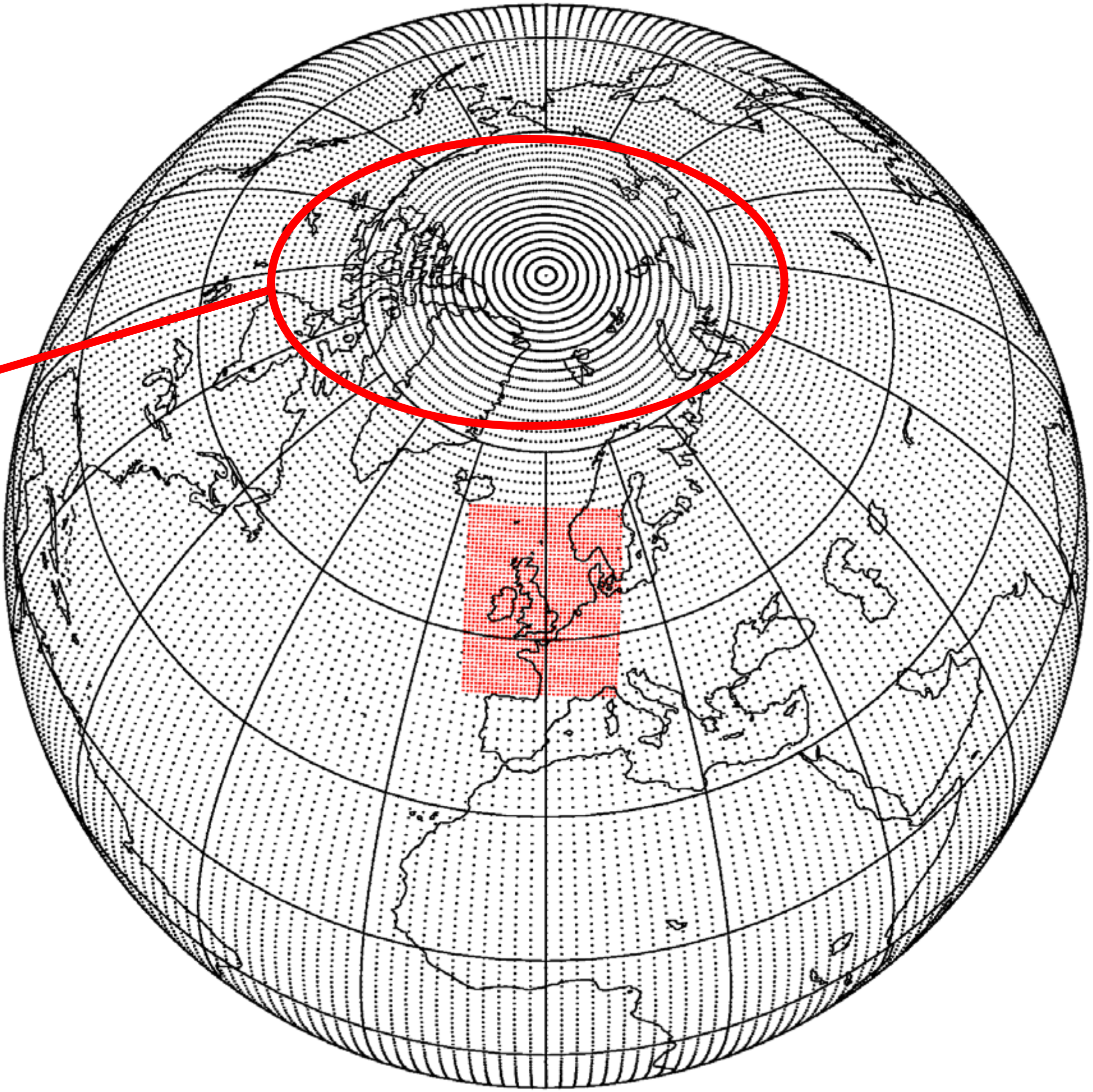


24 nodes

(1 node=32 processors)

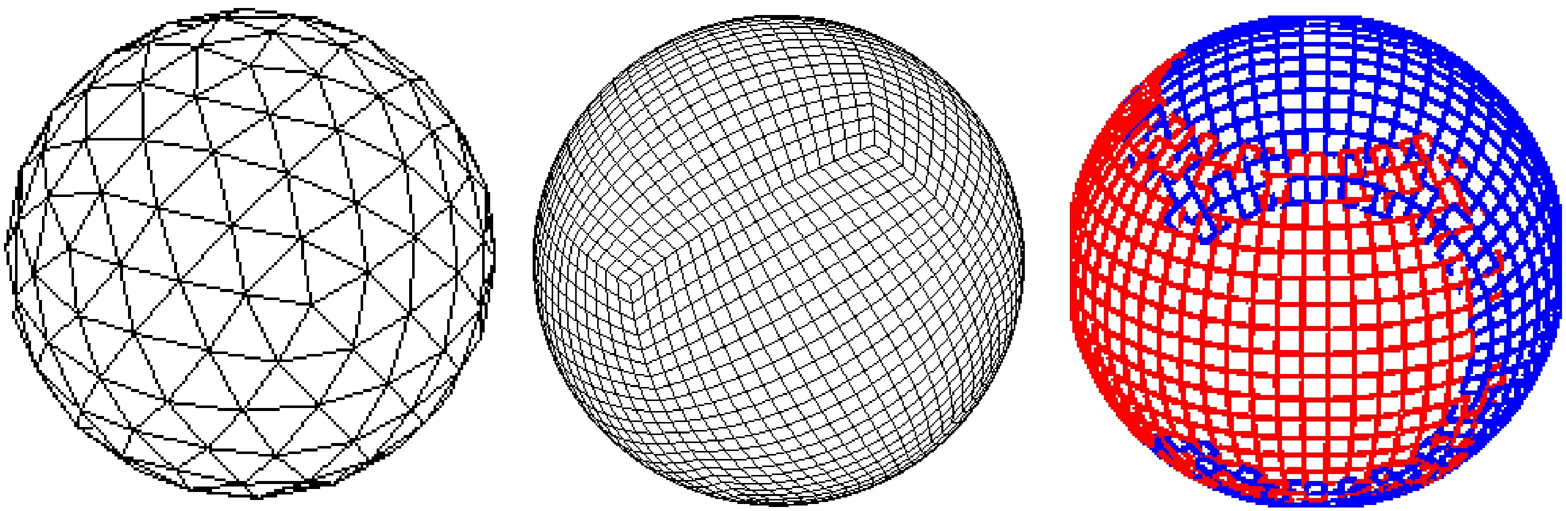
The finger of blame…

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



A new grid?

- Scalability – remove the poles!



GungHo!

