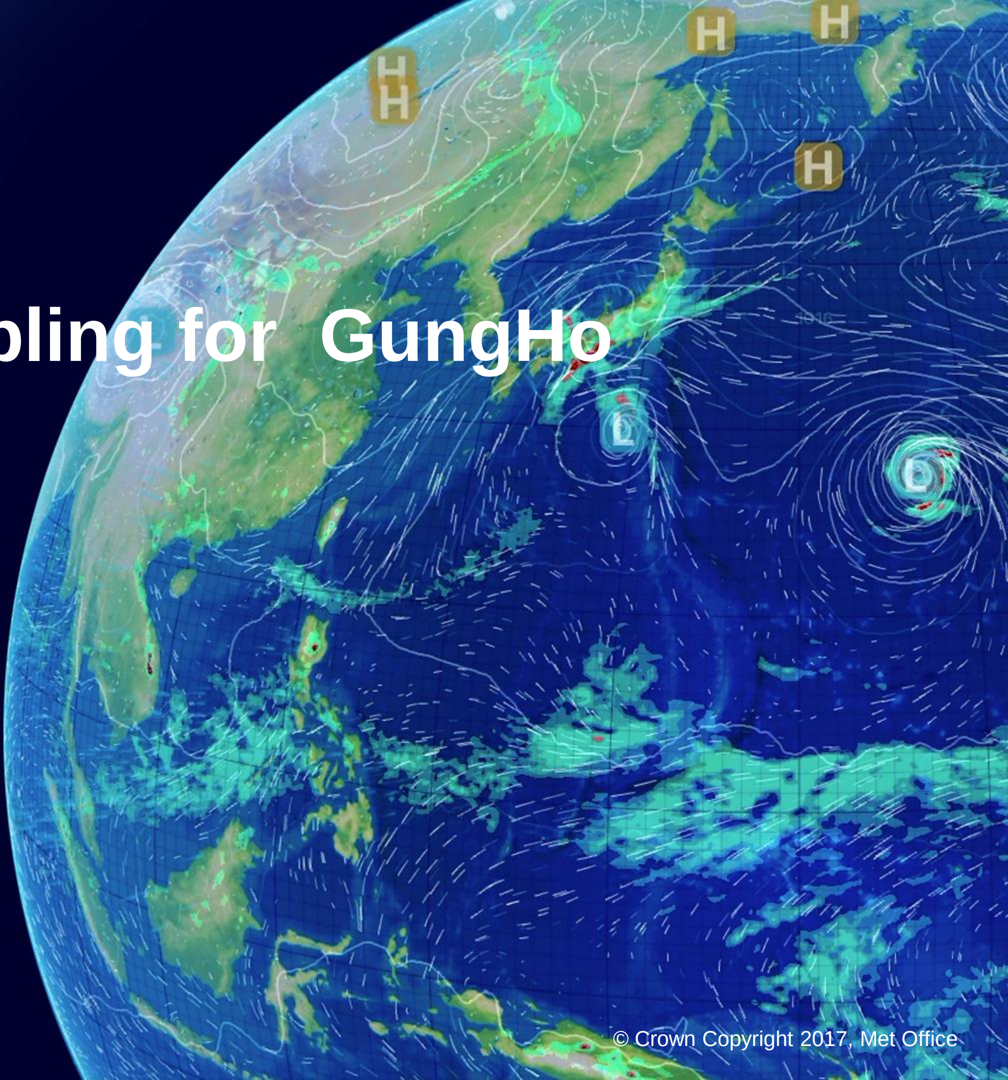
# Physics-Dynamics coupling for GungHo



Ben Shipway, Met Office

15th November 2017

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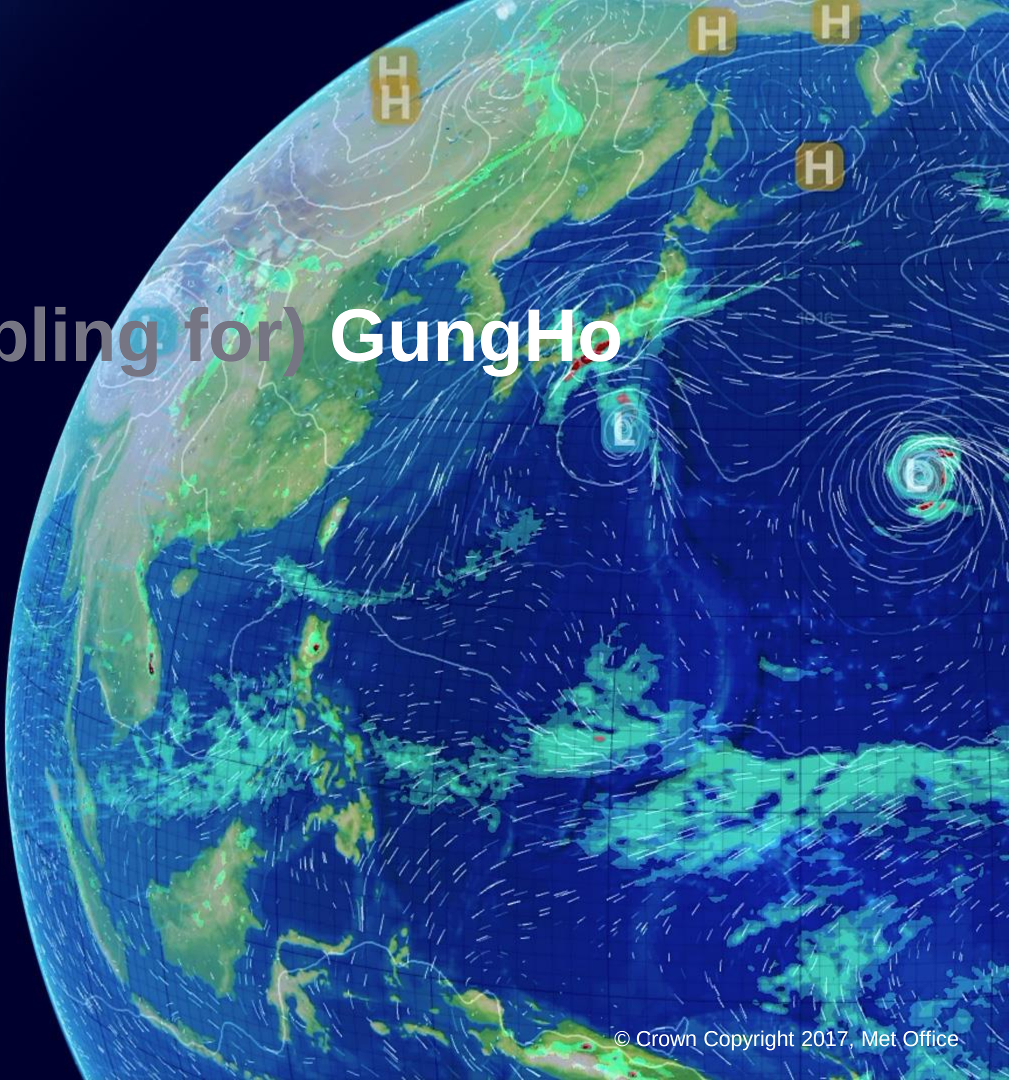

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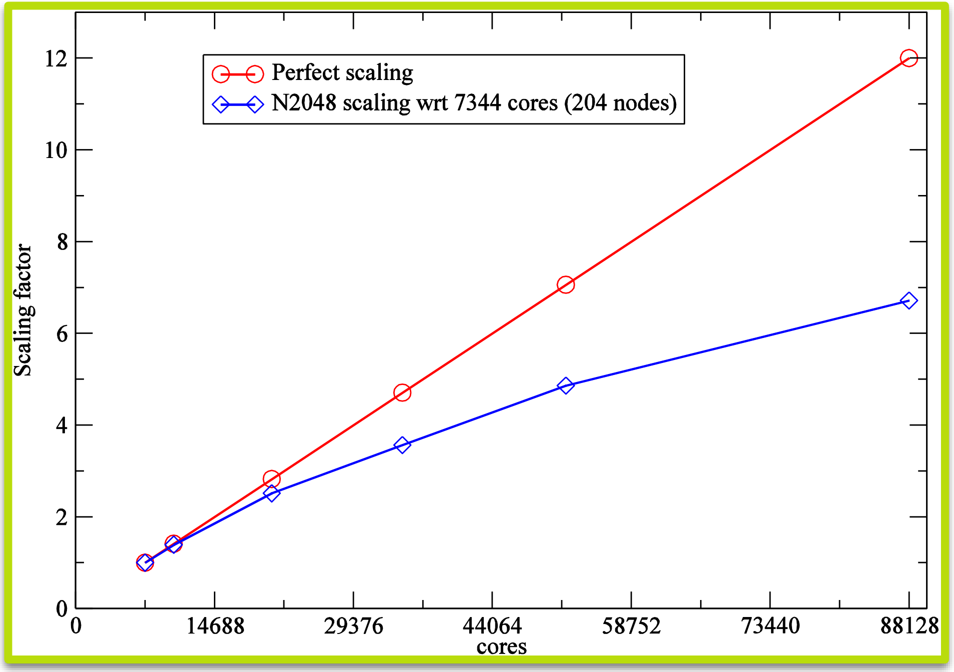
# Acknowledgements


