An Integrated Approach to Coupled Climate Modeling based on Geodesic Grids and Quasi-Lagrangian Vertical Coordinates

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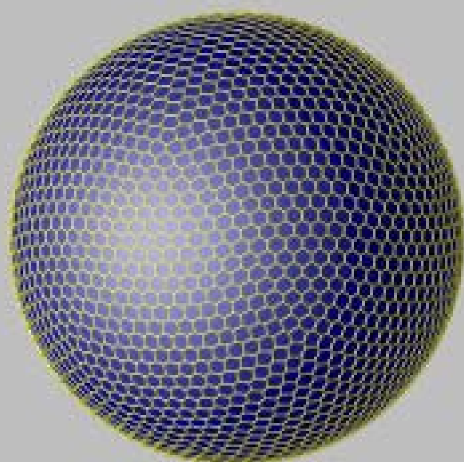
This is what we are trying to do:

“Construct an architecturally unified modeling framework based on geodesic grids and quasi-Lagrangian vertical coordinates that will allow for the creation of a comprehensive, conservative, accurate, portable, and highly scalable coupled climate model.”



This is a multi-institutional effort headed by David Randall from CSU

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John Baumgardner (ocean)
Bill Lipscomb (sea ice)
Phil Jones

Outline of this talk

Quasi-Lagrangian Vertical Coordinates
- why?
- the atmosphere model approach
- the ocean model approach

Tesselations of the sphere
- how do we generate them?
- what are there properties?
- a transport algorithm

The flux coupler
- tying it all together
- domain decomposition

Other fun stuff (time permitting)

Summary

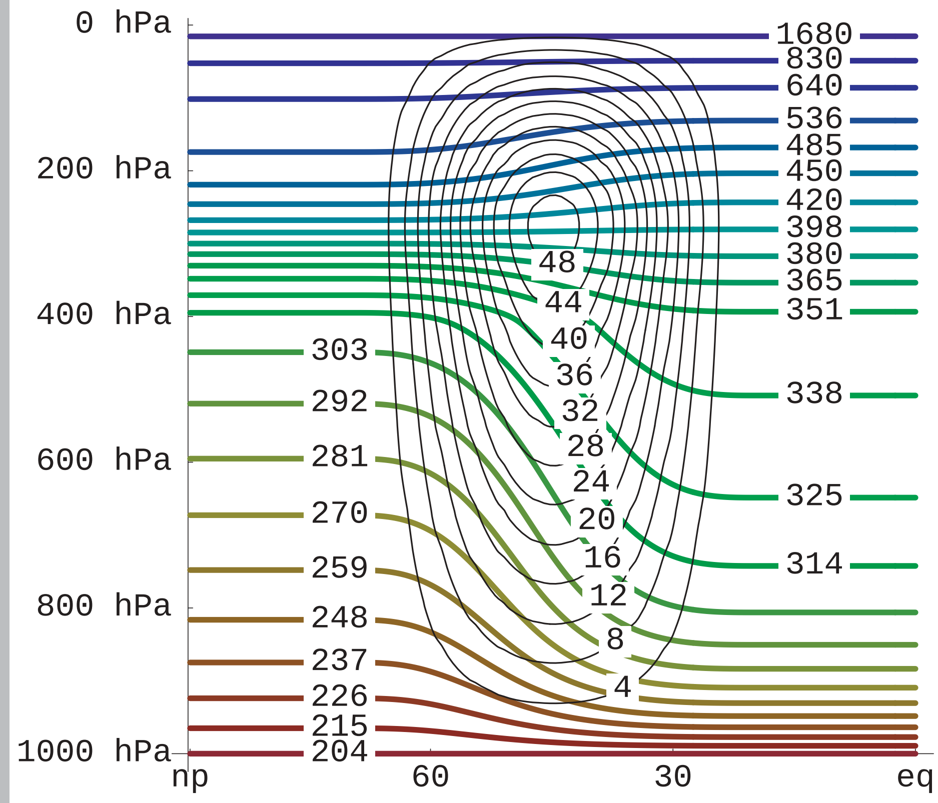
This talk is very much a summary discussion of the most important aspects of the project. If something here catches your eye, please stop by and I would be happy to discuss it further.

Why Quasi-Lagrangian Vertical Coordinates?

By construction, these coordinates recognize the importance of material surfaces.

Minimizes discretization error in vertical advection by minimizing the fluxing across surfaces.

The “quasi” part of quasi-Lagrangian recognizes that there are parts of the ocean and atmosphere where motion is not along material surfaces.



Atmospheric Model Approach
(Konor and Arakawa 1997)

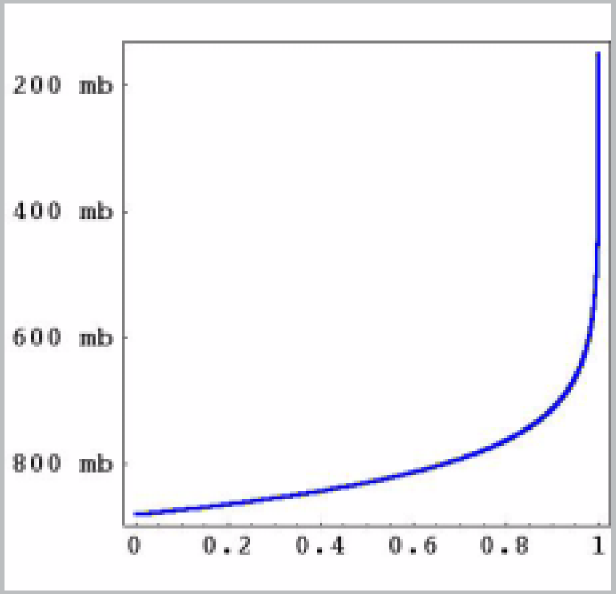
the vertical coordinate ζ is a generalized vertical coordinate

$$\zeta = f(\sigma) + g(\sigma)\theta$$

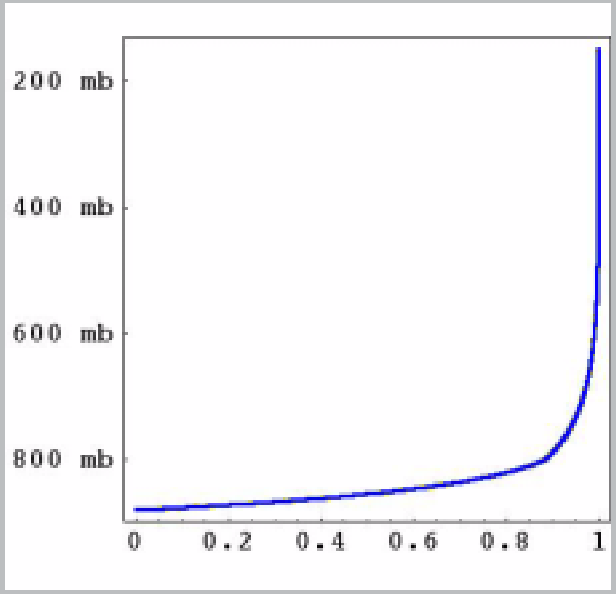
Depending on the functions f and g, the coordinate is “sigma-like” or “theta-like”