Globally

Uniform

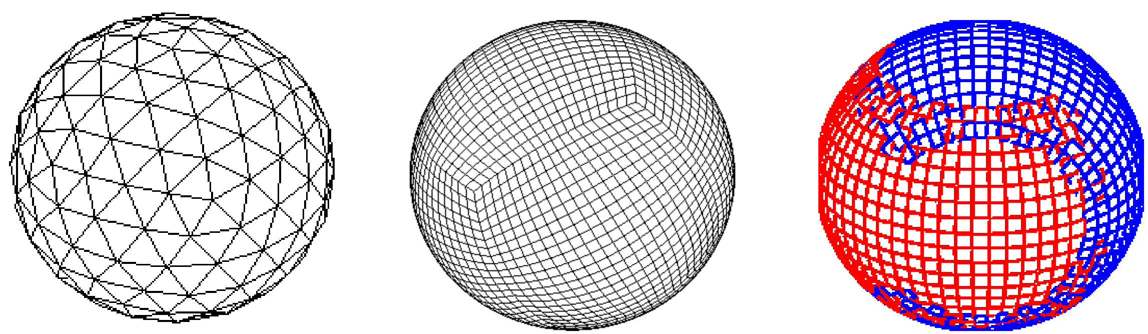
Next

Generation

Highly

Optimized

工合



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Science & Technology Facilities Council

"Working together harmoniously"

From GungHo! to not so gungho…

GungHo Issues

- How to maintain accuracy of current model on a GungHo grid?
- Principal points about current grid are:
  - Orthogonal, Quadrilateral, C-grid
- Staniforth & Thuburn (2012) reviewed what benefits these allow…

From GungHo to not so GungHo

Staniforth & Thuburn (2012) identified ten

"*Essential and desirable properties of a dynamical core*":

1. Mass conservation
2. Accurate representation of balanced flow and adjustment
3. Computational modes should be absent or well controlled

From GungHo to not so GungHo

4. Geopotential gradient and pressure gradient should produce no unphysical source of vorticity

$$\nabla \times (\nabla p) = 0$$

5. Terms involving the pressure should be energy conserving.

$$\mathbf{u} \cdot \nabla p + p \nabla \cdot \mathbf{u} = \nabla \cdot (\mathbf{u} p)$$

6. Coriolis terms should be energy conserving

$$\mathbf{u} \cdot (\boldsymbol{\Omega} \times \mathbf{u}) = 0$$

7. There should be no spurious fast propagation of Rossby modes; geostrophic balance should not spontaneously break down

8. Axial angular momentum should be conserved

These 5 properties relate to the *mimetic* properties of the numerics

From GungHo to not so GungHo

9. Accuracy approaching second order
10. Minimal grid imprinting

These are particularly challenging for grids with special points/regions

$\Rightarrow$ likely to require higher order schemes…

…whilst maintaining (1)-(8)

GungHo Issues

- Orthogonal, Quadrilateral, C-grid

$\Rightarrow$ allow good numerical aspects:

  - ➢ Lack of spurious modes
  - ➢ Mimetic properties
  - ➢ Good dispersion properties

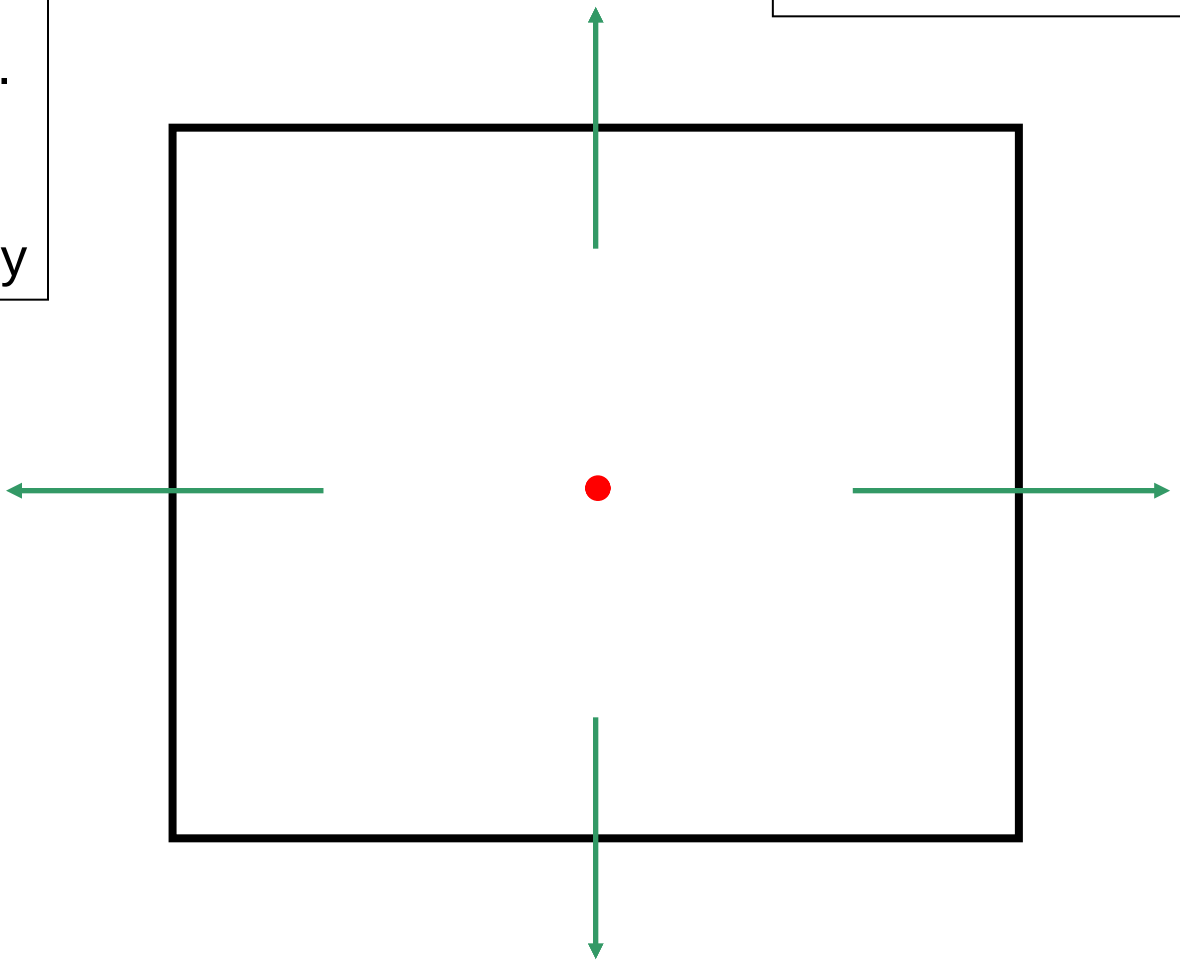
- How to obtain these on *non-orthogonal* grids?

