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NEPTUNE: Next Generation Atmospheric Modeling at the U.S. Naval Research Laboratory

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- DCMIP 2016, NCAR

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- 3: National Research Council; 4: UCAR Visiting Scientist
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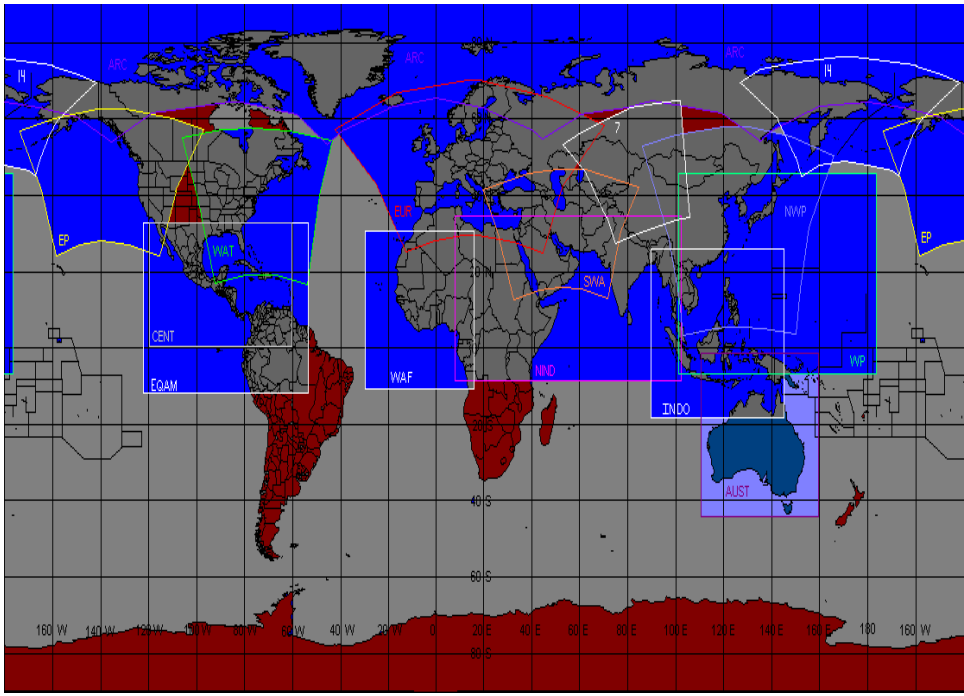
NRL Marine Meteorology Division and Operational Partner FNMOC

- **Weather and seasonal climate**

- **Global Forecasting:**
  - NAVGEM, SL-SI spectral transform
    - 4 times daily, currently 31km resolution
- **Limited Area (Mesoscale) Forecasting:**
  - COAMPS®, split-explicit FD
    - Over 70 unclassified COAMPS domains run daily down to 500m resolution
    - Domains are always in flux
- **Why invest in a new system?**
  - Neither system is positioned to exploit next generation architectures
  - Both systems are low order and non-conservative (though skillful nonetheless)
  - We are not a large laboratory, roughly 100 scientists, less than half working on model development



- **consolidation to a unified system would be advantageous in many ways**

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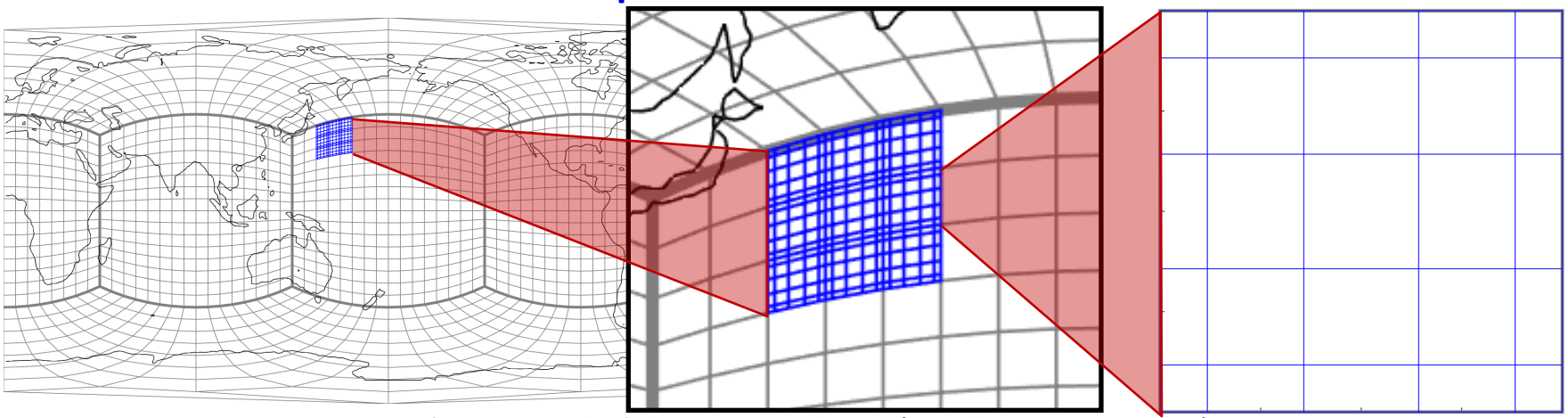
Next Generation Modeling

- **Navy goal to develop next generation model, with capabilities:**
  - **Multi-scale non-hydrostatic dynamics (global-scale to mesoscale)**
  - **Highly scalable, flexible, accurate, and conservative numerical methods**
  - **Structured, unstructured, or adaptive grids; scale-aware parameterizations**

- **A spectral element (SE) technique is the selected numerical method**
  - **Solution is represented by a local polynomial expansion, good convergence**
  - **Very small communication footprint implies excellent computational scaling**

- **Use the *NUMA*[1] dynamical core as the foundation for our NWP system**
  - **Global and limited area capabilities.**



[1]***NUMA***: ***N****onhydrostatic* ***U****nified* ***M****odel of the* ***A****tmosphere (Giraldo et. al. 2013)*

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Features

- Deep atmosphere equations
- Non-hydrostatic
- Unified **3D** CG/DG dynamical core
- Cartesian coordinate system for limited area
- Sphere centered Cartesian coordinate system for global prediction
- Inexact integration (mass lumping)
- 1D/3D IMEX for efficiency
- Non-conforming AMR

Kelly and Giraldo 2012 JCP, Giraldo et. al J. Sci. Comput. 2013, Kopera and Giraldo 2014 JCP

