Higher resolution: reinventing the sphere and other elements of Model E

GISS lunch seminar series
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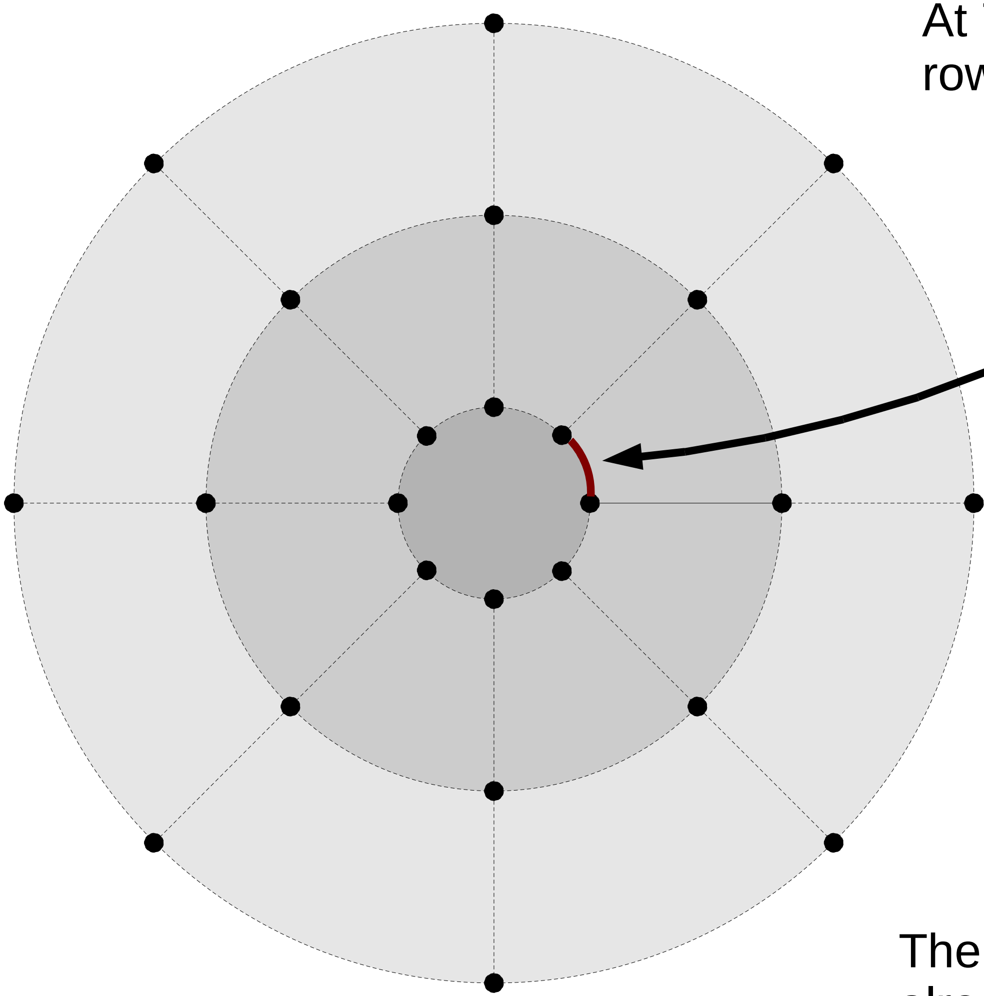
Maxwell Kelley
with massive assistance from
GSFC contributors

Model E at “high” resolution?

- Centered differencing is problematic
- Some parameterizations not designed for it
- Pole problems
- 1D parallelization does not scale very well
- Diagnostics: how to quantify the mechanisms by which resolution improves results