two prototypical $g(\sigma)$ profiles

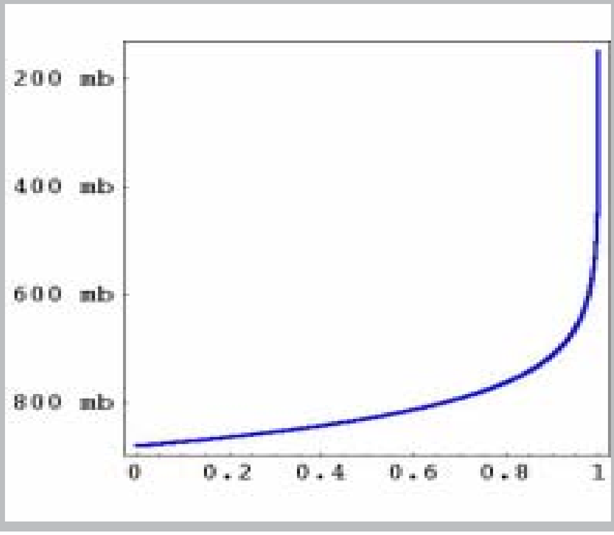
smooth transition to theta

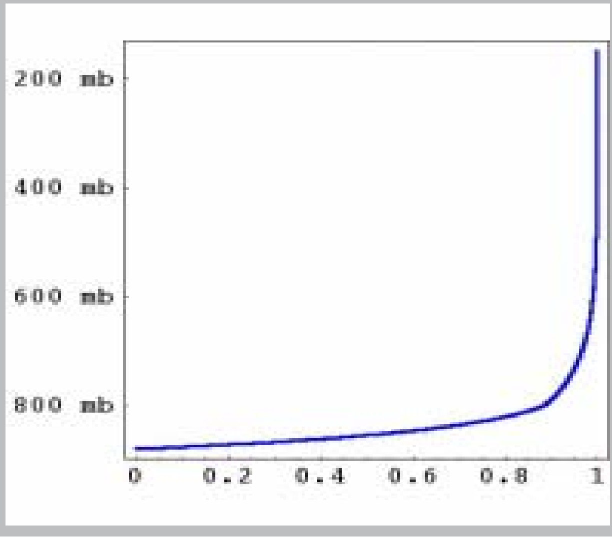


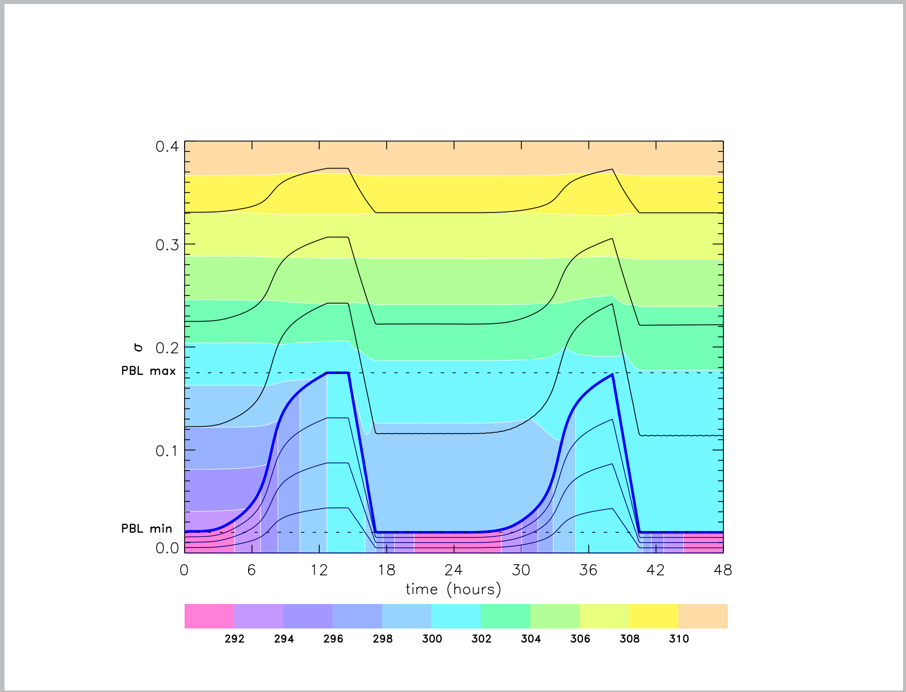
rapid transition to theta

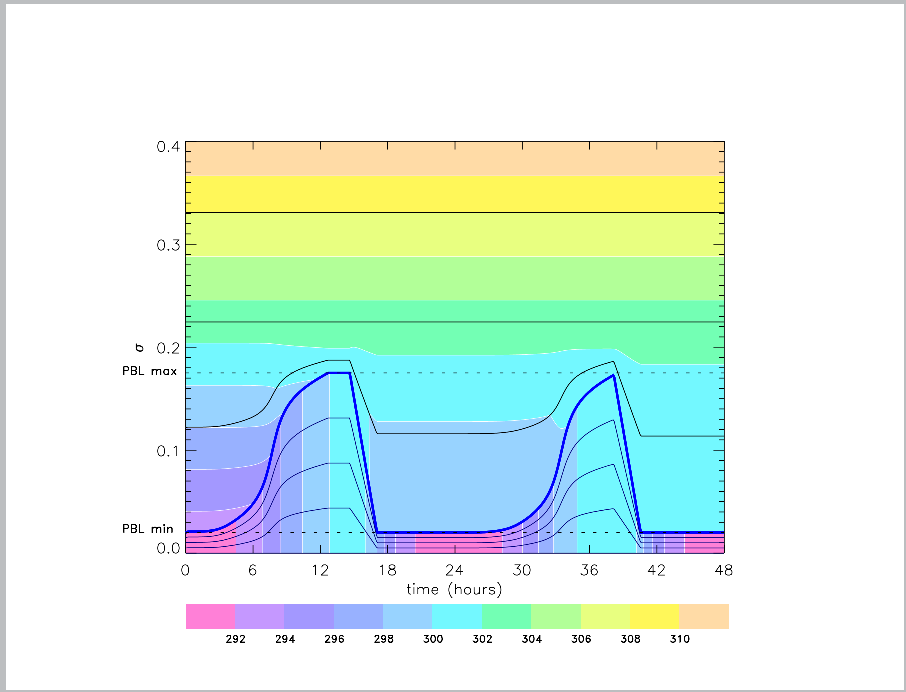


Impact of transition on coordinate surfaces









The atmosphere component implements quasi-Lagrangian coordinates by choosing a coordinate variable that transitions from pressure to theta.

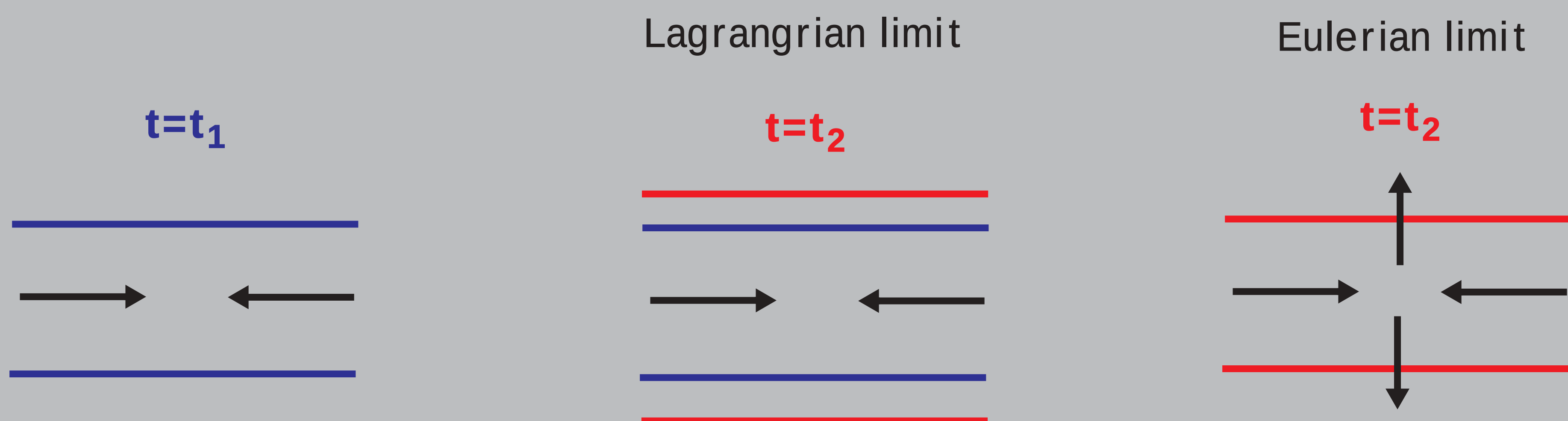
In contrast, the ocean component implements quasi-Lagrangian coordinates a less formal, but more flexible, manner.

