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Variable-resolution modeling of the atmosphere

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National Center for Atmospheric Research
Advance Study Program (ASP)/Climate and Global Dynamics (CGD)

DCMIP-2016
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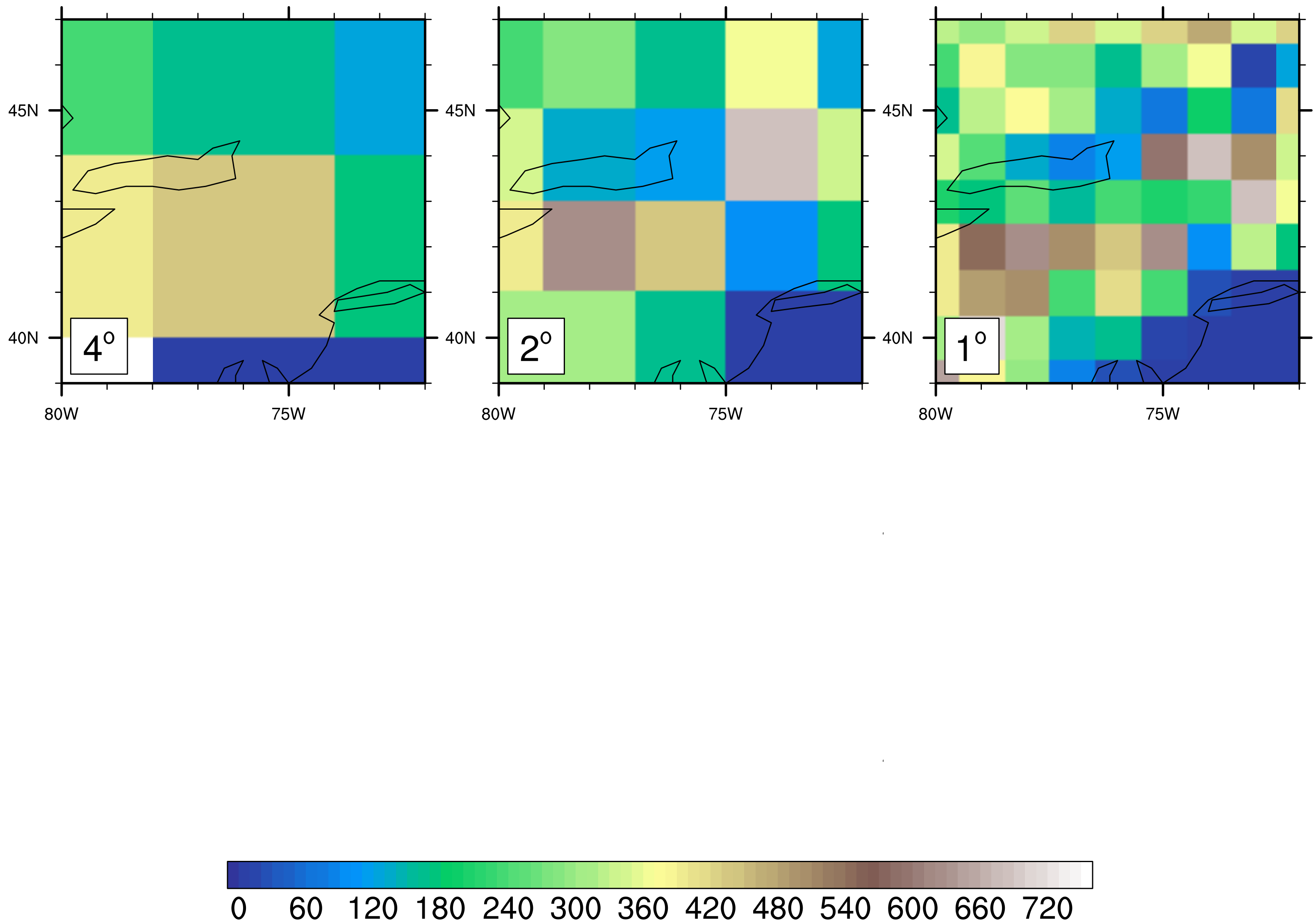
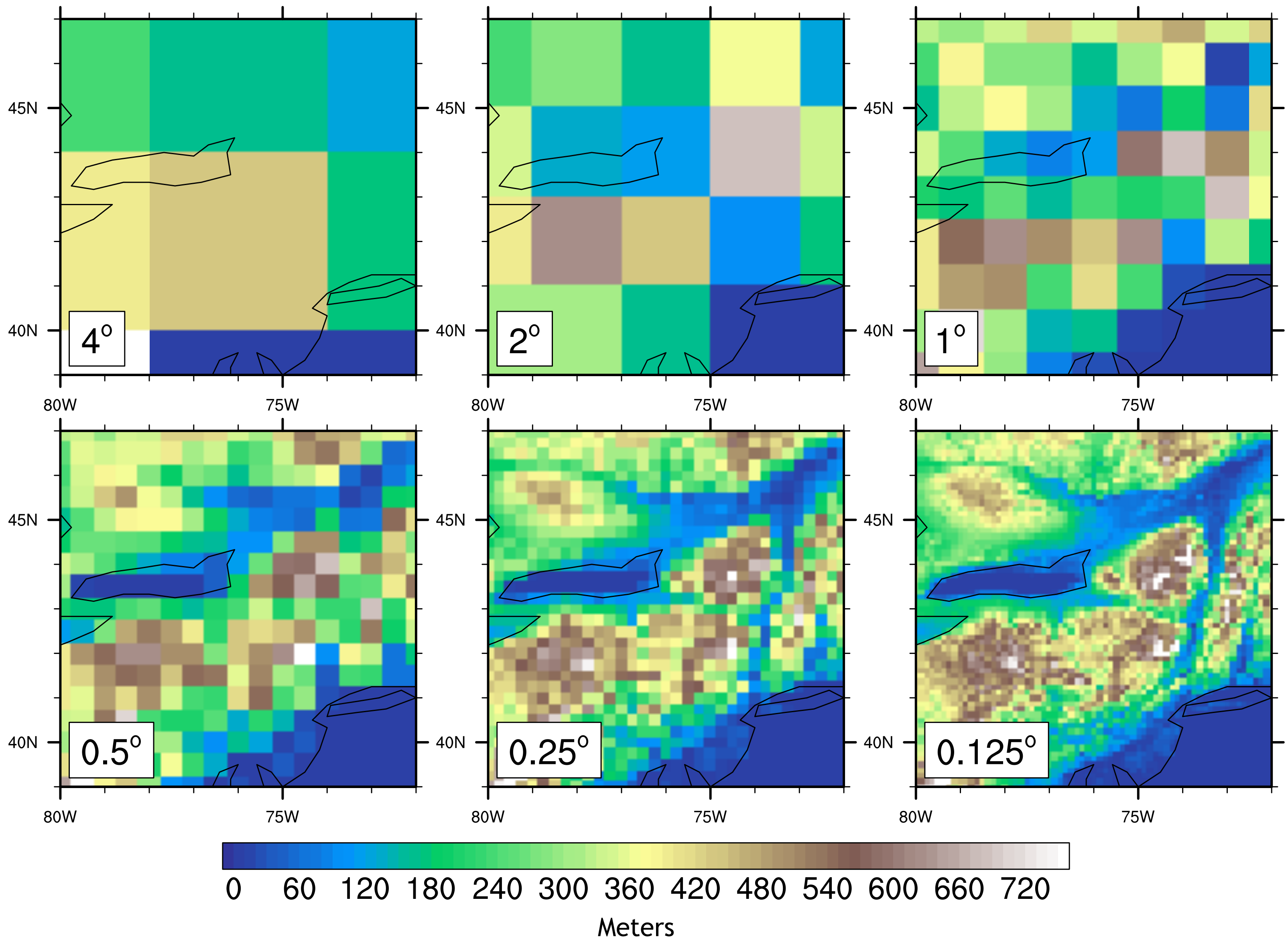
#dcmip2016

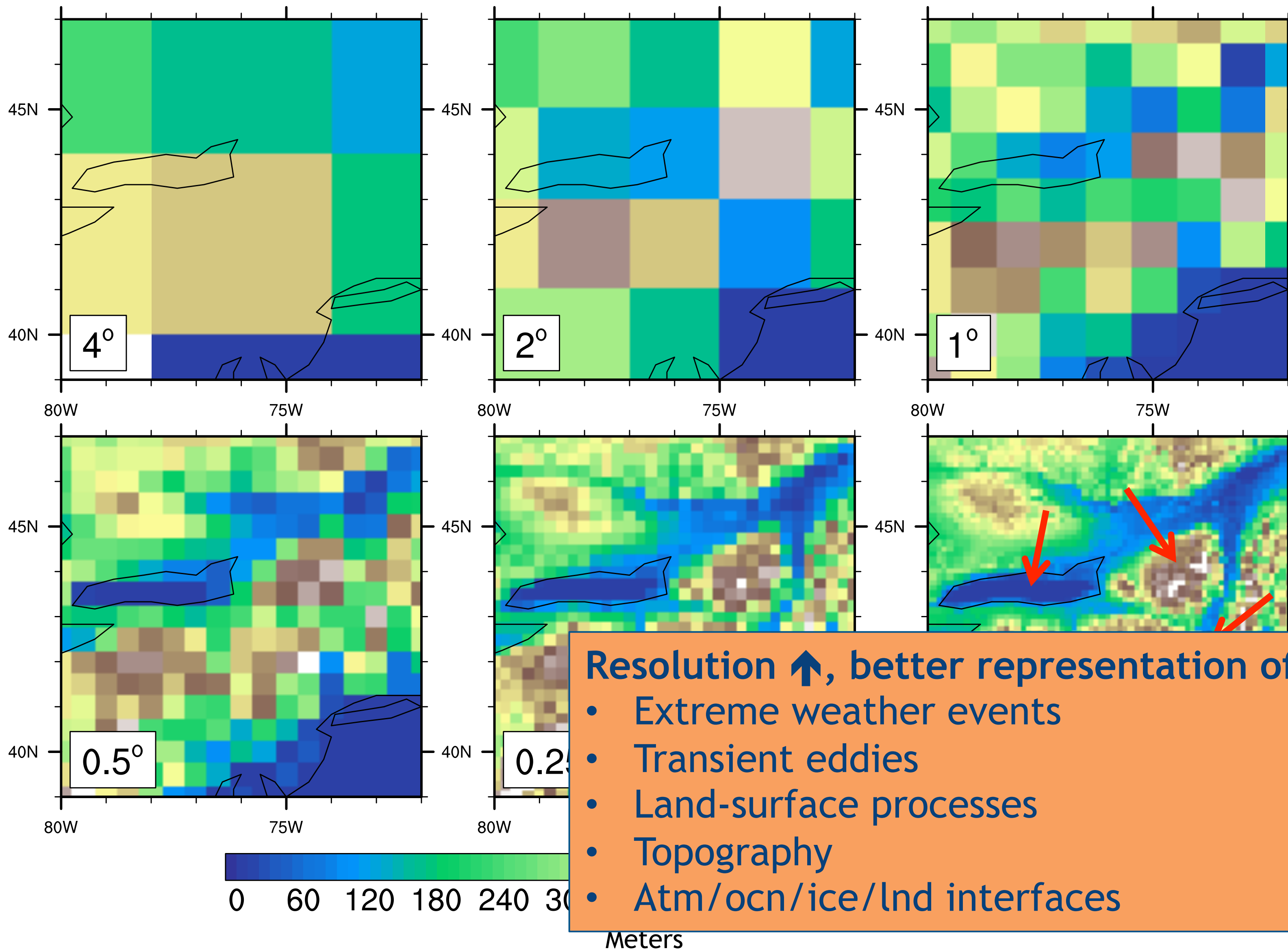
Impact of model resolution



Impact of model resolution



Impact of model resolution



Resolution ↑, better representation of:

- Extreme weather events
- Transient eddies
- Land-surface processes
- Topography
- Atm/ocn/ice/lnd interfaces

Climate extremes

- Climate events disproportionately affect health and welfare if…
  - Rare
  - Severe
- Many require high resolution (small Δx)
  - *Mesoscale convective storms*
  - *Nor'easters*
  - *Tropical cyclones*
  - *Polar lows*
  - *Flash floods*
  - *… and others*

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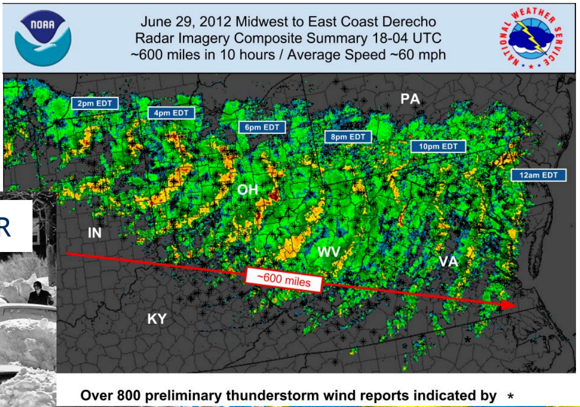
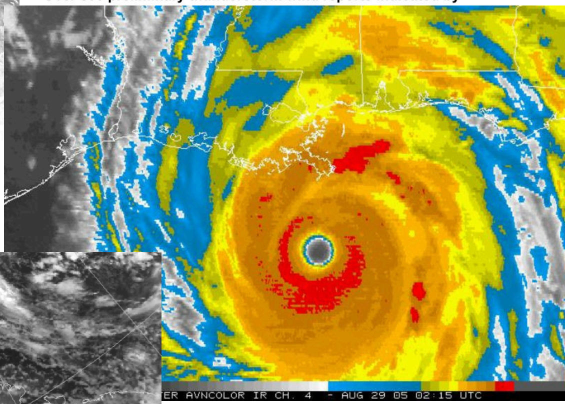
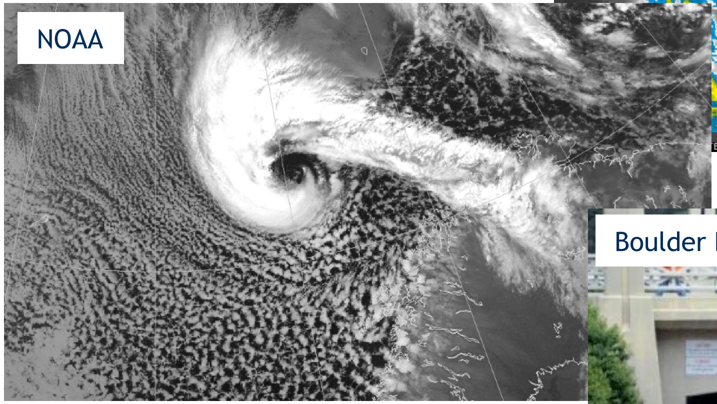
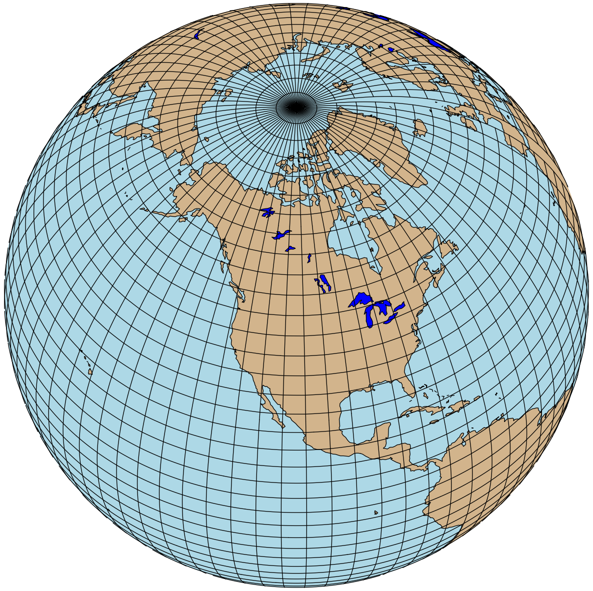




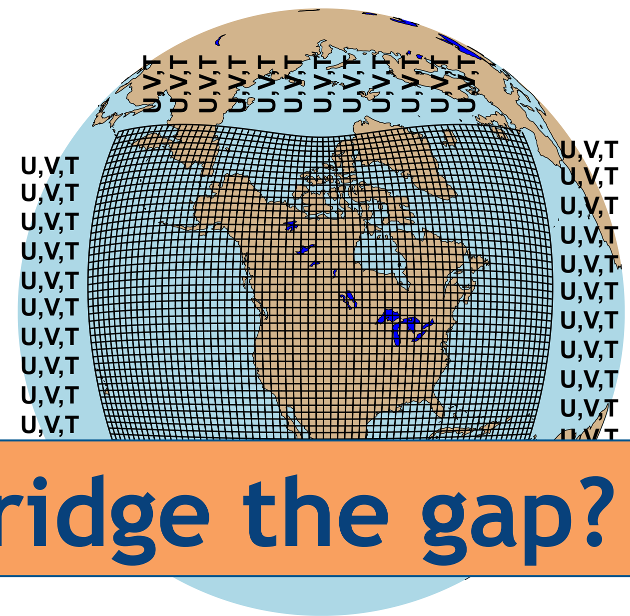


Climate modeling paradigms

- **Global models**
  - Proper representation of global large-scale dynamics
  - Unified system
  - Computationally-expensive for high-resolution!



