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High Resolution Modeling: Current Approaches and Future Prospects

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EMF Workshop on Climate Change Impacts and Integrated Assessments: Critical Issues in Climate Change

Snowmass Village, CO, July 20 – July 29, 2016

Why resolution matters?

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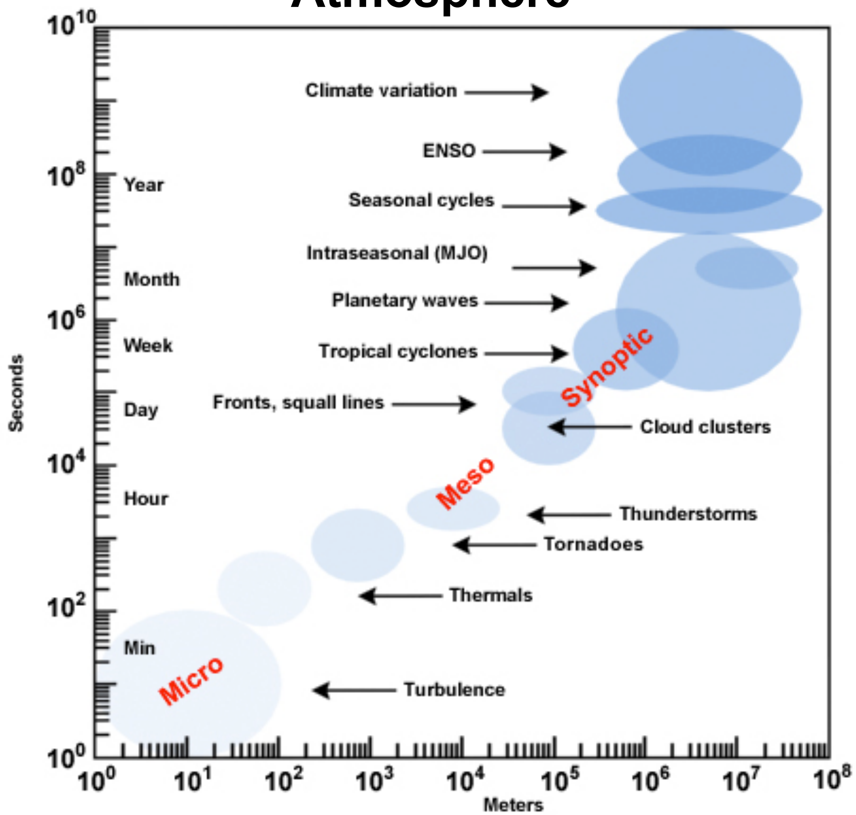
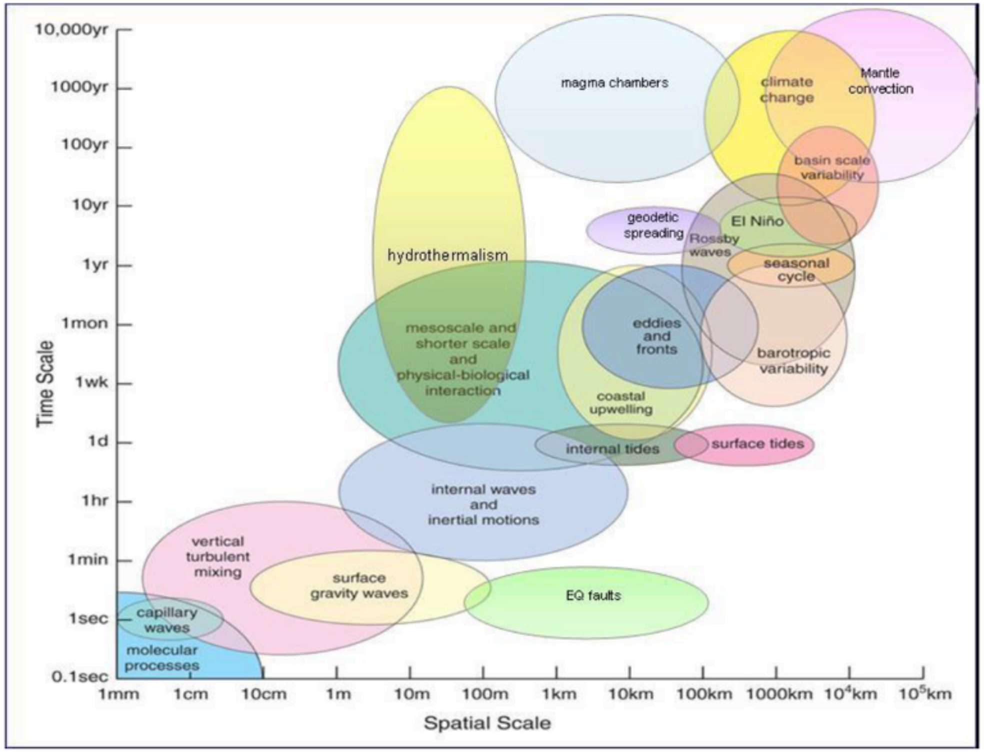
Atmosphere



Ocean



(Chelton and Beranzoli)

- Atmosphere and ocean processes represent a continuum of scales spanning at least 10 orders of magnitude
- Climate model resolution has been determined mainly by computational constraints

Outline

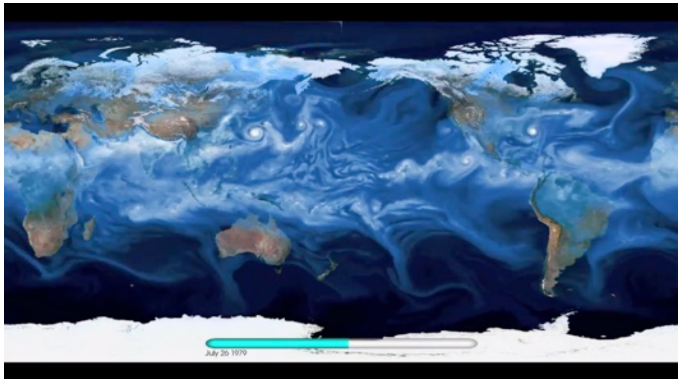
- What dynamical approaches are available for high resolution (10 – 30 km) climate modeling?

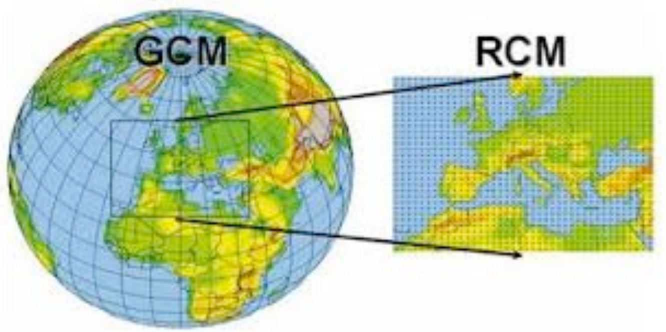
- What are the impacts of model resolution on simulation skill?

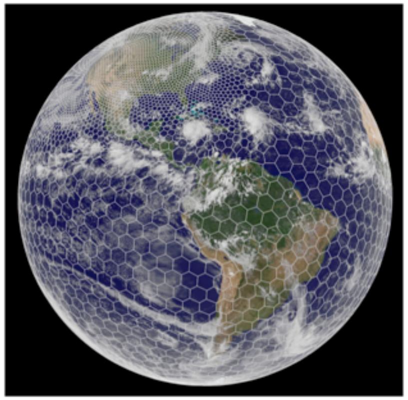
- What are the future prospects in high resolution modeling?