- GungHo, LFRic and PSyclone developers
- DR and APP teams

# UM Scaling Challenge in the future

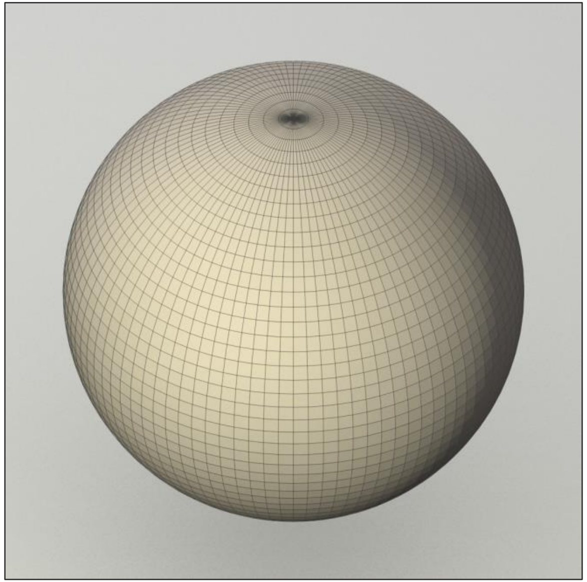
- 6km global UM - ENDGame (N2048)
- Scales reasonably
- But achievable run-time is 40% above current operational configurations
- And future supercomputers will have even more cores




88128 = 2448 nodes of Met Office Cray XC40: 36 Broadwell cores per node

Andy Malcolm and Paul Selwood

# Communications bottleneck



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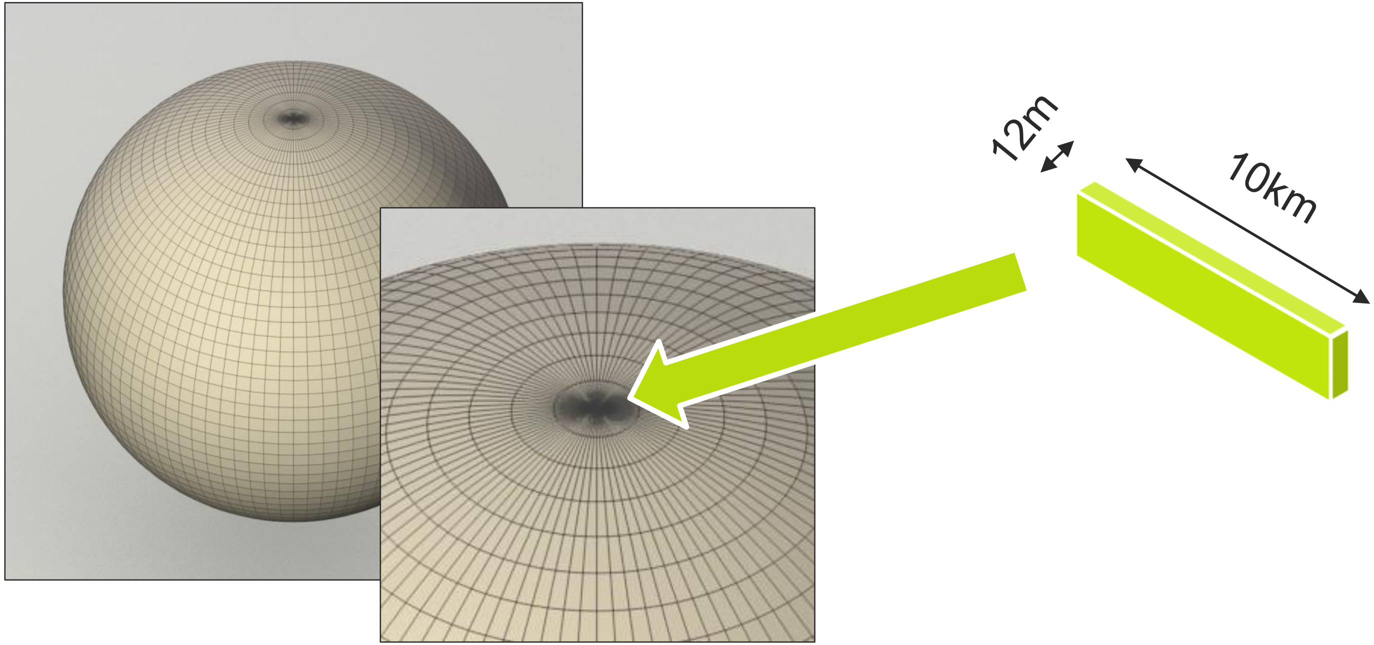
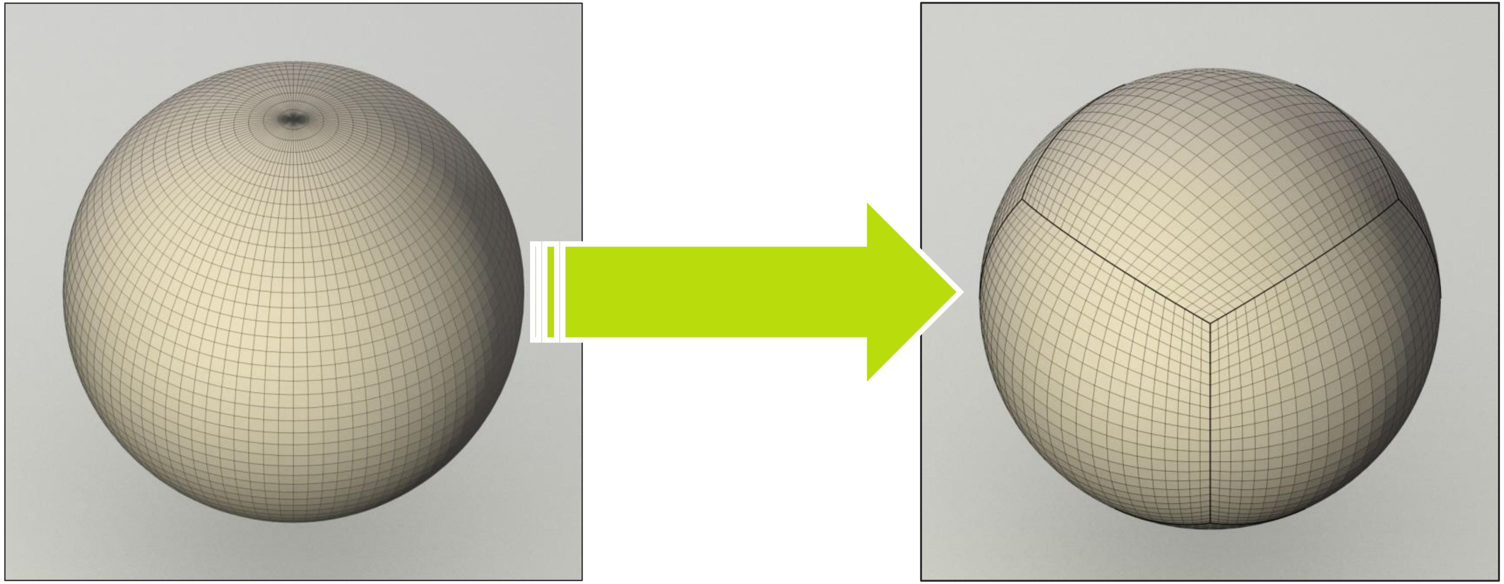
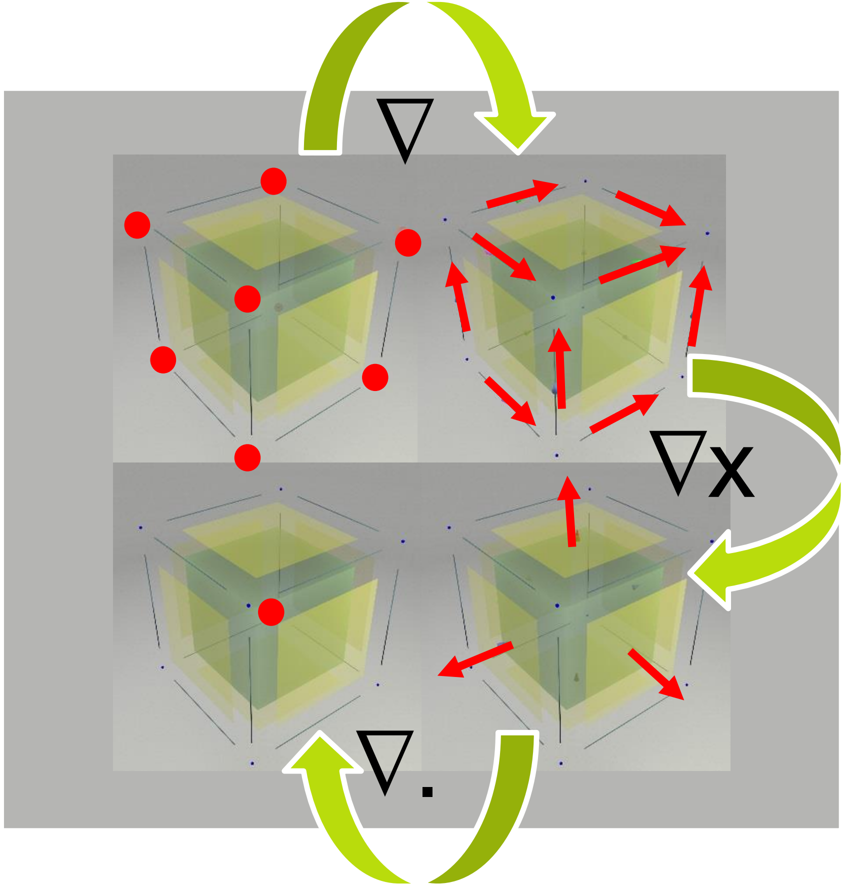