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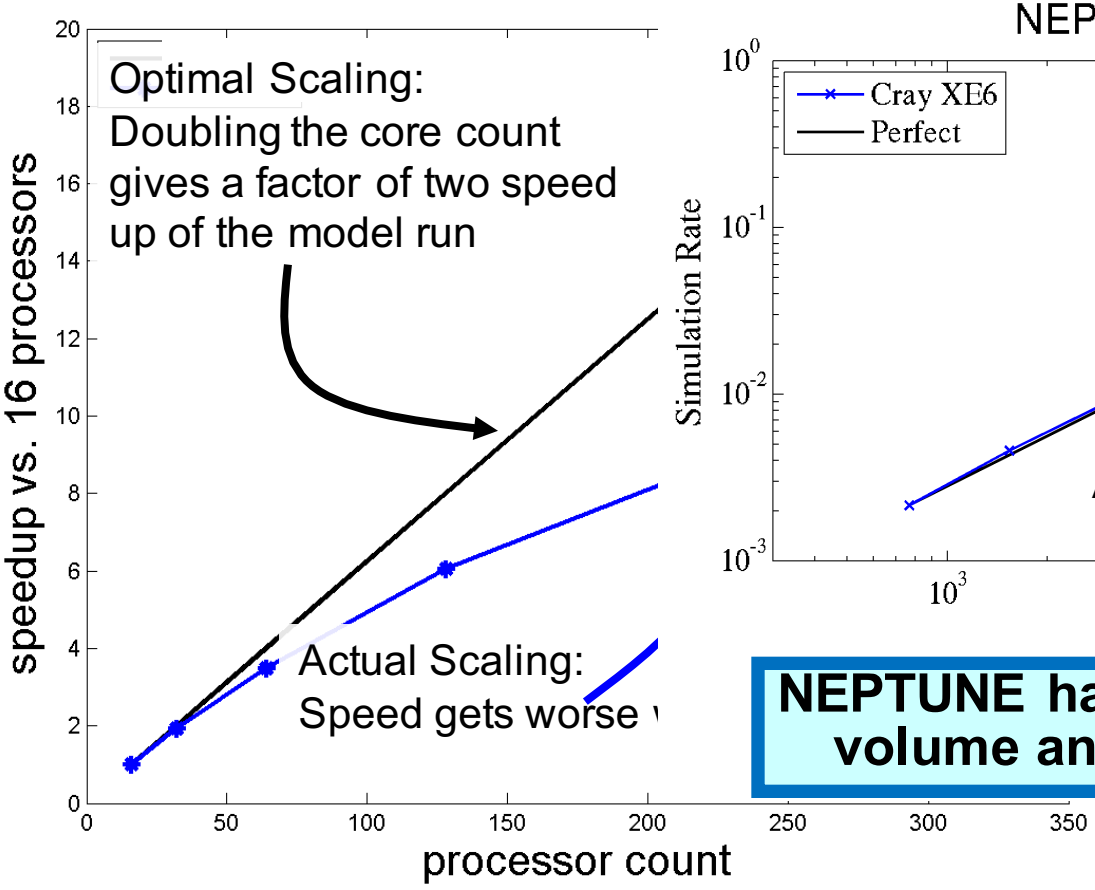
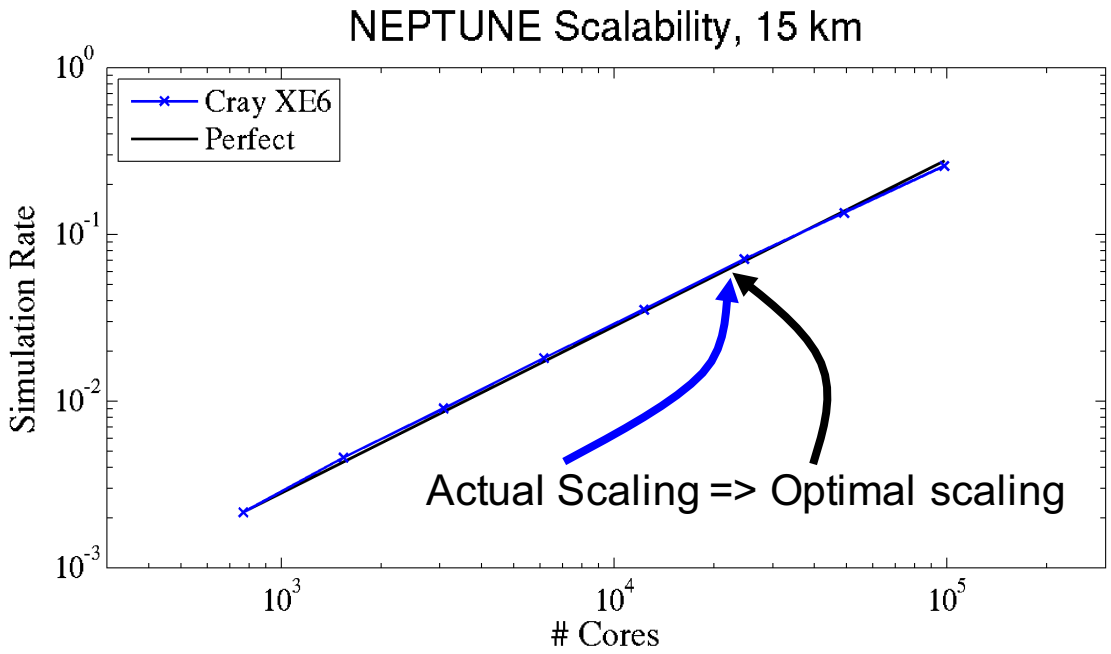
Computational Scaling





NEPTUNE has a small communication volume and scales extremely well

Often with models that require large communication volumes, the cost of communication will dominate the cost of computation as the core count increases.

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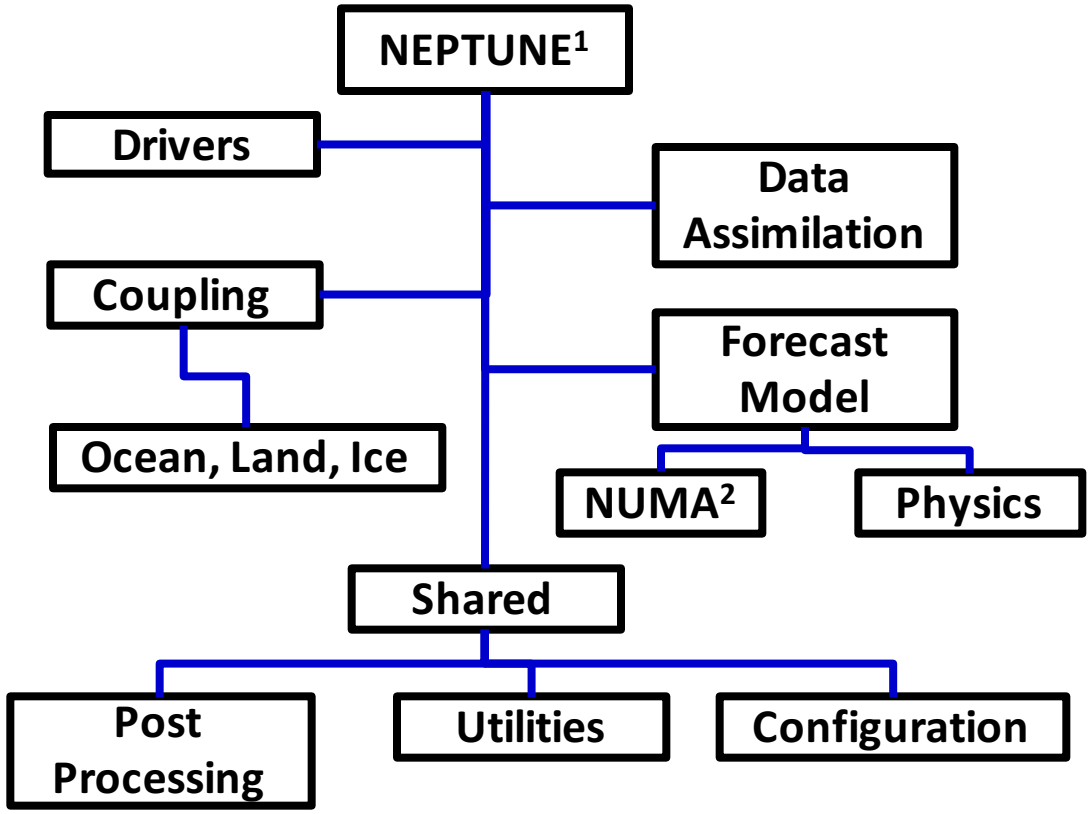
NEPTUNE

NEPTUNE is the US NAVY's next generation NWP system

NUMA is the dynamical core of NEPTUNE

NUMA uses a **three-dimensional** spectral element technique with a sphere centered Cartesian coordinate system on the cubed sphere



[1] ***NEPTUNE:*** *Navy Environmental Prediction sysTem Utilizing the NUMA[2] corE*

[2] ***NUMA:*** *Nonhydrostatic Unified Model of the Atmosphere (Giraldo et. al. 2013)*

