SAND2012-4753P

Global Atmospheric Modeling at Sandia

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June 1, 2012

U.S. Department of Energy

Office of Science

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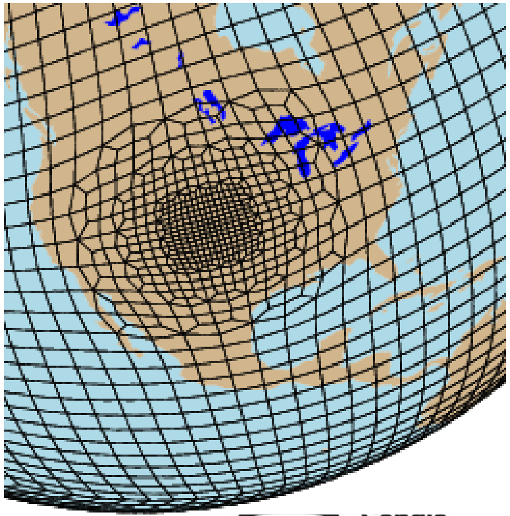
Outline

- Overview of the Spectral Element method in CAM.
  - Spectral elements for the horizontal discretization
  - Vertically Lagrangian (Lin 2004) from CAM-FV
- Global high resolution: CAM at 1/8°
  - Computationally ready
  - Parameterizations need some work
- Variable resolution: CAM with localized regions at 1/8°
  - Initial goal: Efficient "test-bed" for global 1/8°
  - Initial focus: US mid-west diurnal propagating systems



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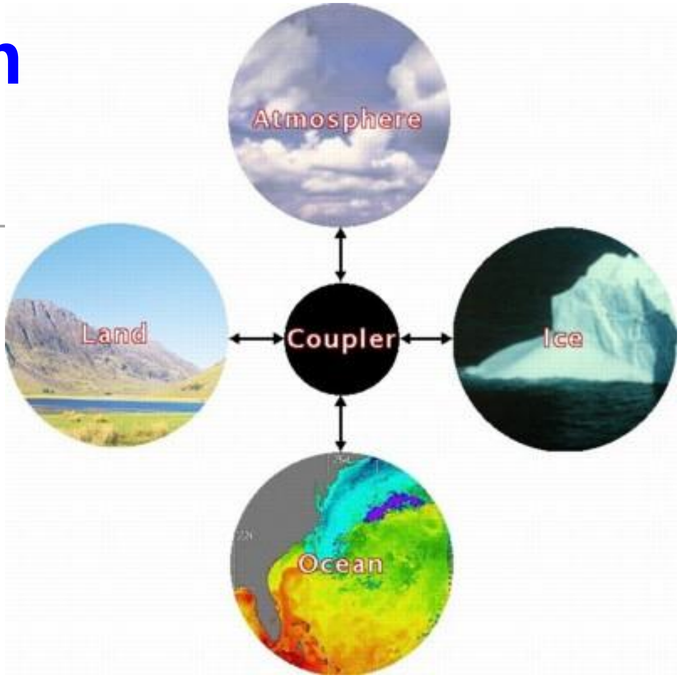
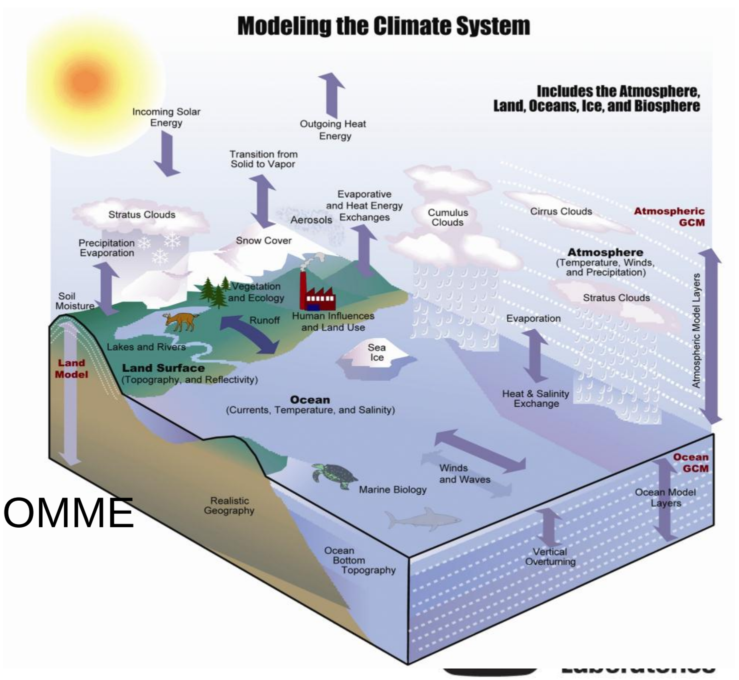
The Community Earth System Model (CESM)



- **IPCC-class model coupling atmosphere ocean, ice and land components**
  - Seasonal and interannual variability in the climate
  - Explore the history of Earth's climate
  - Estimate future of environment for policy formulation
  - Contribute to assessments
- **Developed by NCAR, National Labs and Universities.**



CESM component acronyms:

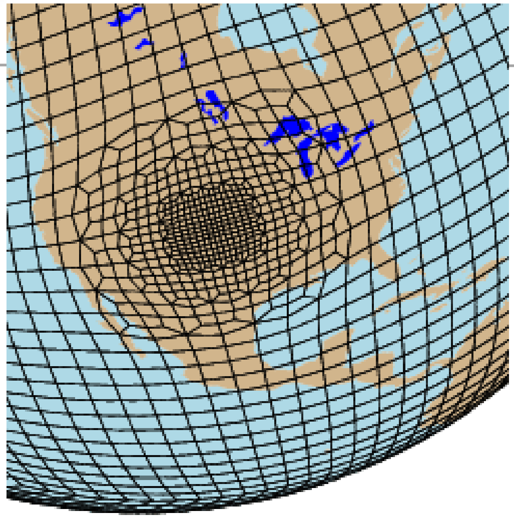
CAM: Community Atmosphere Model

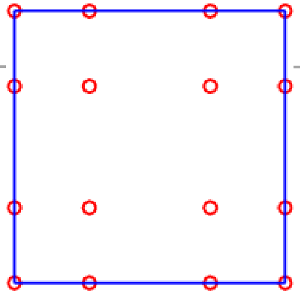
CAM5: Version 5 physics including prognostic aerosols

CAM-SE: CAM with spectral element dynamical core from HOMME

HOMME: High-Order Method Modeling Environment

Spectral Element Method





- Spectral Elements: A Continuous Galerkin Finite Element Method
  - Uses finite element grids made of quadrilateral elements
  - Galerkin formulation, with a Gauss-Lobatto quadrature based inner-product
  - Basis/test functions: degree p polynomials within each element, continuous across elements. Usually p=3
  - Simple Pn-Pn element (velocity and pressure are both in Pn)

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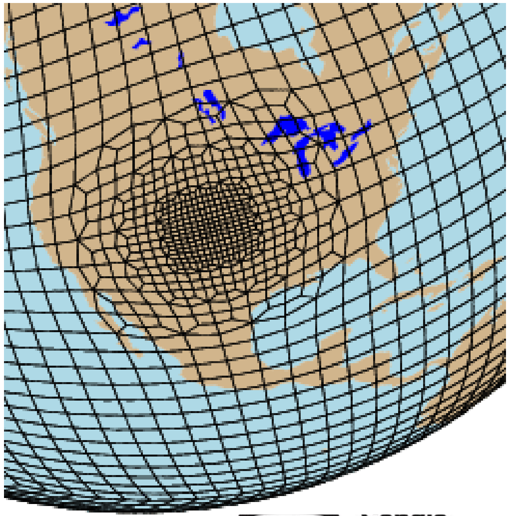
Spectral Element Method

- High-order (4th) discretization
- Mimetic/compatible numerics:
  - Discretization preserves adjoint properties of div, grad and curl operators
  - Discrete versions (element level) of Stokes and Divergence theorem
  - Result: excellent local conservation, even for equations not written in conservation form: mass, energy, potential temperature, 2D PV.
- All properties preserved on fully unstructured grids
- Simple Pn-Pn element (velocity and pressure are both in Pn), stabilized with hyper-viscosity



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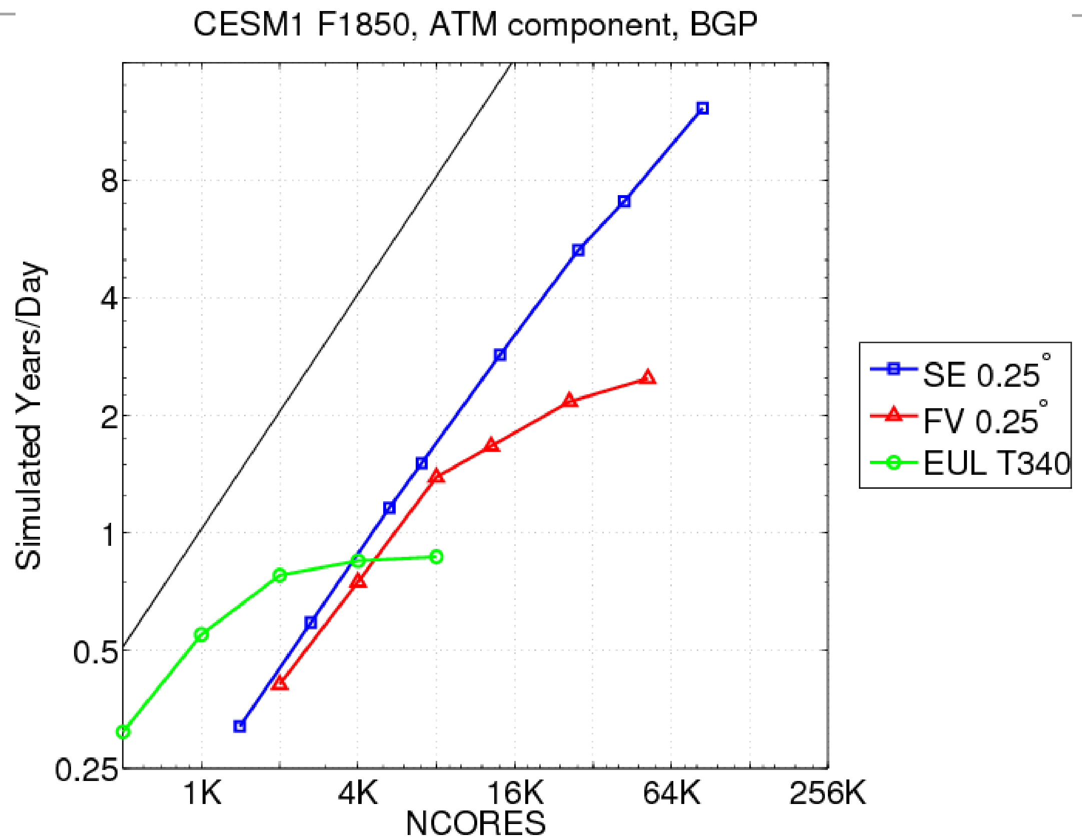
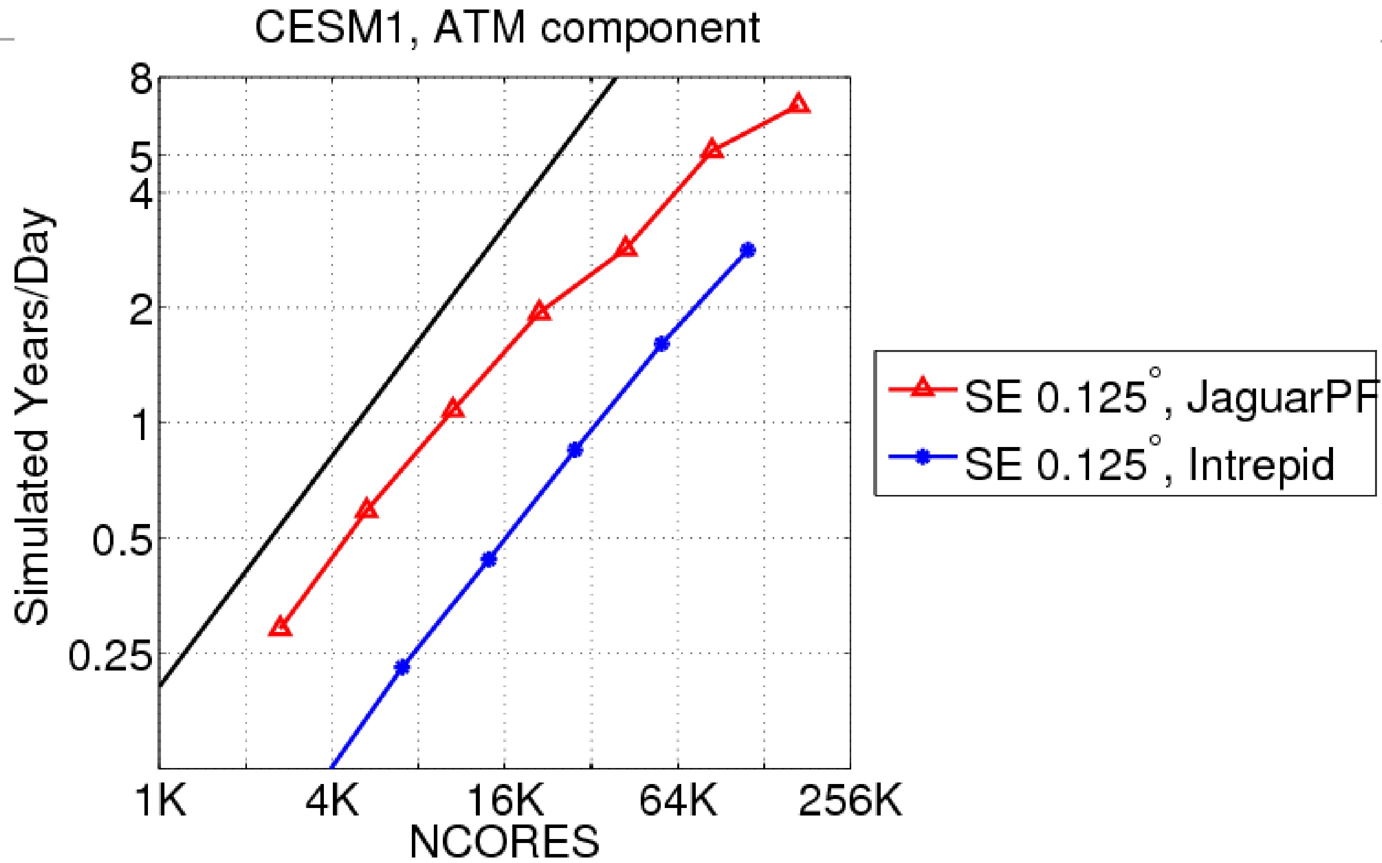
CAM4 Scalability, ANL Intrepid 0.25° (28km)