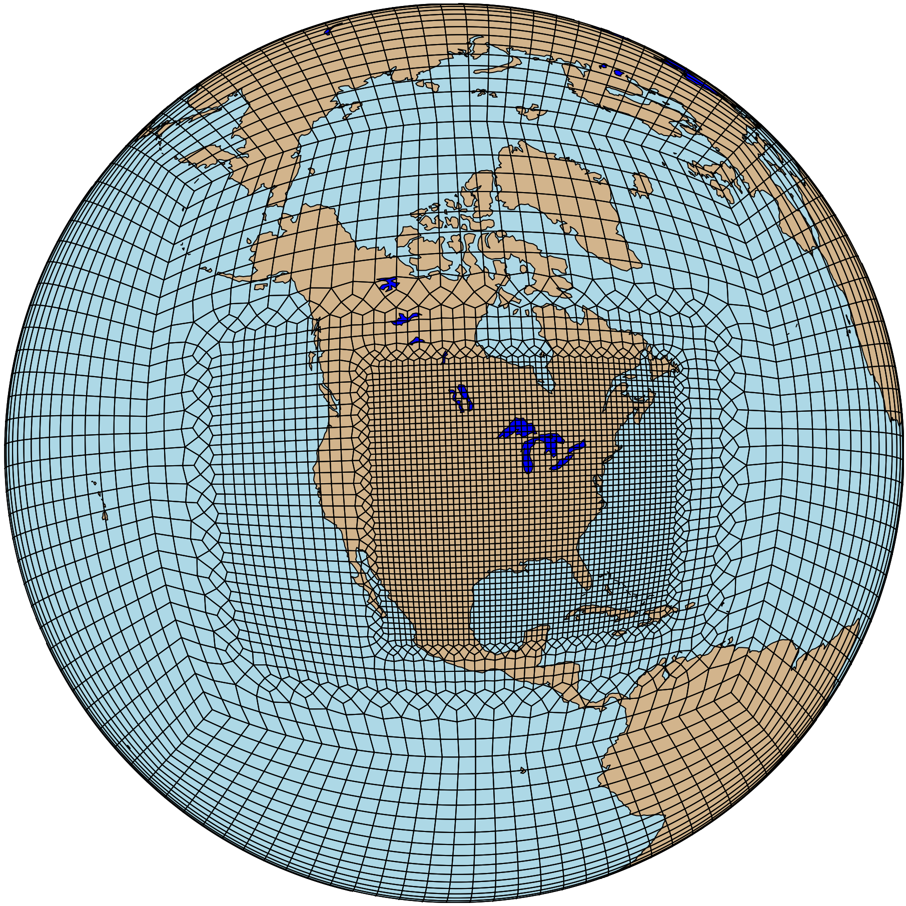
- **Regional (lim. area) models**
  - Efficient use of computing resources for regional problems
  - Boundary conditions – lack mathematical/physical consistency?
  - No teleconnections



Bridge the gap?

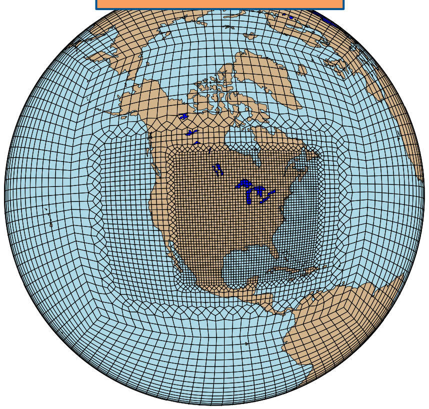
Variable-resolution grids

- Variable-resolution models – unified setup
  - Same numerical scheme spanning multiple resolutions
  - Time integrated in only one direction (subcycling is an option, however)
  - Savings due to reduced computational burden outside of refined region

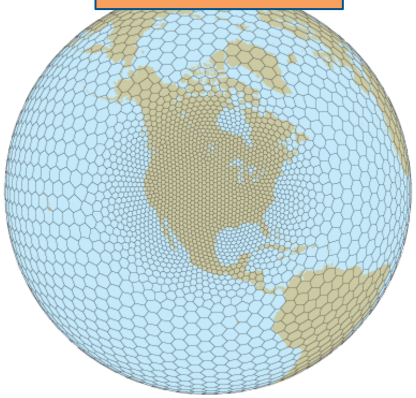


A sampling of V-R models…

CAM-SE



MPAS-A

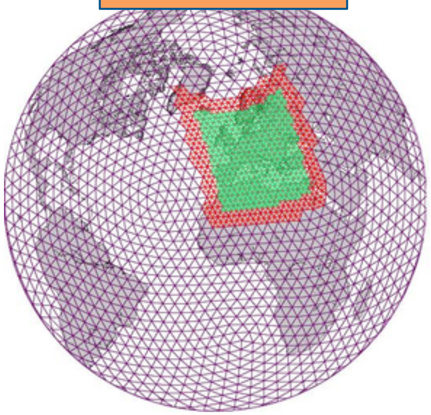


(b)

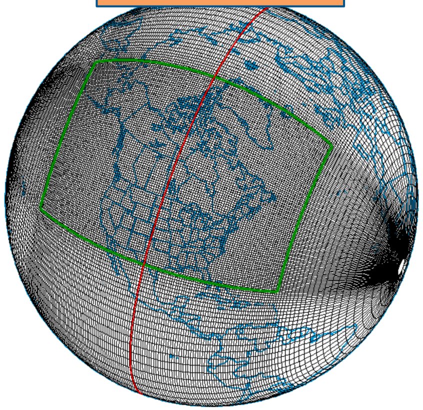
NICAM

2968!

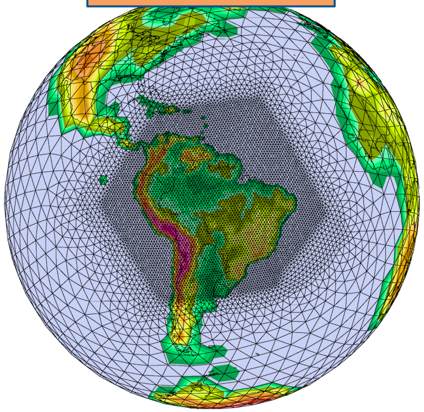
ICON



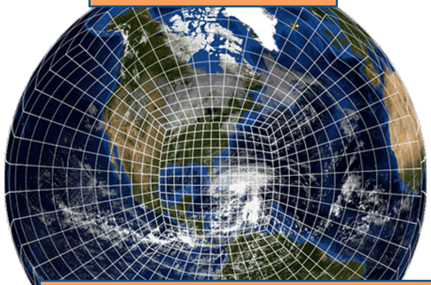
GEM



OLAM



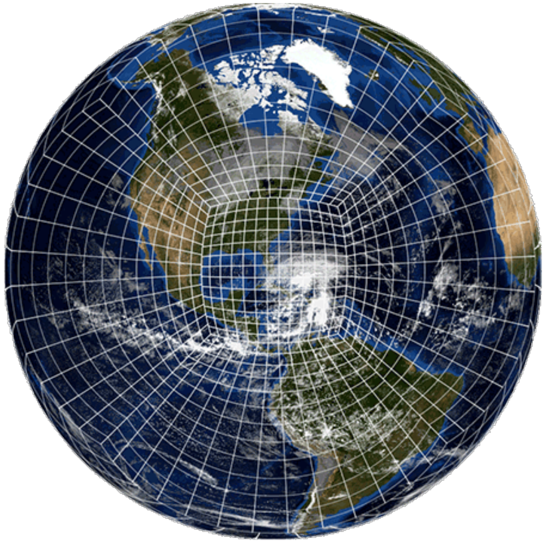
FV^3



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)



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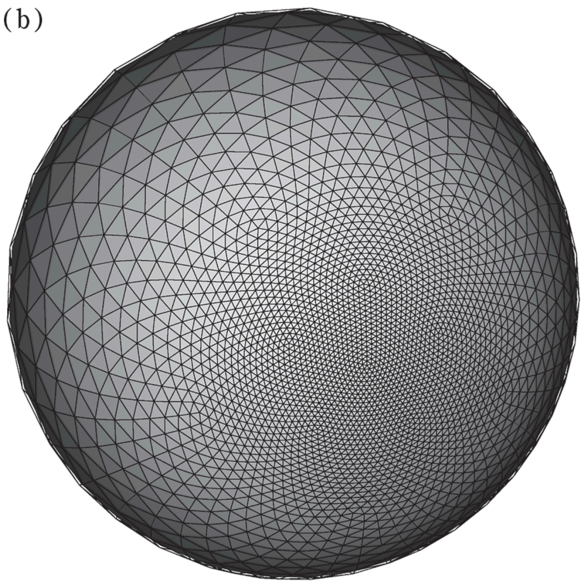
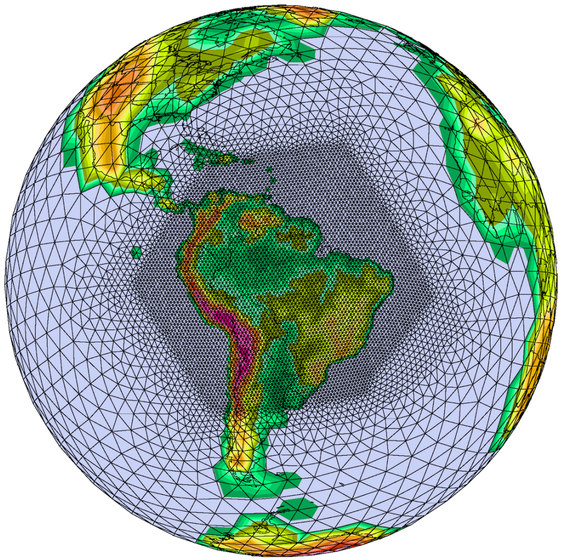
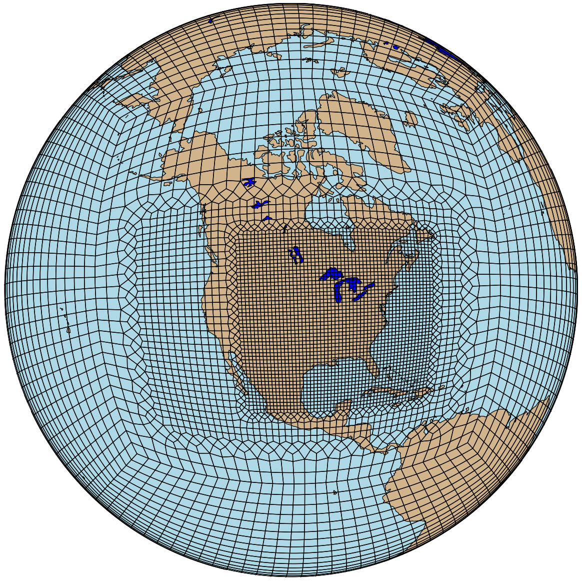


Unstructured/nested refinement

- 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

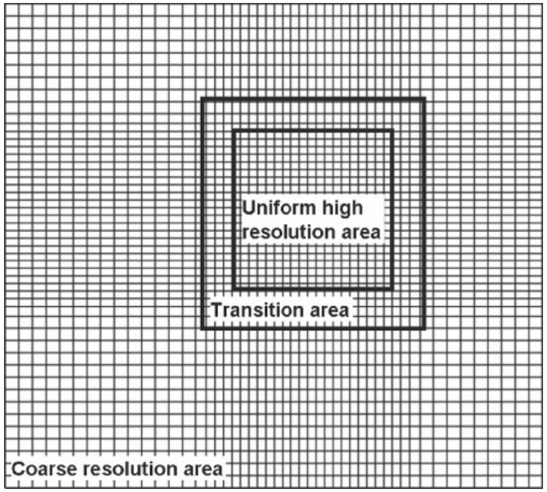


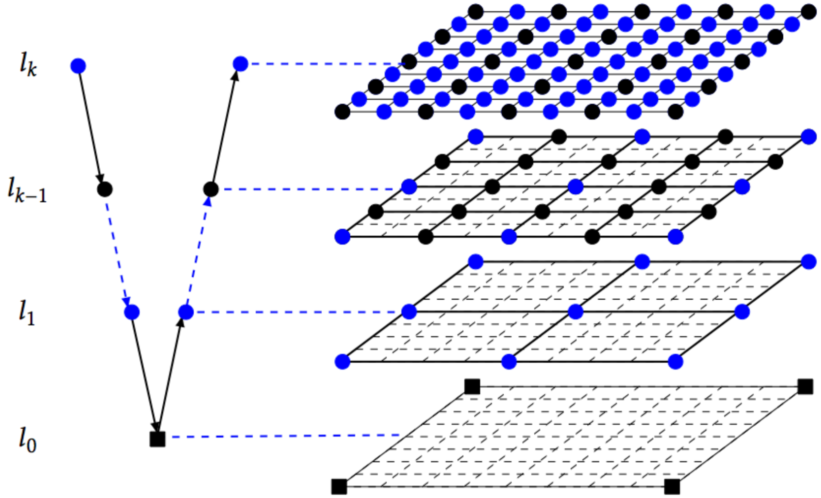


One other distinction

- "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

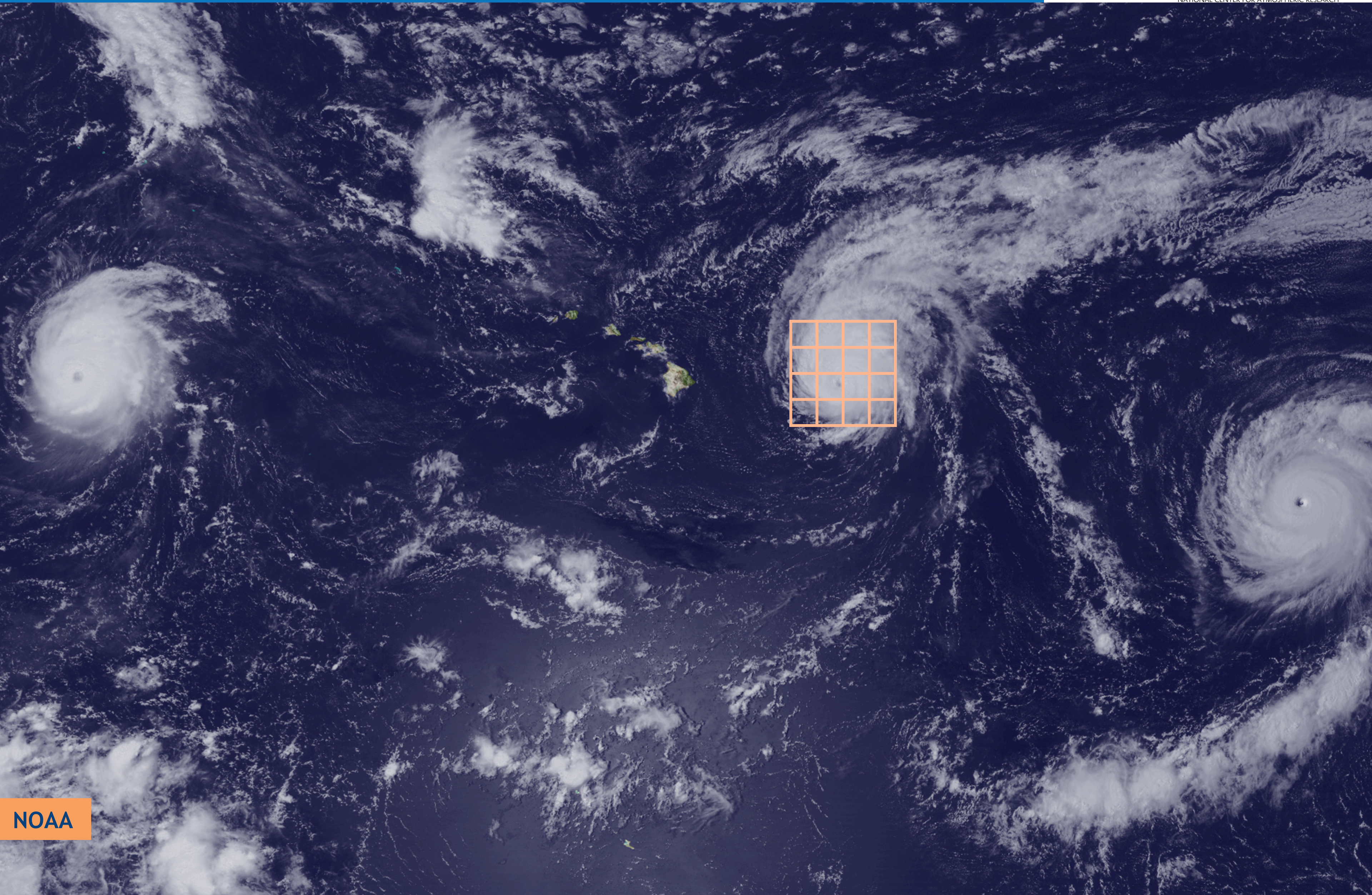
Tong et al., 2013





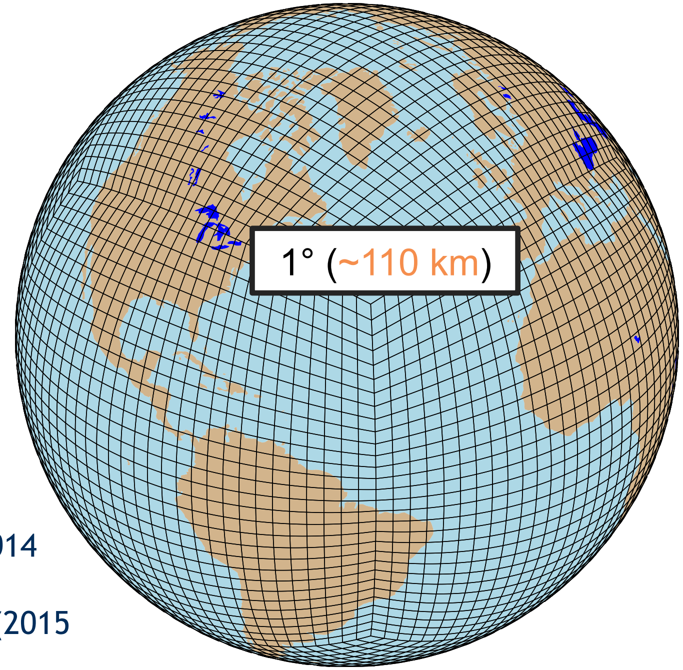
Wenqiang Feng, U. Tenn.