Spurious modes and balanced dof's…

C-grid on Quads

- 2 wind d.o.f's
- 1 pressure d.o.f.
- Cf. analytical
- 2 GWs 1 Rossby

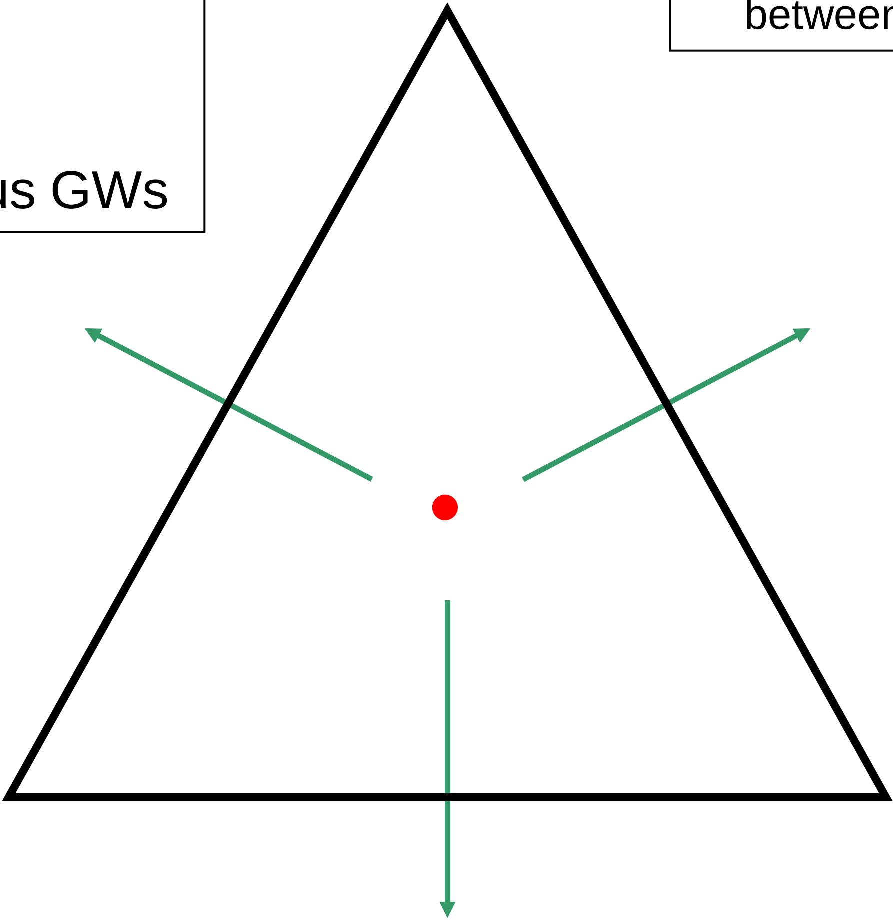
- Green ⇒ Continuous between cells
- Red ⇒ Discontinuous between cells



C-grid on Triangles

- Green ⇒ Continuous between cells
- Red ⇒ Discontinuous between cells

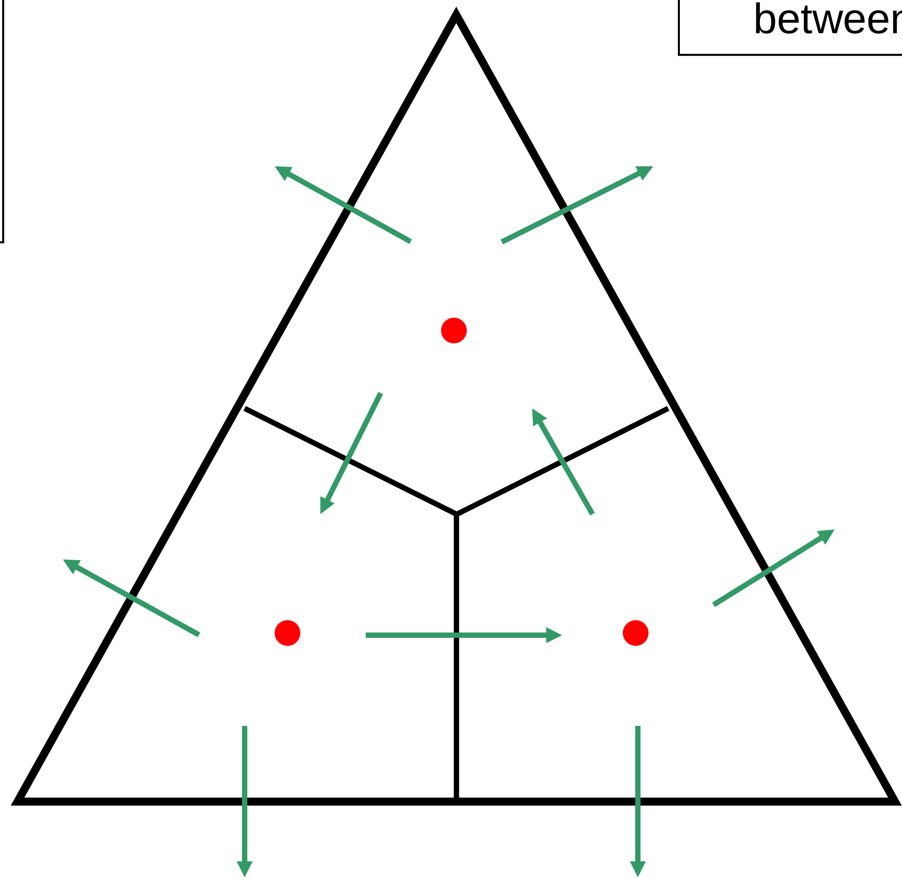
- 3 wind d.o.f's
- 2 pressure d.o.f.'s
- ⇒ Branch of spurious GWs



Triangle as 3 Kites

- 6 wind d.o.f's
- 3 pressure d.o.f.'s
- $\Rightarrow$ Balanced d.o.f.'

- Green $\Rightarrow$ Continuous between cells
- Red $\Rightarrow$ Discontinuous between cells

