Challenges in Coupled Climate Model Development

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May 16, 2005

My last talk here was ....

Adventures with Geodesic Grids

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Colorado State University

Los Alamos National Laboratory
October 24, 2001

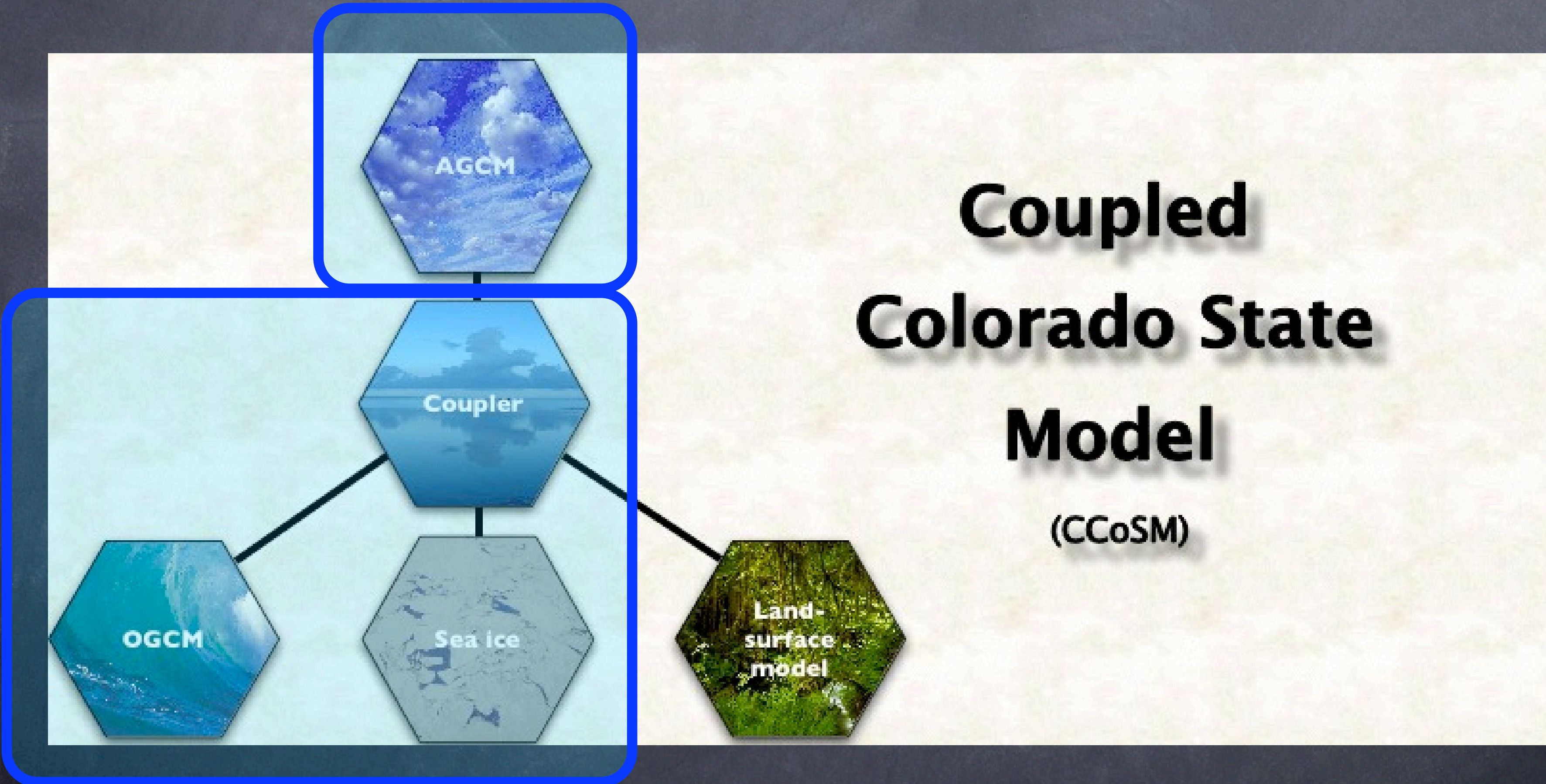
At four years into a five year project, adventures turn into challenges.

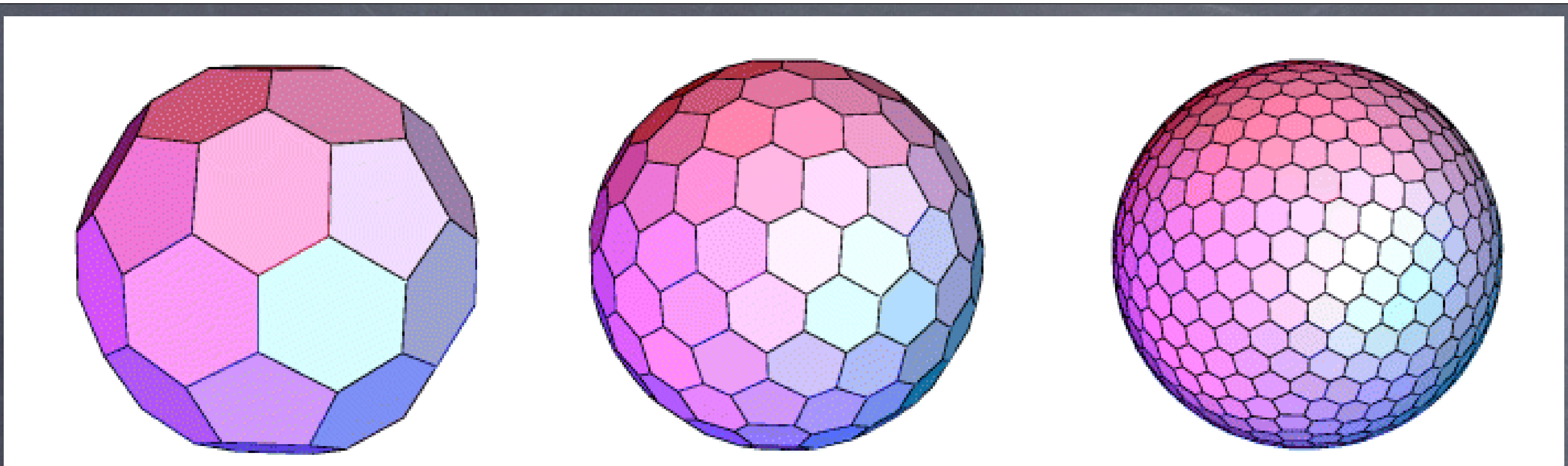
So what exactly are we trying to do here?

Mission Statement:

"To 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."

Somewhere along the line, our model was named CCoSM. Not be confused with COSIM, but the two do share personnel, ideas, and code.





A bit of history regarding the grids we use here:

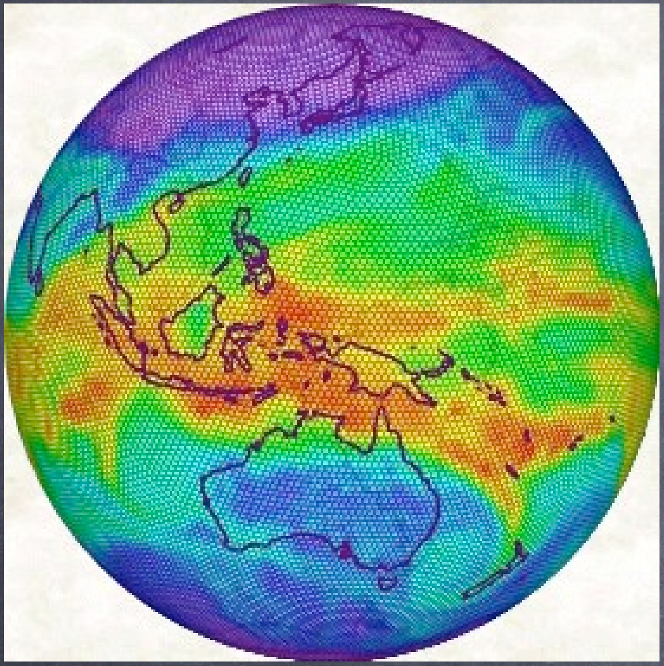
Williamson, 1969: Integration of the barotropic vorticity equation on a spherical geodesic grid.

Sadourny et. al, 1969: A finite difference approximation of the primitive equations for a hexagonal grid on a plane.

Masuda, Y., and H. Ohnishi, 1986: An integration scheme of the primitive equations model with an icosahedral-hexagonal grid system ...

Heikes, R. and D. A. Randall, 1995: Numerical integration of the shallow-water equations on a twisted icosahedral grid.

But as of 1995, we still are working with the shallow-water equations with any physics.

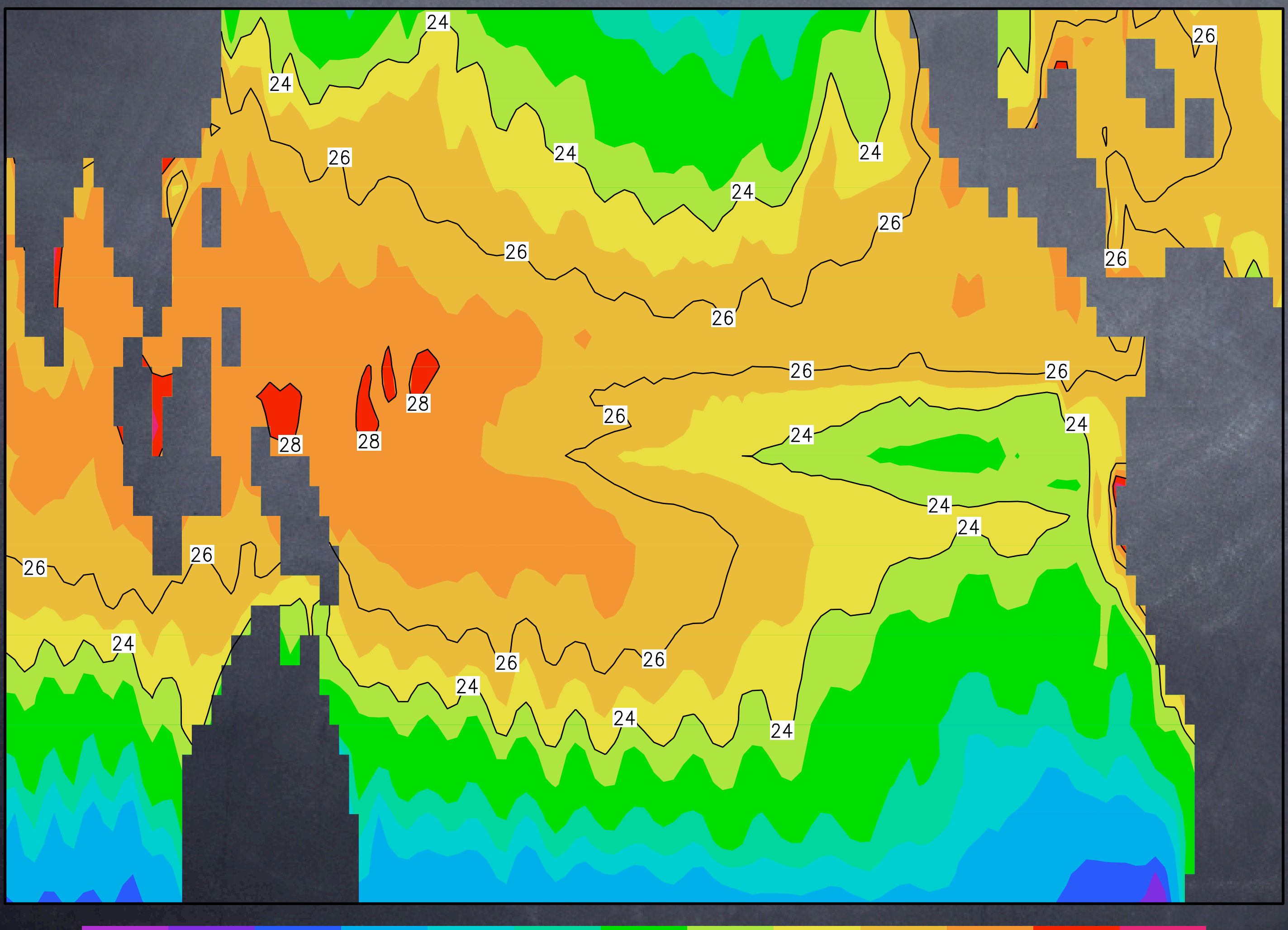


Ringler, T. D., R. P. Heikes, and D. A. Randall, 2000: Modeling the atmospheric general circulation using a spherical geodesic grid: A new class of dynamical cores. Mon. Wea. Rev., 128, 2471-2490.

SWM + Physics + one year work = AGCM

Why was this needed?

Our original AGCM (UCLA) was a lat/lon C-grid and was notable for its noise. Since the numerics conserved energy and potential enstrophy, this noise did not destroy the atmosphere-only simulations. Coupled simulations were another matter ....



SST shown

Lat/Lon

AGCM

coupled to

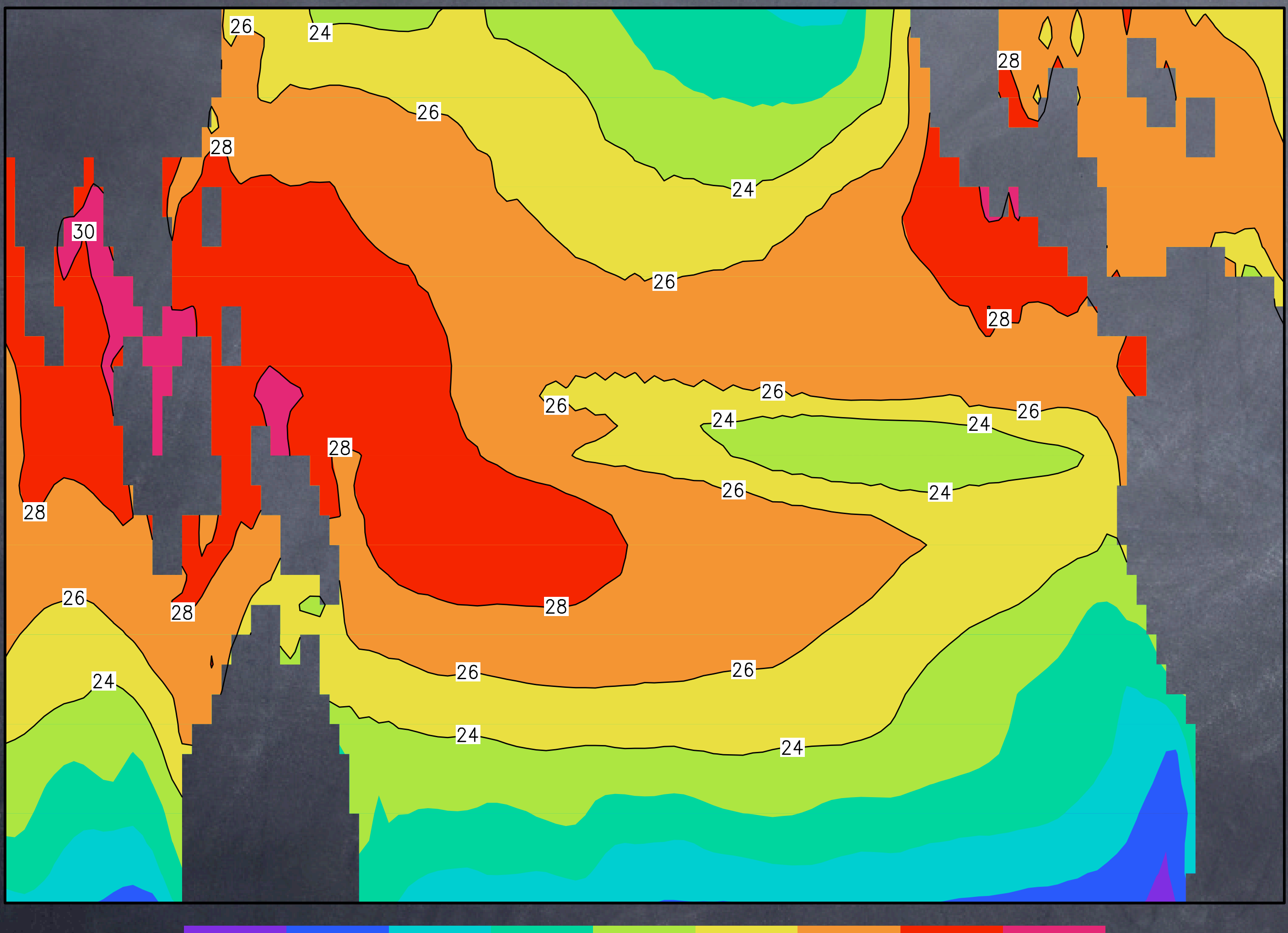
POP

using

SCRIP

(circa 1998)

With our new, improved geodesic AGCM we tried to couple to POP again ....



SST shown

Geodesic AGCM coupled to **POP** using **SCRIP**

(circa 2000)

Seems like a lot of work to get rid of some noise!