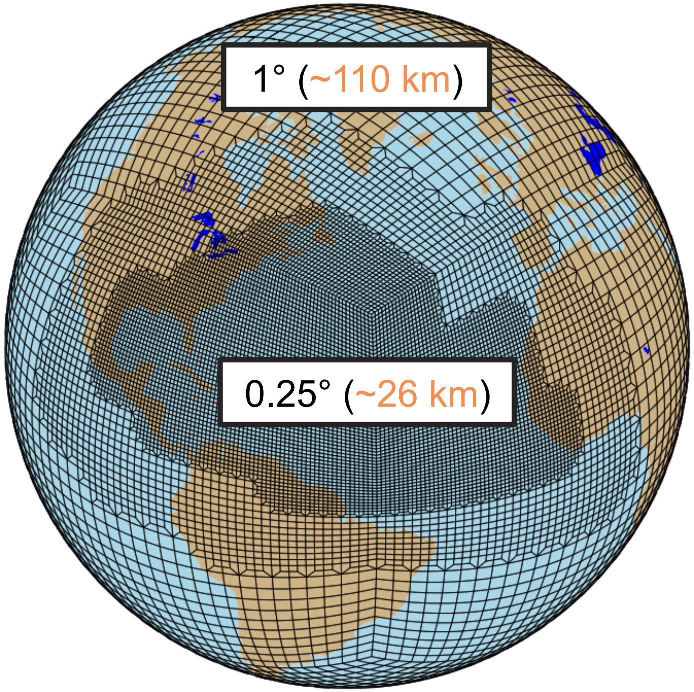
V-R applications: tropical cyclones



V-R applications: tropical cyclones

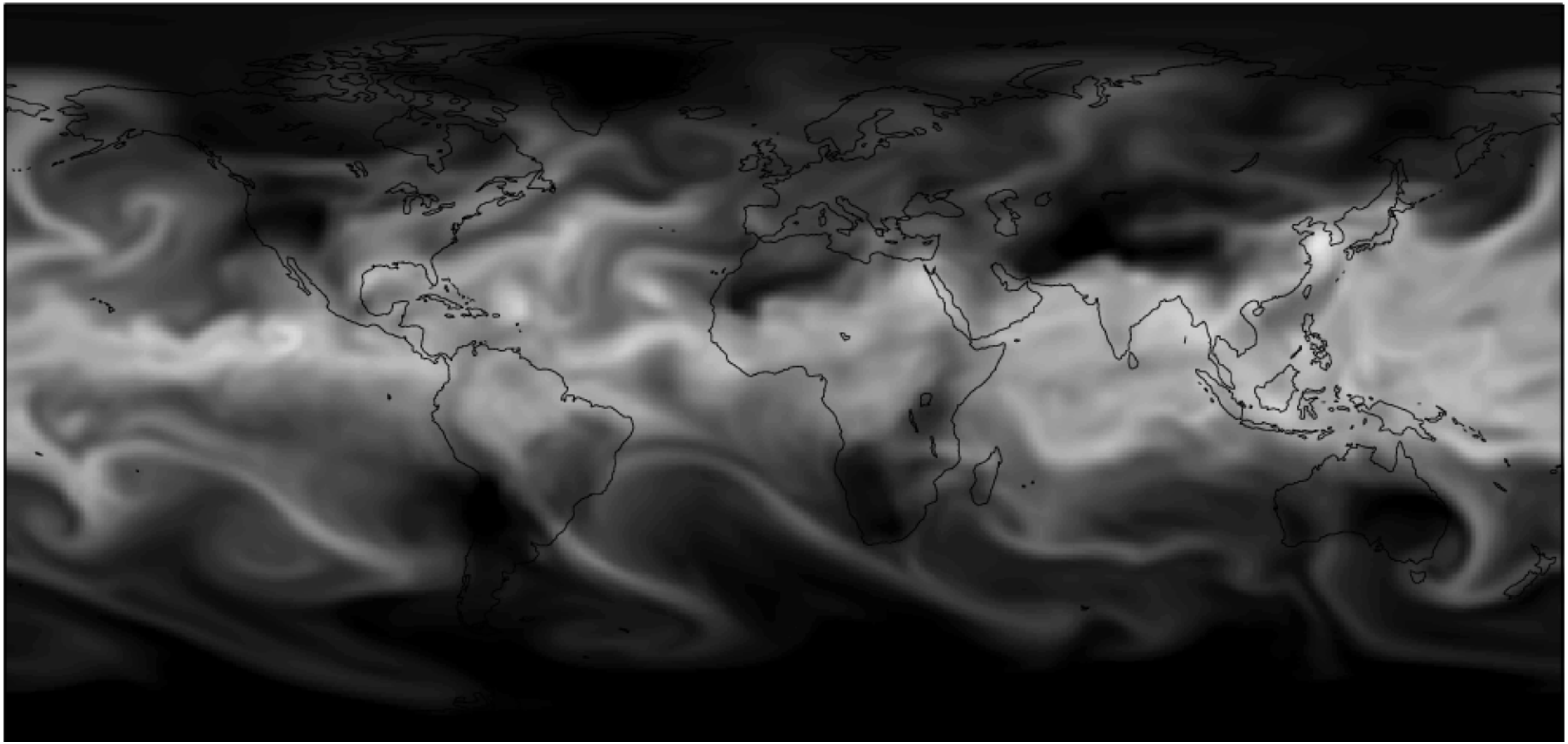
- Community Atmosphere Model Spectral Element (CAM-SE)
- Atmospheric Model Intercomparison Project **(AMIP)** protocols
  - 1980-2002 (23 years)
    - Prescribed SSTs, ozone, aerosols, solar insolation
- Simulate historic, observed climate





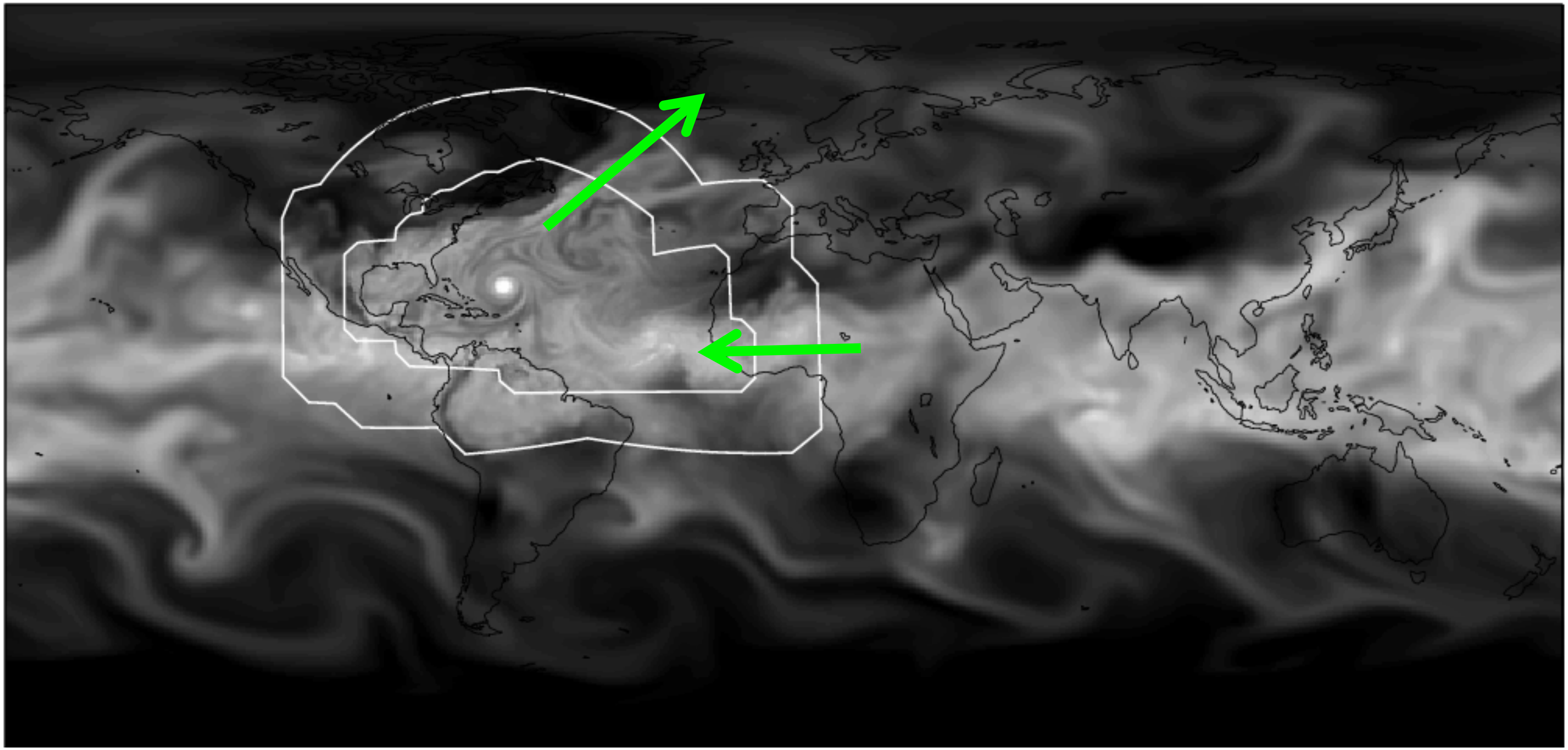
Zarzycki and Jablonowski, (2014 JAMES)
Zarzycki et al., (2015 JClim)

Uniform global simulation



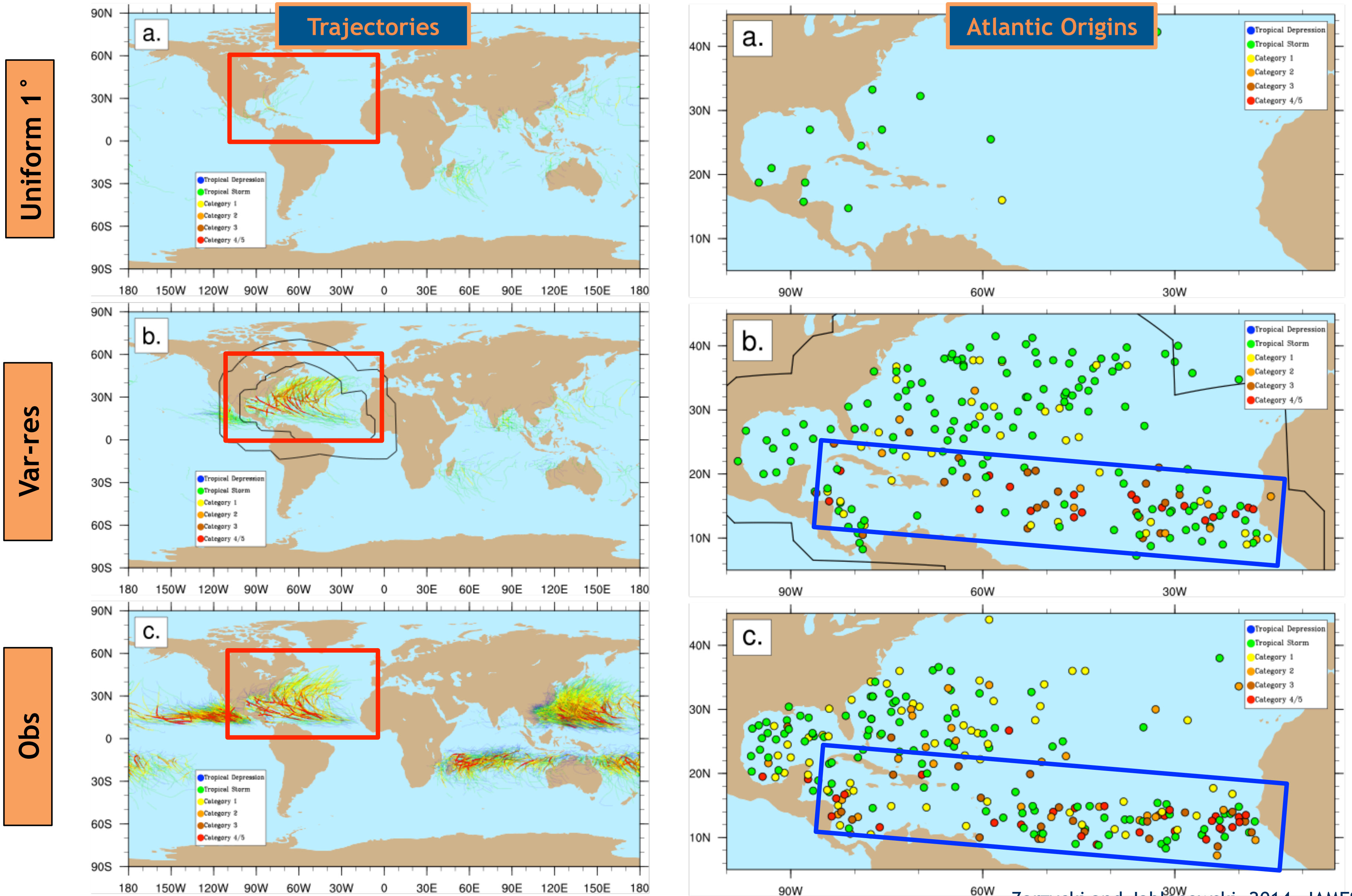
Precipitable water, Sept 1-16

Variable-resolution global circulation



Precipitable water, Sept 1-16

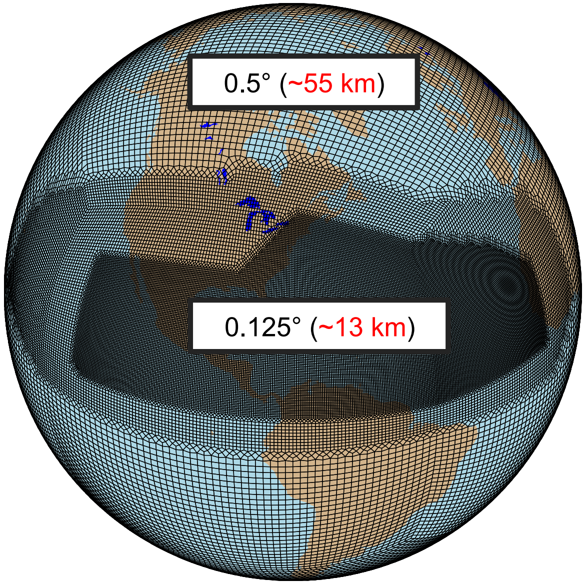
Tropical cyclones



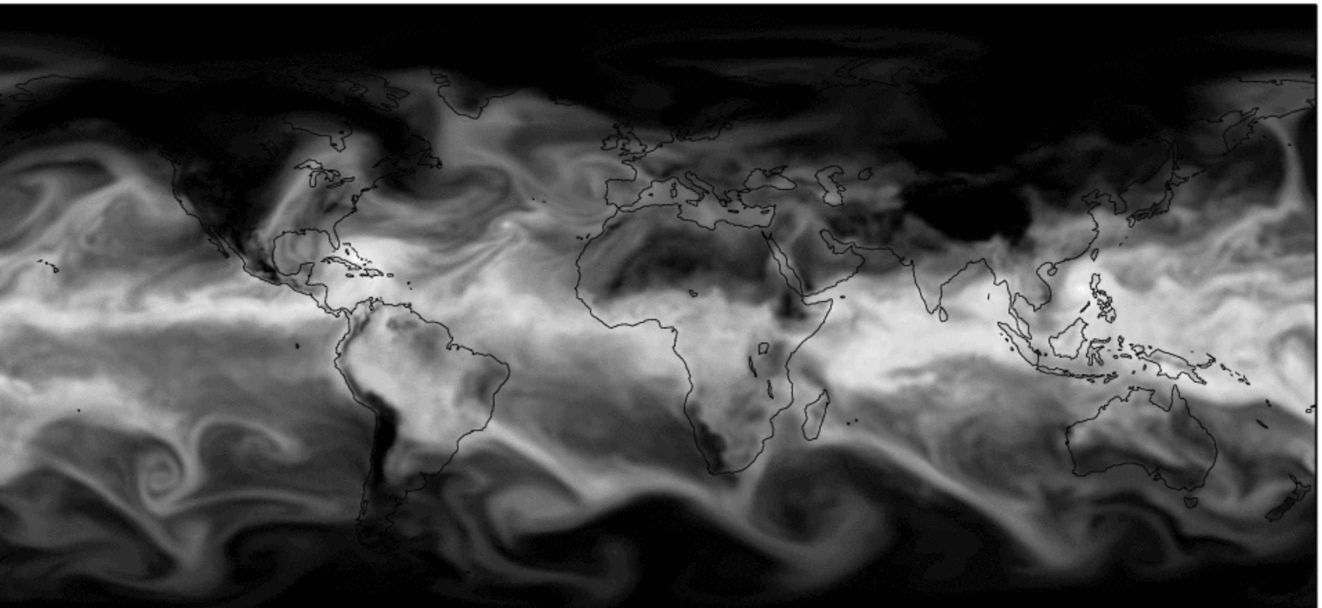
Zarzycki and Jablonowski, 2014, JAMES

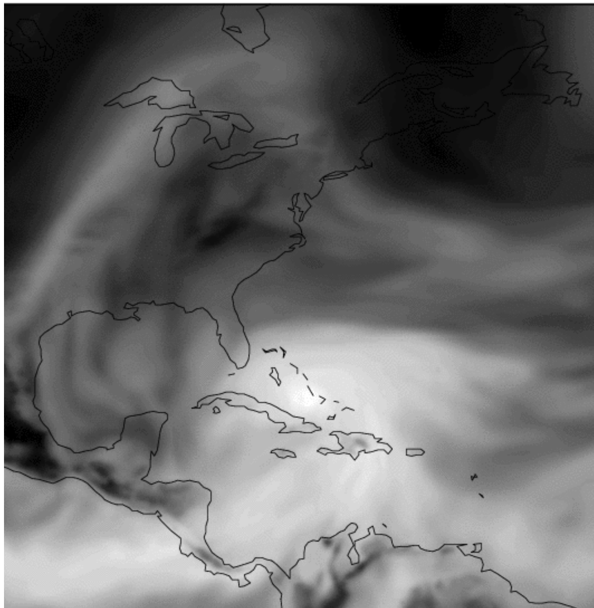
Numerical weather prediction

- 8 day forecast = ~1.5 hours of wall clock time on 800 cores (NCAR Yellowstone)
  - <u>~6-7x cheaper than a globally-uniform 13 km forecast</u>



Sandy TPW:
INIT 12Z
10/25/12



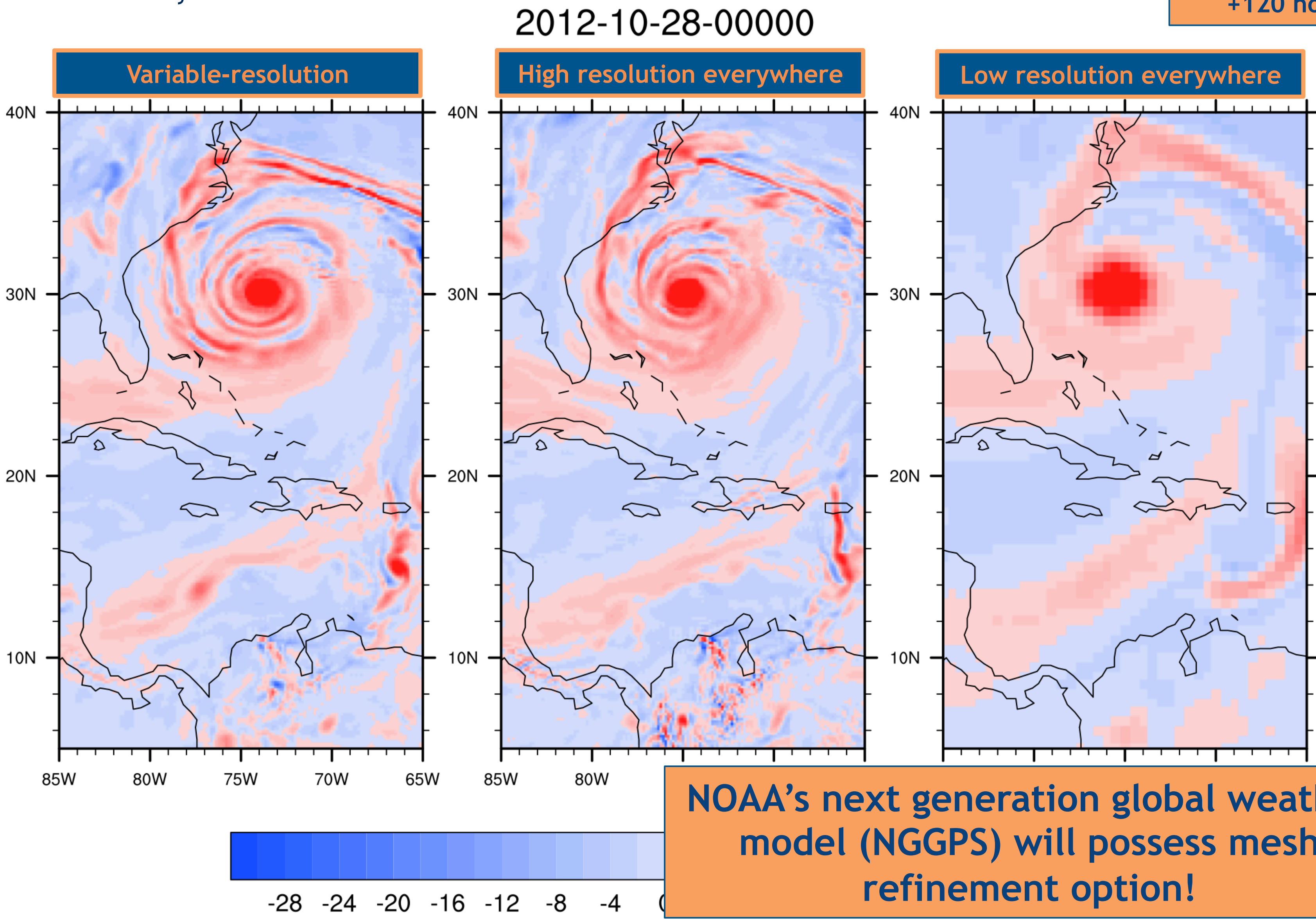


zarzycki@ucar.edu - DCMIP-2016, Boulder, CO, June 2016

Resolution comparison

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

+120 hours



NOAA's next generation global weather model (NGGPS) will possess mesh refinement option!

