ATM 265, Spring 2019
Lecture 8
Variable Resolution Modeling
April 24, 2019

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Slides are based on Colin Zarzycki's talk on variable resolution from the DCMIP workshop (2016)

High-Resolution Modeling

Why do we want higher resolution?

- Improved resolution of land-surface processes (snowpack, runoff)
- Resolution of transient eddies (synoptic-scale frontal systems, local convective systems)
- Resolution of extreme weather events
- Improvement in representation of geographic features (mountain ranges and islands)

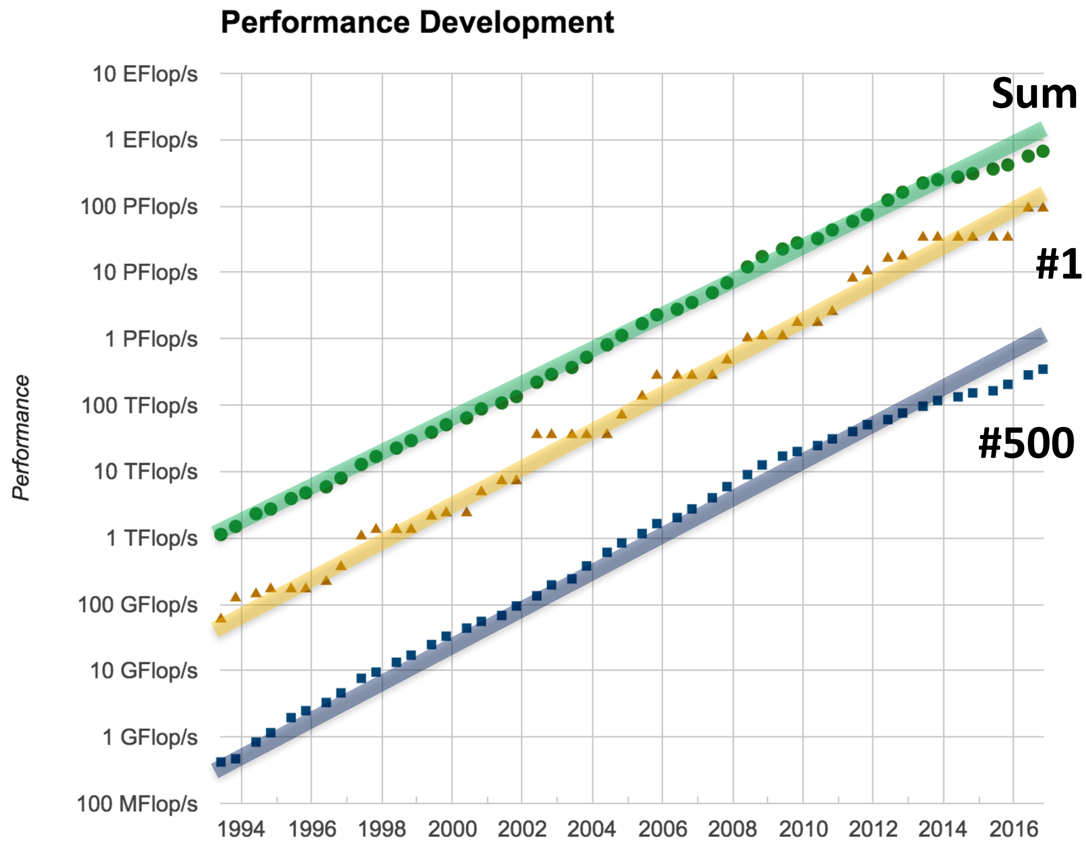
The California coastal ranges have a profound effect on regional climate which is poorly captured in current climate models.

Computing Power vs. Resolution

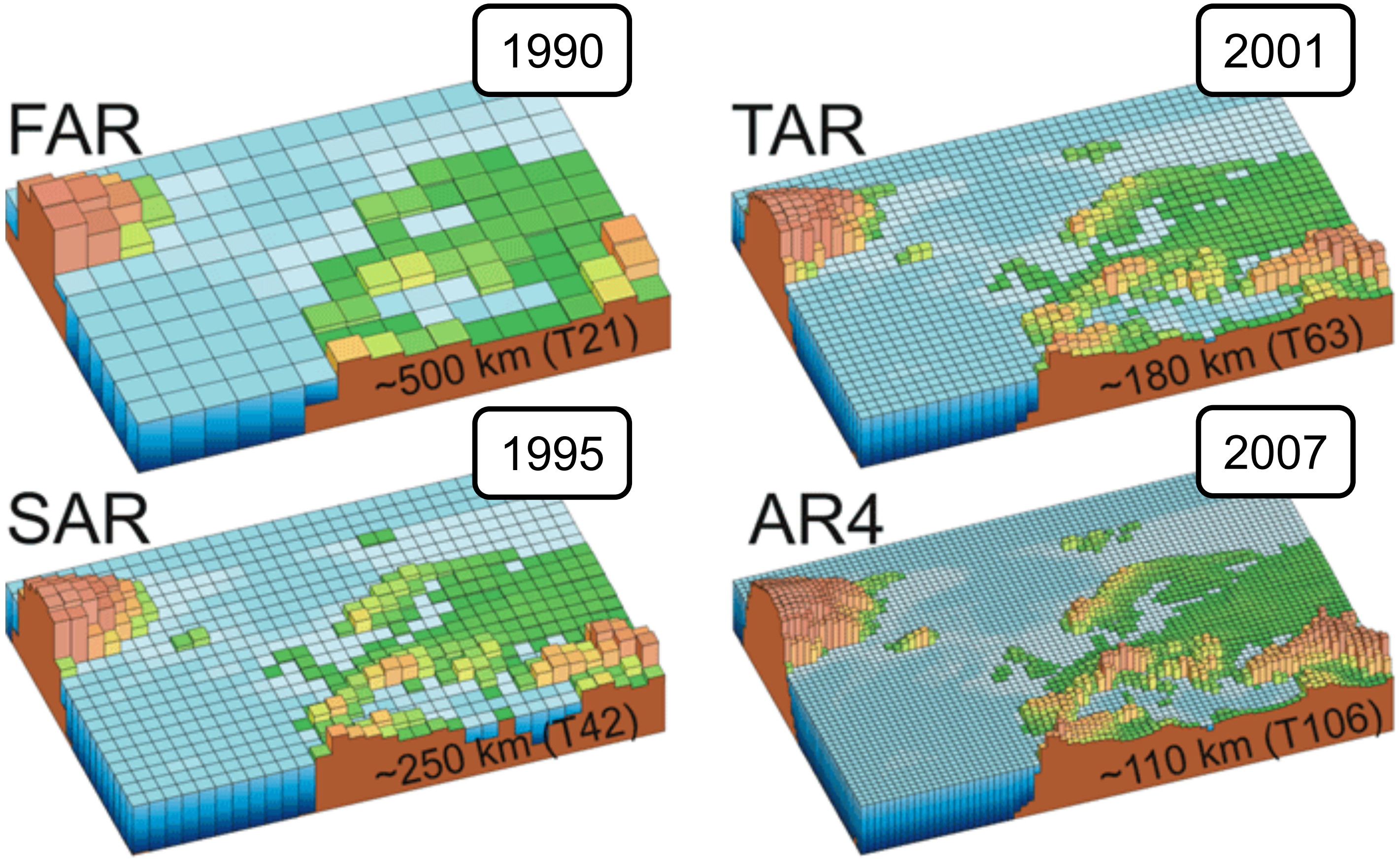
Computational power doubles approximately every 1.2 years.

To obtain a factor of 2 horizontal refinement, numerical models require 8x the computational power.

Doubling of horizontal resolution every 3.6 years?



Climate Model Resolution



AR5 (2013) included some model simulations at ~50km, but most runs were at 110km.

AR6 (2019) will rely on CMIP6 runs, which include many runs at 25-50km global resolution.

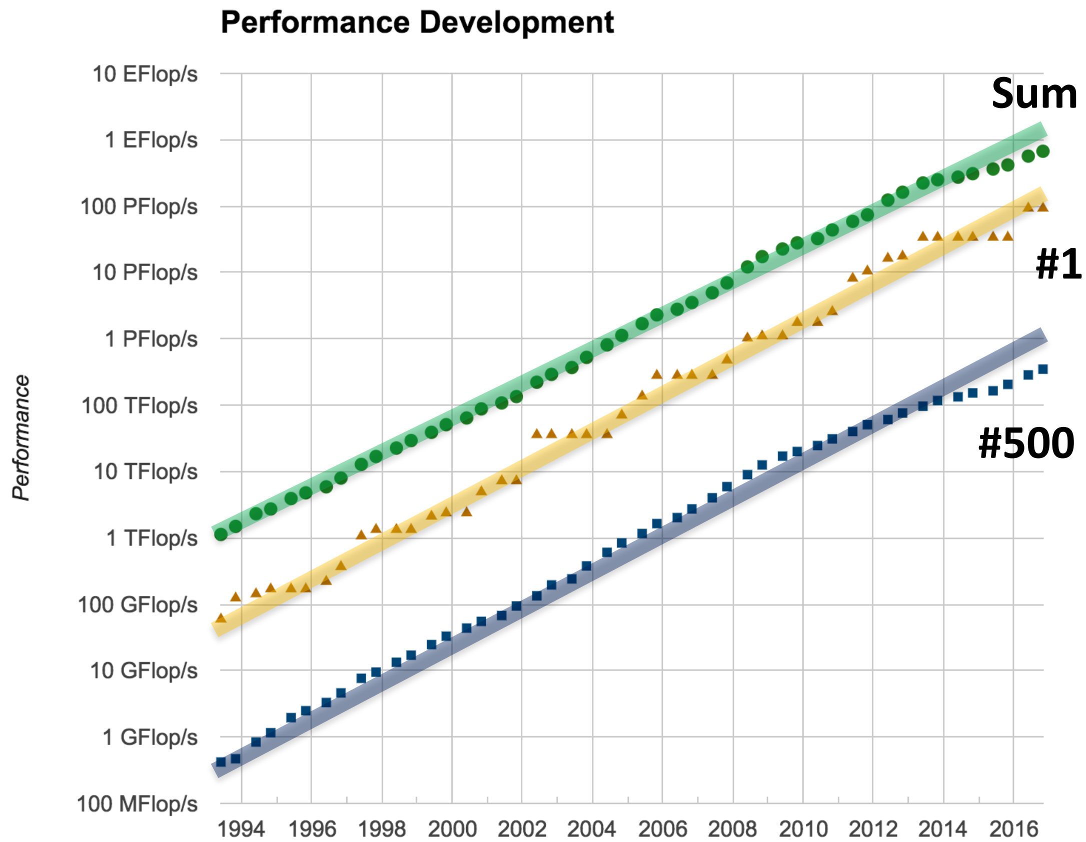
Computing Power vs. Resolution

Doubling of horizontal resolution every 3.6 years?

Reality is quite different – doubling of resolution is closer to every 10 years.

Why?

High resolution models are **expensive to run**. This implies they are **hard to tune**, and so it is difficult to demonstrate **significant improvements** in simulation quality.



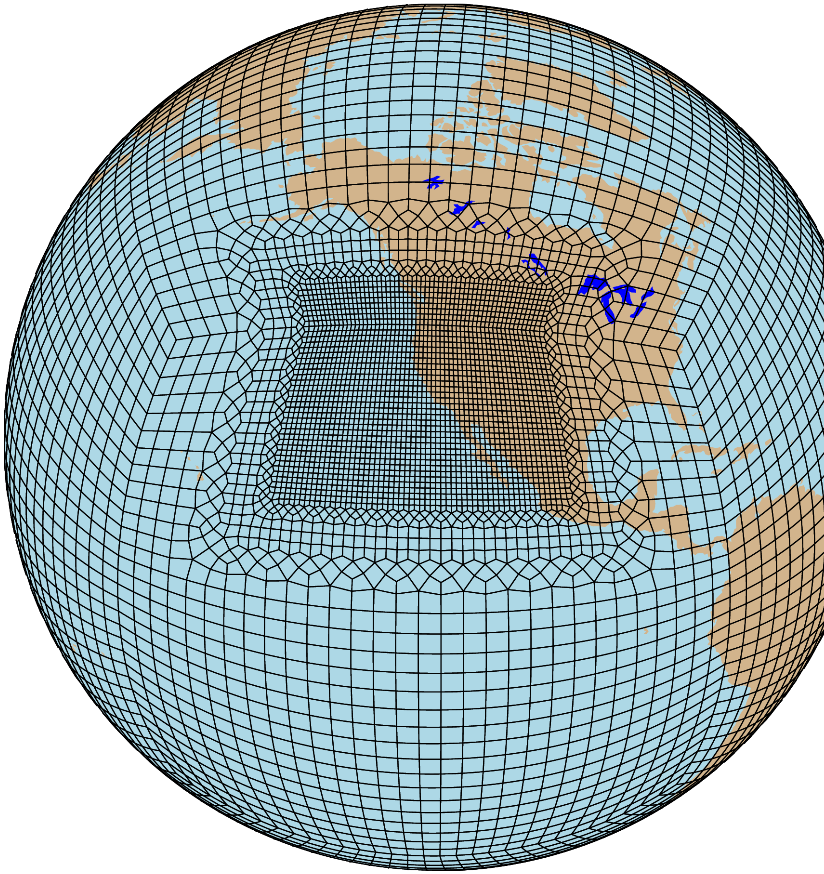
Quasi-Uniform Grids

Cubed-Sphere Grid

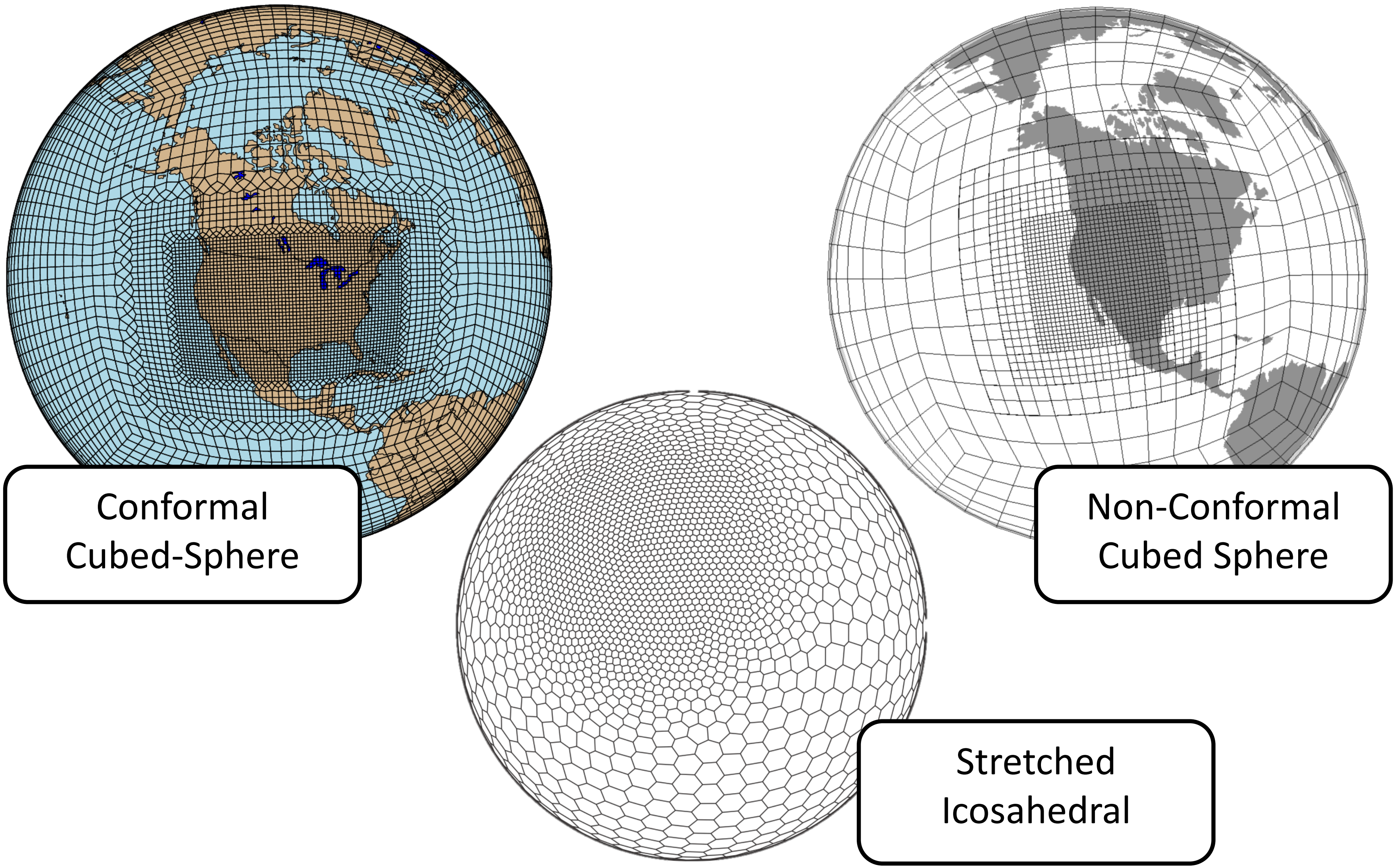
Geodesic Grid

Variable Resolution (VR) Models

- VR allows for **fewer computational resources** to be spent sparingly on a single problem.
- Fully coupled global modeling system, useful for **seasonal to subseasonal forecasting**.
- More **ensemble members** can be produced for a particular region (uncertainty quantification).
- **Resolution where you need it.**