# Evolution or Revolution?



# GungHo dynamical core

- Low order quadrilaterals on cubed-sphere…
- Coupled to finite volume transport scheme
- Semi-implicit timestepping
- …flexible approach to maintain backup options if accuracy is not good enough/future development
  - Higher order quadrilaterals
    - More accurate but more complex
  - Higher order triangles
    - Potentially reduced grid imprinting
    - Untested in complex problems

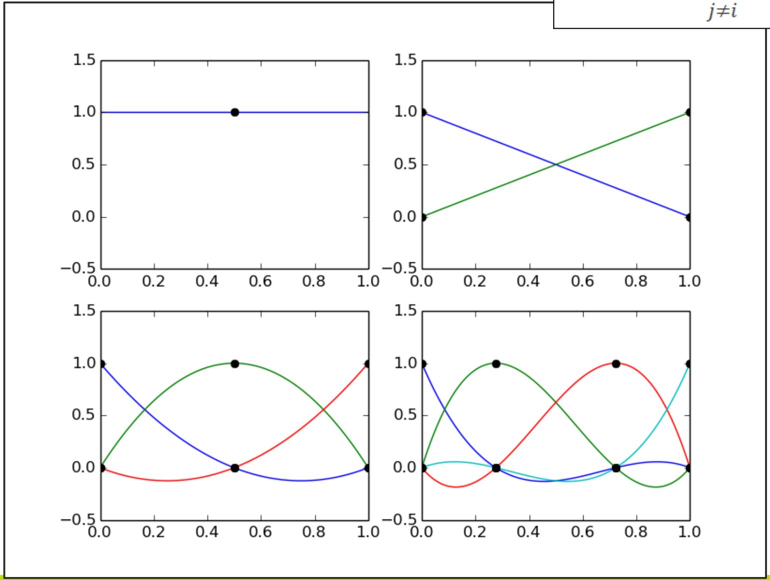


# GungHo Dynamical core: Mixed Finite Elements

- Rather than point values, fields are represented as a series expansion of polynomials and the coefficients, $\{a_i\}$, are stored, e.g.

$$\theta = \sum_{i=1}^{n} a_i L_i(x)$$

$$L_i(x) = \prod_{\substack{j=1 \\ j \neq i}}^{n} \frac{x - x_j}{x_i - x_j}$$



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c.f. Finite Volume

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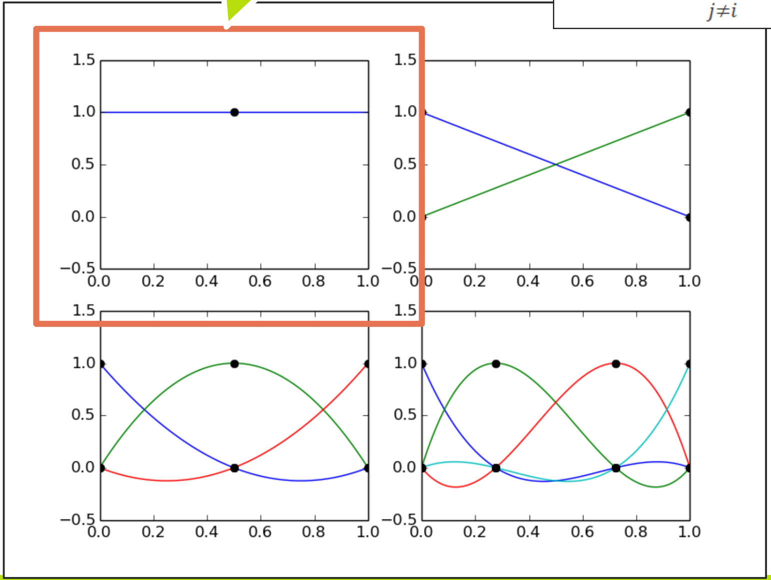

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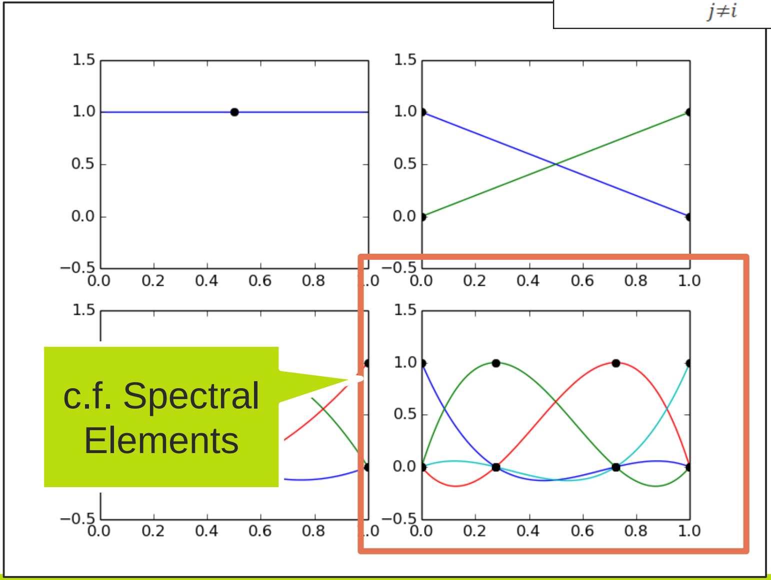

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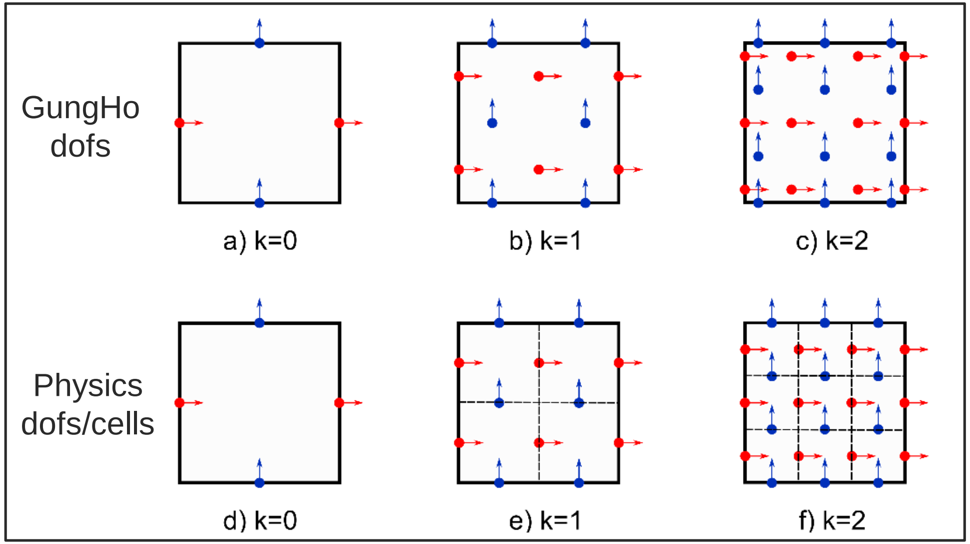
# Conservation of information?

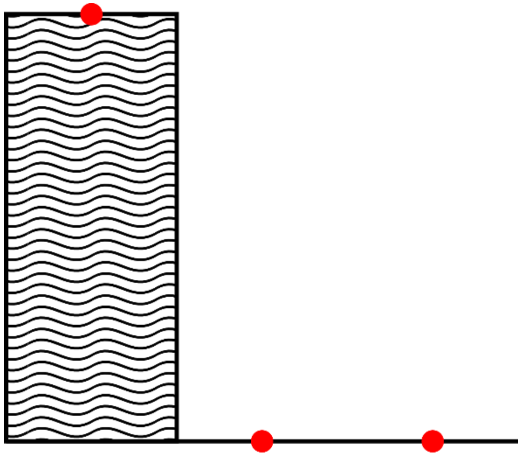
The key challenge is to couple the Finite Difference physics schemes to the Finite Element dynamical core.