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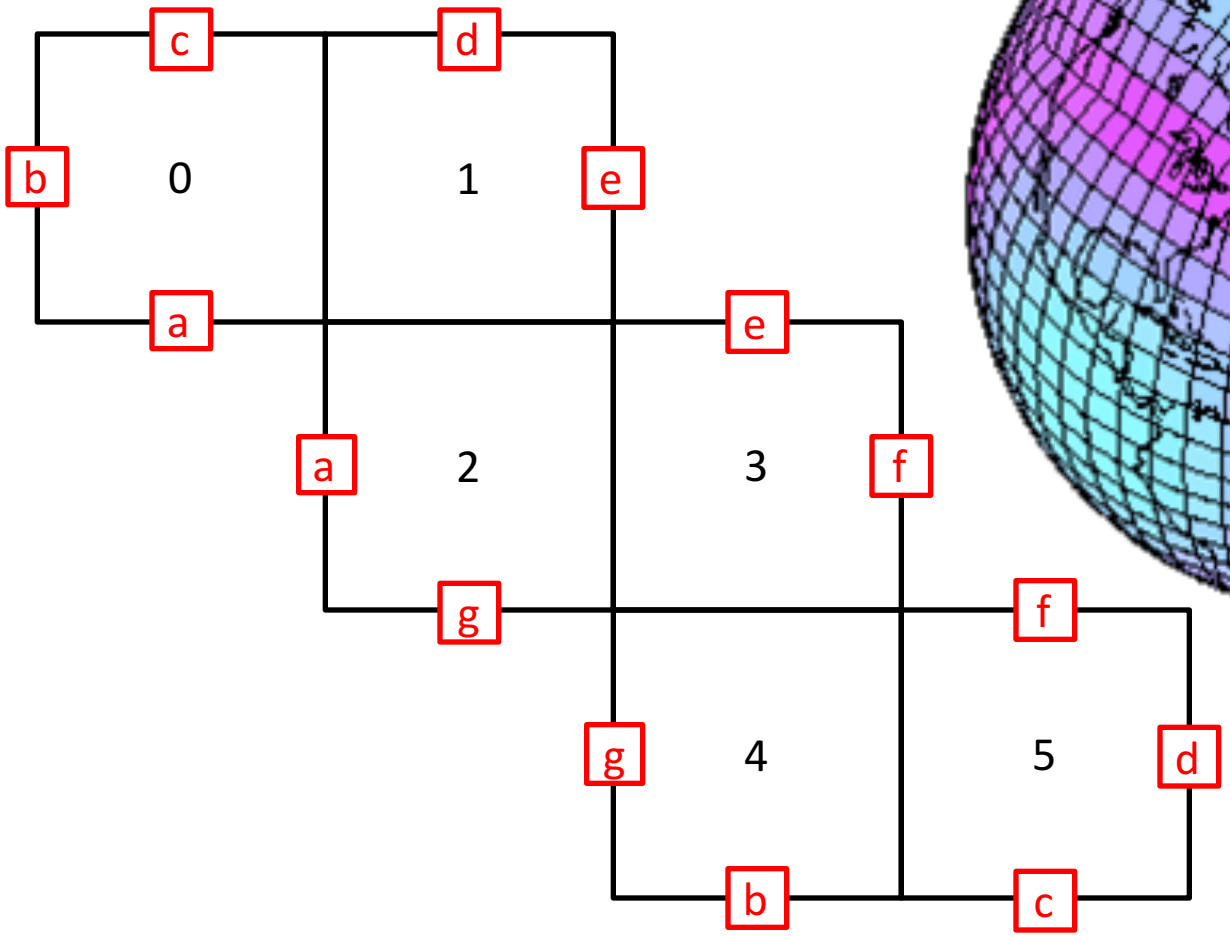
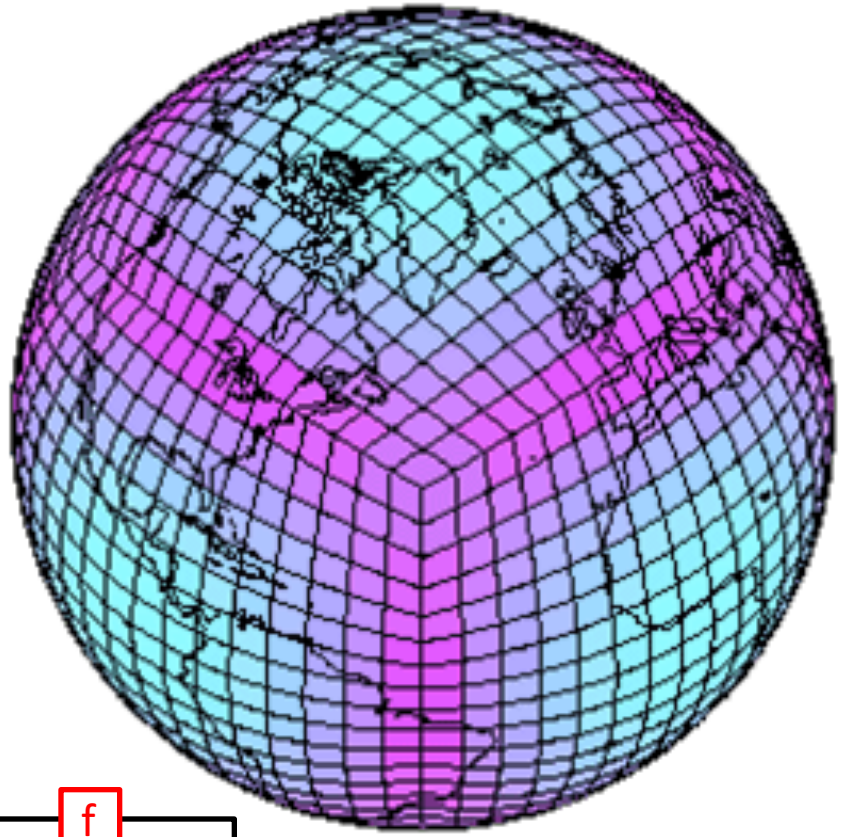
NUMA Grid on the Sphere (Cubed Sphere)





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NUMA Grid on the Sphere (Cubed Sphere)

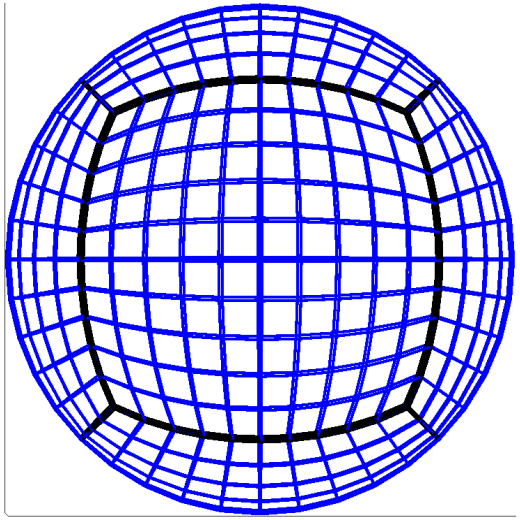
- Equi-angular gnomonic plane
- Equi-distant gnomonic transform
- Local spherical transform (template face)
- Rotate to respective faces to build cubed sphere
  - expand radially
  - Cartesian transform

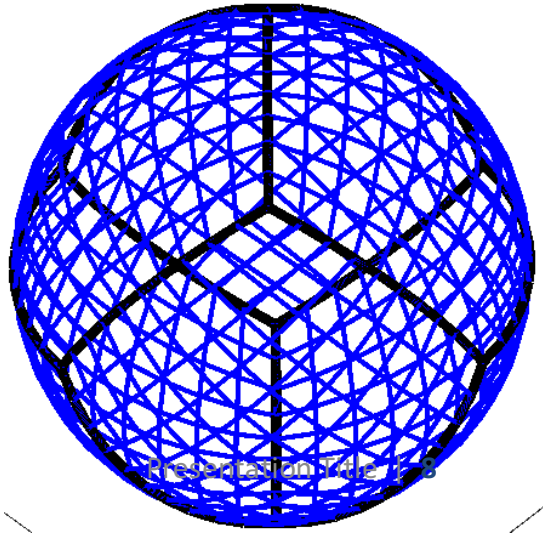
$$\vec{\lambda}^f \begin{Bmatrix} \lambda^{fc} + \tan^{-1}\left(\dfrac{\cos\phi^1 \sin\lambda^1}{\cos\phi^1 \cos\lambda^1 \cos\phi^{fc} - \sin\phi^1 \sin\phi^{fc}}\right) \\ \sin^{-1}(\sin\phi^1 \cos\phi^{fc} + \cos\phi^1 \cos\lambda^1 \sin\phi^{fc}) \end{Bmatrix}$$

– *Superscripts: f* for face number, *fc* for face center, *1* for template face at (0,0)

$$\{\lambda, \phi\} \rightarrow \{\lambda, \phi, r\}$$

$$\vec{x} = \{x, y, z\} \in [-r, r] \qquad \vec{x} = \begin{Bmatrix} r\cos\phi\cos\lambda \\ r\cos\phi\sin\lambda \\ r\sin\phi \end{Bmatrix}$$



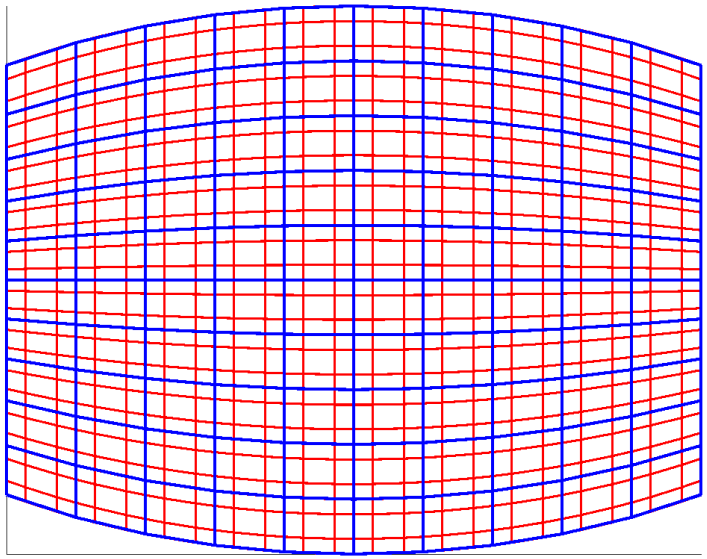


Original Metric Terms

- Metric terms for transforming between physical ($\vec{x} = \{x, y, z\}$) and canonical ($\vec{\xi} = \{\xi, \eta, \zeta\}$) spaces use the SE machinery (basis functions) and are built ***discretely***

$$\nabla_{\vec{\xi}} \vec{x} = \begin{Bmatrix} x_\xi & x_\eta & x_\zeta \\ y_\xi & y_\eta & y_\zeta \\ z_\xi & z_\eta & z_\zeta \end{Bmatrix}$$