Arbitrary Lagrangian-Eulerian Methods

a framework for modeling vertical advection

Main Features:

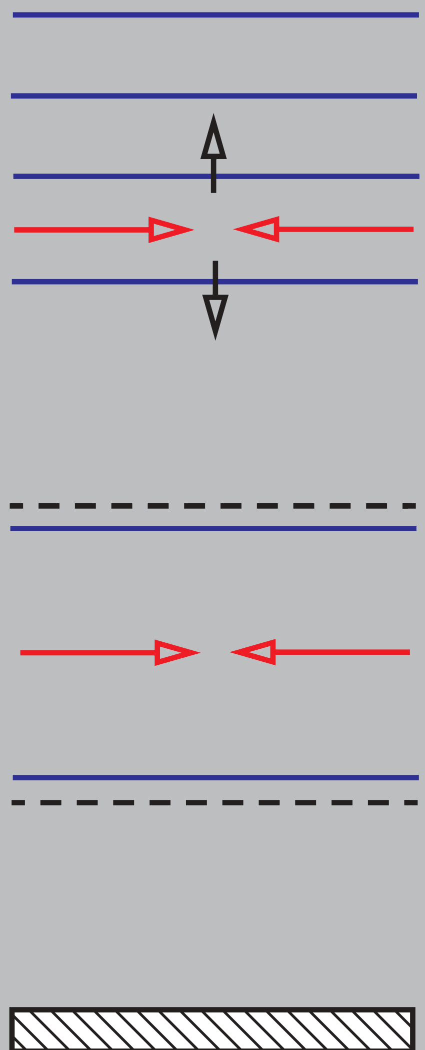
Allows nearly isopycnal treatment of deep ocean (Lagrangian)
Allows high resolution time-dependent treatment of mixed layer (Eulerian)
The treatment is adaptive in both time and space.
The fully-Lagrangian and fully-Eulerian reference frames are “built-in”



Remapping: the crux of ALE methods

when do we do it? how do we do it?

ALE



In the mixed-layer region vertical fluxes are relatively large and are used to maintain constant layer thickness.

At depth, vertical fluxes are relative small (mostly zero) and are used only to keep the layer thickness inside prescribed bounds.

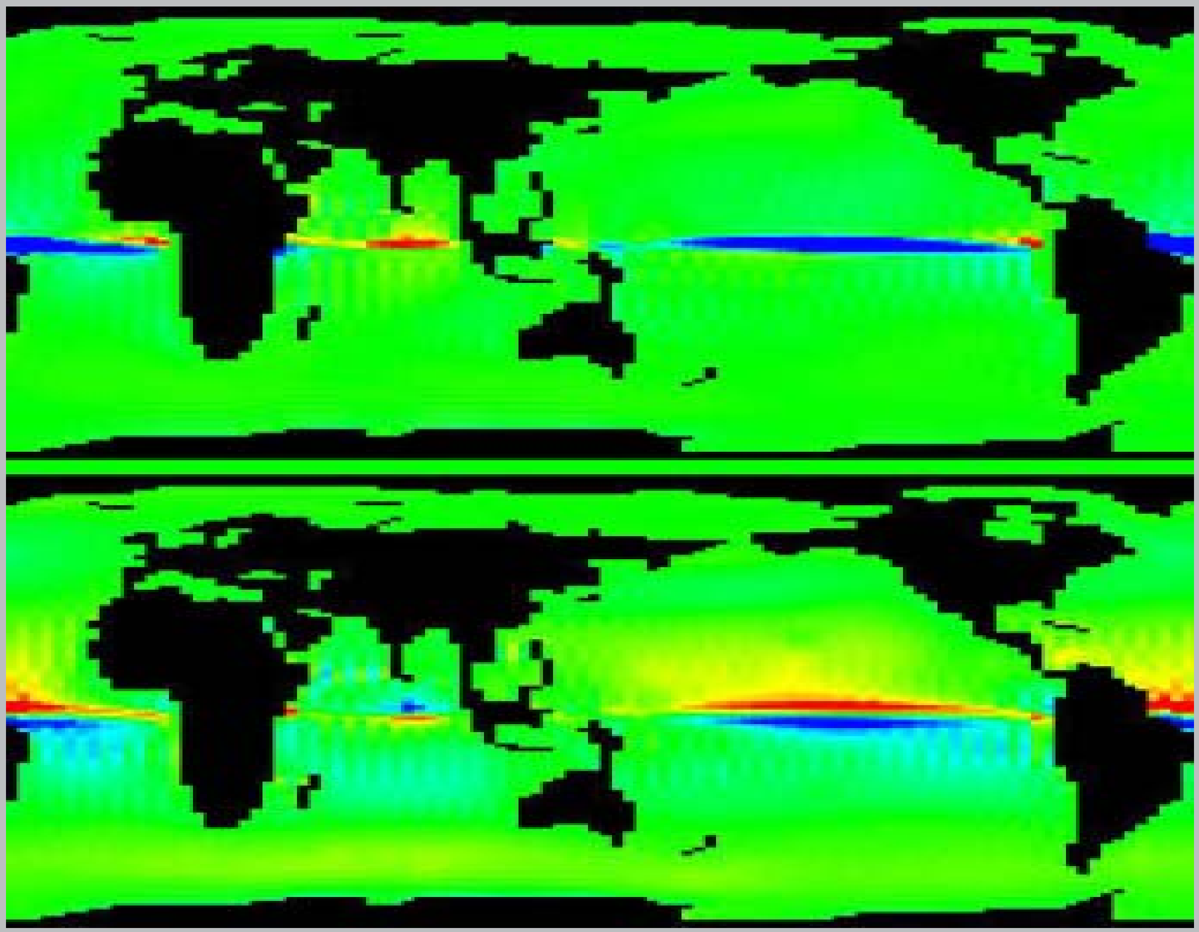
Over some period of time, the system is integrated forward in the Lagrangian reference frame.

Before the mesh becomes “tangled,” the conserved quantities are fit with cubic splines. The continuous functions are then evaluated at the nodes of the new mesh.

By remapping the conserved quantities directly and by enforcing the zero-flux boundary condition at the upper and lower boundary, conservation is guaranteed.

Vertical Coordinate Results

(quad HYPOP, real wind forcing, real topography)



east velocity

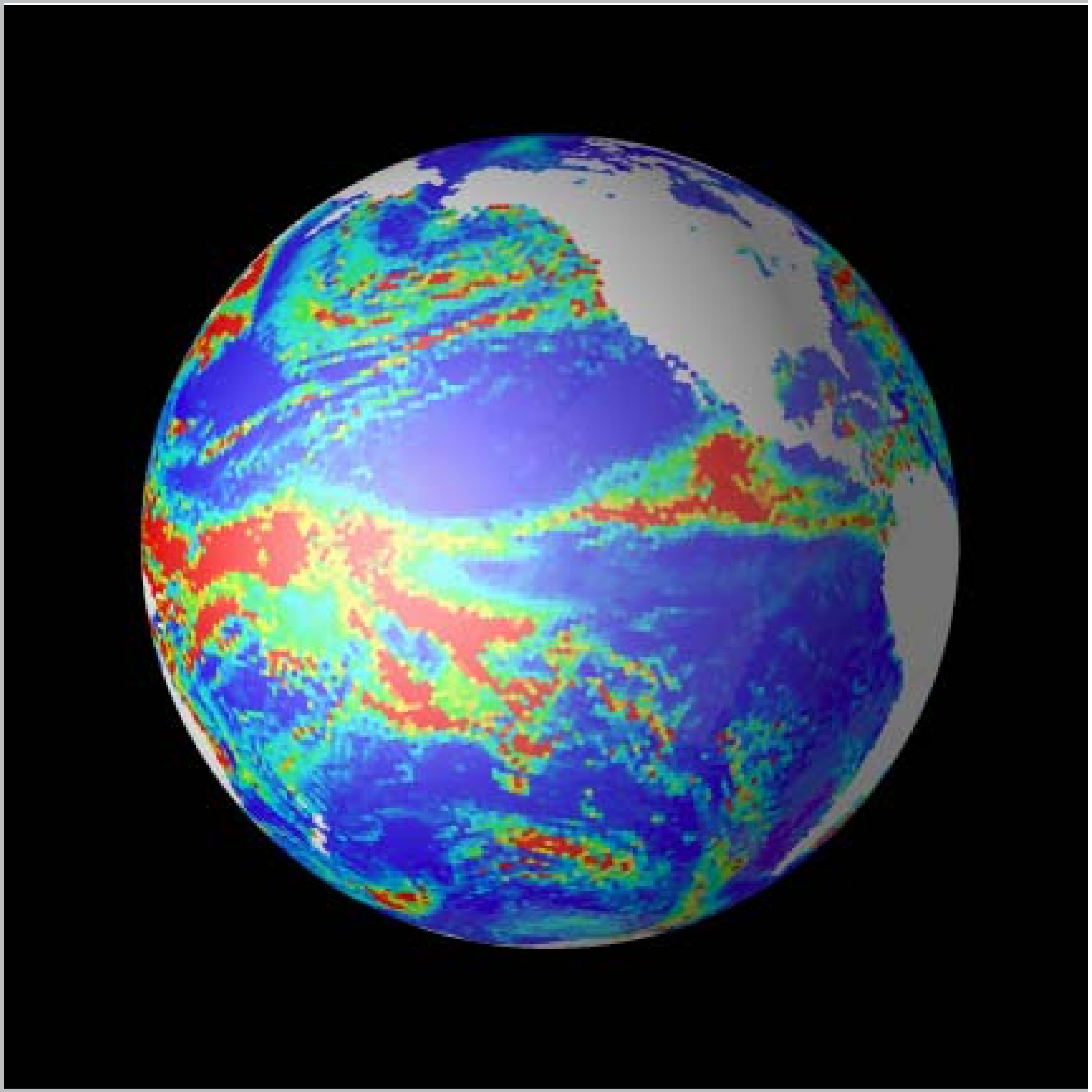
north velocity

Why Geodesic Grids?