Differential topography smoothing

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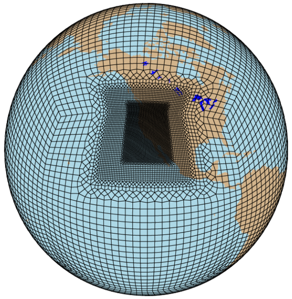
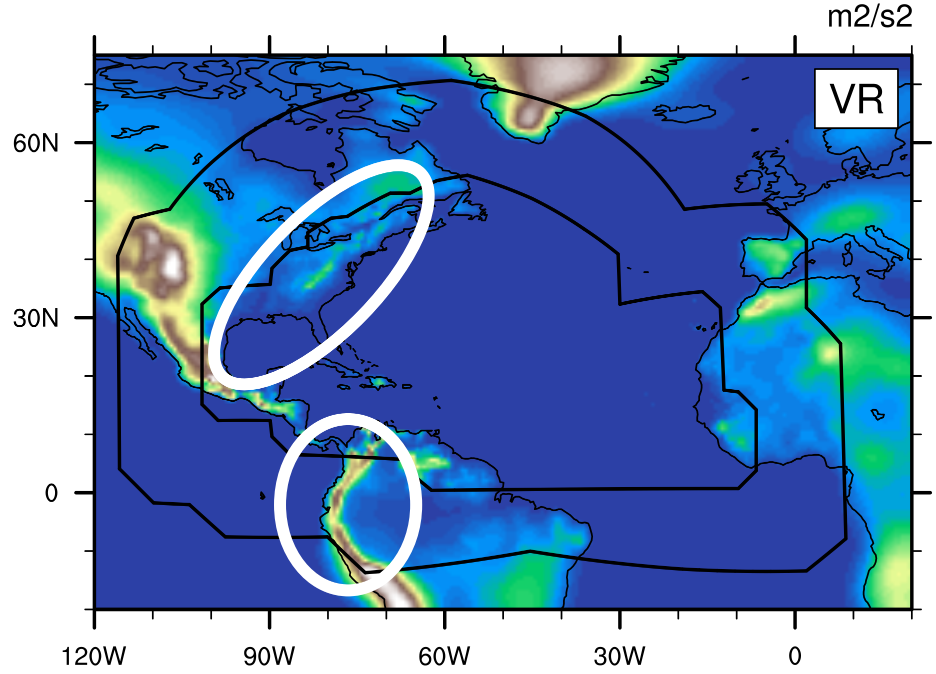
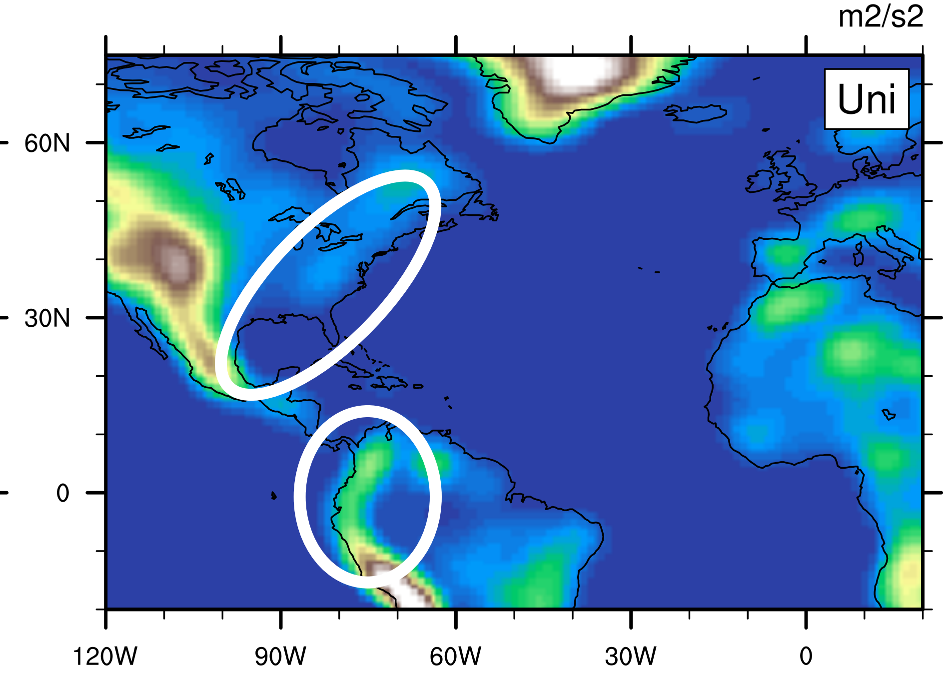
Hyperviscosity order

$$\underset{\text{Var-res topo}}{\Phi_{VR}} = \underset{\text{High-res topo}}{\Phi_{U}} + \underset{\text{Tunable constant}}{c}\,\underbrace{K_o(\Delta x)}_{\text{Diffusion coefficient (scale selective!)}}\nabla^o \Phi_U$$







Zarzycki et al., 2015, JClim

Differential topography smoothing

Hyperviscosity order

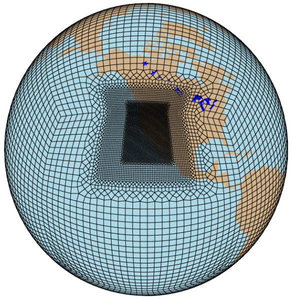
$$\Phi_{VR} = \Phi_U + c\underbrace{K_o(\Delta x)\nabla^o}_{\text{Diffusion coefficient (scale selective!)}}\Phi_U$$

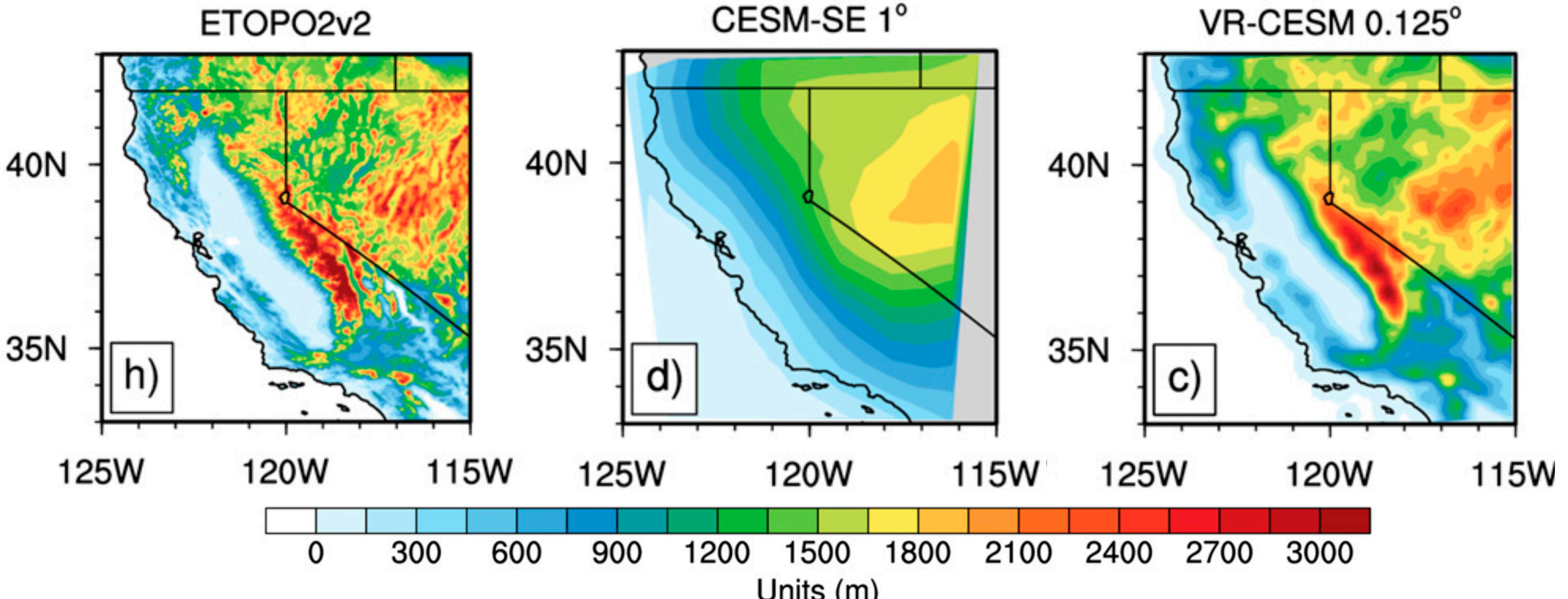
Var-res topo

High-res topo

Tunable constant

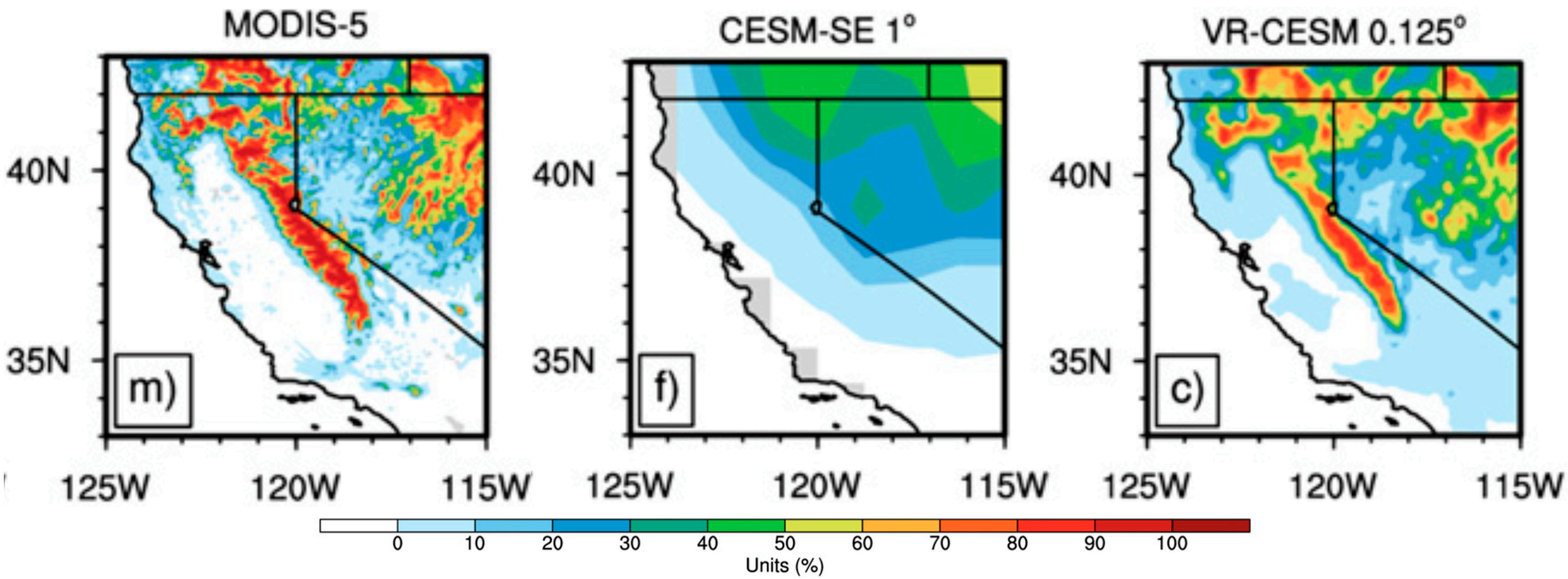
Diffusion coefficient
(scale selective!)



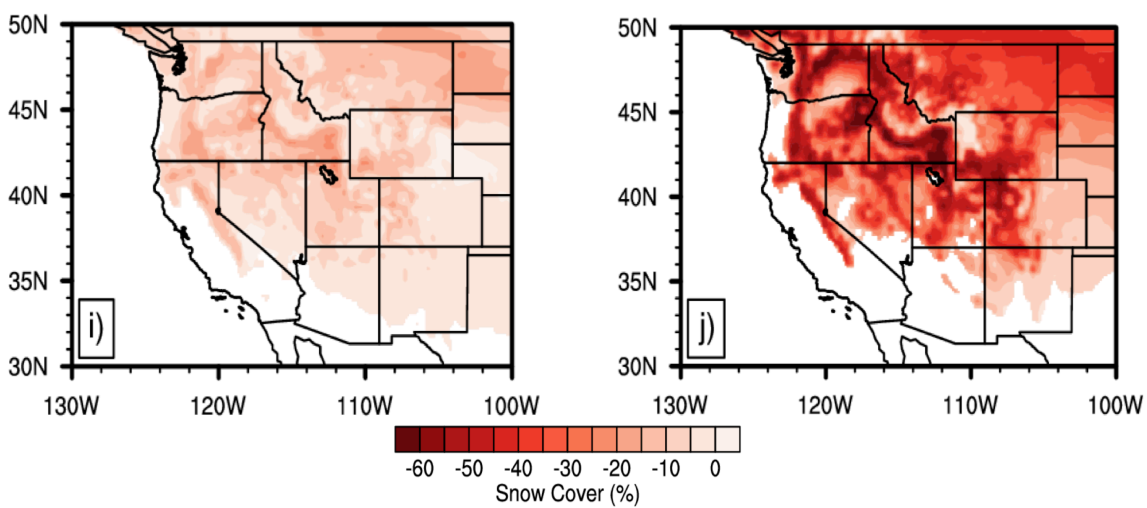


Zarzycki et al., 2015, JClim + Rhoades et al., 2016, JAMC

Simulated snow cover fraction



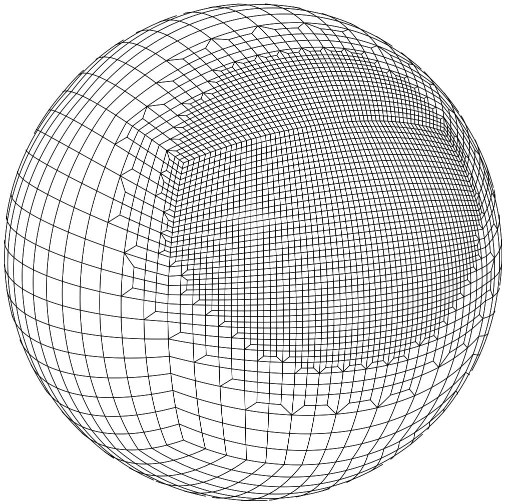
2025-2050



2075-2100

Rhoades et al, in prep

Computational benefits



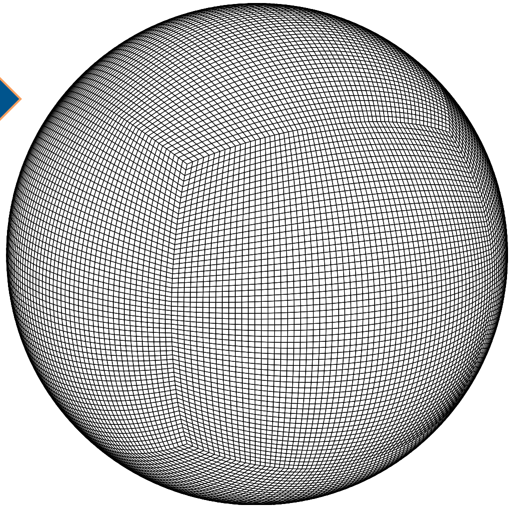
21,600 elements

÷

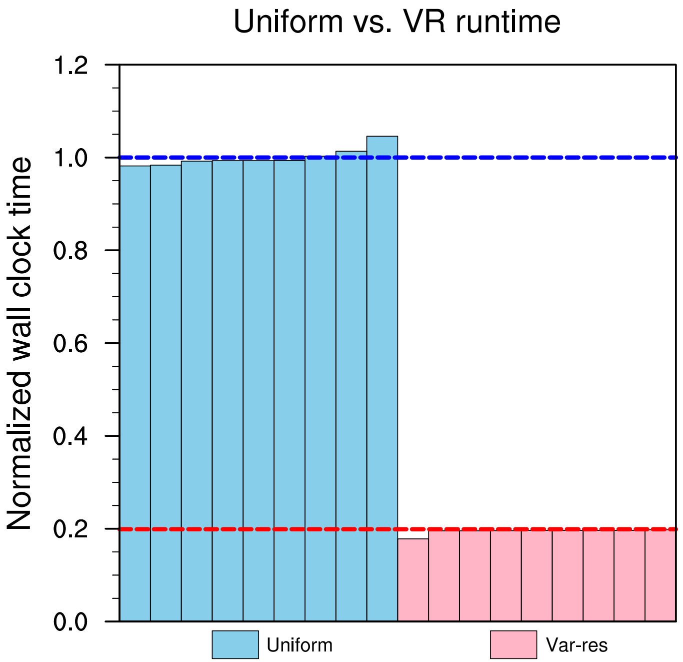
4,296 elements

=

~5



- ~**5x speedup** wall-clock time with *variable-resolution* vs. *uniform high-resolution* grid
- For same cost of global uniform/quasi-uniform…
  1. **Higher regional resolution**
  2. **Additional ensemble simulations**
  3. **Longer model runs**