High resolution modeling approaches

- Global high resolution modeling
  - Computationally expensive considering the needs for ensemble, multi-scenario simulations and storage, data transfer, and analysis
- Regional climate modeling (limited area modeling)
  - Inconsistency between the GCM and RCM: artificial gradient and numerical artifacts
  - Lack of two-way interactions
- Global variable resolution modeling
  - No physical boundary separating the low and high resolution regions leading to better behaved numerical solutions and allows two-way interactions
  - Computational cost comparable to regional climate modeling

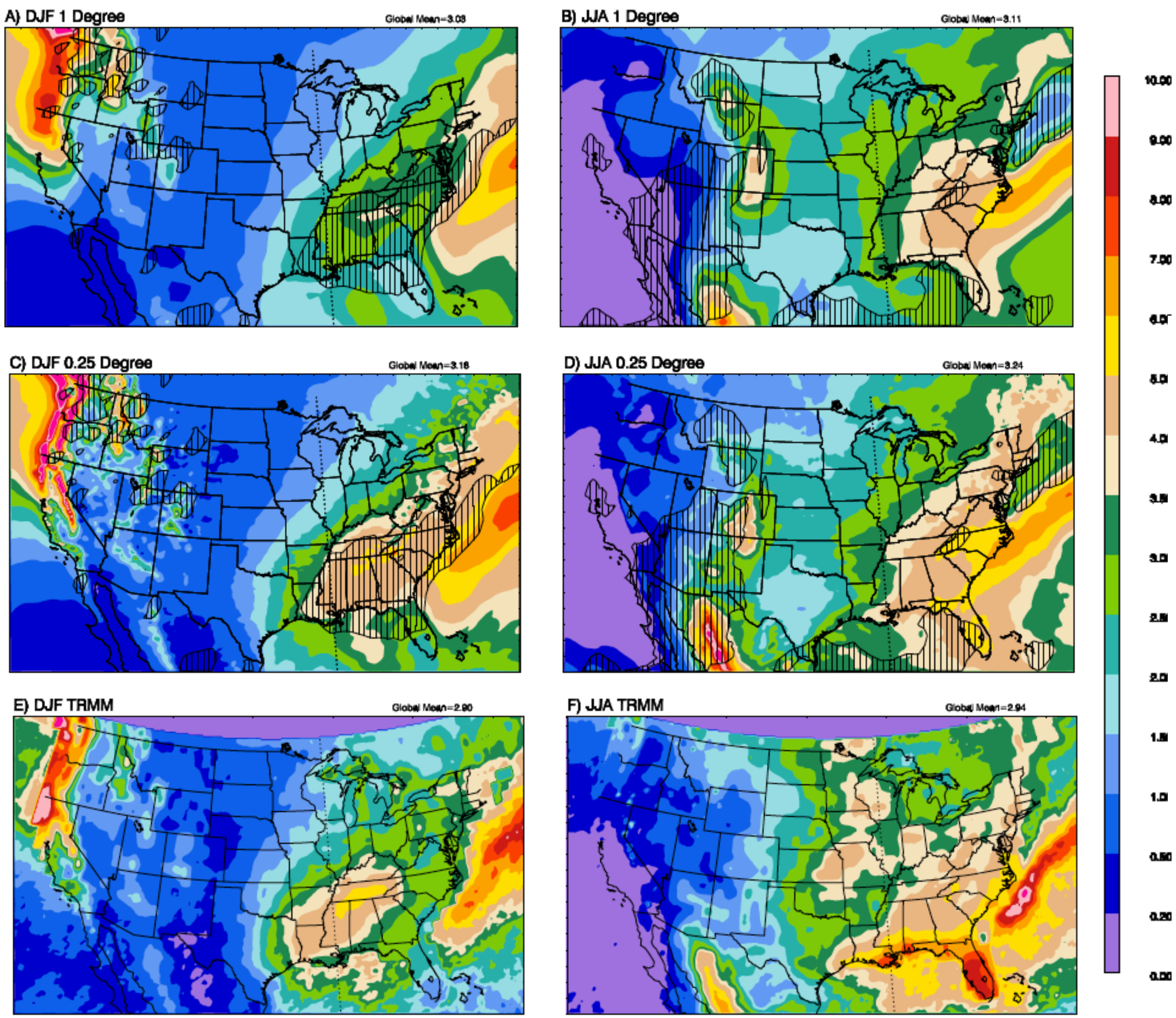




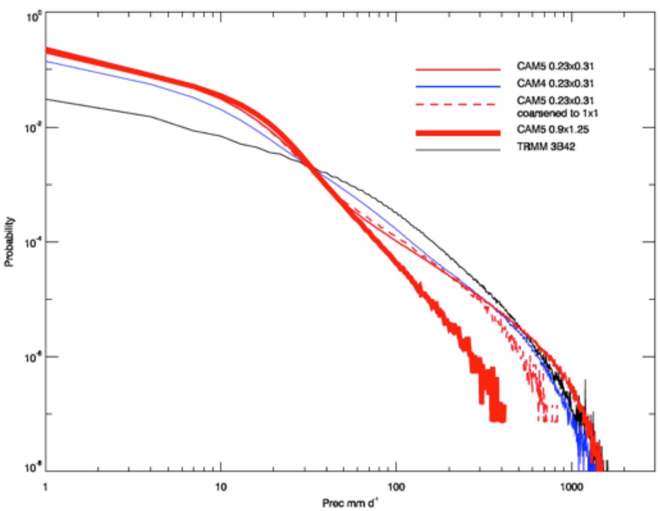


Increasing horizontal resolution produces mixed results

- Cold season precipitation, complex terrain, rain rates ☑
- Warm season precipitation ☒



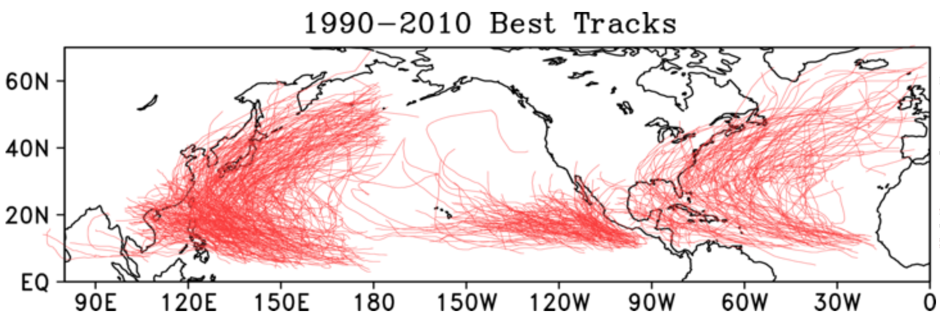
Rain rate PDF



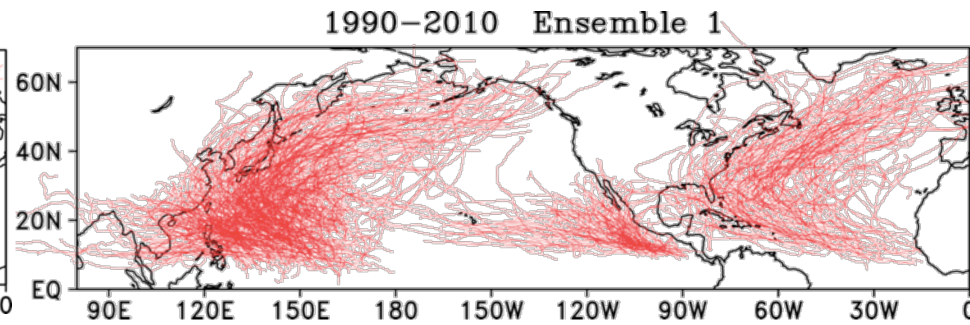
(Bacmeister et al. 2014, JCLIM)