Quasi-uniform: no problematic grid singularities

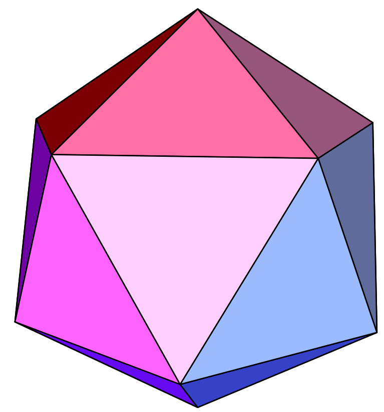
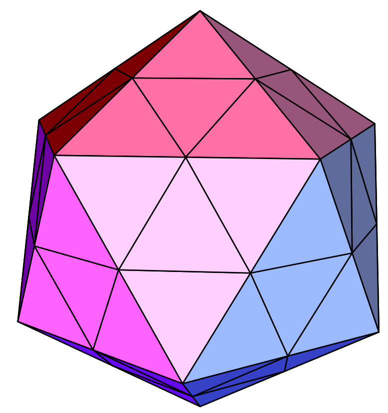
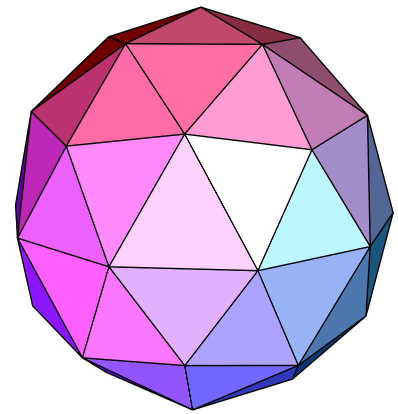
Highly isotropic: all neighbors "live" across cell walls

Equally applicable to all model components: atmosphere, ocean, land-surface, and sea-ice.



Spherical Voronoi Tesselations (SVTs) derived from an inscribed icosahedron

Each vertex will be a grid point (Voronoi region generator)

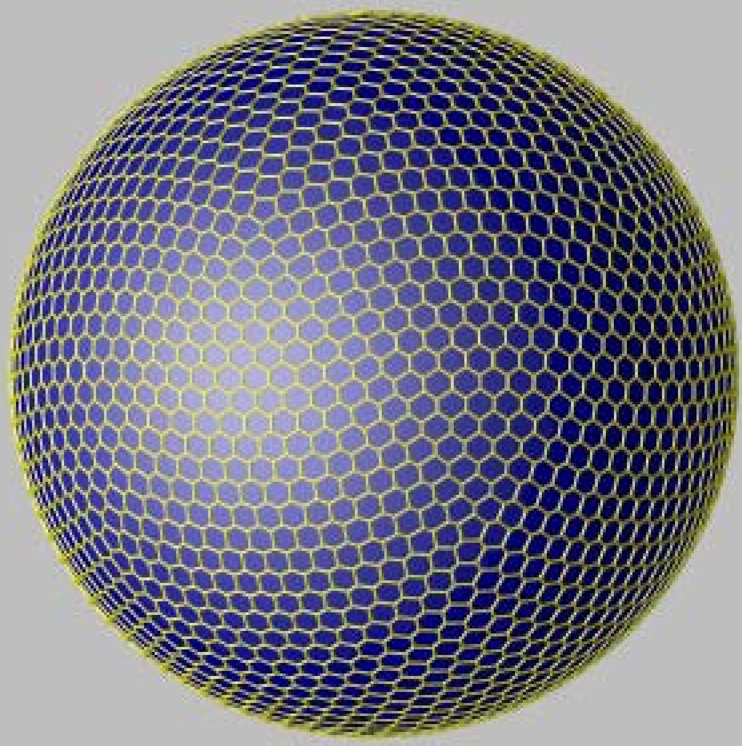
Icosahedron	Bisect each edge and connect	Project new vertices to the sphere
		

The "unmodified SVT"

Grid Properties

Each Voronoi region is hexagonal in shape, except for twelve regions that are pentagonal. These twelve regions correspond to the vertices of the original icosahedron.

Highly-uniform in horizontal coverage
Highly-uniform in refinement
Highly isotropic
No problematic grid singularity