Pole problem #1



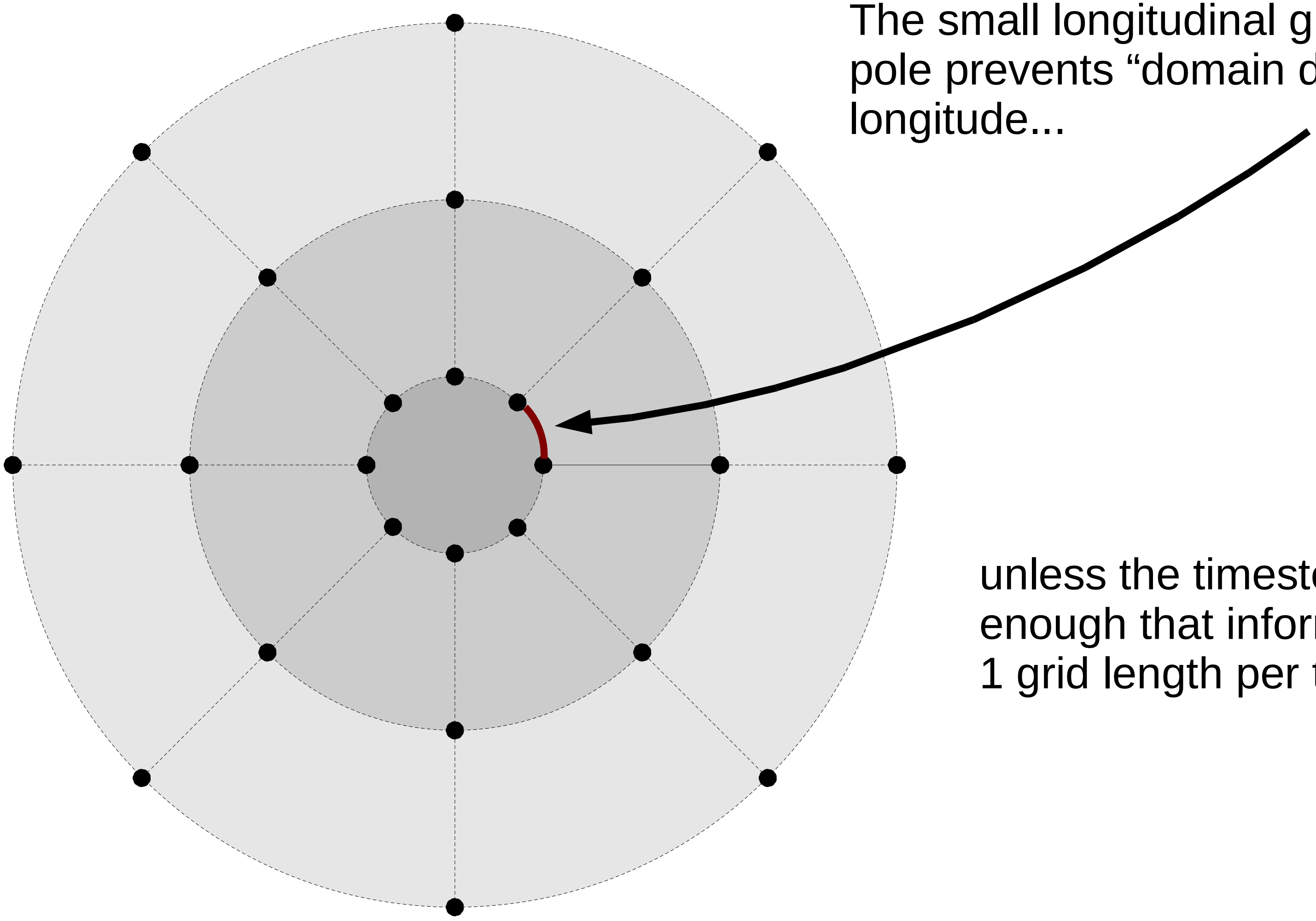
At 720x361 resolution, the polar velocity row has a longitudinal grid spacing of 240 m!

If using centered differencing, a 30 m/s flow across the pole would require a timestep of 8 s to ensure computational stability (courant number < 1).

Semi-lagrangian advection permits a much longer timestep.

The direction-splitting approach in the QUS already allows it to take a shorter timestep in the longitudinal direction when necessary.