Zarzycki et al., 2014, MWR

Some other recent V-R applications…

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- MPAS
  - Park et al., (2014, MWR)
  - Klemp et al., (2015, JAMES)
  - Sakaguchi et al., (2015, J. Clim)
- FV^3
  - Harris and Lin (2014, J. Clim)
  - Harris, Lin, and Tu (2016, J. Clim)
- NICAM
  - Uchida et al., (2016, MWR)
- OLAM
  - Medvigy et al., (2013, J. Clim)

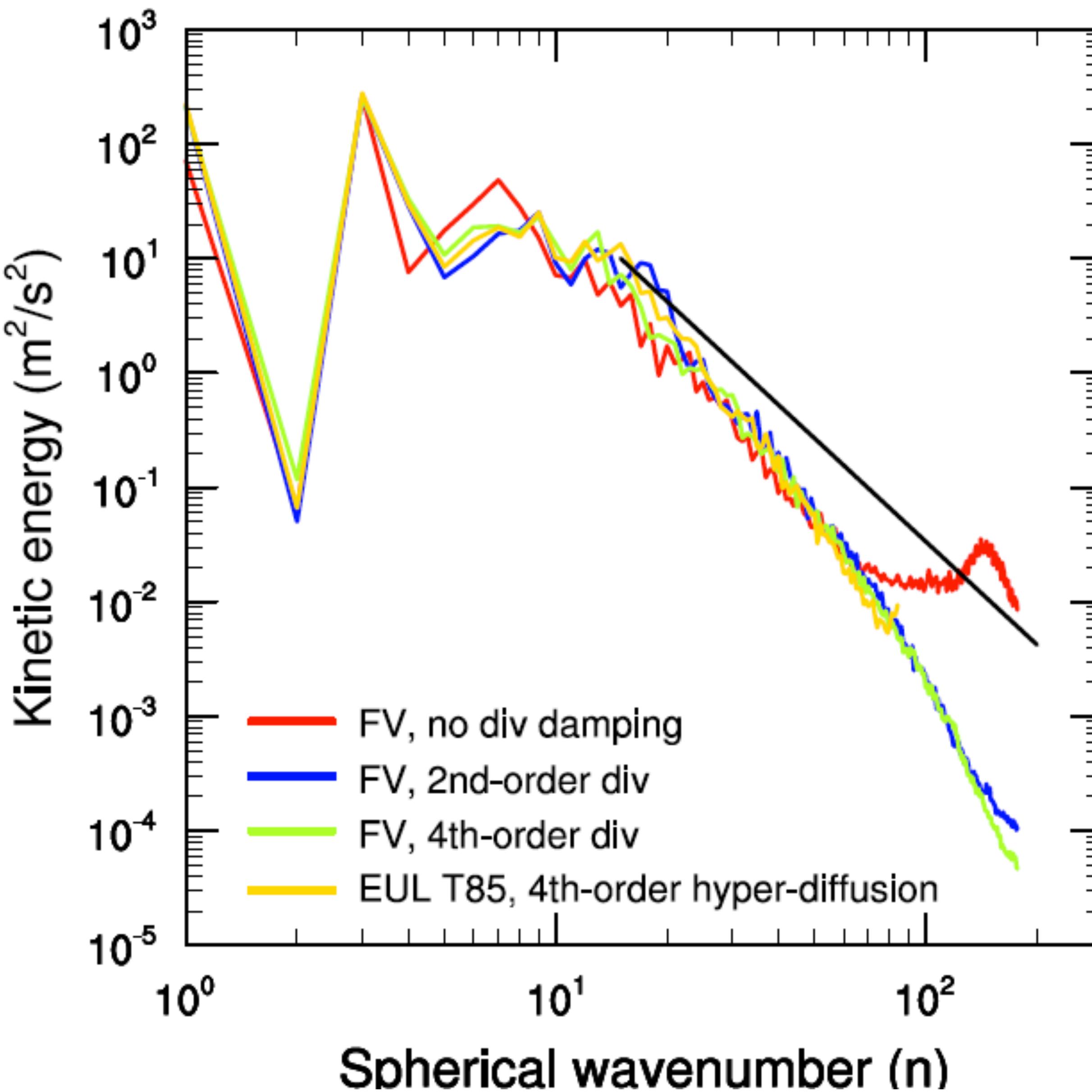
NOT an exhaustive list!

V-R challenges

- As you may have guessed -> host of V-R challenges!
- For example, on the software side…
  - Parallelization
  - Communication
  - Load balancing
- Want to focus on a few more relevant to this workshop and climate modeling…

Challenges: diffusion

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



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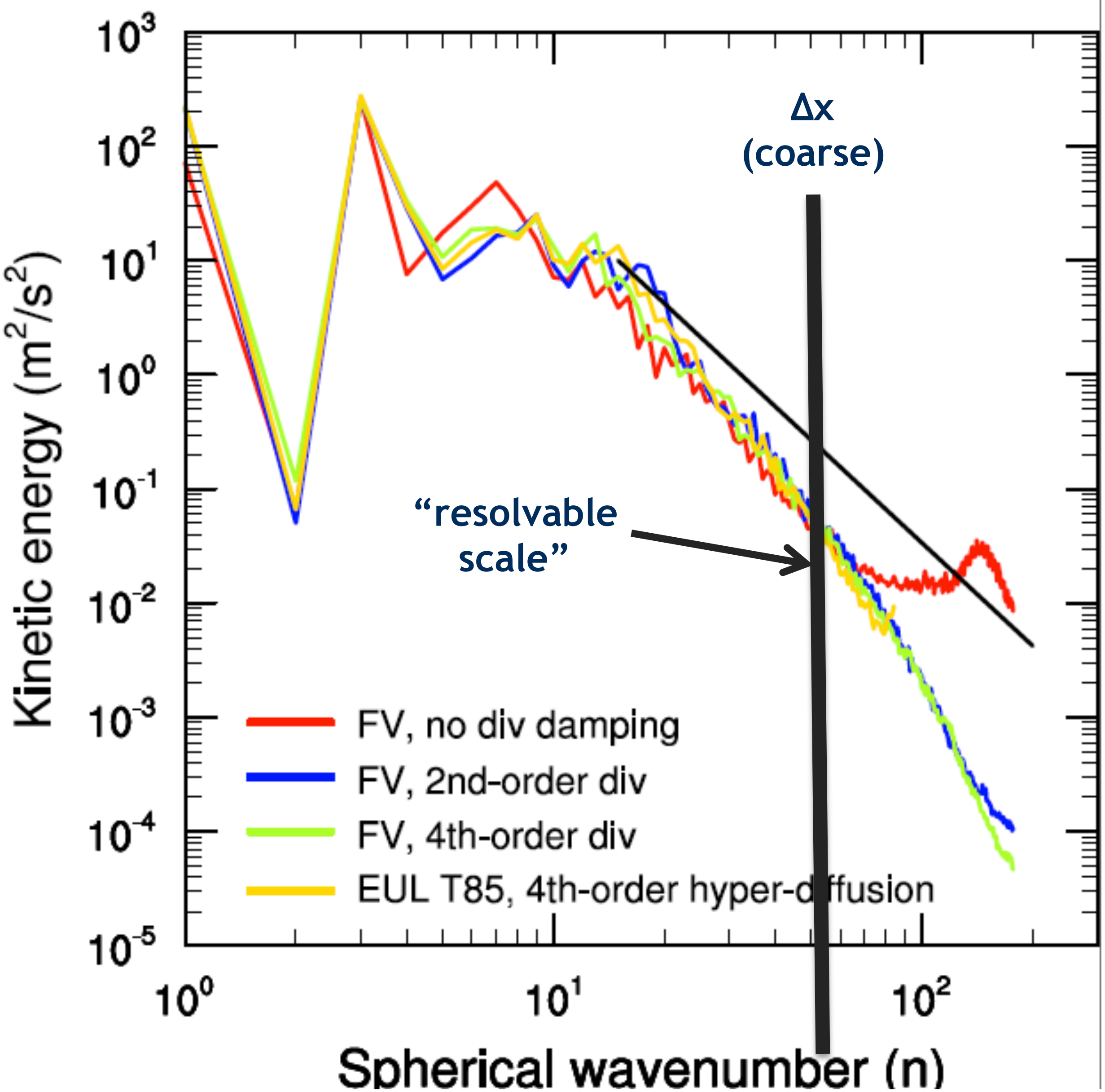

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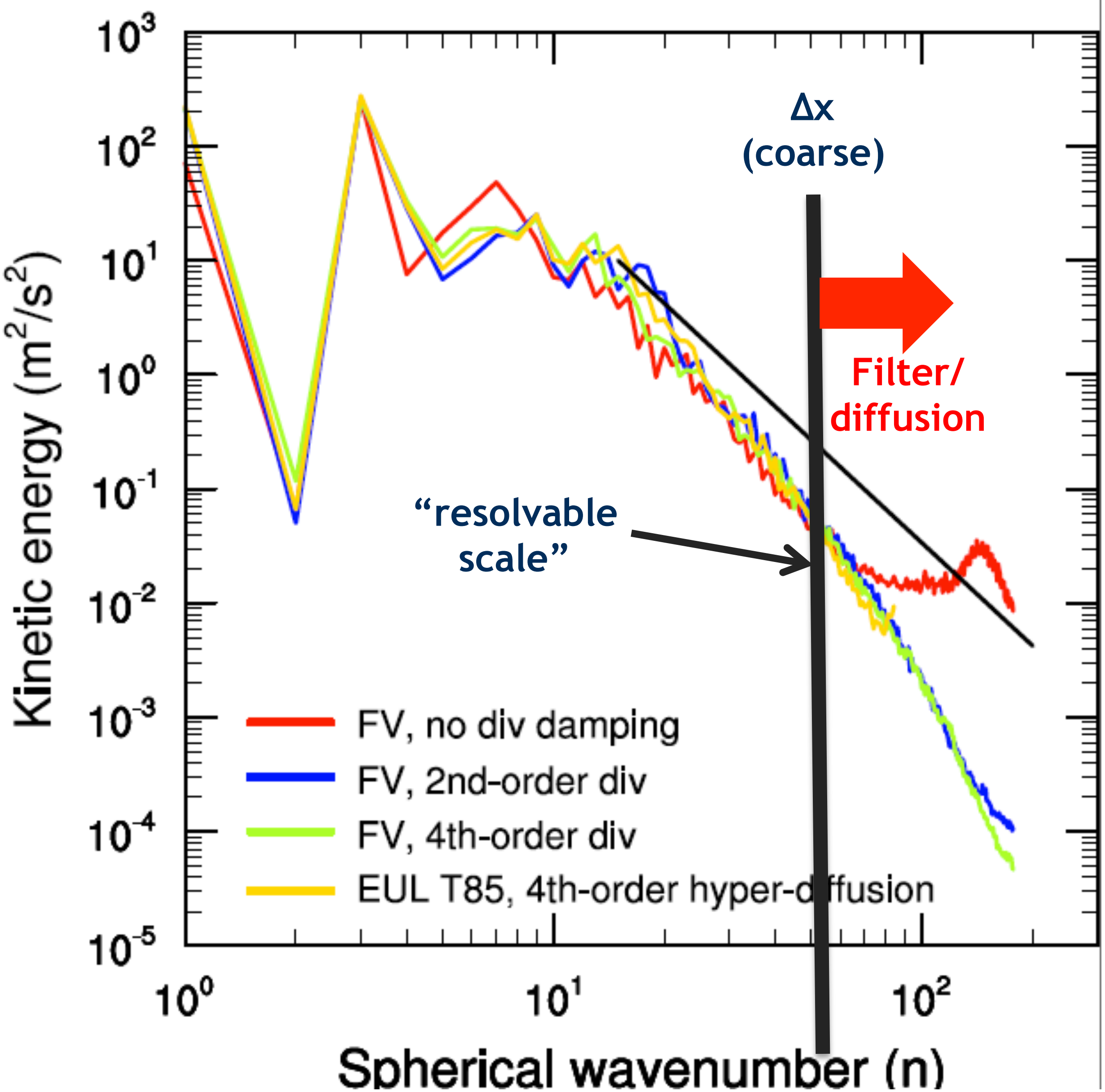

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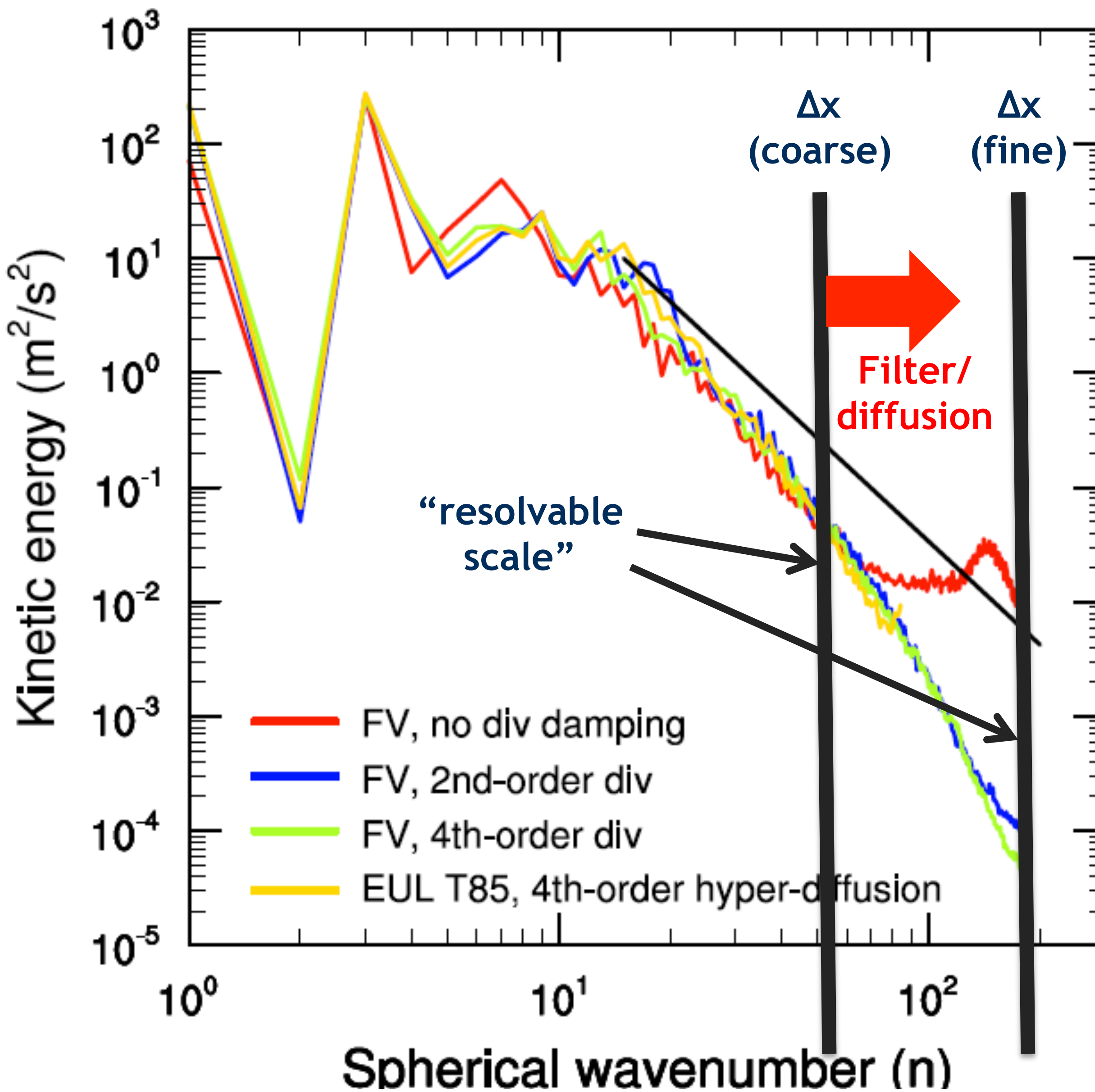

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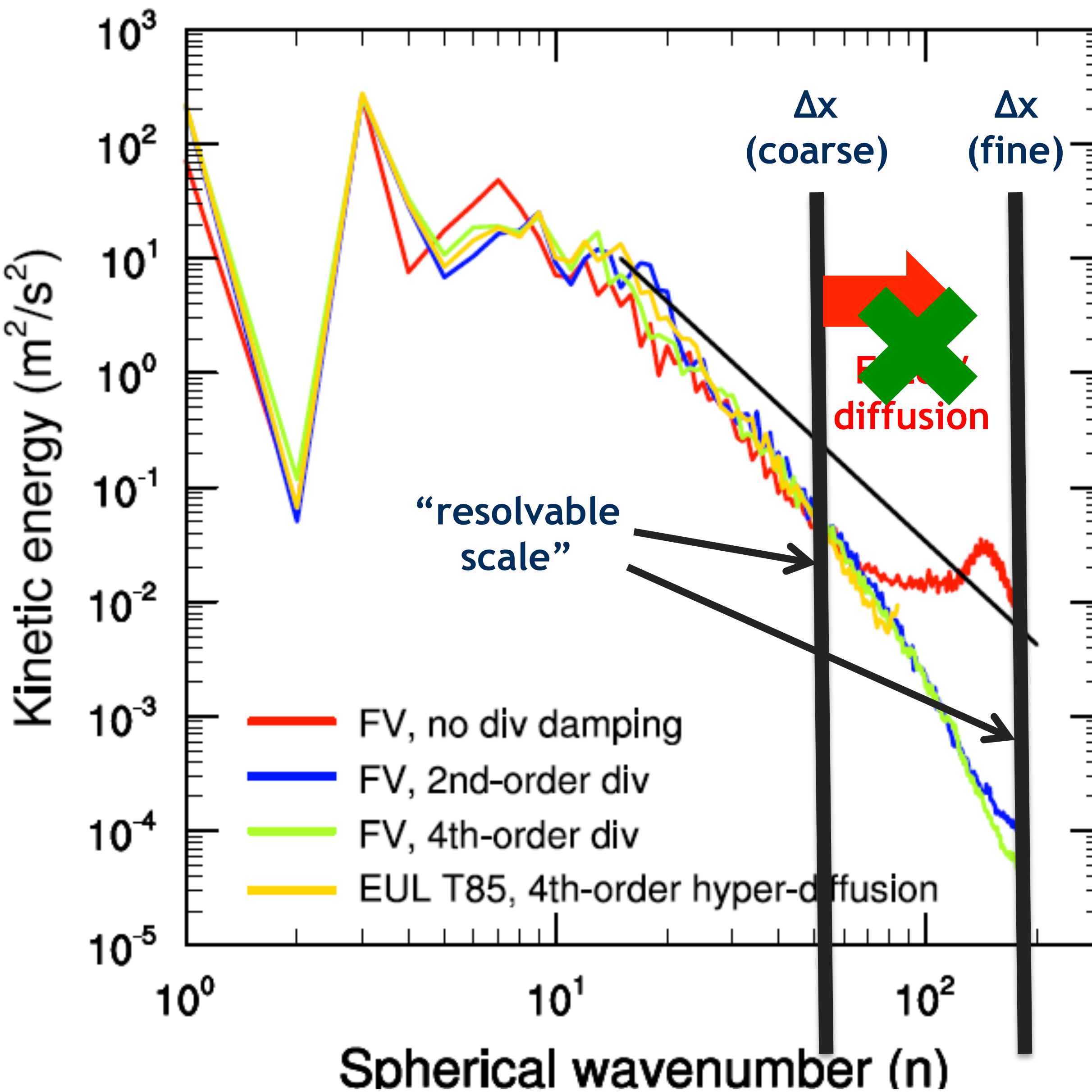