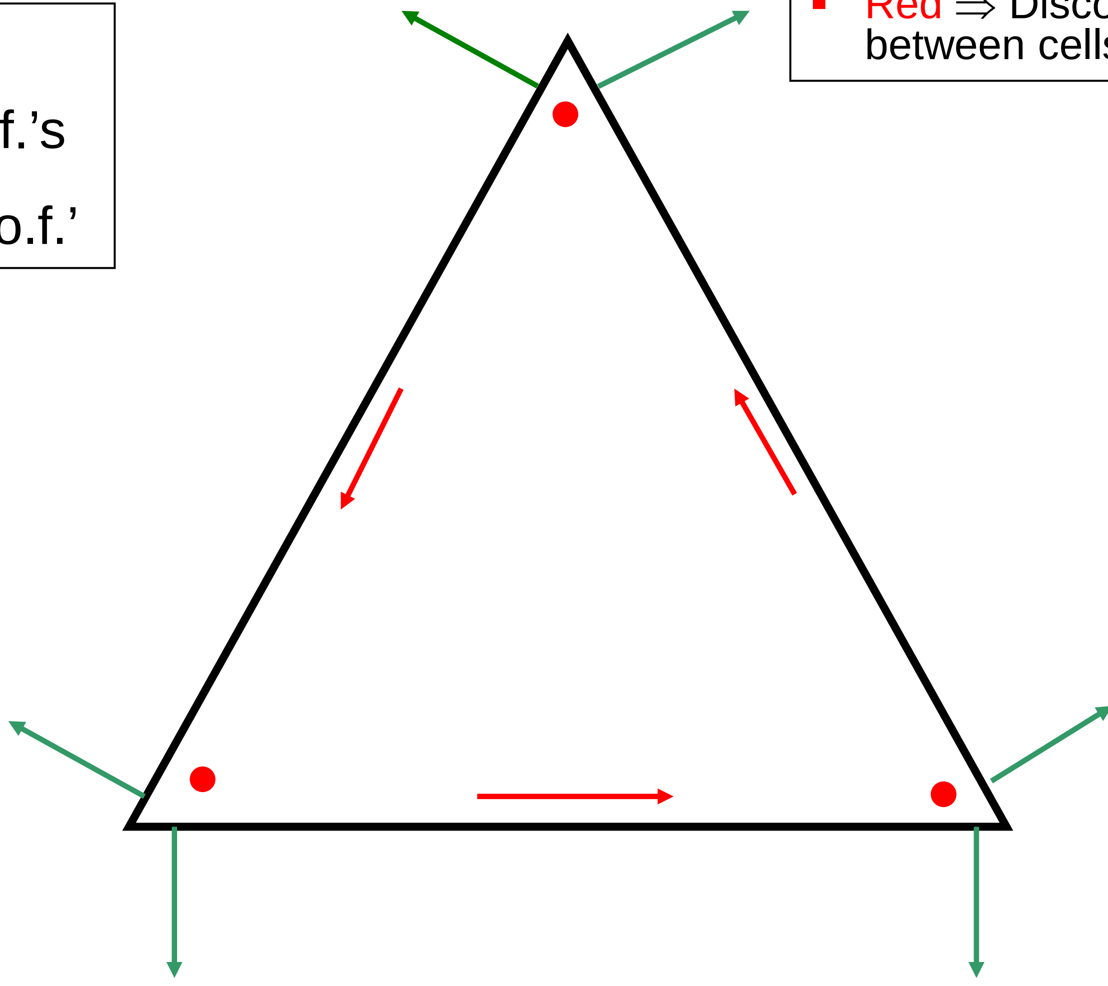


Staniforth (Met O)
Cotter (Imperial)

⇒ BDFM1 element!

- Green ⇒ Continuous between cells
- Red ⇒ Discontinuous between cells

- 6 wind d.o.f's
- 3 pressure d.o.f.'s
- ⇒ Balanced d.o.f.'



Mimicking the continuous equations…

From Staniforth & Thuburn

4. Geopotential gradient and pressure gradient should produce no unphysical source of vorticity $\nabla \times (\nabla p) = 0$

5. Terms involving the pressure should be energy conserving. $\mathbf{u} \cdot \nabla p + p \nabla \cdot \mathbf{u} = \nabla \cdot (\mathbf{u} p)$

6. Coriolis terms should be energy conserving

$$\mathbf{u} \cdot (\mathbf{\Omega} \times \mathbf{u}) = 0$$

7. There should be no spurious fast propagation of Rossby modes; geostrophic balance should not spontaneously break down

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These 5 properties relate to the *mimetic* properties of the numerics

Hexagonal C-Grid Problem: Non-Stationary Geostrophic Mode

Slide courtesy of Bill Skamarock and Joe Klemp (NCAR)

New Coriolis velocity evaluation (Thuburn, 2008 JCP)

$$\partial_t u_1 + g\delta_{x_1} h + \frac{f}{\sqrt{3}}(u_{31} - u_{21}) = 0$$

$$\partial_t u_2 + g\delta_{x_2} h + \frac{f}{\sqrt{3}}(u_{12} - u_{32}) = 0$$

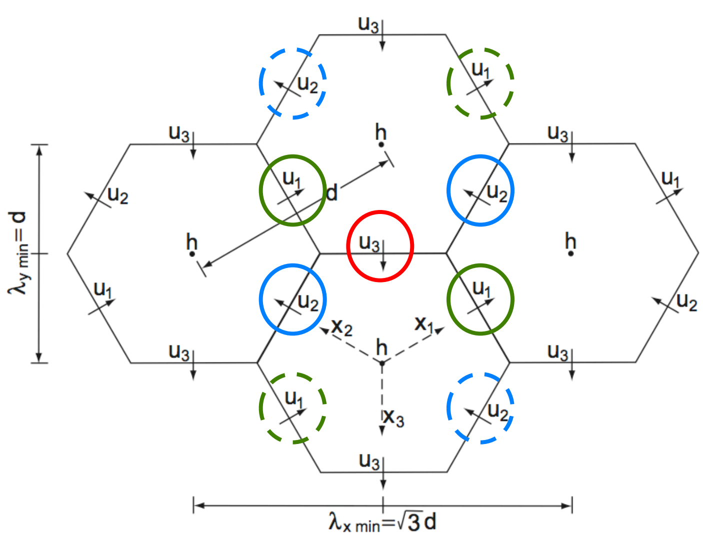
$$\partial_t u_3 + g\delta_{x_3} h + \frac{f}{\sqrt{3}}(u_{23} - u_{13}) = 0$$

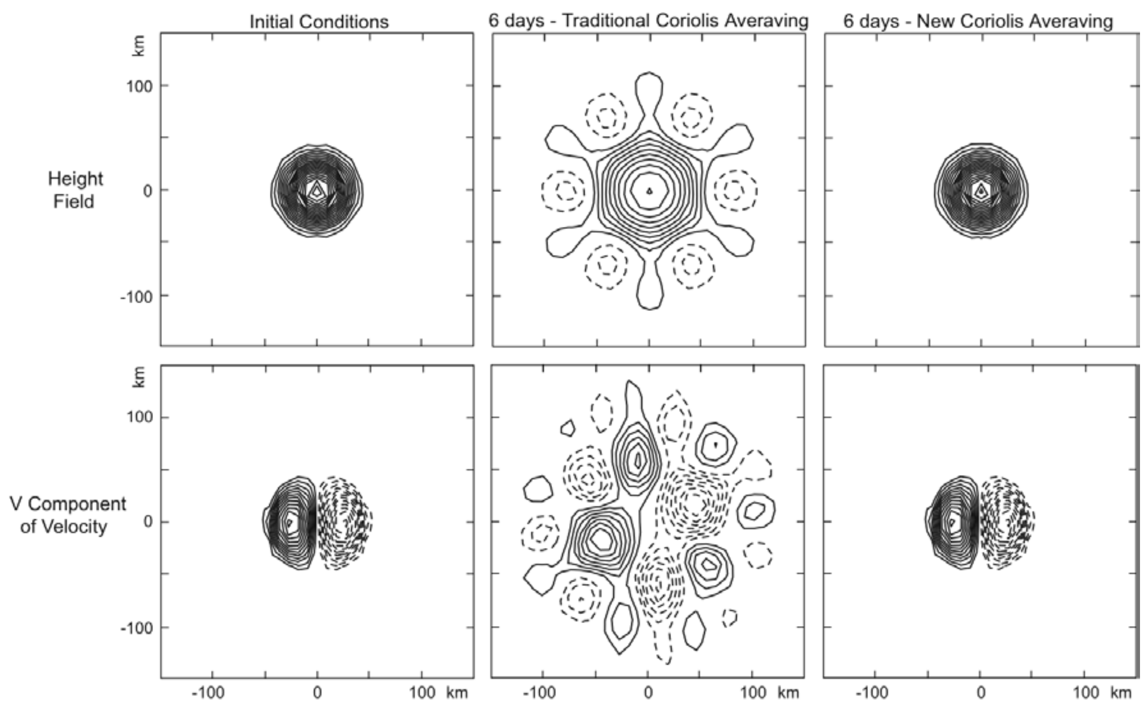
$$\partial_t h + \tfrac{2}{3} H(\delta_{x_1} u_1 + \delta_{x_2} u_2 + \delta_{x_3} u_3) = 0$$

$$u_{21} = \tfrac{1}{3}\overline{u_2}^{x_3} + \tfrac{2}{3}\overline{\overline{u_2}^{x_1}}^{x_2}, \quad u_{31} = \tfrac{1}{3}\overline{u_3}^{x_2} + \tfrac{2}{3}\overline{\overline{u_3}^{x_1}}^{x_3},$$

$$u_{12} = \tfrac{1}{3}\overline{u_1}^{x_3} + \tfrac{2}{3}\overline{\overline{u_1}^{x_1}}^{x_2}, \quad u_{32} = \tfrac{1}{3}\overline{u_3}^{x_1} + \tfrac{2}{3}\overline{\overline{u_3}^{x_2}}^{x_3},$$

$$u_{13} = \tfrac{1}{3}\overline{u_1}^{x_2} + \tfrac{2}{3}\overline{\overline{u_1}^{x_1}}^{x_3}, \quad u_{23} = \tfrac{1}{3}\overline{u_2}^{x_1} + \tfrac{2}{3}\overline{\overline{u_2}^{x_2}}^{x_3}$$