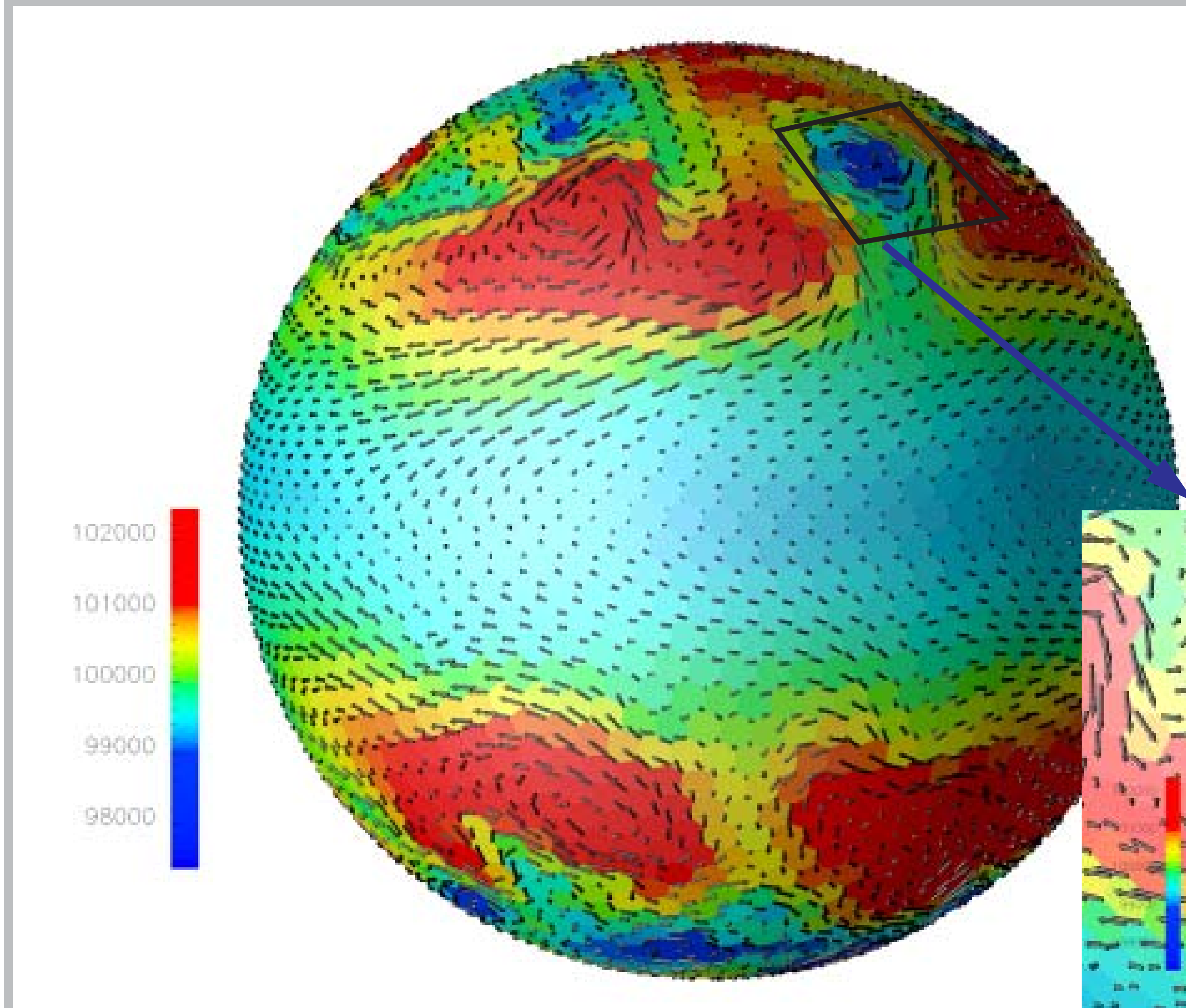
Properties of the Unmodified SVT

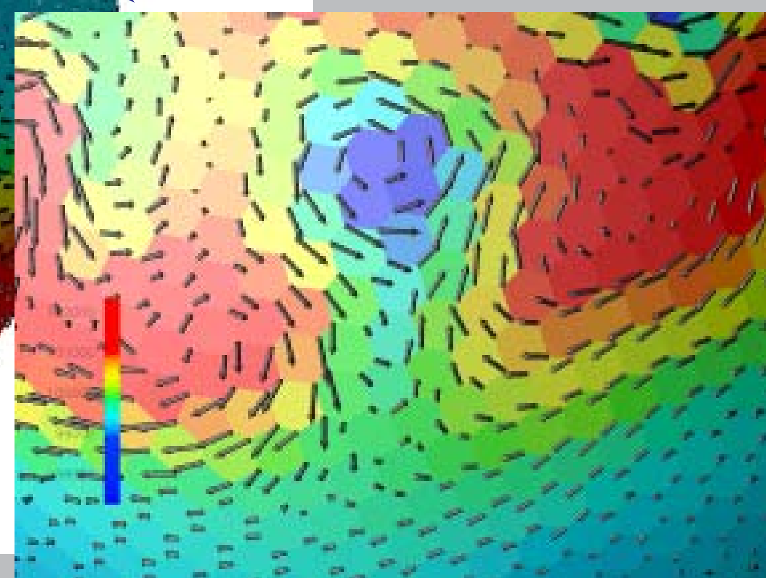
glevel	Number of generators	GlobalU	Avg(LocalU)
1	42	0.88	0.92
2	162	0.85	0.88
3	642	0.84	0.87
4	2562	0.84	0.88
5	10242	0.84	0.89
6	40962	0.84	0.89
7	163842	0.84	0.89
8	655362	0.84	0.89

The grid is extremely uniform at the global scale.
The grid is not much more uniform at the grid scale.

Held-Suarez Test Case/Momentum Formulation

a snapshot of surface pressure and velocity, μ = 1e14





The AGCM is using a numerical scheme that conserves mass, tracer mass, energy, potential enstrophy, and a host of other quantities.

The Sea-Ice Component

a testbed for tracer compatibility algorithms

$$\frac{\partial a}{\partial t} + \nabla \bullet (aU) = 0;$$ a = fractional ice area

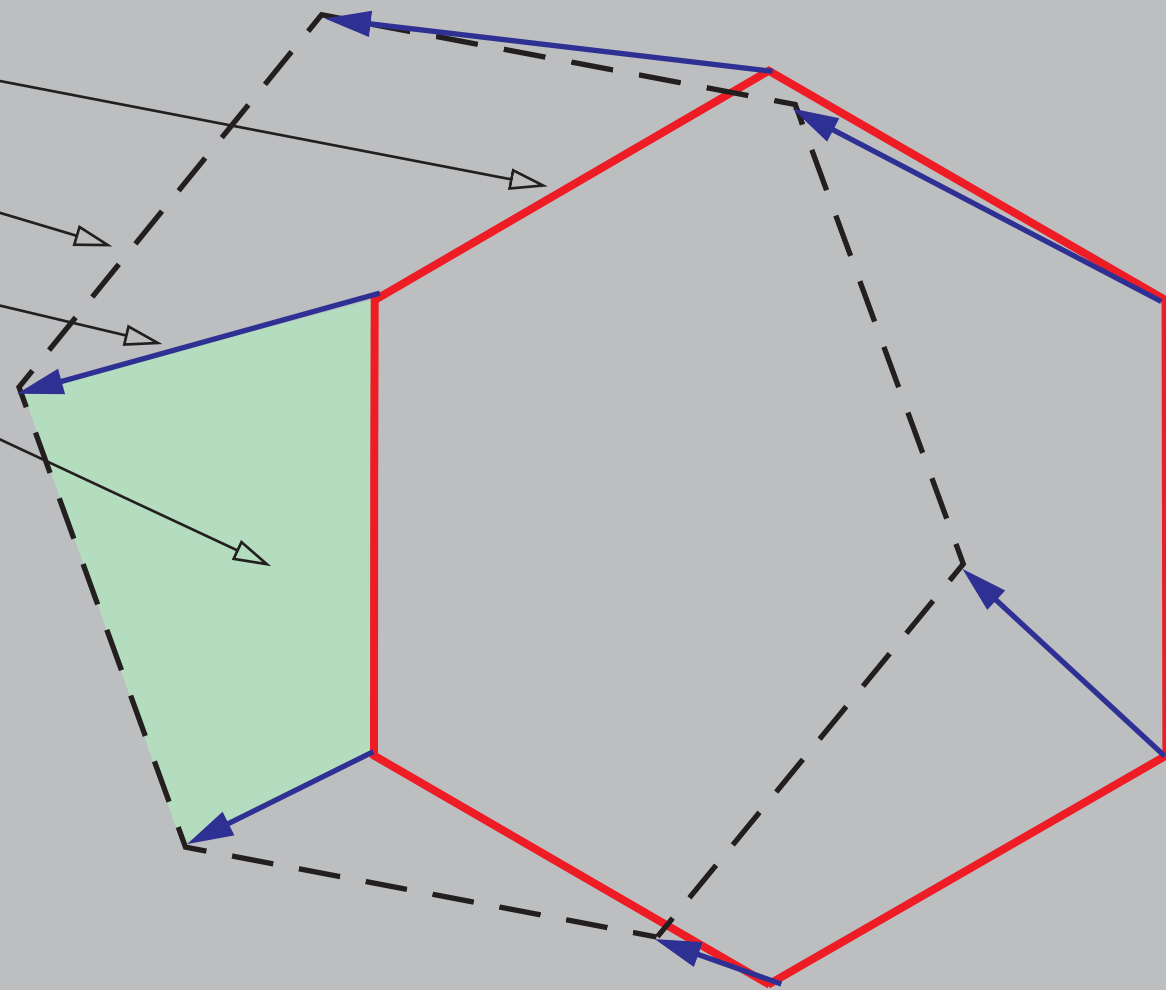
$$\frac{\partial}{\partial t}(ah) + \nabla \bullet (ahU) = 0;$$ h = ice thickness

$$\frac{\partial}{\partial t}(ahq) + \nabla \bullet (ahqU) = 0;$$ q = latent energy per unit volume

It is critical that these coupled prognostic equations are handled in a consistent and compatible manner. Failure to do so can lead to h and q having unrealistic values even though (ah) and (ahq) are conserved.

Incremental remapping

(Dukowicz and Baumgardner, JCP 2000)