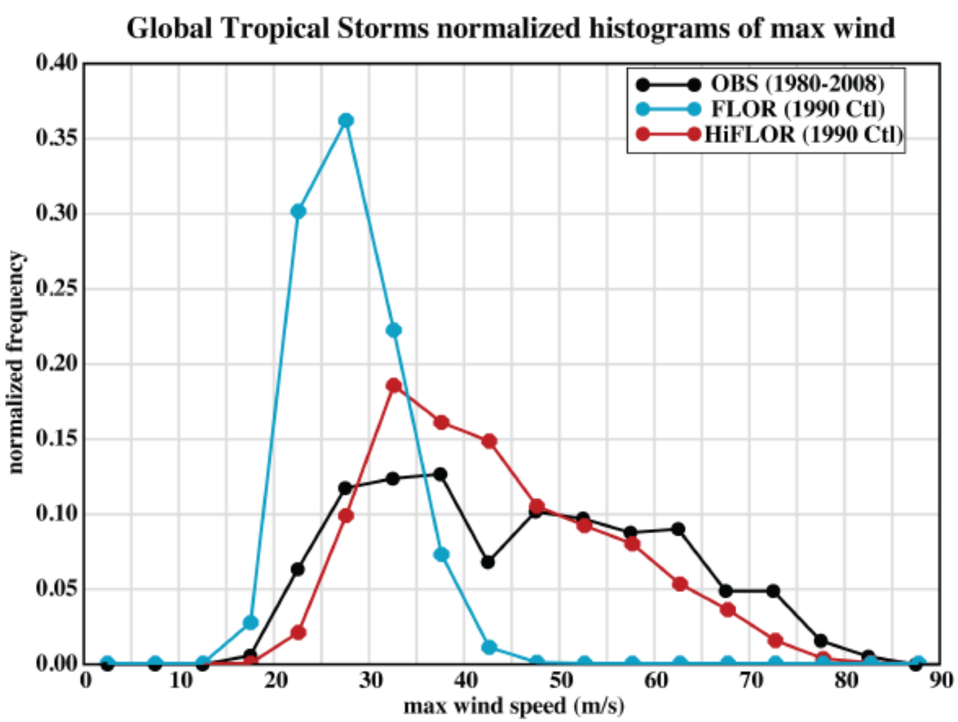
Seasonal hurricane predictions: GFDL 25 km global model

Observed tracks



GFDL seasonal prediction

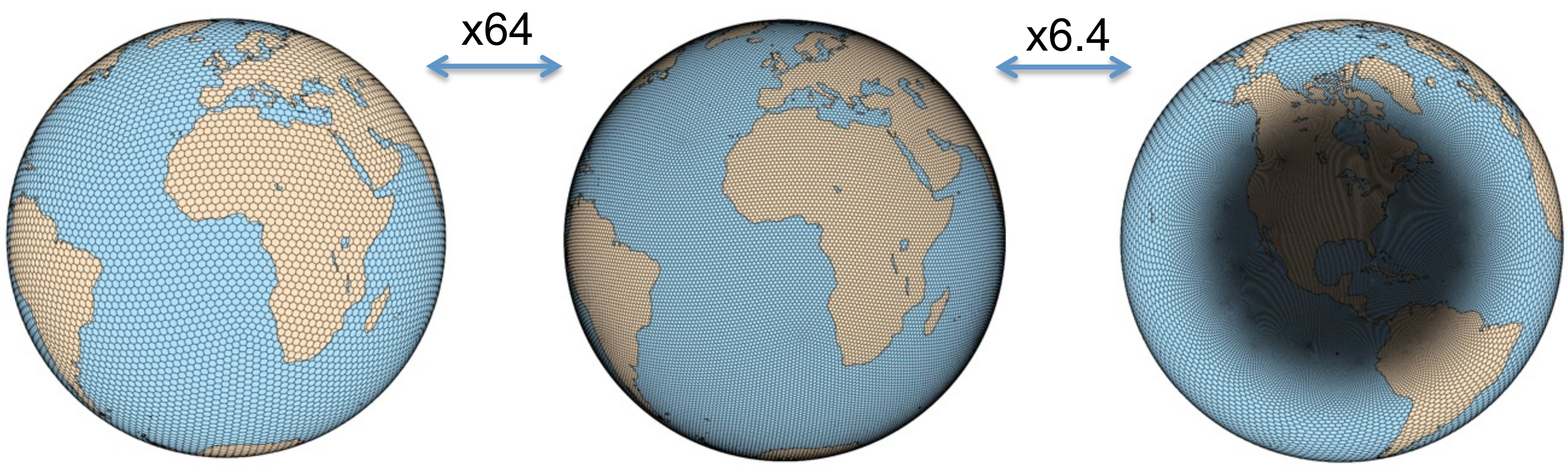




Higher resolution simulations capture cat. 4 – 5 hurricanes

(Murakami et al. 2015)

Global variable resolution modeling

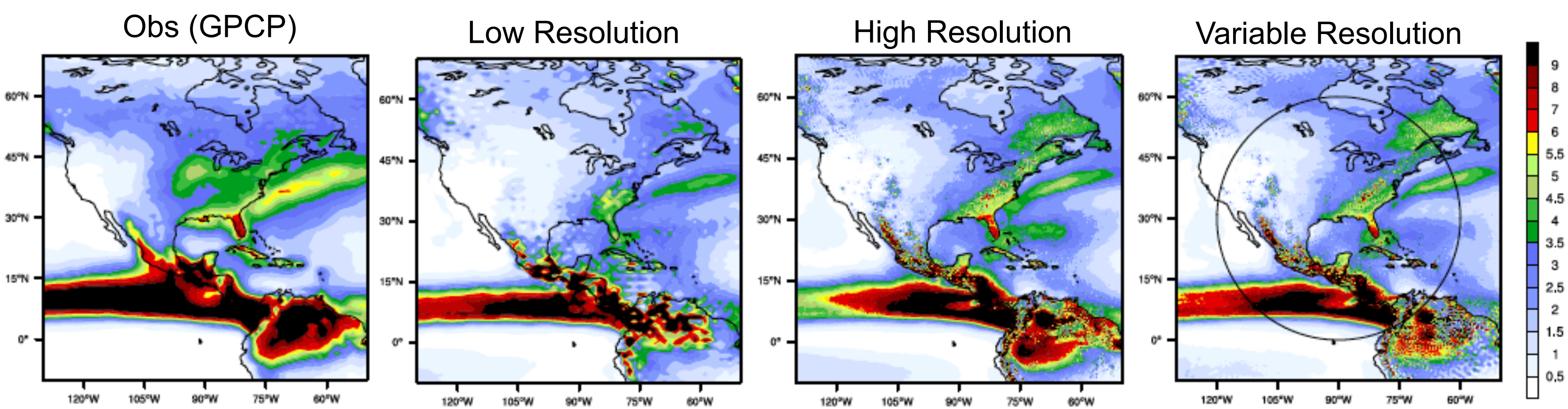


Uniform Low Resolution (ULR)
(120 km and 40,962 cells)

Uniform High Resolution (UHR)
(30 km and 655,362 cells)