Ideally we want to satisfy the following conditions with regard to this coupling:

1. **Number of degrees of freedom** (ndof):
   $$\text{ndof}_{\text{dynamics}} = \text{ndof}_{\text{physics}}$$
2. **Conservation**: we don't lose or gain mass or energy through the mapping
3. **Monotonicity:** we don't generate new maxima or minima
4. **Reversibility:** if we map to physics/dynamics fields and back again without any physics/dynamics sources, then we should retrieve the field we started with.

# Mapping physics to dynamics



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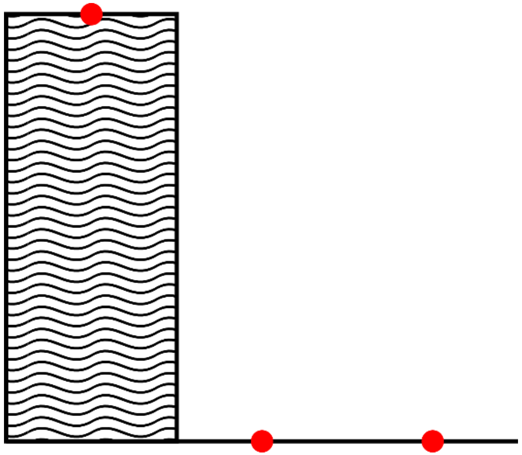

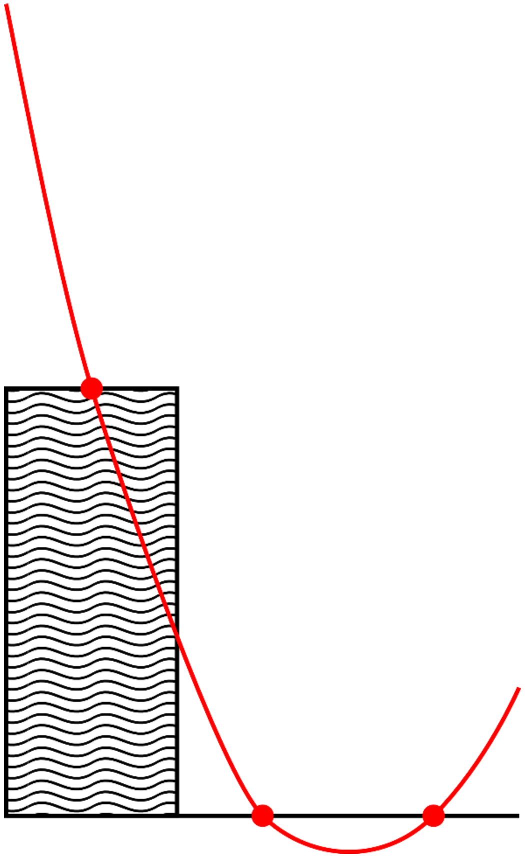

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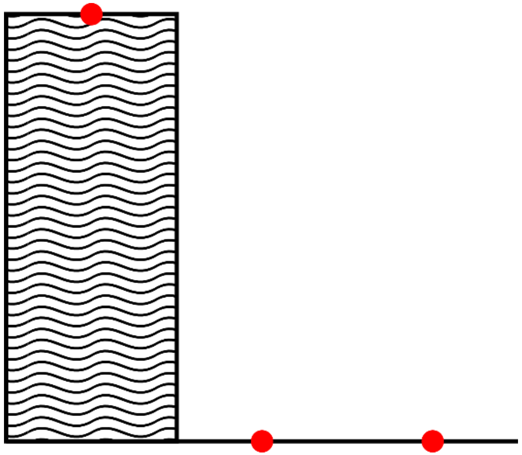
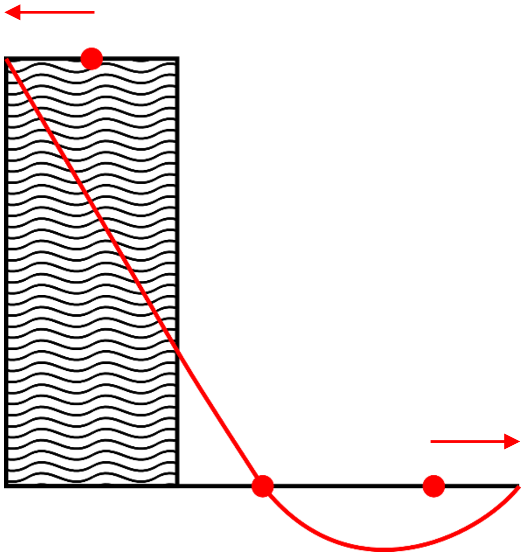
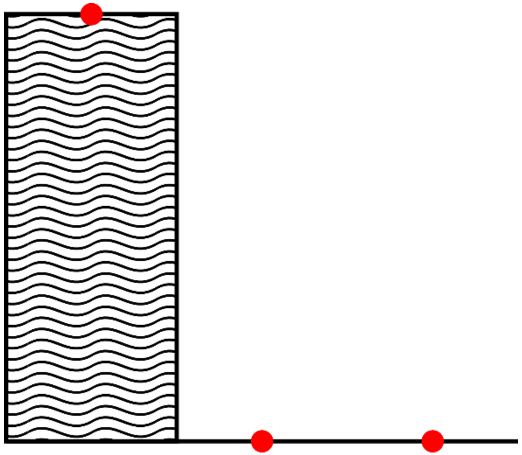
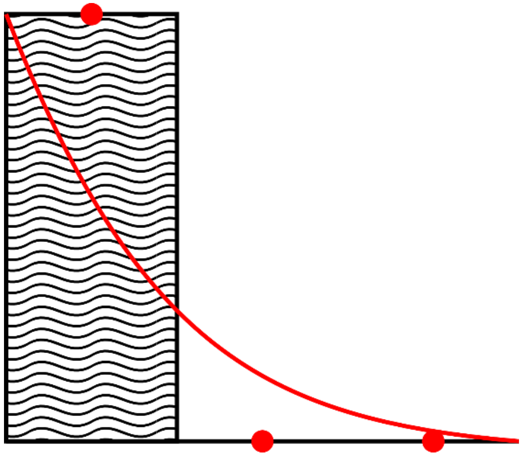




# Mapping physics to dynamics

Change basis to Bernstein polynomials





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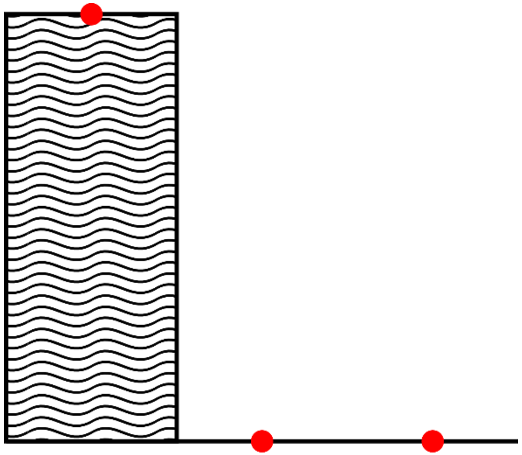

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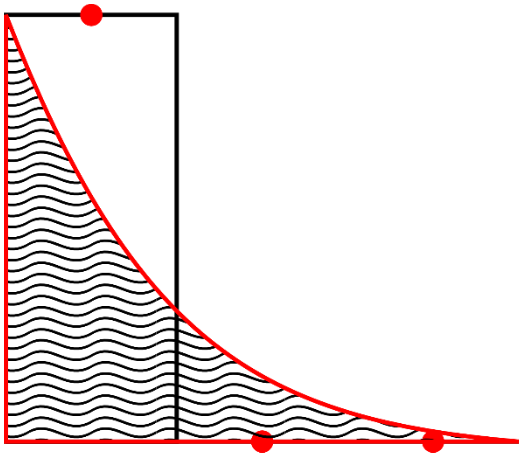
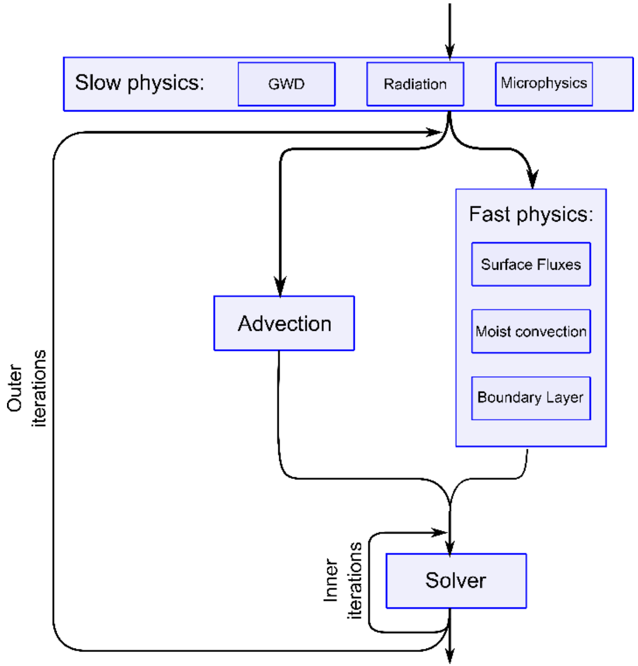