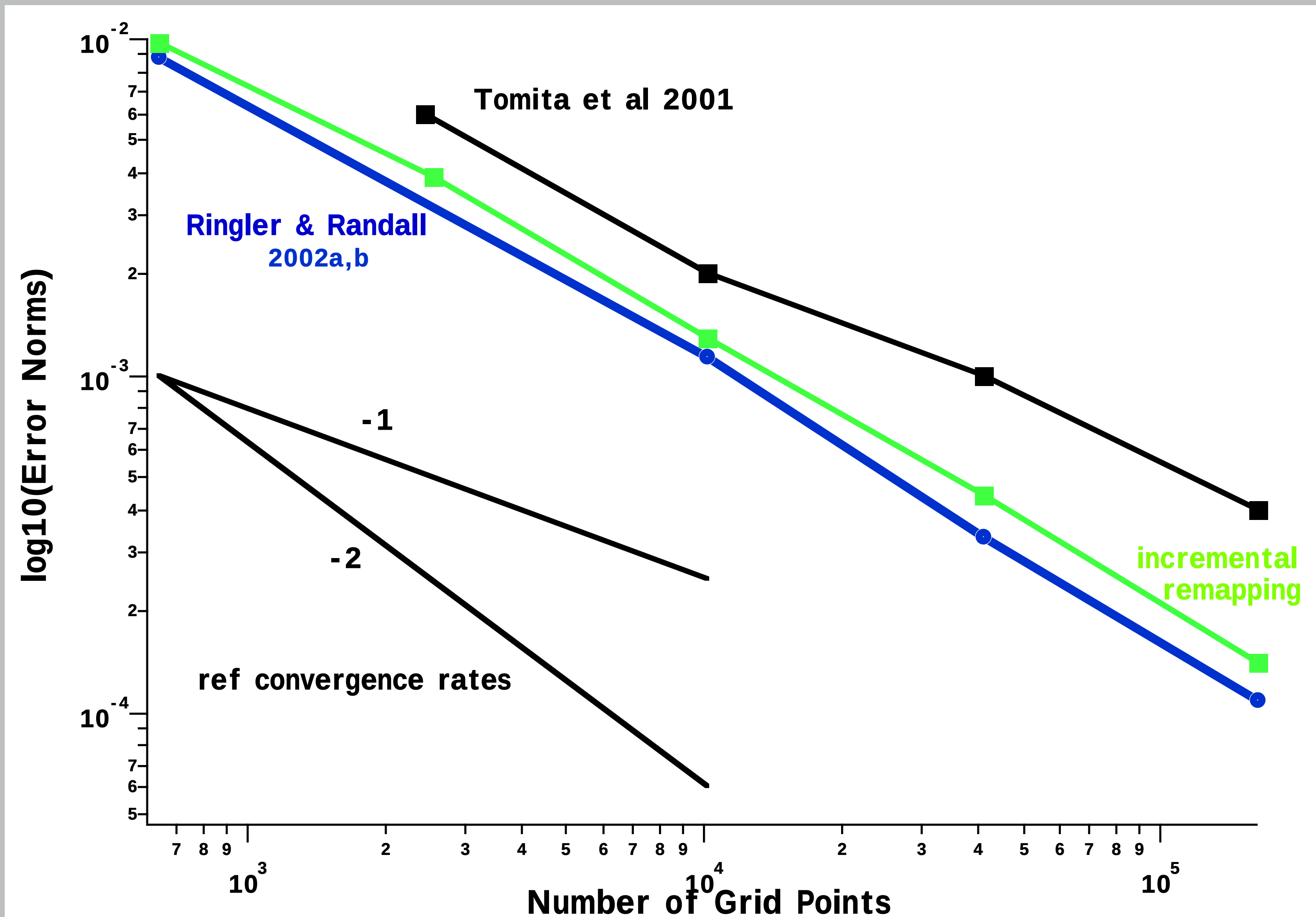


Knowing the velocity at the corners allows for a truly multi-dimensional advection scheme.

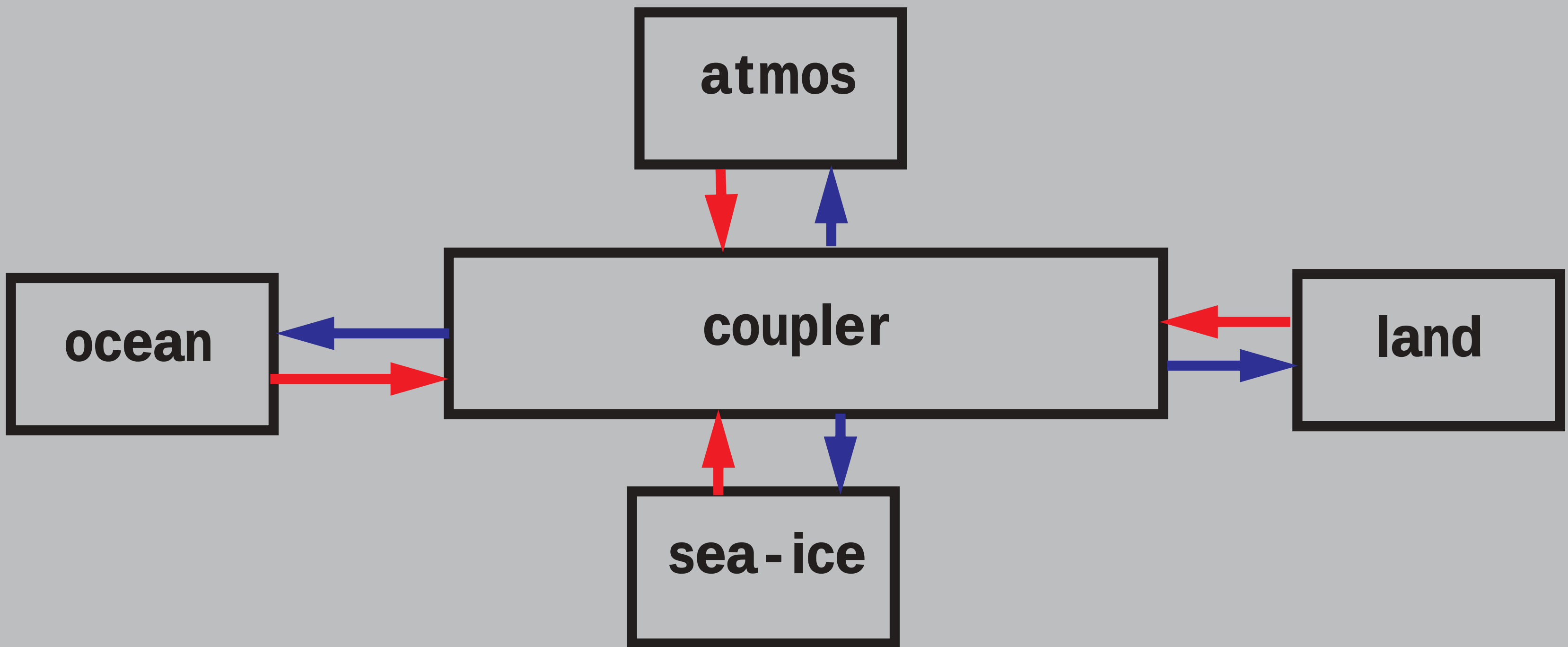
This scheme is based on the backward Lagrangian derivative written in flux form, so it is in the family of conservative semi-Lagrangrian advection schemes.

Convergence Rate of Mass Field

(Shallow Water Test Case #5)



So we have all of these model components...
how do we build a coupled climate system model?



The purpose of the coupler is to provide the ability (and the software) to allow the model components interact in physically realistic ways.

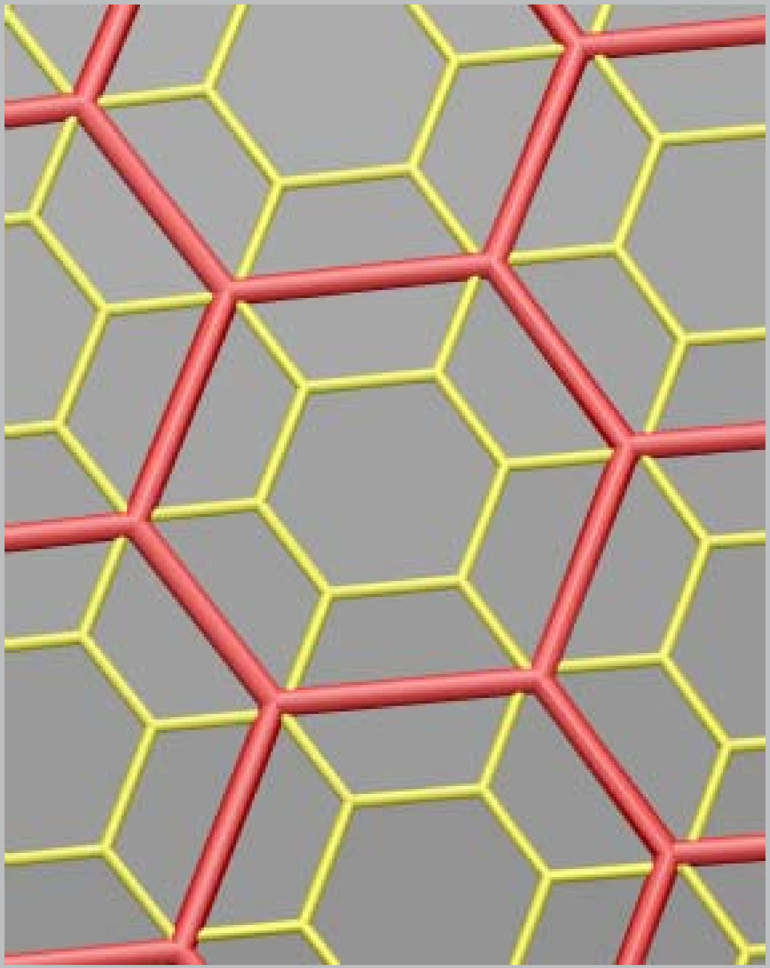
The Flux-Coupler Component

The flux-coupler is not an after-thought. Overall model performance is strongly dependent upon flux-coupler performance.