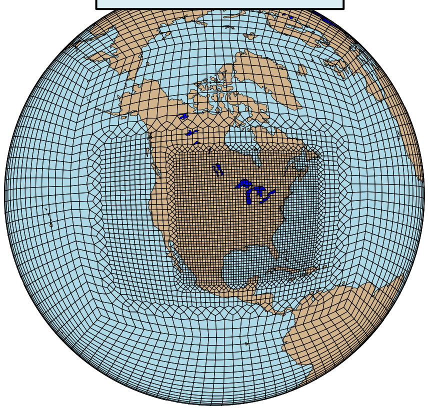


Variable Resolution Models

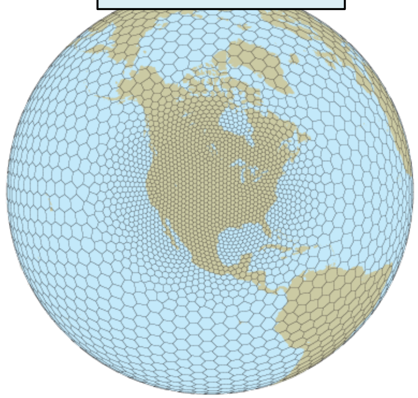


A Sampling of VR Models

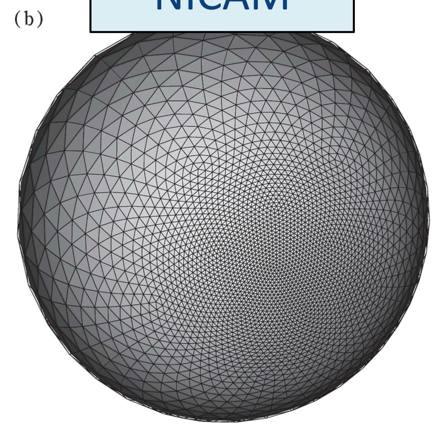
CAM-SE



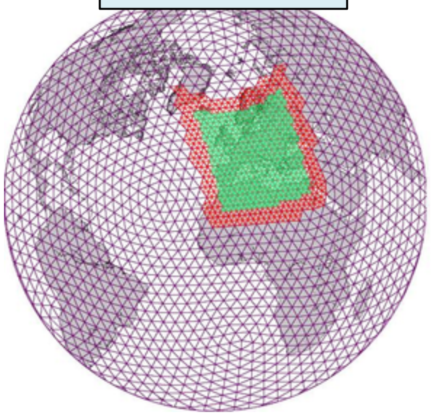
MPAS-A



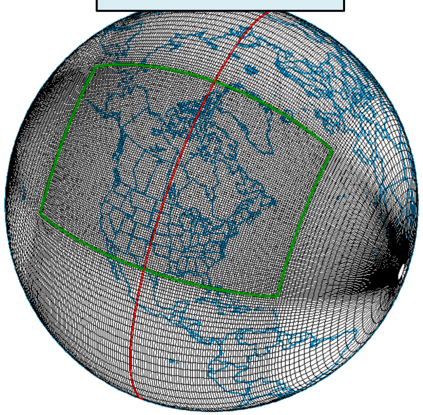
NICAM



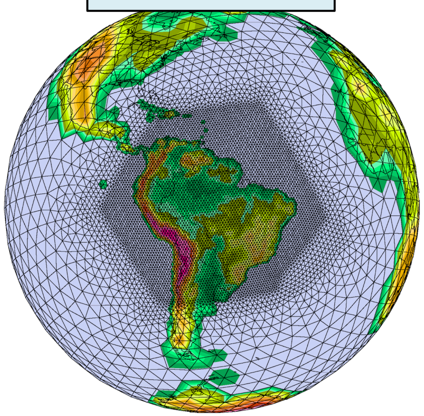
ICON



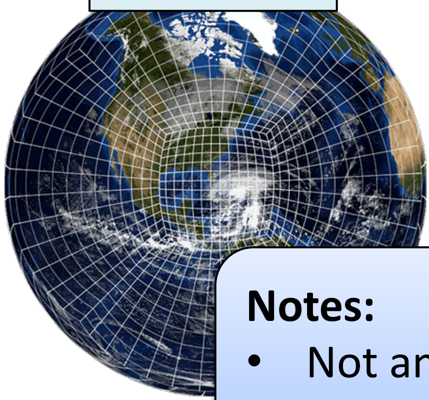
GEM



OLAM



FV^3



Notes:

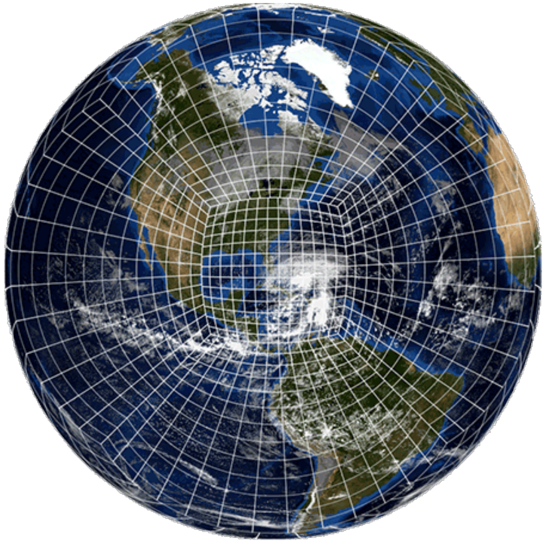
- Not an exhaustive list
- Static mesh refinement

Stretched Grids

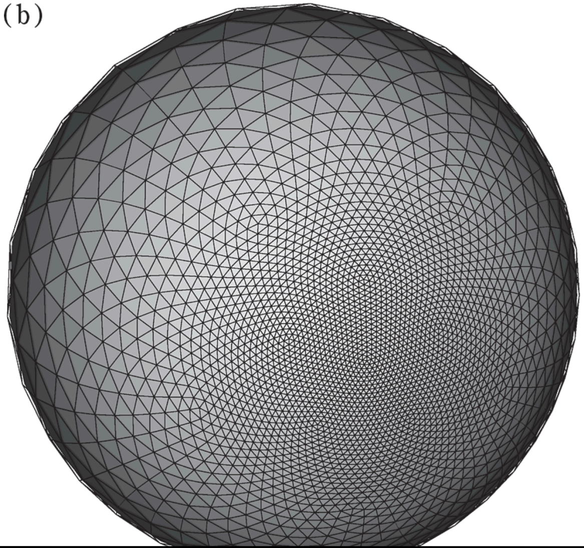
- Examples going back nearly 40 years (e.g., Schmidt, 1977; Staniforth and Mitchell, 1978)
- Generally pole-symmetric dilation

- Benefits
  - Numerical modifications trivial
  - Grid structurally unchanged

- Drawbacks
  - At high stretching factors, far field quickly under-resolved
  - Stretching beyond ~7x problematic (Caian and Geleyn, 1997)

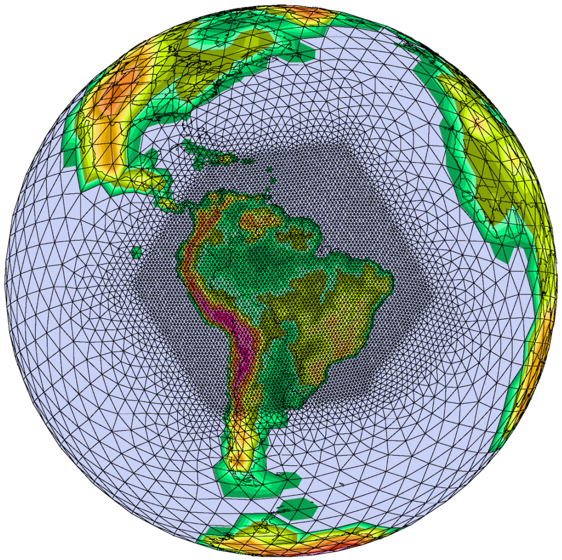


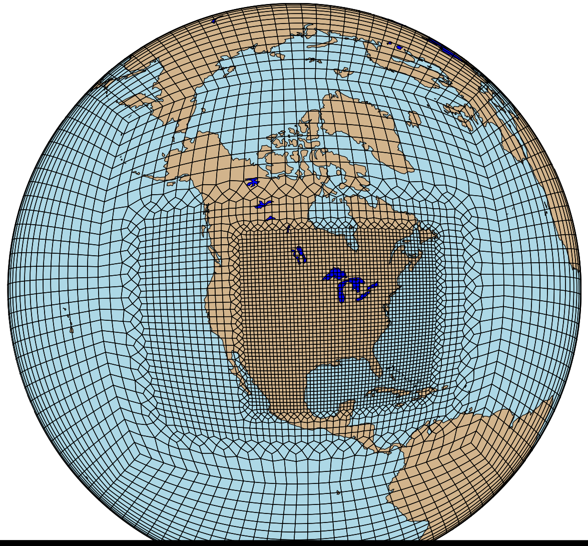
(b)



Unstructured / Nested Refinement

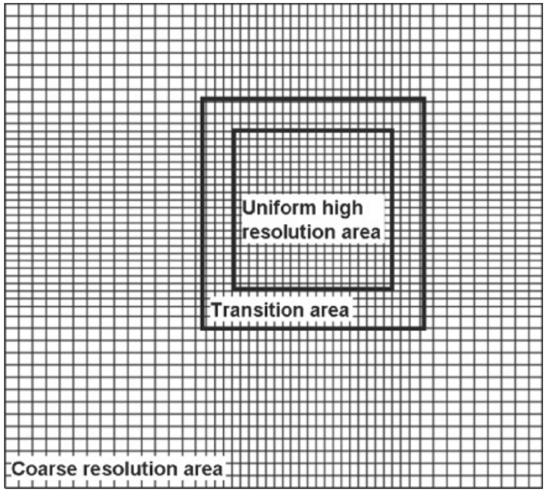
- Many "next-generation" VRGCMs adopting more flexible avenues
  - *Add* cells in area of interest
- Require more "local" stencils capable of operating on arbitrary grids
- *h*-refinement
- Benefits
  - Doesn't coarsen far-field
  - Multiple regions, flexibility in shape of refinement patches
- Drawbacks
  - Adds cells (cost containment), requires unstructured grids
  - Load balancing, communication (connectivity) may not be as trivial