# Conservation of information?

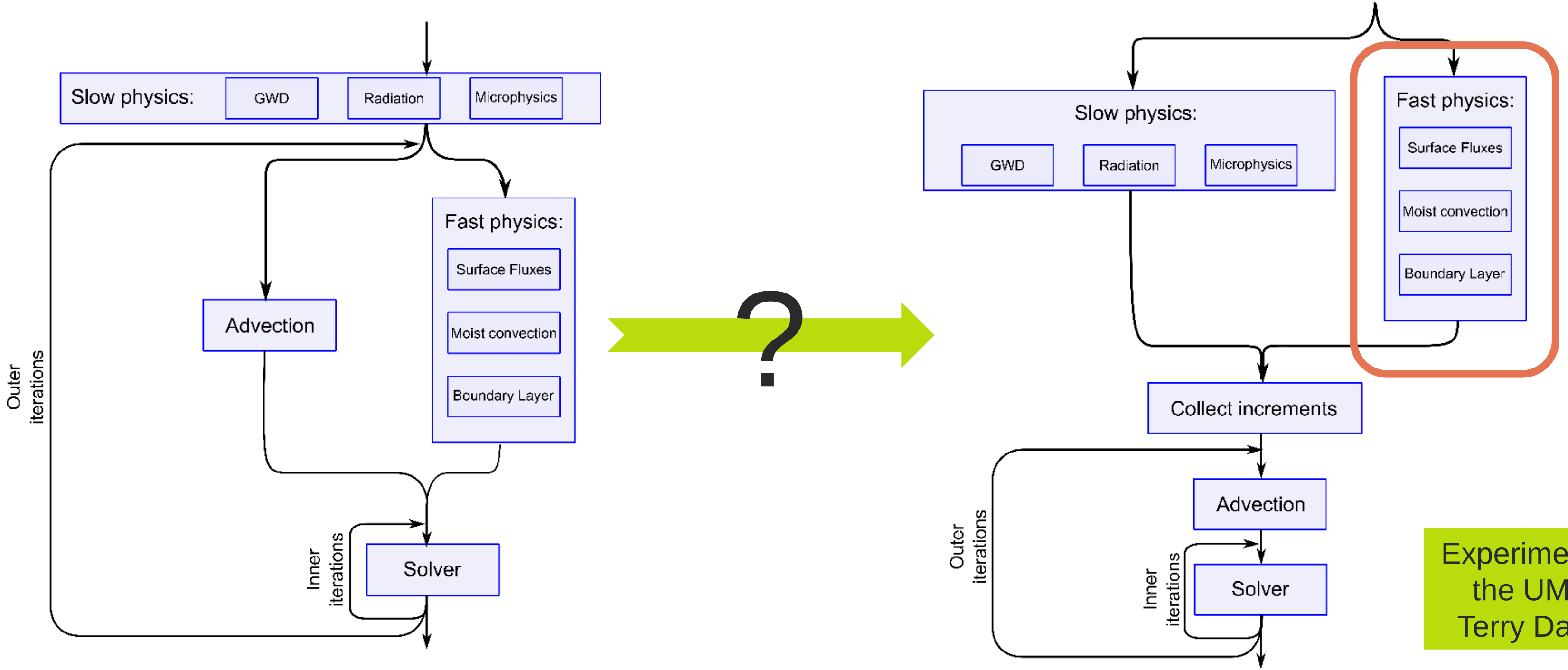
| $ndof_{dynamics} < ndof_{physics}$ | $ndof_{dynamics} = ndof_{physics}$ | $ndof_{dynamics} > ndof_{physics}$ |
|---|---|---|
| • Physics can respond to smaller spatial scales, e.g. orography, land surface.<br>• Stochastic sampling?<br>• Computational efficiency (embarrassingly parallel physics?) | • Natural thing to do.<br>• Optimal use of information??? | • Physics doesn't see unphysical (unresolved) fields.<br>• Computational efficiency (more so with high order dynamics?) |

# Balance & temporal coupling

# Balance?

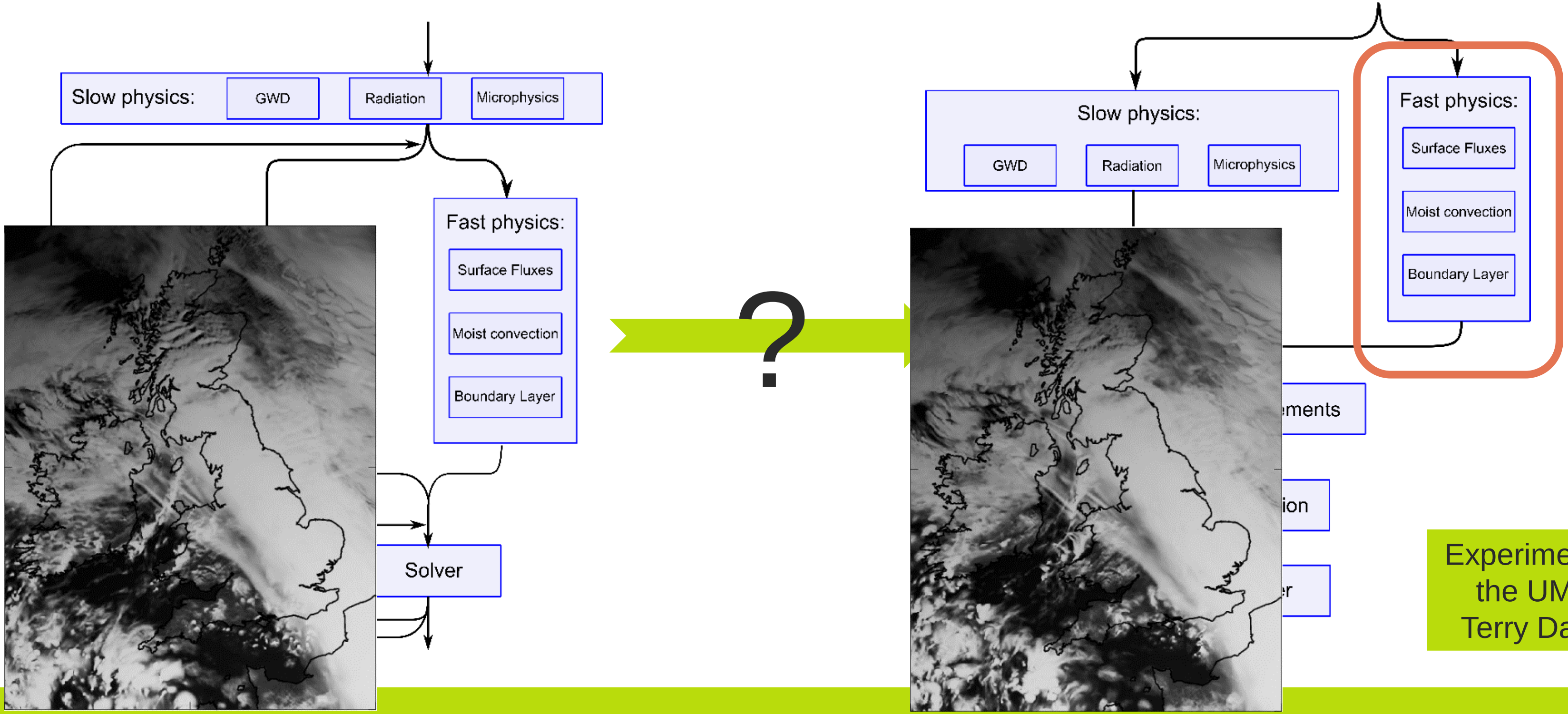

Slow physics:
GWD
Radiation
Microphysics
Fast physics:
Surface Fluxes
Moist convection
Boundary Layer
Advection
Outer iterations
Inner iterations
Solver