- *Attempts to resolve the result of several trigonometric transforms using a low-order basis*



- *Results in significant error in representing the sphere for polynomial degrees less than 8*

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Semi-Analytic Metric Terms (Current)

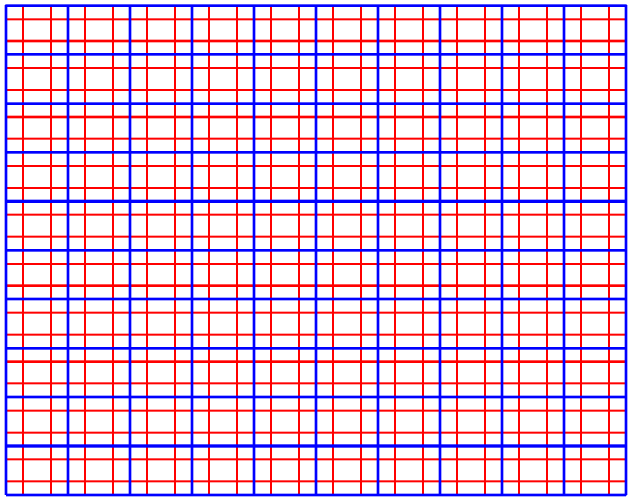
- Replace discrete metric terms with analytic terms wherever possible using the chain rule and the steps used to create the cubed sphere

$$\nabla_{\vec{\xi}}\vec{x} = (\nabla_{\vec{\xi}}\overrightarrow{x_\alpha})\left[(\nabla_{\overrightarrow{x_\alpha}}\overrightarrow{x_e})(\nabla_{\overrightarrow{x_e}}\vec{\lambda})\boldsymbol{R}^{-1}(\nabla_{\vec{\lambda}}(\boldsymbol{R}\vec{x}))\right]_A$$

- Uses analytic representations of Jacobians from the:
  - Equidistant gnomonic transform
  - Local spherical transform
  - Cartesian coordinate transform

- Subscript *A* is for *analytic*
- **R** is a rotation matrix back to face 1 (0,0) of the cubed sphere to avoid pole problems and apply metrics consistently across each face

- Discrete derivatives in canonical space are performed on the equiangular plane
  - This is linear and representable by a low order basis in the absence of terrain



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Shallow Atmosphere Approximation

- Applying the shallow atmosphere approximation is trivial using the semi-analytic metric terms

$$\vec{x} = \begin{Bmatrix} r\cos\phi\cos\lambda \\ r\cos\phi\sin\lambda \\ r\sin\phi \end{Bmatrix}$$

- In the Jacobian of the mapping from spherical to Cartesian space, replace all instances of **r** with **a**
  - **a** is the radius of the earth and **r** = (**a**+z)

$$\nabla_{\vec{\lambda}}\vec{x} = \begin{Bmatrix} -r\cos\phi\sin\lambda & -r\sin\phi\sin\lambda & \cos\phi\cos\lambda \\ r\cos\phi\cos\lambda & -r\sin\phi\cos\lambda & \cos\phi\sin\lambda \\ 0 & r\cos\phi & \sin\phi \end{Bmatrix}$$

$$\left\{\nabla_{\vec{\lambda}}\vec{x}\right\}_{SA} = \begin{Bmatrix} -a\cos\phi\sin\lambda & -a\sin\phi\sin\lambda & \cos\phi\cos\lambda \\ a\cos\phi\cos\lambda & -a\sin\phi\cos\lambda & \cos\phi\sin\lambda \\ 0 & a\cos\phi & \sin\phi \end{Bmatrix}$$

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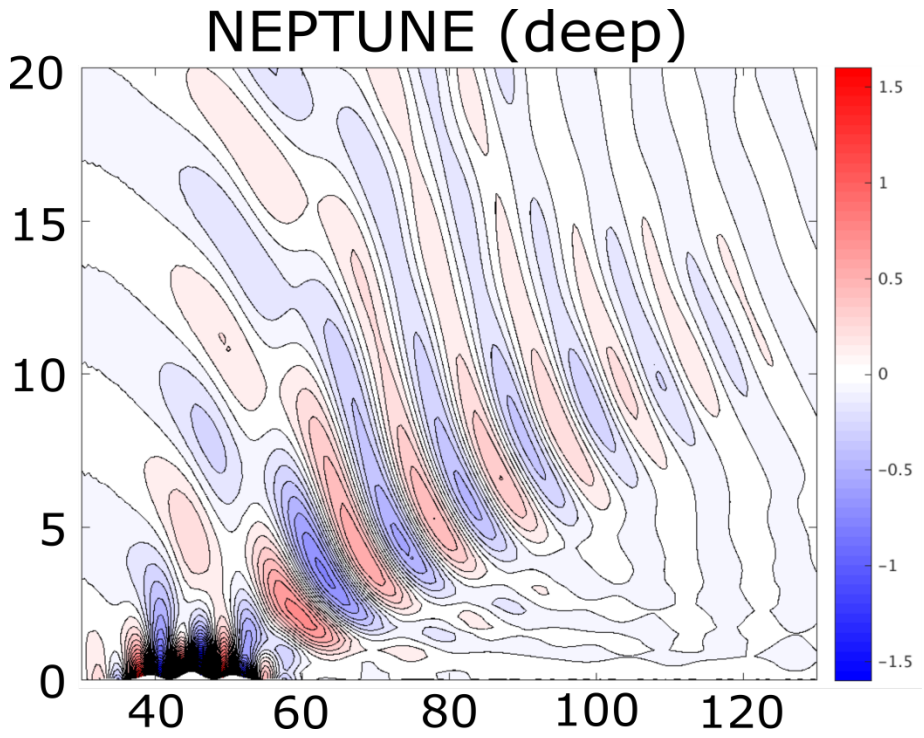
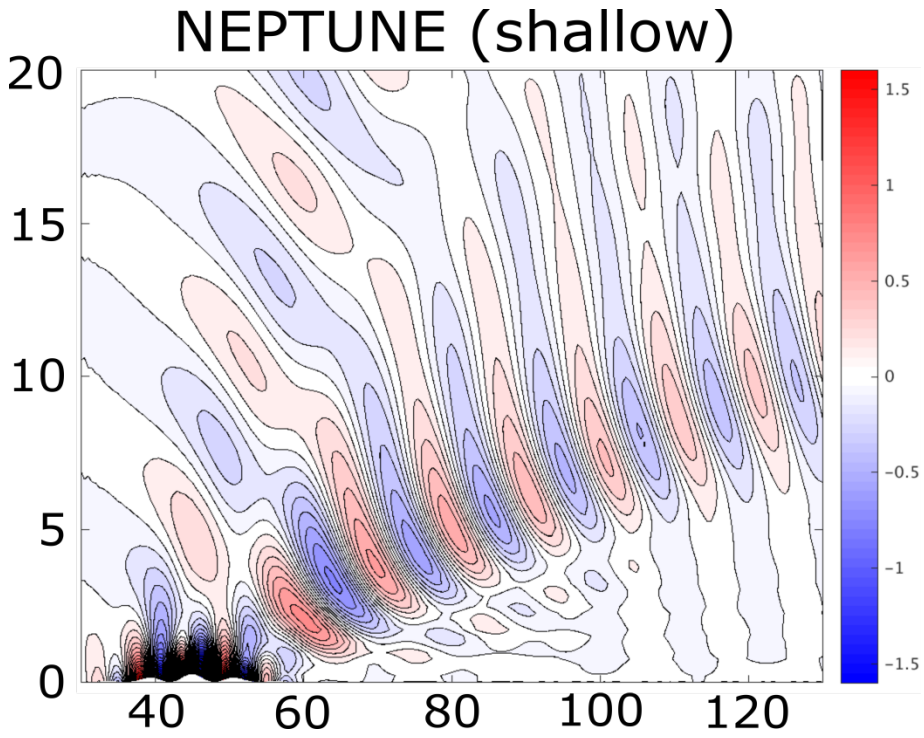
Sheared Flow over Schär Mountain





- Horizontal grid stretching with increasing z which attenuates the vertically propagating wave energy using the deep atmosphere equations

- The shallow equations eliminate the attenuation resulting in increased wave amplitude both aloft and downstream