Challenges: diffusion

- 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>

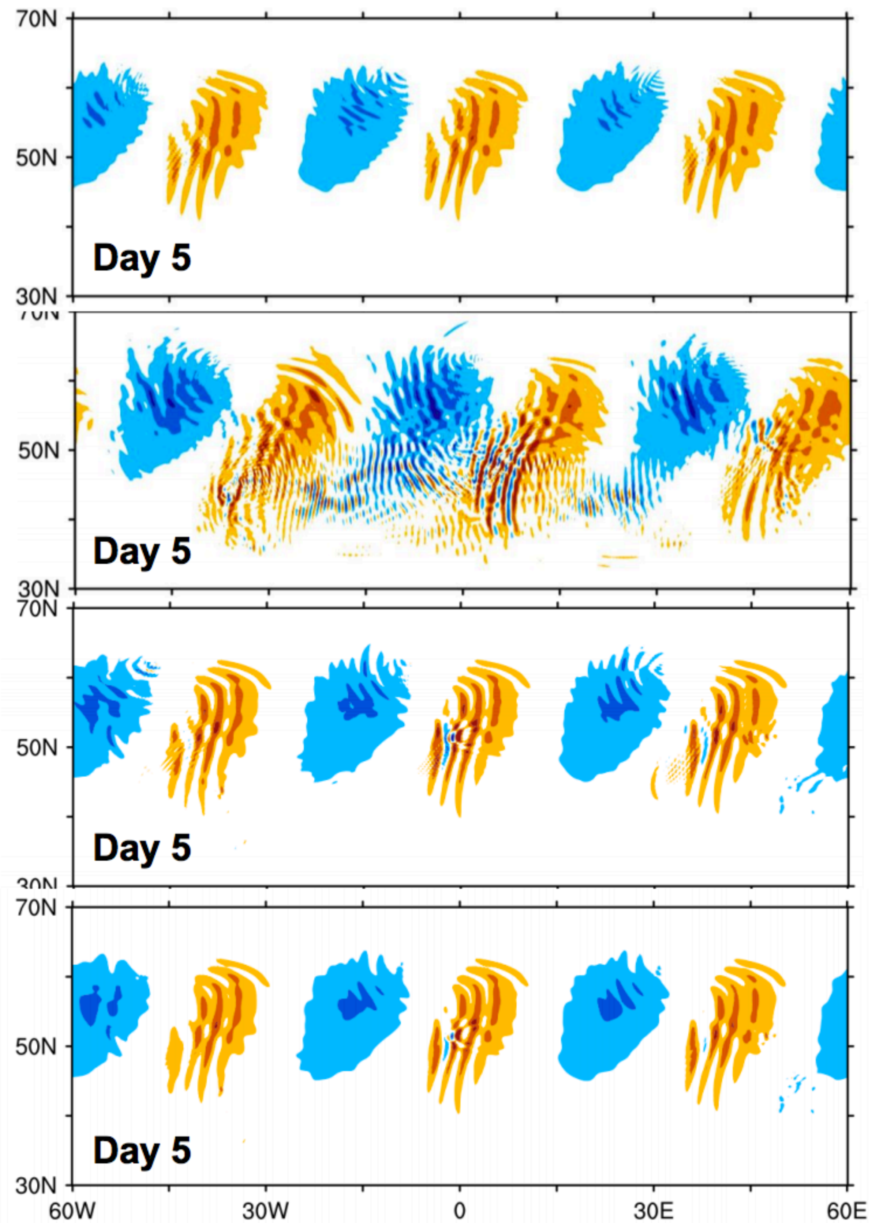
Challenges: diffusion

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 $K_4 = 1 \times 10^{12}\ m^4 s^{-1}$
(30 km mesh value, Δx^4 scaling)

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

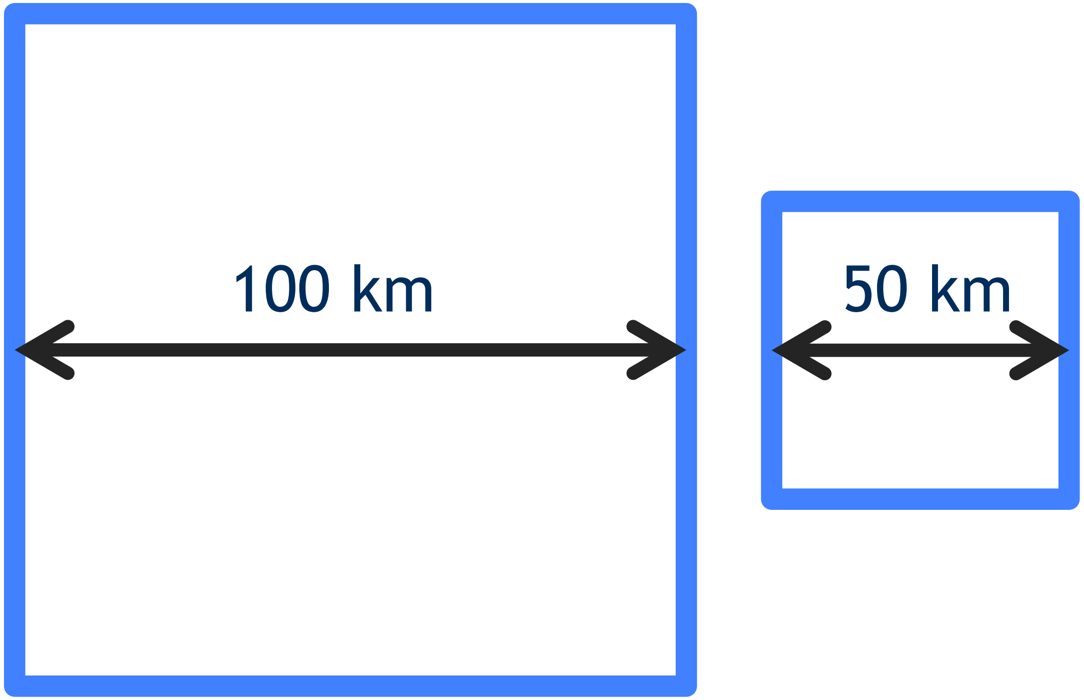


Skamarock, 2012, PDES

Challenges: diffusion

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

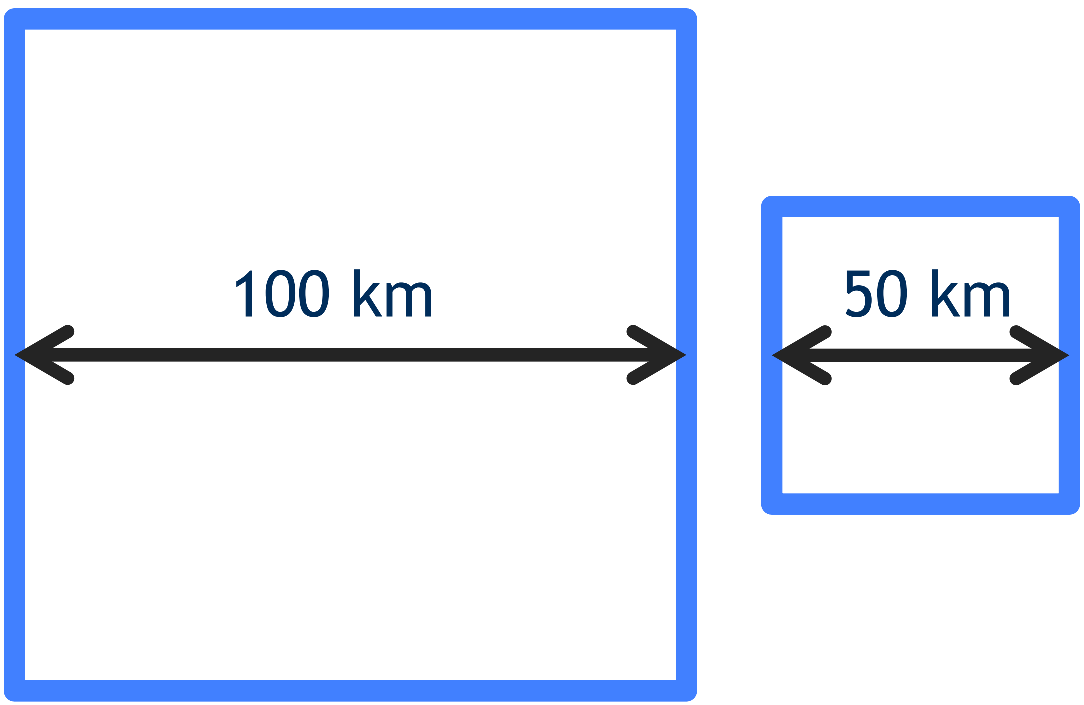
$$K_4\left(\Delta x\right) = K_4\left(\Delta x_{ref}\right)\left(\frac{\Delta x}{\Delta x_{ref}}\right)^y$$



Challenges: diffusion

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

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



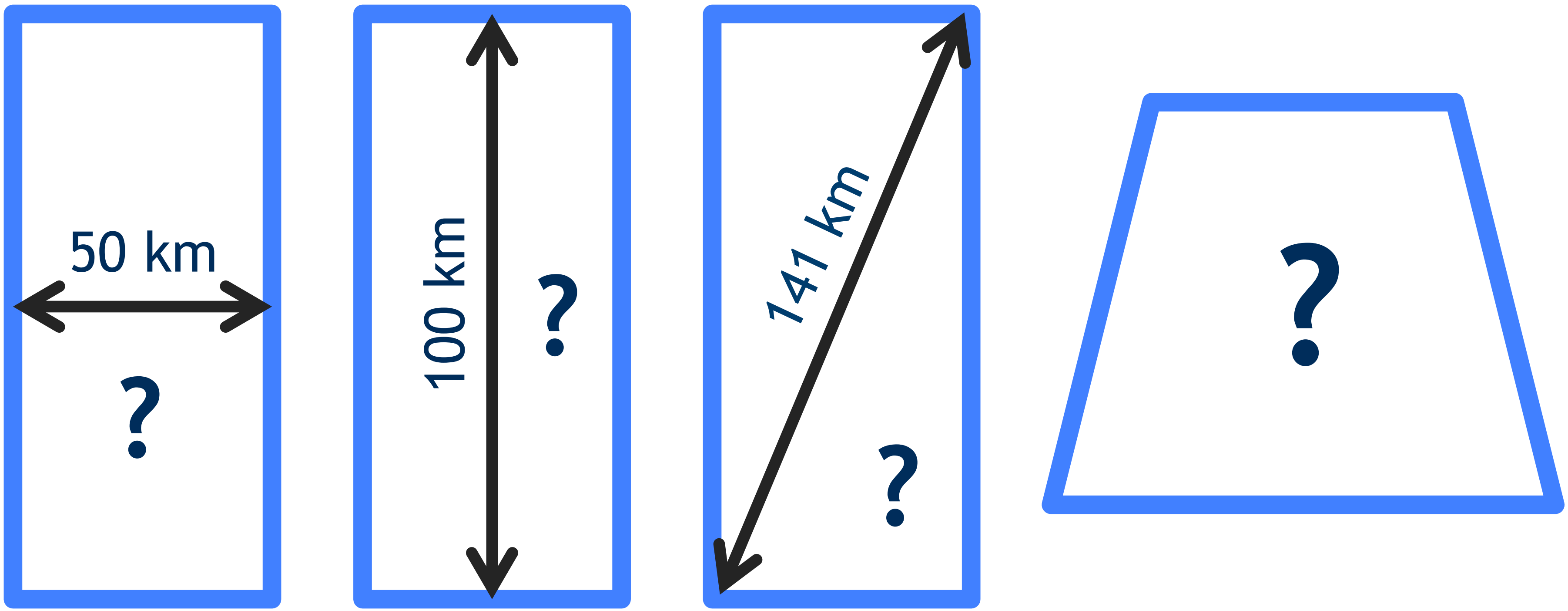
Let's say 100 km cell is our "reference" and y = 3.321

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

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?



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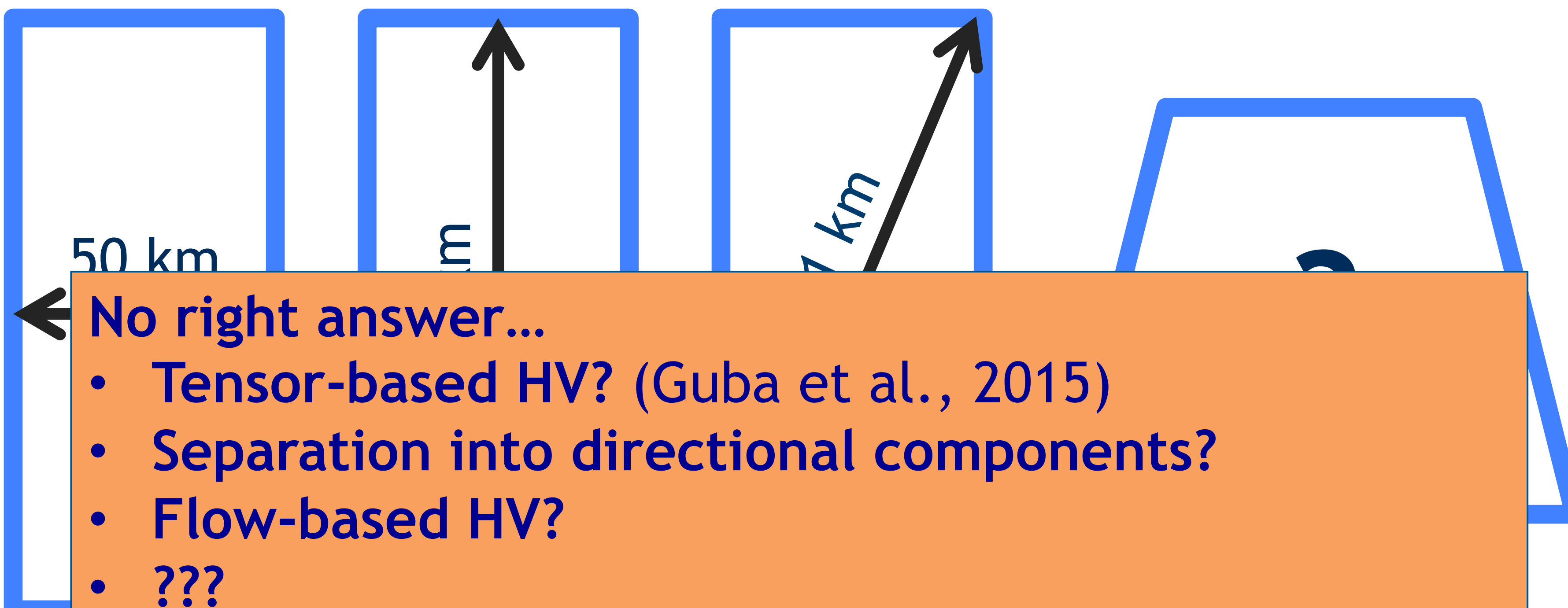

No right answer…

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

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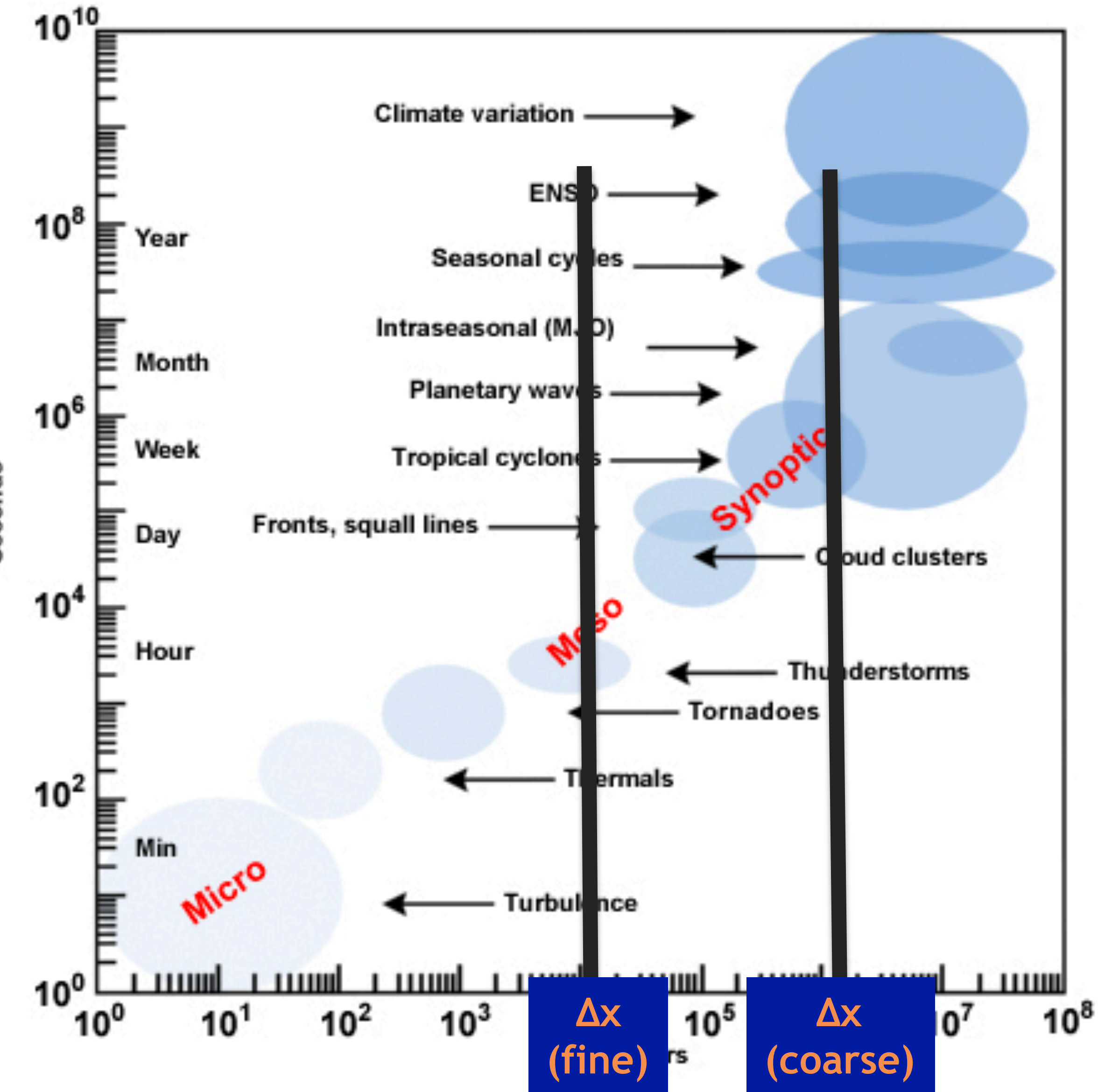
Challenges: scale-aware physics