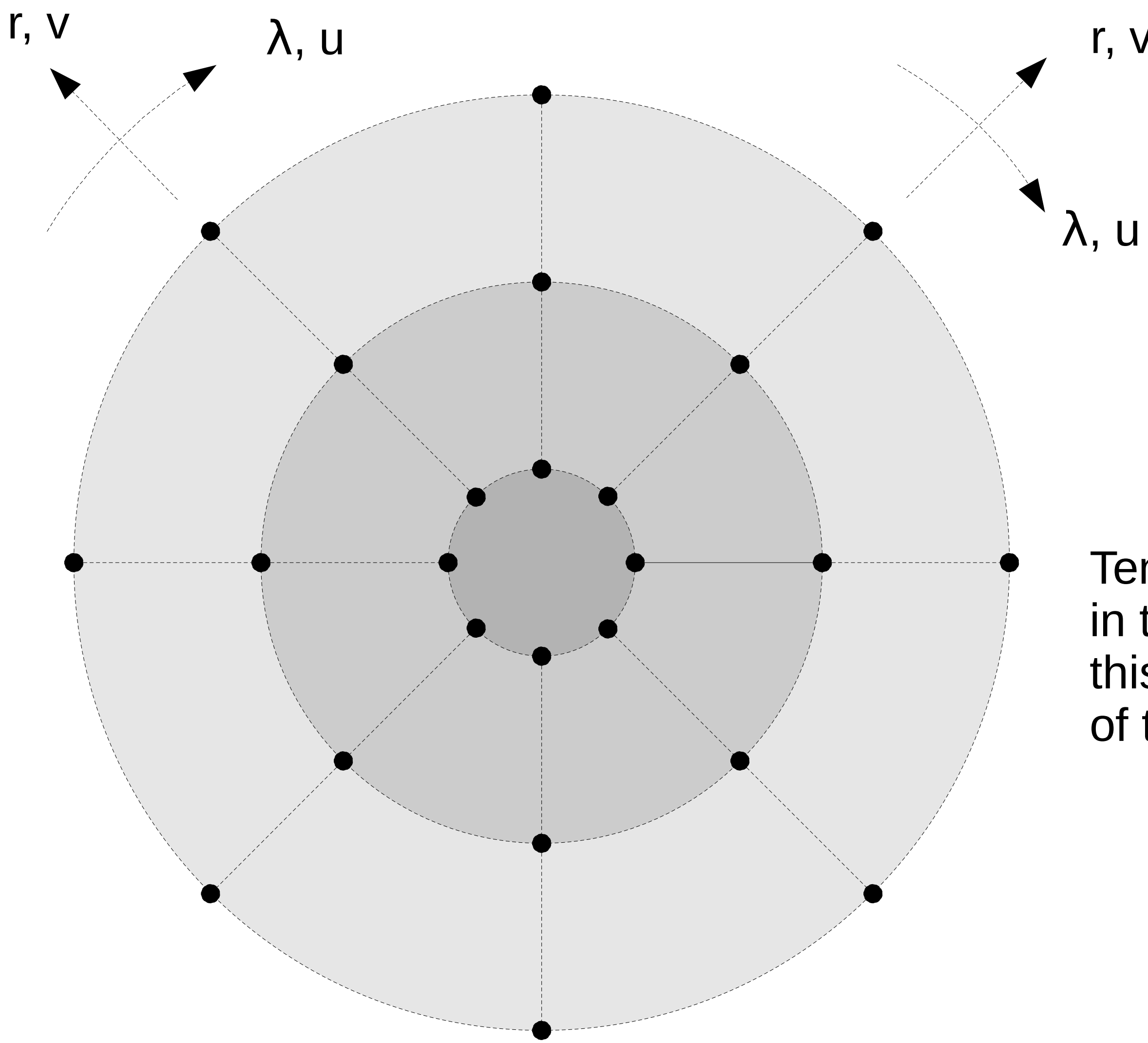
Pole problem #2



The small longitudinal grid spacing near the pole prevents “domain decomposition” over longitude...

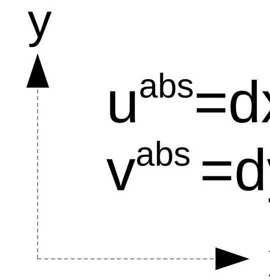
unless the timestep is chosen short enough that information only travels 1 grid length per timestep.

Pole problem #3



Near the pole, the definition of u and v as E-W and N-S velocities means that their net advective tendencies are the small residual of two large terms: advection in the lat-lon coordinate minus a “metric” term.

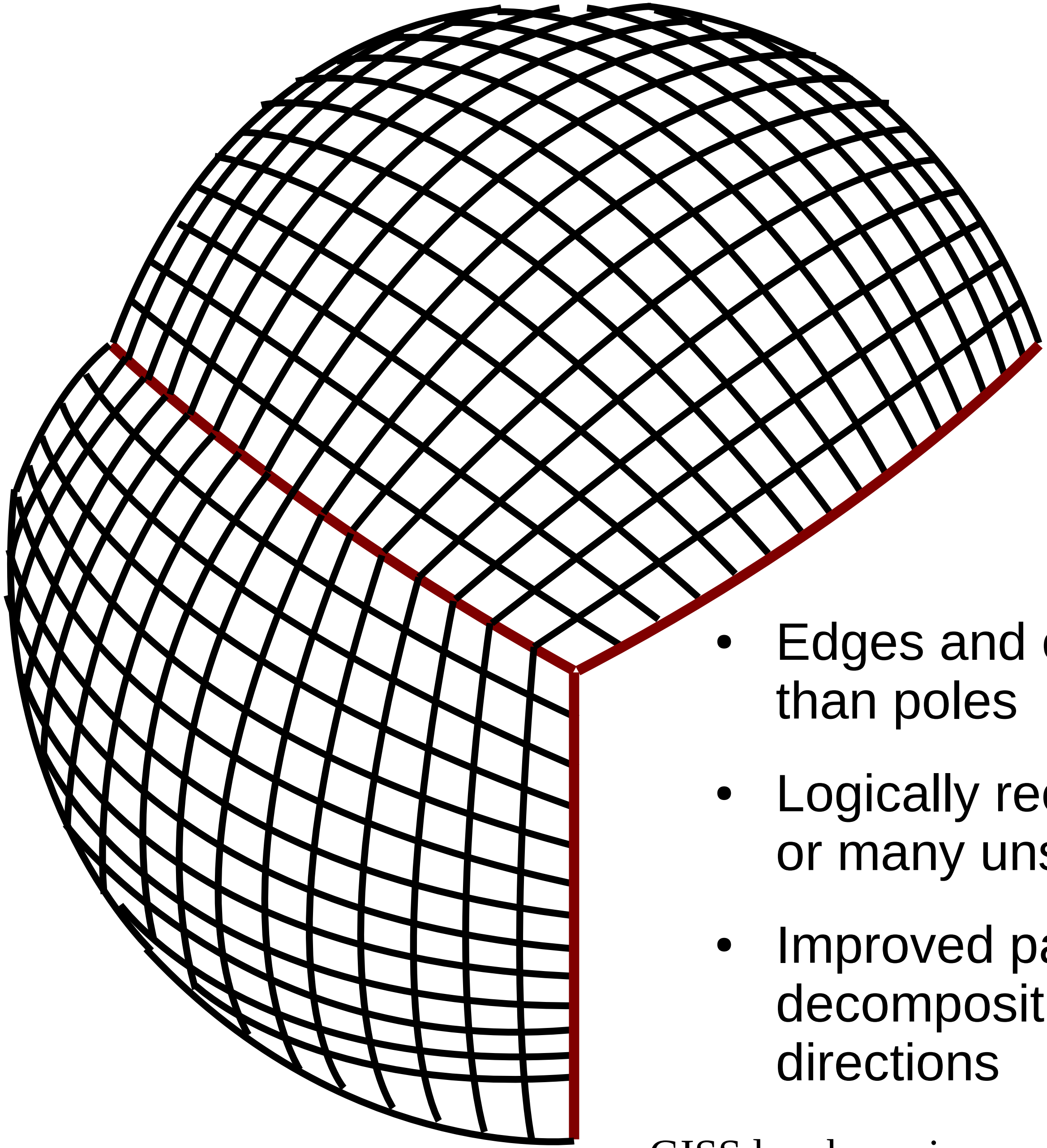
Temporary redefinition of u and v in terms of fixed unit vectors avoids this issue, and simplifies treatment of the polar cap.