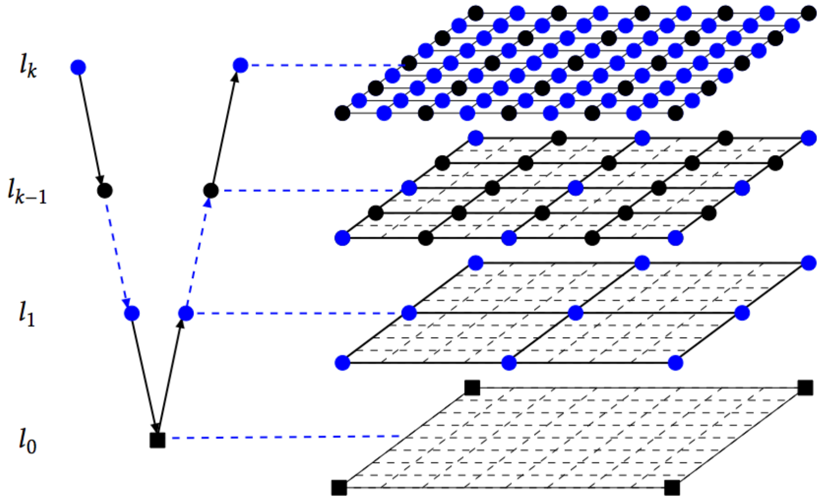


One Other Distinction

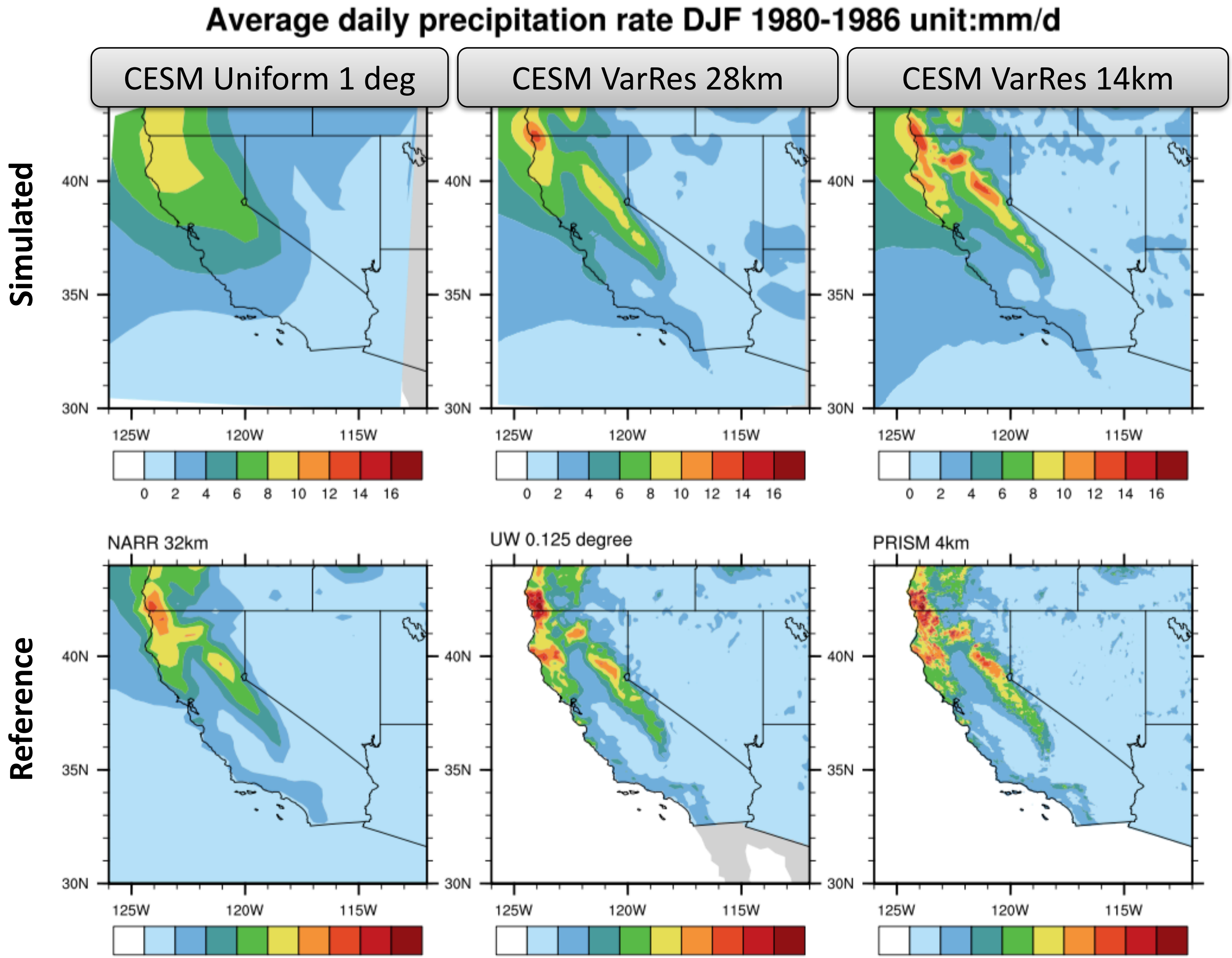
Tong et al., 2013



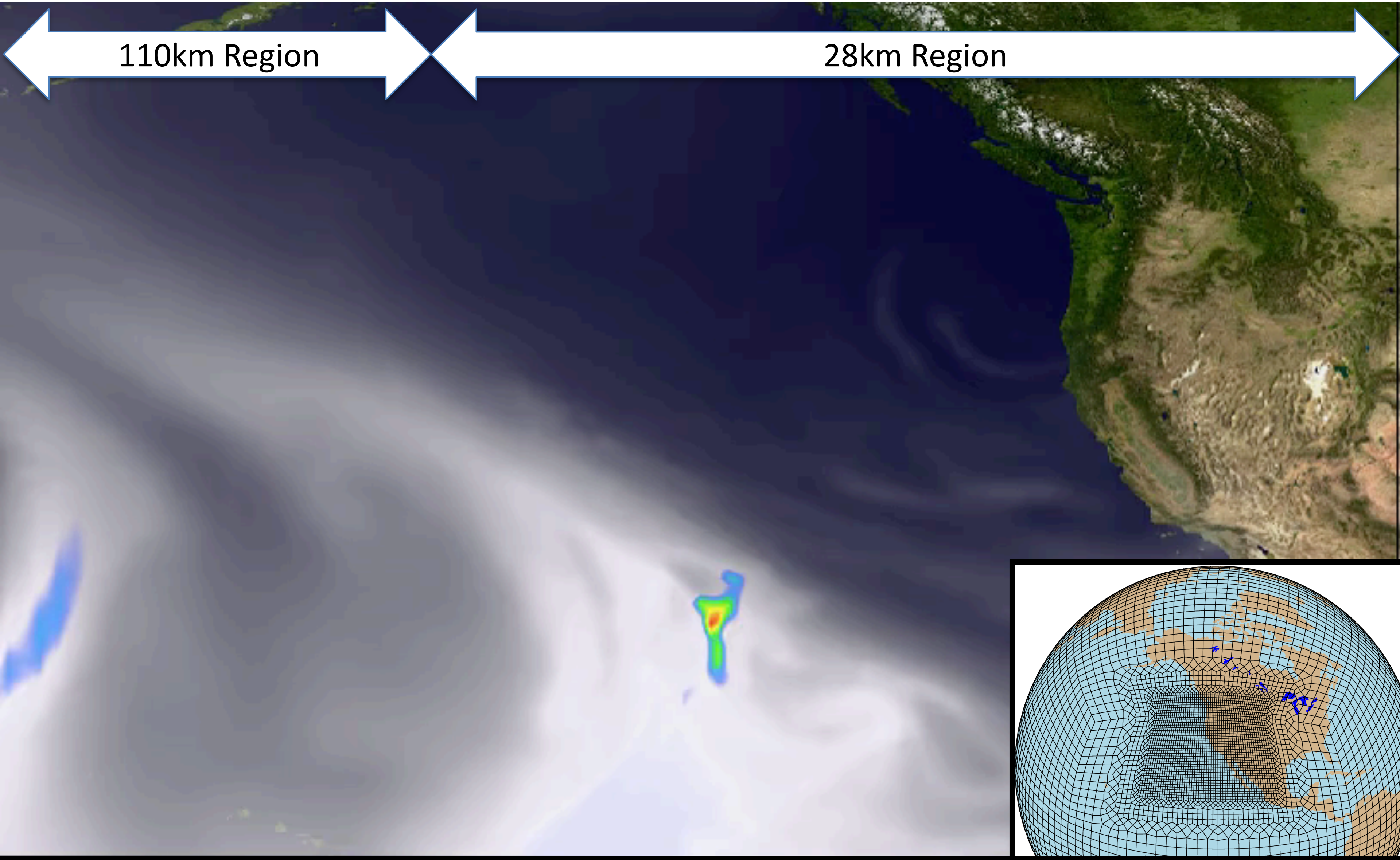
- “Single-grid” or “uni-grid” variable-resolution
  - Every lat/lon point is covered by one and only one grid cell
  - No remapping/interpolation between grid scales
  - Trivial conservation
- “Multi-grid” variable-resolution
  - More analogous to two-way nesting
  - High-resolution nest “overlays” coarser grid
  - Difference from embedded RGCM? Same model, “single direction” timestepping



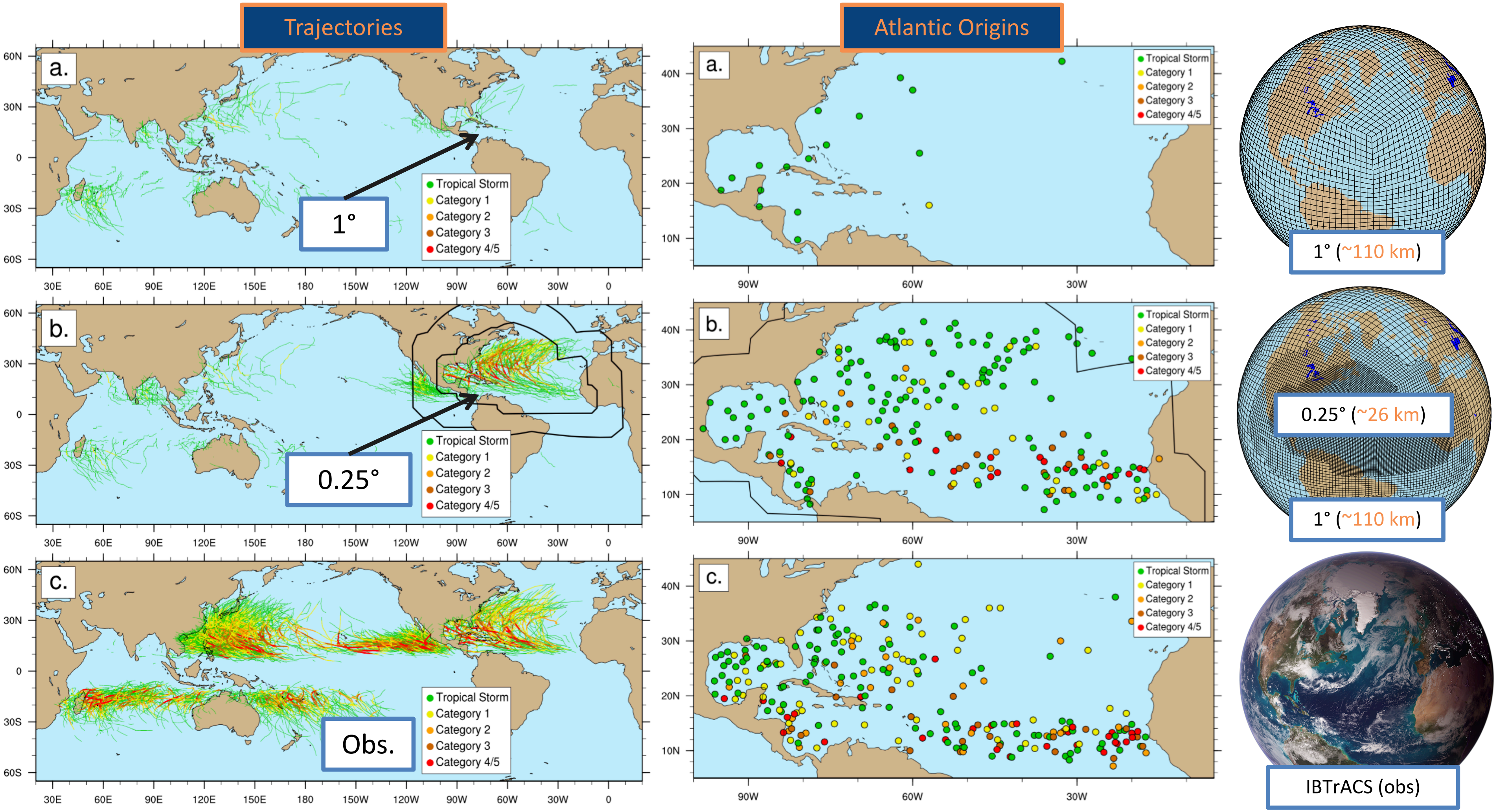
Wenqiang Feng, U. Tenn.


Average daily precipitation rate DJF 1980-1986 unit:mm/d
CESM Uniform 1 deg
CESM VarRes 28km
CESM VarRes 14km
Simulated
Reference
NARR 32km
UW 0.125 degree
PRISM 4km
40N
35N
30N
125W
120W
115W
0 2 4 6 8 10 12 14 16

Applications: Atmospheric Rivers



Applications: Tropical Cyclone Climatology

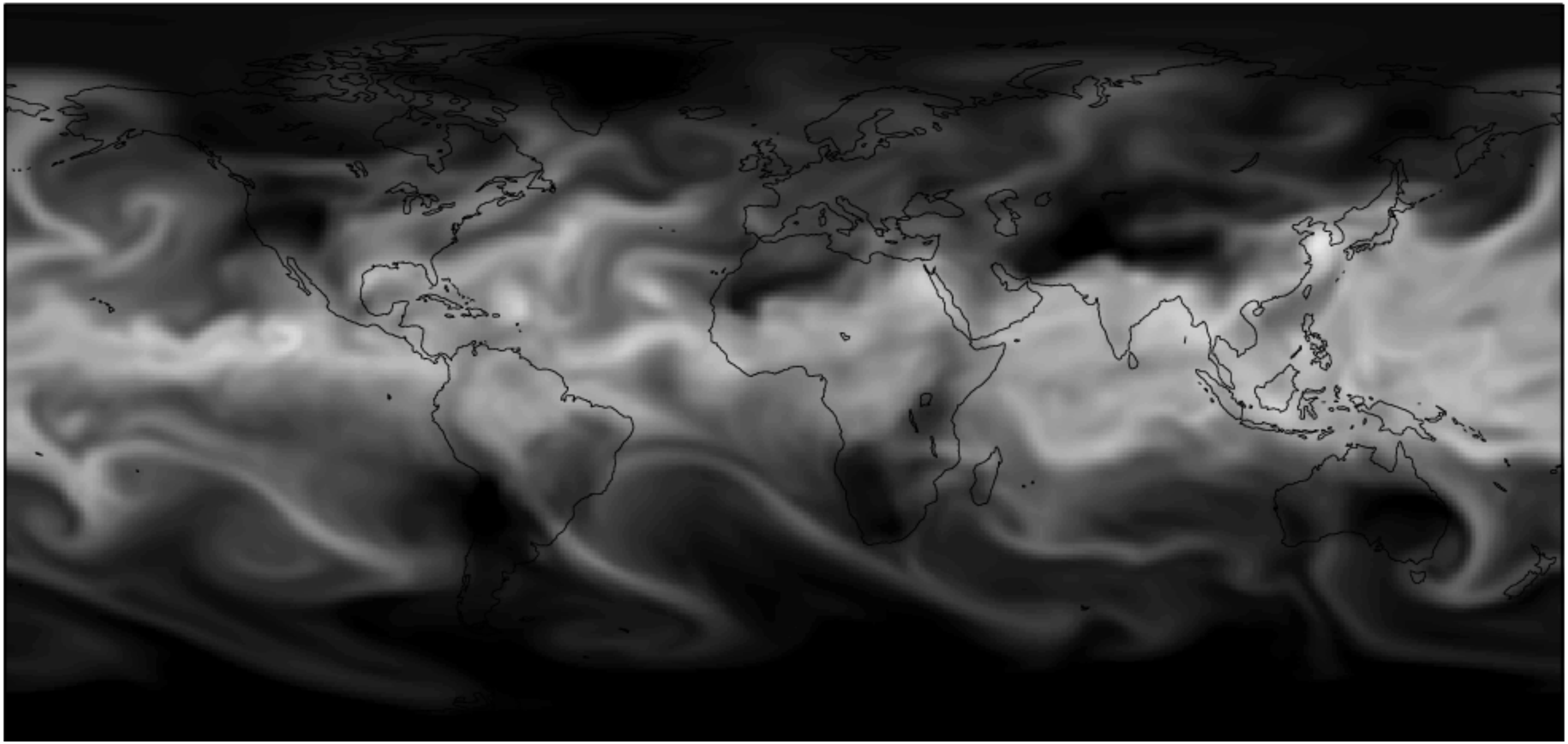


1980-2002

Zarzycki and Jablonowski, 2014, JAMES

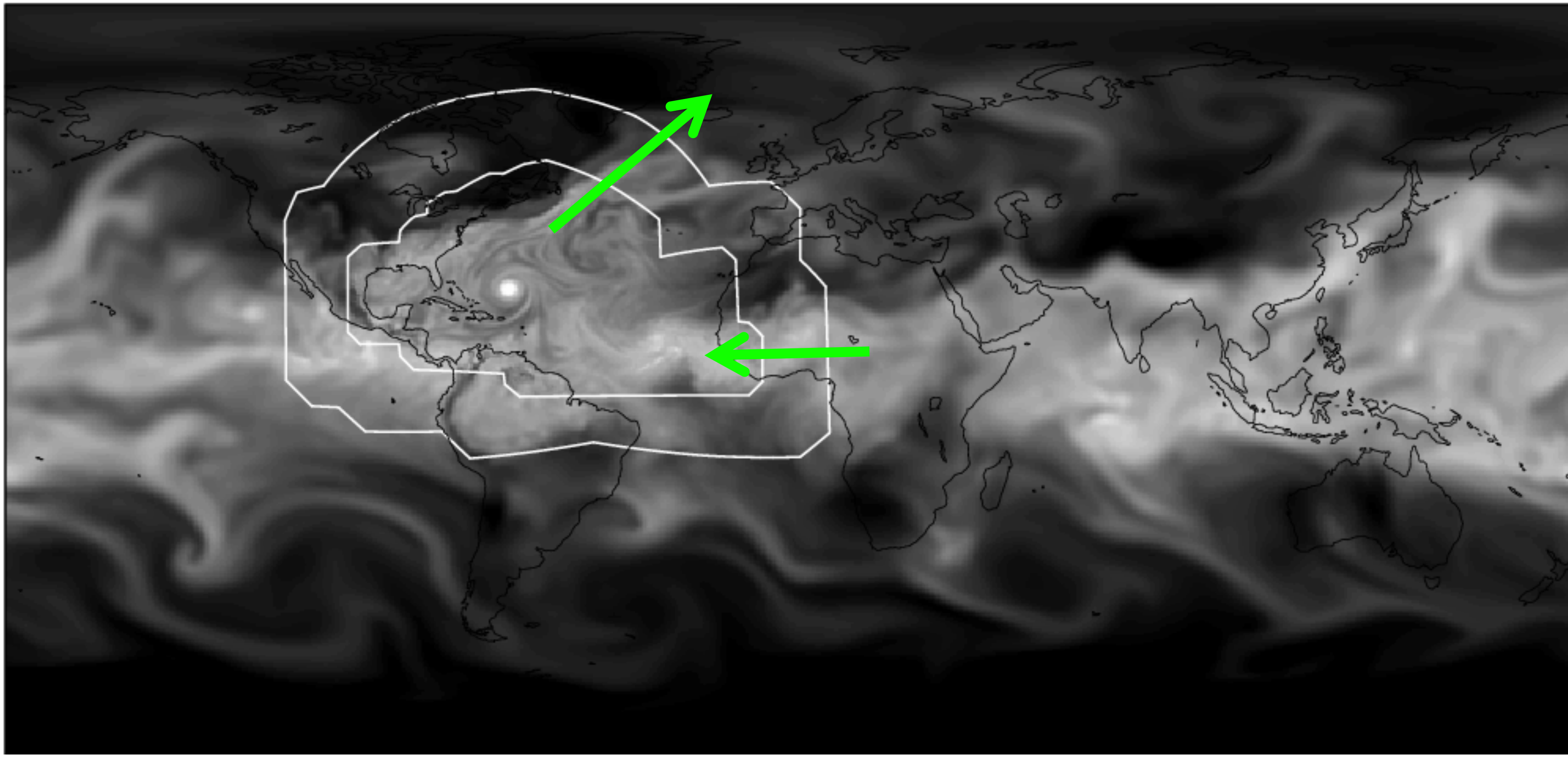
Applications: Tropical Cyclone Climatology