# Balance?




Experiments in the UM by Terry Davies

# Balance?




Experiments in the UM by Terry Davies

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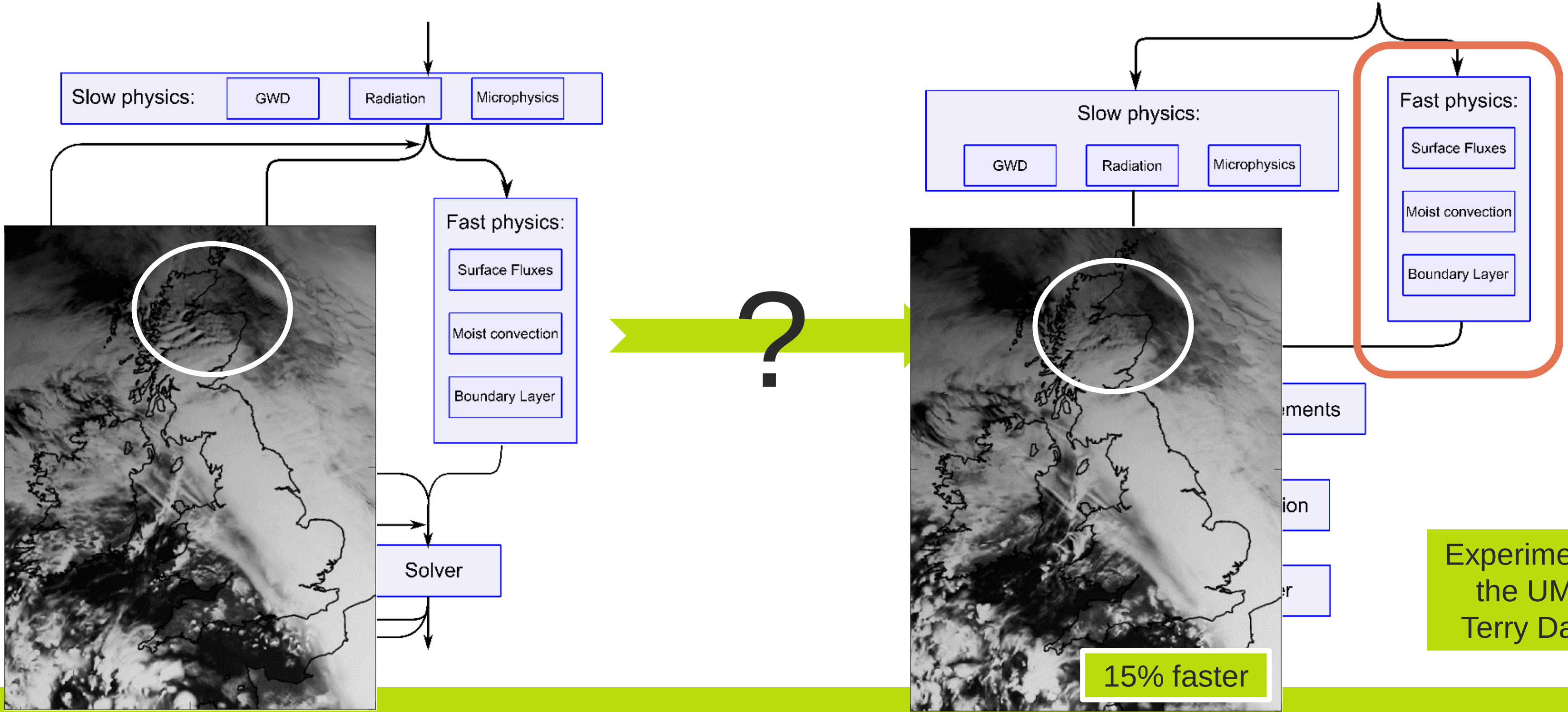
# Balance?




Experiments in the UM by Terry Davies

# Problems at the grid scale?

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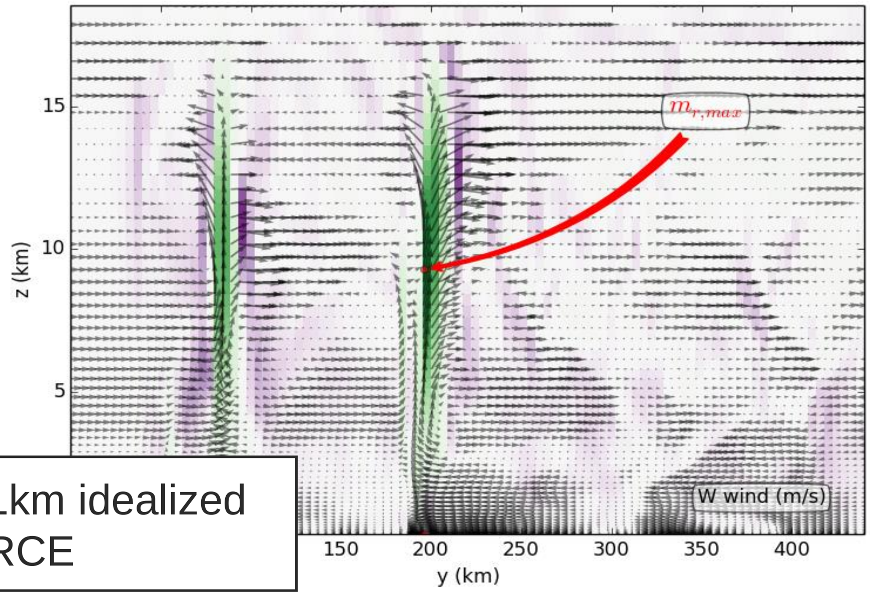
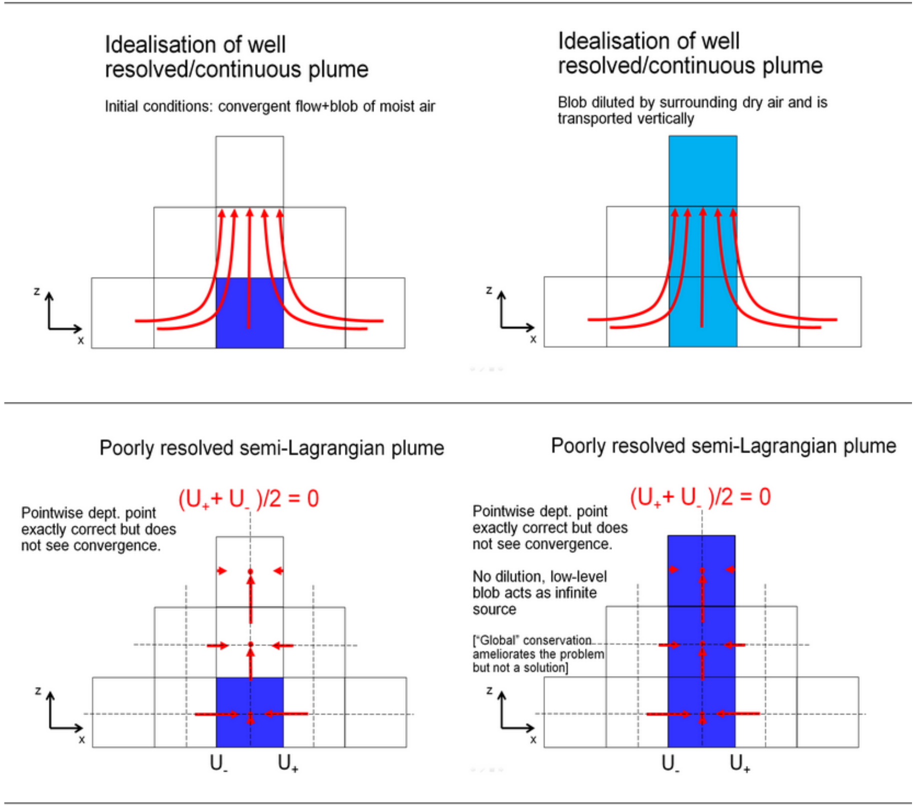
# Conservation **is** important




1km idealized RCE



# Conservation **is** impo

Research Article

**An alternative cell-averaged departure point reconstruction for pointwise semi-Lagrangian transport schemes**

Sylvie Malardel[1,*] and Didier Ricard[2]