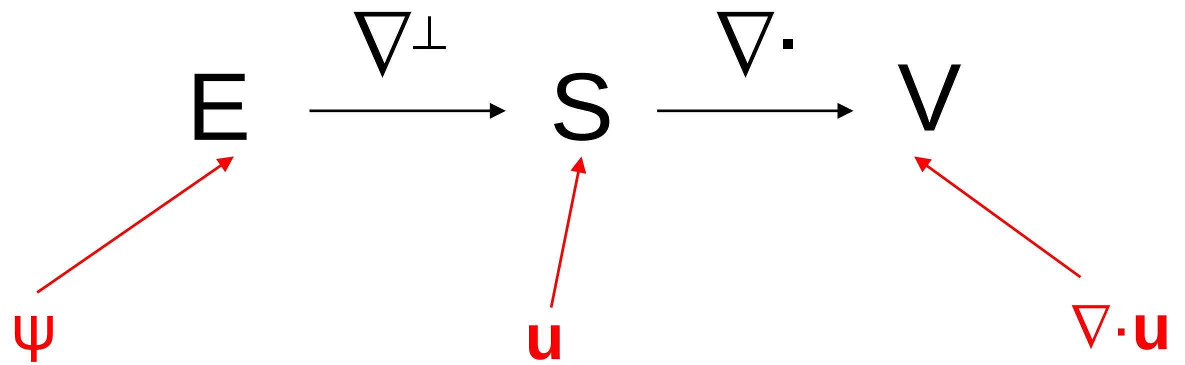
Two ways forward

Cotter (Imperial)

- Vector invariant form of equations:

$$\mathbf{u}\cdot\nabla\mathbf{u} \rightarrow (\nabla\times\mathbf{u})\times\mathbf{u} + \nabla(\mathbf{u}\cdot\mathbf{u}/2)$$

- *Mixed* finite-elements, Primal-only:



Velocity space
Eg RTn or BDFM1

Pressure space
Eg Qn or $P1_{DG}$

Exploiting ideas from discrete exterior calculus & differential geometry

Two ways forward

Cotter (Imperial)
& Thuburn (Exeter)

- Vector invariant form of equations:

$$\mathbf{u}\cdot\nabla\mathbf{u} \rightarrow (\nabla\times\mathbf{u})\times\mathbf{u} + \nabla(\mathbf{u}\cdot\mathbf{u}/2)$$

- *Mixed* finite-elements, Primal-Dual:

$$\begin{array}{ccccc}
E_p & \xrightarrow{\nabla^{\perp}} & S_p & \xrightarrow{\nabla\cdot} & V_p \\
\uparrow & & \uparrow & & \uparrow \\
V_d & \xleftarrow{k\cdot\nabla\times} & S_d & \xleftarrow{\nabla} & E_d
\end{array}$$