Definition of Spherical Voronoi Tesselations

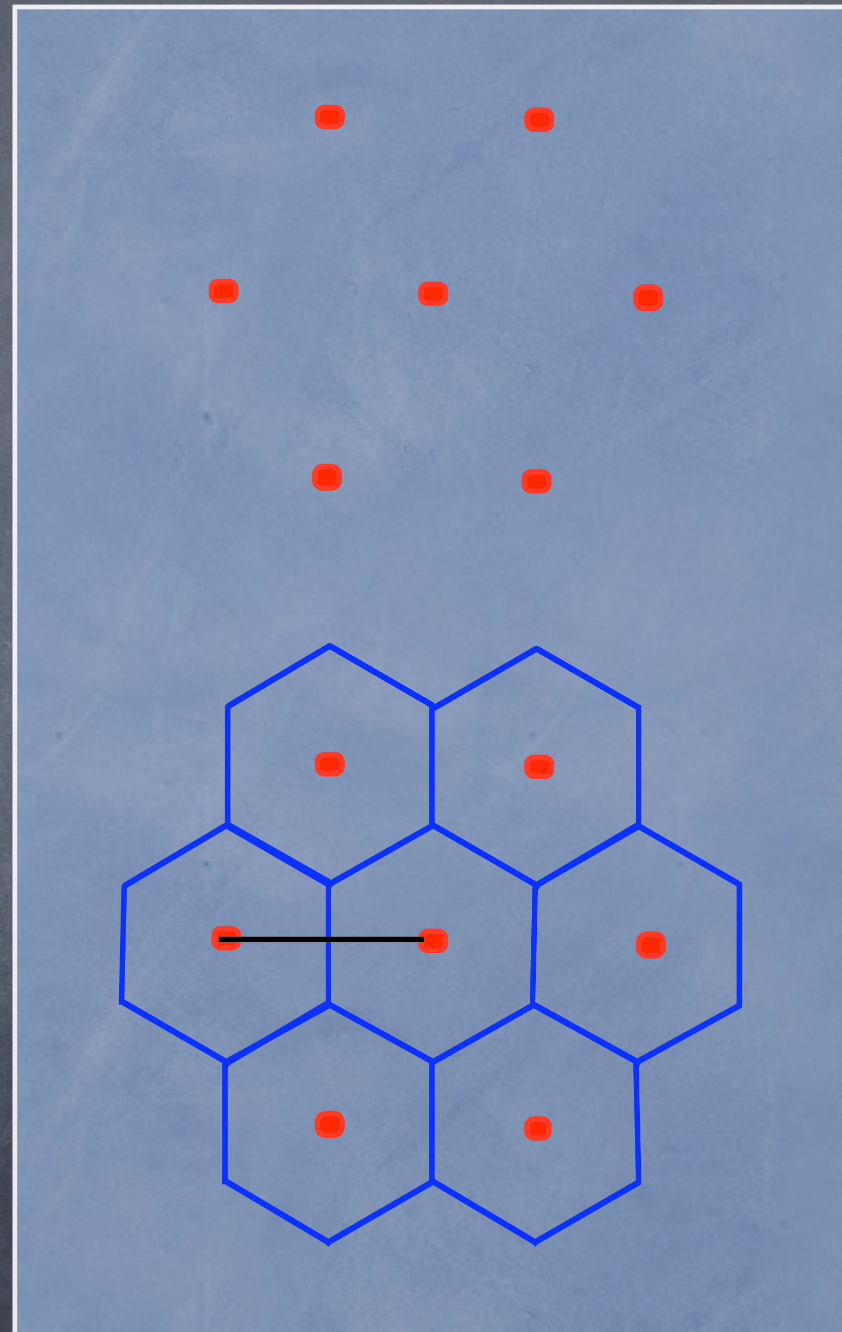
Given the vector positions of a set of points, p_i that lie on the unit sphere, we define for each p_i a corresponding Voronoi region, Ω_i, as the set of all points on the sphere that lie closer to i than for all $i \neq j$

Properties of SVTs: Every cell wall is an orthogonal bisector of the geodesic connecting the grid points that share that cell wall.

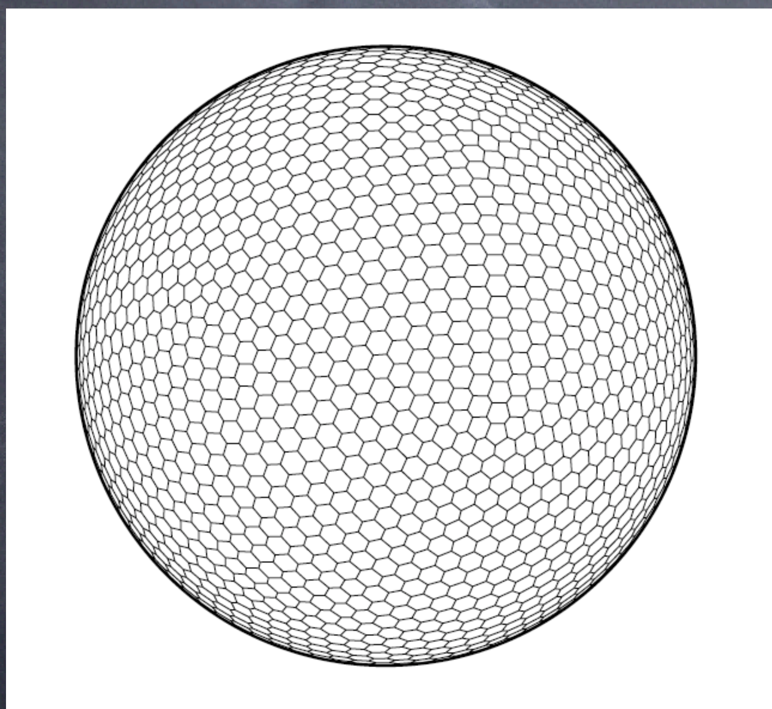
How to choose the generators?

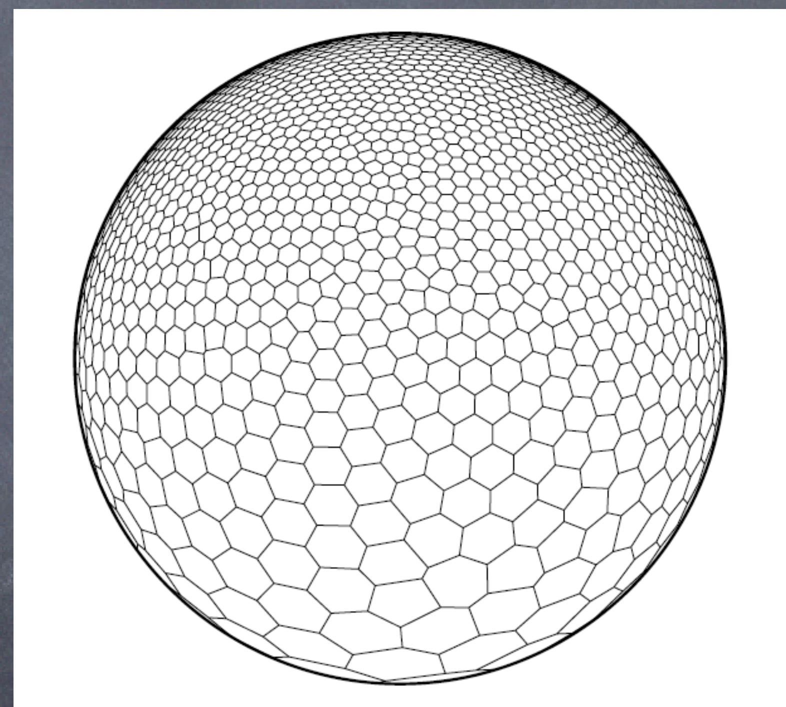
Ringler et al., 2003, SIAM Conference.

(TSTT project (Knupp, Shashkov, ..)



One nice property of SVTs is that the grids can be highly uniform or slowly varying in resolution.





figures generated by Du et. al

Energy Conservation

Can we design numerical schemes that use spherical Voronoi grids that also conserve quadratic quantities such as total energy and/or potential enstrophy?

Why might we want to do this?

1) because the continuous equations do
2) practical stability of numerical methods
3) correct simulation of energy spectrum

Grid Staggering: The B-Grid on hexagons....

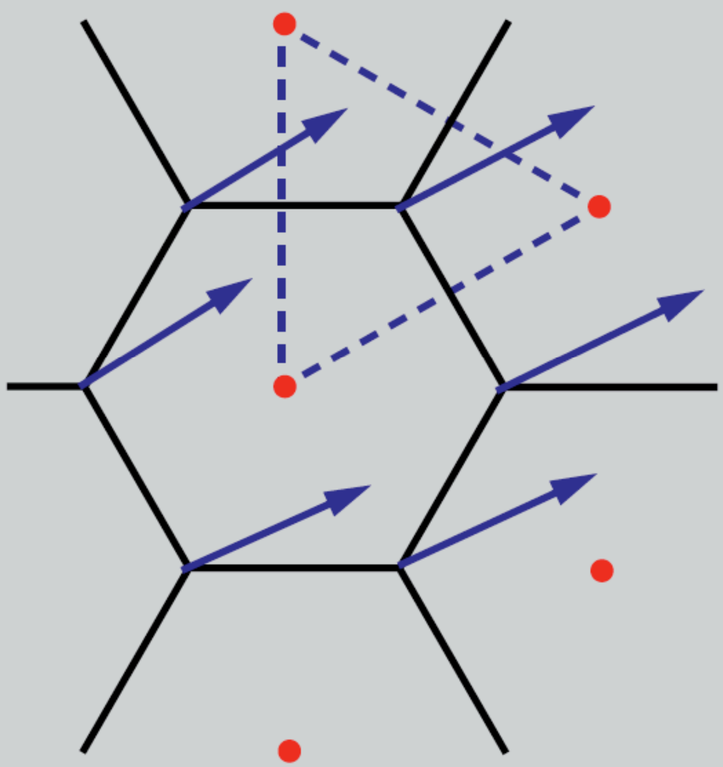
All scalars at grid cell centers
- Mass
- Kinetic Energy
- Vorticity
- Divergence

All vectors at grid cell corners
- Velocity
- Gradients of scalar fields

area of each momentum point

is $\frac{1}{2}$

the area of each mass point



Mimicking the Continuous System.....

Continuous Equations

$$\frac{\partial h}{\partial t} = -\nabla \bullet (h \underset{\sim}{V})$$

$$\frac{\partial}{\partial t}\underset{\sim}{V} = -\eta \underset{\sim}{k} \times \underset{\sim}{V} - \nabla[K + gh]$$

Discrete Equations

$$\frac{\partial h_0}{\partial t} = -D_0[\bar{h}_c \underset{\sim}{V}_c]$$

$$\frac{\partial \underset{\sim}{V}_c}{\partial t} = -\bar{\eta}_c \underset{\sim}{k} \times \underset{\sim}{V}_c - \underset{\sim}{G}_c[K_0 + g h_0]$$

D_0 = discrete divergence operator

$\underset{\sim}{G}_c$ = discrete gradient operator

$\bar{h}_c$ = averaging of mass to cell corners

$\bar{\eta}_c$ = averaging of vorticity to cell corners

C_0 = discrete curl operator

Then Mimicking the Continuous Derivation.....

<u>Continuous Equations</u>	<u>Discrete Equations</u>
$K\left\{\frac{\partial h}{\partial t} = -\nabla\bullet(h\underset{\sim}{V})\right\}$	$K_0\left\{\frac{\partial h_0}{\partial t} = -D_0[\bar{h}_c, \underset{\sim}{V}_c]\right\}$
$gh\left\{\frac{\partial h}{\partial t} = -\nabla\bullet(h\underset{\sim}{V})\right\}$	$gh_0\left\{\frac{\partial h_0}{\partial t} = -D_0[\bar{h}_c, \underset{\sim}{V}_c]\right\}$
$h\underset{\sim}{V}\bullet\left\{\frac{\partial}{\partial t}\underset{\sim}{V} = -\eta\underset{\sim}{k}\times\underset{\sim}{V} - \nabla[K+gh]\right\}$	$h_0\sum_{c=1}^{6}\underset{\sim}{V}_c\bullet\left\{\frac{\partial \underset{\sim}{V}_c}{\partial t} = -\bar{\eta}_c\underset{\sim}{k}\times\underset{\sim}{V}_c - \underset{\sim}{G}_c[K_0+gh_0]\right\}$
$\int_A h\left[K+\frac{1}{2}gh\right]dA = 0$	$\sum_{i=0}^{n} h_i\left[K_i+\frac{1}{2}gh_i\right]A_i = 0$

We use our degrees of freedom in G_c, K_0, and $\bar{h}_c$ to make this happen.

This could be called the Arakawa energy method.
The mimic method (Shashkov) gives the same results.

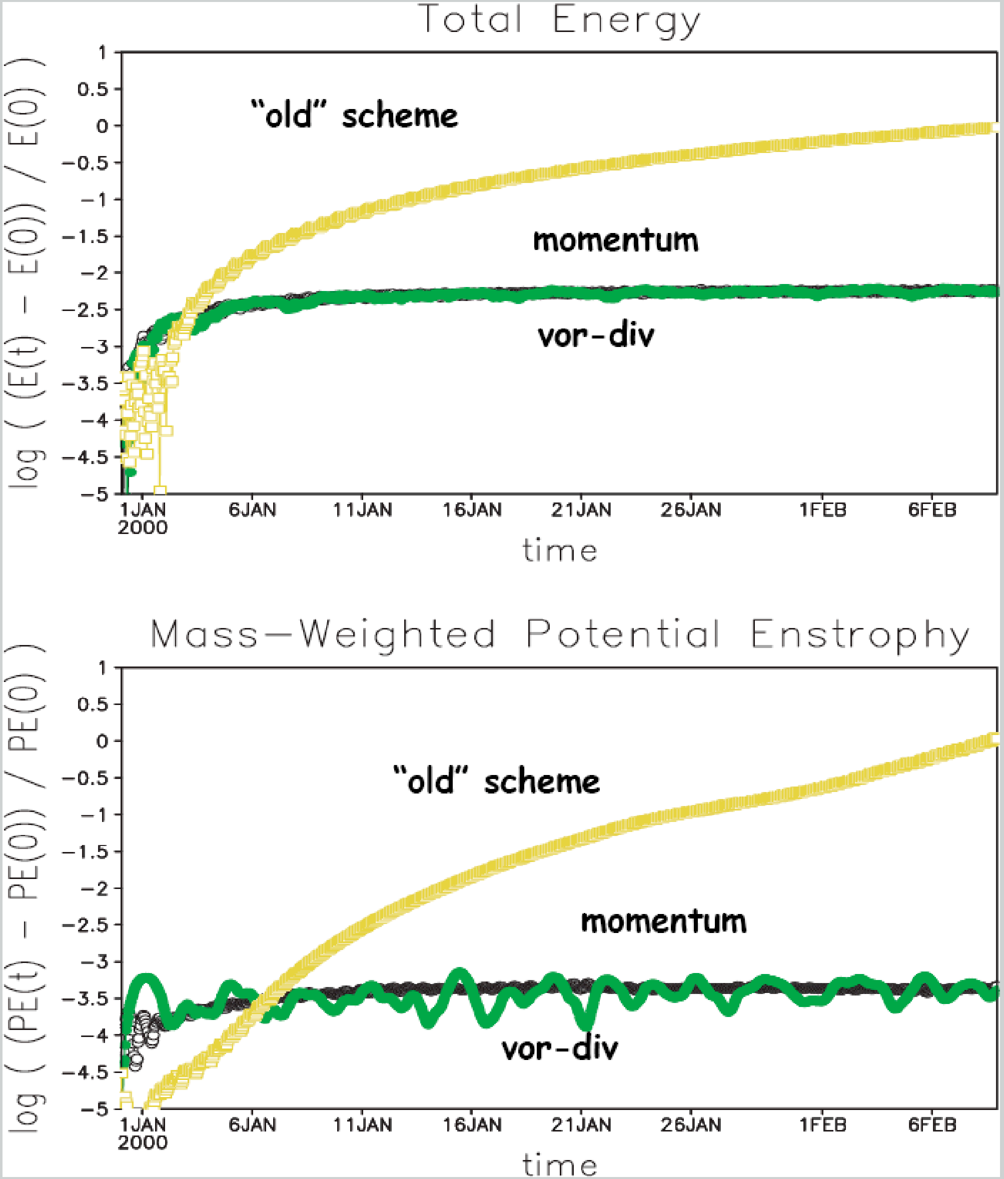
2-D Turbulence an a Plane:
Comparison with "old" scheme

Top figure: the fractional change in total energy relative to the initial amount of energy.