Sub-models must communicate, possibly at a high temporal frequency.

The high level of conformity between geodesic grids of different resolutions leads to balanced loading and communication.

For MPP architectures, balanced loading and communication is a must.



Domain Decomposition

The spherical geodesic grid is decomposed into square sub-domains

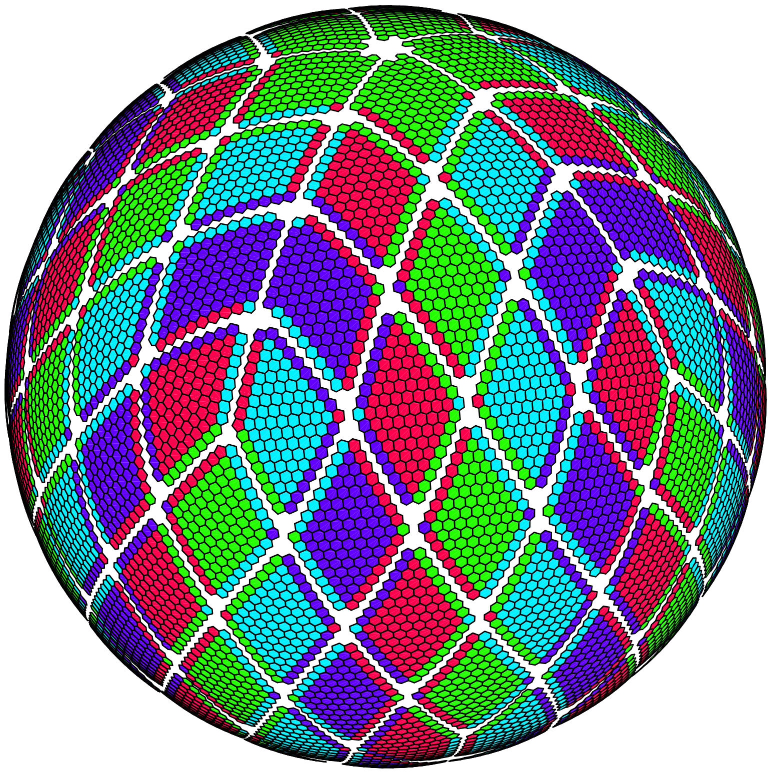
A processor owns an arbitrary number of these sub-domains

Message passing between processors

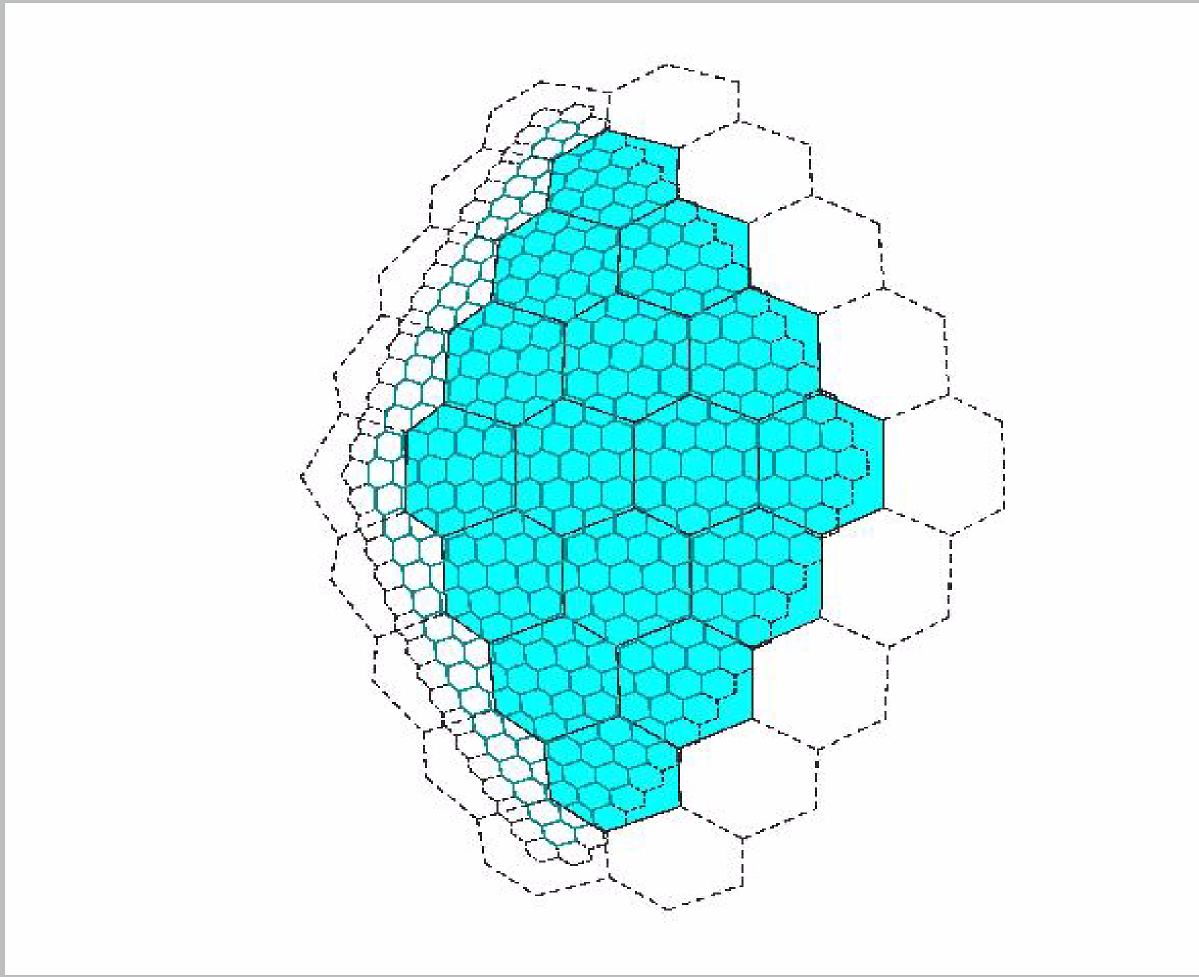
OpenMP within a processor

Algorithm updates “ghost cells” via MPI or shared-memory copy

Multiple layer data sent in single message



Corresponding Atmosphere-Surface Subdomains



The atmosphere and surface grids will, in general, be of different resolution. Furthermore, the domain decomposition may be different. The coupler is able to gather data on different grids owned by different components running on different processors. This allows for an efficient and local remapping between grids.

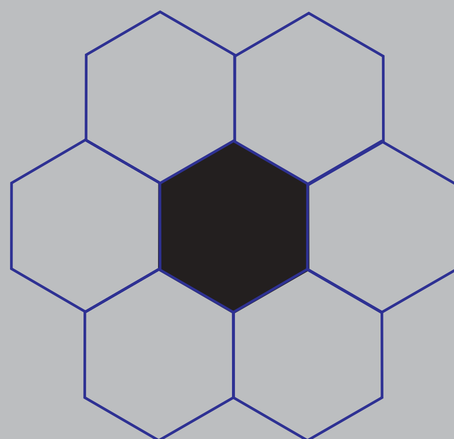
It is not all work....sometimes we get to solve something fun. For instance, how can we do a “spectral transform” directly from our Voronoi grid?