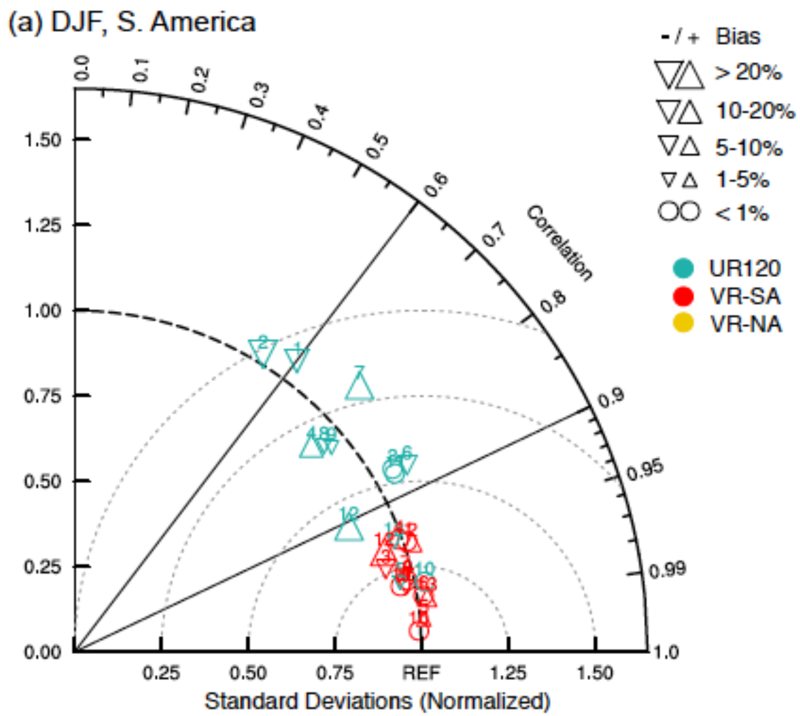
Variable Resolution (VR)
(120 km → 30 km and 102,402 cells)

Summer season rainfall (10-yr average in mm/day)

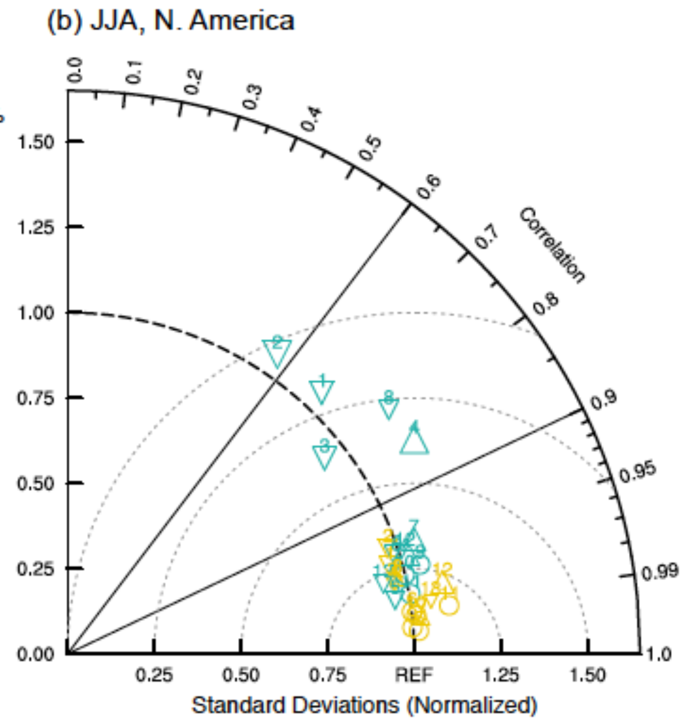


Downscaling: VR reproduces UHR in the high resolution regions

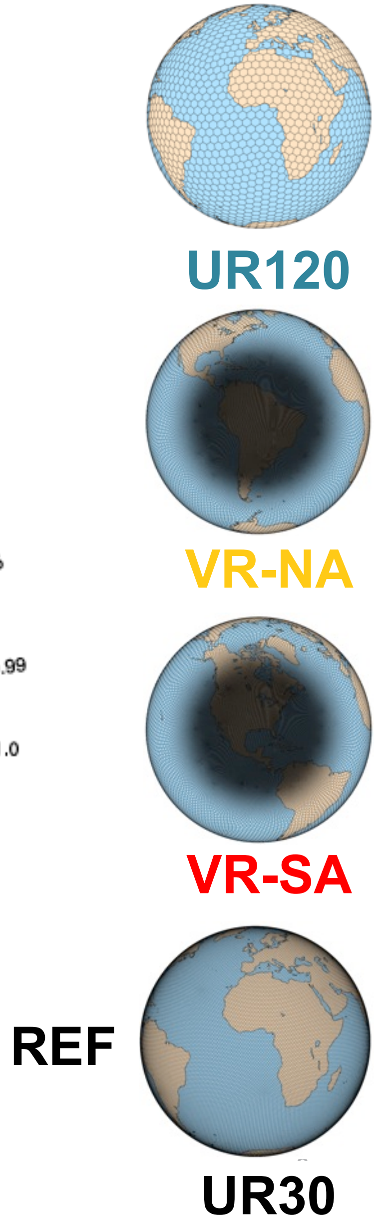
S. America (wet season)



N. America (summer)



1: total precipitation
2: grid-scale precipitation
3: subgrid-scale (convective) precipitation
4: cloud cover fraction
5: precipitable water
6: surface evaporation
7: surface sensible heat flux
8: surface downward solar radiation
9: air temperature at 2 m height
10: geopotential height at 500 hPa level
11: wind vector at 200 hPa level
12: wind vector at 850 hPa level



(Sakaguchi et al. 2015 JCLIM)

Upscaling: VR captures some UHR features in the low resolution region

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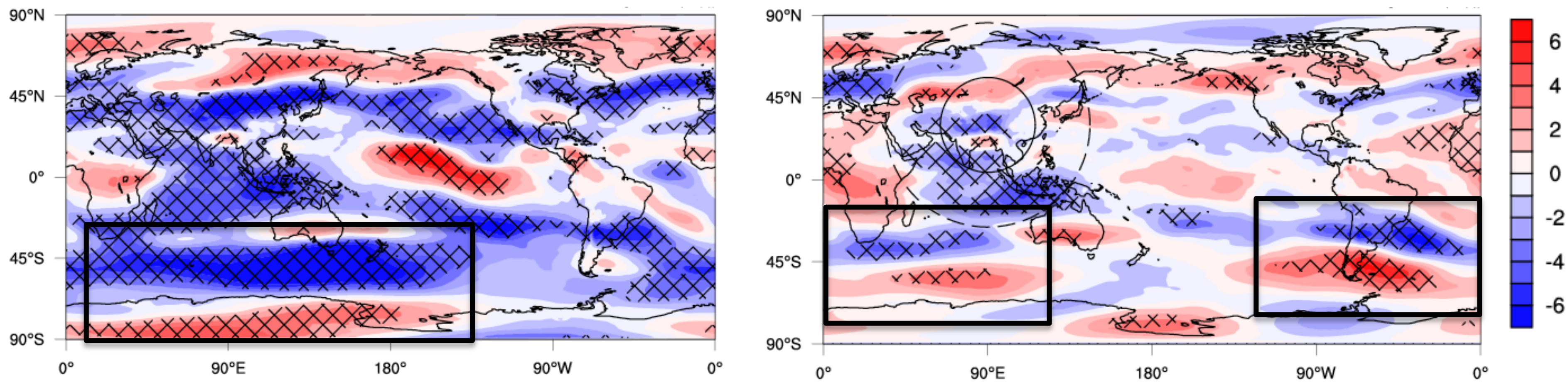
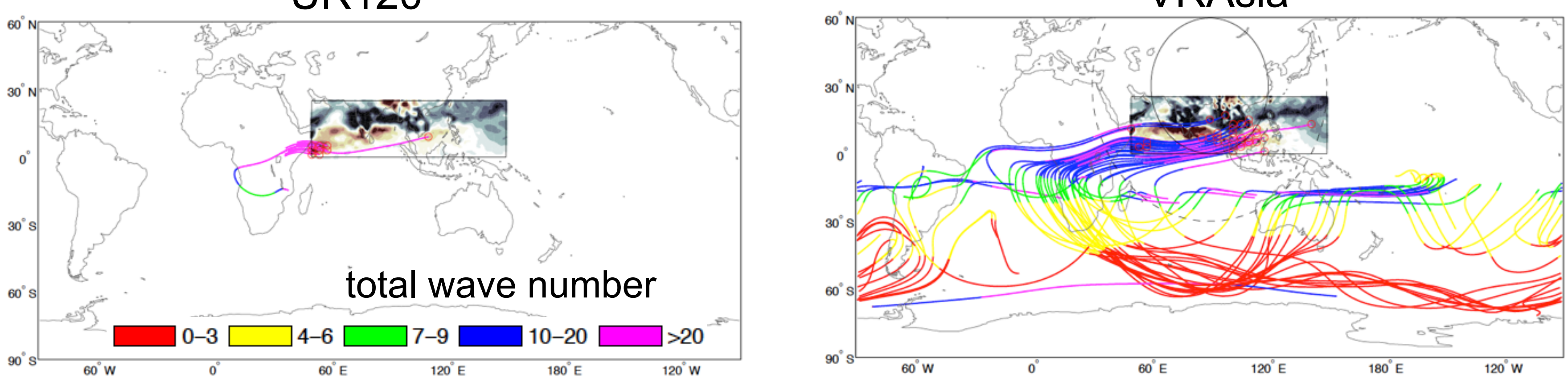
- Regional refinement has remote effects on the Southern Hemisphere jets