Uniform-Resolution Global Simulation



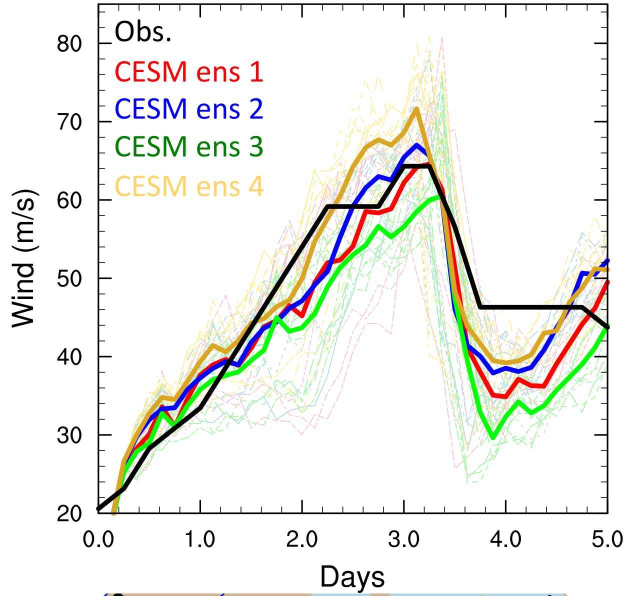
Applications: Tropical Cyclone Climatology

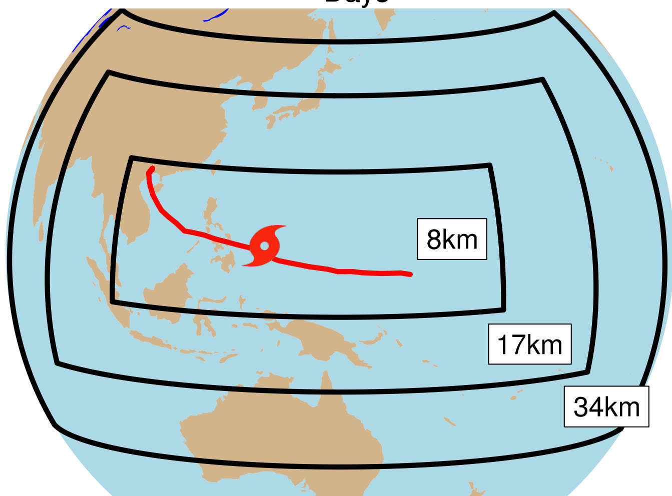
Uniform-Resolution Global Simulation

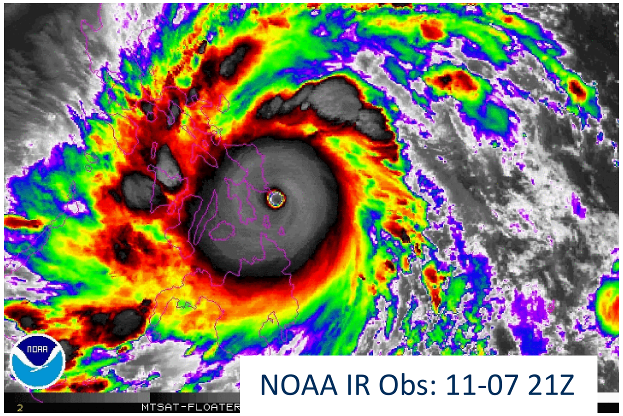


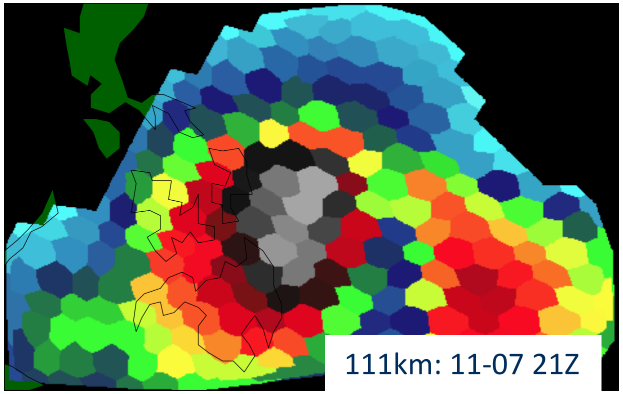
Applications: Typhoon Haiyan Forecasts

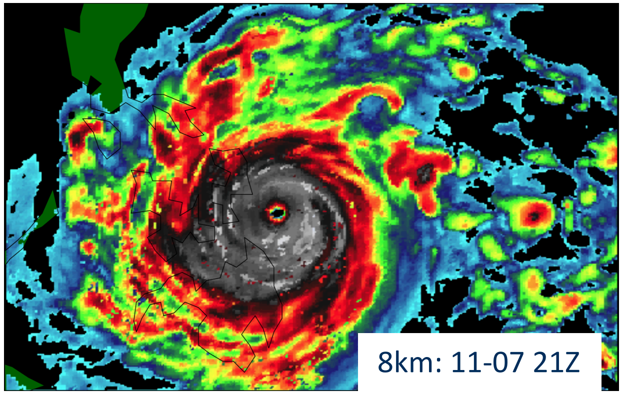
- VR-CESM produces realistic track, intensity and structure
- Computationally inexpensive within coupled earth system model





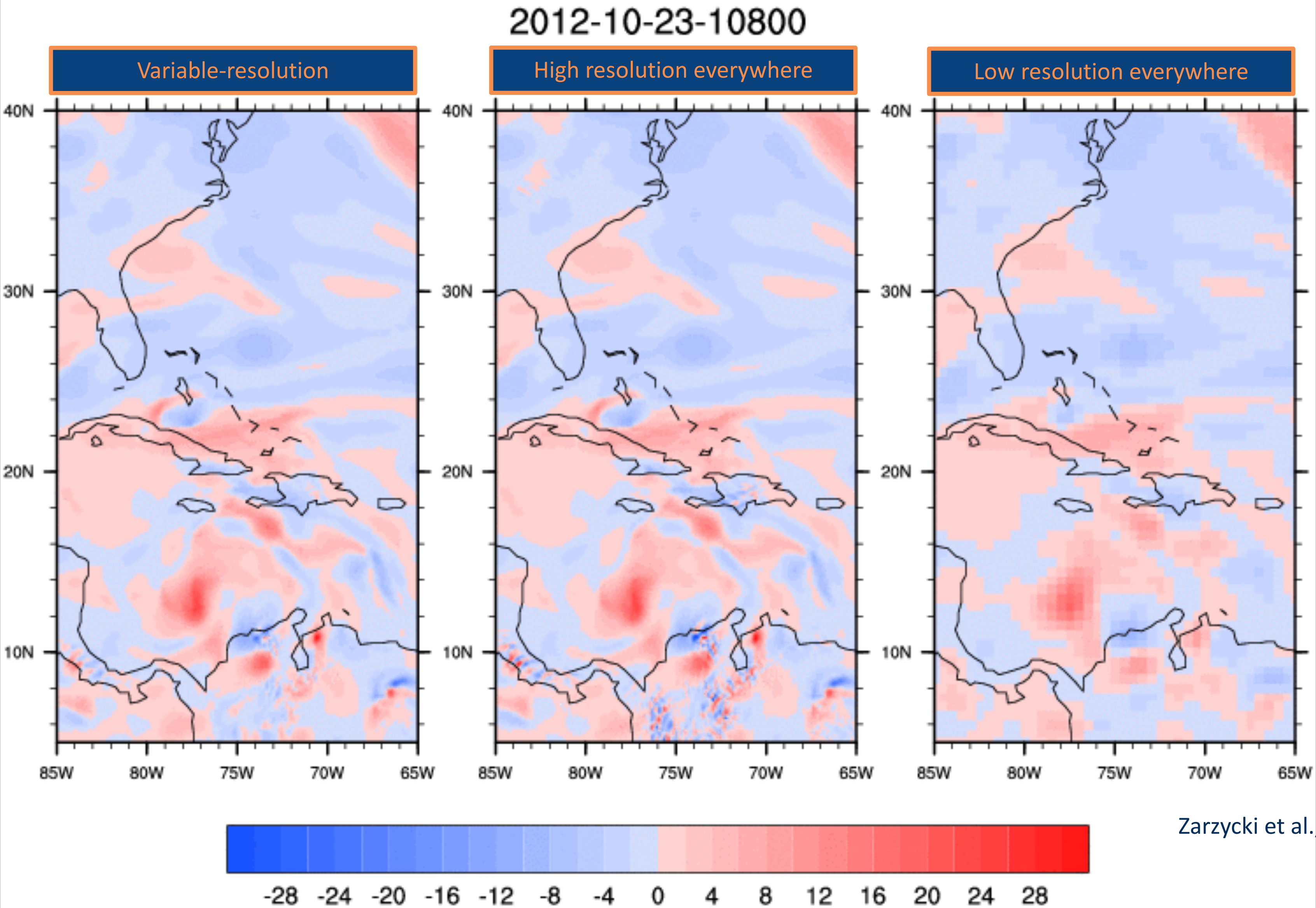






Applications: Hurricane Sandy Forecast

Sandy 500 hPa vorticity: INIT 00Z 10/23/12

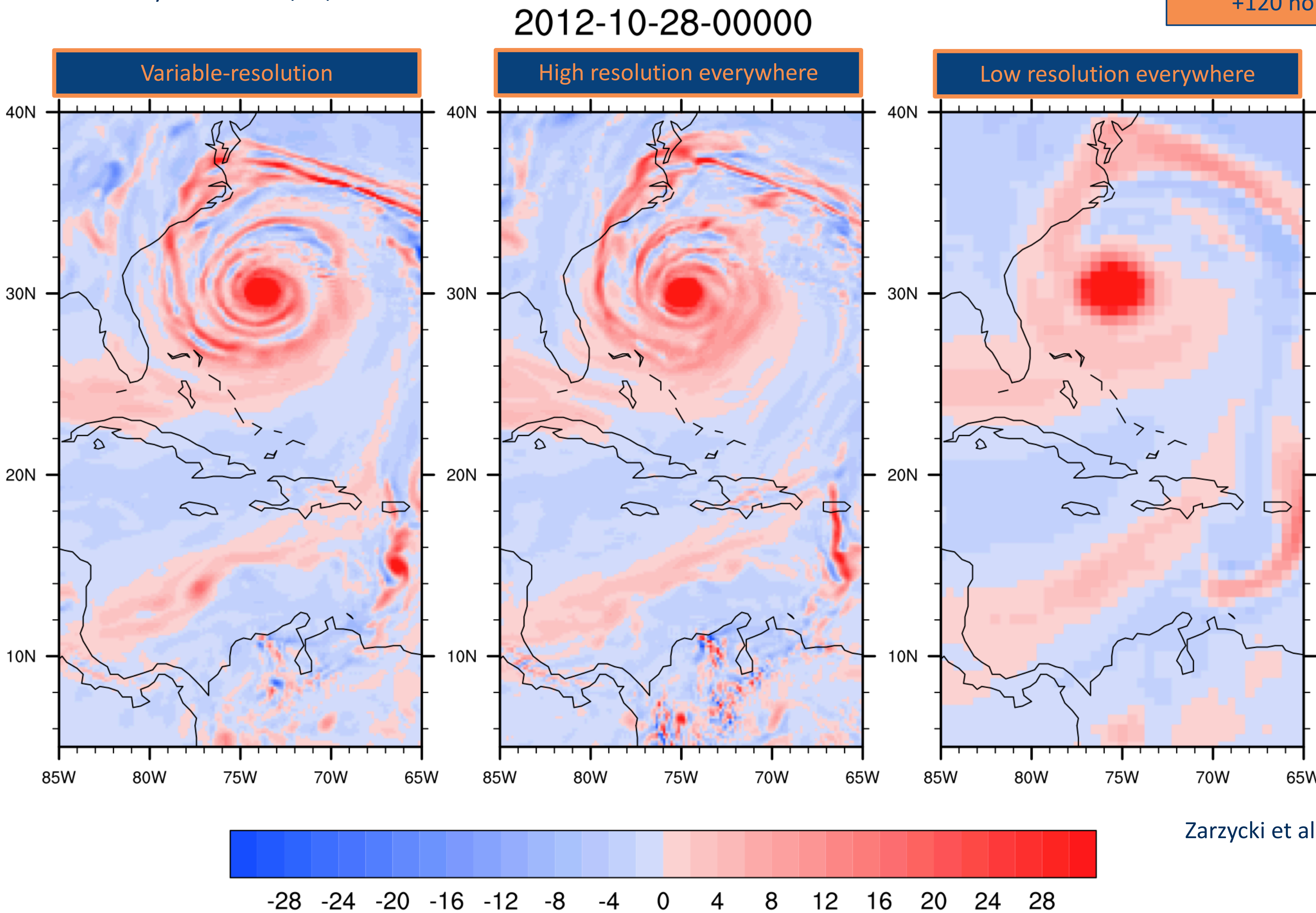


Zarzycki et al., 2015, MWR

Applications: Hurricane Sandy Forecast

Sandy 500 hPa vorticity: INIT 00Z 10/23/12

+120 hours



Zarzycki et al., 2015, MWR

Applications: Hurricane Sandy

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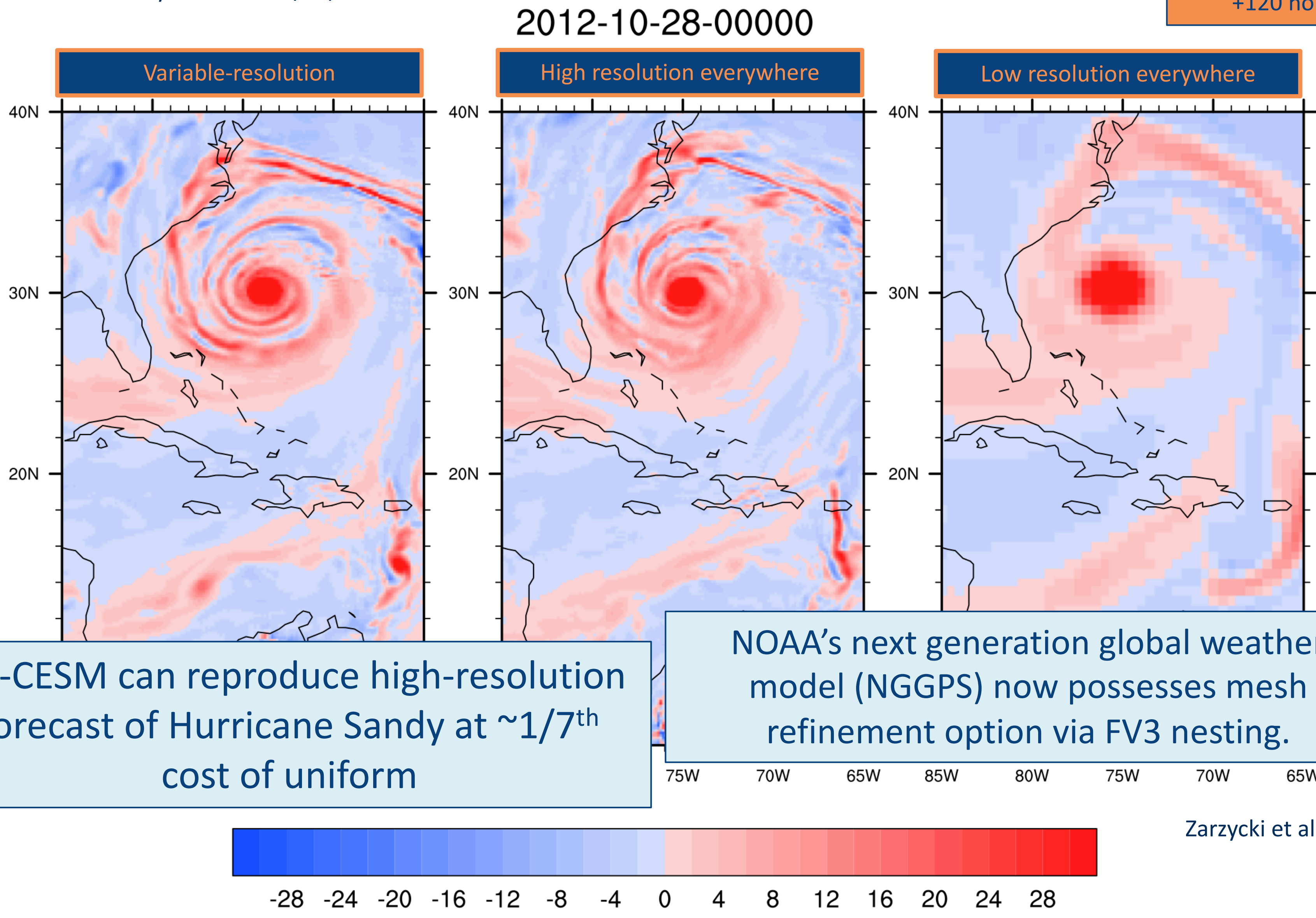