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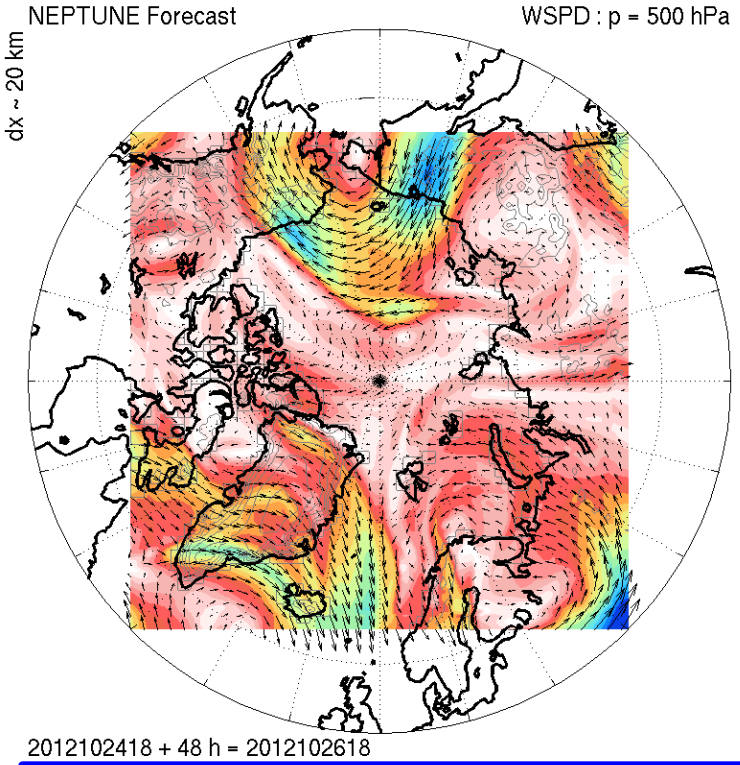
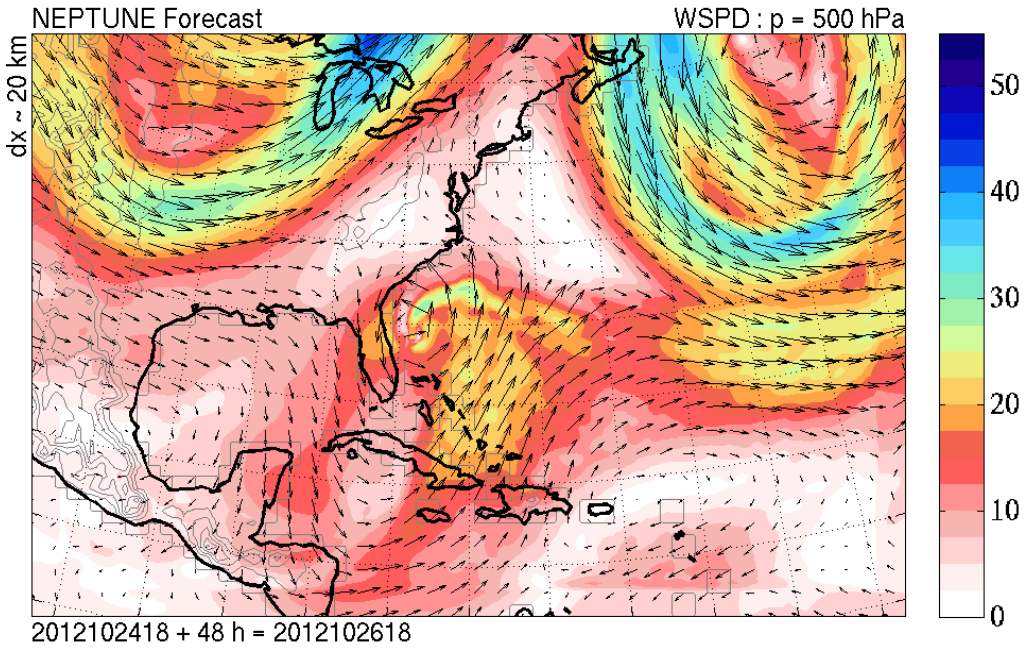
Limited Area Model Application





- Developed a limited area version of NEPTUNE with set of projections
  - Lambert Conformal, Mercator, Stereographic
  - Solution prescribed at lateral boundaries using Davies BC's
- Used to test high-resolution physics without needing to run a high-resolution version of the global configuration

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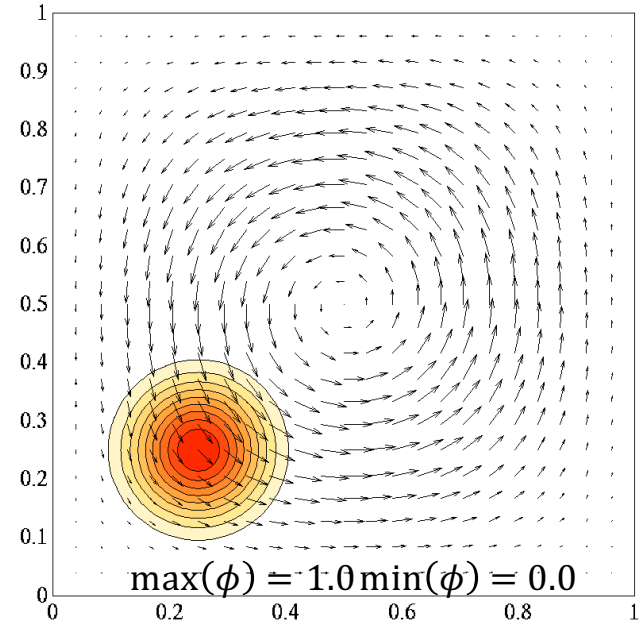
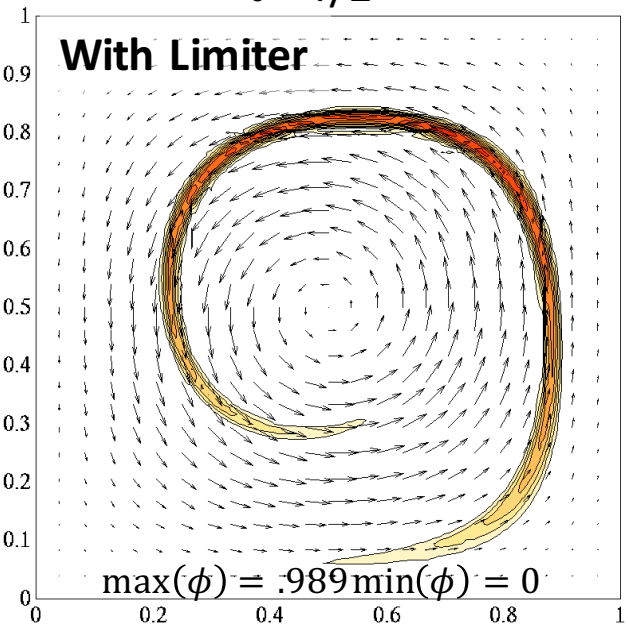
Positive Definite Tracer Transport

Implement a high-order, global conservative, positive definite limiter (TMAR) into NEPTUNE based on Light and Durran, 2016

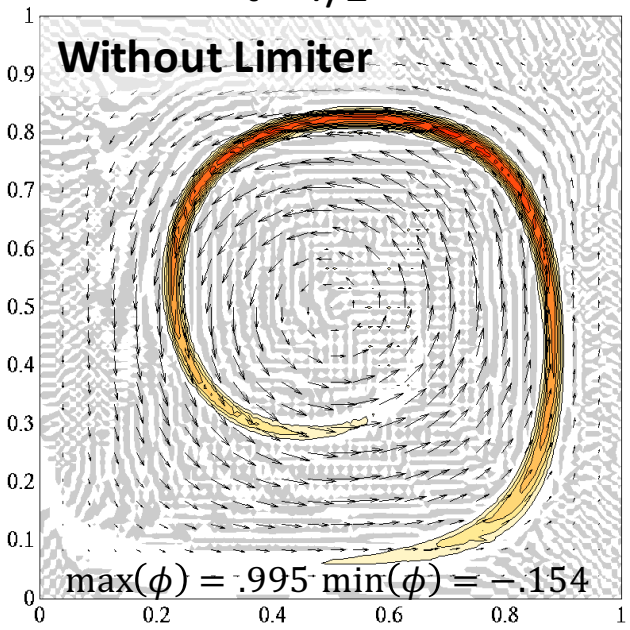
t = 0



t = T/2



t = T/2



Stream function defines the non-divergent velocity field

$$\Psi(x,y,t) = \frac{1}{\pi}\sin(\pi x)^2 \sin(\pi y)^2 \cos\left(\frac{\pi t}{T}\right)$$

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Time Integration

A wide range of high-order IMEX (1D and 3D) time integrators available in NUMA

Problem

- Horizontal sound waves limit Δt for 1D-IMEX (e.g. Δt = 30 s for 60 km horizontal resolution)
- Convergence rates for 3D-IMEX are too slow for real-data

Result

- Up to 8x larger Δt over 1D-IMEX
- More applicable to NWP

Solution

- Implement a split-explicit scheme Runga-Kutta scheme
- Sound waves integrated on a small time step
- Not necessarily a long term solution