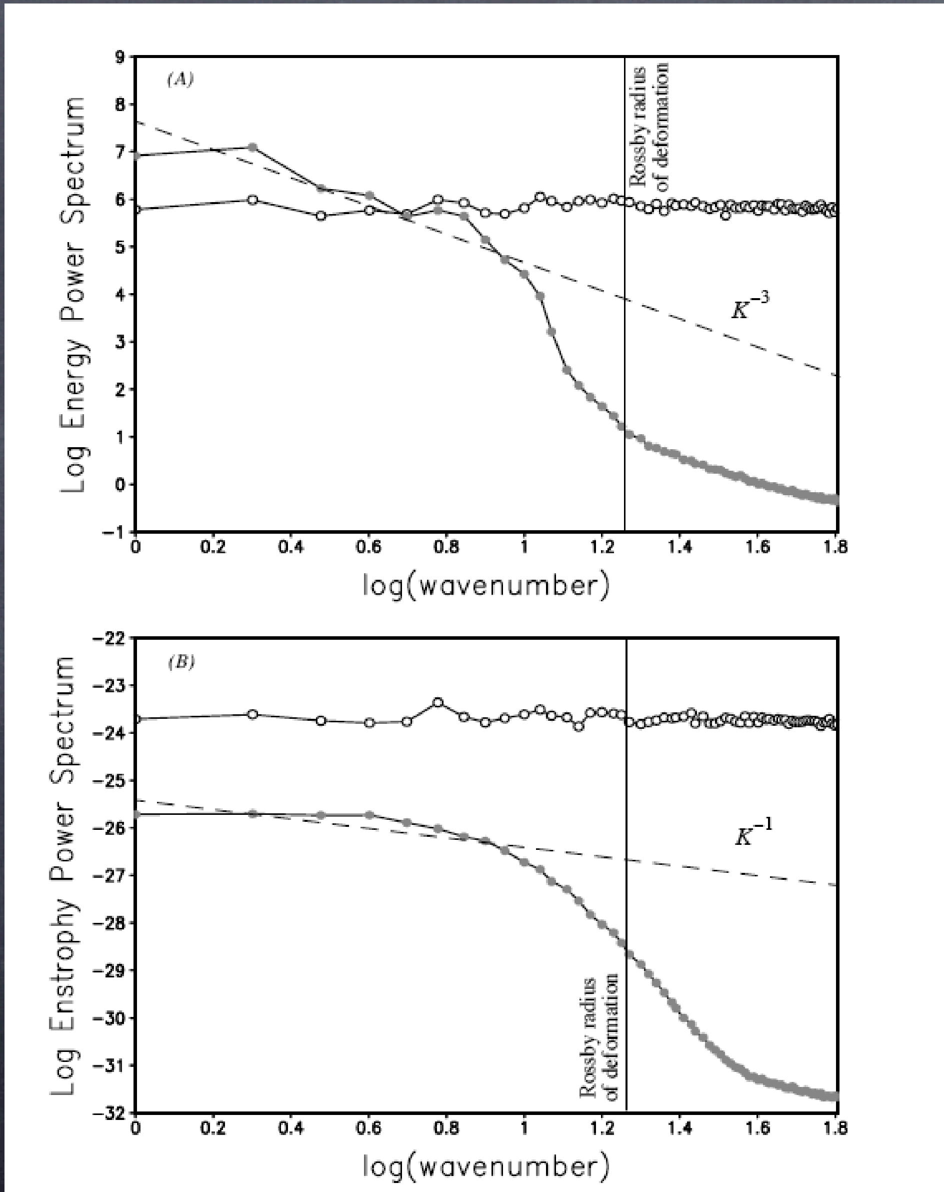
Bottom figure: same as top, expect for potential enstrophy.

Over 40 days of integration, the "old" scheme shows an order one change in both total energy and potential enstrophy.

The new scheme shows a change of ~0.3% in total energy and ~0.03% in potential enstrophy.



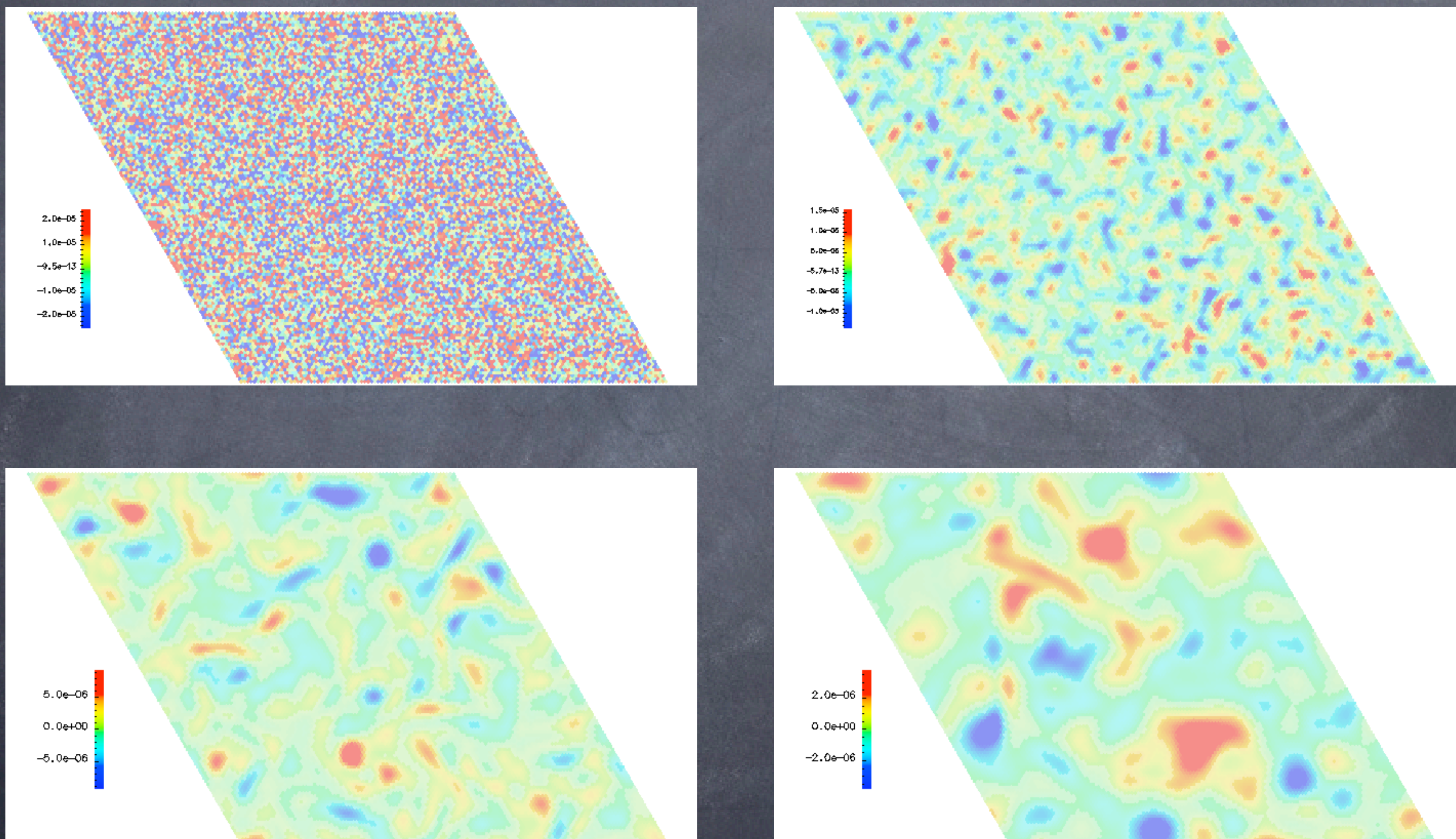
Ringler and Randall, 2002a



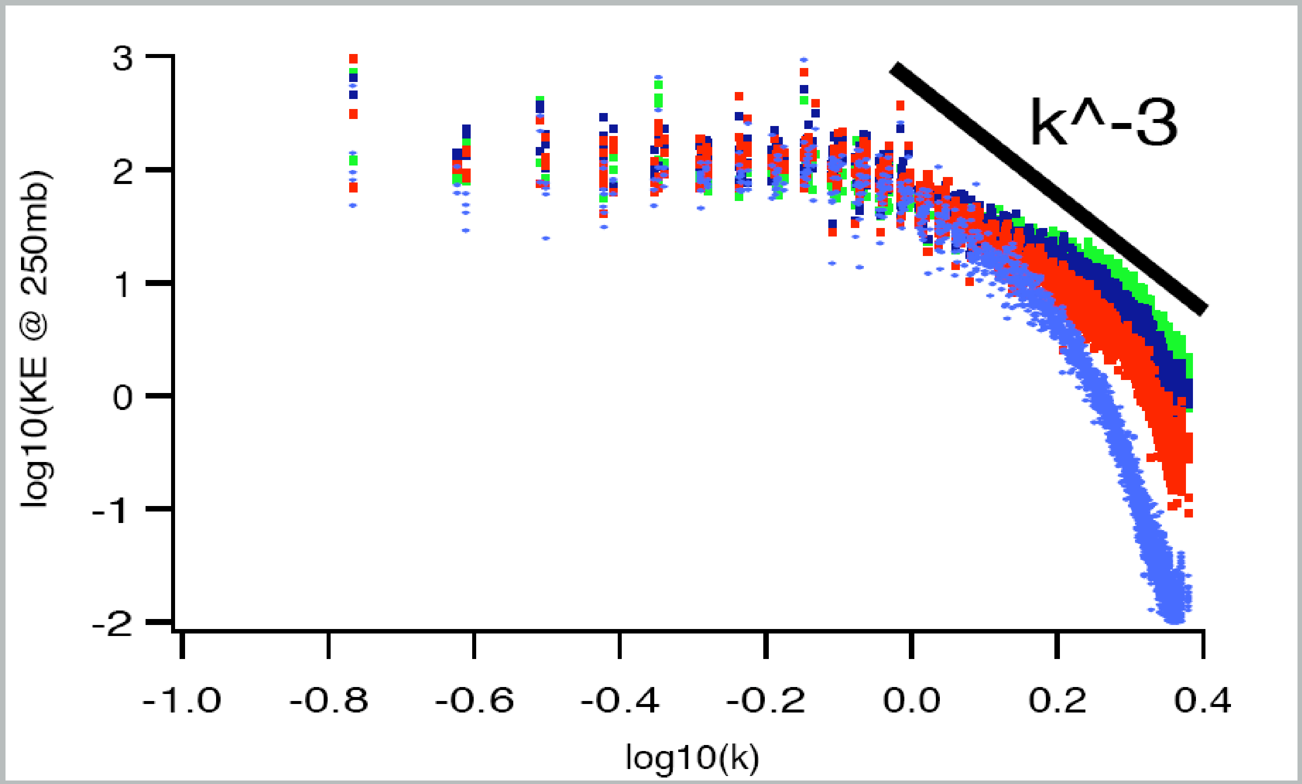
With the conservation of these quadratic quantities, we can start to look at spectra.

Ringler and Randall, 2002a

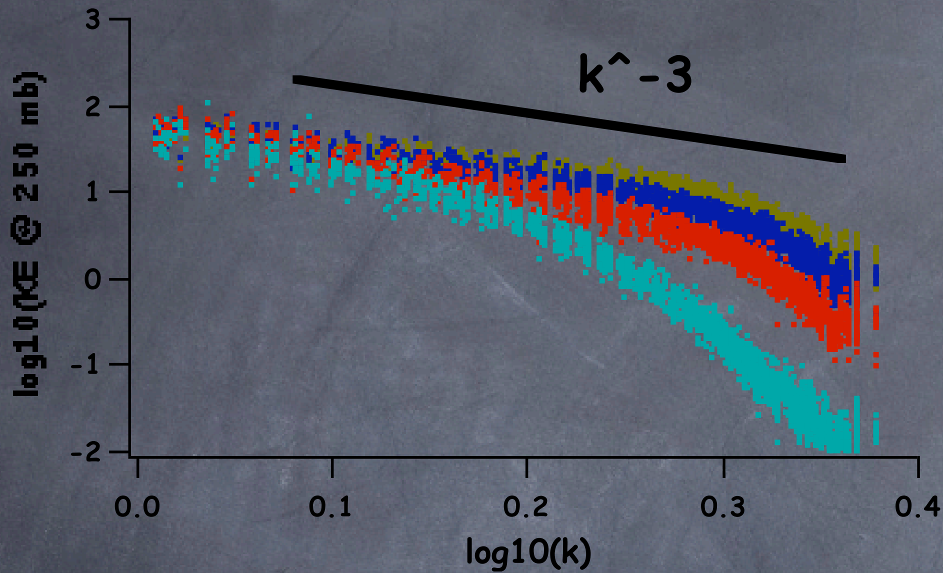
The vorticity evolves appropriately in time.

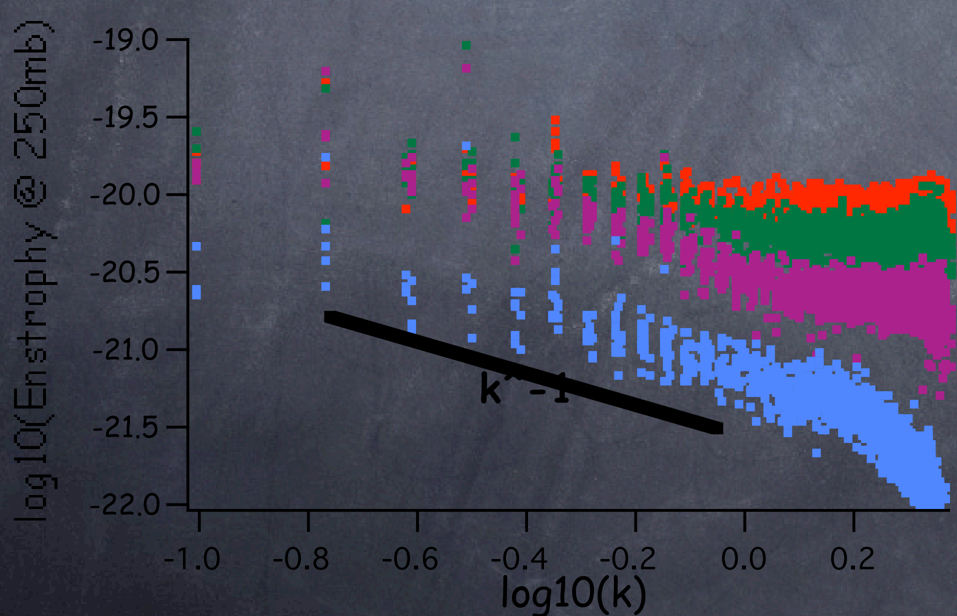


Held-Suarez Test Case/Momentum Formulation
Spectra of Kinetic Energy per unit mass at 250mb
four values of μ: 1e12, 1e13, 1e14, 1e15 m4/s



Ringler et al., 2004, CCSR Japan



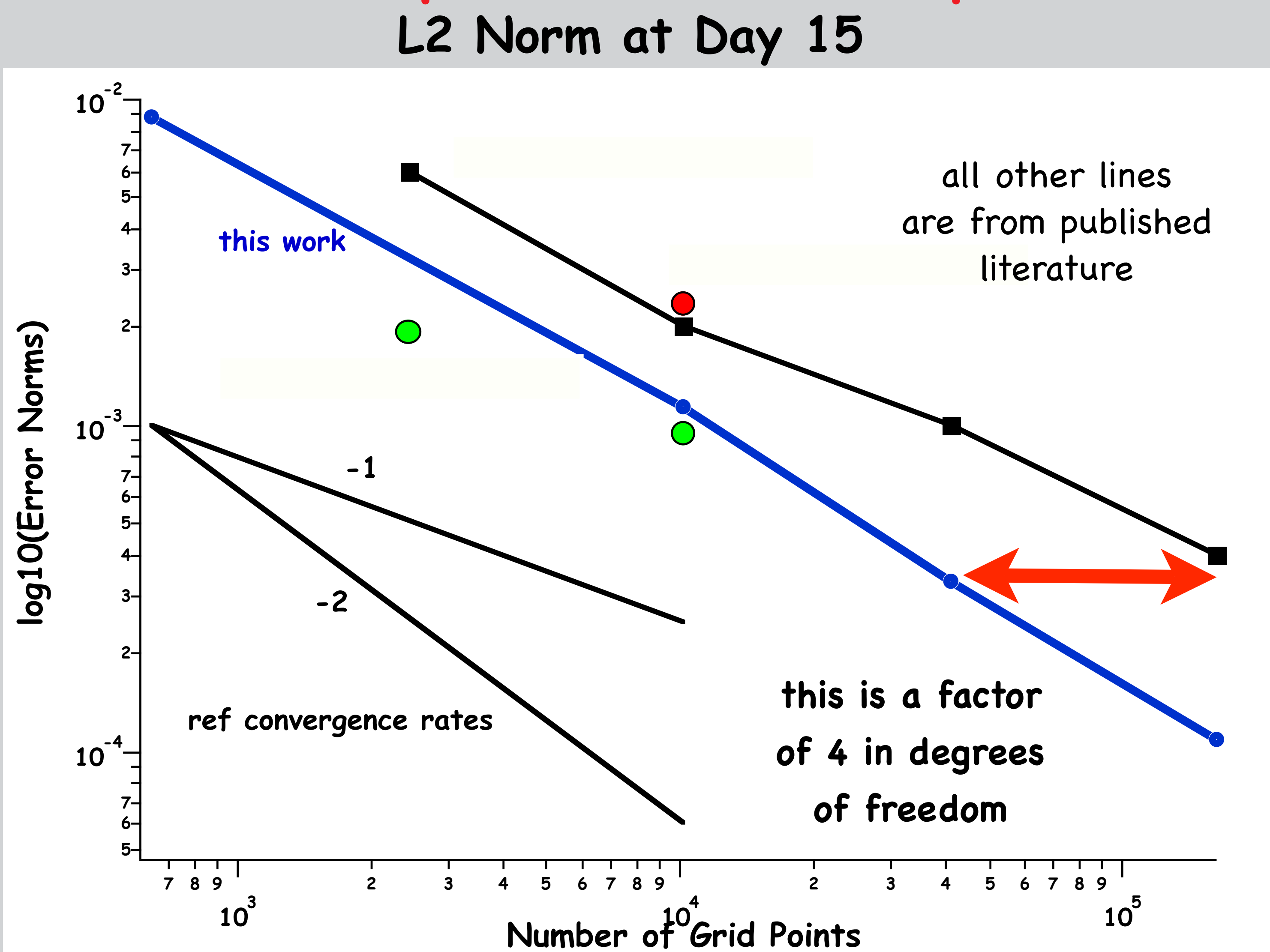


Now that we don't need dissipation to maintain stability in the 3-D simulations, we can use the dissipation to control the energy and enstrophy spectra.