$u^{abs}=dx/dt$

$v^{abs}=dy/dt$

Why use a cubed sphere grid?



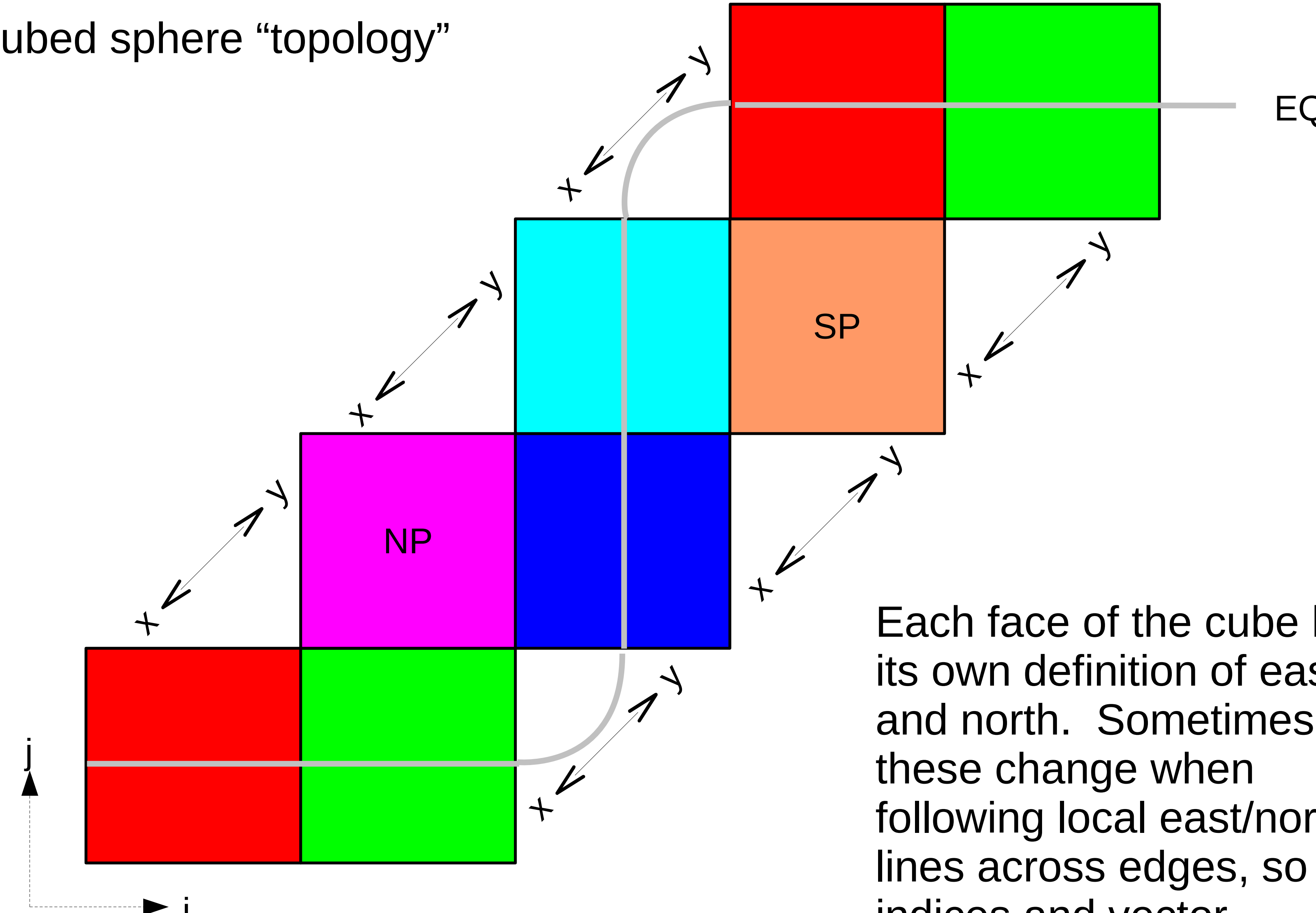
"Gnomonic" projection:

Gridlines are great circles

Mean nonorthogonality is 8°, maximum 30° at corners

- Edges and corners are less problematic than poles
- Logically rectangular, unlike icosahedral or many unstructured grids
- Improved parallel scalability with domain decomposition in both horizontal directions