p/w linear+RT0+p/w constant

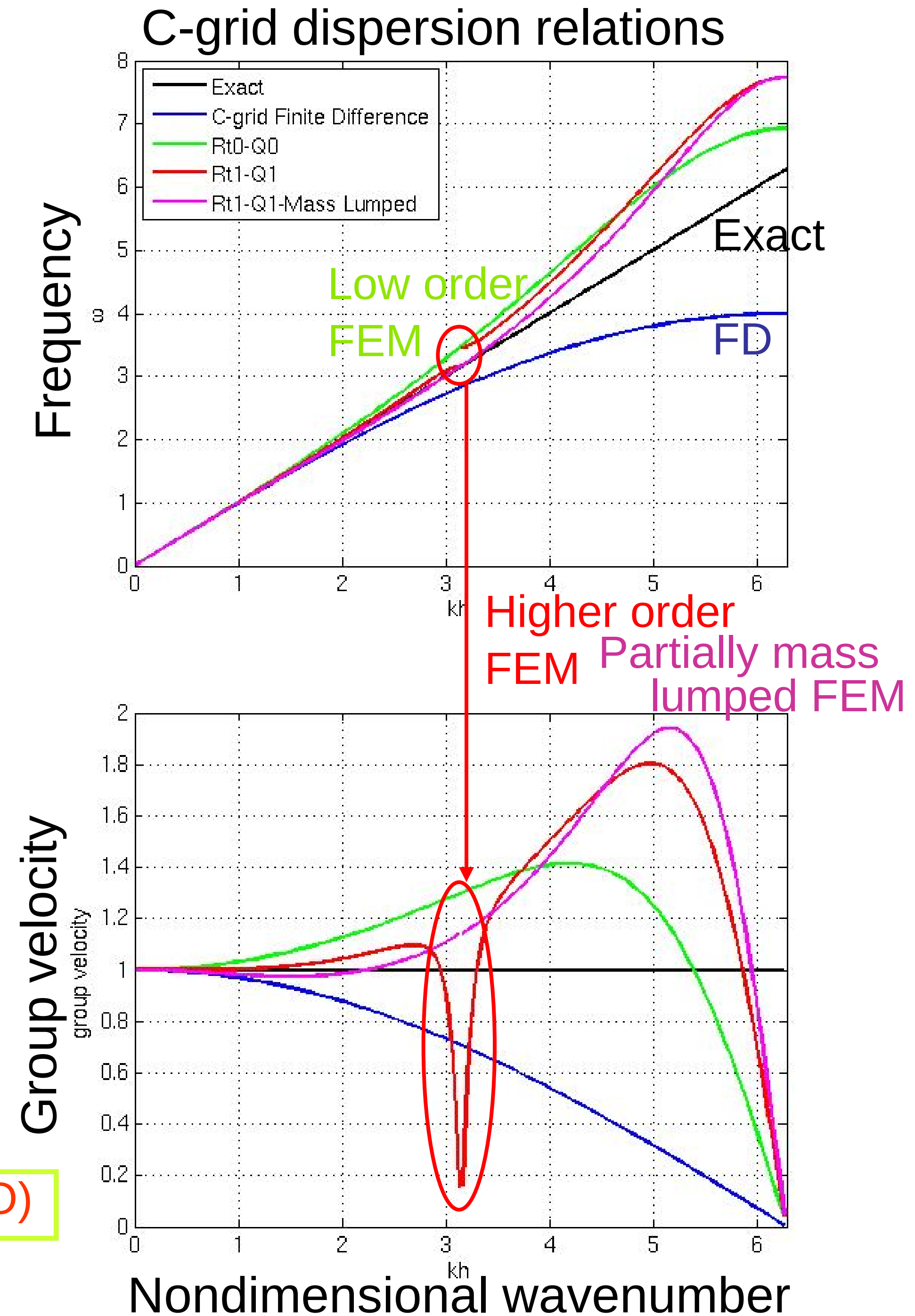
p/w constant+N0+p/w linear

Exploiting ideas from discrete exterior calculus & differential geometry

Dispersion properties…

Dispersion

- Even with good balance…
- And good mimetic properties…
- All is not rosy

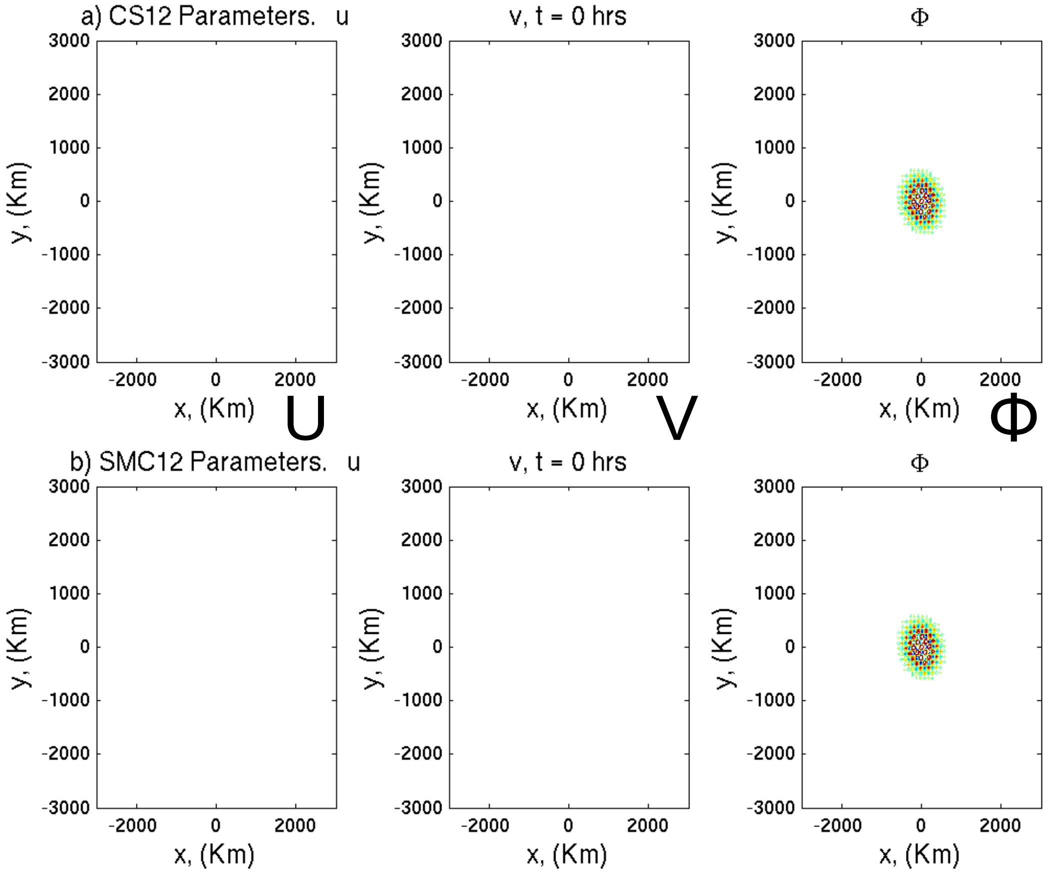


Cotter (Imperial), Melvin & Staniforth (MetO)

Dispersion

- Even with good balance…
- And good mimetic properties…
- All is not rosy

Higher order FEM

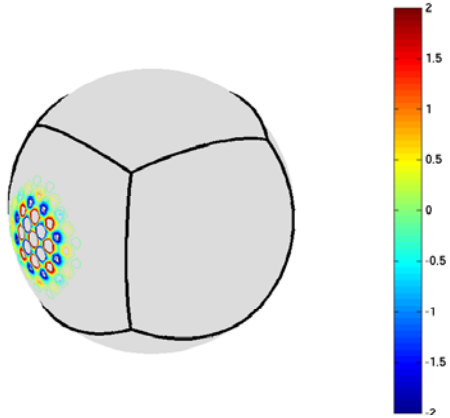


Partially mass lumped FEM

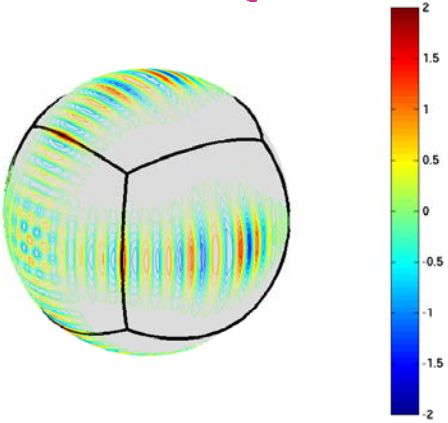
Cotter (Imperial), Melvin & Staniforth (MetO)

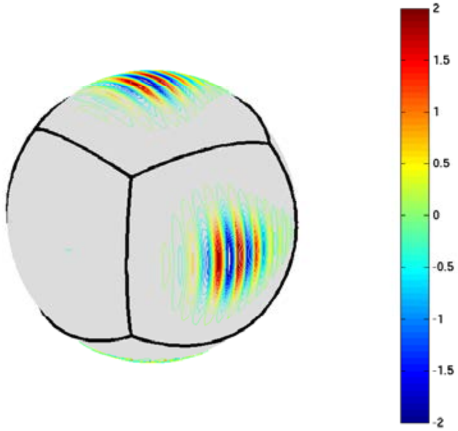
…and on a Cubed-Sphere

Initial conditions

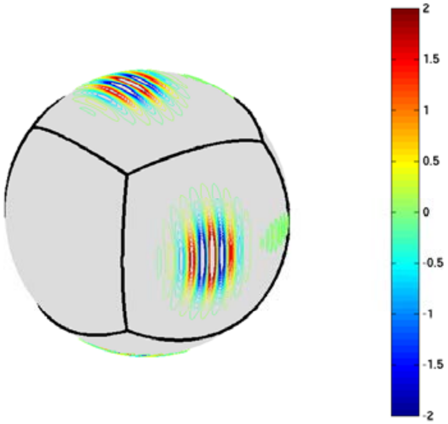


Standard RT1-Q1 scheme





Partially mass lumped scheme



Standard scheme at double resolution

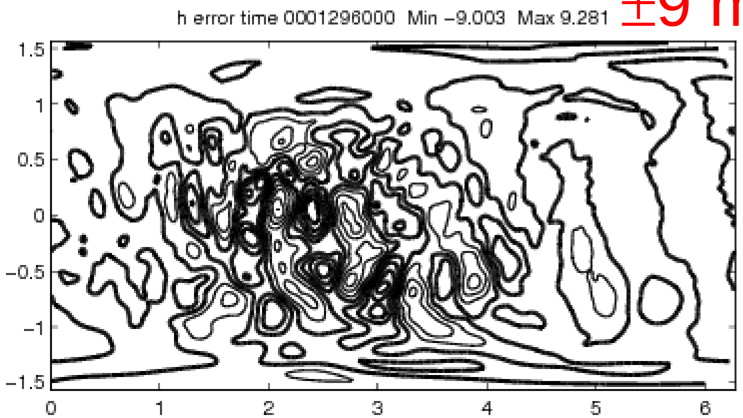
Melvin & Staniforth (MetO), Cotter (Imperial)