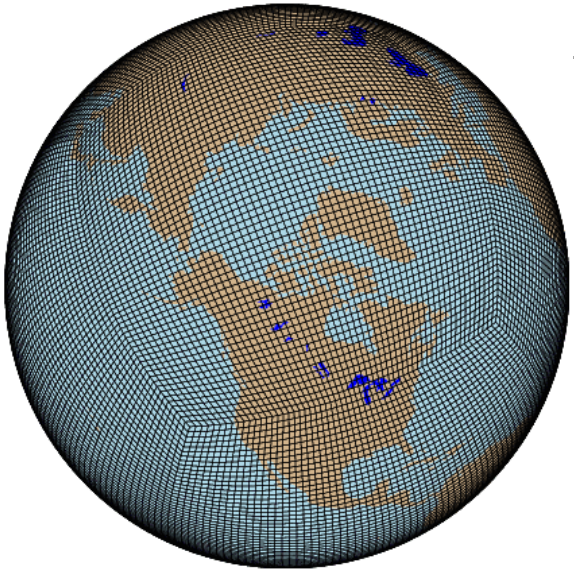
- Compare CAM with SE, FV and EUL (global spectral) dycores
- CAM-SE achieves near perfect scalability to 1 element per core (86,000 cores). Peak performance: 12.2 SYPD.
- Atmosphere only times. Full CESM runs ~50% slower because of other components

CAM4 Scalability
Intrepid and JaguarPF   1/8° (14km)



- Excellent scaling to near full machine on both LCFs:
- Intrepid (4 cores/node):   Excellent scalability, peak performance at 115K cores, 3 elements per core, 2.8 SYPD.
- JaguarPF (12 cores/node): Good scalability, peak performance at 172,800 cores (2 elements per core), 6.8 SYPD.

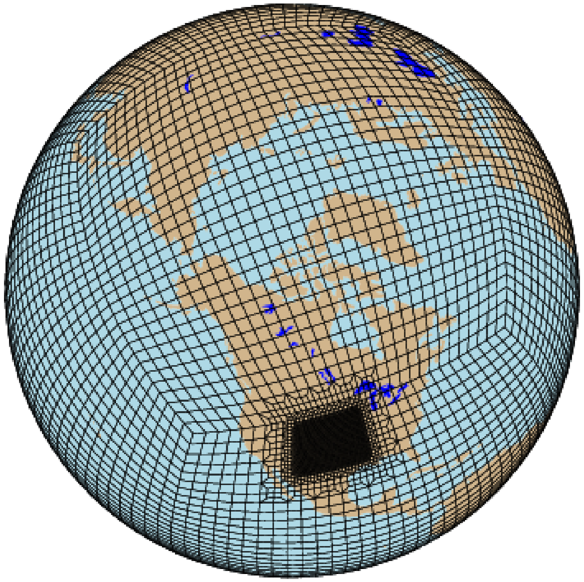
CAM5-SE at 1/8°



Global 1/8°

CAM5-SE has a very efficient, scalable and *expensive* global 1/8° configuration.

- 6M core hours per year (ANL Intrepid)
- Yellowstone: 1-2M core hours?
- 3.1M physics columns
- dtime=600, dynamics dt=9.2



SGP 8x Regionally Refined

1° global resolution, refined to 1/8° continental sized region centered over SGP ARM site.

- 0.12 M core hours per year (Sandia Linux cluster).
- 67K columns.
- dtime=600, dynamics dt=7.9

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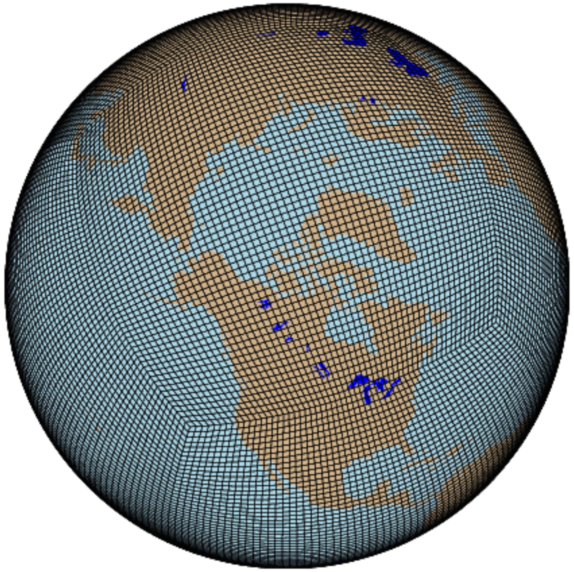
CAM5-SE 1/8° Simulations



- Many topographically induced precip biases substantially reduced
- Produces cat5 tropical cyclones. CAM5 physics produces more realistic cyclones.
- Nastrom-Gage transition in KE is well simulated, indicating more realistic mesoscale variability
- Large scale climate biases typically not improved. Some longstanding CAM biases degraded:
  - LWCF weakens in mid-latitudes
  - Icelandic low intensifies
- US mid-west diurnal propagating systems dramatically improved.

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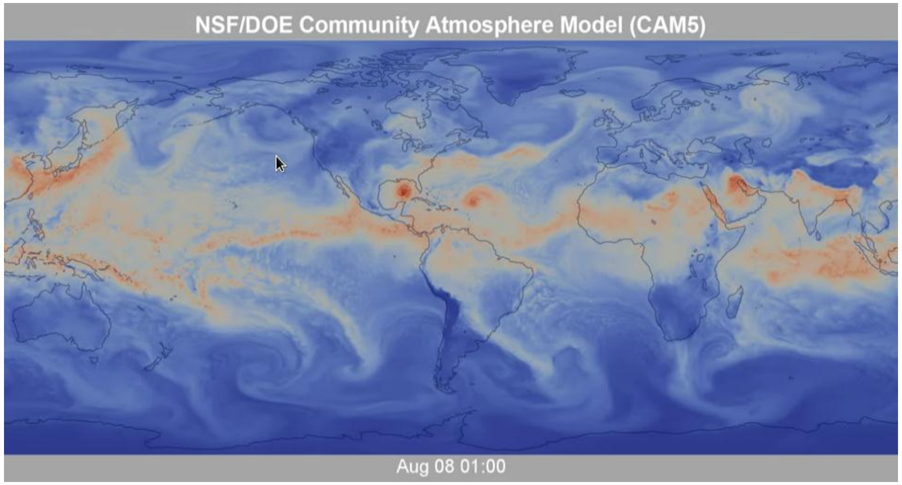
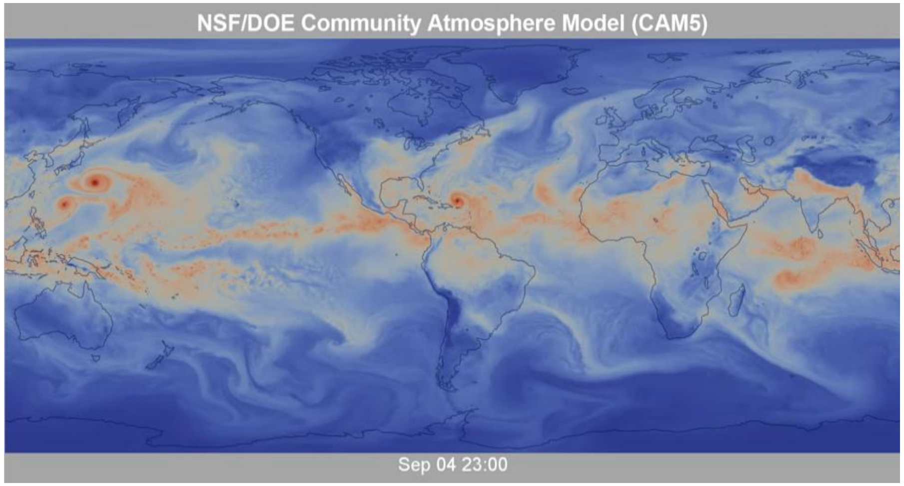
CAM5-SE at 1/8°
Precipitable water animations