Ringler et al., 2004, CCSR Japan

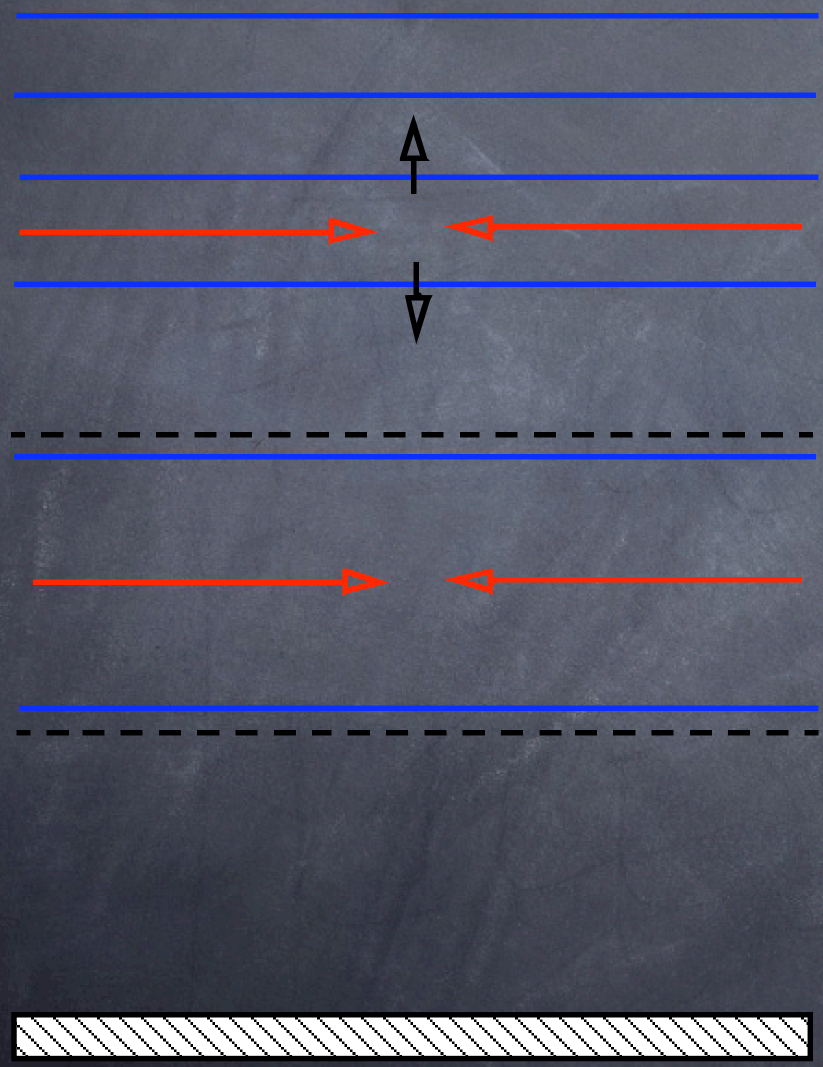
The accuracy of this scheme compares well to its peer group.

Error Norms compared to a T213 spectral model



Making use of these numerical methods in an ocean model

The vertical coordinate is chosen to be an Arbitrary Lagrangian Eulerian (ALE) coordinate.

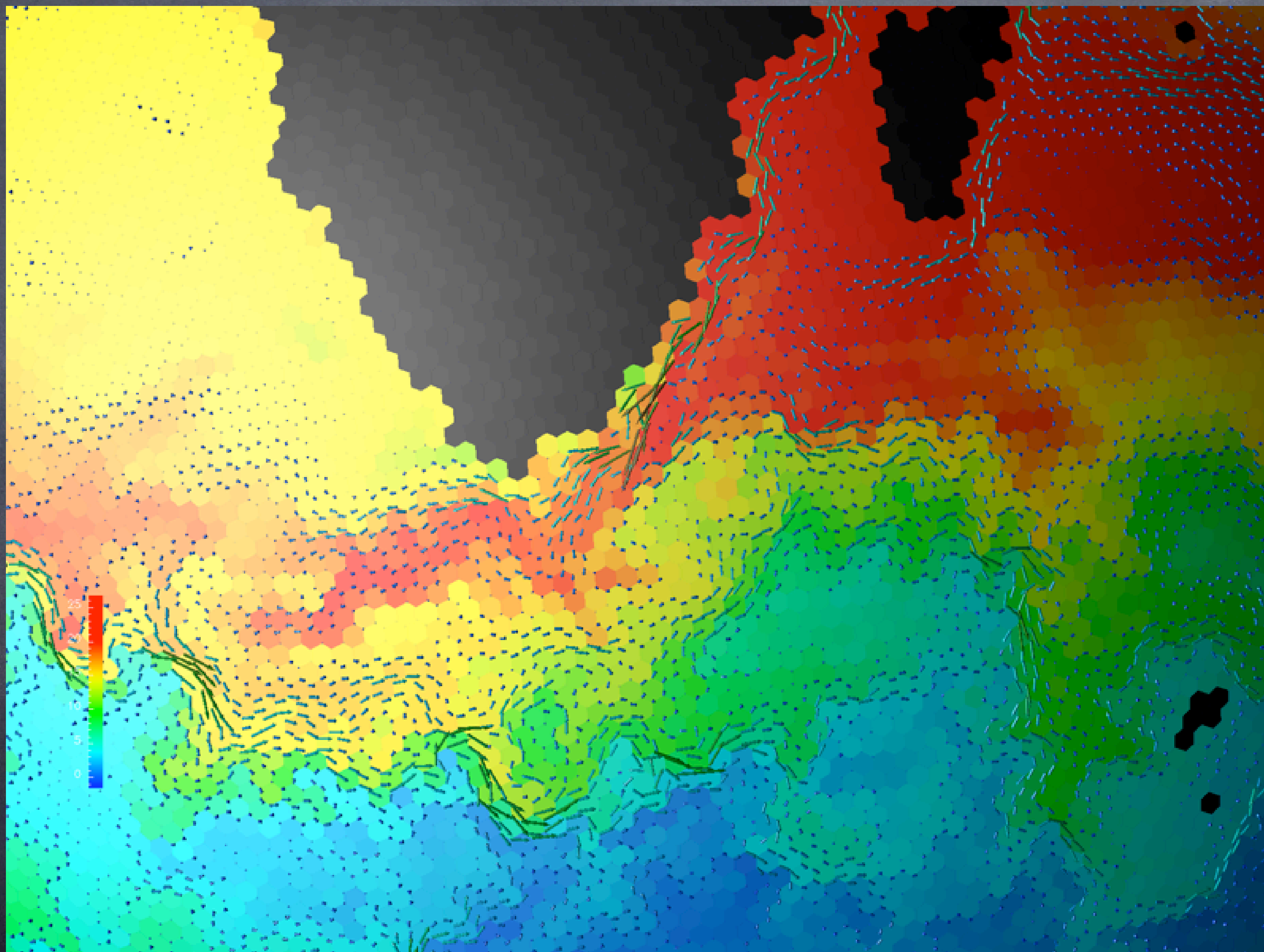


ALE coordinates can mimic fixed z-level Eulerian coordinates by forcing mass across coordinate surfaces to maintain a uniform layer thickness.

Alternatively, ALE coordinates can mimic floating or Lagrangian coordinates by allowing the layer to inflate while requiring zero mass flux across the coordinate surface.

ALE coordinates accommodate any blending of the Eulerian and Lagrangian limits.

Since the vertical coordinate is largely independent of the horizontal discretization, we are working closely with the HYPOP effort in this area.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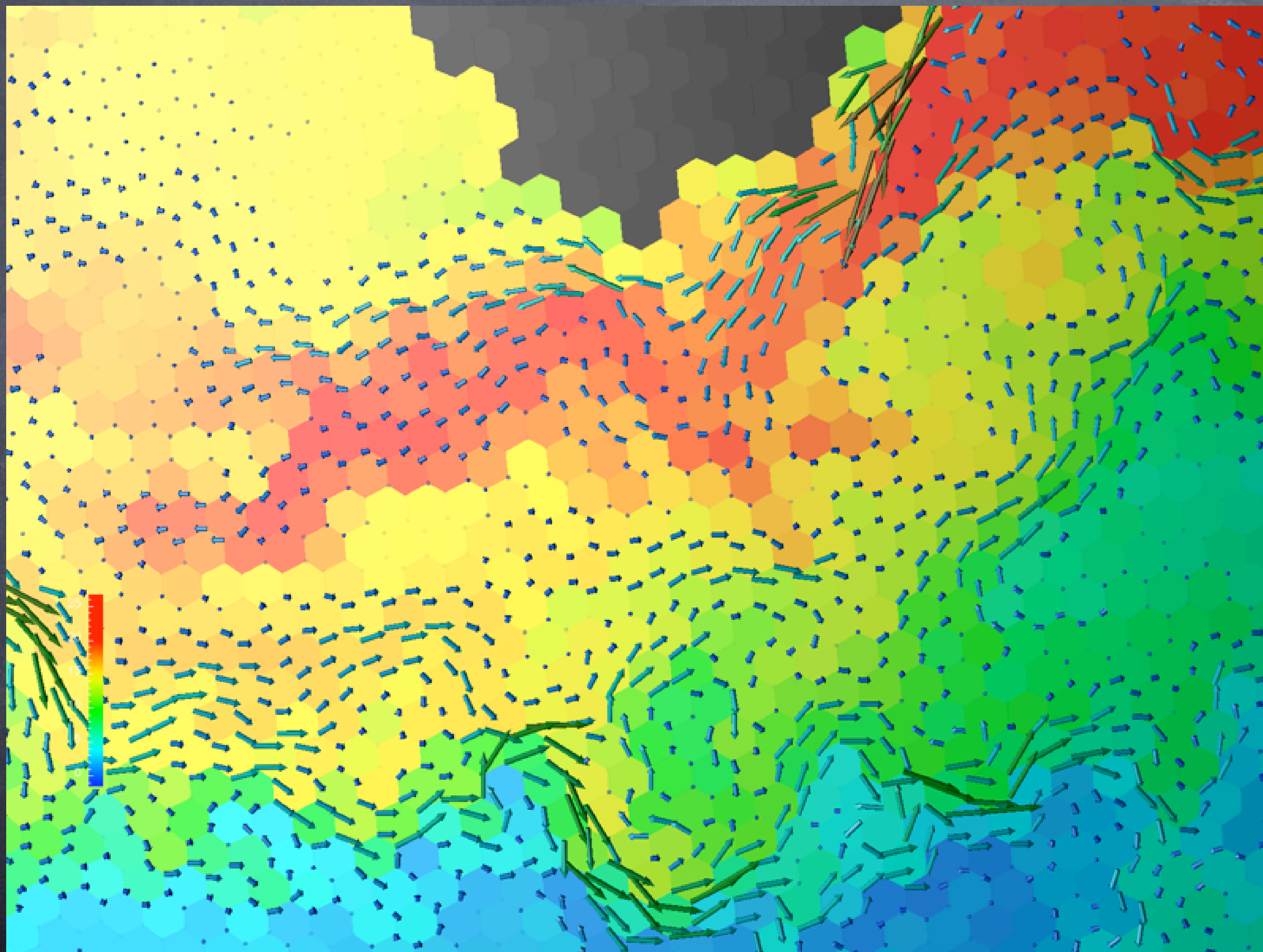
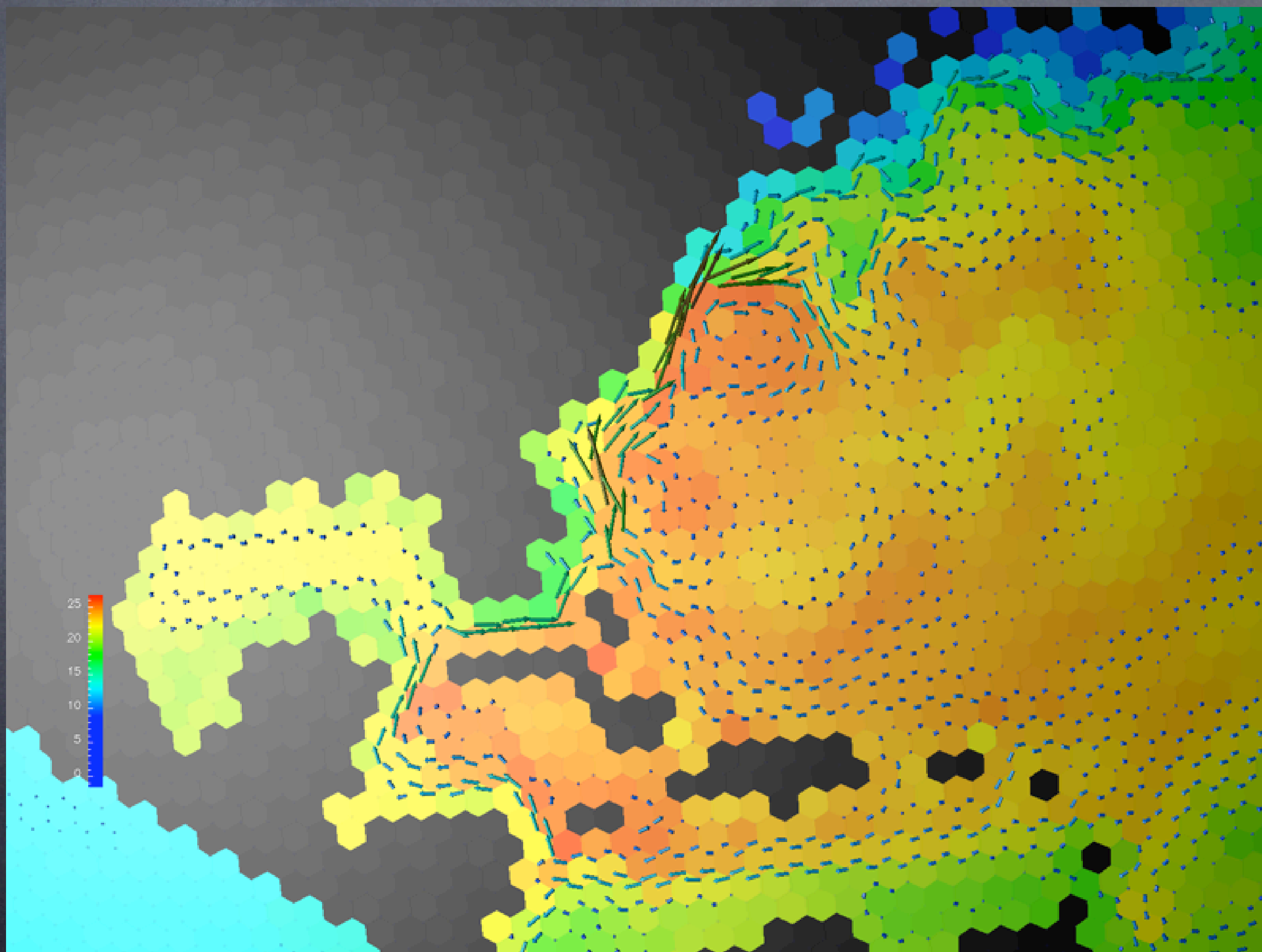

25
0



25
20
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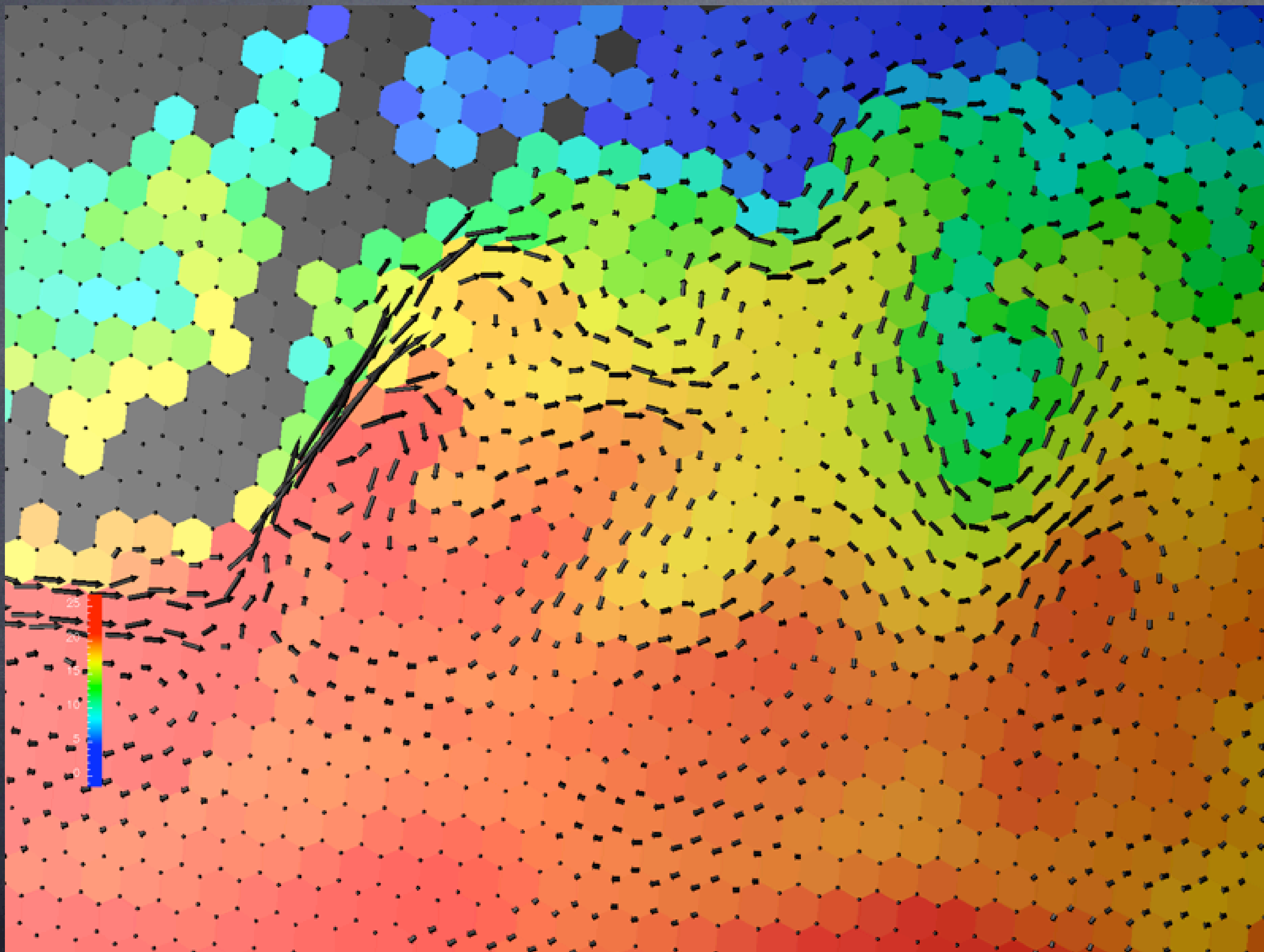
25
20
15
10
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0

Designing a Coupler....