Recent results

Thuburn (Exeter)

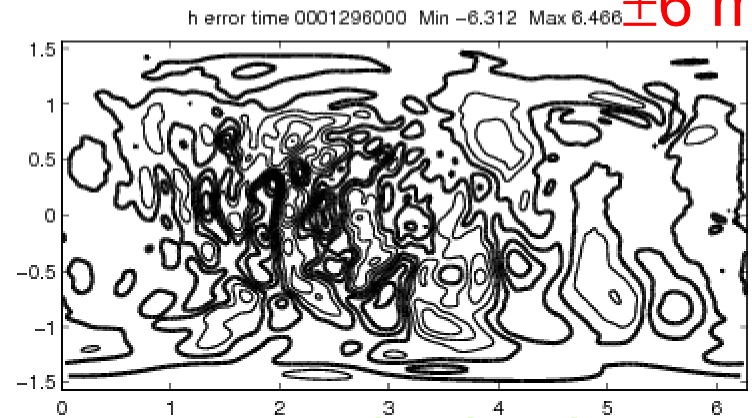
Williamson Test Case 5 with 160K d.o.f.s (320x160)

±9 m



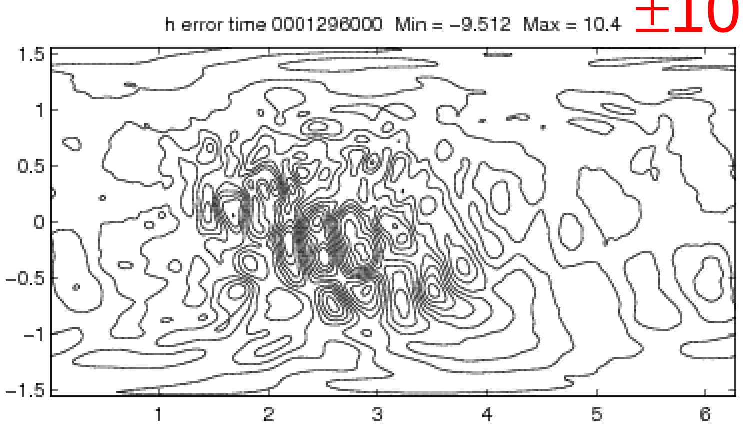
FEM Hexagonal

±6 m



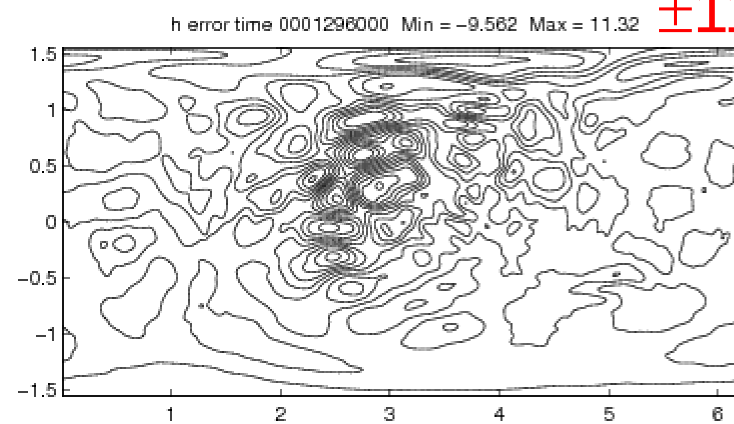
FEM Cubed-sphere

±10 m



ENDGame lat-lon

±11 m



ENDGame rotated lat-lon

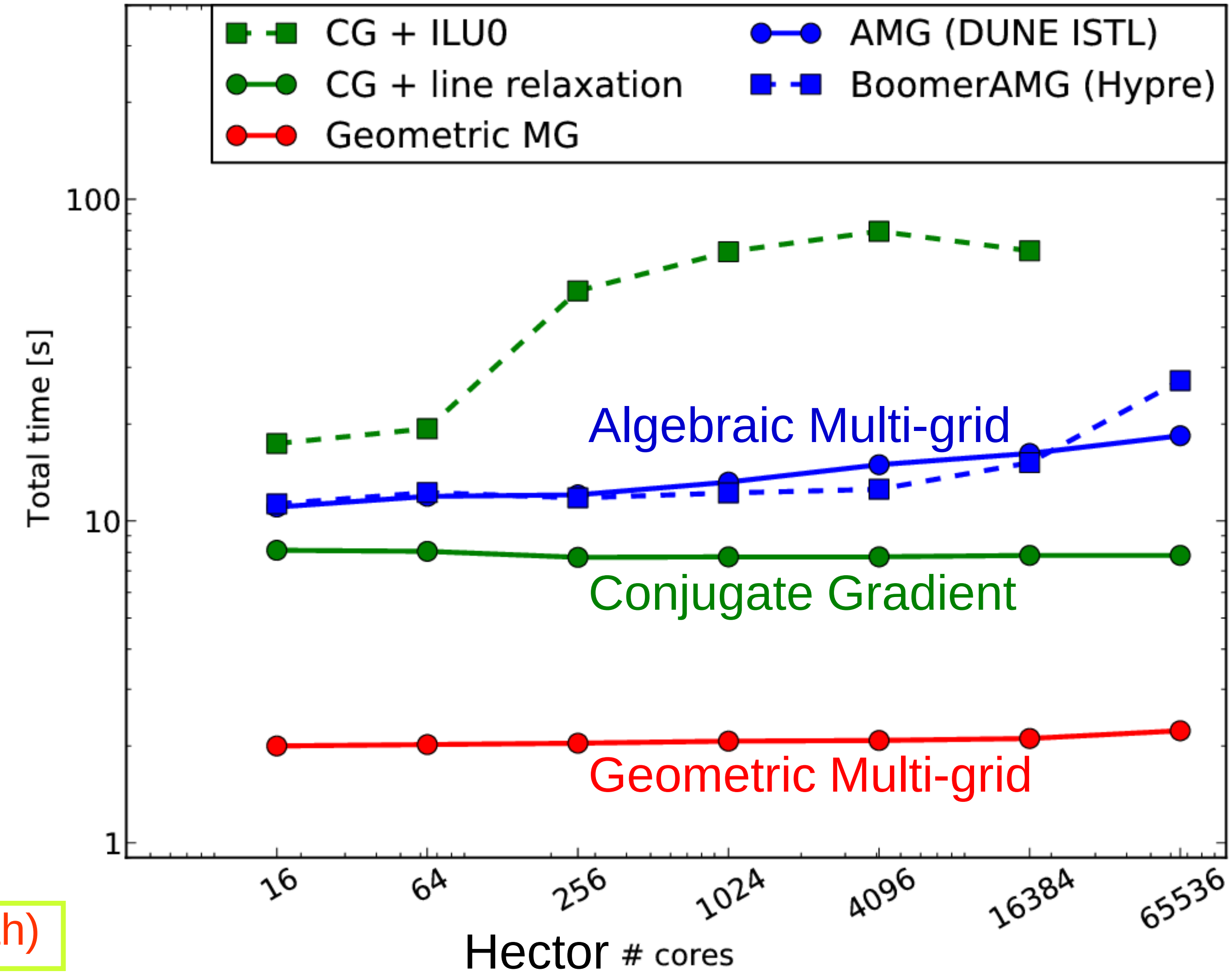
It's not all about space…

Are implicit schemes viable?