Category 5 storm in the Gulf of Mexico



Fujiwhara effect in the Pacific

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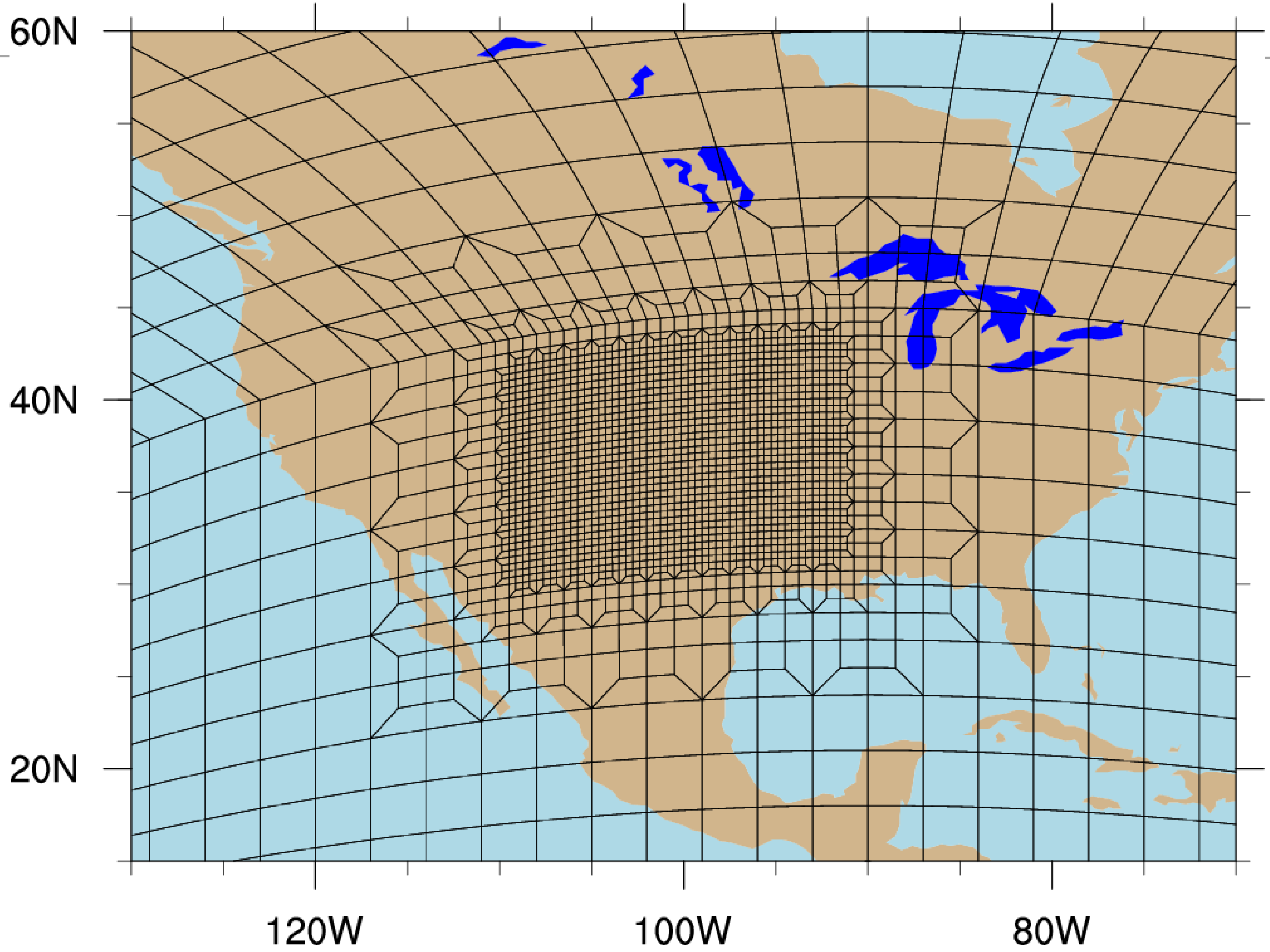
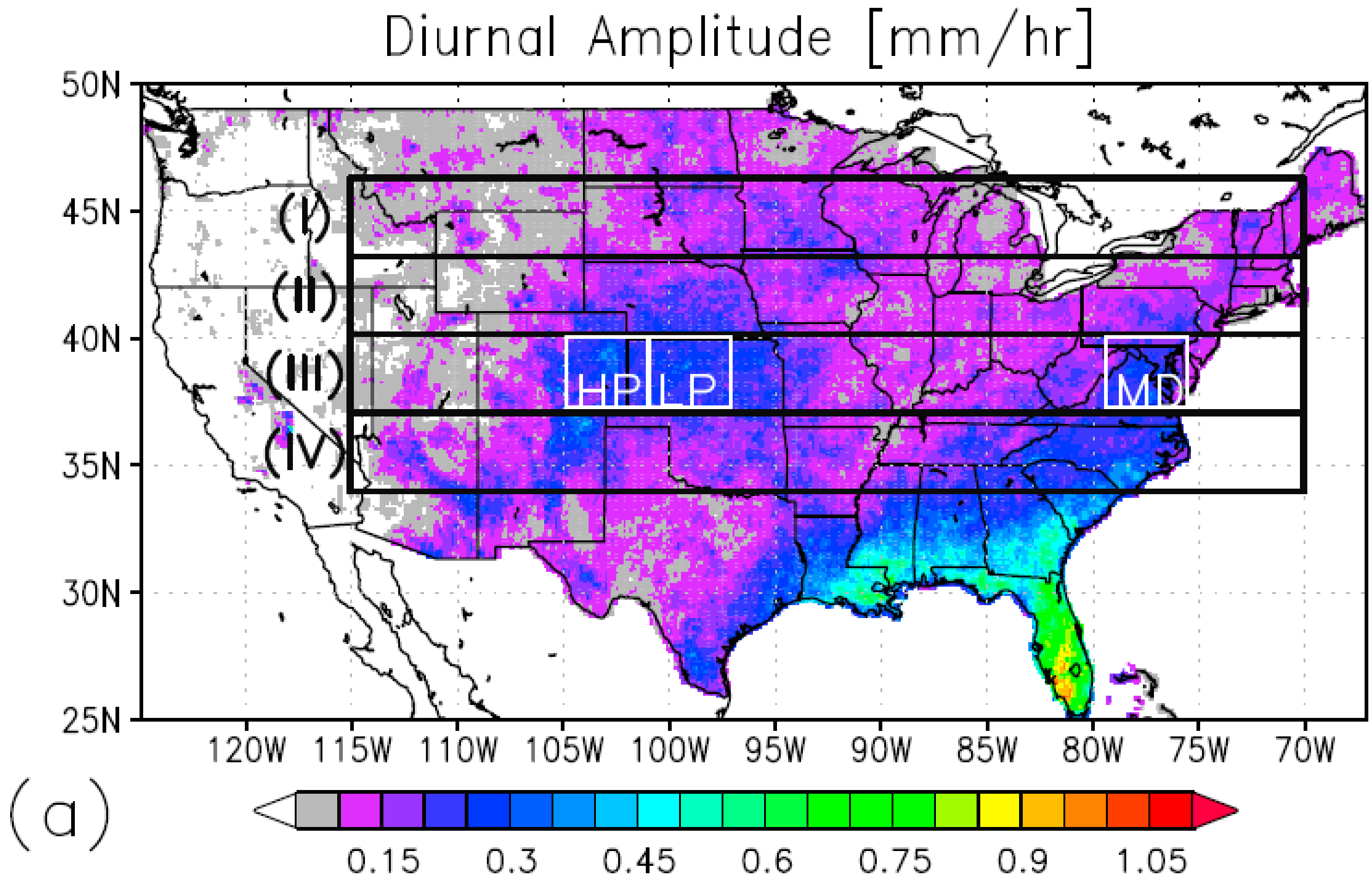
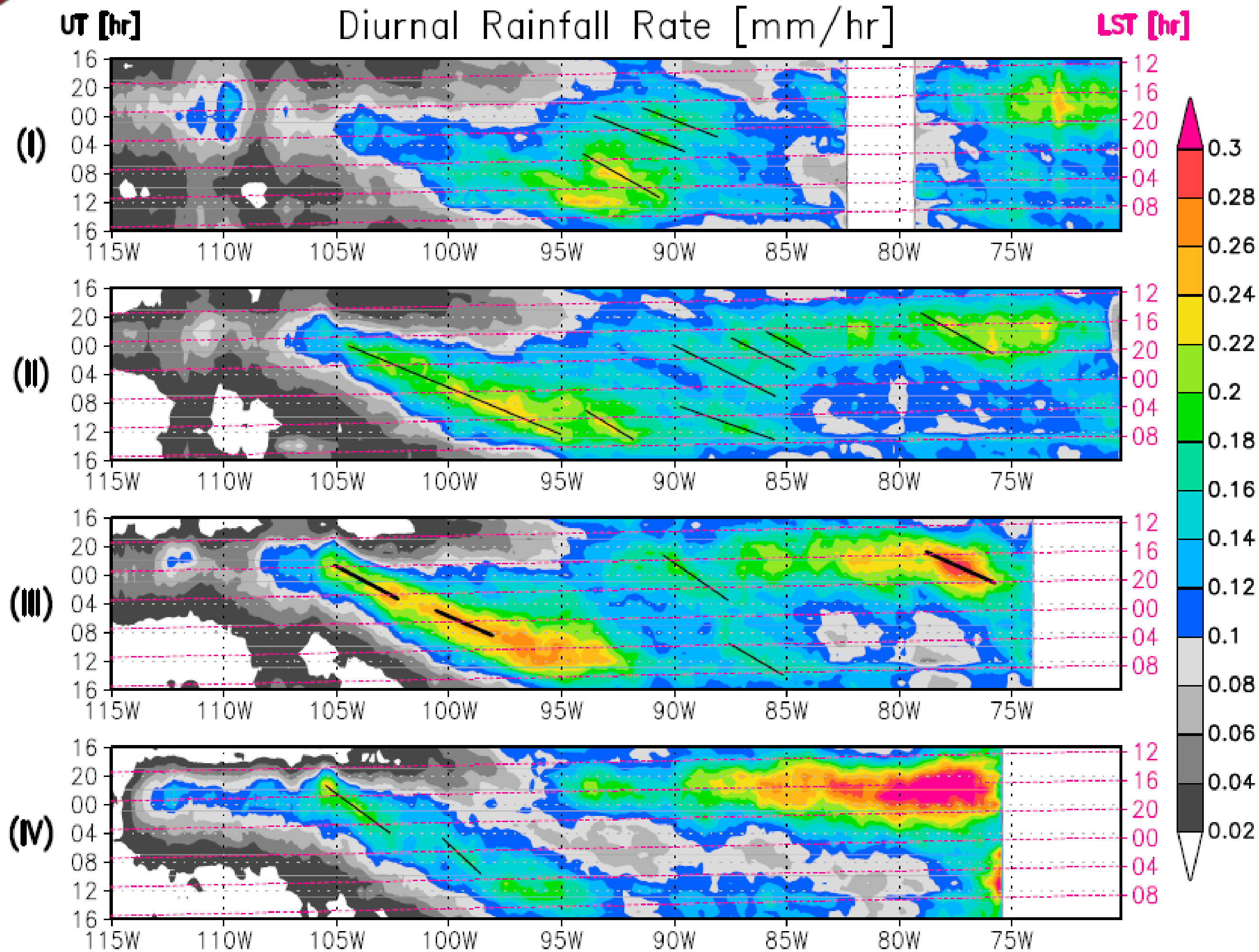
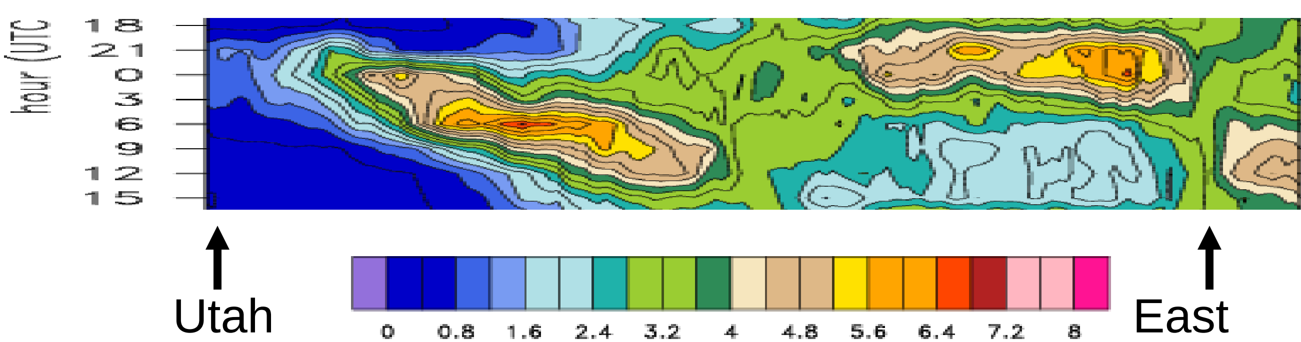