VR-CESM can reproduce high-resolution forecast of Hurricane Sandy at ~1/7th cost of uniform

NOAA's next generation global weather model (NGGPS) now possesses mesh refinement option via FV3 nesting.

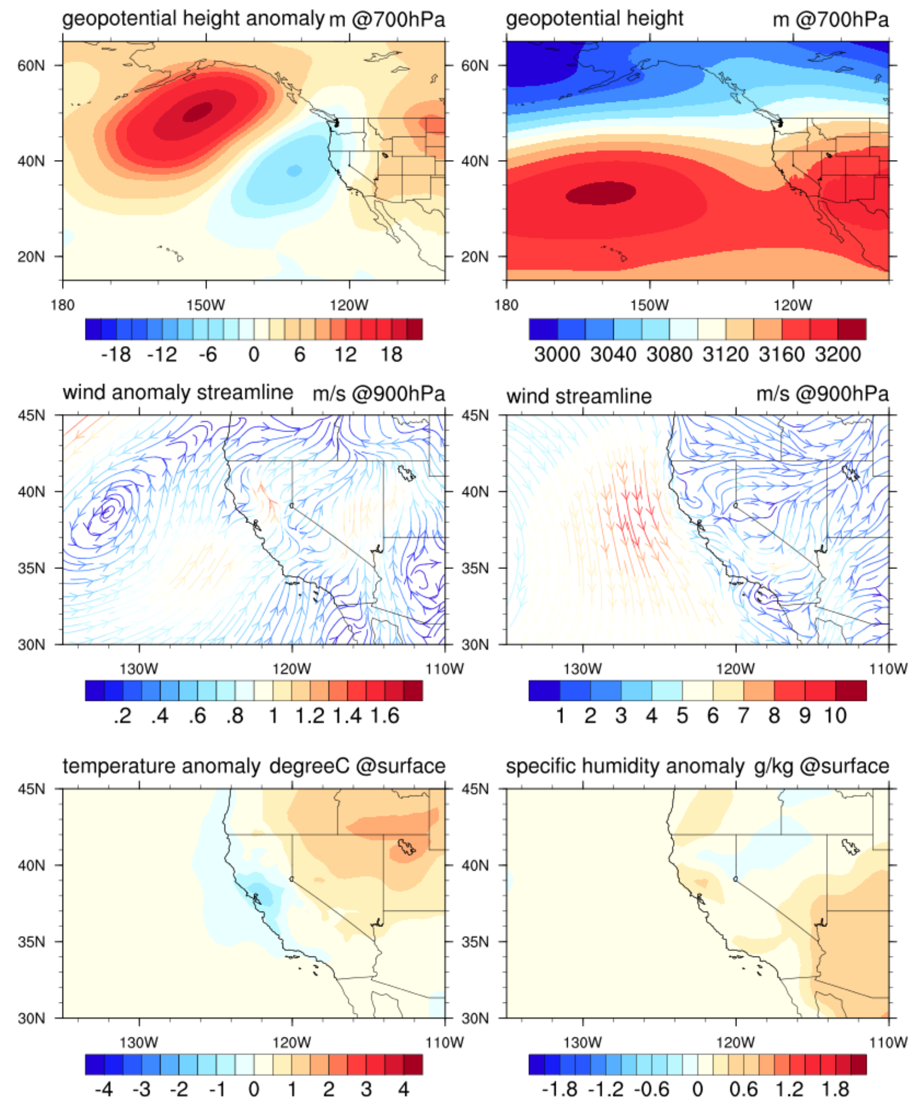
Zarzycki et al., 2015, MWR

Applications: Marine Air Intrusion

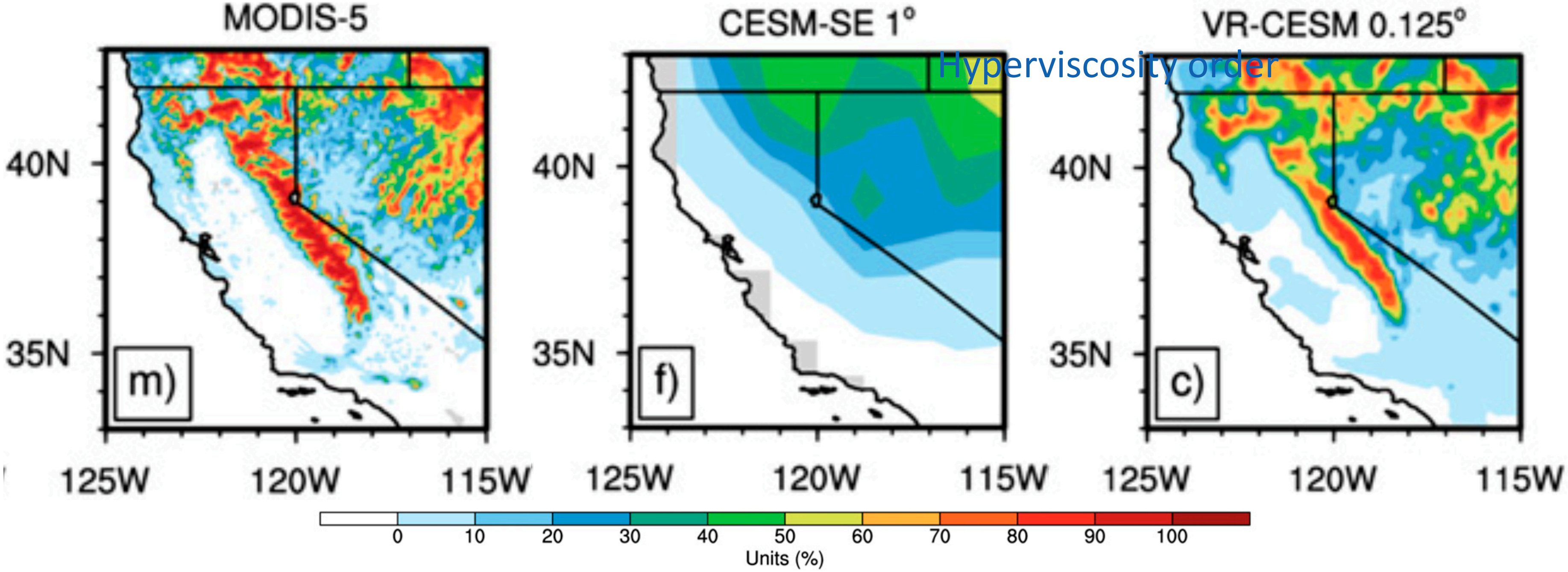
Central Valley Delta Breeze events are important for cooling and ventilating the central valley, and bringing relief from heat waves

These are regional meteorological features driven by large-scale meteorological patterns (LSMPs).

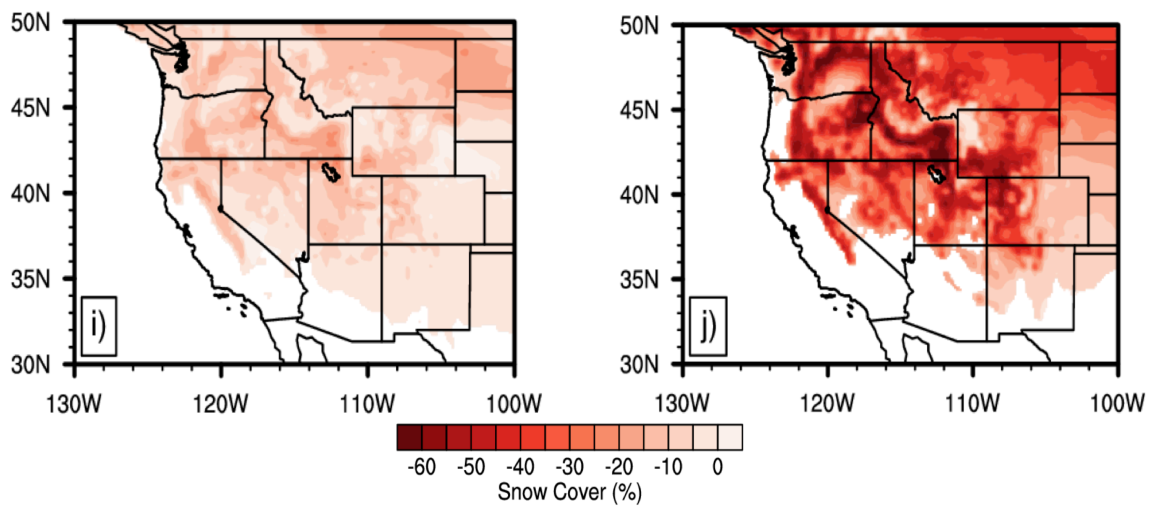
Variable-resolution ensembles have been used to isolate the LSMPs associated with Delta Breeze events, allowing them to be predicted based on simulations that only resolve the large-scale flow.



Applications: Snowpack



2025-2050



2075-2100

Rhoades et al. (2017)

Challenges: Differential Topography Smoothing

$$\Phi_{VR} = \Phi_U + cK_o(\Delta x)\nabla^o\Phi_U$$

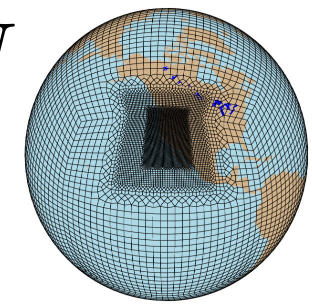
Hyperviscosity order

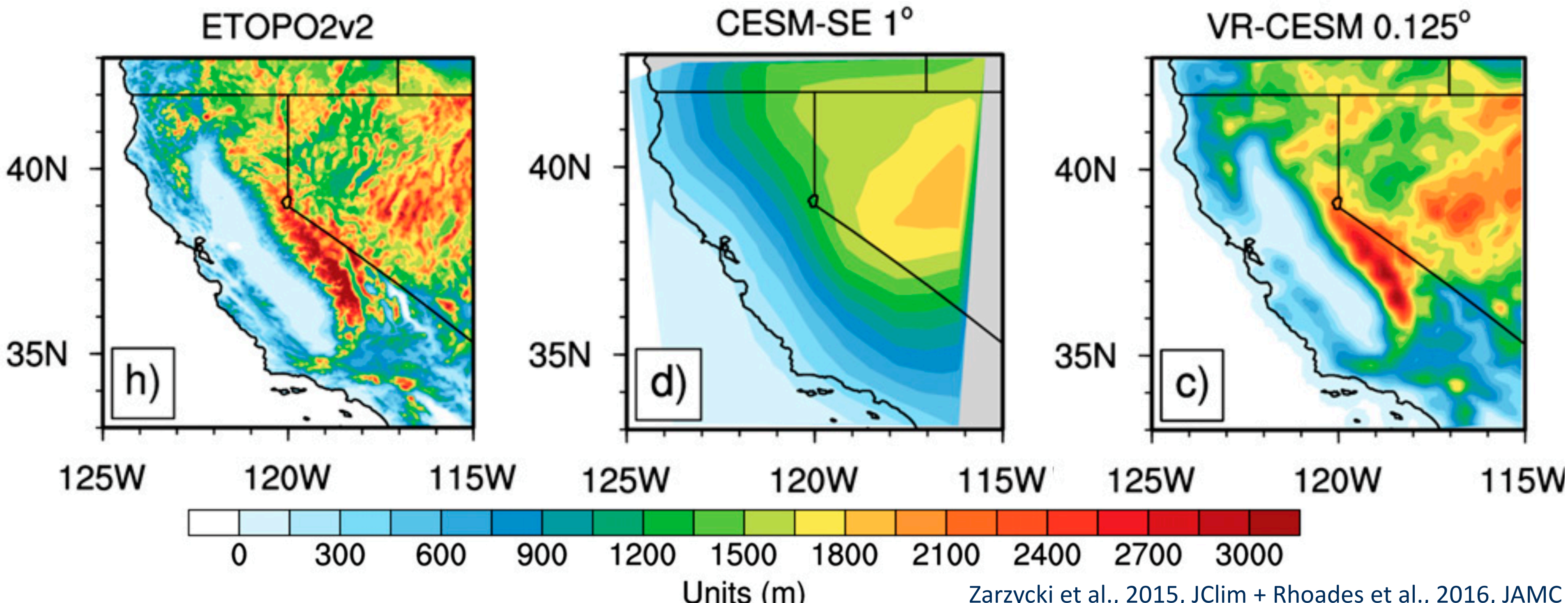
Var-res topo

High-res topo

Tunable constant

Diffusion coefficient (scale selective!)