We can solve the eigenvalue problem

$$\nabla^2 f = \lambda f$$

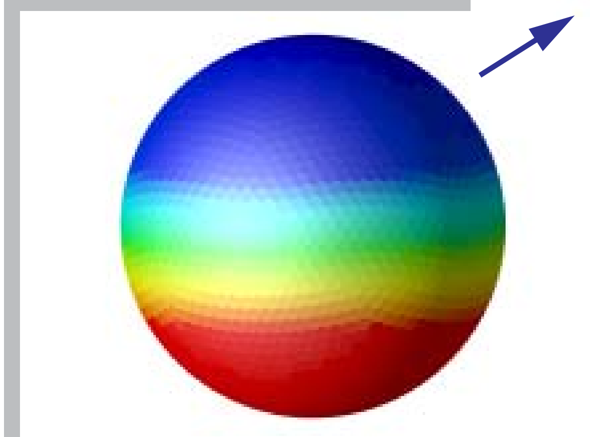
where ∇^2 **is the discrete Laplacian.**

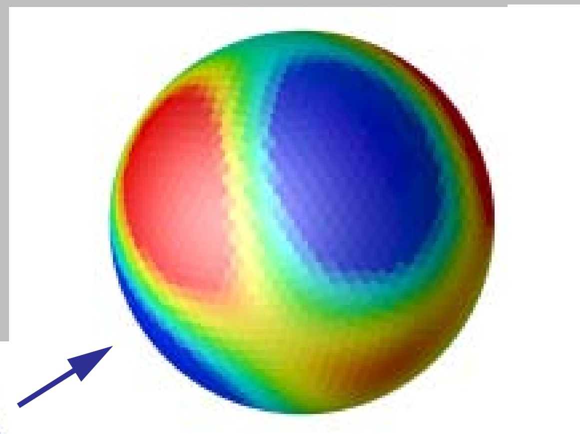
$$L(f_0) = \frac{f_1 + f_2 + f_3 + f_4 + f_5 + f_6 - 6f_0}{\sqrt{3}A_0}$$

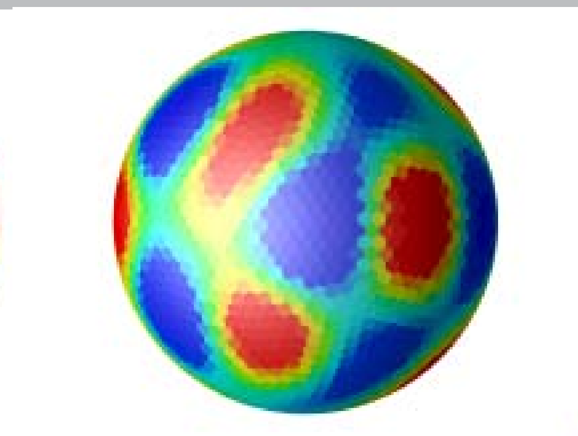


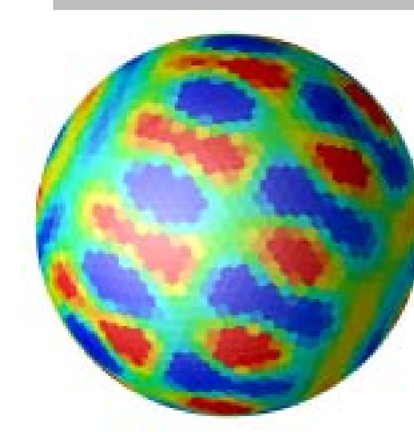
A “spectral” transform directly from the geodesic grid

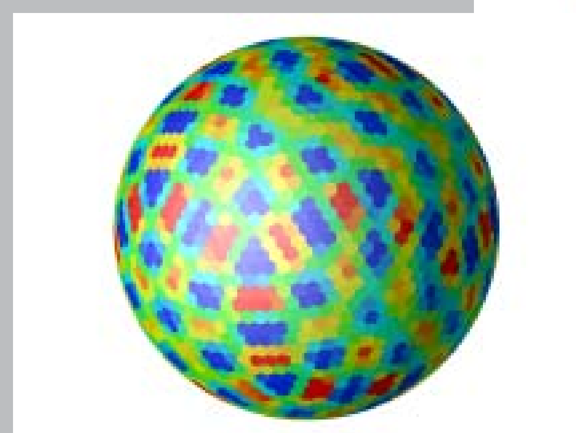
We solve the eigenvalue problem $\nabla^2 f = \lambda f$.





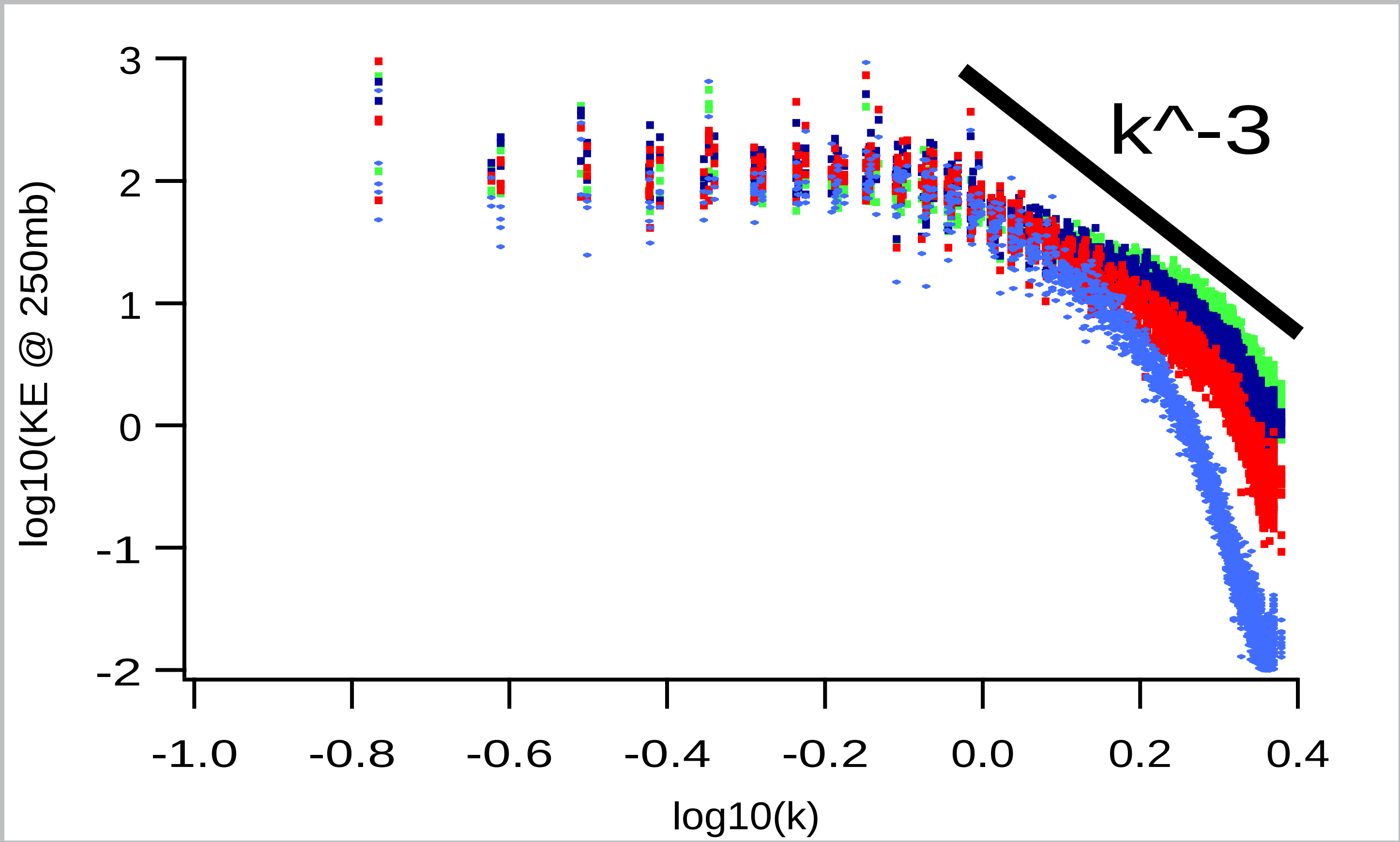






The eigenvectors form a complete and orthogonal basis.

Held-Suarez Test Case/Momentum Formulation
Spectra of Kinetic Energy per unit mass at 250mb
four values of μ: 1e12, 1e13, 1e14, 1e15 m4/s



Summary

We have embarked on an ambitious project to design, develop, and implement a suite of numerical algorithms that encapsulate a set of basic ideas.

1) The use of quasi-Lagrangian vertical coordinates will lead to more accurate simulations since vertical advection is minimized and horizontal advection is along material surfaces.

2) The use of a quasi-uniform horizontal grid can naturally lead to conservative numerical schemes without “problem points.”

3) This quasi-uniform grid is applicable to all model components, therefore the entire coupled system model can to be developed on the same data structures using the same software.

.....please feel free to stop by to talk, Room 046.