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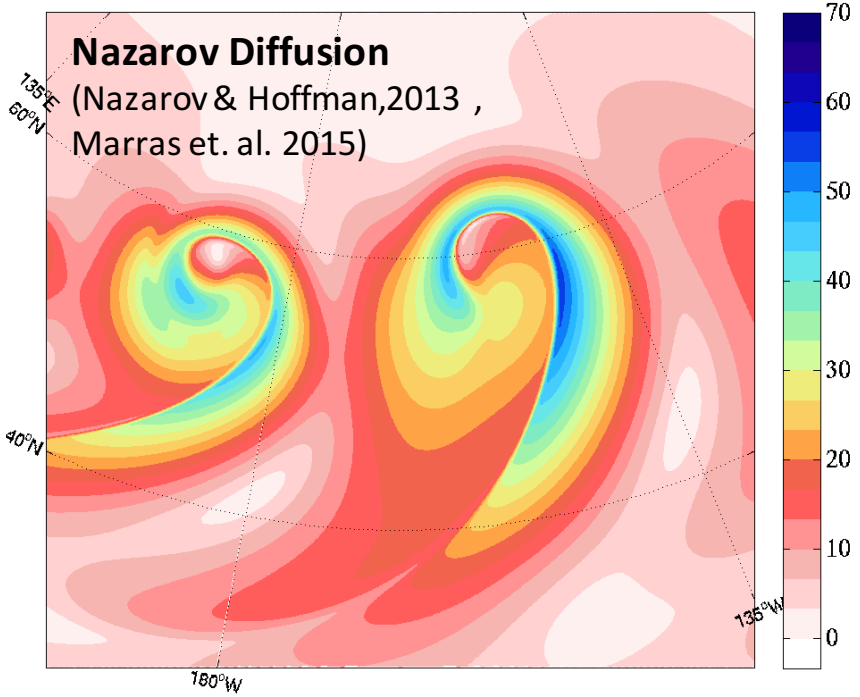
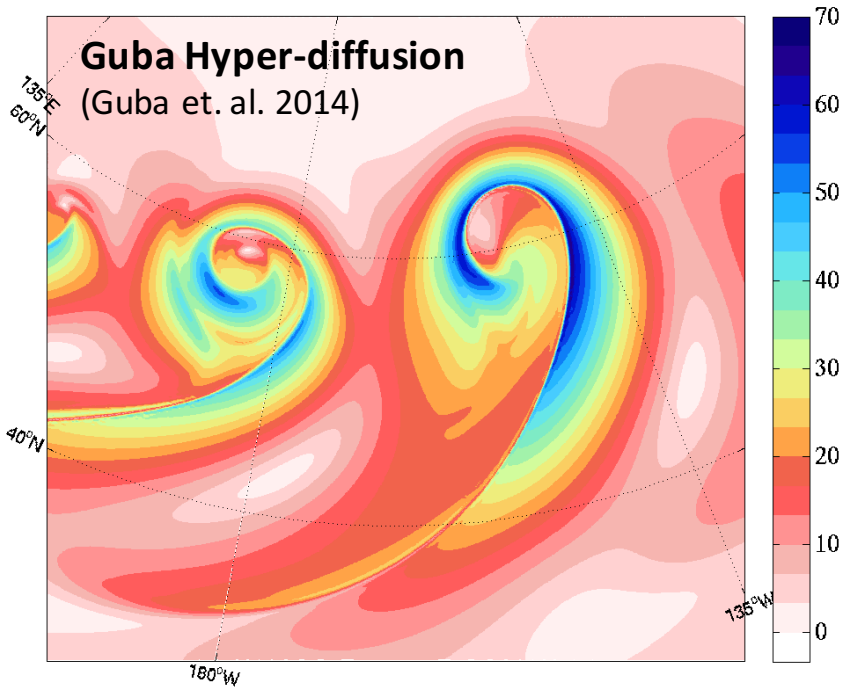
Dry Baroclinic Wave Test

Surface Winds – Day 9





- Initially not able to maintain stability –> 3-D diffusion operator
- Implemented Nazarov based diffusion for stabilization
- Change to Guba hyper-diffussion (4^{th}-order) → horizontal and vertical

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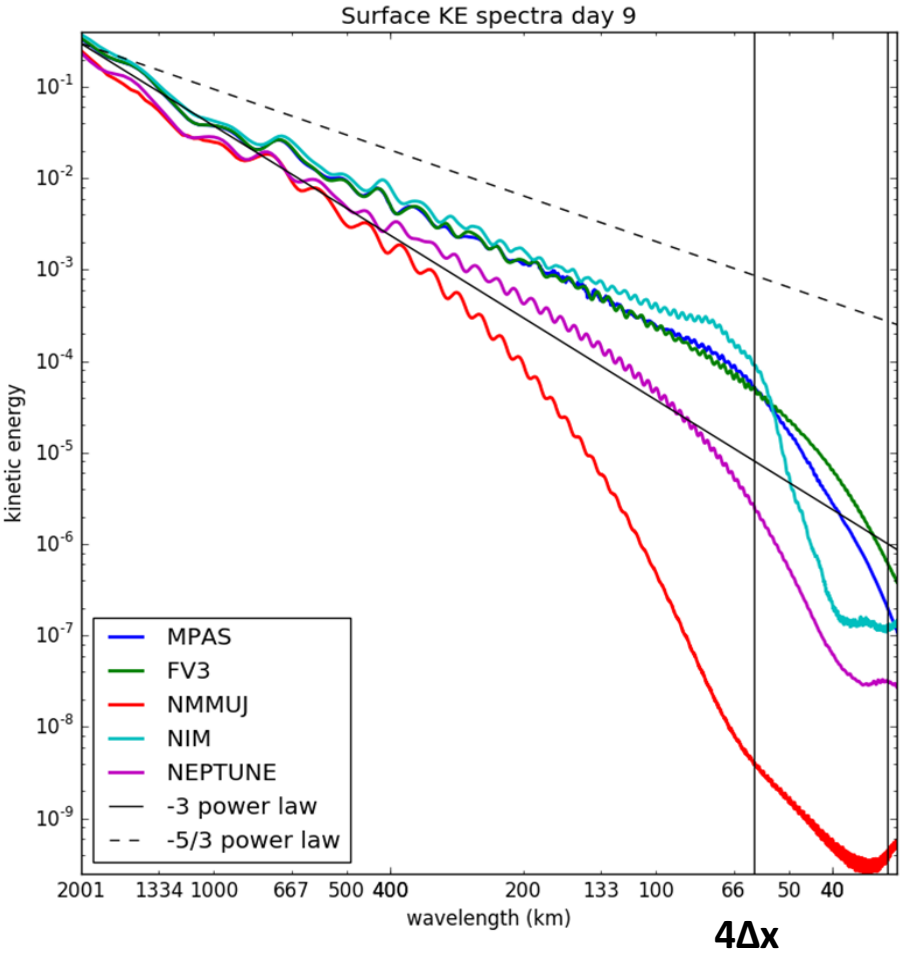
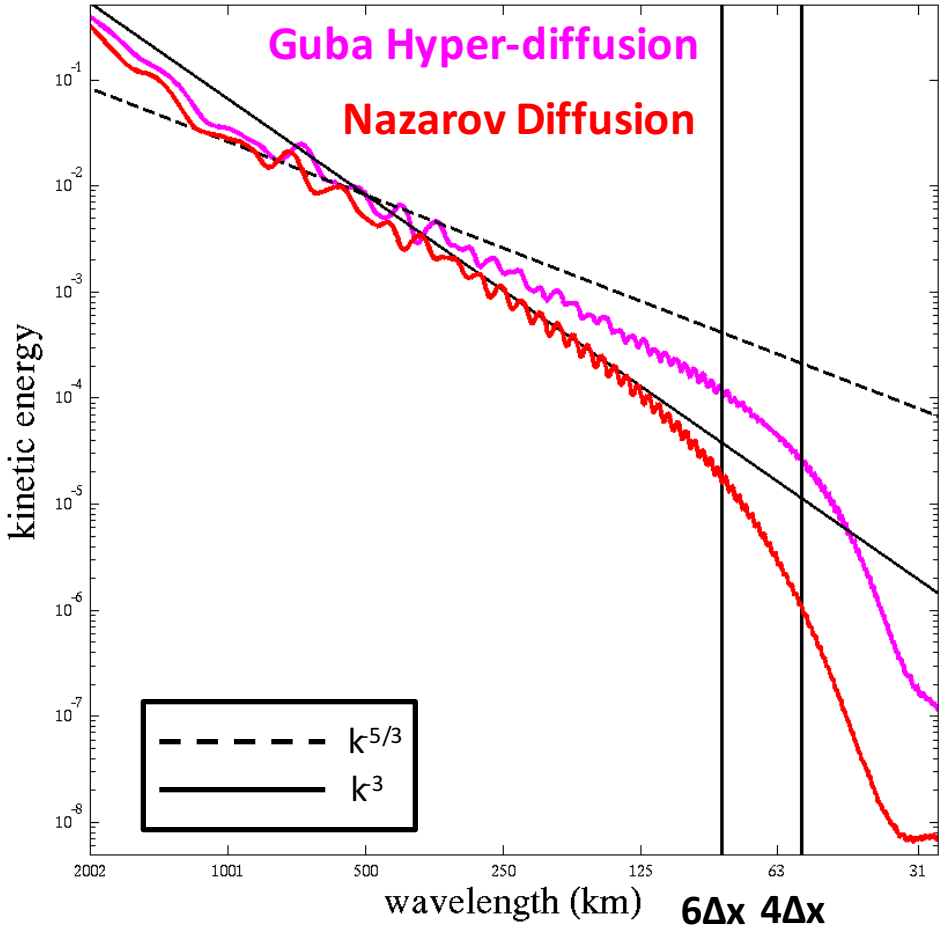
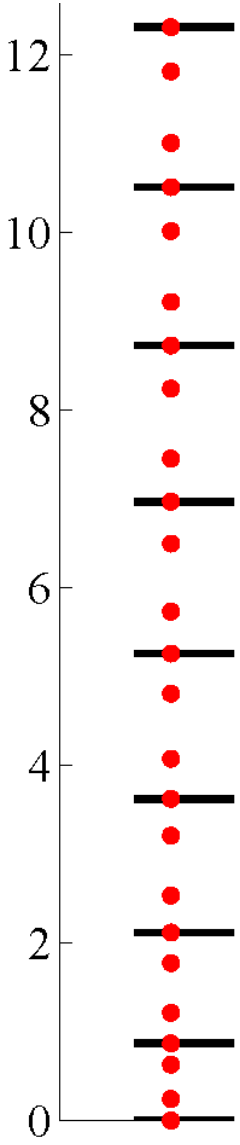
Baroclinic Wave Spectra