Met Office

Weak horizontal scaling for a 3D Helmholtz problem

- Baseline resolution = 64x64
- Nz=128
- Grid cells per processor = 520K
- Cs*Dt/Dx=const=8.4
- One side of cubed-sphere



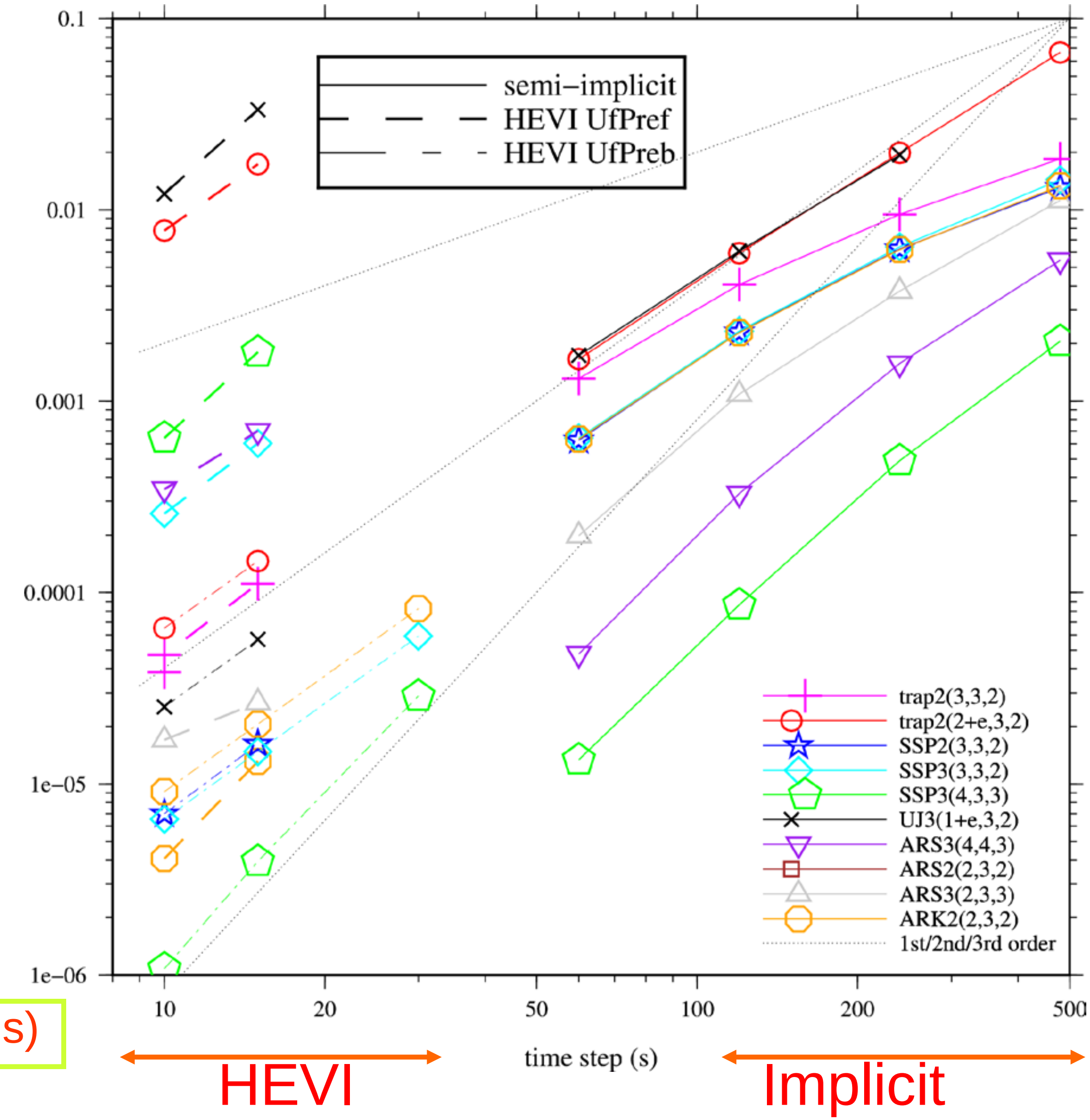
Mueller & Scheichl (Bath)

What to do if not…

Met Office

- Horizontally Explicit – Vertically Implicit (HEVI)
- Computational modes arise from multistep schemes

⇒ Examine range of Runge-Kutta Implicit-Explicit (IMEX) schemes



Weller (Reading) & Lock (Leeds)

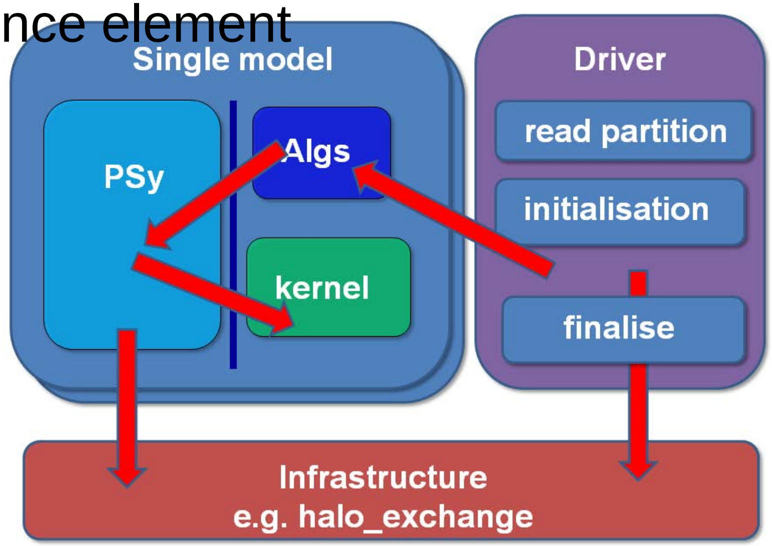
Summary…

Where we are and whither next

- Requirements rule out a number of options
- Triangles:
  - ➢Higher-order mixed finite elements
  - ➢Dispersion problem…solution?
- Quadrilaterals:
  - ➢Low-order mixed finite elements…grid imprinting?
  - ➢Higher-order approach…Dispersion problem…solution✓
- Temporal scheme:
  - ➢Looks feasible via multi-grid approach

Where we are and whither next

- So far focus has been horizontal SWEs
  - ➢Focus shifting now to vertical aspects
- And we need to be able to run whatever we settle on!
  - ➢Large computational science element



Ham (Imperial), Riley (Manchester), Glover, Hobson, Maynard, Mullerworth (MetO)
Ford & Pickles (STFC)

And finally…

(with thanks to Mike Ashworth)

"It would appear that we have reached the limits of what is possible to achieve with computer technology, although one should be careful with such statements, as they tend to sound pretty silly in five years"

John von Neumann, 1949

Thank you!

Questions?