The two ends of the coupling spectrum.....

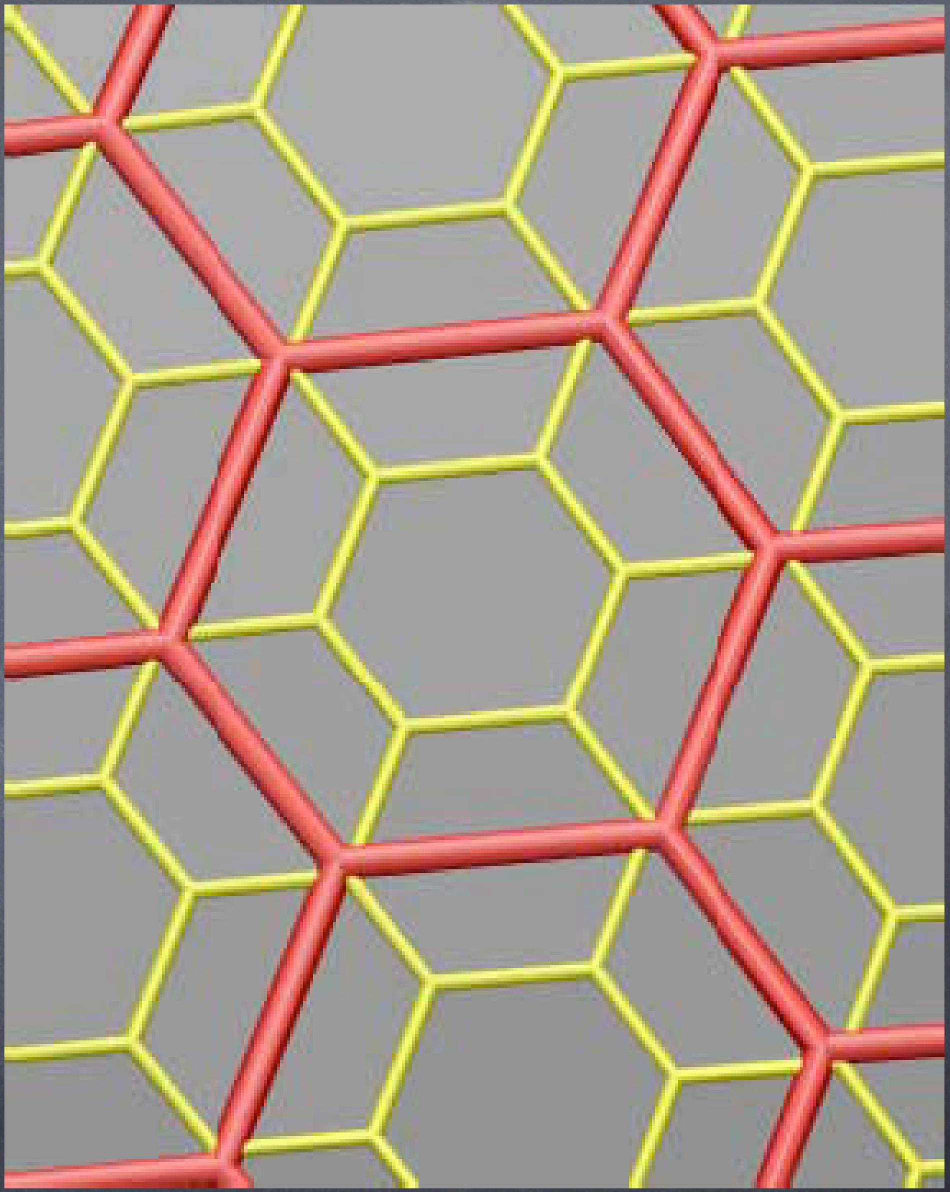
one end: couple any component to any other component. example ... couple the sun to the atmosphere.

the other end: design couple to deal with a specific grid structure and constrained by strict rules.

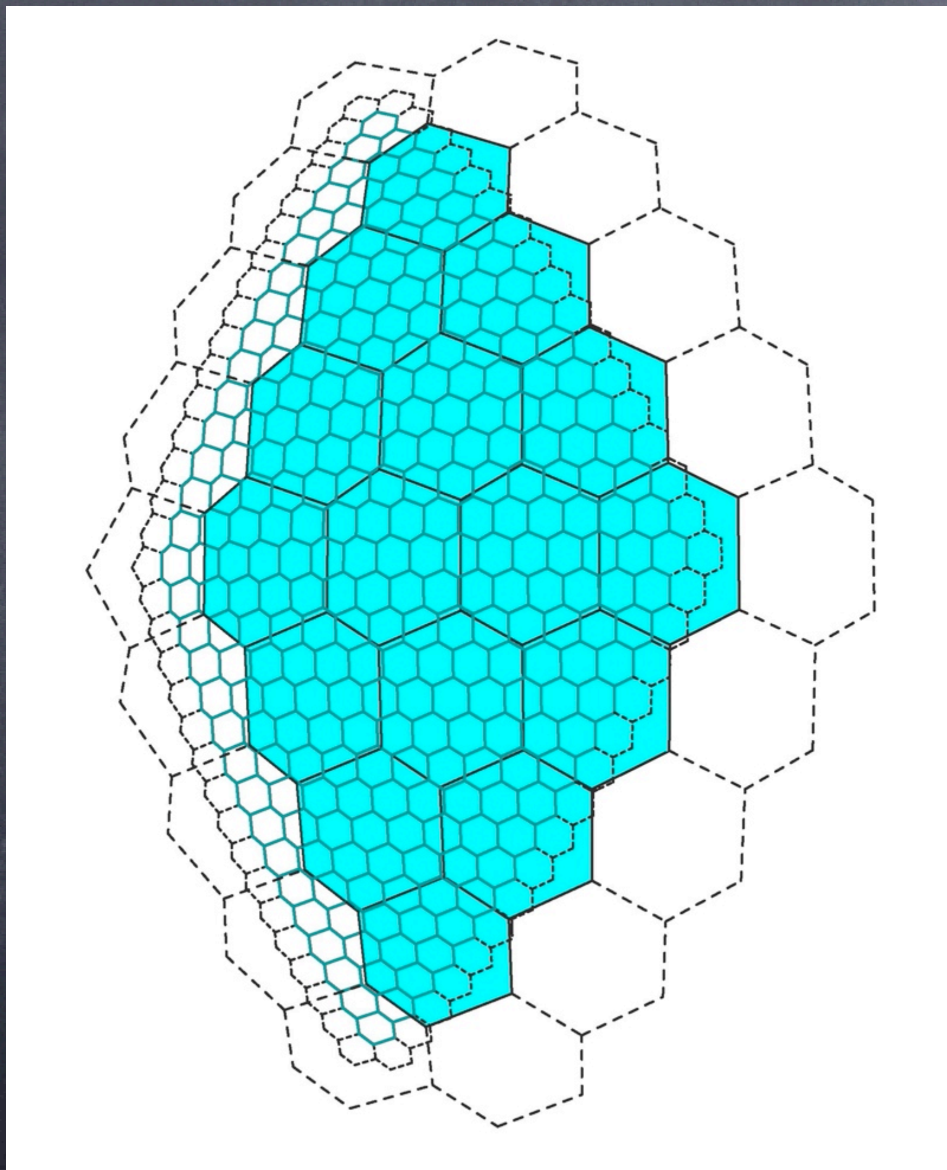
Climate sub-models generally use different resolutions.

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.



Dazlich et al., 2005, in prep.



Sea-Ice Modeling

advection and the rate-of-strain tensor

We already had much of what we needed from CICE: thermodynamics and EVP. What we needed was an accurate, monotone advection scheme and a formulation of the rate-of-strain tensor.

more on advection in a little later ....

What about rank-two tensors?

Rate-of-strain and stress tensors are of primary importance in sea-ice models and are increasingly important in anisotropic viscosity formulations in ocean models.

For us, the guiding principal for this development has been the tensor identity of

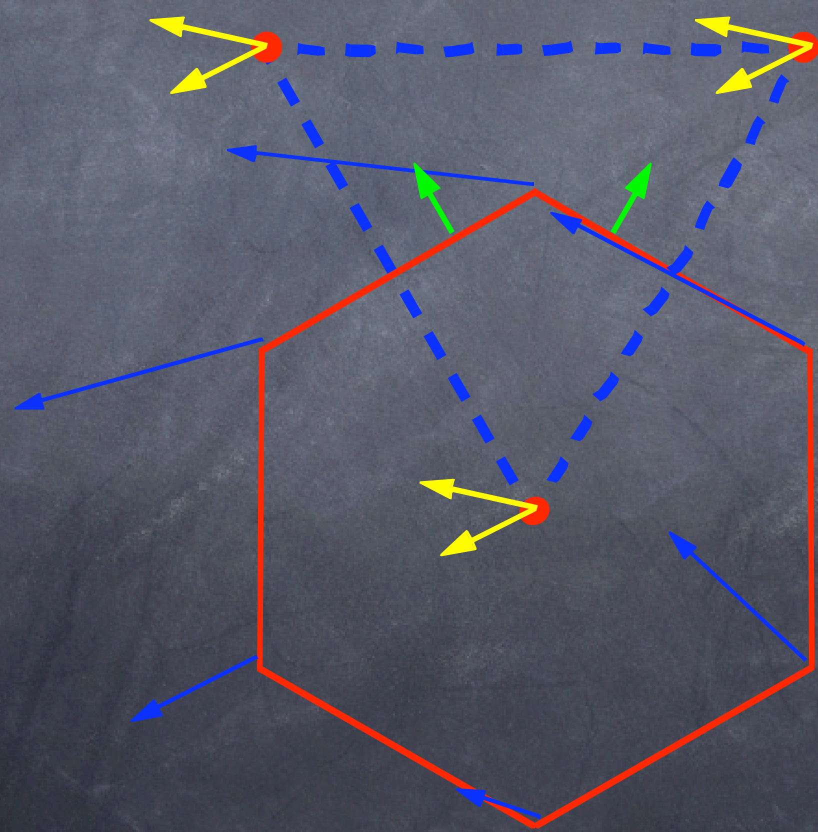
$$\int_{\partial V} \left[\underset{\sim}{V} \bullet \left(\underset{\sim}{n} \bullet \underset{\sim}{\sigma} \right) \right] \partial A = \int_{V} \left(\nabla \underset{\sim}{V} : \underset{\sim}{\sigma} \right) \partial V + \int_{V} \underset{\sim}{V} \bullet \left(\nabla \bullet \underset{\sim}{\sigma} \right) \partial V$$

Assuming the boundary conditions vanish, we have

$$\int_{V} \left(\nabla \underset{\sim}{V} : \underset{\sim}{\sigma} \right) \partial V = -\int_{V} \underset{\sim}{V} \bullet \left(\nabla \bullet \underset{\sim}{\sigma} \right) \partial V$$

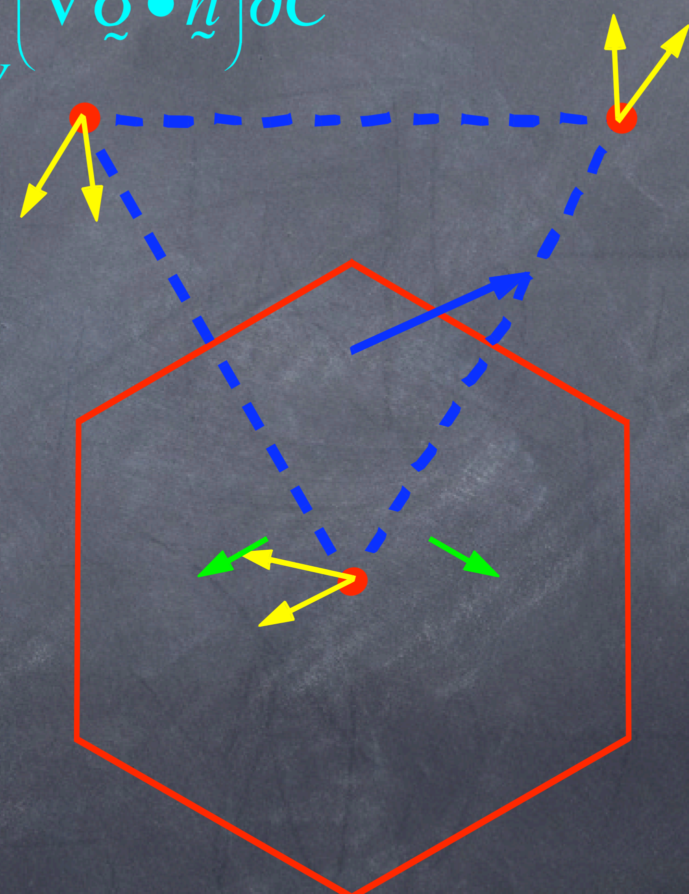
If we are only interested in symmetric rank-2 tensors, we can just extend the weak formulation that we have already developed for scalars and tensors.

$$\nabla \underset{\sim}{V} = \lim_{A \to \infty} \int_V \left(\underset{\sim}{V}\, \underset{\sim}{n} \right) \partial C$$



The divergence of the rank-2 tensor follows directly from its weak formulation

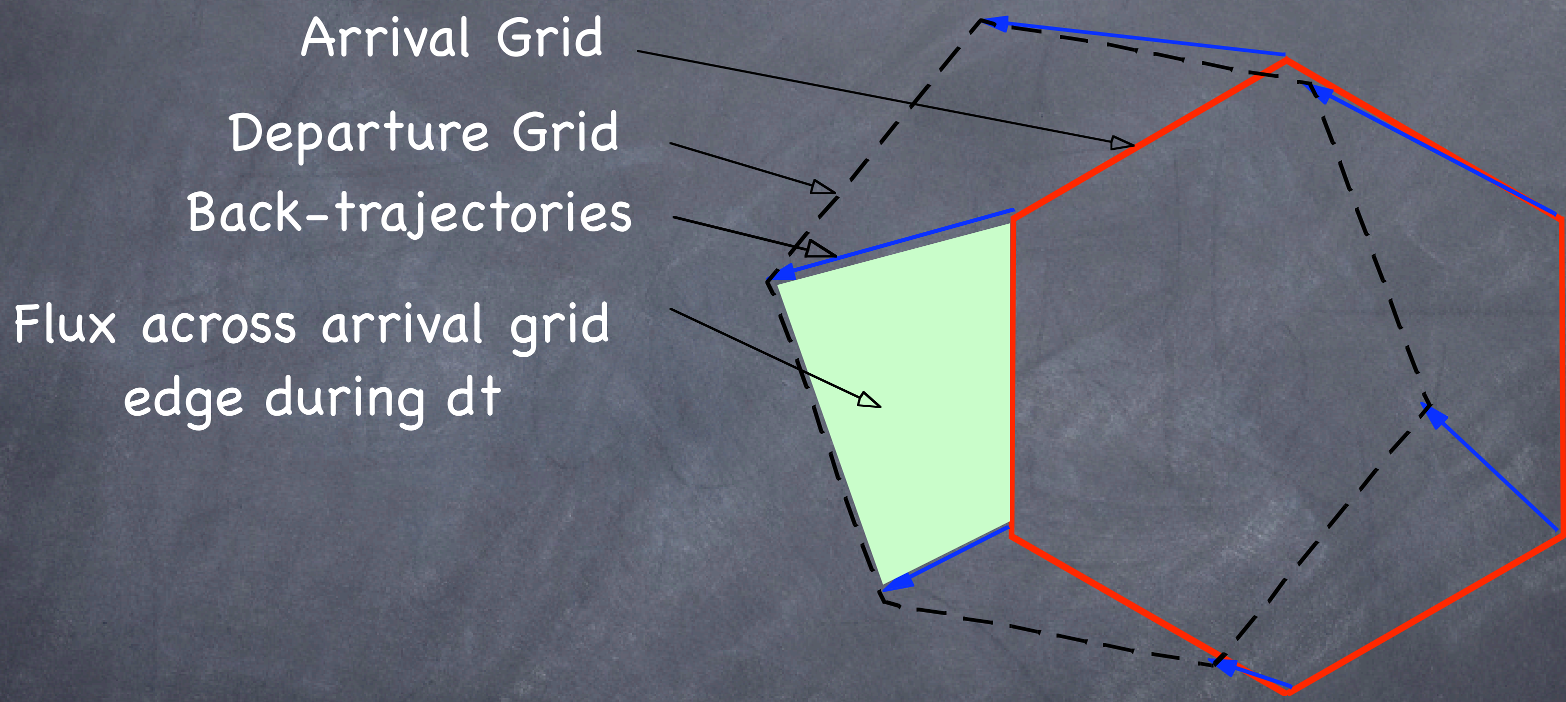
$$\nabla \bullet \underset{\sim}{\sigma} = \lim_{A \to \infty} \int_V \left(\nabla \underset{\sim}{\sigma} \bullet \underset{\sim}{n} \right) \partial C$$



This approach to discretizing the gradient of a vector and divergence of a tensor allows the relevant vector identity to told and assures that the dissipation operator is negative definite.