60N
40N
20N
120W
100W
80W

US mid-west diurnal propagating systems June-July



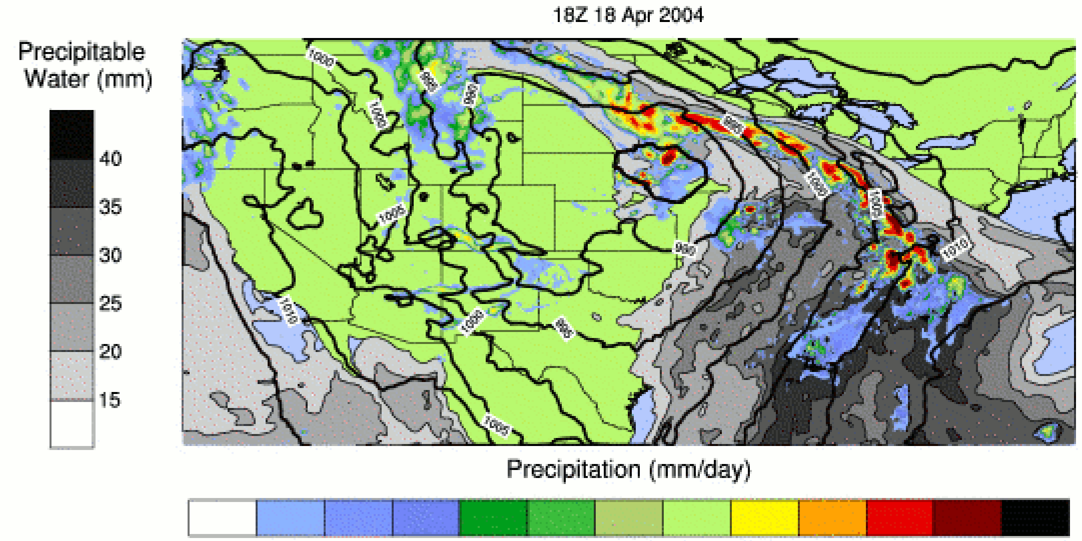
Matsui, T., D. Mocko, M.-I. Lee, W.-K. Tao, M. J. Suarez, and R. A. Pielke Sr., 2010: Ten-year climatology of summertime diurnal rainfall rate over the conterminous U.S. *Geophys. Res. Lett.*, **37**, L13807, doi:10.1029/2010GL044139.





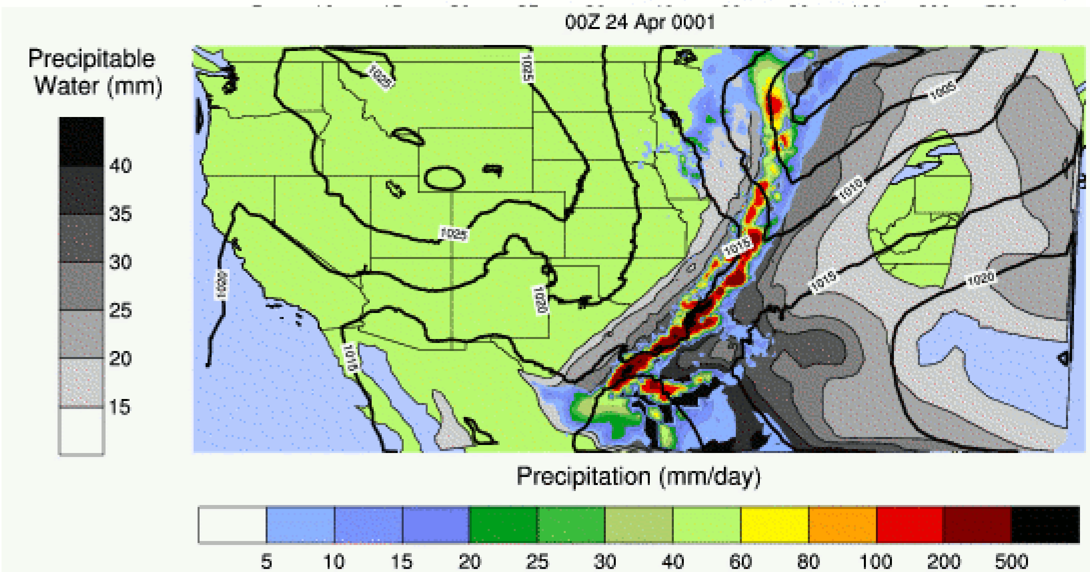
Tropical Rainfall Measuring Mission (TRMM) (35-45N, mm/day)

Precipitable water (gray), precip rate (color), sea level pressure (contours)



Global 1/8° Simulation

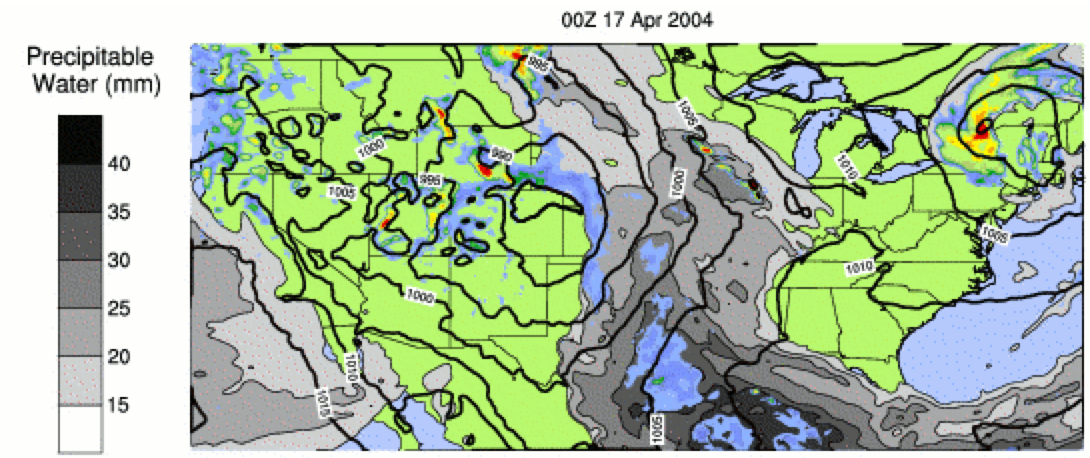
Snapshots show propagating convective system not seen at lower resolutions. Detailed frontal structure and tapping of moisture



Regionally Refined Simulation

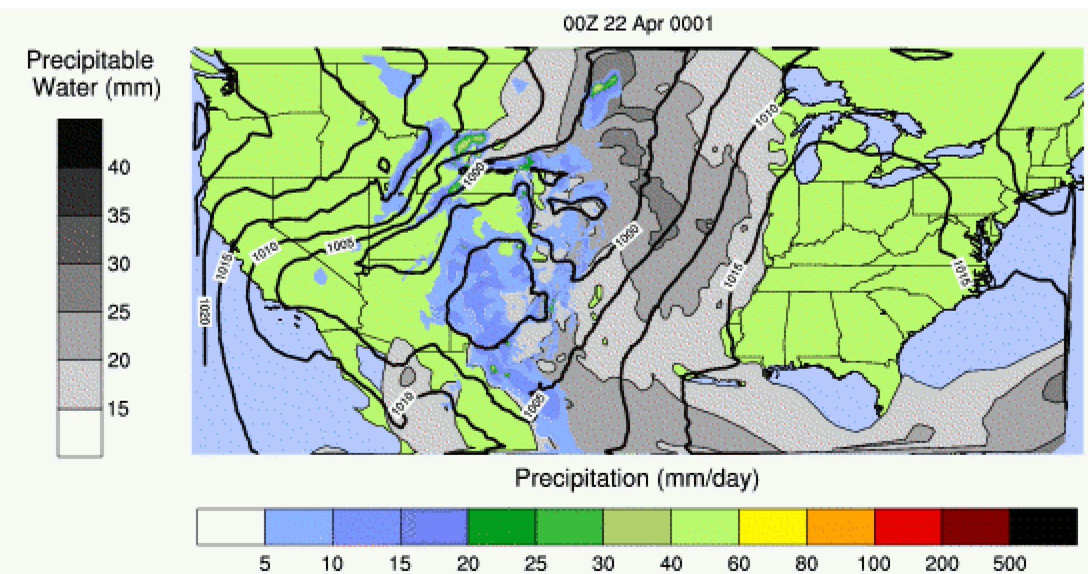
Similar convective systems form in the 1/8° region, strongly dissipated as it propagates into the 1° region

Precipitable water (gray), precip rate (color), sea level pressure (contours)



Global 1/8° Simulation

Snapshots show propagating convective system not seen at lower resolutions. Detailed frontal structure and tapping of moisture



Regionally Refined Simulation

Similar convective systems form in the 1/8° region, strongly dissipated as it propagates into the 1° region