- Original KE spectra of NEPTUNE falls off too rapidly with wavenumber
- Improved performance with updated diffusion options

Physics Grid



Three Dimension Spectral Element implies vertical grid spacing is non-uniform

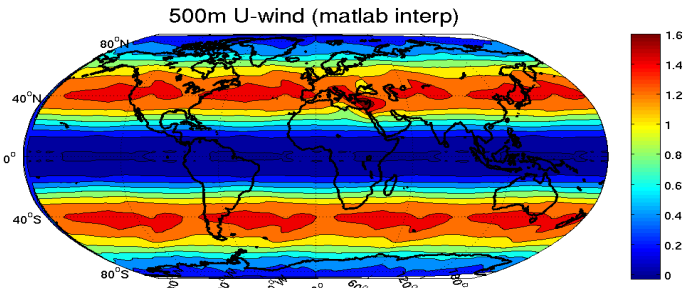
Unknown how this will impact physical parameterizations

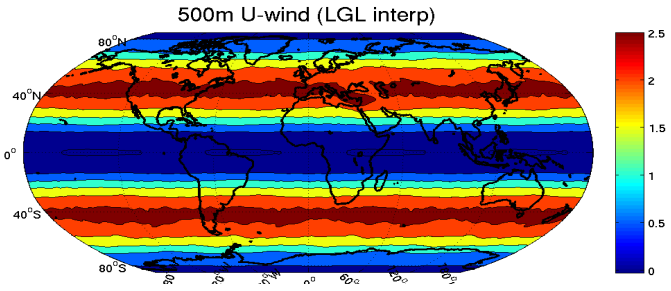
1. **Do nothing. Apply physics on GLL grid**
2. **Linear remap of fields to a regularly spaced grid within each element. Linear map tendencies back to GLL grid.**
3. **Use basis functions to perform a high-order remap to a regularly spaced grid. High-order map tendencies back to GLL grid (invert the remap operator).**

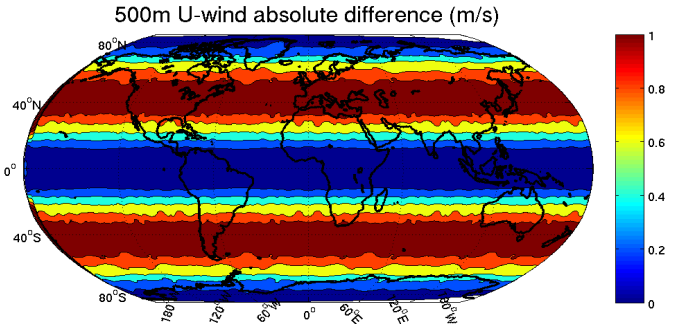
Post-Processing: Remapping

- We can use the basis functions to remap the solutions from the LGL grid to any output grid we choose in a conservative manner

- Involves iterative quasi-Newton method to find:
  - 1) the element in which the new point lies
  - 2) it's canonical coordinate so we can build the 3D interpolating function