200 hPa winds

UR30 – UR120 VRAsia – UR120



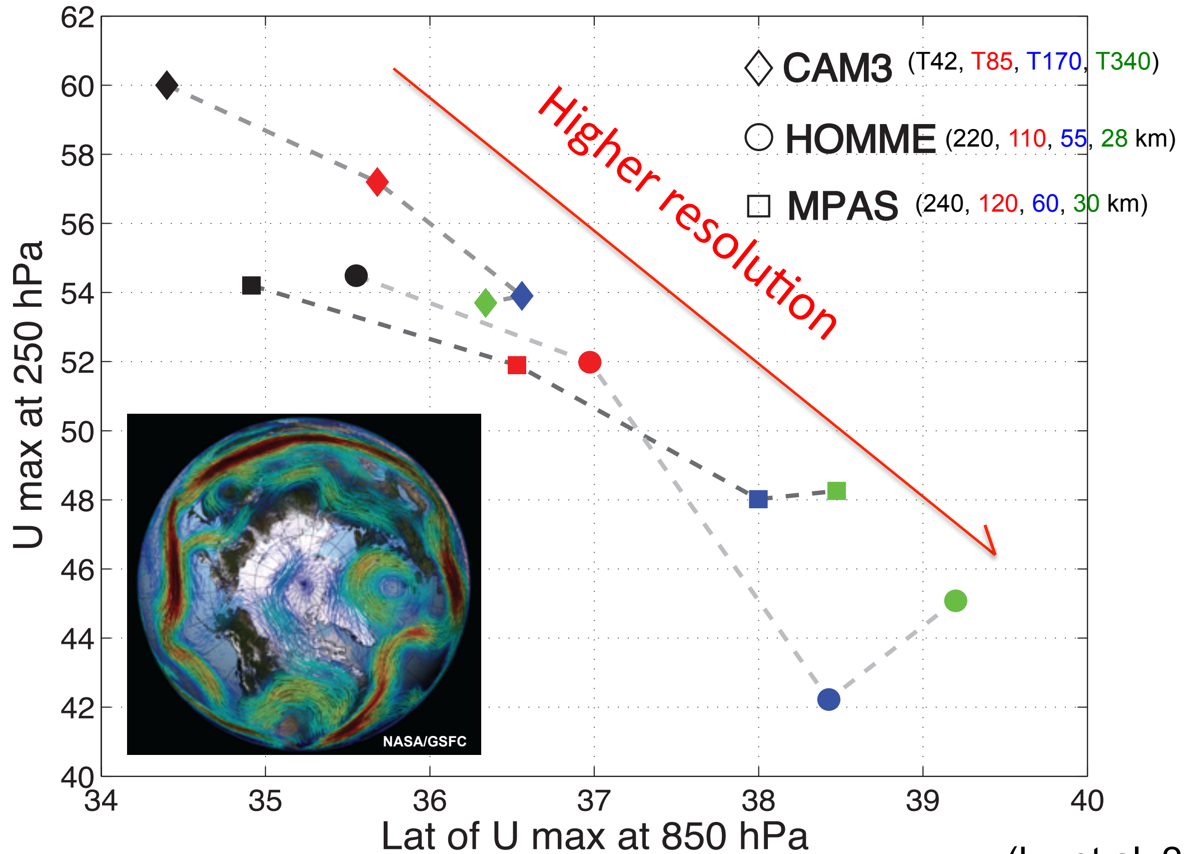
UR120 VRAsia



(Sakaguchi et al. 2016 JAMES, in review)

Dynamical convergence of the jet stream

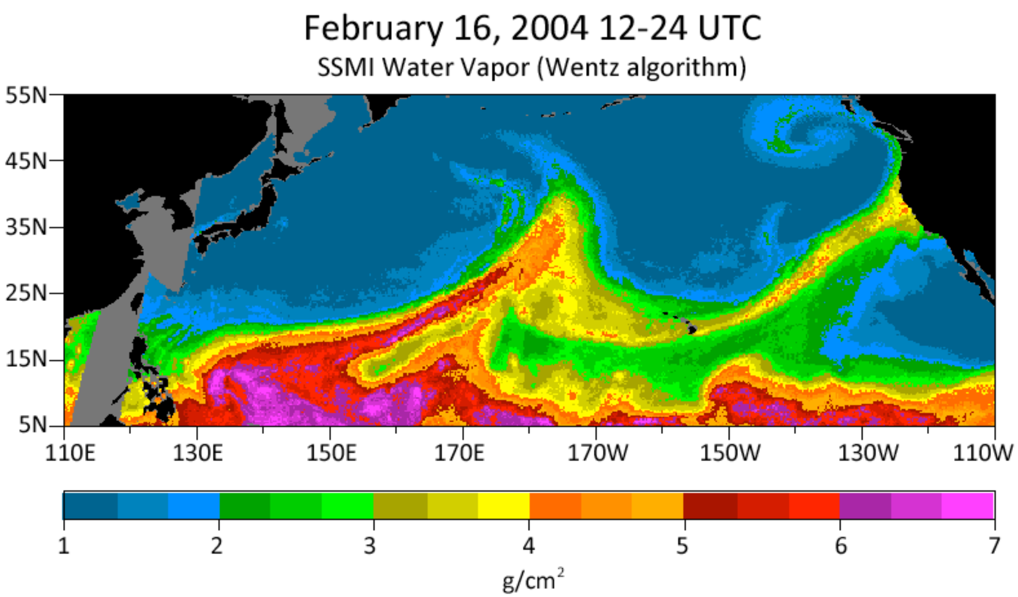
- More vigorous eddy mixing at higher resolution maintains the jet in a more poleward position
- A hint that the eddy-driven jet stream may dynamically converge at ~50km resolution ➔ storm tracks and precipitation



(Lu et al. 2015, JCLIM)