- Unified model setups need to be able to properly estimate subgrid properties in all cells
  - Challenging when spanning large spatial scale gaps…

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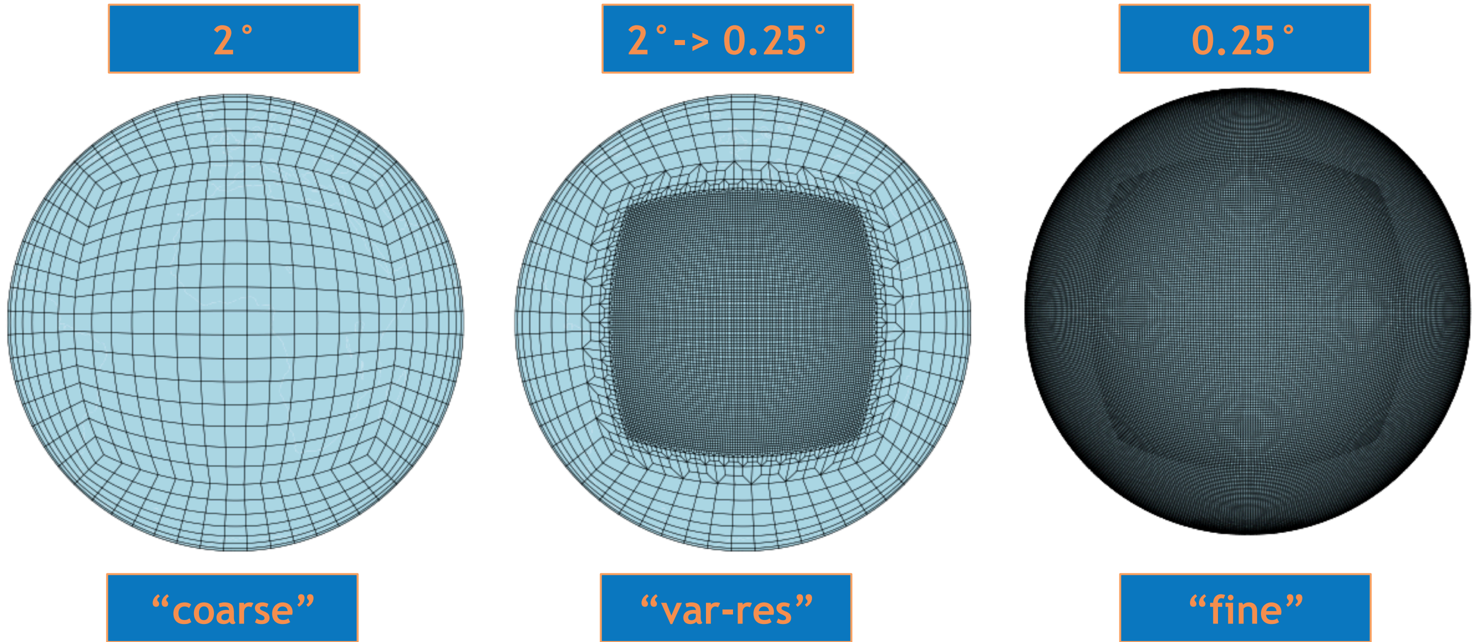
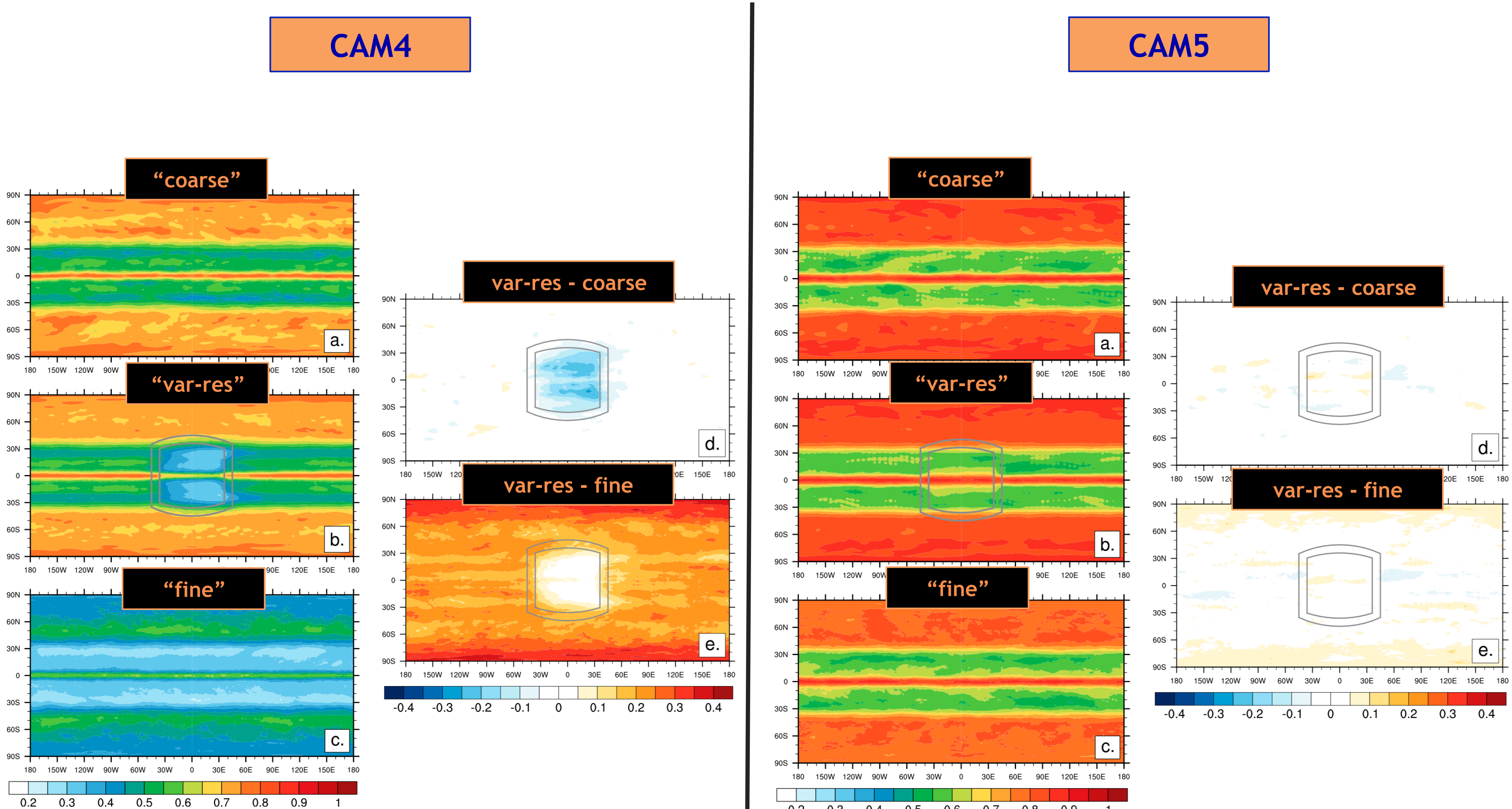
Challenges: scale-aware physics

- **Goals:**
  A. **Validate that refined nests can "match" climatology from globally-uniform grids**
  B. **Test CAM subgrid physical parameterizations (convection, PBL, radiation, etc.) at multiple grid scales**
- Perform 6 simulations using **aquaplanet**
  - Three using **CAMv4** physics
  - Three using **CAMv5** physics



Challenges: scale-aware physics



Mean annual cloud fraction

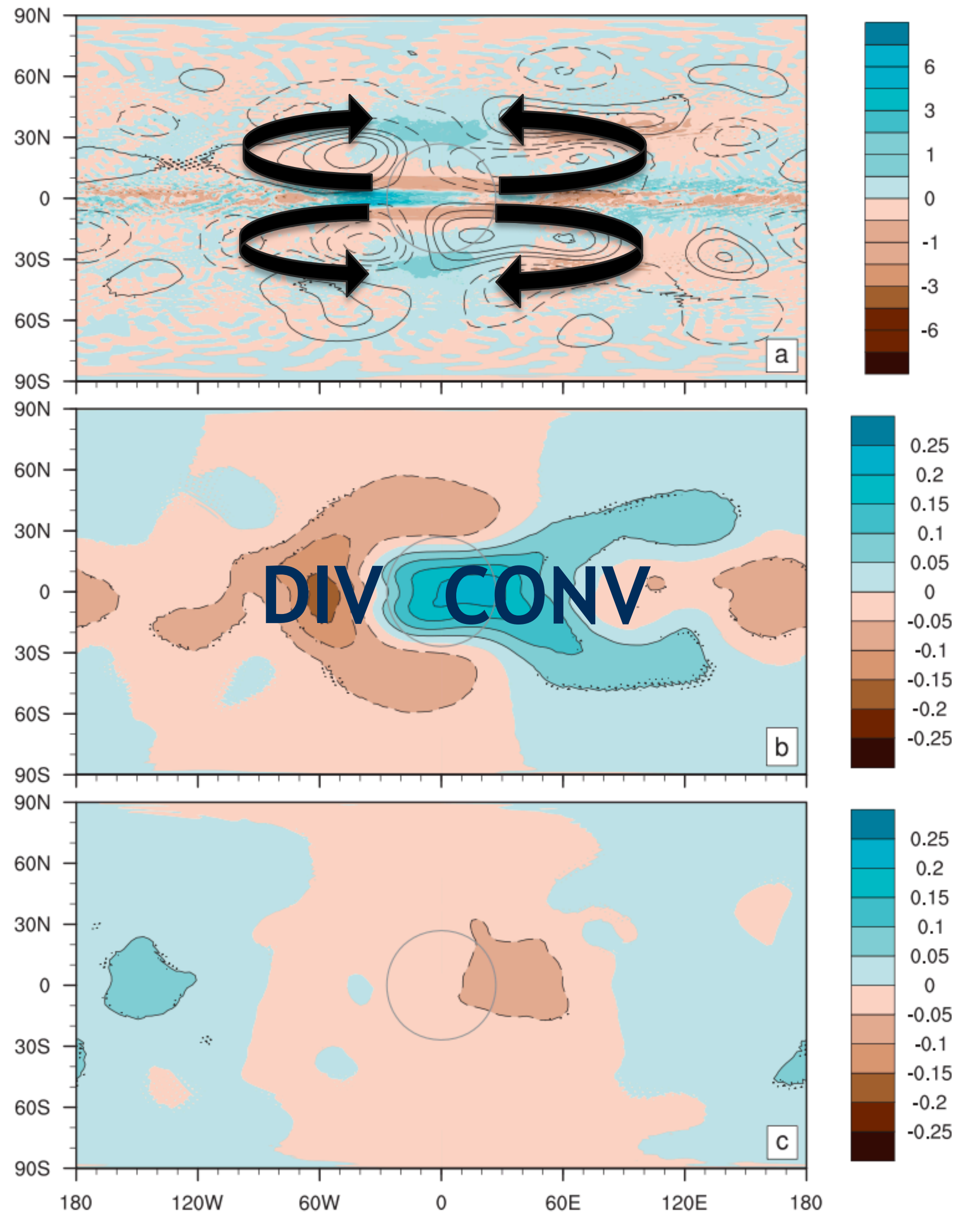
Zarzycki et al., 2014, JClim

Challenges: scale-aware physics

Rauscher et al., 2013, MWR

Aquaplanet (Moist)

Held-Suarez (Dry)

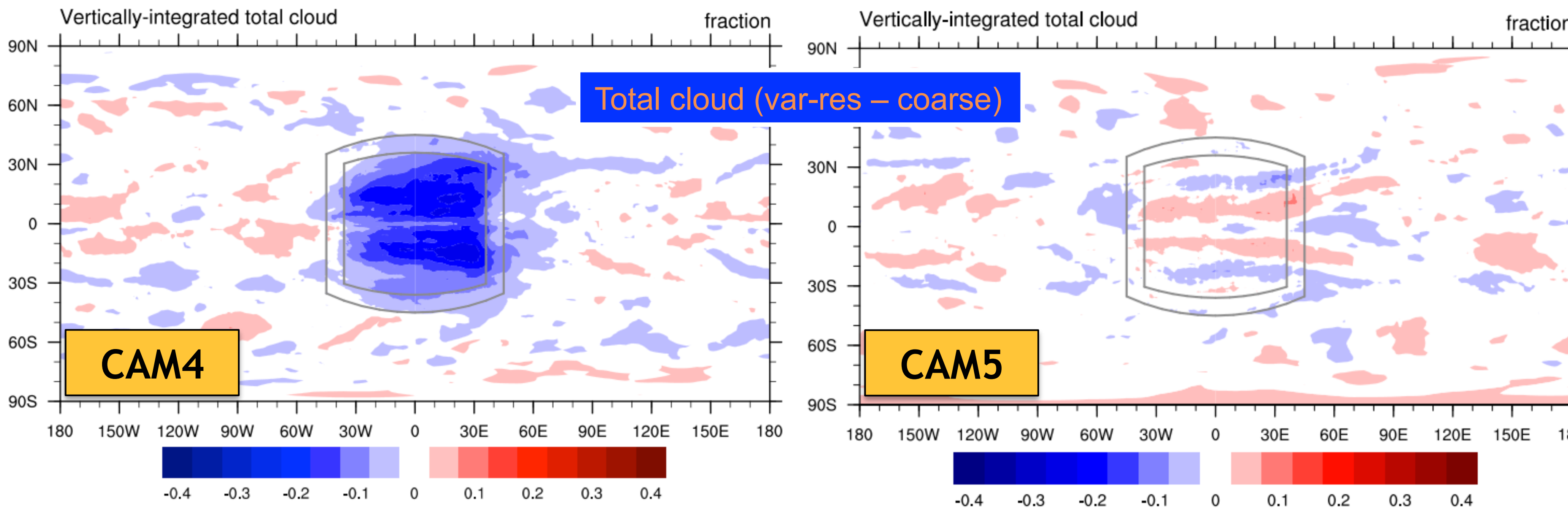


Precip. anom. / Streamlines

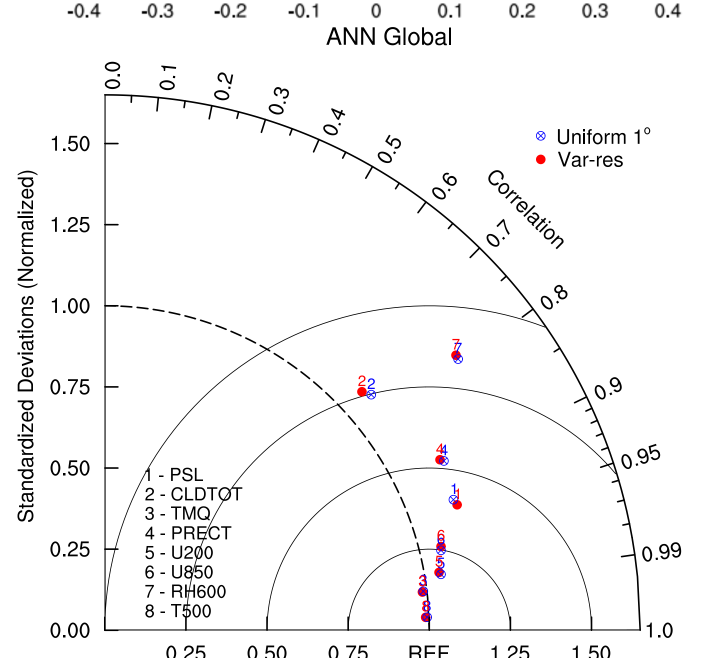
200 hPa Eddy Velocity Potential

200 hPa eddy Velocity Potential

Challenges: scale-aware physics

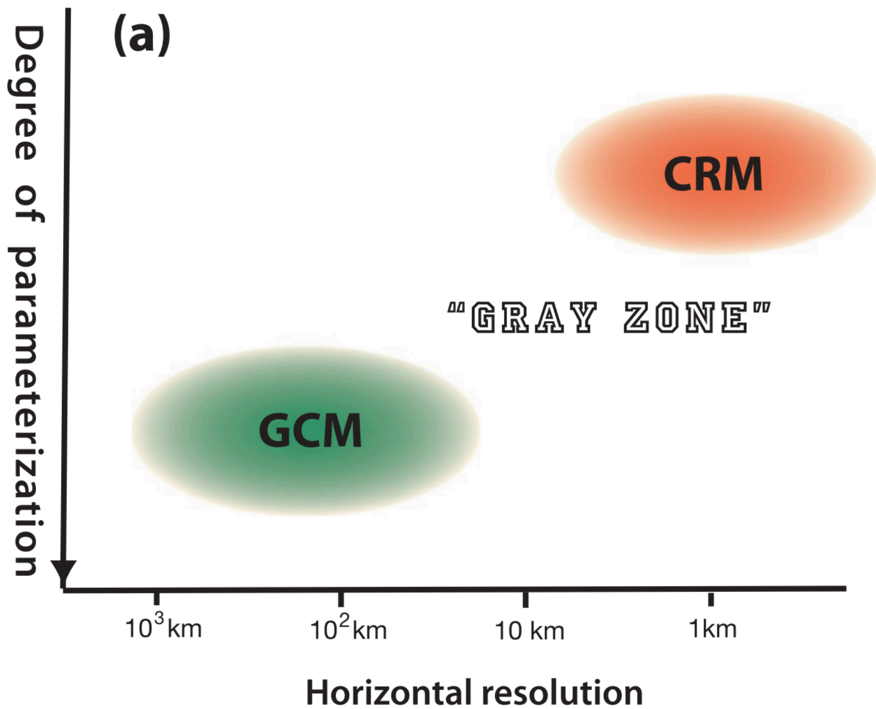


- CAM5 physics an improvement
  - Changes in microphysics scheme, less scale-sensitive behavior globally
  - Regional biases?