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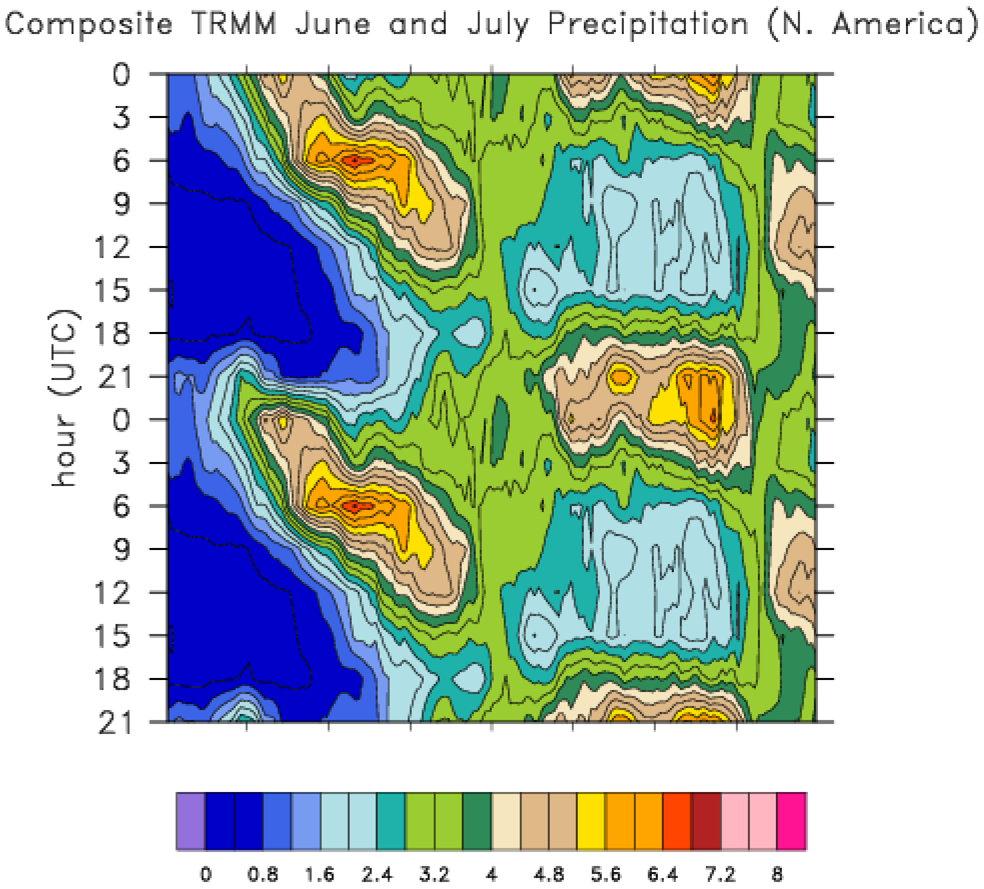
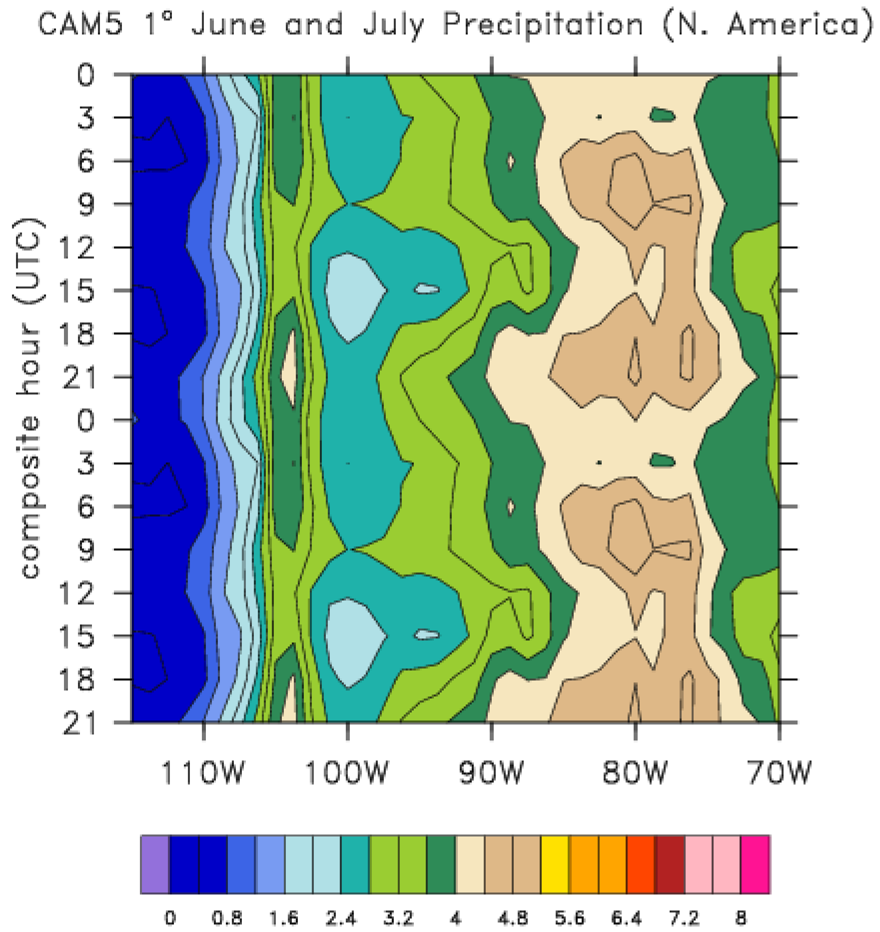
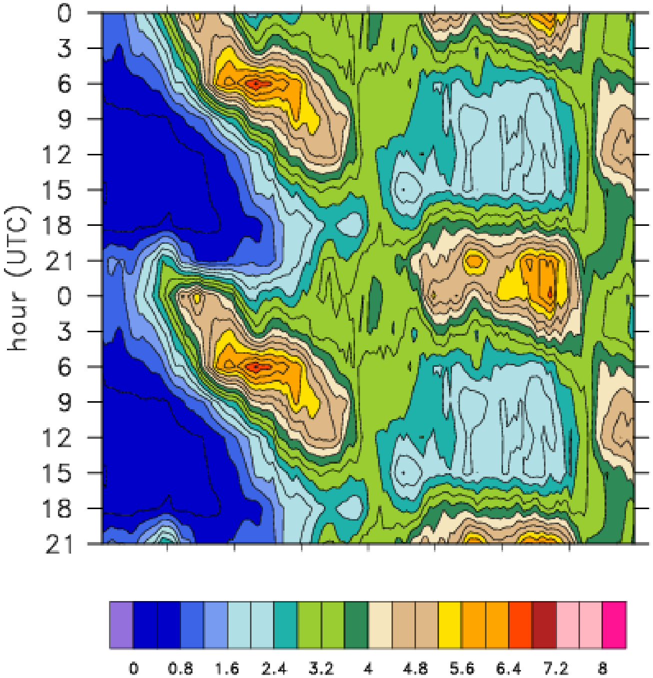
Precip Hovmoller Diagrams
June/July 1° Resolution





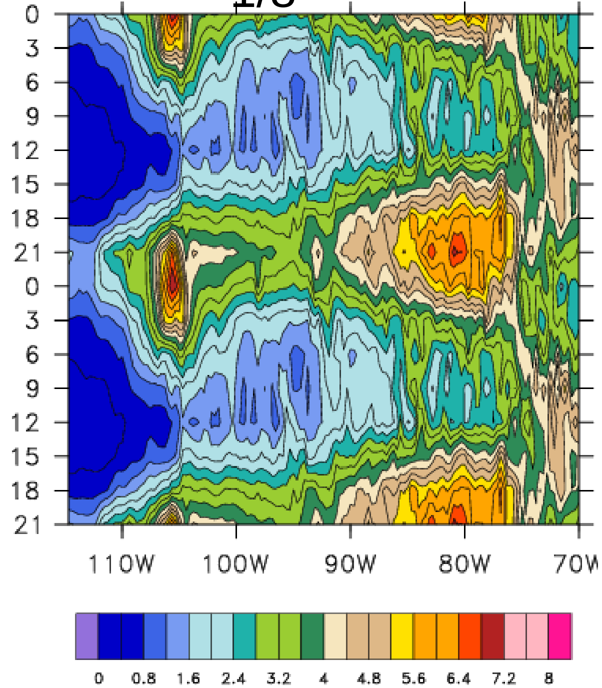
June/July 1/8°

TRMM



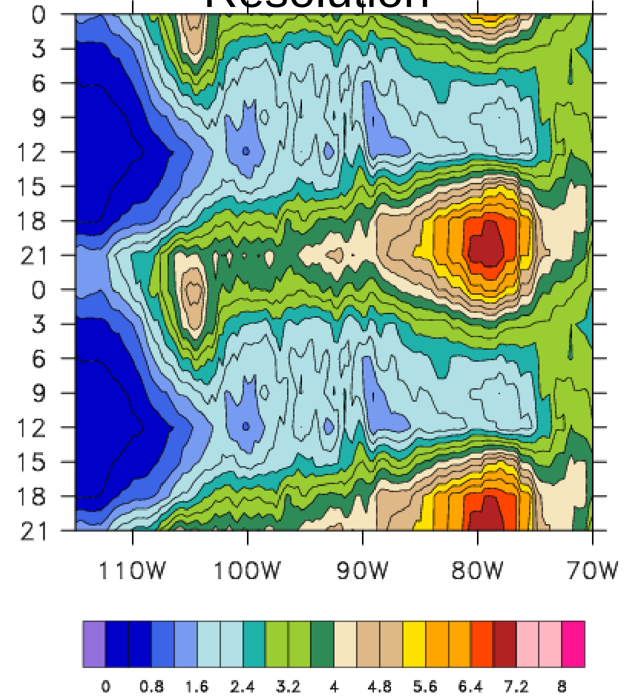
2000-2004

Global 1/8



2005-2006

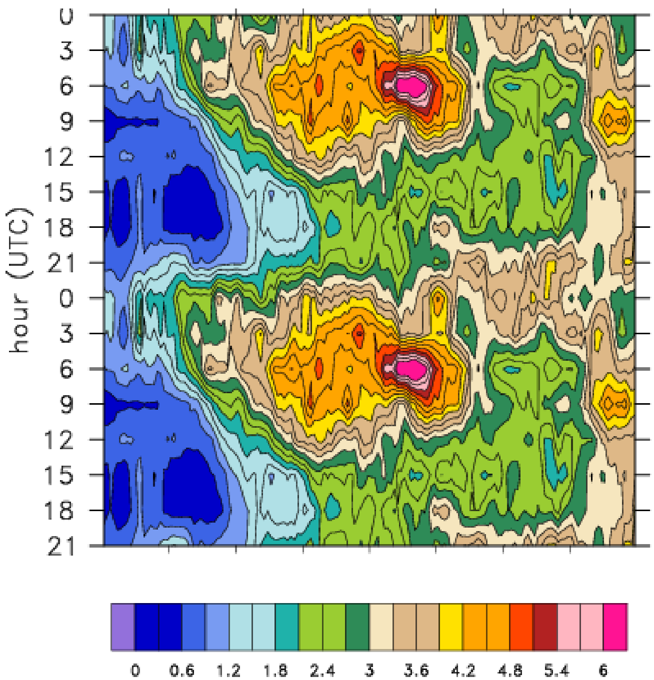
Var. Resolution



2000 YEAR 1-4

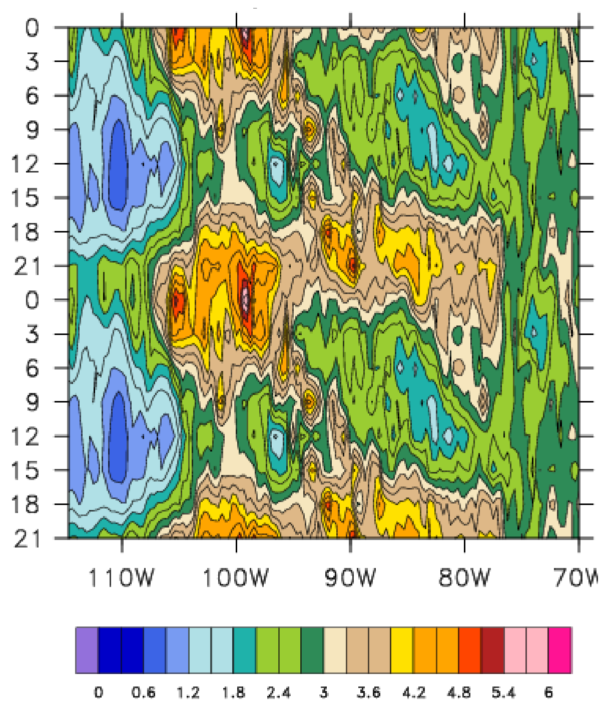
April/May 1/8°

TRMM



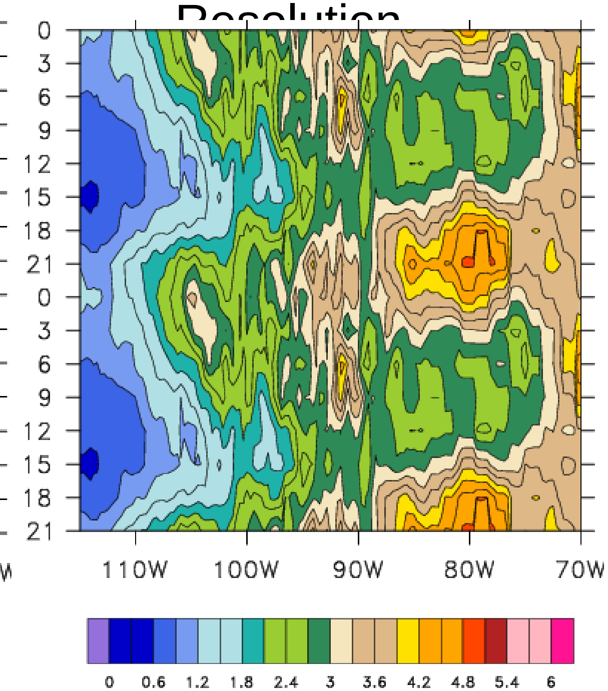
2000-2004

Global



2005-2006

Var. Resolution



2000 YEAR 1-4

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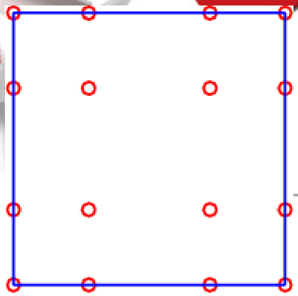
Backup slides



Galerkin FE Approach Ideal for Modern Architectures

- Galerkin formulation of the equations leads to a 2 step solution procedure:
  - Step 1:   All computations local to each element and on a tensor-product grid. Structured data with simple access patterns and arithmetically intensive operations: Extremely efficient on modern CPUs or GPUs
  - Step 2: Apply inverse mass matrix (projection operator).
- All inter-element communication is embedded in Step 2, providing a clean decoupling of computation & communication.
  - Only a single routine has to be optimized for parallel computation.
  - Gordon Bell Awards: 2000 (best performance, NEK5000), 2001 (honorable mention, HOMME) , 2003 (best performance, SPECFEM3D)

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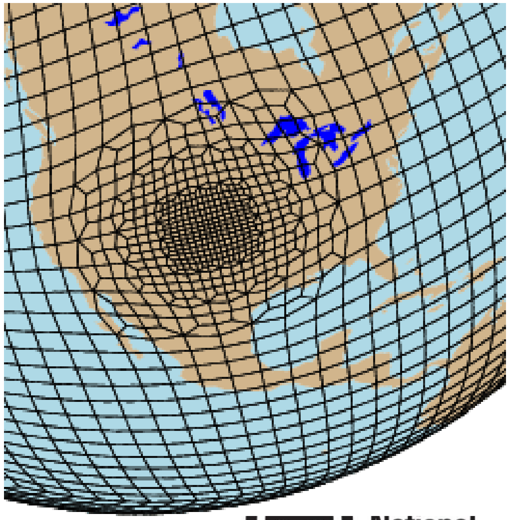
$P^n - P^n$ Wave Propagation

- Diagonal mass matrix makes the method attractive for time-dependent, explicit problems (wave propagation and geophysical flows)
- High-order representation of resolved waves, even on unstructured grids
- Near grid-scale waves ($\lambda < 2\pi h/(2n+1)$) are "erratic": *method requires stabilization to control these waves.*
- Ainsworth & Wajid, *Dispersive and dissipative behavoir of the spectral element method,* SINUM 2009.



