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From diurnal variability to land-atmosphere interactions: Implications for high resolution modeling

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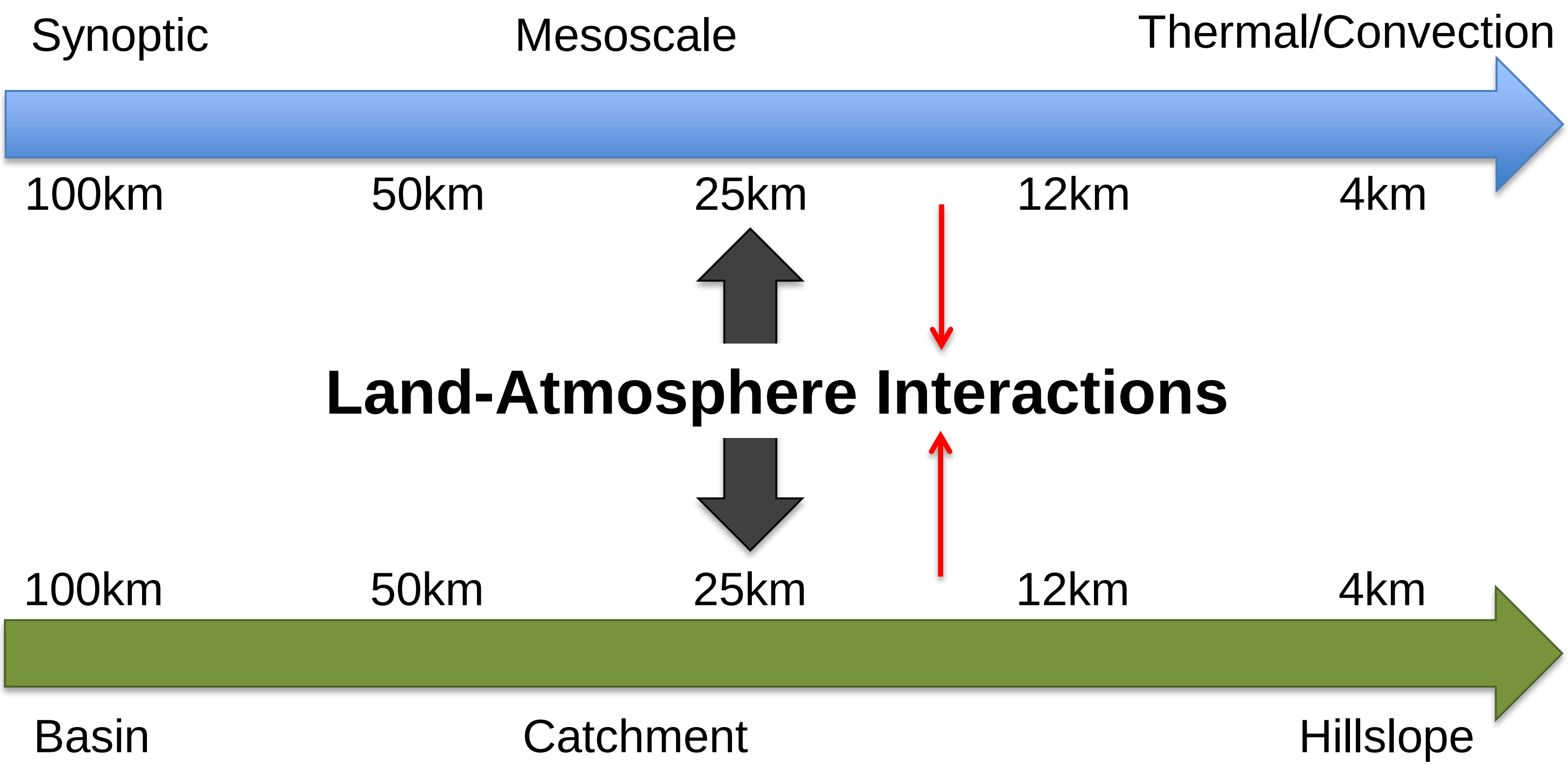
Framing the resolution challenge