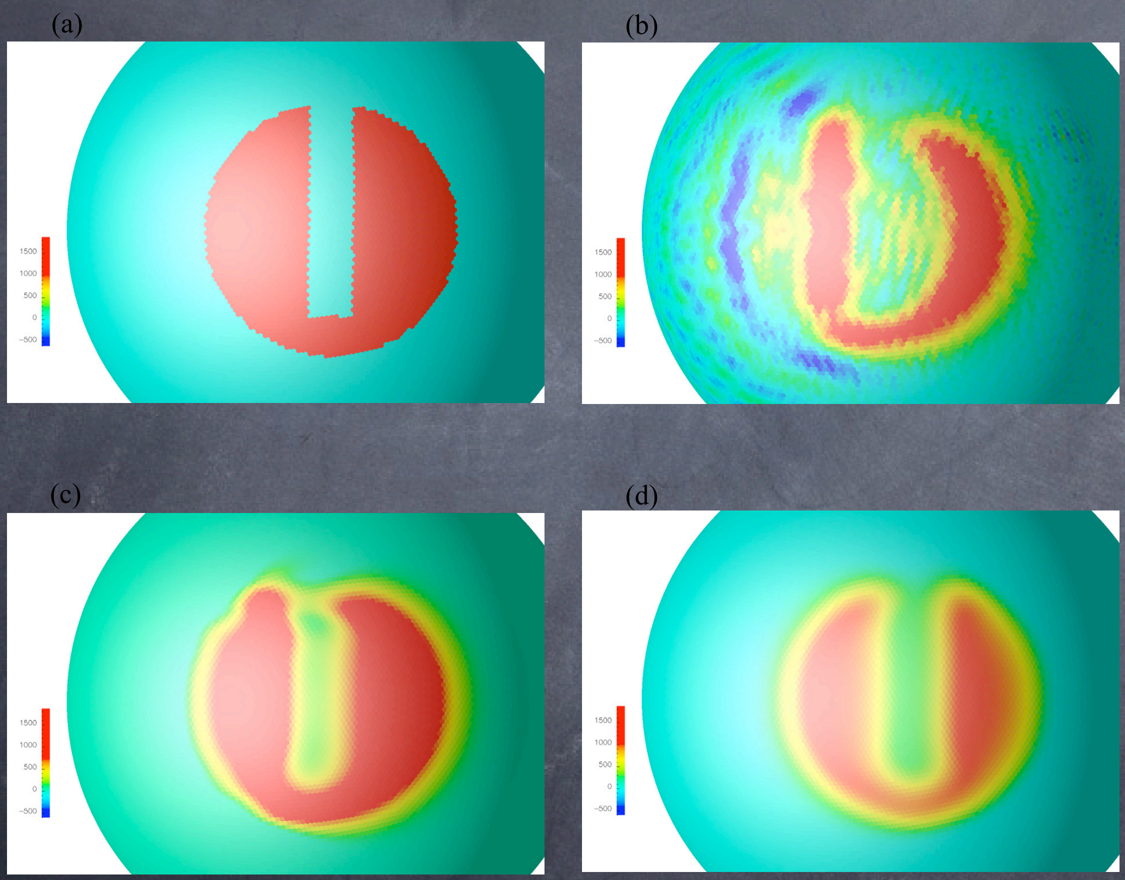
Ringler and Stark, 2005, in prep.

Incremental Remapping
Dukowicz and Baumgardner (JCP 2000)



Flux is computed via quadrature methods with limiting on the reconstruction to produce a compatible, conservative, and monotone advection scheme.

Incremental Remapping seemed to work great for quadrilateral grids, what about SVTs?

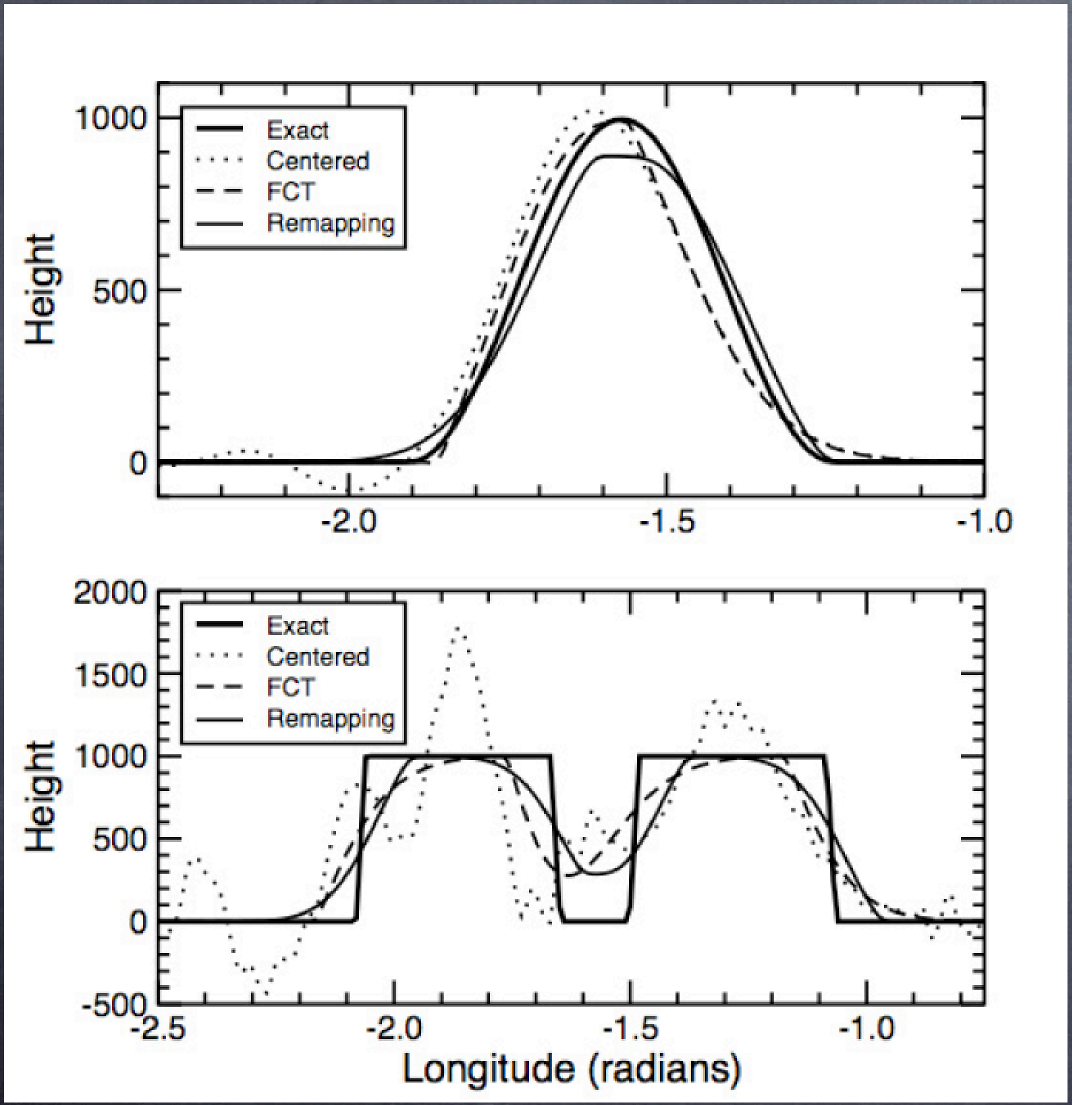


Advection of slotted cylinder one revolution around a sphere.

a) exact
b) 2nd-order centered
c) FCT
d) IR

Lipscomb and Ringler, 2005, to appear.

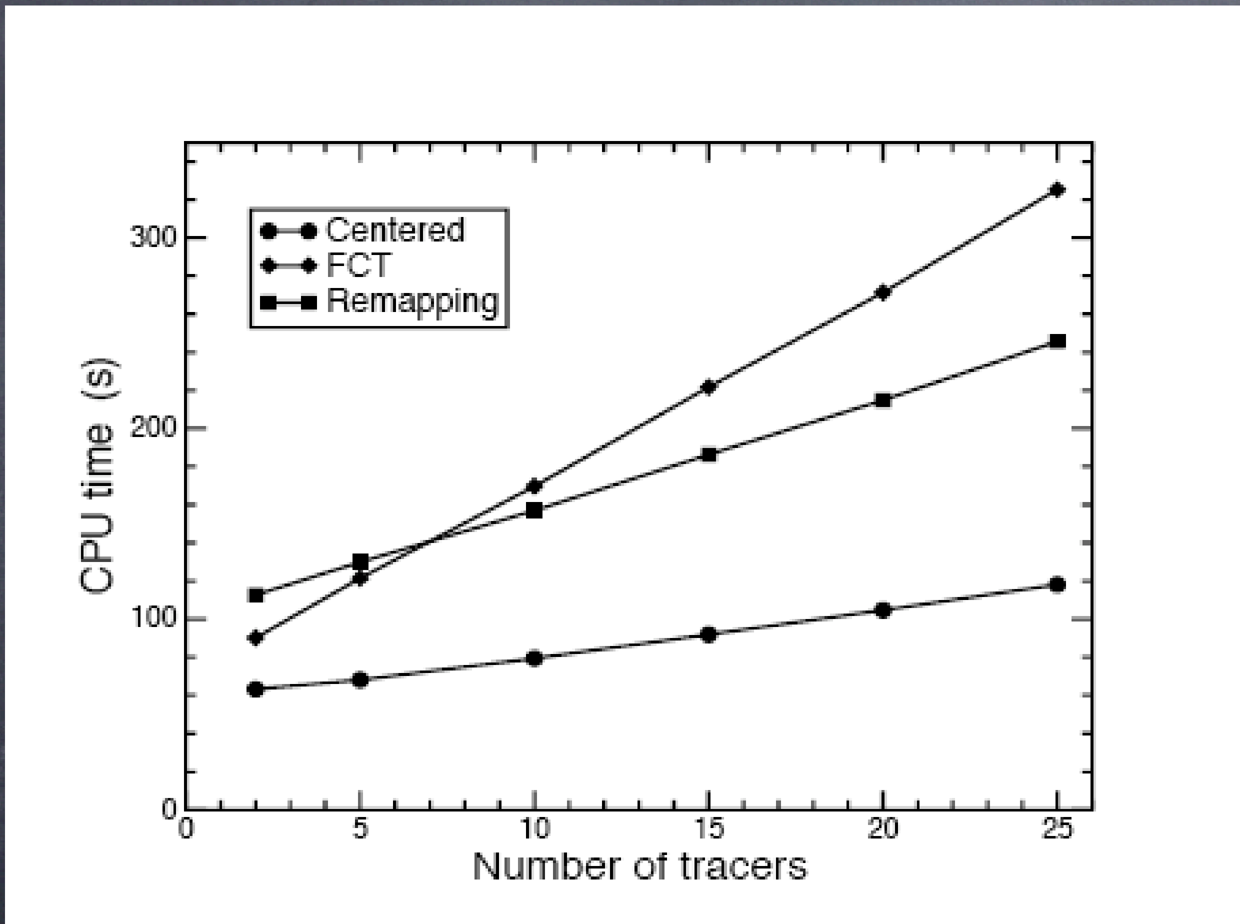
Looking a cross-section after 15 days of a cosine-bell and a slotted cylinder.



As far a accuracy goes, incremental remapping is the best of the three schemes.

Lipscomb and Ringler, 2005, to appear.

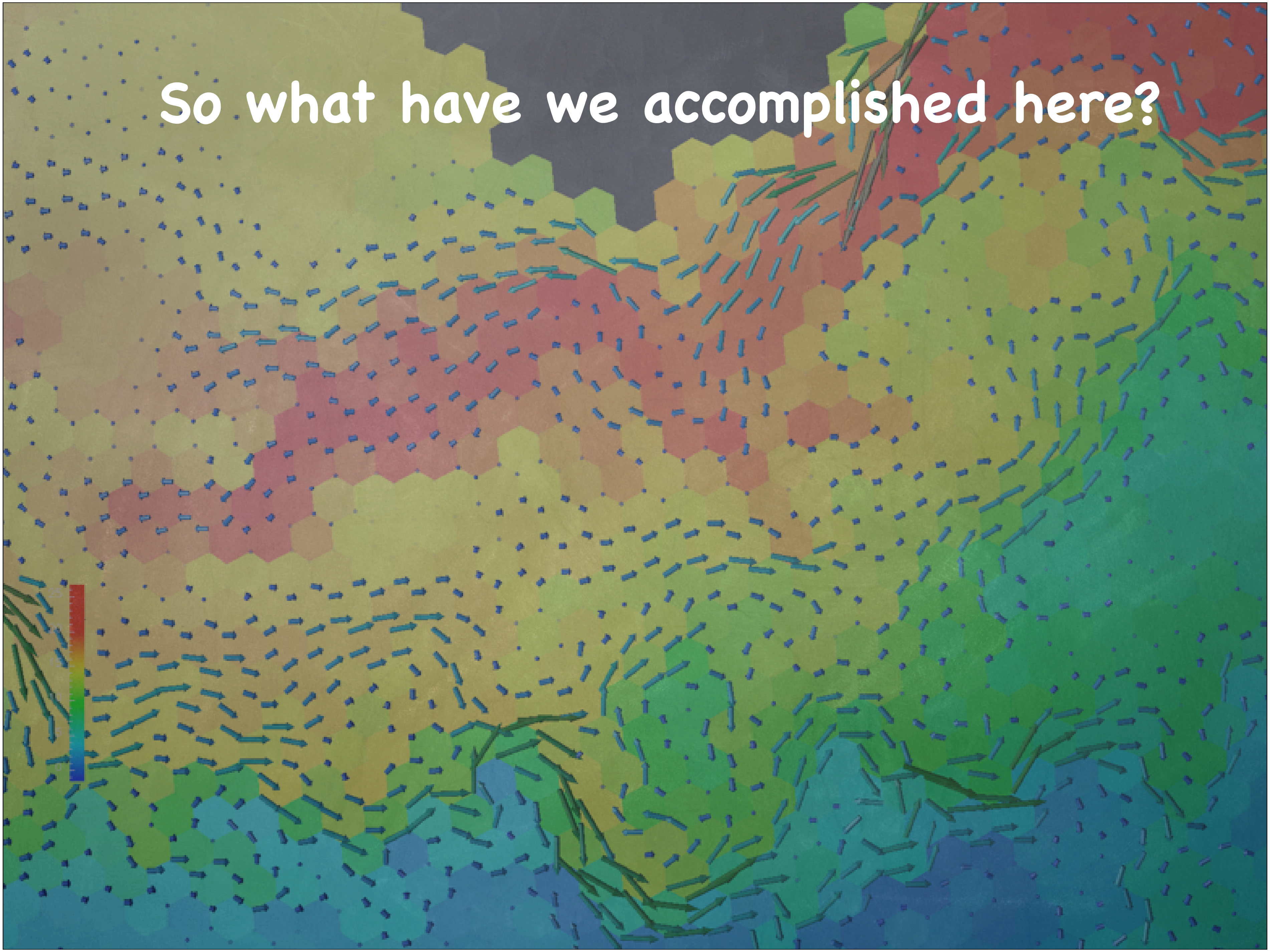
What about computational efficiency?

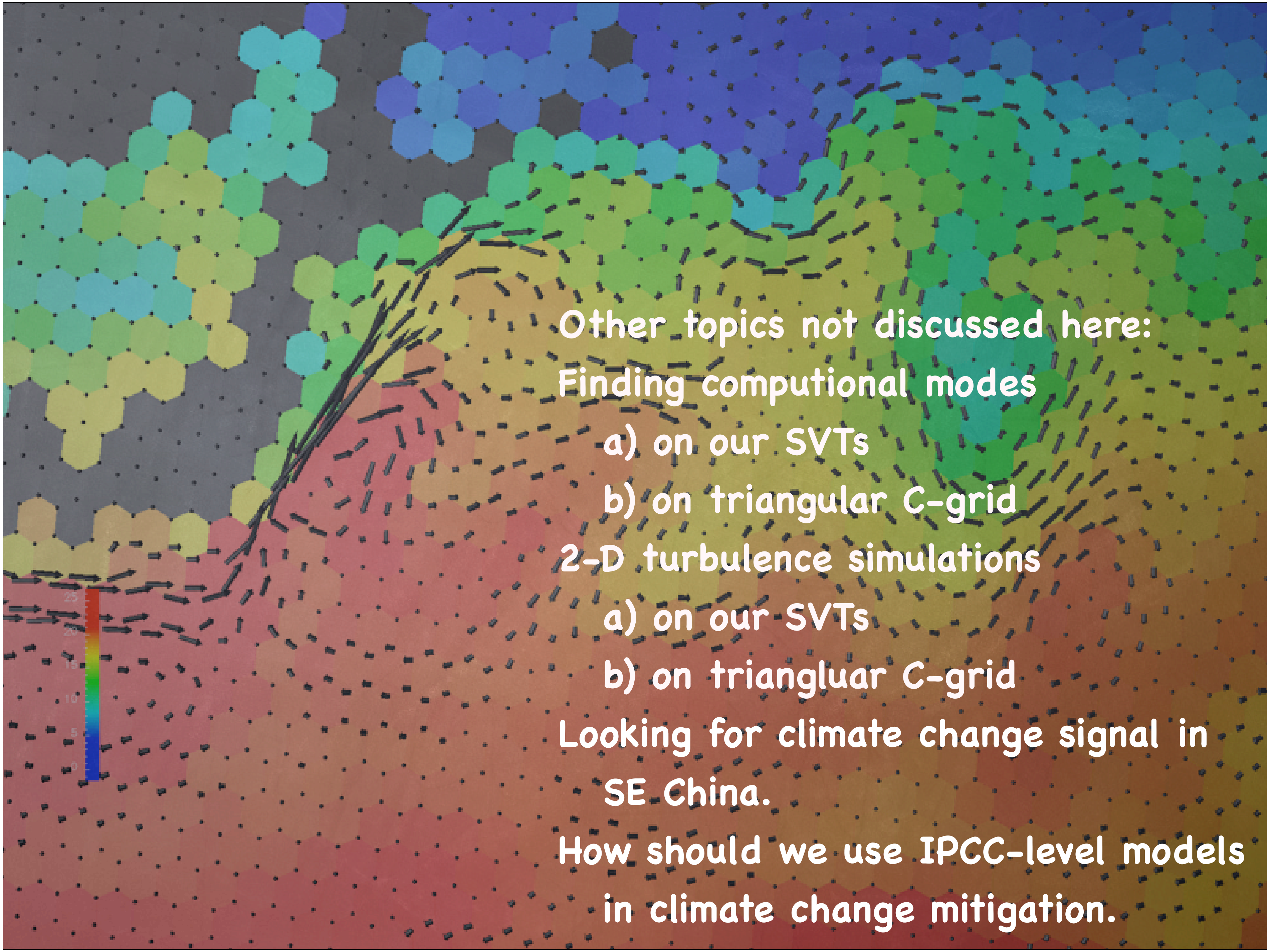


For more than 7 tracers, IR wins over FCT.