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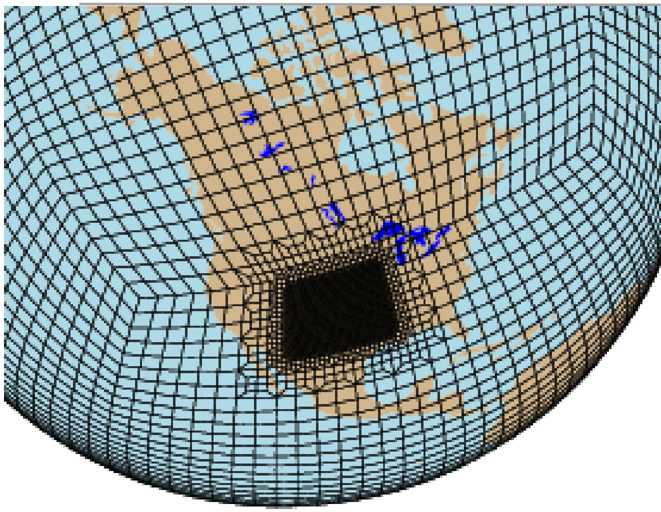
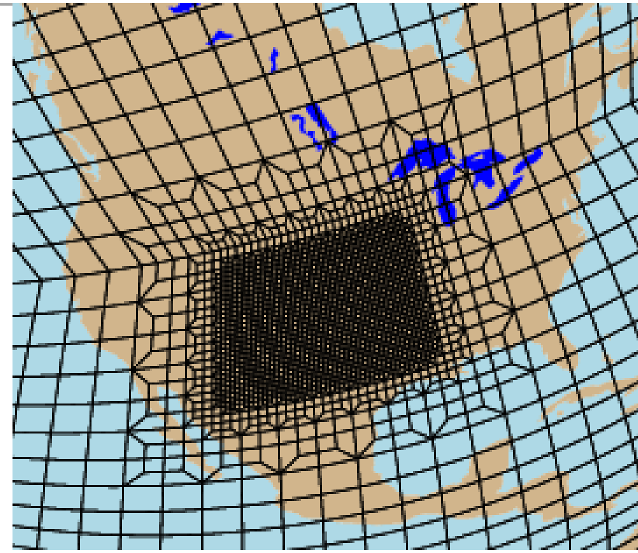
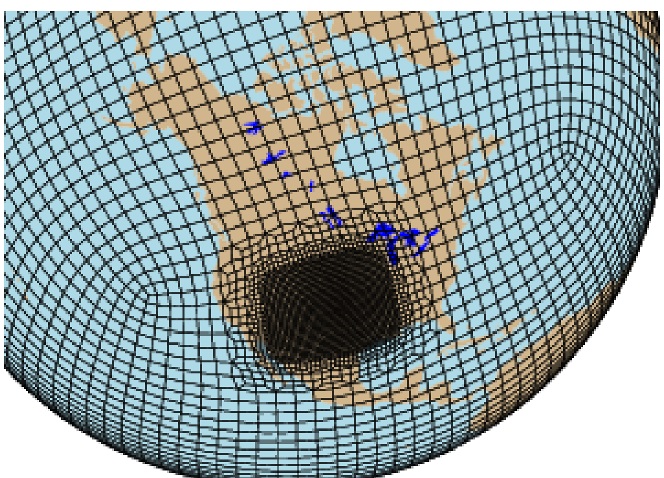
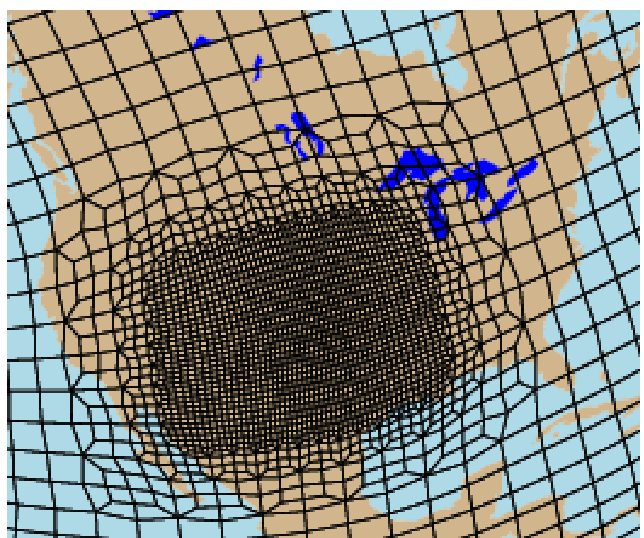
"SGP 8x" Variable Resolution Grid
1° global -> 1/8° regional

Unsmoothed
Grid generated with CUBIT GUI-based meshing tool. Starting with global grid, apply refinement in selected regions.

Smoothed
CUBIT's Winslow smoothing option uses metric appropriate for spectral elements. But also *smooths the cube corners* – Need option to apply smoothing in limited region.

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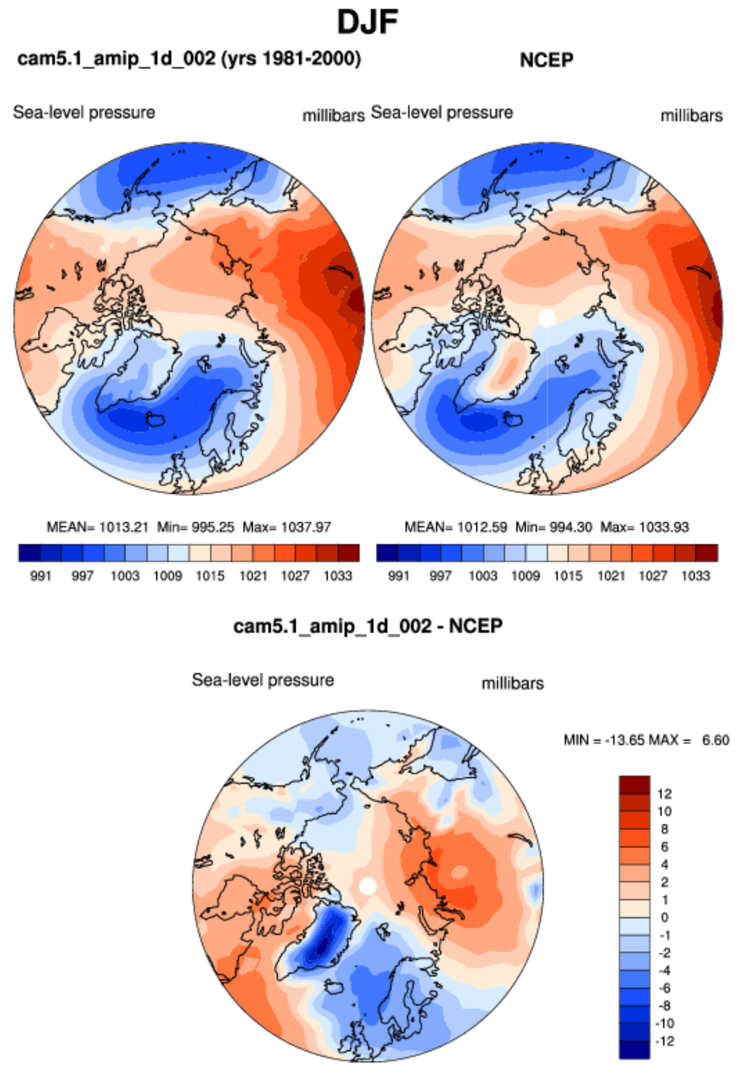
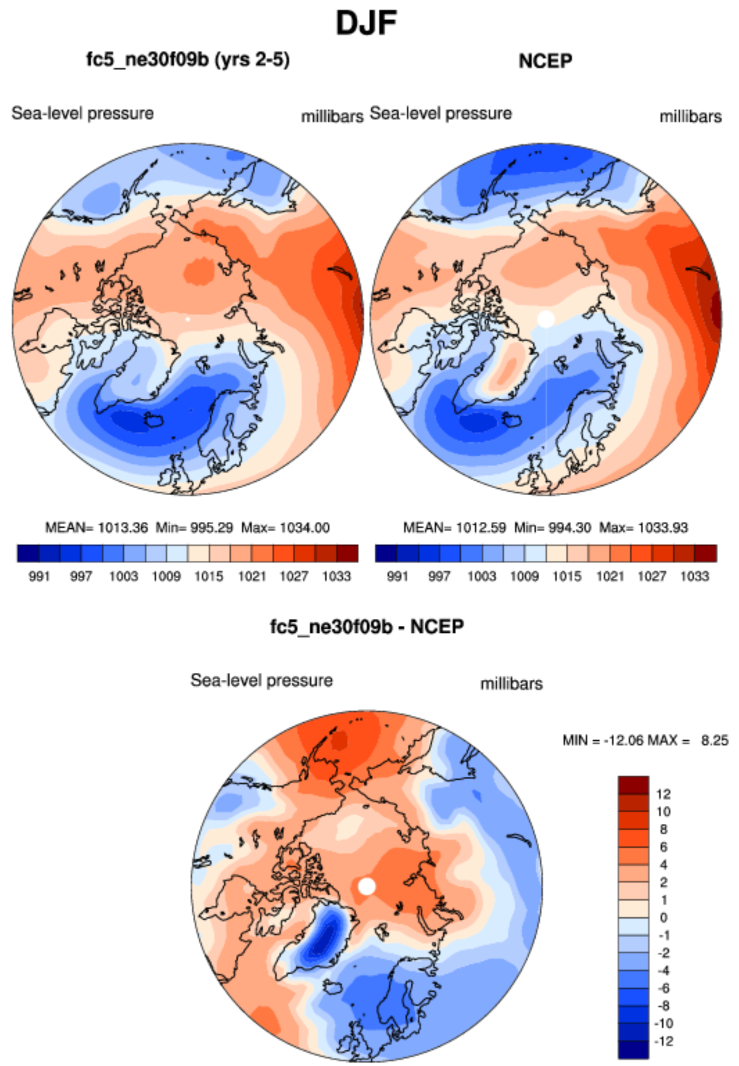
CAM-FV 110km