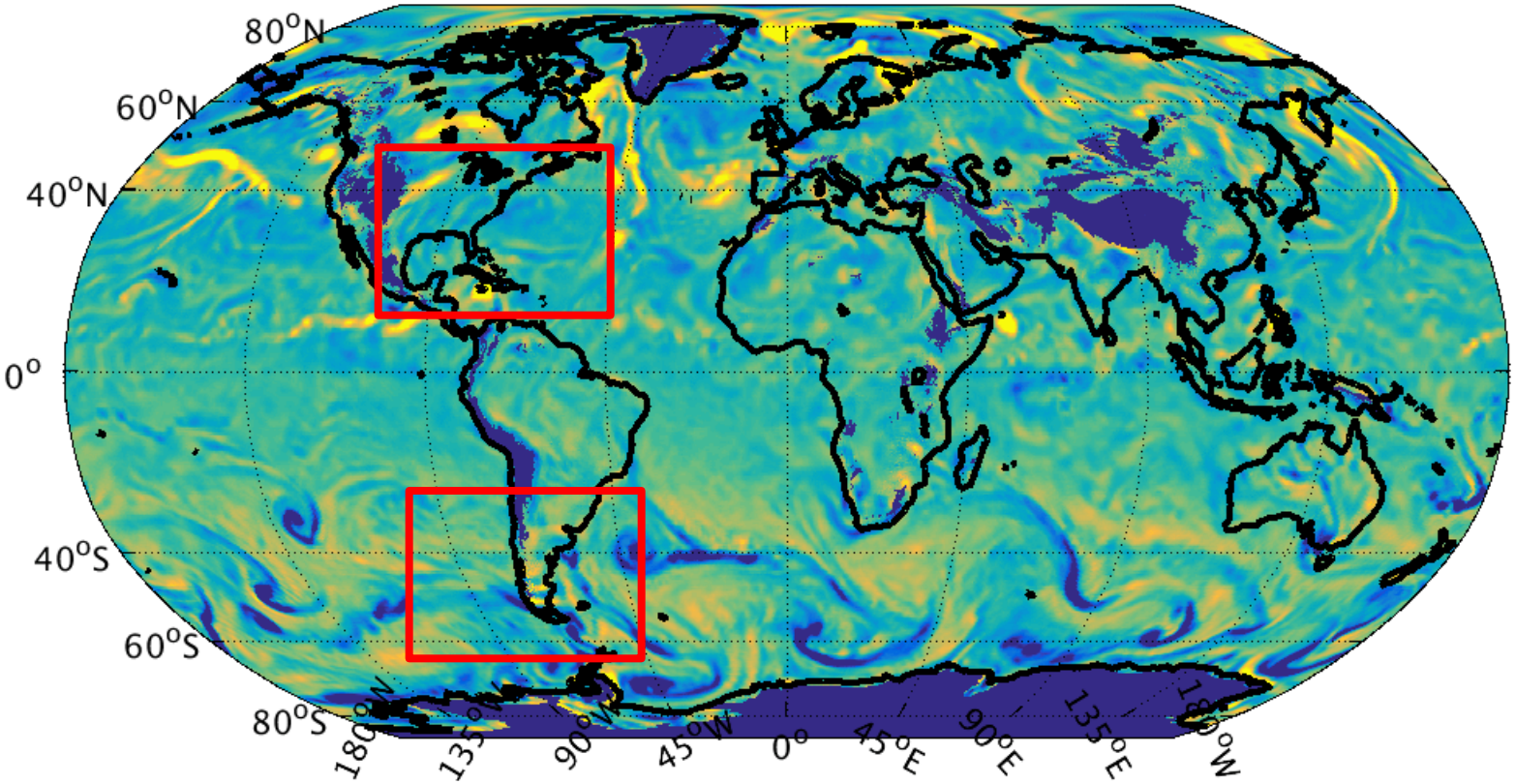




Real Data Test Case

E256P3L43 : <Δx> = 13 km; Full physics

850 hPa vertical vorticity

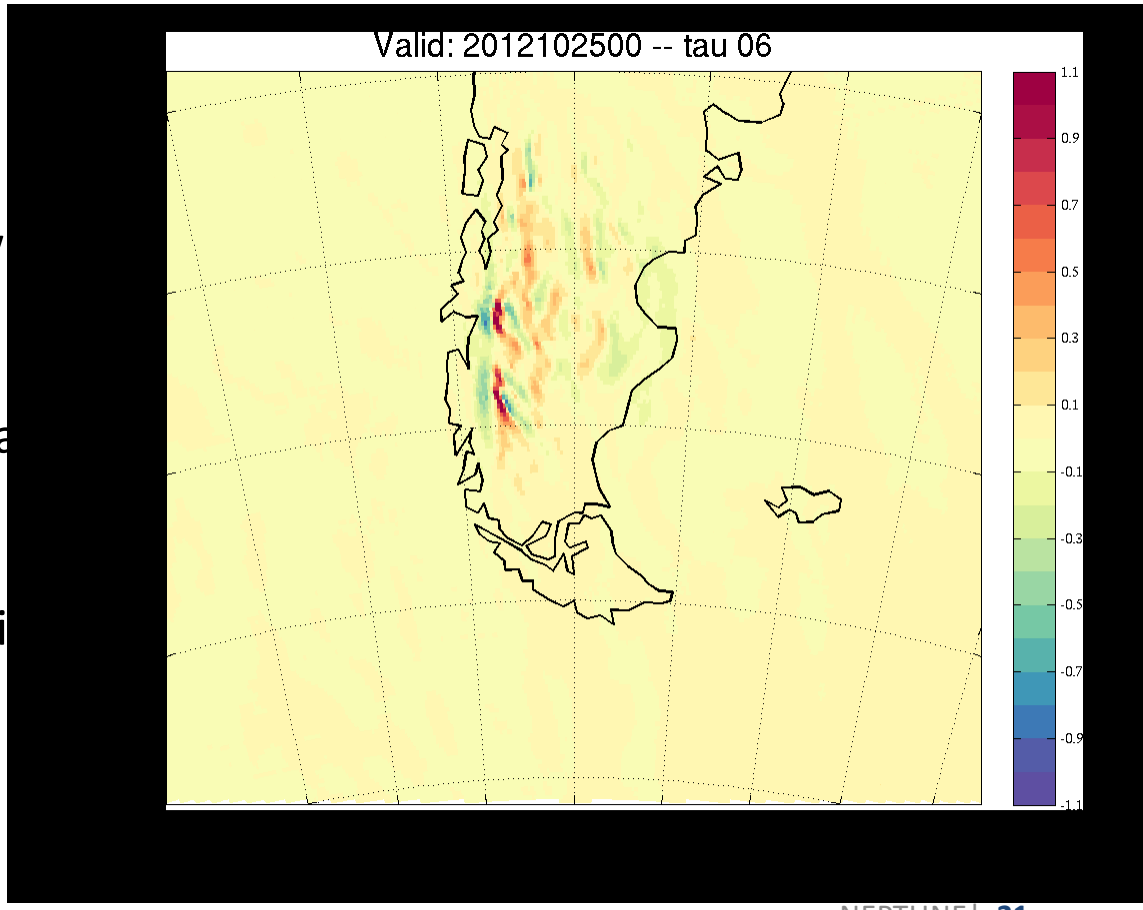


Real Data Test Cases

- **Southern Andes are hotspot for orographic gravity wave activity**
- **Play dominate role in the momentum budget of middle atmos.**

200 hPa Vertical Velocity

- Two frontal features interact w
  Andes during forecast period
- Vorticity streaks from individua
  peaks (maybe PV banners)
- Vertically propagating mountai
  wave at 200 hPa



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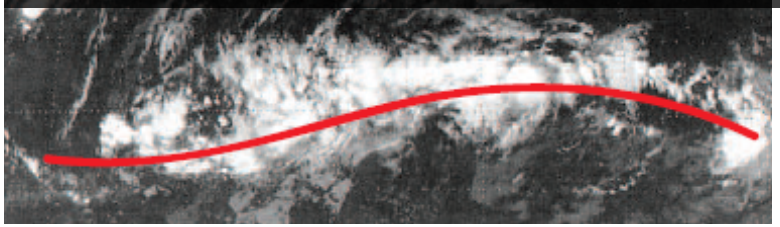
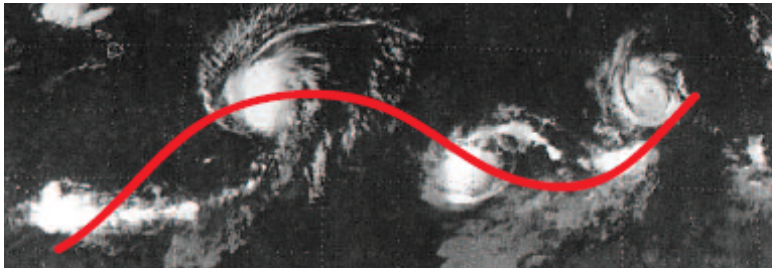
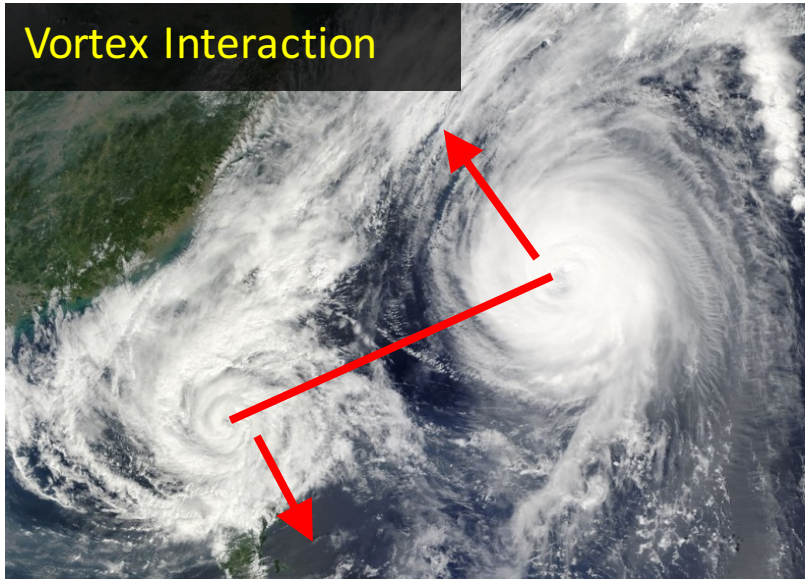
NUMA AMR/Naval Interests

Inter-Tropical Convergence Zone Instability

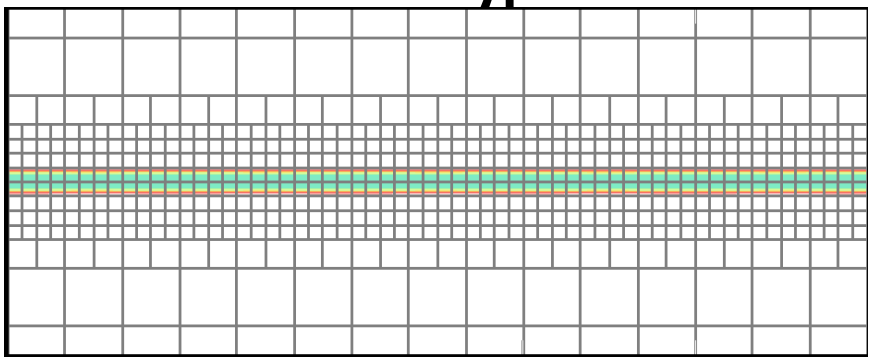




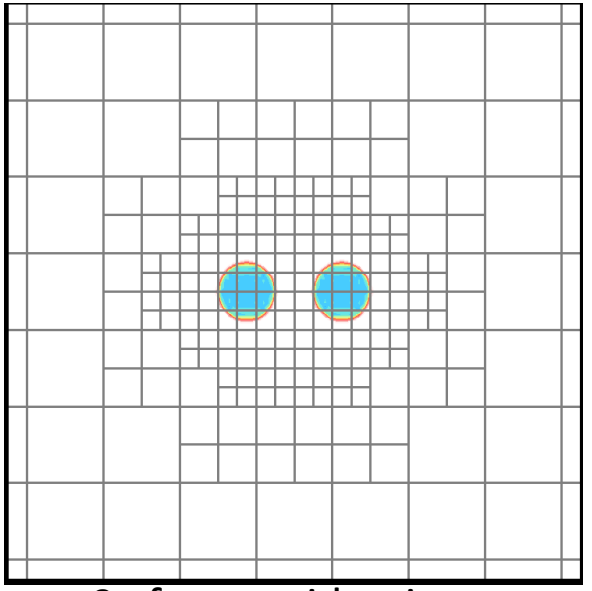
Vortex Interaction



Prototypes



3x fewer grid points



9x fewer grid points