Implications for modeling atmospheric rivers

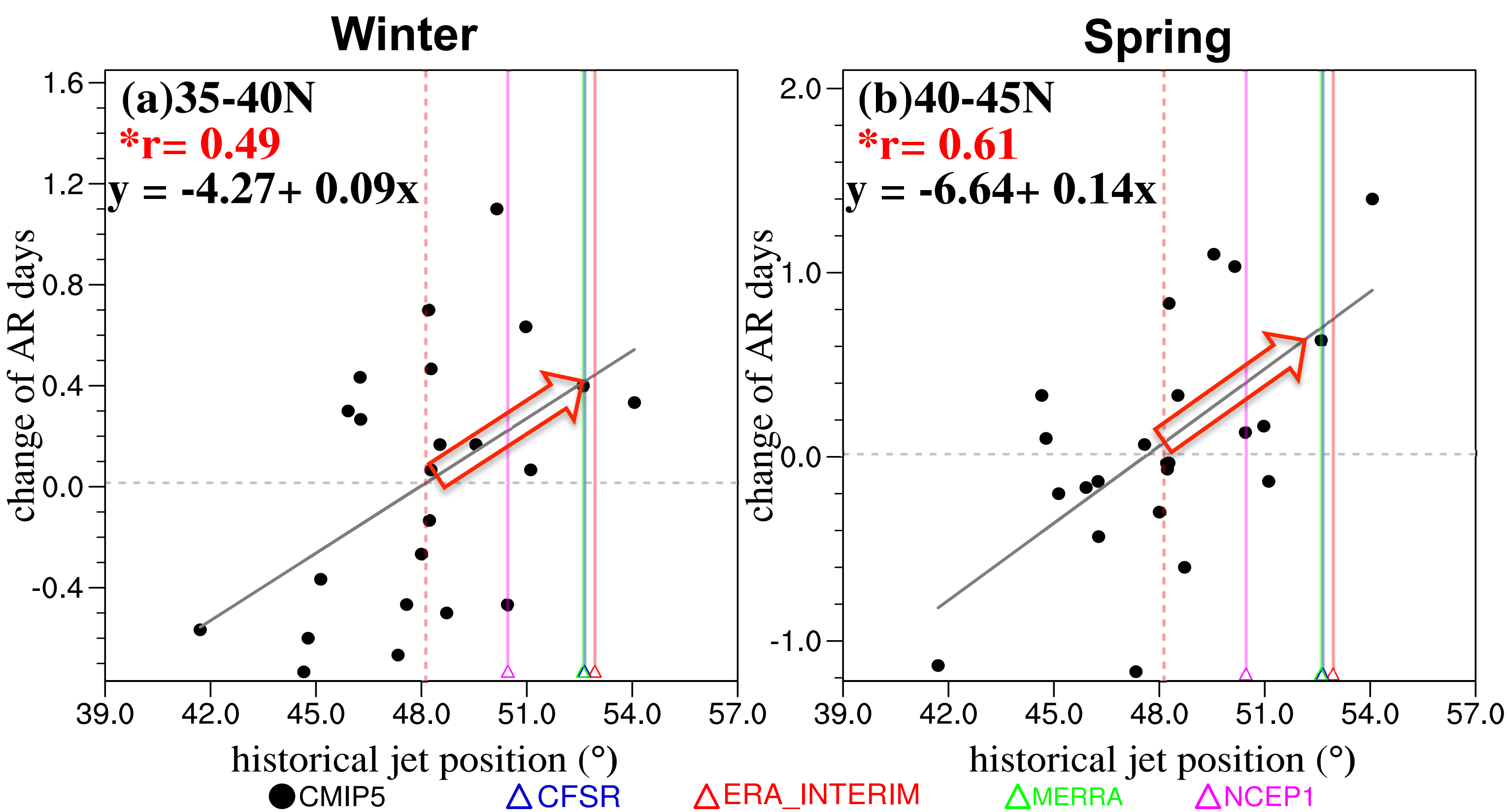
- Atmospheric rivers (ARs) are responsible for over 90% of moisture transport across the subtropical zone (Zhu and Newell 1998)
- Comparable water flux to that of the Amazon (~8x Mississippi River)
- A few ARs / year account for over 30% of annual precipitation in CA
- Contribute to most flooding events in CA and PNW, but are also drought busters (Dettinger 2014)



A landfalling AR on December 11 – 12, 2015 caused flooding in San Francisco

Jet stream ⟷ Atmospheric rivers

- Uncertainty in projecting AR frequency changes in the future is correlated with uncertainty in simulating the historical jet position



(Gao et al. 2016, JCLIM)

Variable resolution modeling in ACME

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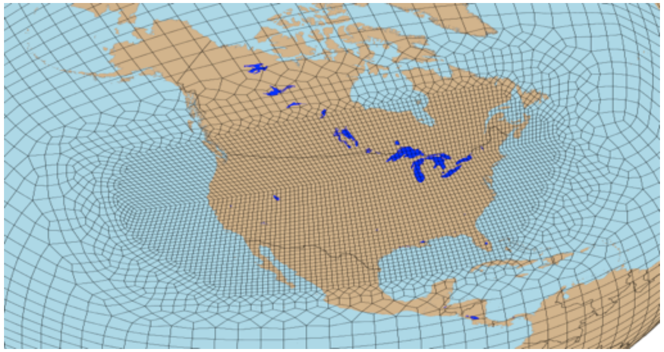
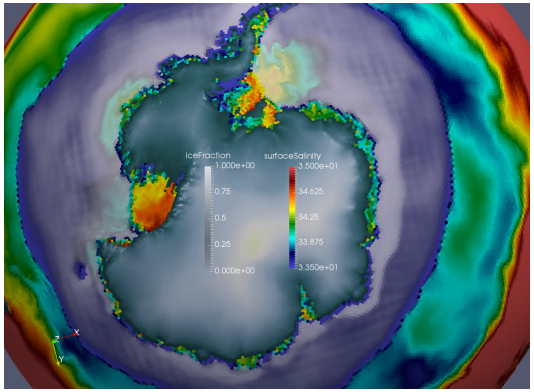
- Each component model features variable resolution modeling capability
- Potential improvements: large-scale circulation features, orographic effects
- Large ensemble simulations to be performed with regional refinement in North America

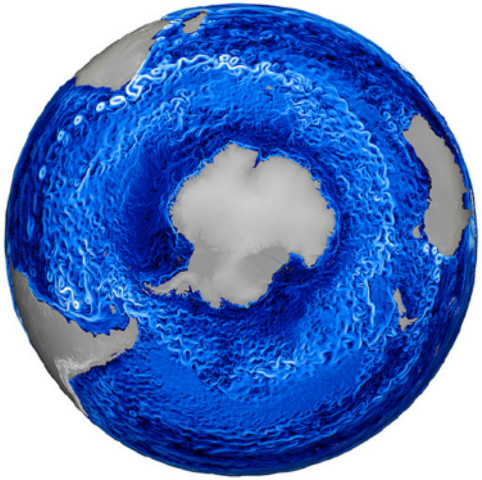
Atmosphere/Land (1° – 0.25°)



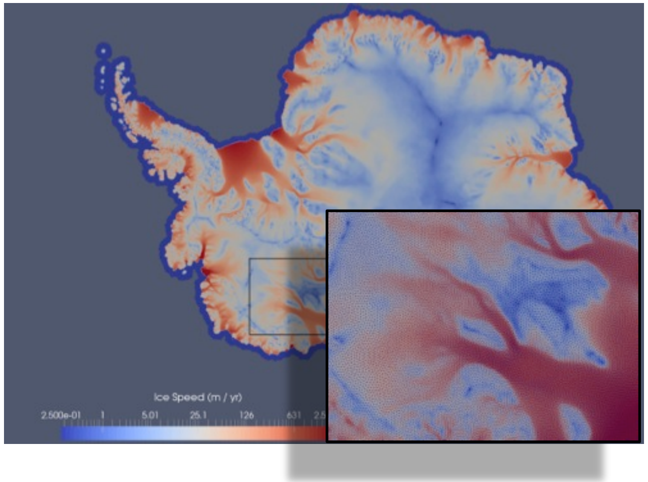
Sea Ice (60km – 5km)



Ocean (60km – 5km)



Land Ice (0.5km – 1km in regions)



Regional convection permitting simulations capture mesoscale convective system (MCS)