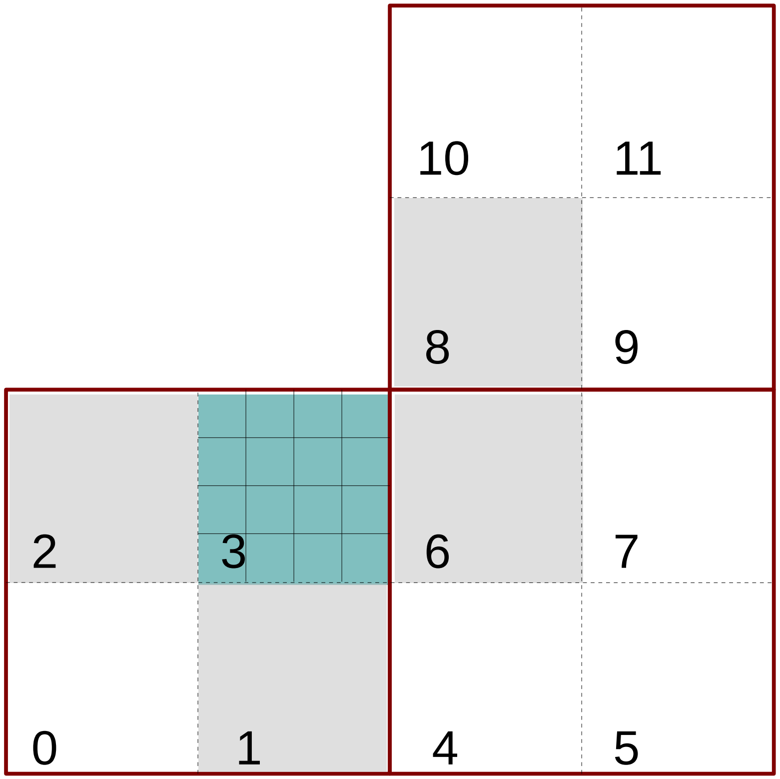
Cubed sphere "topology"



Each face of the cube has its own definition of east and north. Sometimes these change when following local east/north lines across edges, so x/y indices and vector components are swapped.

Cubed sphere domain decomposition

- Each face of the cube is divided in both horizontal directions
- `mpp_domains` module from GFDL keeps track of which processors exchange data and the changes of coordinate orientation across edges
- Improved parallel scalability with domain decomposition in both horizontal directions (for model E as well?)



Processor 3 exchanges data with processors 1, 2, 6, and 8.

Test of cubed sphere feasibility: adapting the GISS tracer advection scheme (QUS)

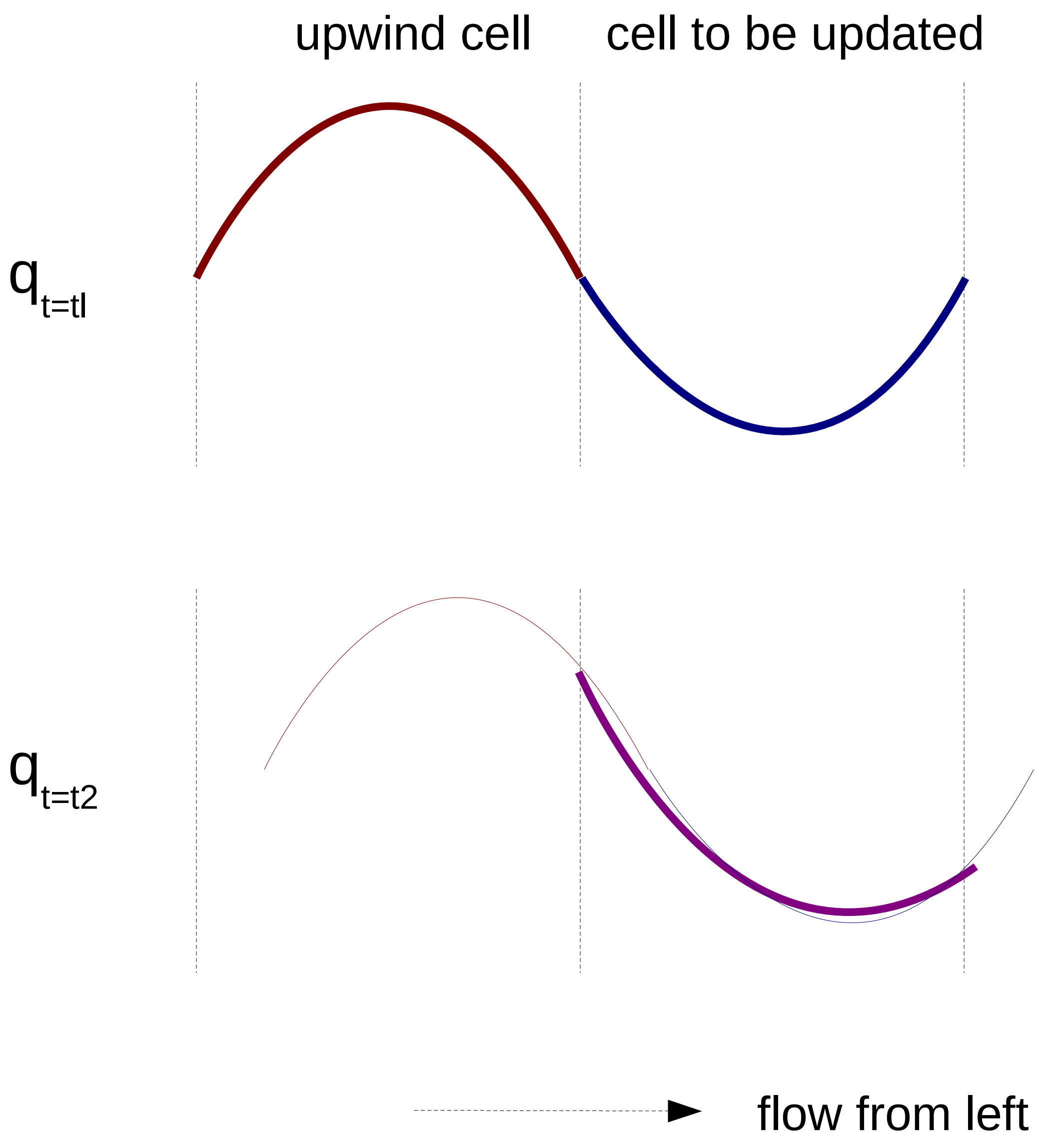
Test environment: GSFC FV dynamical core which provides geometry, wind fields, and grid conversion infrastructure