Lipscomb and Ringler, 2005, to appear.

So what have we accomplished here?





Other topics not discussed here:

Finding computional modes

- a) on our SVTs
- b) on triangular C-grid

2-D turbulence simulations

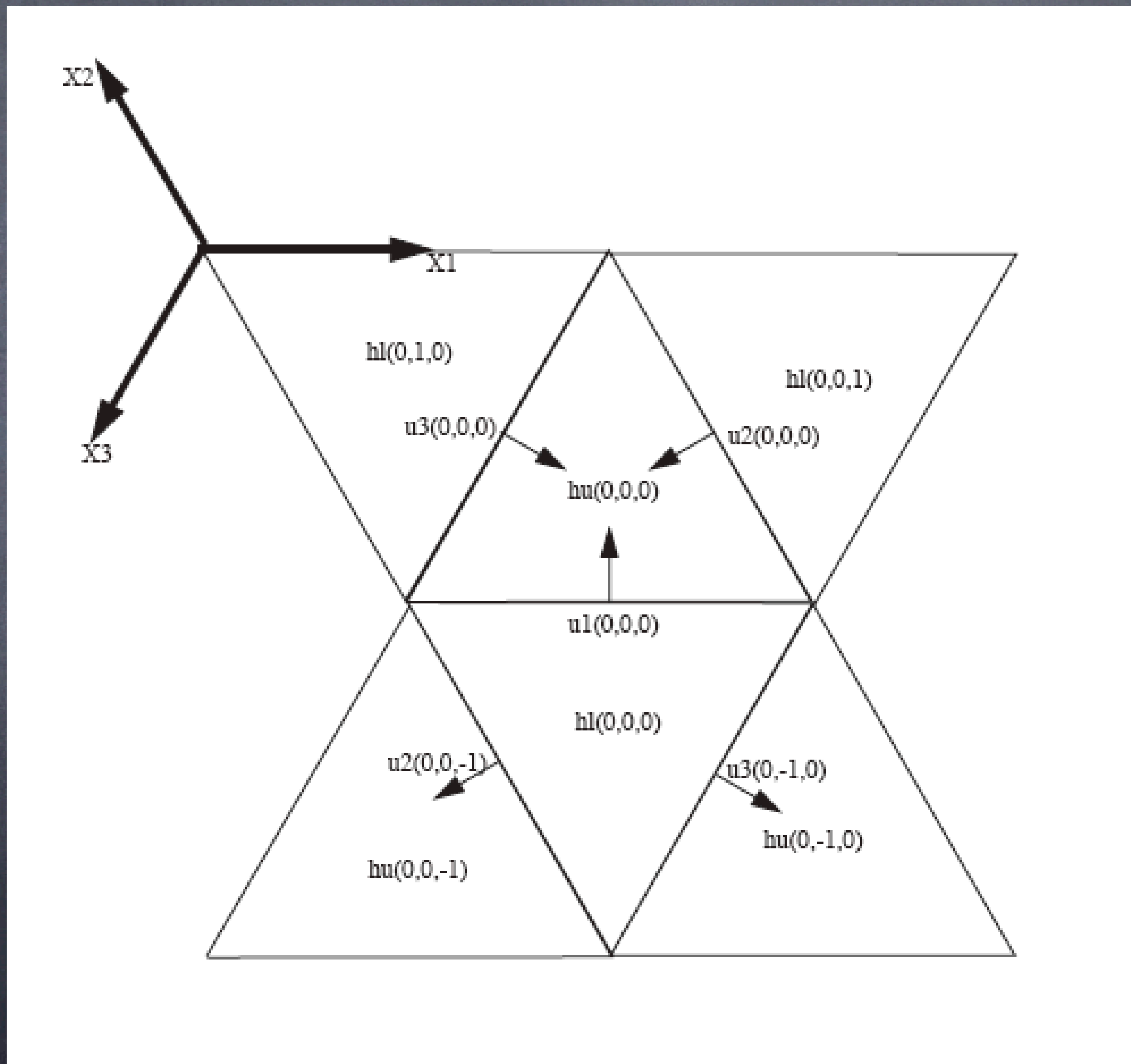
- a) on our SVTs
- b) on triangluar C-grid

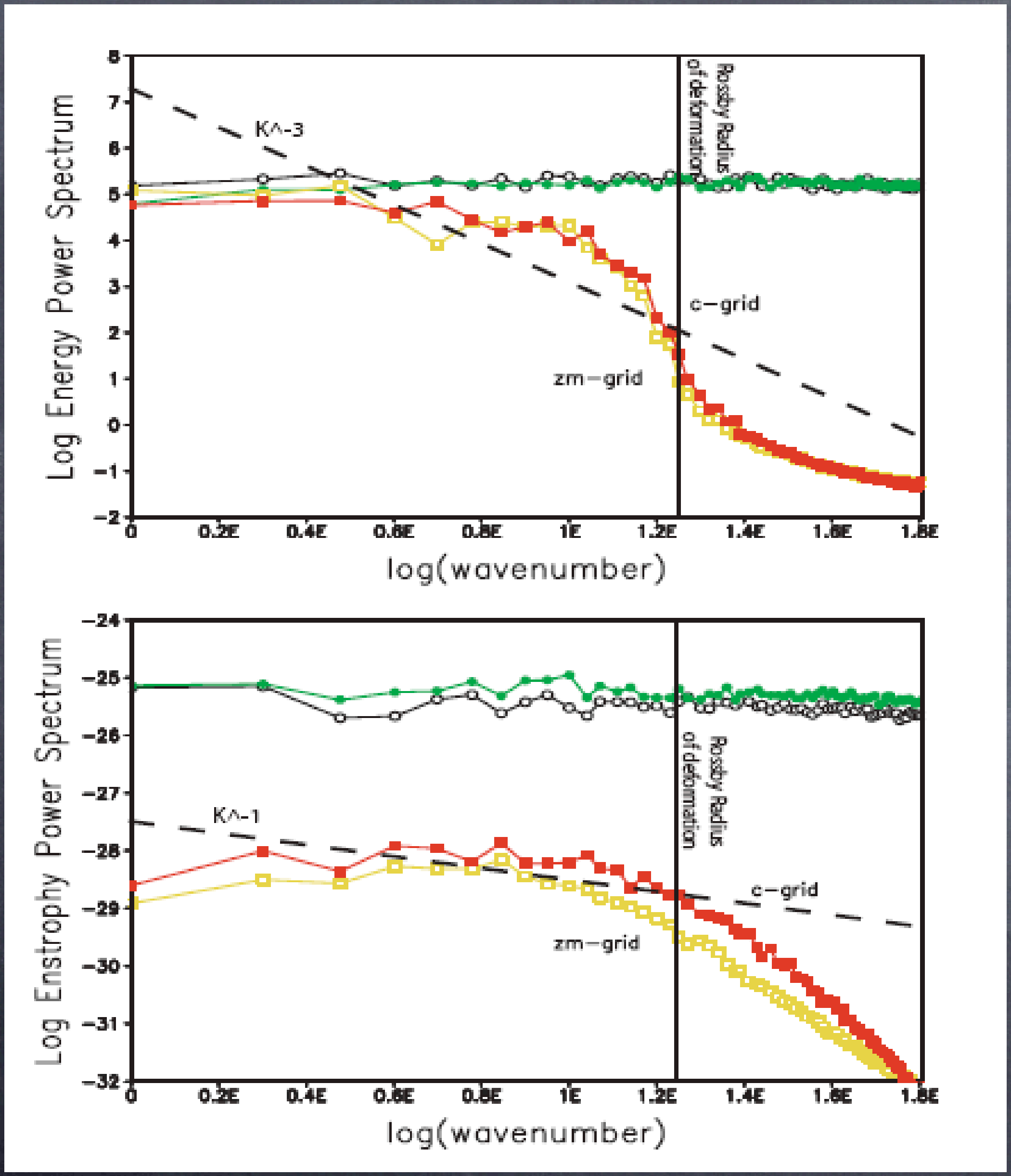
Looking for climate change signal in SE China.

How should we use IPCC-level models in climate change mitigation.

Other topics

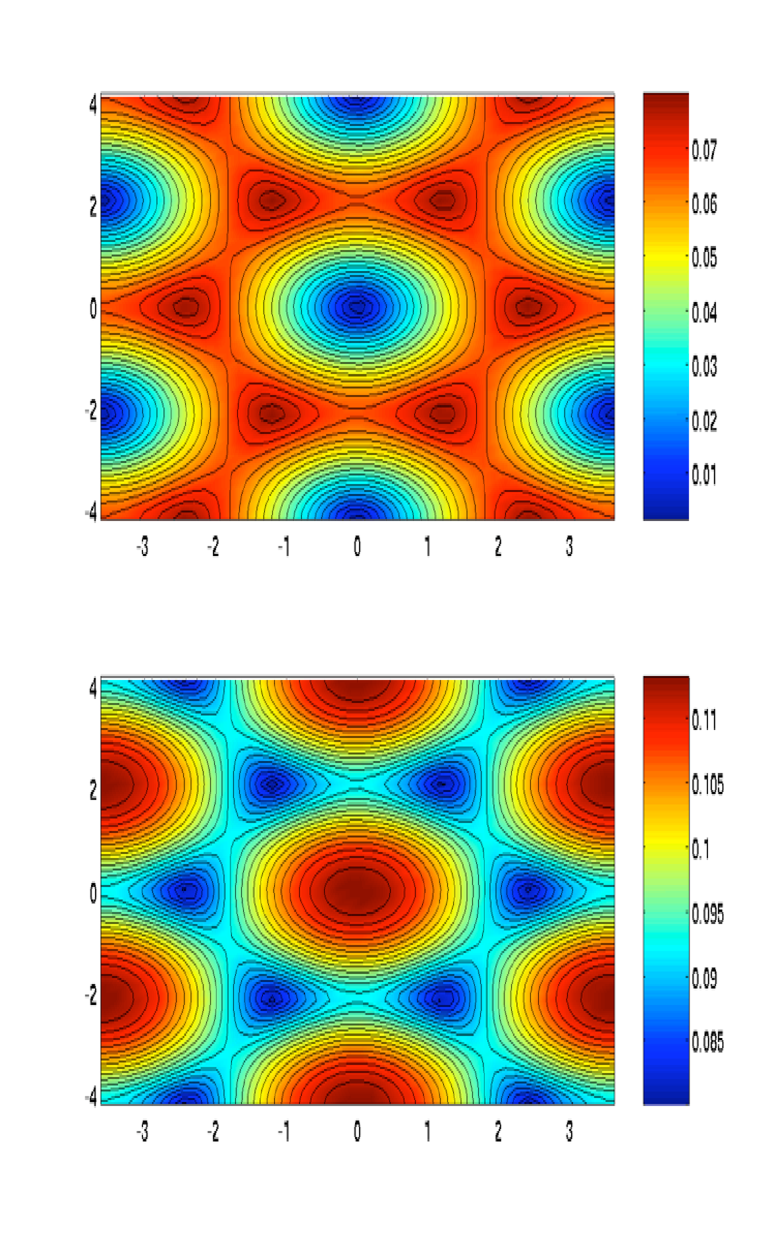
Designing a trianglular C-grid model





Designing a triangluar C-grid model to simulate the correct energy and enstrophy spectra.

Bonaventura and Ringler, 2005, to appear.



Pure Gravity Waves

Physical Mode: has zero group velocity in resolved wavenumber space.

Computational Mode: has frequency always greater than physical mode.