Zarzycki et al., 2015, JClim + Rhoades et al., 2016, JAMC

Challenges: Differential Topography Smoothing

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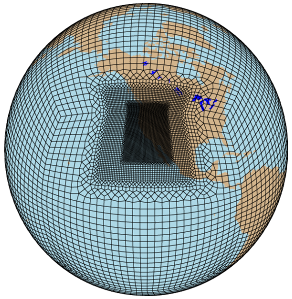
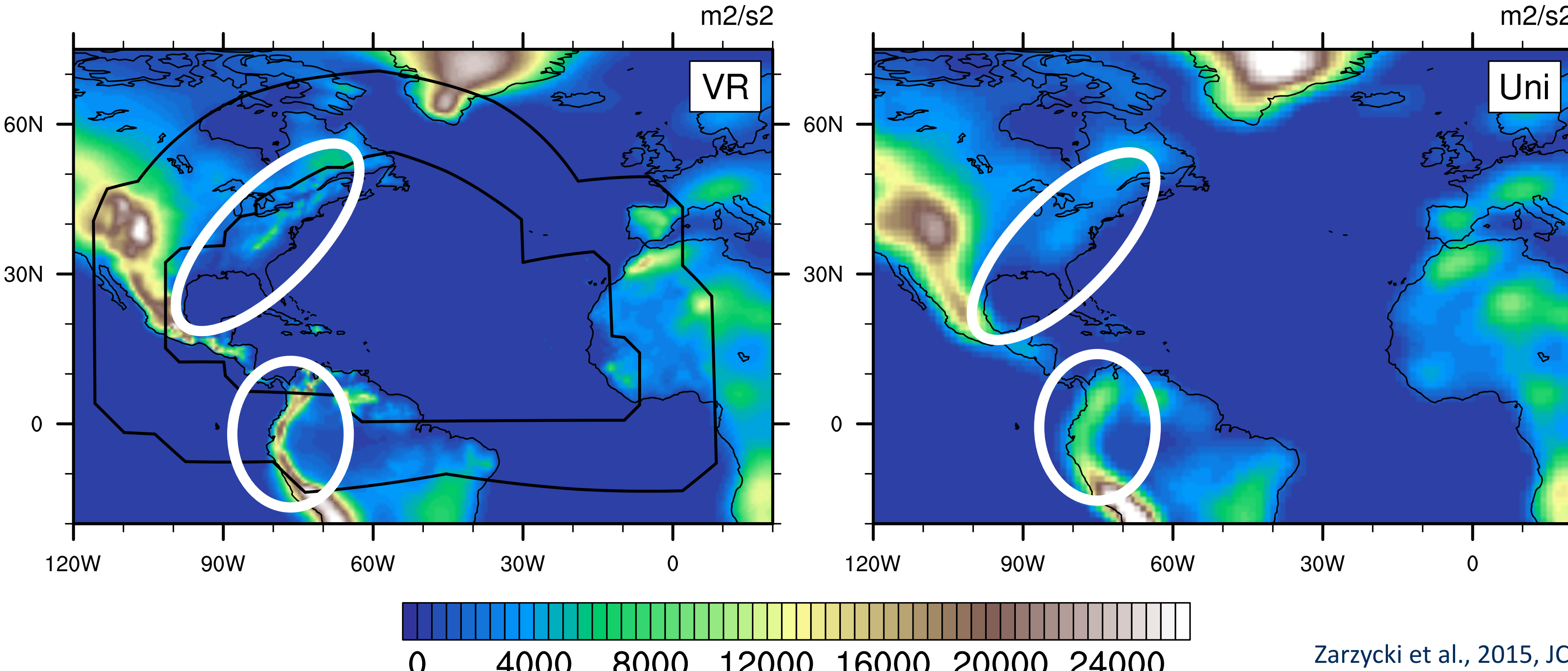
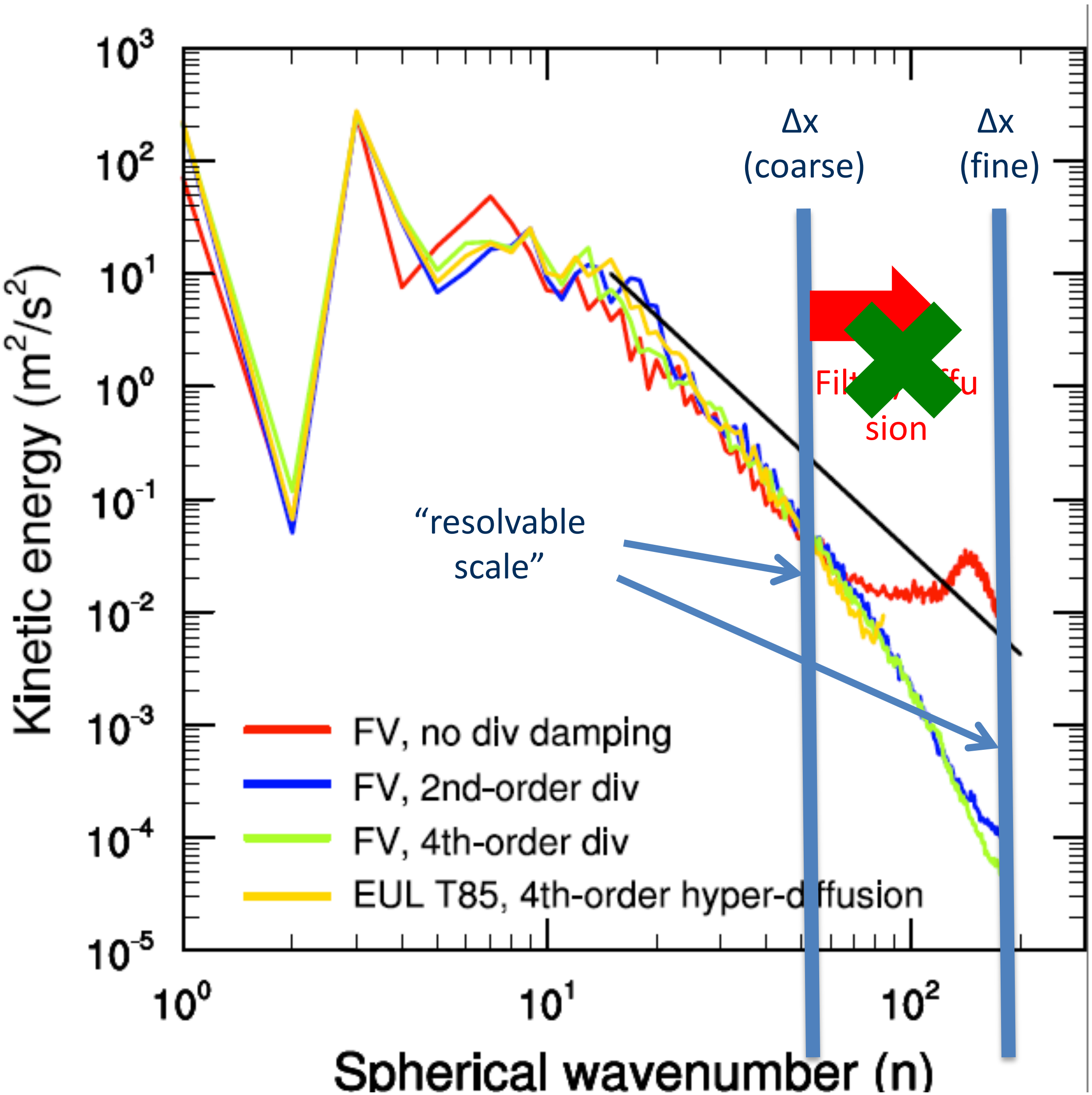




Zarzycki et al., 2015, JClim

Challenges: Diffusion

Has been covered that models generally need some form of diffusion to **remain stable** and **produce realistic results**



Challenges: Diffusion

- Some schemes have enough implicit diffusion that they don't require additional filtering
  - Implicit diffusion inherently scale-selective

- Other models require explicit diffusion for numerical stability and to remove grid-scale noise
  - Smagorinsky
    - Controlled by deformation/stability of local flow
  - (Hyper)-viscosity
    - Applied as forcing term in relevant state equations

- Explicit diffusion requires careful care to <u>only operate on spurious energy near grid scale (e.g., numerical noise, wave reflection, etc.)</u>

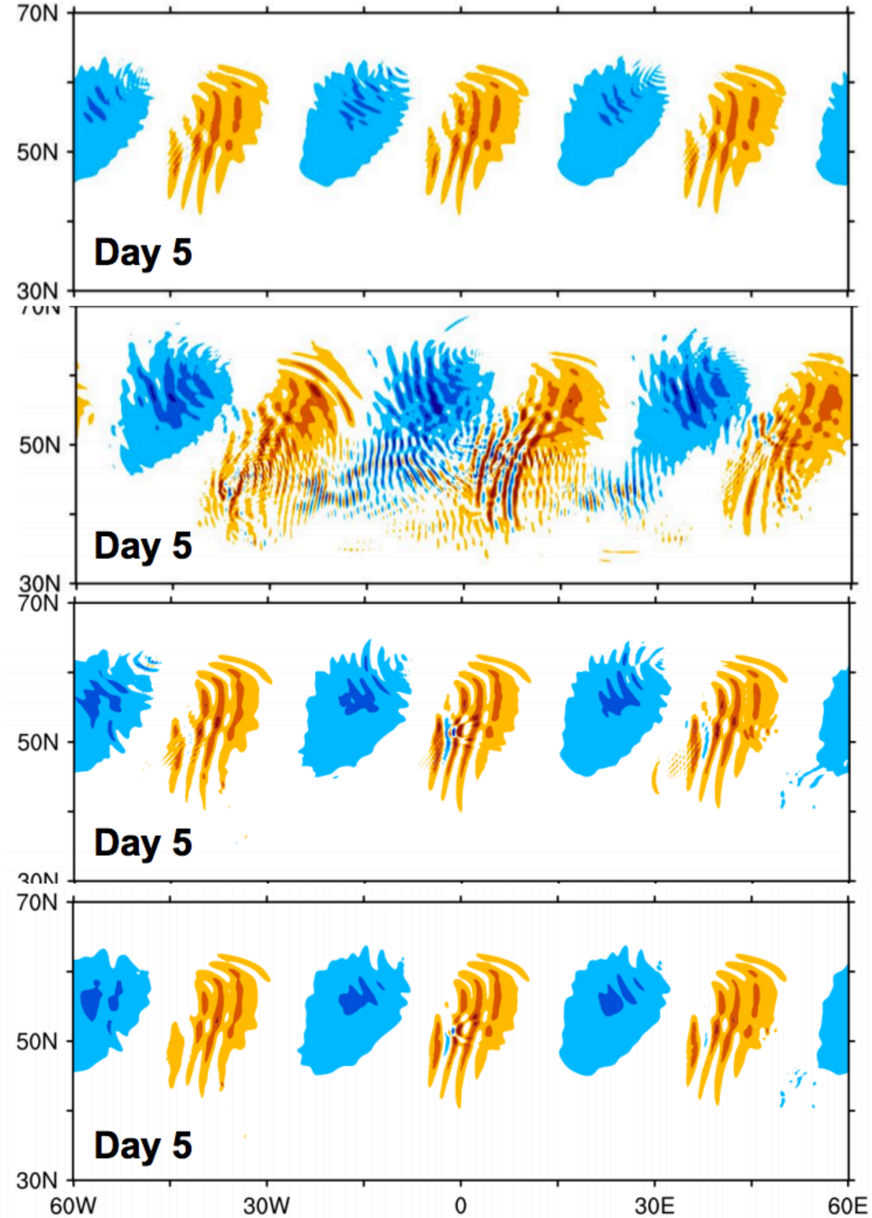
Challenges: Diffusion

Uniform mesh ($\Delta x = 30$ km)
Smagorinsky

TR10 mesh ($\Delta x = 90\text{-}30$ km)
Smagorinsky, Δx^2 scaling

TR10 mesh ($\Delta x = 90\text{-}30$ km)
background $K_4 = 1\text{x}10^{12}\ m^4 s^{-1}$
(30 km mesh value, Δx^4 scaling)

TR10 mesh ($\Delta x = 90\text{-}30$ km)
background $K_4 = 3\text{x}10^{12}\ m^4 s^{-1}$
(30 km mesh value, Δx^4 scaling)

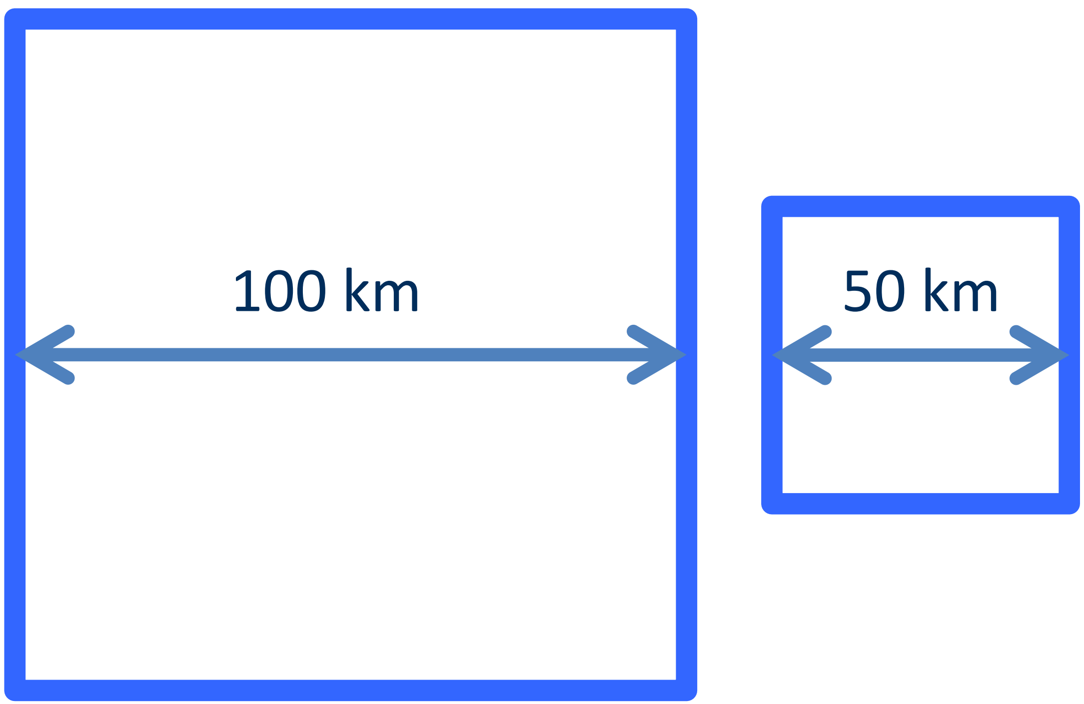


Skamarock, 2012, PDES

Challenges: Diffusion

CAM-SE, Zarzycki et al., 2014, JClim

$$K_4\left(\Delta x\right) = K_4\left(\Delta x_{ref}\right)\left(\frac{\Delta x}{\Delta x_{ref}}\right)^y$$



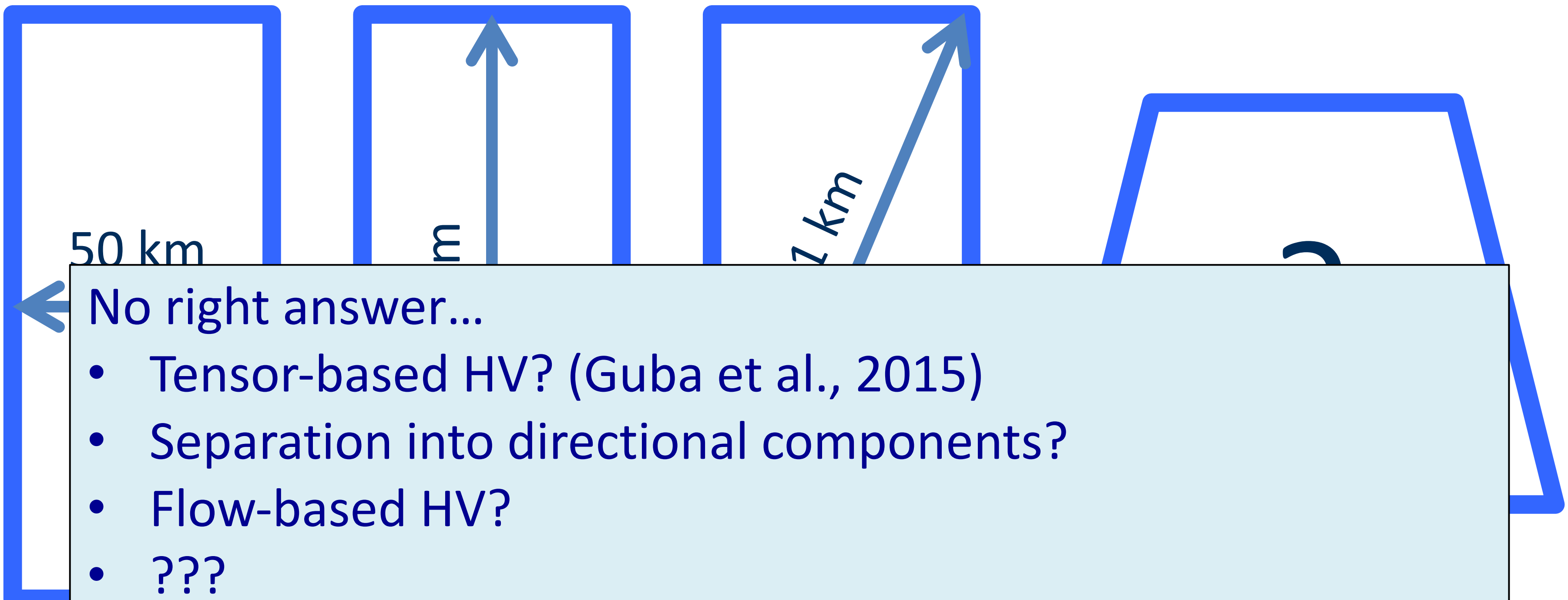
Let's say 100 km cell is our "reference" and y = 3.321

$$\left(\frac{50}{100}\right)^{3.321} = \frac{1}{10}$$

Our diffusion coefficient (K_4) in the 50 km box is 1/10th that of 100 km box!