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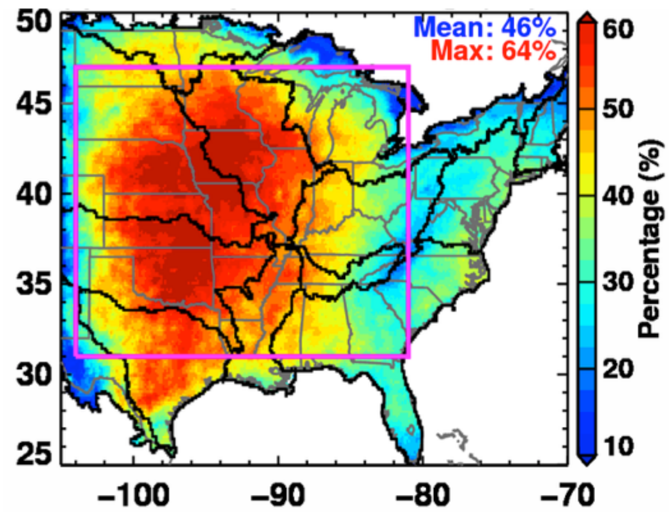
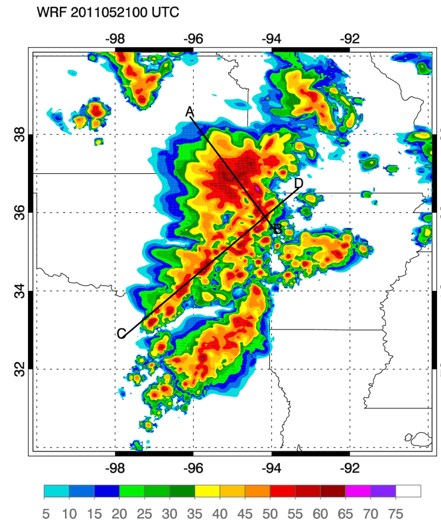
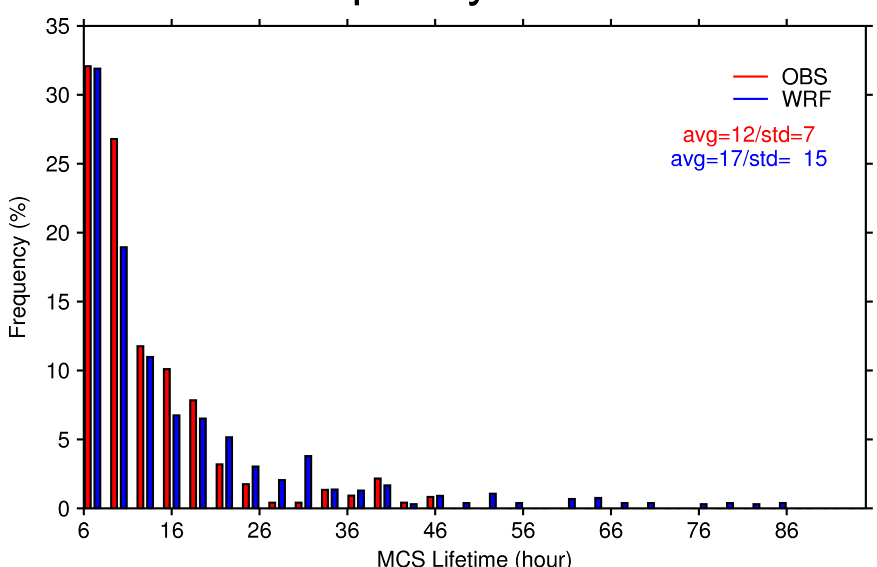
MCS accounts for up to 64% of warm-season precipitation