Challenges:

- QUS direction splitting more difficult near edges
- Adapting the 1D QUS operators at edges and corners
- `mpp_domains` module requires modification to handle QUS and other model E data structures

The QUS in pictures

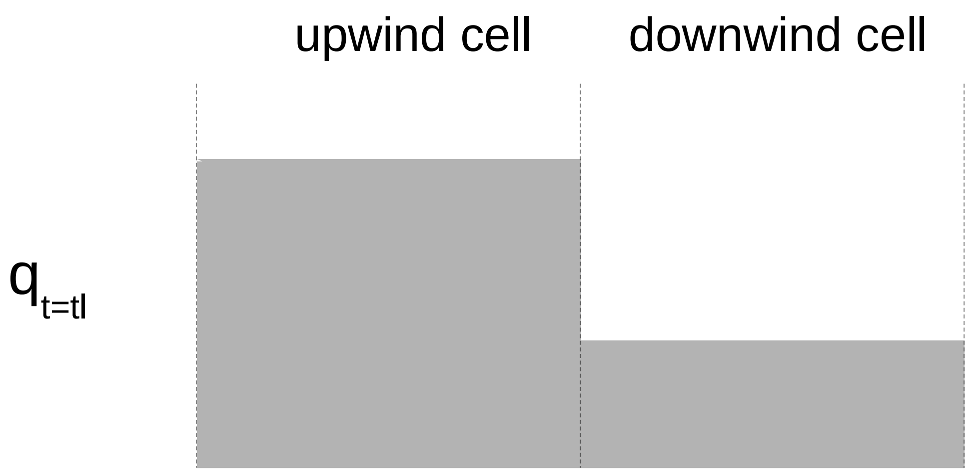
M. Prather, 1986



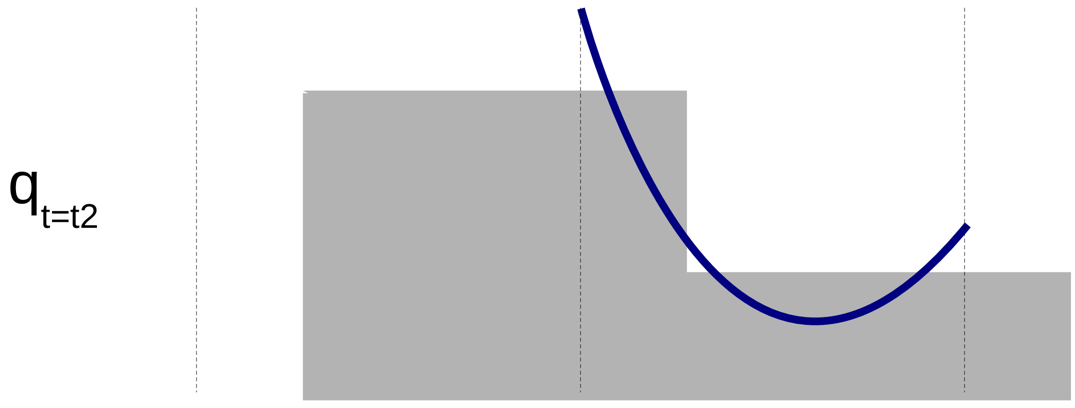
At t=t1, each cell has a parabolic profile determined by local prognostic variables (polynomial coefficients). No requirement of continuity at cell edges.

The purple curve is the new parabola at t=t2, determined as the least-squares fit to the combination of the red segment from the upwind cell and the blue segment from the local cell. Flux form conserves tracer mass.

The QUS in pictures



When there are large discontinuities at cell edges,



overshoots and undershoots are introduced by the fitting procedure. While their subsequent amplitudes do not grow indefinitely, flux limiters must be applied to prevent negative tracer concentrations. This adds some additional numerical diffusion.

The QUS in 3 dimensions, in words

Cell mean + coefficients of 9 orthogonal basis functions = 10 quantities to update each timestep:

$$c_x, c_{xx}, c_y, c_{yy}, c_z, c_{zz}, c_{xy}, c_{yz}, c_{zx}$$

Direction-splitting approach: X, Y, Z

Advance in the x direction, followed by the y and z directions.