Article first published online: 19 FEB 2015

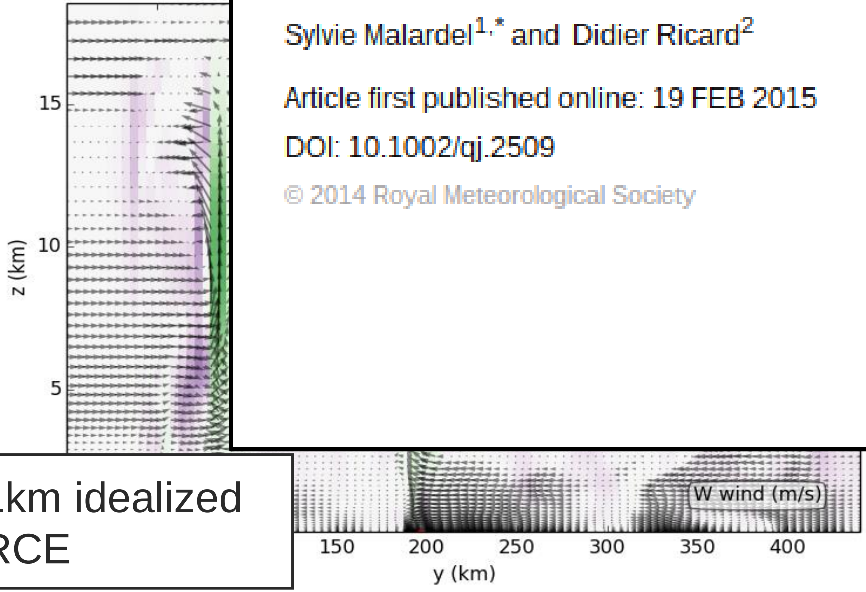
DOI: 10.1002/qj.2509



Issue

Quarterly Journal of the Royal Meteorological Society

Volume 141, Issue 691, pages 2114–2126, July 2015 Part B

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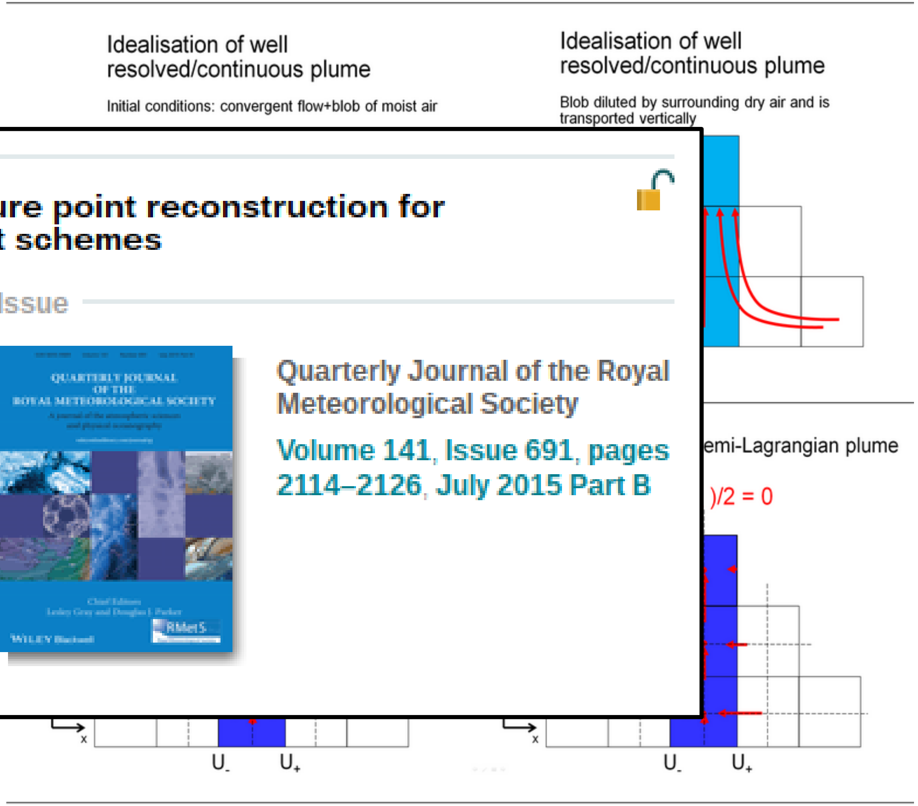

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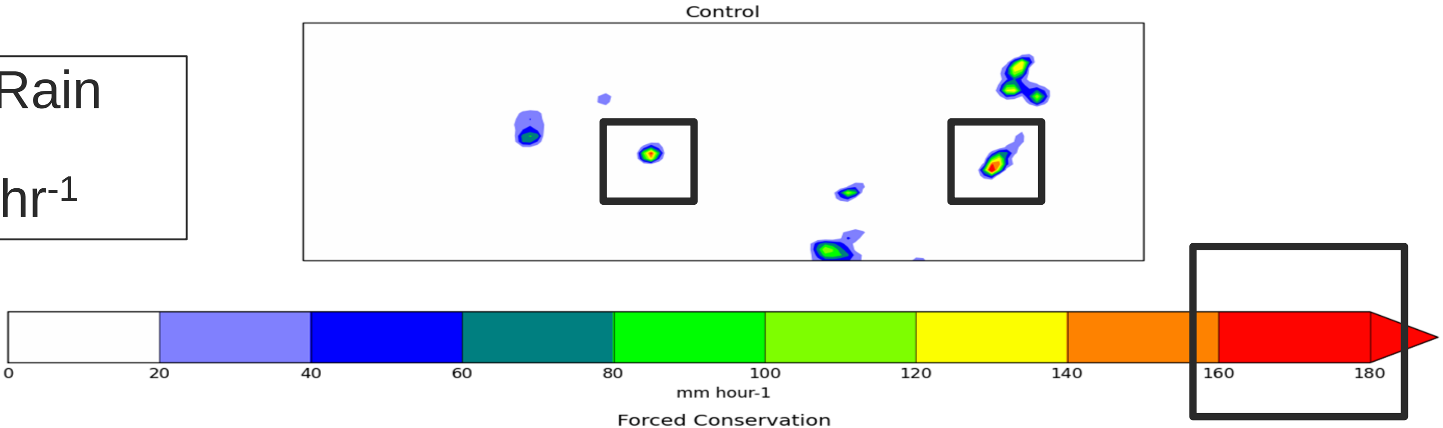
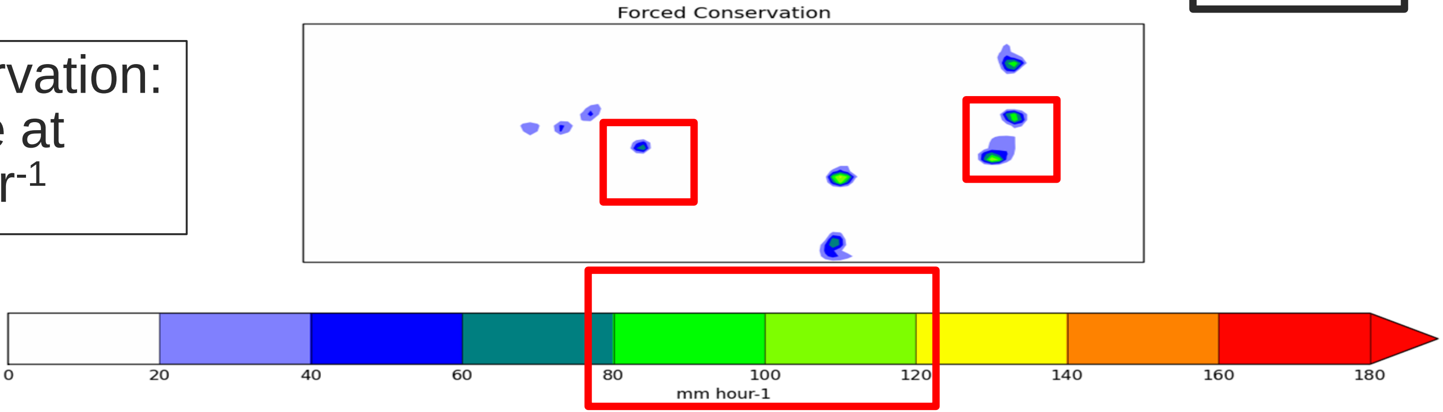
Control: Peak Rain Rate at 160-180+ mm $hr^{-1}$




Forced Conservation: Peak Rain rate at 80-120+ mm $hr^{-1}$

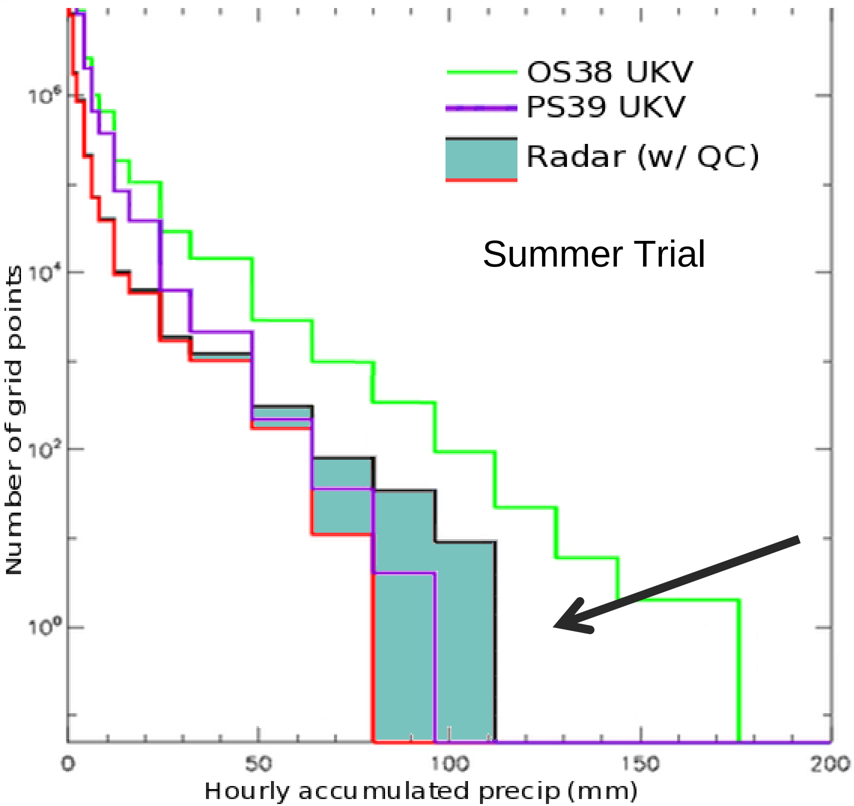


- Scheme optimized for regional models, avoiding expensive boundary flux calculation (Zerroukat and Shipway, 2017)