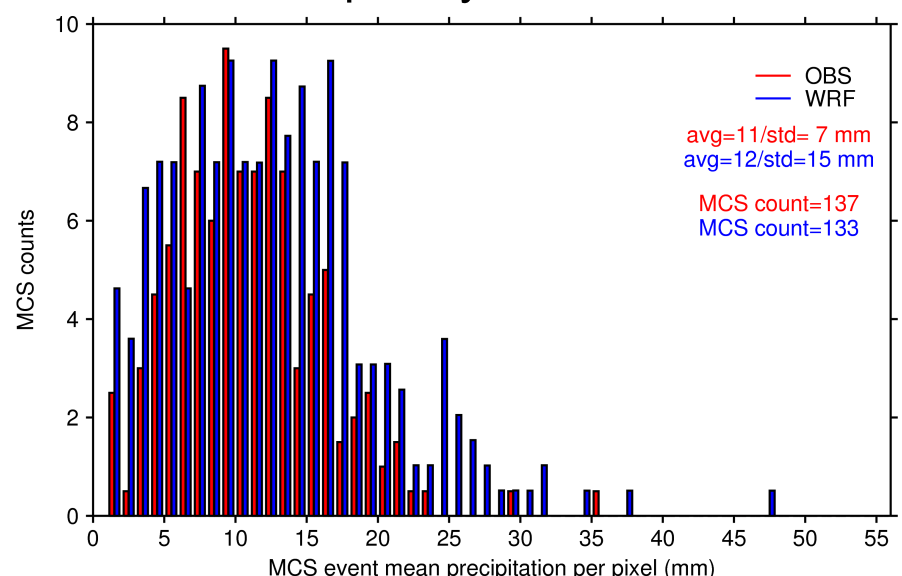
Simulation of an MCS at 4km resolution



MCS frequency vs. lifetime

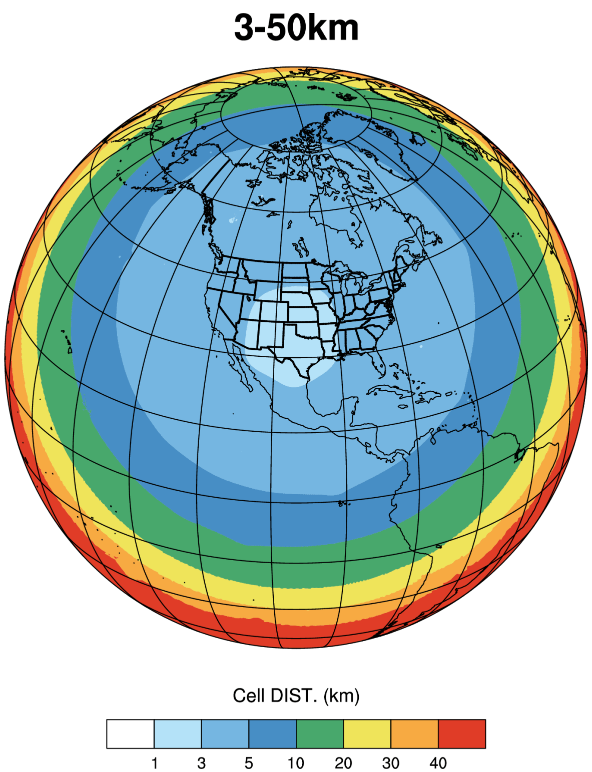


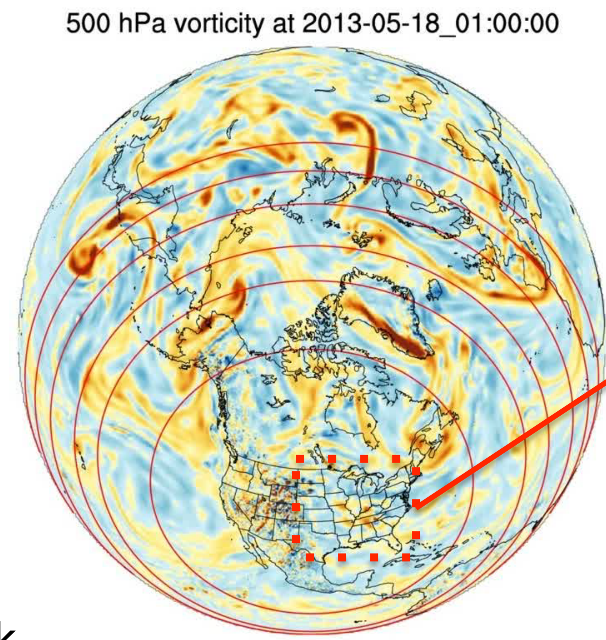
MCS frequency vs. event rainfall

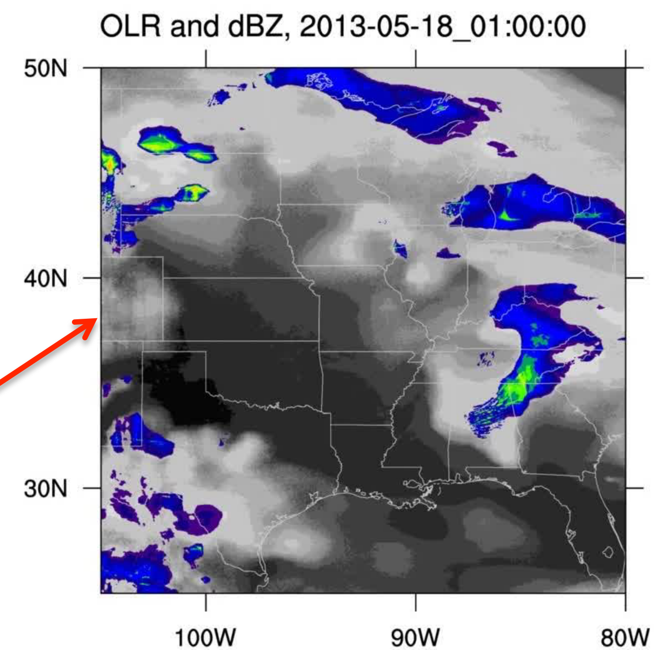


Convection permitting simulations in a global variable resolution modeling framework

- MPAS (Model for Prediction Across Scales) with WSM6 microphysics and the scale-aware Grell-Freitas convection scheme
- Variable resolution forecast for 0 UTC 18 May – 12 UTC 21 May 2013



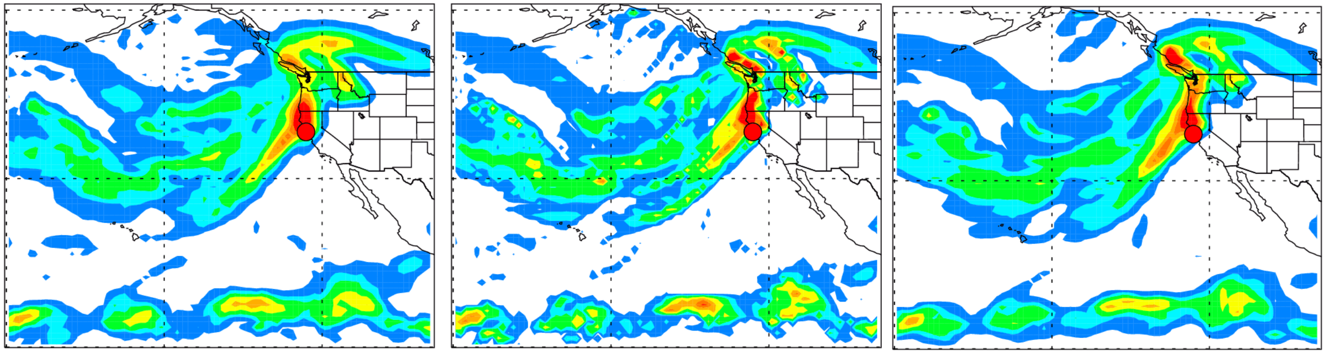


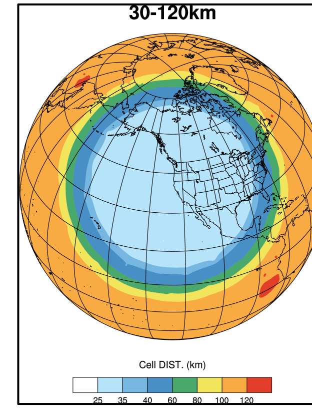


Source: Bill Skamarock

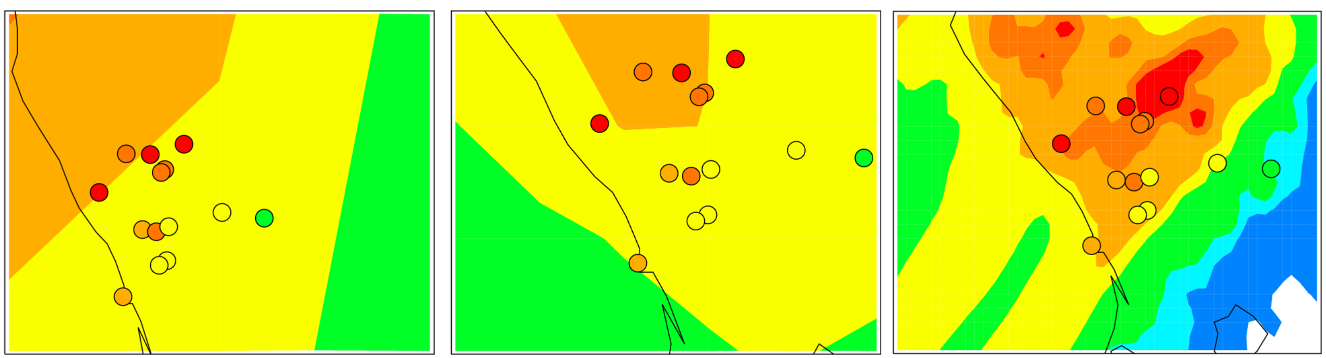
Convection permitting simulations better capture fine scale precipitation of an AR

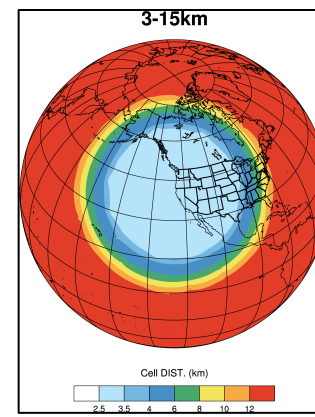
120km 30km 3km





120km 30km 3km





Approaches for high resolution modeling at lower computational cost

- Parameterization of subgrid orographic precipitation (Leung and Ghan 1998; Ghan et al. 2006)
  - Can be used in global or regional models
  - Partition flow regimes to determine orographic enhancement for a nominal number of subgrid elevation classes
- Intermediate Complexity Atmospheric Research Model (ICAR) for orographic precipitation (Gutmann et al. 2016)
  - Leverages an analytical solution for high resolution perturbations to wind velocities (from GCMs) in complex terrain
  - Simulate precipitation using numerical physics schemes
- Hybrid downscaling (Walton et al. 2015)
  - Regional climate model is used to dynamically downscale outputs from a few GCMs
  - Statistical relationships between the downscaled and GCM patterns are used to downscale other GCMs

Summary

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- What are the effects of increasing resolution?
  - Positive impacts on mid-latitude large-scale circulation features such as the jet stream, with some hints of convergence at ~ 50 km resolution
  - Simulations of jet stream have important effects on atmospheric rivers and associated heavy precipitation
  - Global variable resolution modeling has the potential for improving large-scale circulation and regional precipitation at viable computational cost
- What are the near-term prospects for ultra-high resolution climate information?
  - Regional modeling and global variable resolution modeling at convection permitting scale (~ 2 – 4 km resolution)
  - Statistical-dynamical approaches