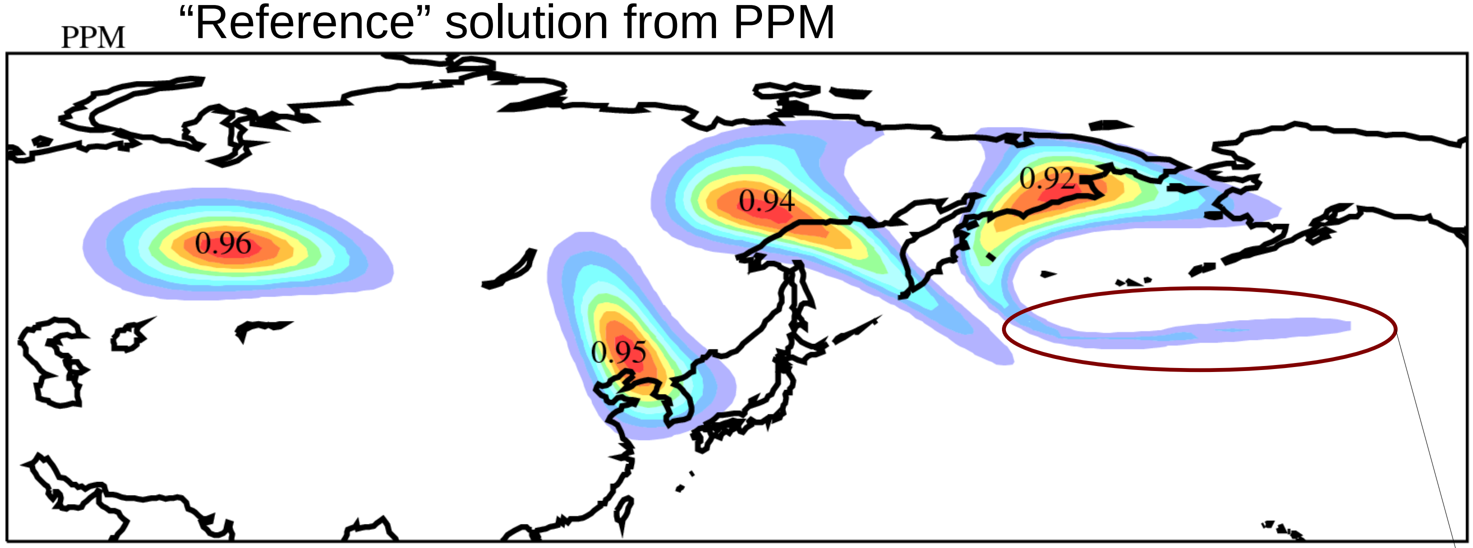
To advance in the x direction:

- Update cell mean, c_x, and c_{xx} using the original 1-dimensional parabolic fits.
- Jointly update c_y and c_{xy} by temporarily treating c_y as a “tracer” with c_{xy} as its subgrid variation. This is an application of the “linear” upstream scheme. Follow the same procedure for c_z and c_{zx} .
- Update c_{yy} and c_{zz} by computing their fluxes assuming no subgrid variations.

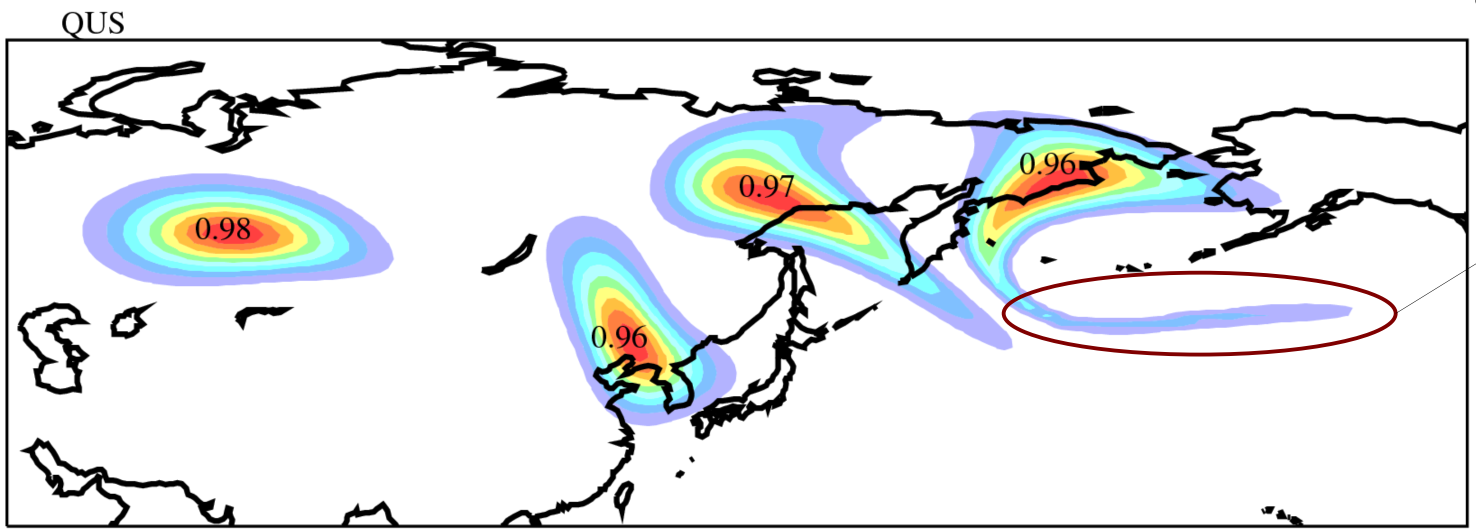
To advance in the y direction, follow the same procedure as for x, but permute the x and y coefficients. Likewise for z.