Atmosphere

3D Navier Stokes equation + physical processes (e.g., moist processes, turbulence)



1D Richards equation + physical processes (e.g., topography/gravity, surface properties, lapse rates)

Land

Effects of model resolution on land processes

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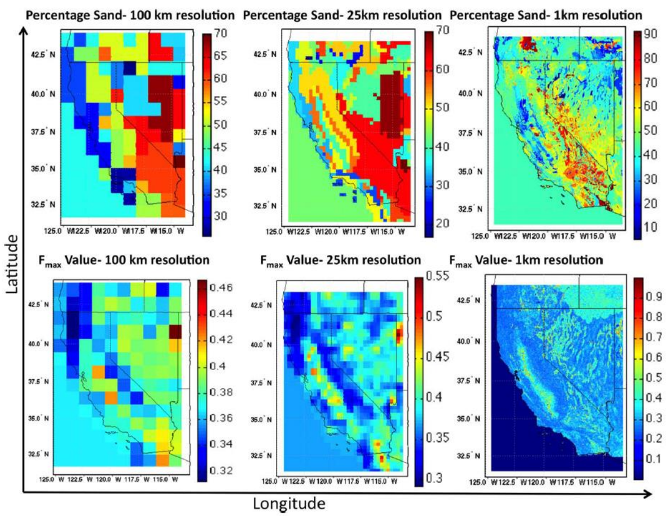
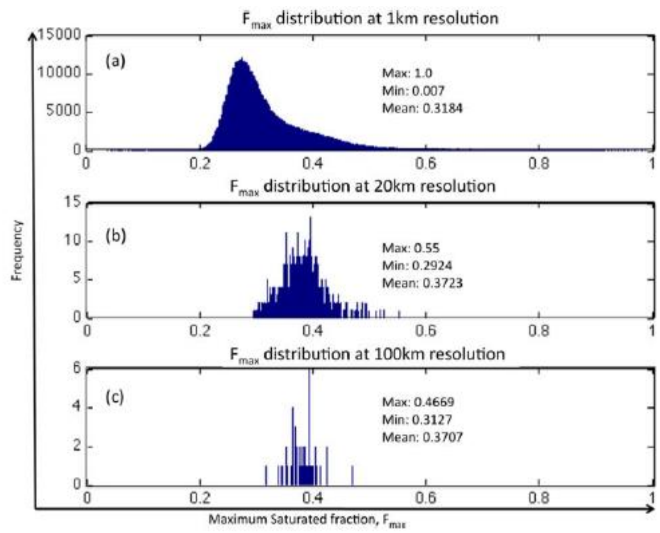
Soil texture (infiltration)



Topography (saturation fraction)



Air temperature (precipitation phase)

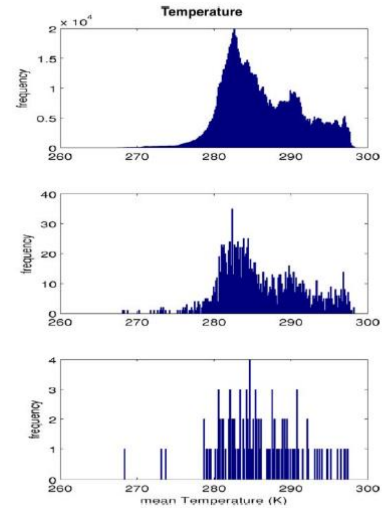


Table 3. Average Root Mean Square Error (RMSE) Between Observation Data and Model Outputs at Various Resolutions