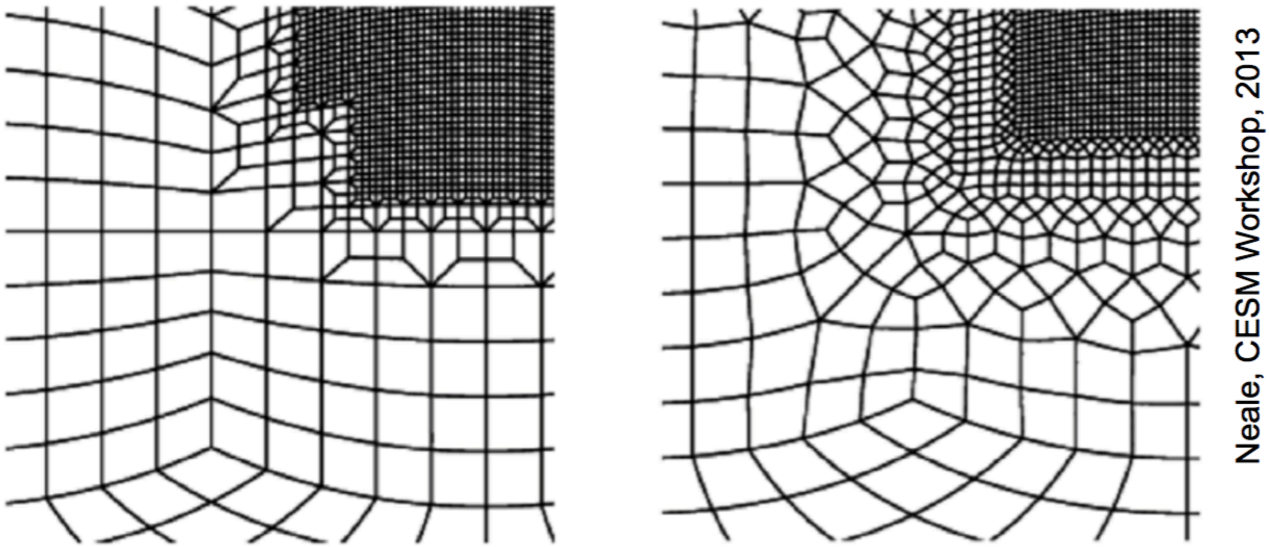
Challenges: scale-aware physics

Arakawa et al., 2013, JAS

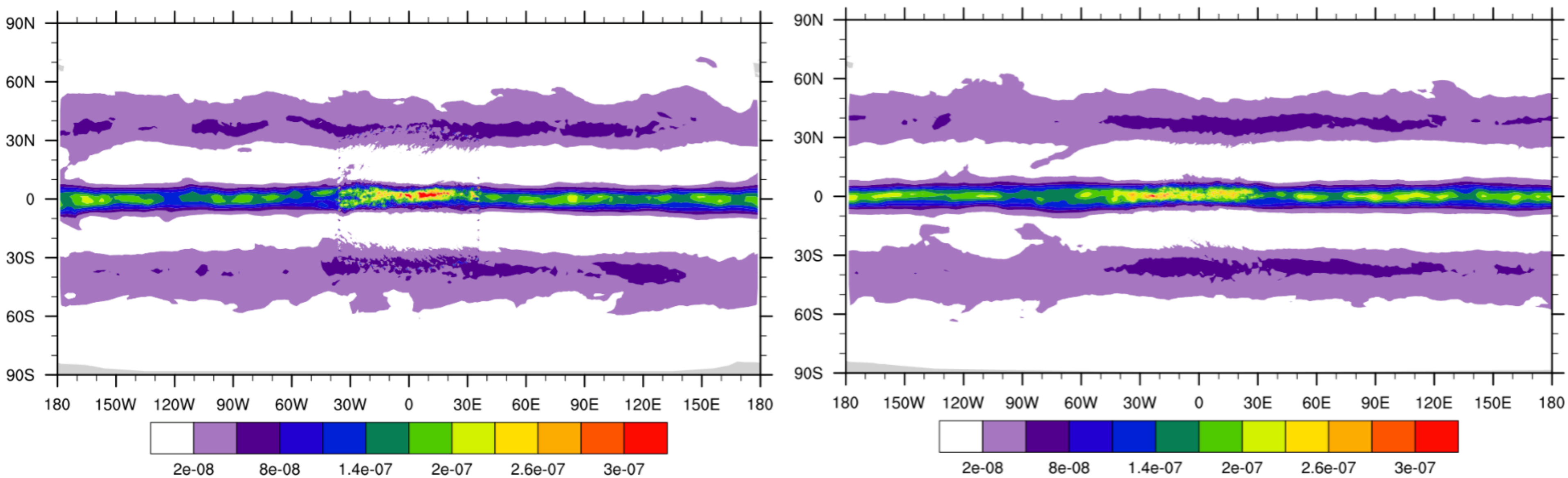


- Scale aware tuning?
  - Physics asks "**how big is my grid cell?**"
- Schemes such as Arawka, Grell-Freitas
- Entering the gray zone?
  - Convective permitting and convective resolving in fine mesh?

Challenges: grid shape/orientation

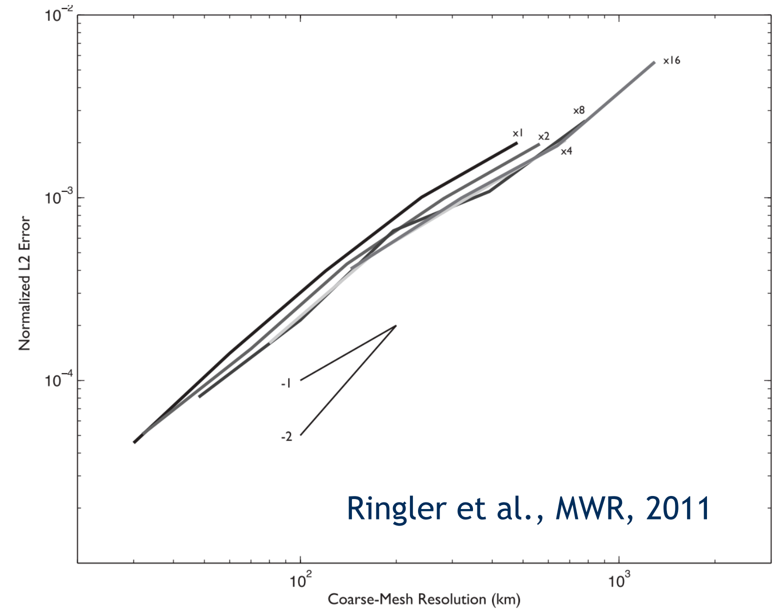


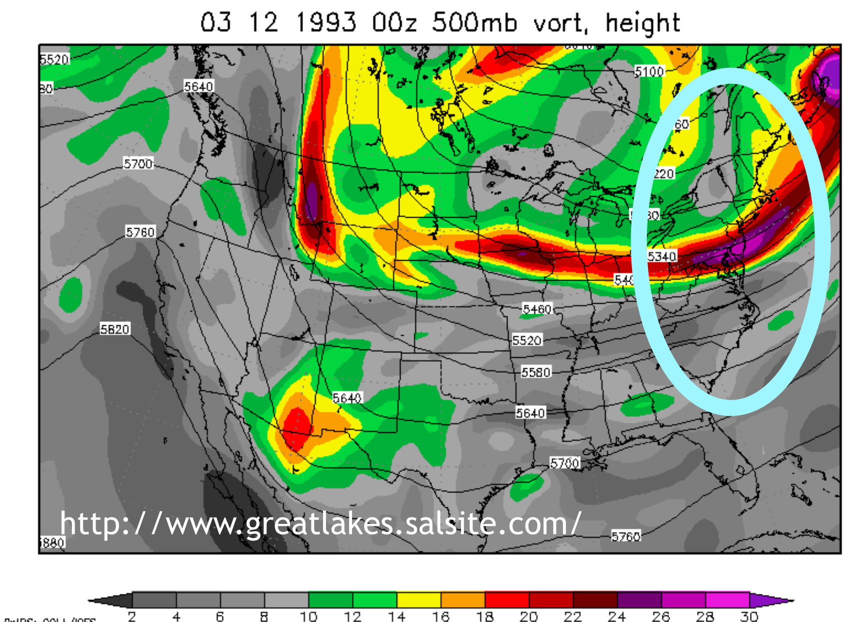
(a) CUBIT approach (b) SQuadGen approach



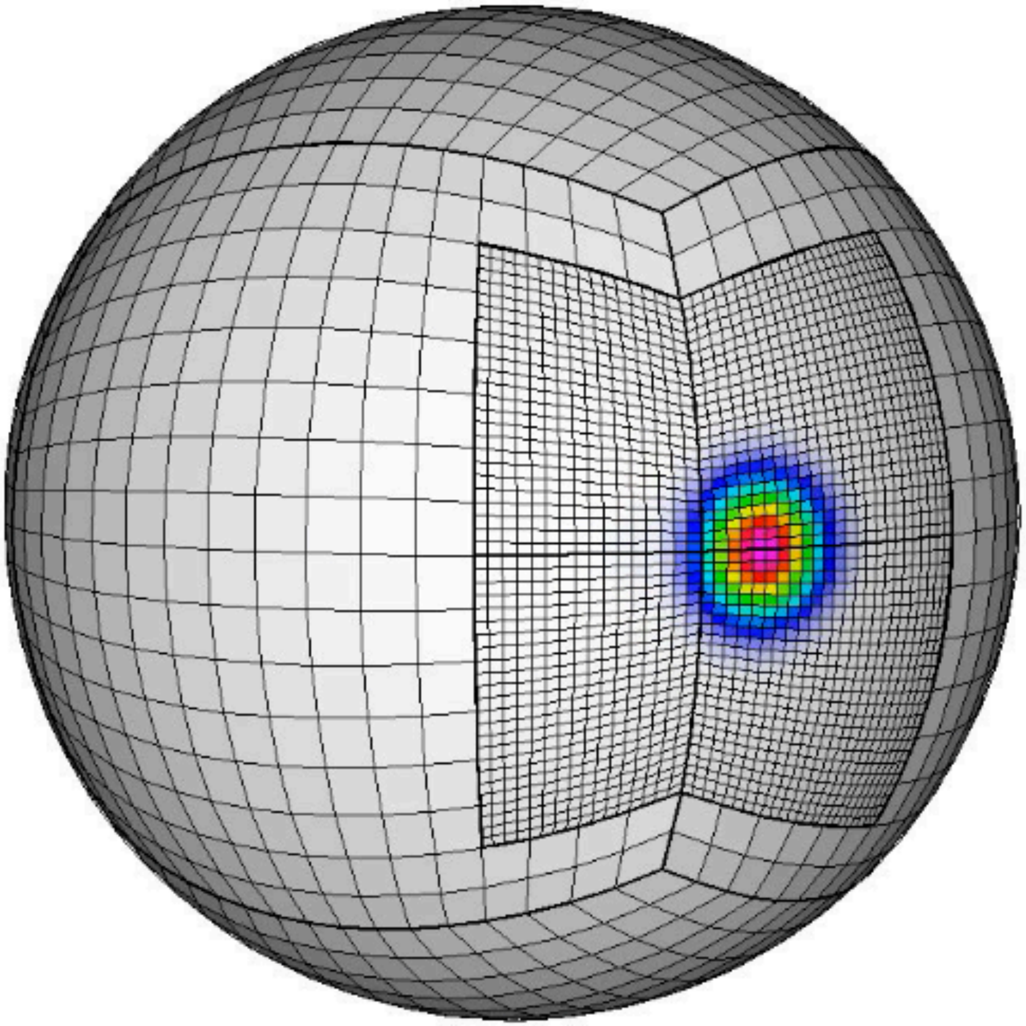
Challenges: refinement details

- Long-term *solution error* of VR simulation controlled by coarsest grid scales
- For improvements in dynamical representation, refine area of interest
  - If upstream effects dominate -> not best solution?
  - Ex: vorticity phasing for eastern US winter storms impacted by upstream topographical effects (lee of Rockies)





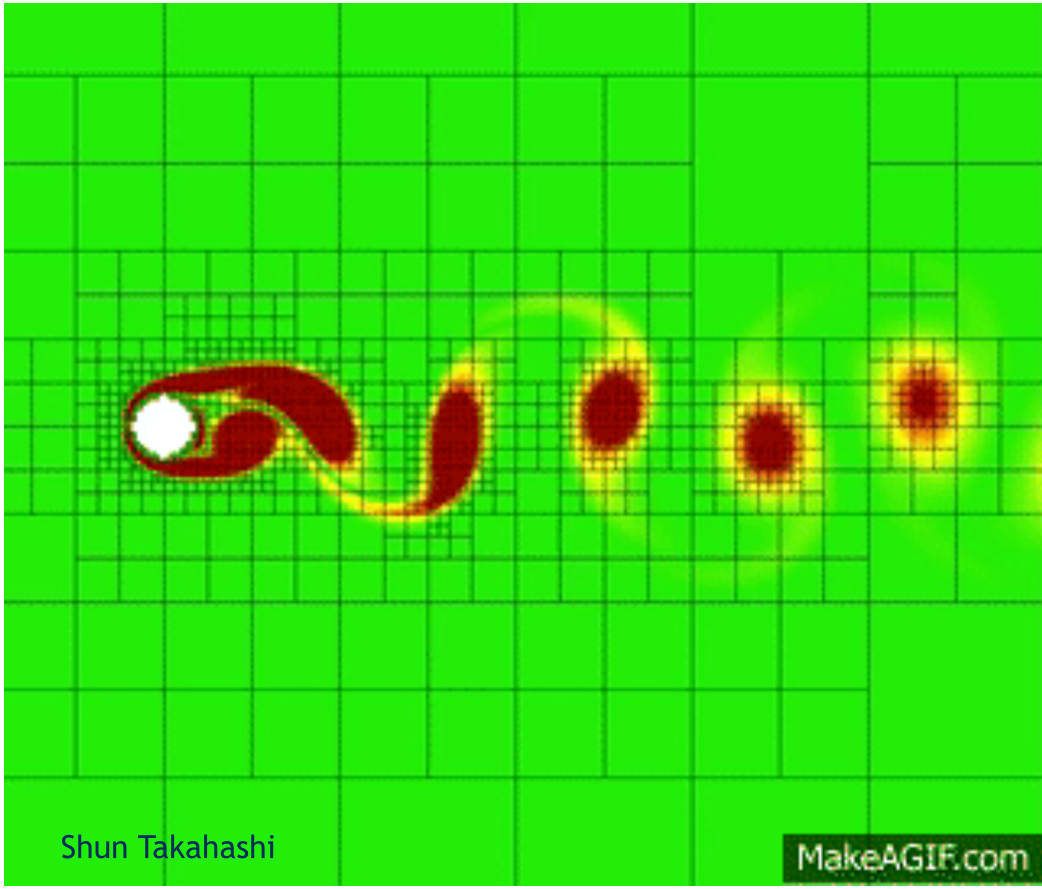
Adaptive mesh refinement



- Adaptive Mesh Refinement (**AMR**)
  - Grid not only varies in space, but in time!
- All challenges regarding static refinement hold!

Adaptive Mesh Refinement

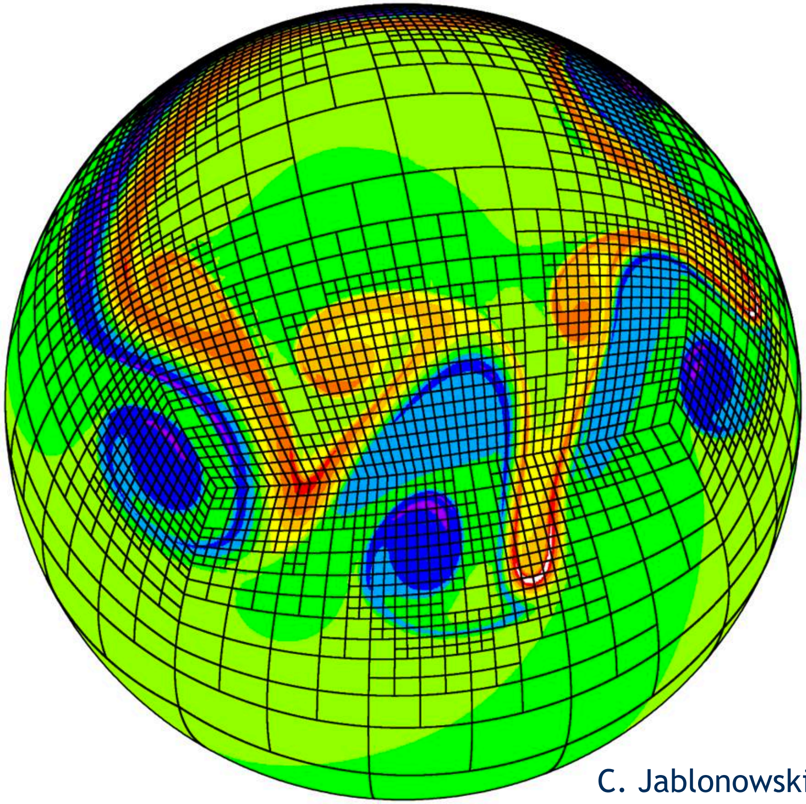
- Basic solution structure:
  - Start with coarse mesh and “tolerance” (tol)
- Solve
- Calculate “error” (E) at each grid cell
  - If E > tol, add grid cells until E ~= tol
  - If E << tol, remove grid cells until E ~= tol
- Solve
- Back to step 3 and repeat



In reality, there is no way of knowing “error” a priori, therefore we generally choose something like a gradient or extreme value to target refinement

Adaptive Mesh Refinement

- 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.



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Summary

- 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