Sea Level Pressure: Icelandic Low



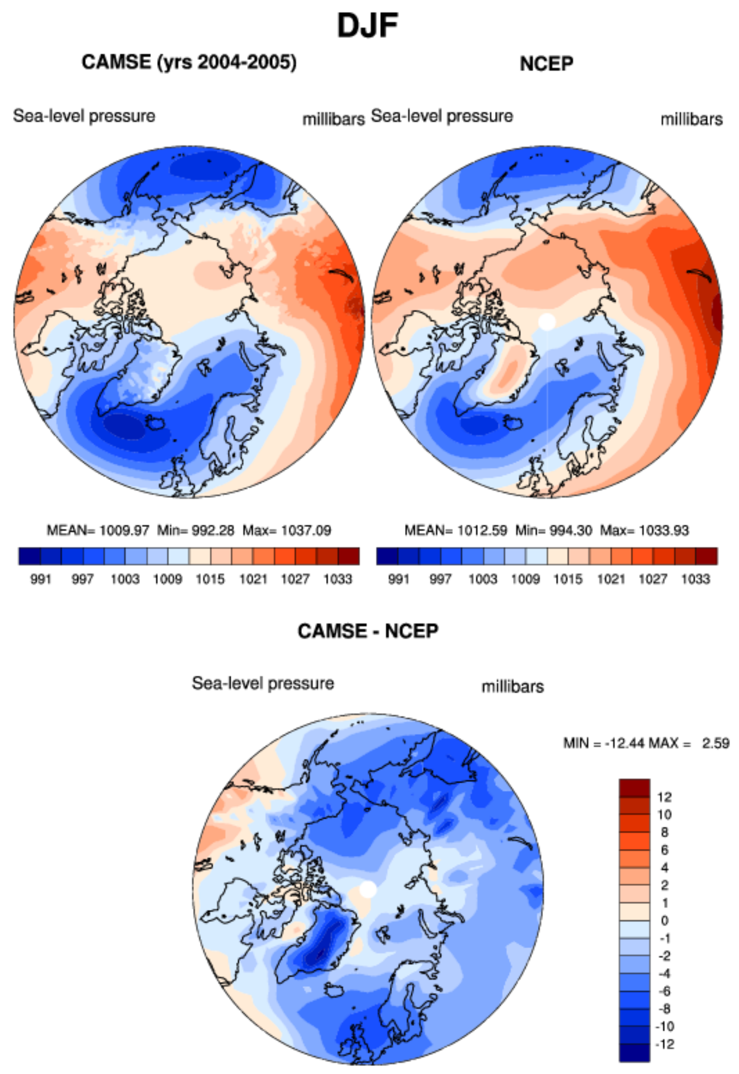
CAM-SE 110km

Sea Level Pressure: Icelandic Low



CAM-SE 13km

Sea Level Pressure: Icelandic Low



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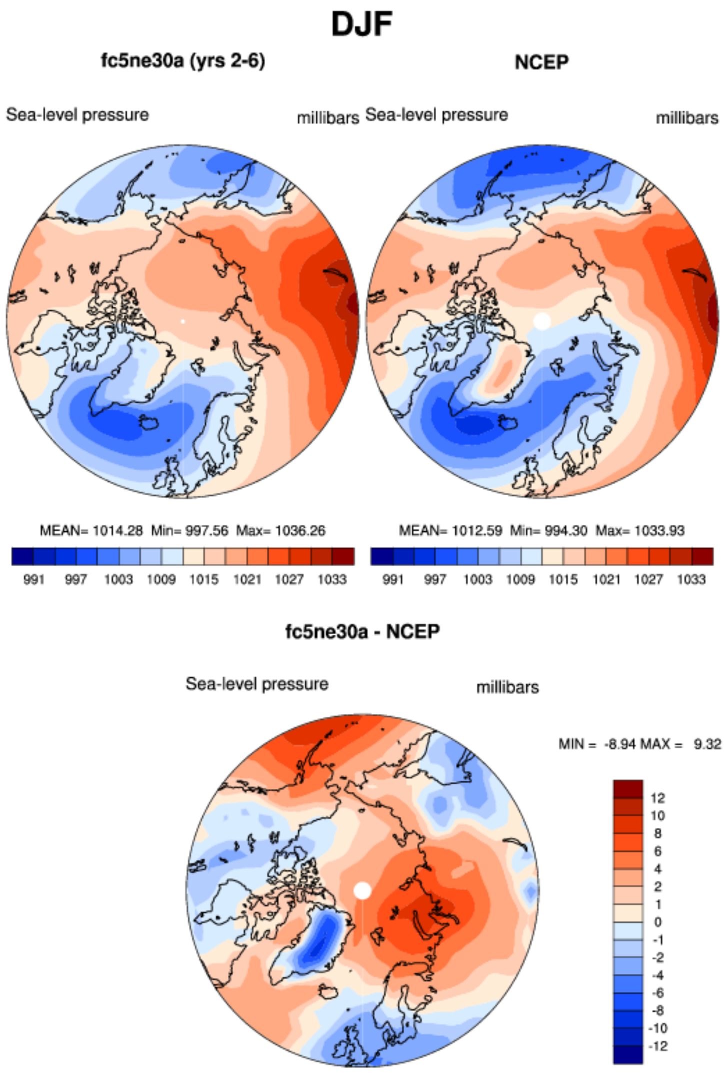
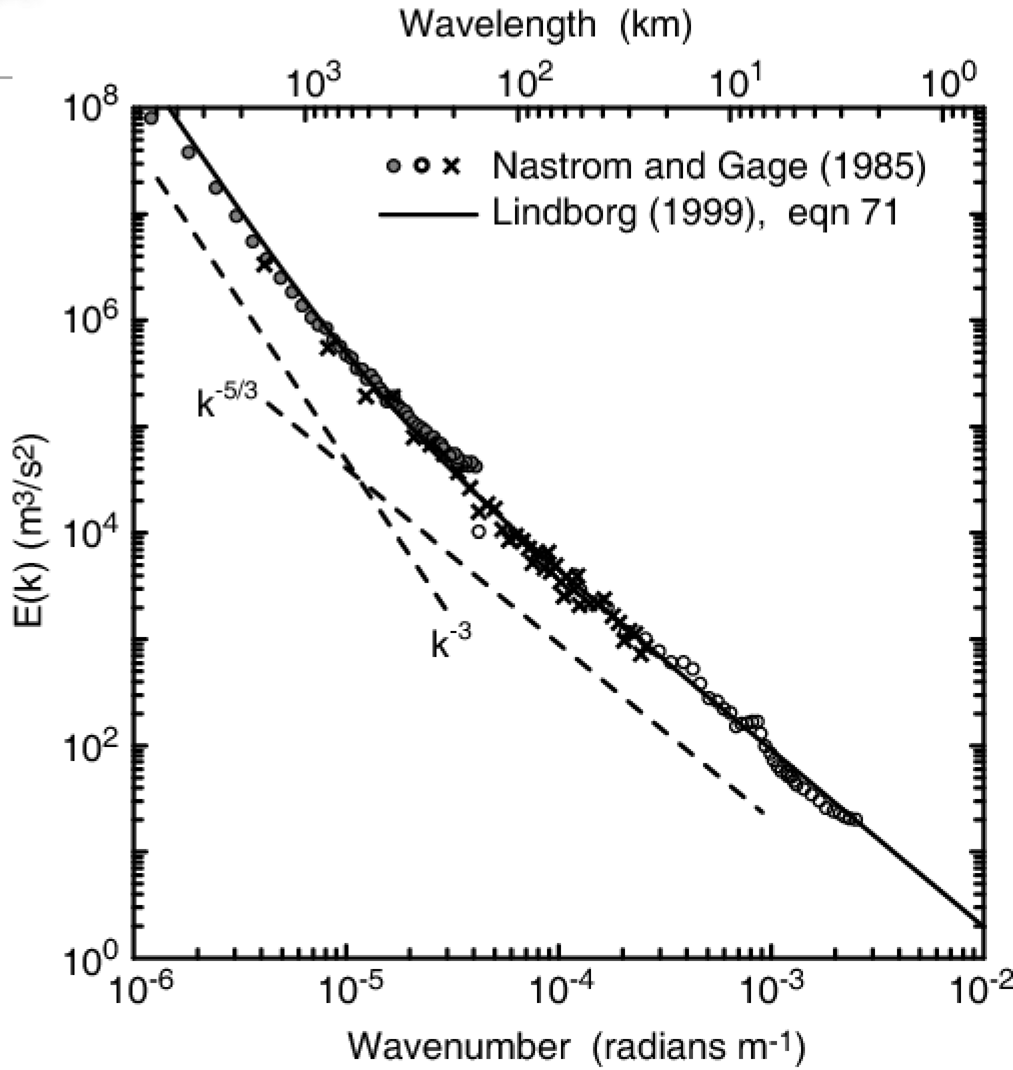
CAM-SE 110km + SGH
Sea Level Pressure: Icelandic Low



Some improvement with more consistent topography and surface roughness boundary data sets. (Lauritzen, Bacmeister, Taylor, Neale, JAS, under review.)

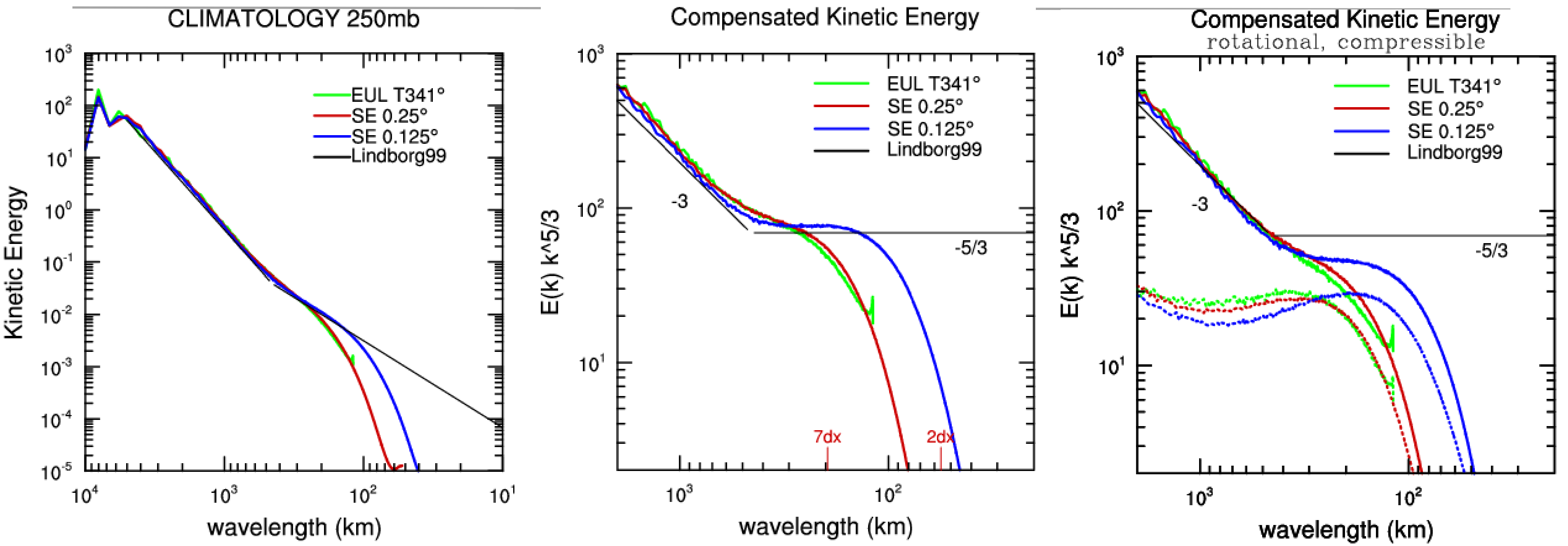
Kinetic Energy Spectra



KE spectra from aircraft observations (symbols, Nastrom and Gage 1985) and functional fit (solid line, Lindborg, 1999). Figure from Skamarock, 2004.