Mountain-induced Rossby wave: Tracer distributions at 3, 6, 9, 12 days

“Reference” solution from PPM

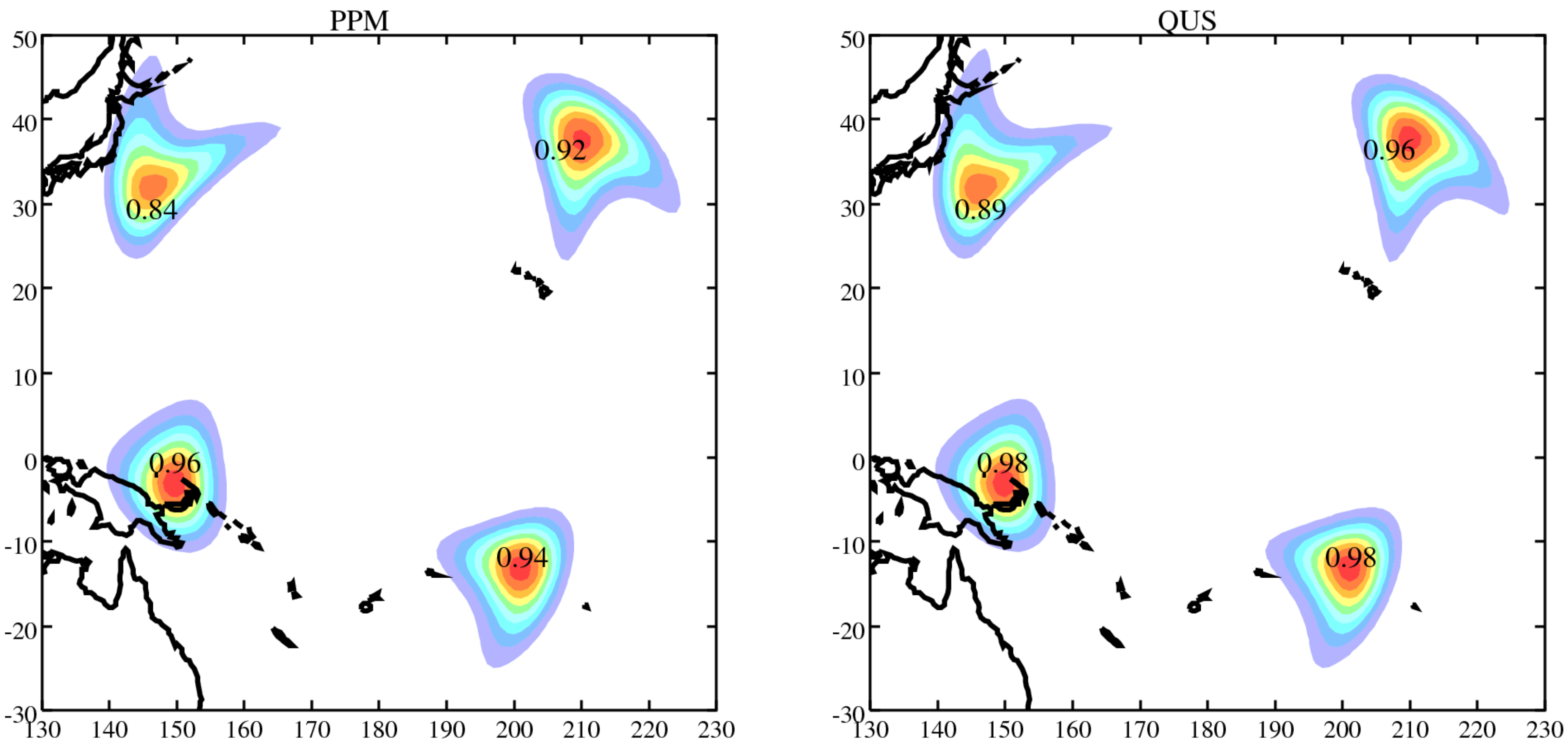


PPM has no prognostic subgrid information, so it is more diffusive than the QUS



10-20% differences in the tail grow with time

Tracer distributions at 3, 6, 9, 12 days



Rotation around a vortex centered at 15 N. Tracer maximum moves at the peak angular velocity.

Parallel scaling of QUS for C90L26 resolution, 5 tracers

# PEs	Efficiency*	Time (s)
24	1.00	73
54	0.95	34
96	0.89	21

→ Estimate of QUS time for C90L60 res. with 50 tracers is ~ 1 minute per day using 54 PEs

* calculated relative to 6 PE case

Diagnostics: quantifying effects of resolution

- Characterize small-scale features such as “atmospheric rivers”, chemistry occurring in tracer plumes, orographic effects, etc.
- Lagrangian in addition to Eulerian information, e.g. “computational” tracers.

$\rightarrow$ Need new software tools which facilitate adding new classes of diagnostics to model E