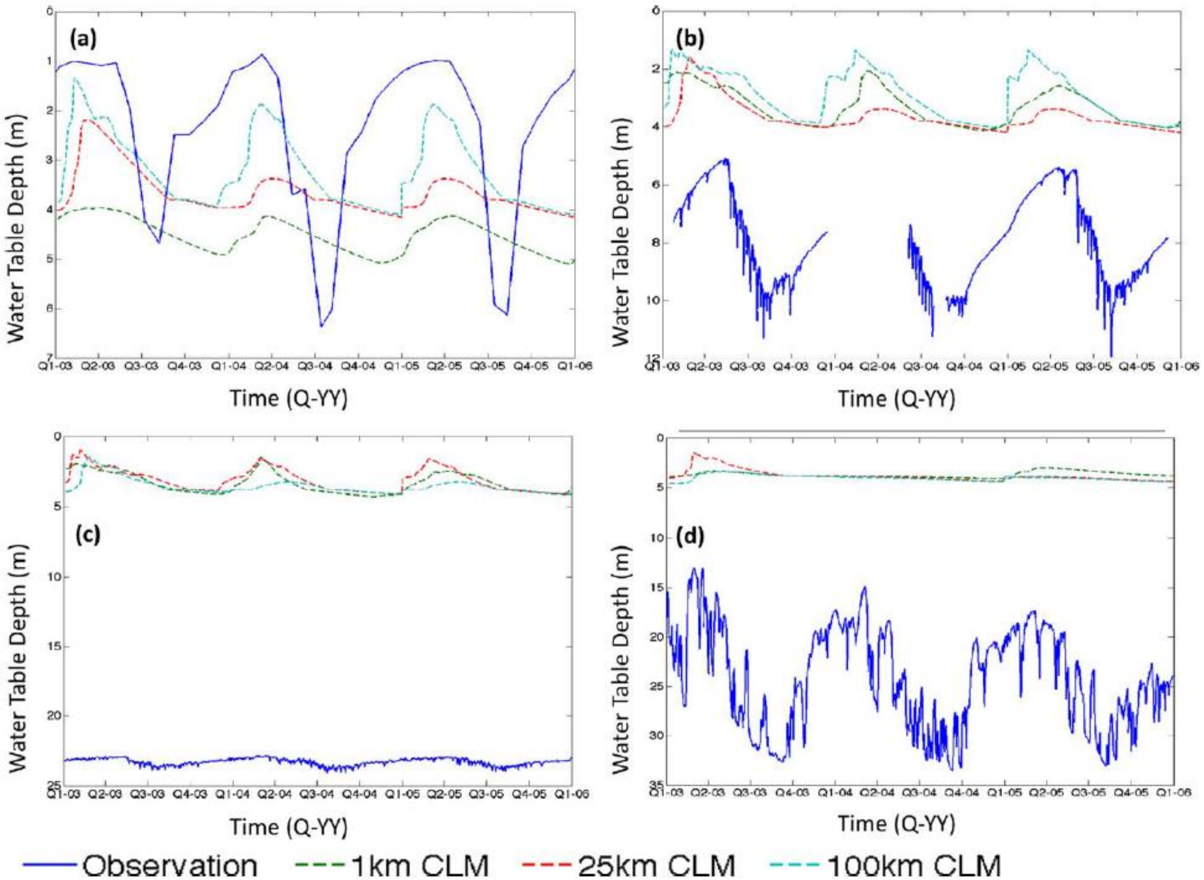
RMSE	Soil Moisture (mm^3/mm^3)	ΔTWS (mm)	Latent Heat (W/m^2)	Sensible Heat (W/m^2)	SWE (mm)
Observation-1 km CLM	0.077	214.130	22.724	20.737	0.081
Observation-25 km CLM	0.104	290.156	26.160	27.850	0.091
Observation-100 km CLM	0.100	262.589	23.356	30.093	0.117

- No systematic skill difference between 100km and 25km resolution, but lowest RMSE at 1km resolution

(Singh et al. 2015 WRR)