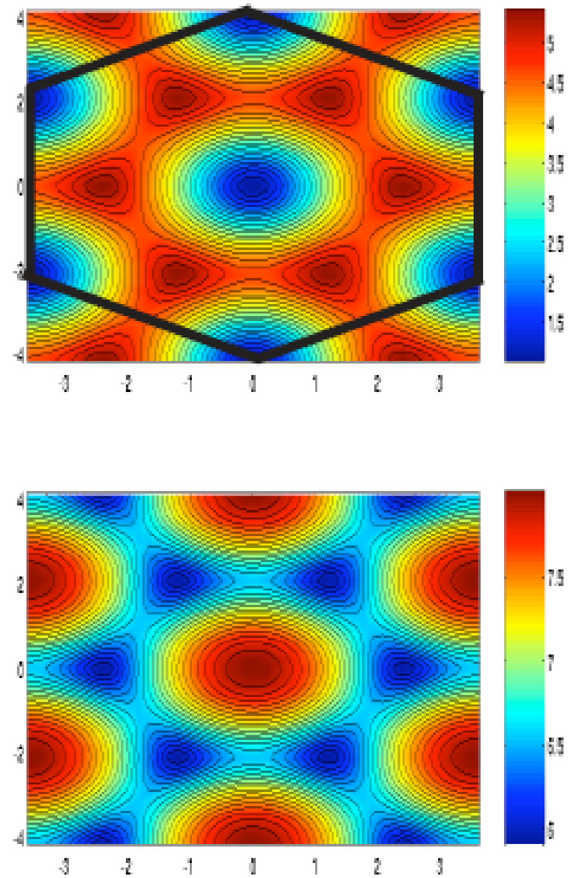
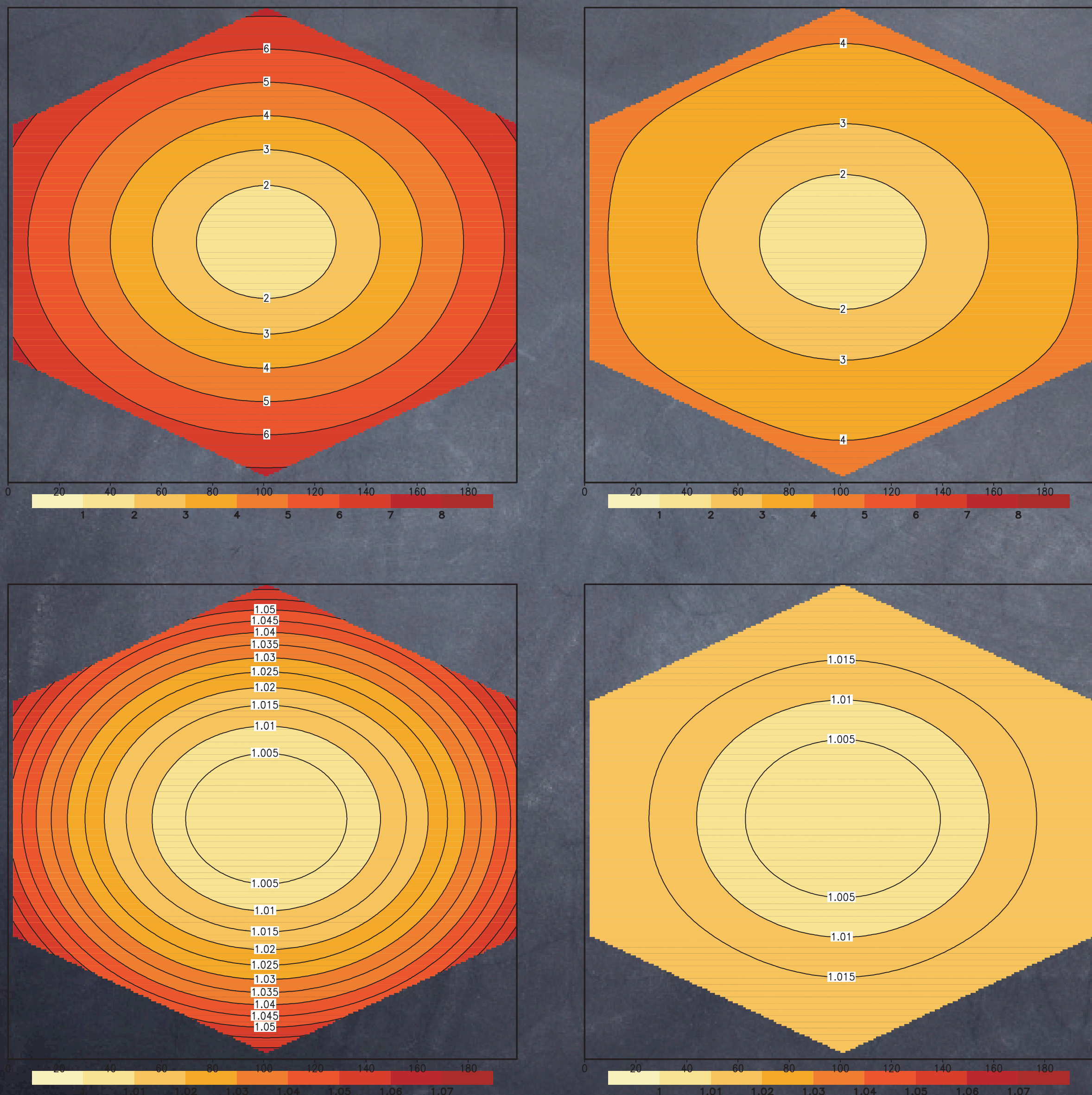
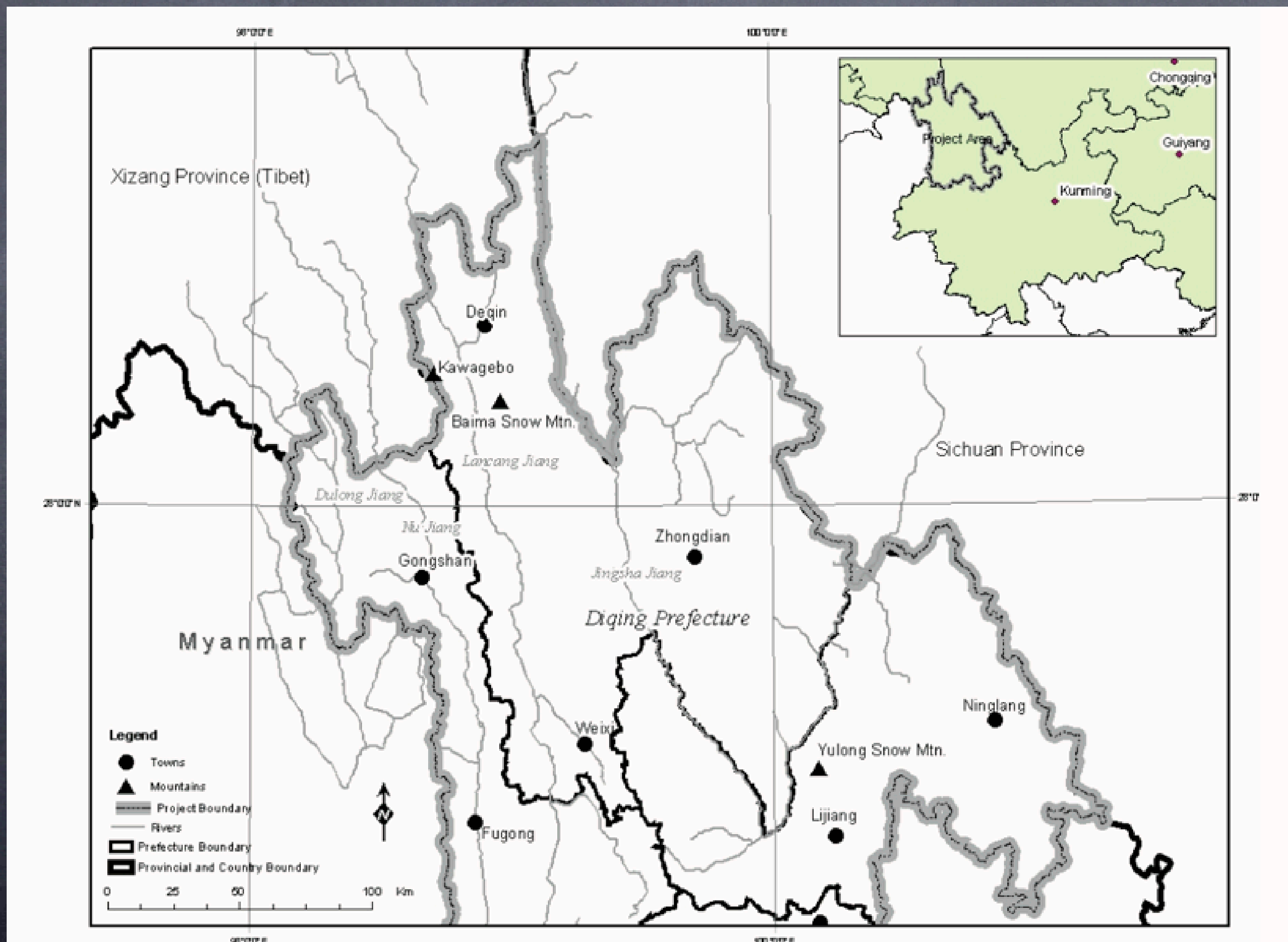


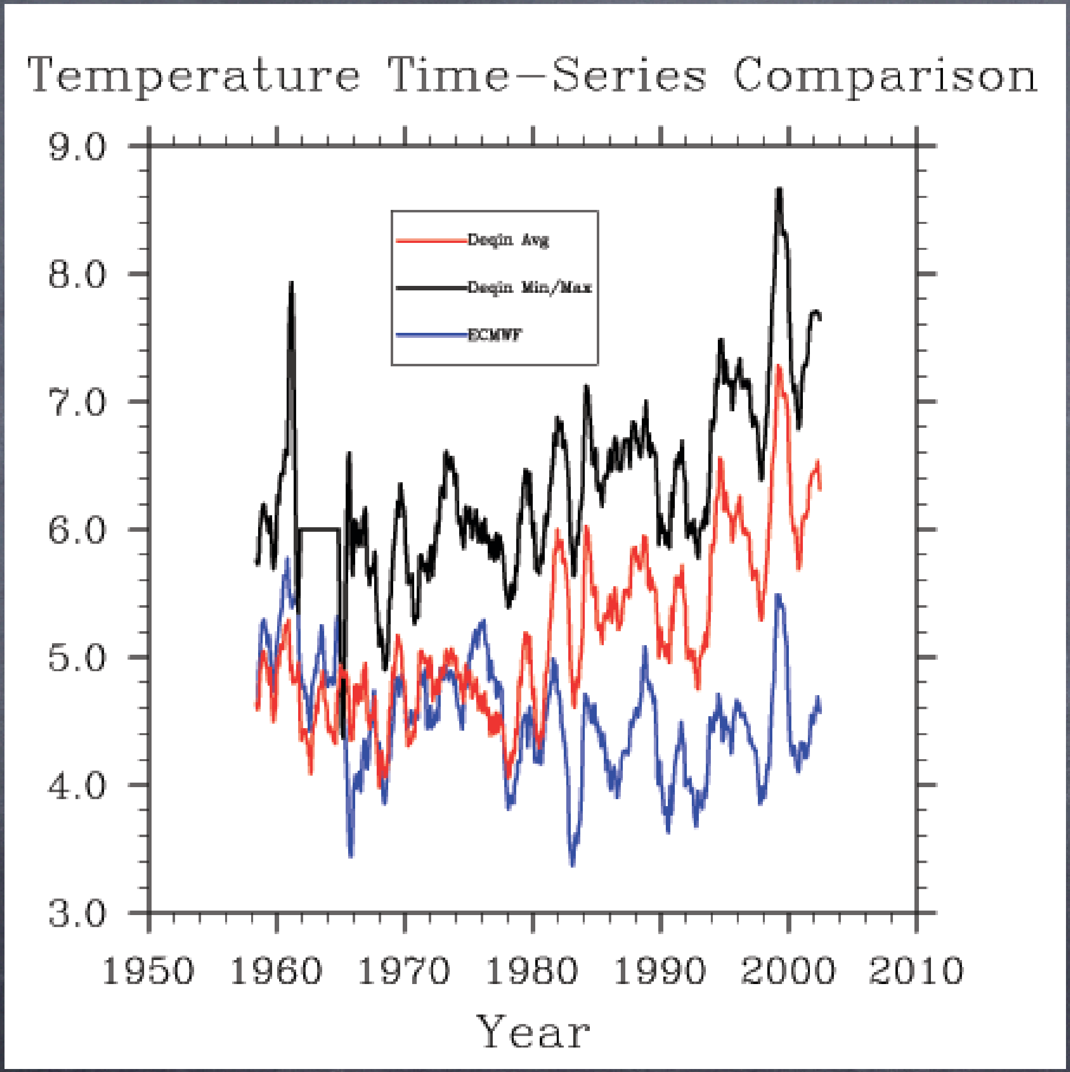
Figure 3: Rossby radius over d = 2. Physical modes on top, computational modes on bottom.



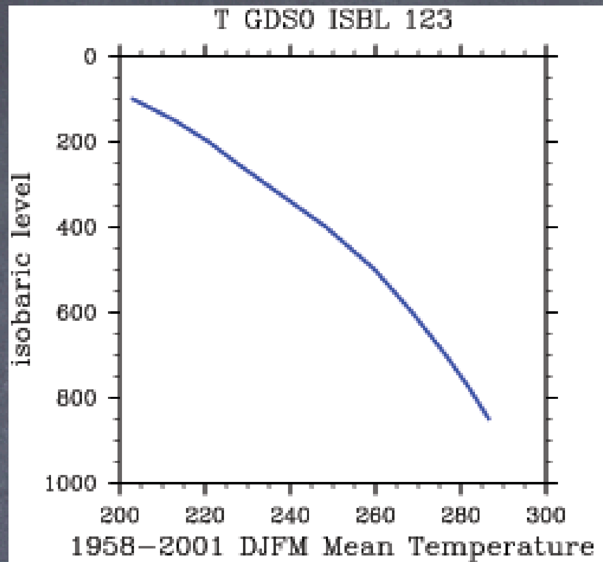
Our scheme faithful reproduces the geostrophic adjustment process.

Collaboration with The Nature Conservancy



Temperature Time–Series Comparison
Deqin Avg
Deqin Min/Max
ECMWF
9.0
8.0
7.0
6.0
5.0
4.0
3.0
1950
1960
1970
1980
1990
2000
2010
Year


T GDS0 ISBL 123
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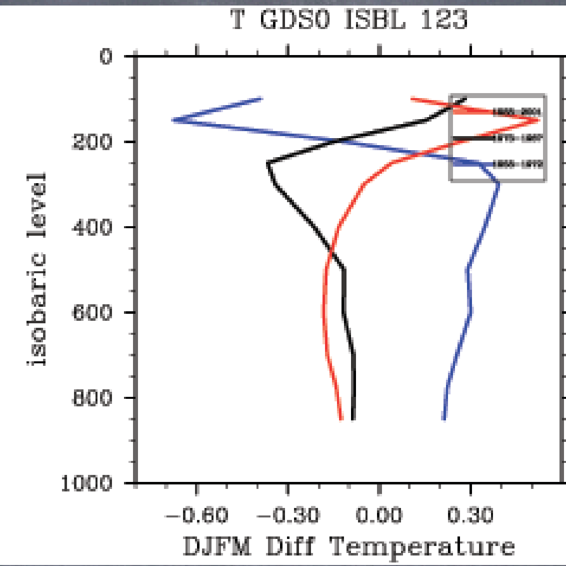
1958−2001 DJFM Mean Temperature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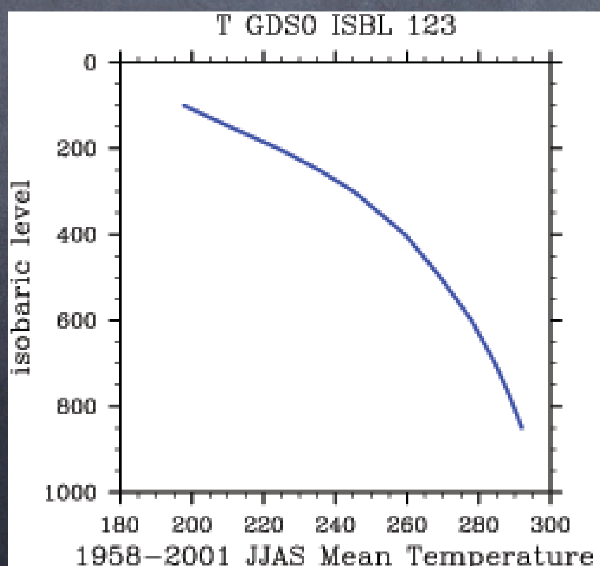
DJFM Diff Temperature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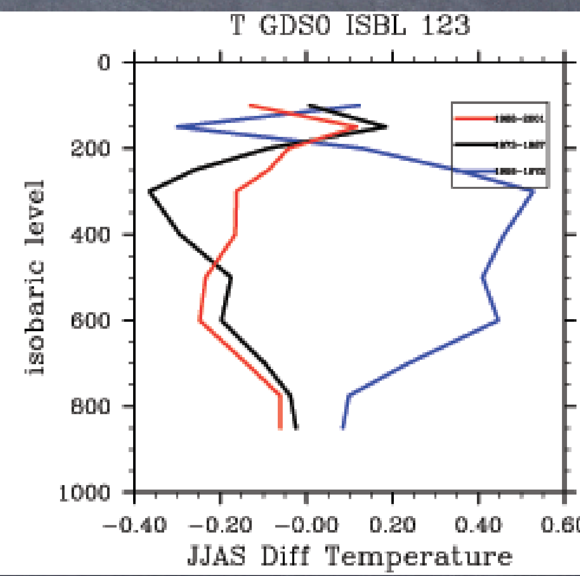
1958−2001 JJAS Mean Temperature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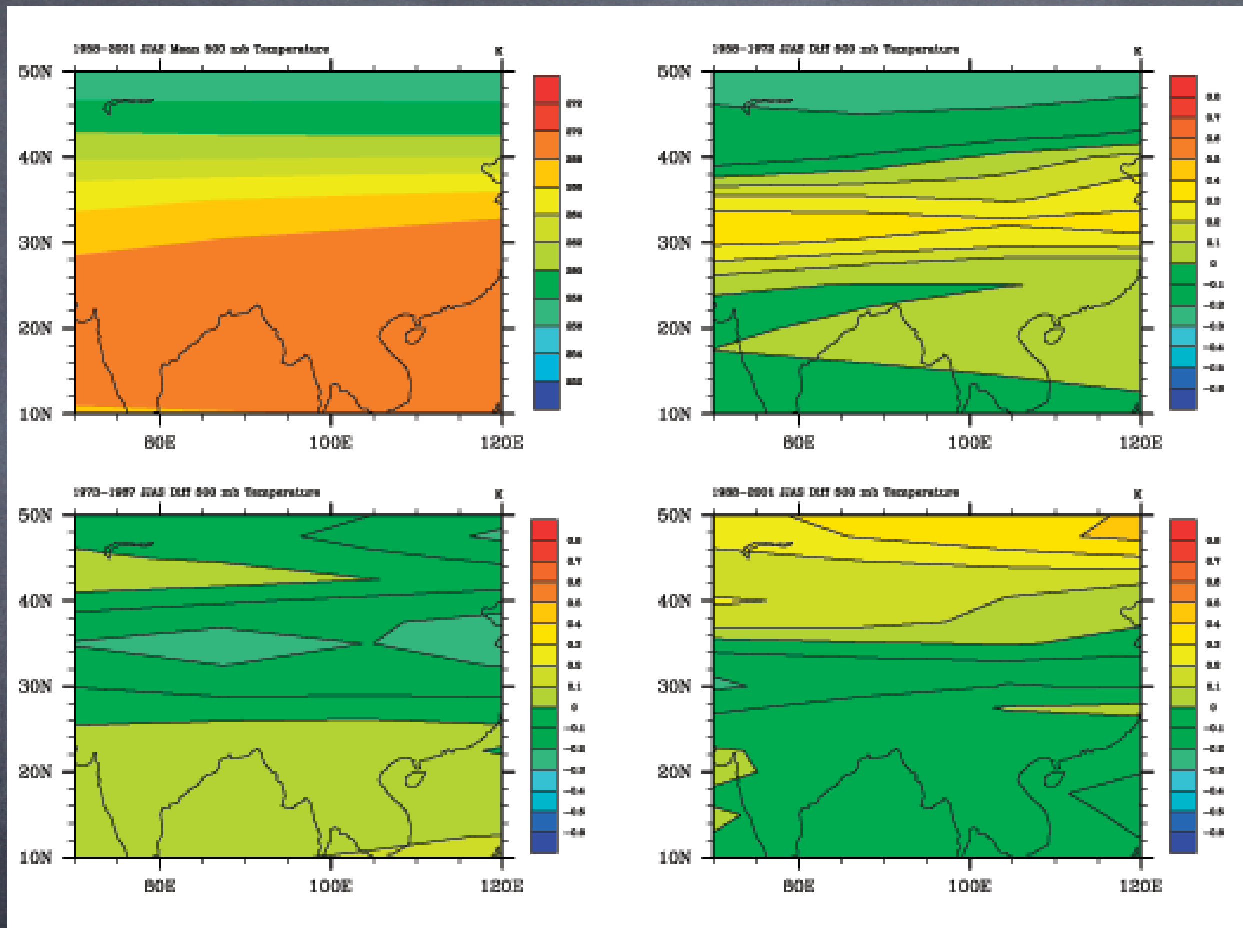
JJAS Diff Temperature


1958-2001 JJAS Mean 500 mb Temperature
1958-1972 JJAS Diff 500 mb Temperature
1973-1987 JJAS Diff 500 mb Temperature
1988-2001 JJAS Diff 500 mb Temperature
K
50N
40N
30N
20N
10N
80E
100E
120E