Challenges: Diffusion

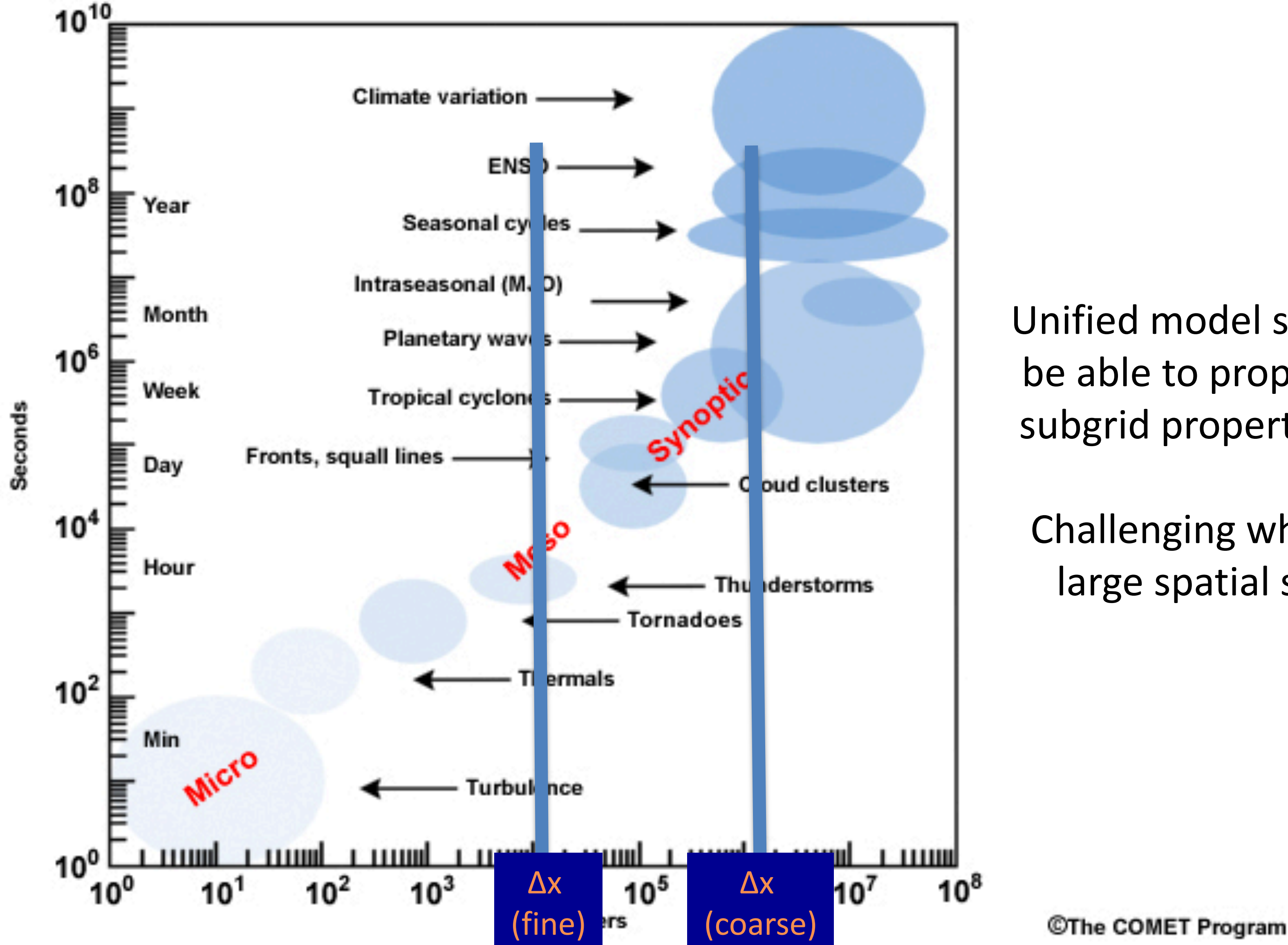
- Works well for meshes with undistorted elements
- But what happens when you have odd shapes?



No right answer…

- Tensor-based HV? (Guba et al., 2015)
- Separation into directional components?
- Flow-based HV?
- ???

Challenges: Scale-Aware Physics

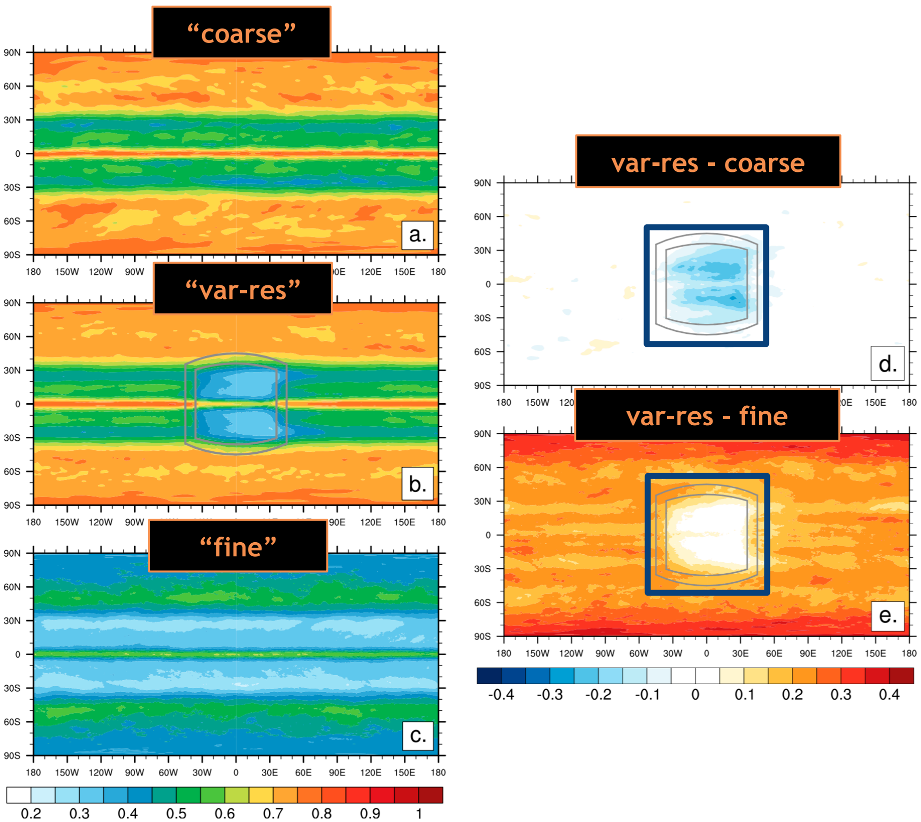


Unified model setups need to be able to properly estimate subgrid properties in all cells

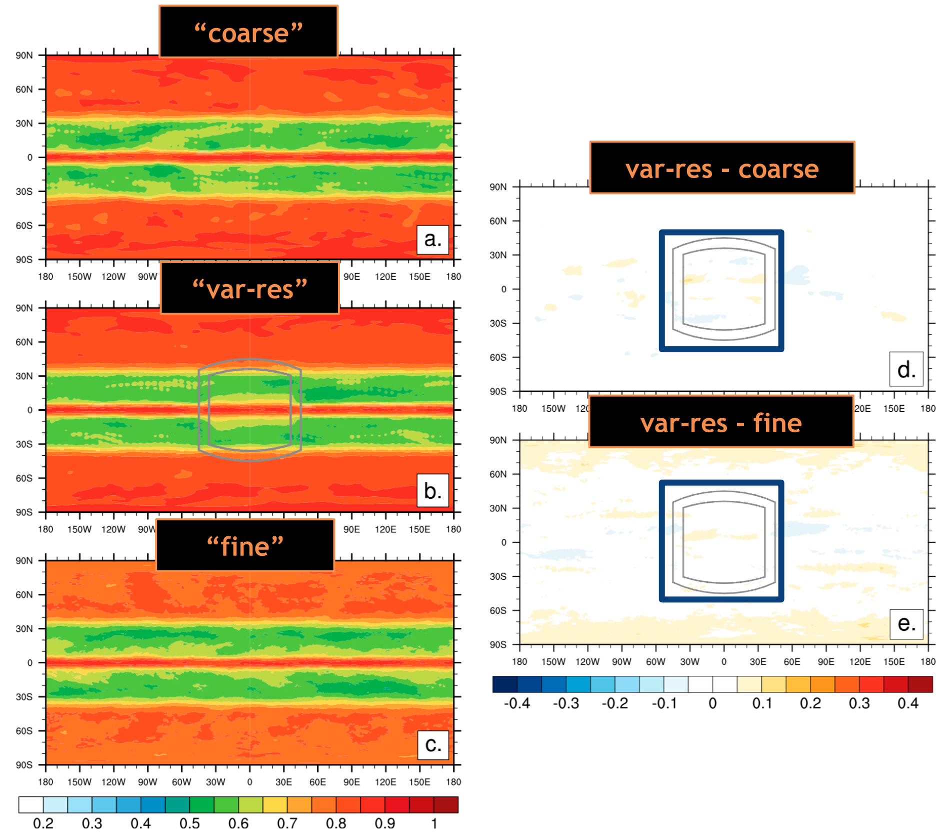
Challenging when spanning large spatial scale gaps…

Challenges: Scale-Aware Physics

CAM4



CAM5



Mean annual cloud fraction

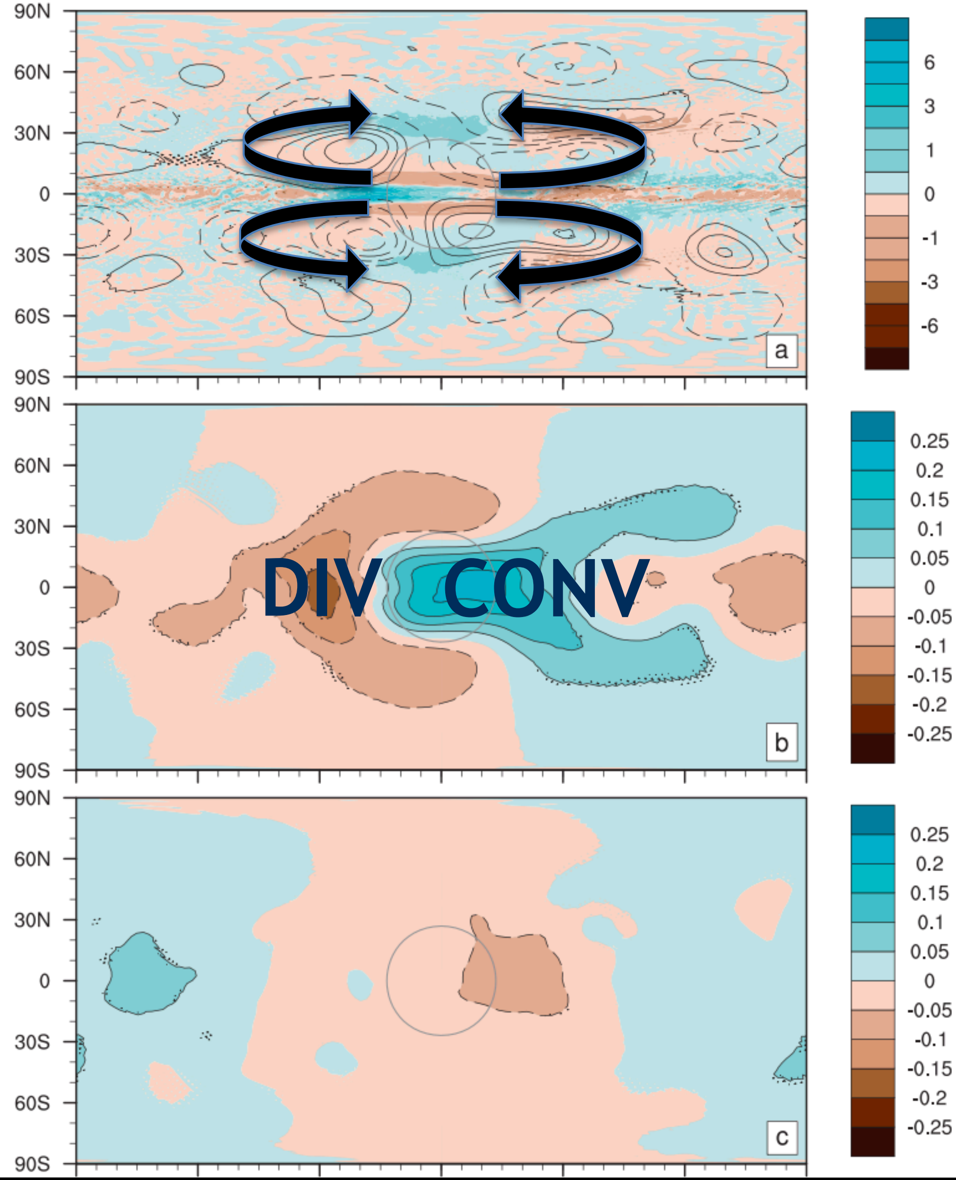
Zarzycki et al., 2014, JClim

Challenges: Scale-Aware Physics

Rauscher et al., 2013, MWR

Aquaplanet (Moist)

Held-Suarez (Dry)