- Reduces occurrence of spuriously high precipitation rates

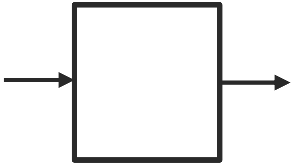
- Implemented in PS39 for UKV

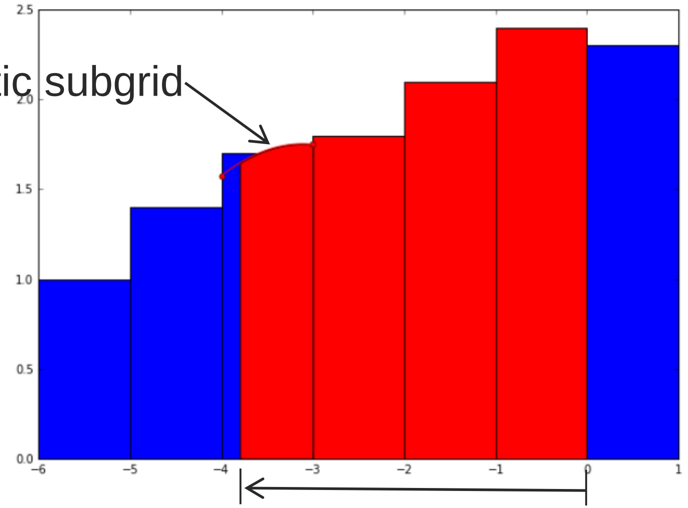
Average summer hourly accumulations




Improved frequency bias, especially at highest thresholds

# Finite Volume Transport



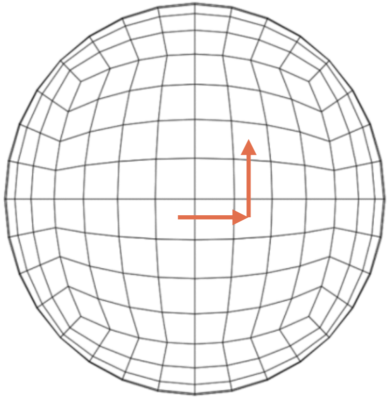



$$
\begin{aligned}
\text{flux} &= \frac{1}{\Delta t}\left[\int_{x_{dep}}^{x_{arr}} \phi dx\right] \\
&= \frac{1}{\Delta t}\left[\int_{-3.8}^{0} \phi dx\right] \\
&= \frac{1}{\Delta t}\left[\int_{-3.8}^{-3} \phi dx + \int_{-3}^{-2} \phi dx + \int_{-2}^{-1} \phi dx + \int_{-1}^{0} \phi dx\right] \\
&= \frac{1}{\Delta t}\left[\int_{-3.8}^{-3} \phi dx + M_3 + M_2 + M_1\right]
\end{aligned}
$$

- Subgrid approximation (quadratic, linear)
- Fluxes unique on each cell face
- Monotonicity limiters available

# COSMIC

$$\frac{\partial \phi}{\partial t} + \frac{\partial(\phi u)}{\partial x} + \frac{\partial(\phi v)}{\partial y} = 0$$



$$\phi^{n+1} = \tfrac{1}{2}\{Y(X(\phi^n)) + X(Y(\phi^n))\}$$

x step

$$\begin{aligned}\phi^* &= \phi^n - \Delta t \frac{\partial(\phi^n u)}{\partial x} \\ &= X(\phi^n)\end{aligned}$$

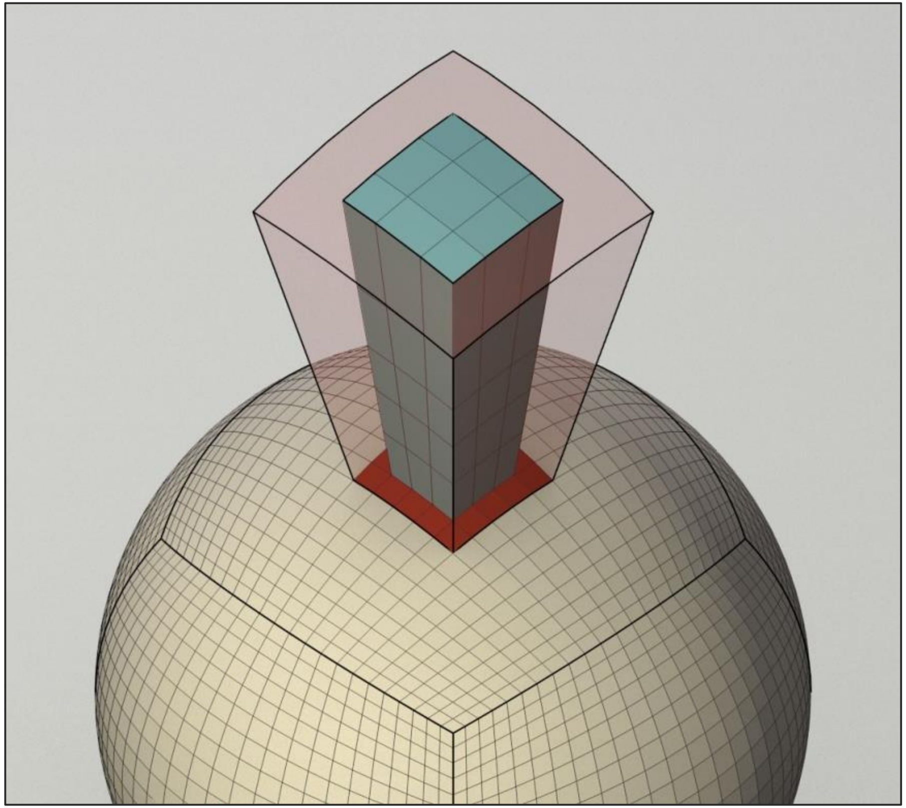
y step

$$\begin{aligned}\phi^{n+1} &= \phi^* - \Delta t \frac{\partial(\phi^* v)}{\partial y} \\ &= Y(\phi^*)\end{aligned}$$

# Computational aspects

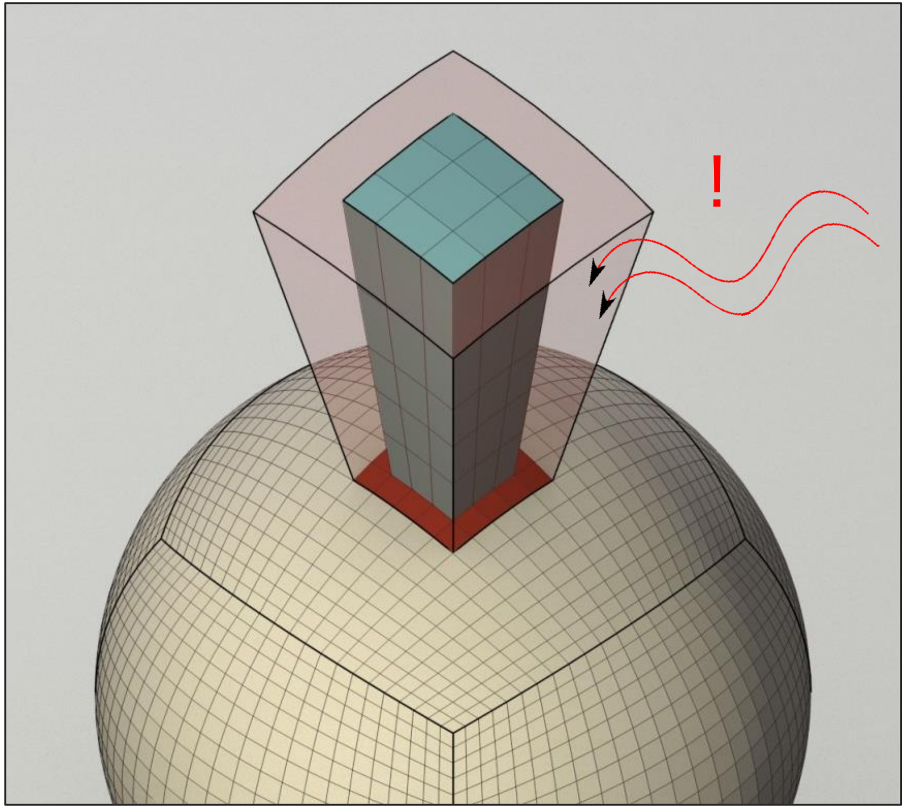
# Computational aspects

- Additional costs of indirect addressing for GungHo are offset by a column-based data layout, which improves **cache-reuse**.
- Physics schemes are typically column-based, but column-independence means that a row-based data layout can achieve good **vector throughput**.



# Computational aspects

- Additional costs of indirect addressing for GungHo are offset by a column-based data layout, which improves **cache-reuse**.
- Physics schemes are typically column-based, but column-independence means that a row-based data layout can achieve good **vector throughput**.
- Introducing fully 3-D physics will make it difficult to get either of these and **increase communication costs**!



# In summary

Physics-dynamics issues are multi-facetted, including

- Spatial couplings: conservation of information?
- Temporal couplings: balance and timestepping
- Maintaining physical properties: conservation, monotonicity…
- Computational science issues: task parallelism, load balancing, data layout, communication patterns…

There are many more…

# Questions