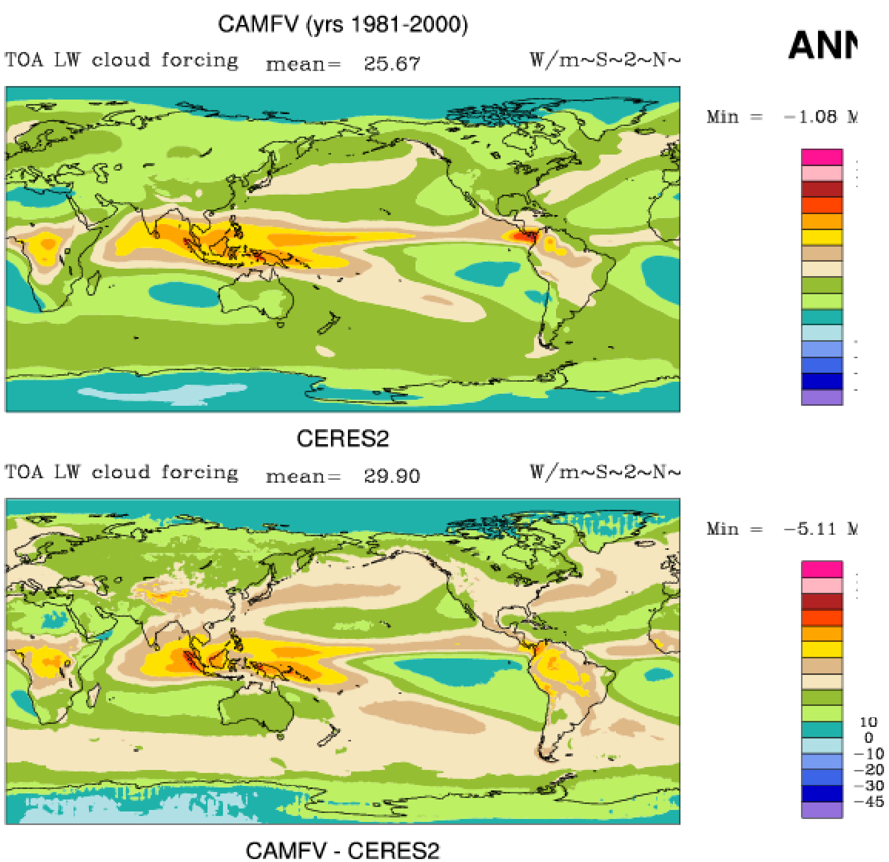
- Nastrom-Gage transition in KE spectra
- Mesoscale shallowing:
- Transition from a -3 regime (representative of quasi-2d large scale flow) to a -5/3 regime (associated with increased variability, increased frequency of extreme events)
- Resolving the -5/3 regime considered necessary if not sufficient to simulate correct mesoscale variability
- Determine effective resolution, following Skamarock 2004

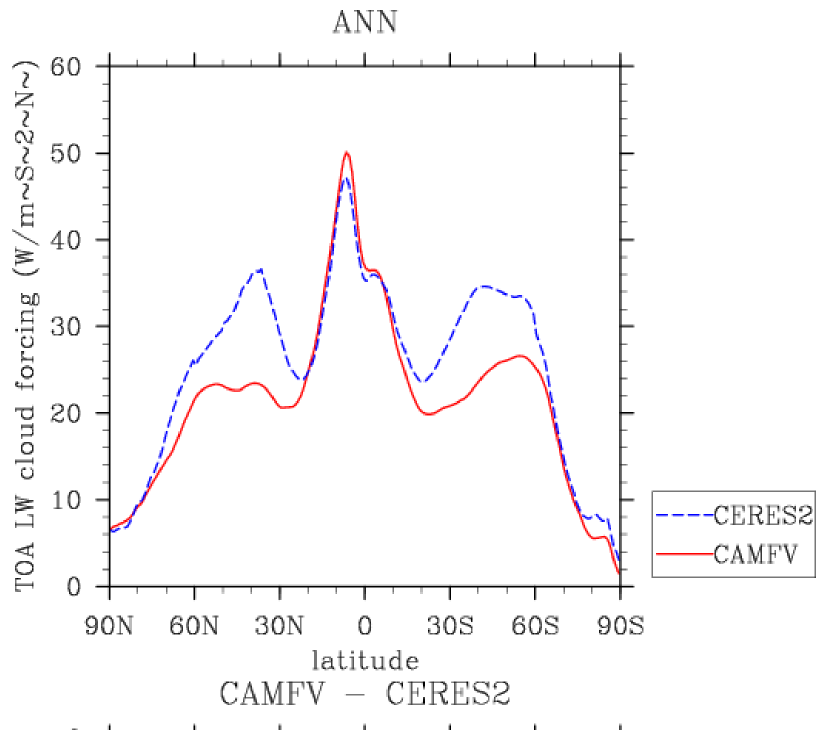
Kinetic Energy Spectra



- Nastrom-Gage transition **resolved in CAM at 1/8.**
- **Effective resolution (Skamarock 2002) ~7dx = 100km at 1/8**
- **Divergence component?**

Long Wave Cloud Forcing
CAM-FV 1° and observations





CAM LWCF: close to observations in the tropics, to weak in mid-latitudes.

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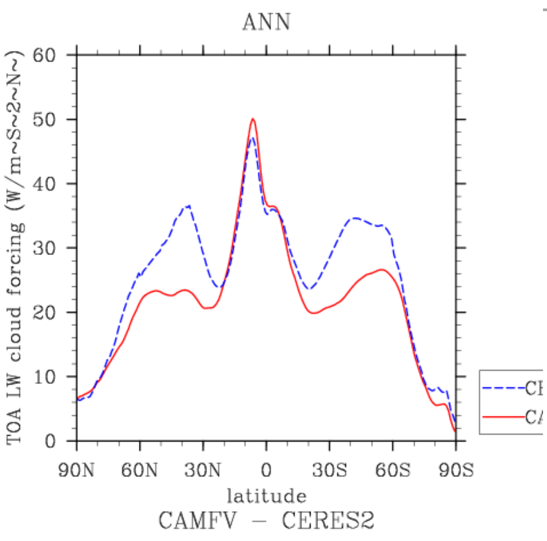
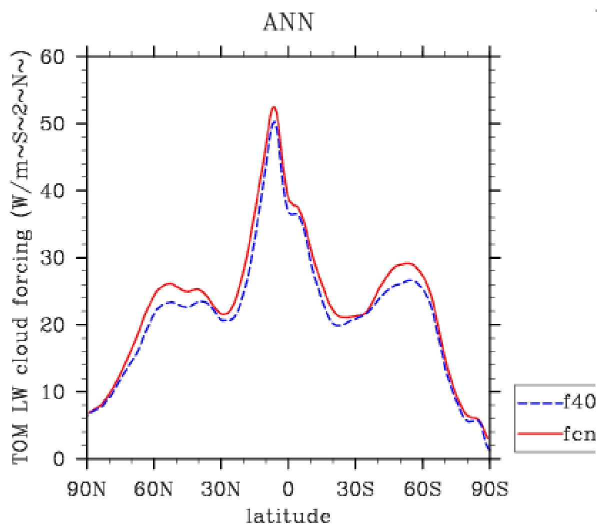
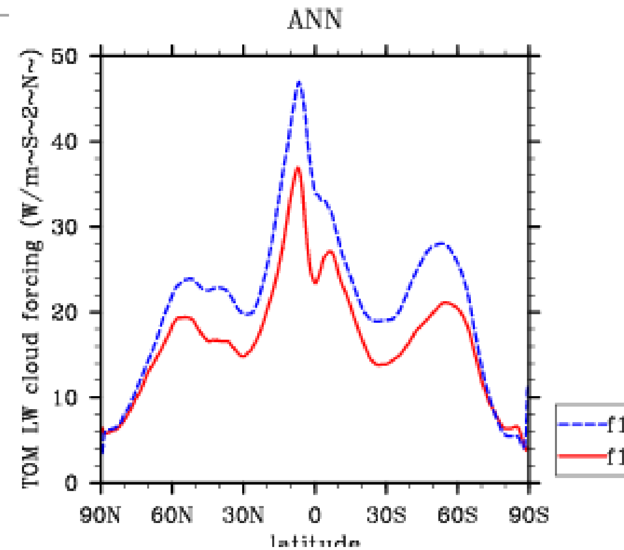
Long Wave Cloud Forcing



CAM-FV 1°
CERES2



CAM-SE 1°
CAM-FV 1°

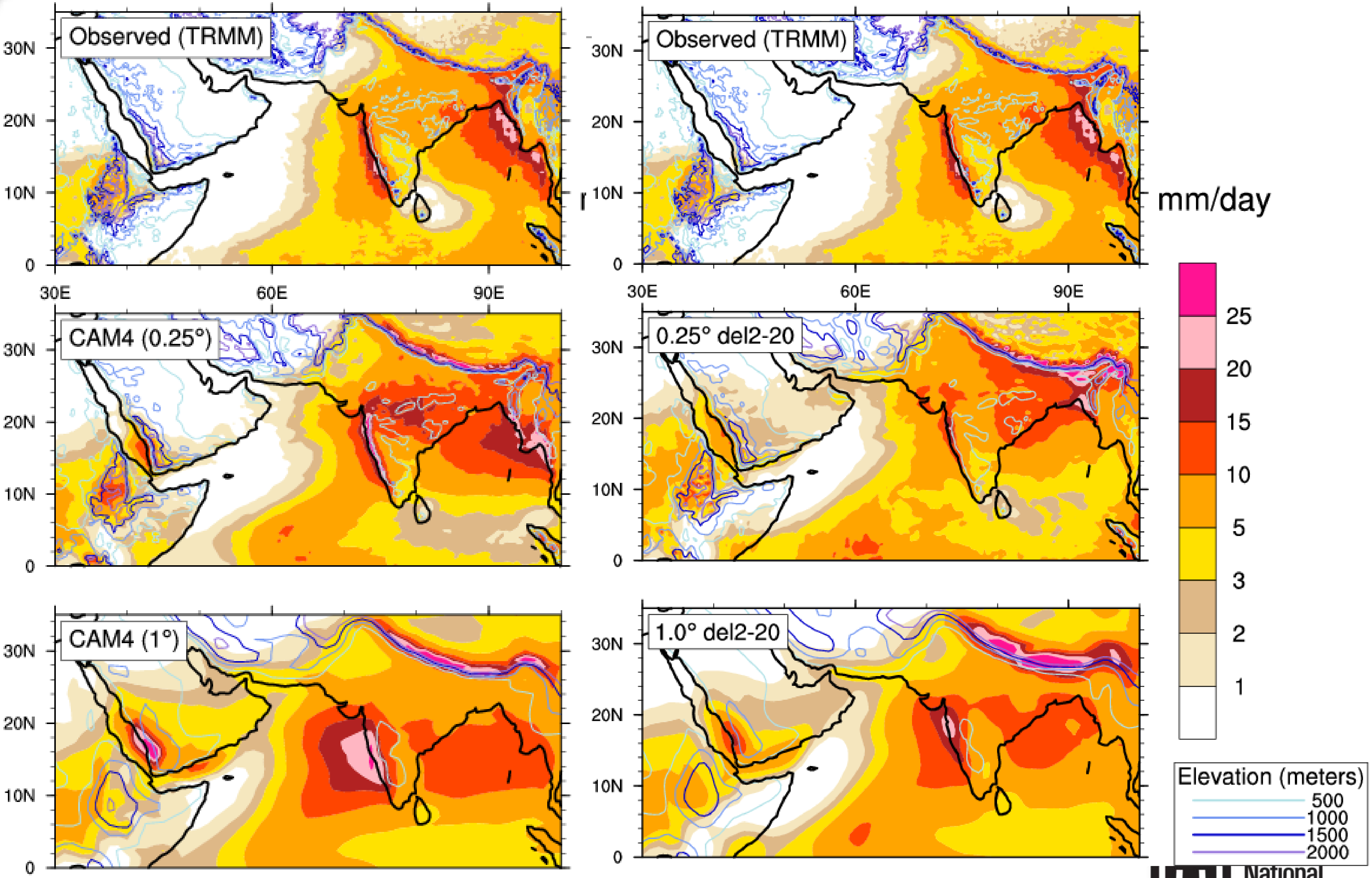


CAM-SE 1/4°
CAM-SE 1°

- At 1 degree resolution – very little sensitivity to the dycore
- Increasing resolution to ¼ degree: large drop in clouds, LWCF, independent of dycore.
- Change is to large to ‘tune’: CAM-SE ¼ degree run already using unreasonably low cloud thresholds (rhminh=.68, rhminl=.84)

Precipitation

CAM-FV   CAM-SE



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