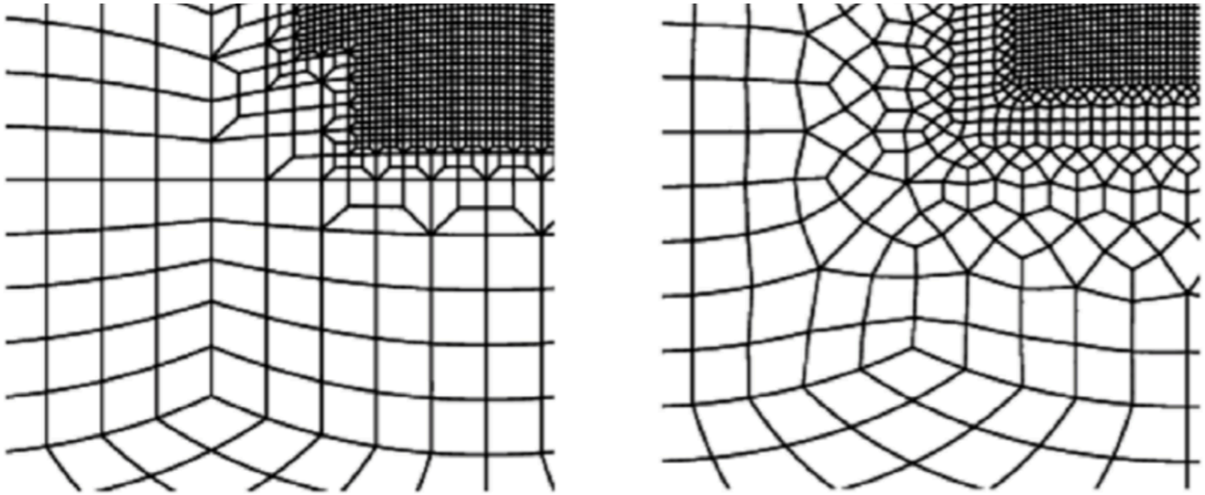


Precip. anom. / Streamlines

200 hPa Eddy Velocity Potential

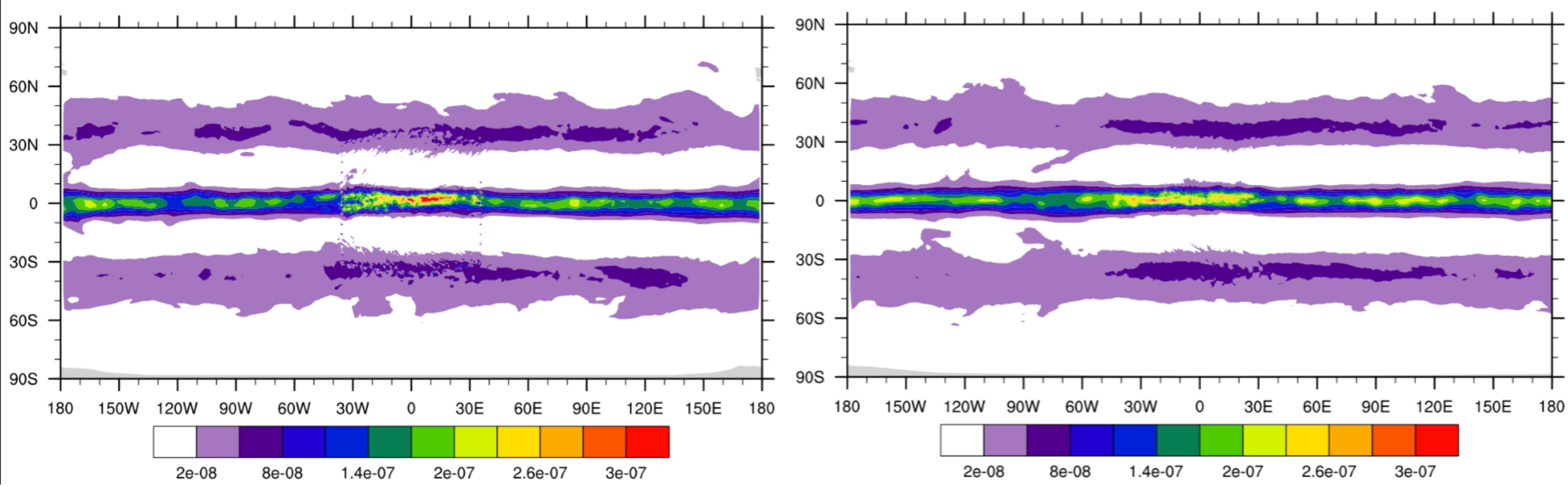
200 hPa eddy Velocity Potential

Challenges: Grid Generation



(a) CUBIT approach (b) SQuadGen approach

Neale, CESM Workshop, 201

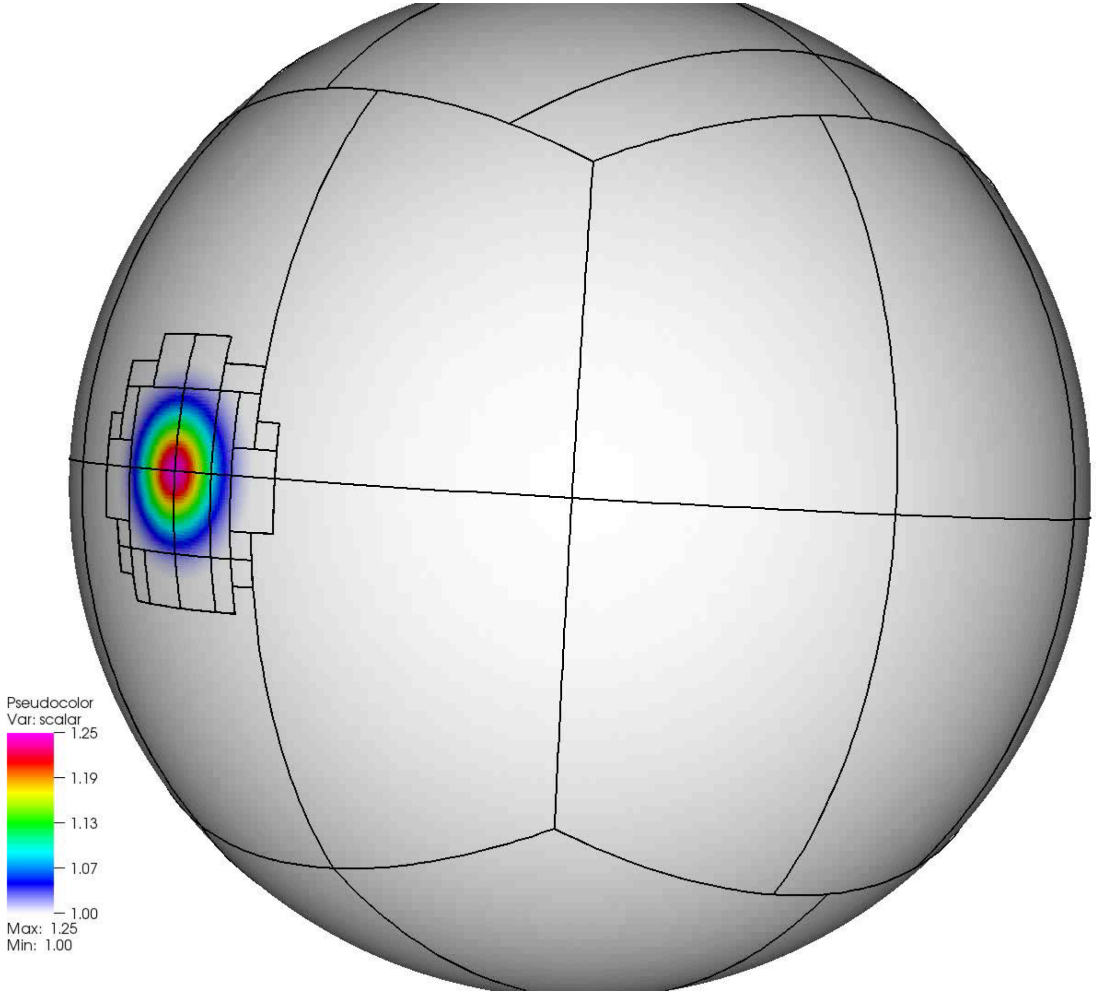


Adaptive Mesh Refinement (AMR)

With Hans Johansen, Phillip Colella and many others (LBNL)

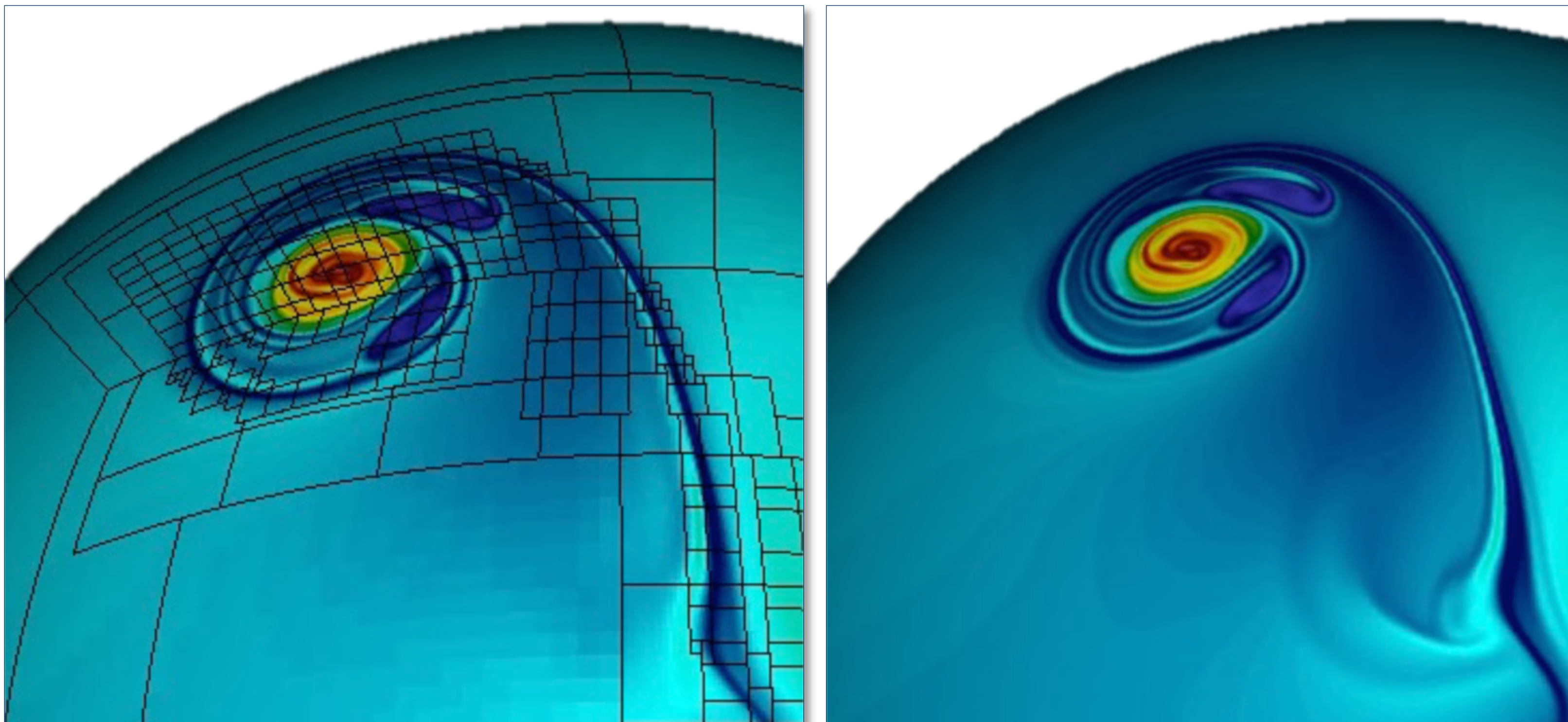
Features of interest can be tracked via adaptive mesh refinement (AMR), which automatically places additional refinement in regions of interest.

In this case, we use the Chombo global circulation model, developed at Lawrence Berkeley National Lab.



Adaptive Mesh Refinement (AMR)

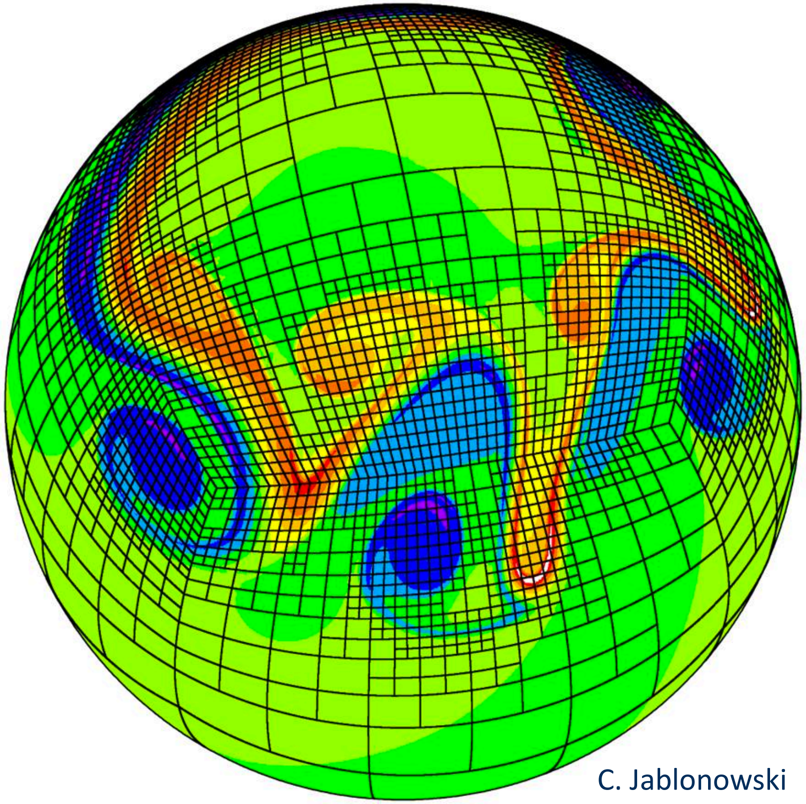
Adaptive mesh refinement poses a particular challenge for future exascale applications due to the need for dynamic load-balancing.



Adaptive Mesh Refinement (AMR)

AMR introduces *new* challenges

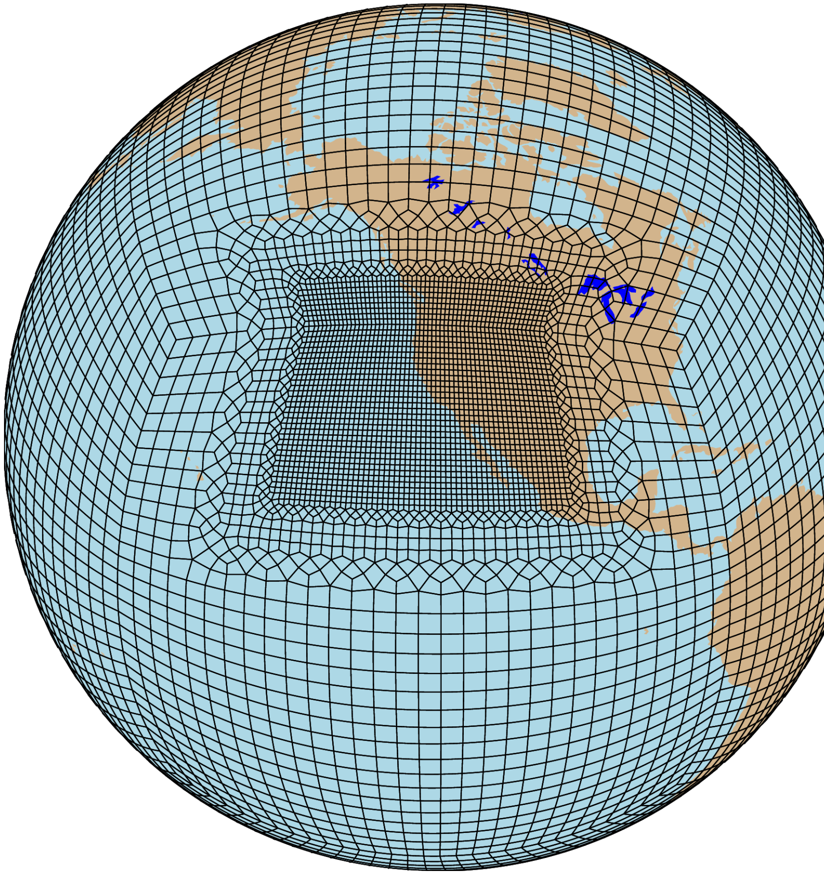
- How to “tag” regions to refine (don’t want to under-refine or over-refine)
- Load balancing on parallel computing systems
- Need to be able to change configuration “on the fly”
  - Topography
  - Diffusion
  - Sub-grid physics
  - Etc.



C. Jablonowski

Summary: Variable Resolution Models

- VR allows for **fewer computational resources** to be spent sparingly on a single problem.
- Fully coupled global modeling system, usable for **seasonal to subseasonal forecasting**.
- More **ensemble members** can be produced for a particular region (uncertainty quantification).
- **Resolution where you need it.**



Summary: Variable Resolution Models

- Variable-resolution dynamical cores offer ability to have **fine regional resolution** in a global modeling framework
- Demonstrated fidelity with tropical cyclones, orographic precipitation, mesoscale convection
- New challenges (hint: avenues for research!)
  - Numerical techniques
  - Scale-aware physics
  - Grid and refinement choices
  - Software engineering