Not all processes are better simulated with increasing resolution

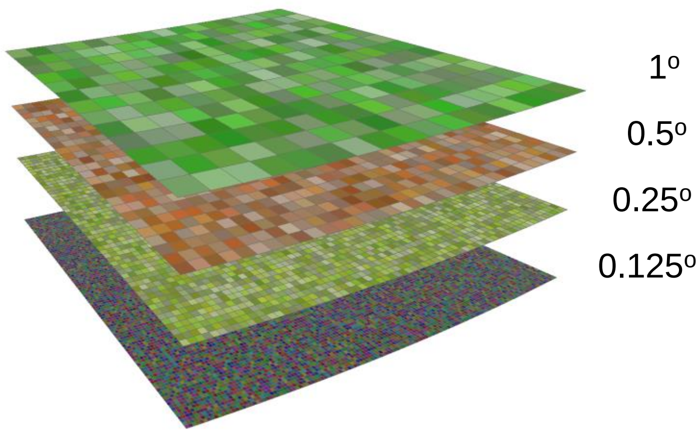
- No skill difference in groundwater table depth among resolutions due to the simple parameterization and missing processes (e.g., lateral flow)

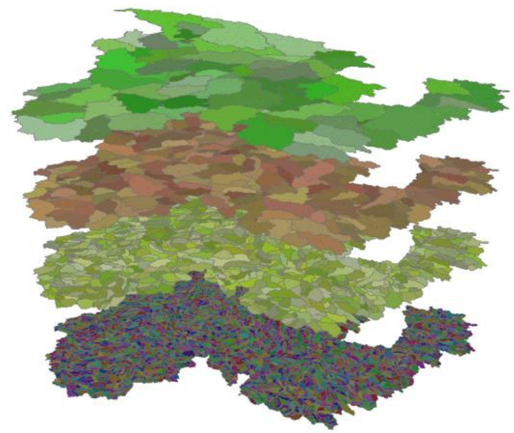


- But sensitivity of the water balance to resolution is indicative of scale variance issues due to subgrid parameterizations and/or spatial structure

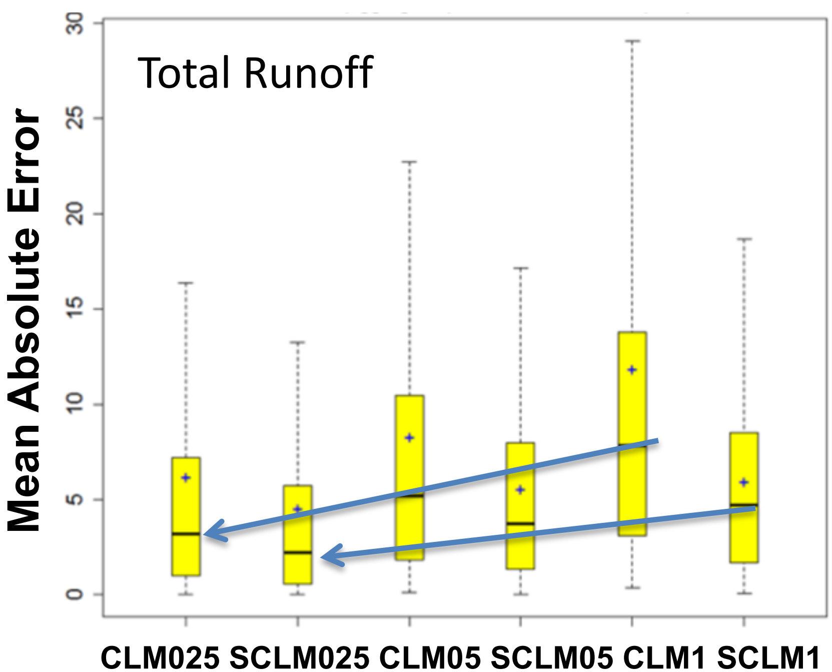
A subbasin representation can improve model scalability

Grid-based representation (CLM) **Subbasin-based representation (SCLM)**





(Tesfa et al. 2014 JGR)
(Tesfa et al. 2014 GMD)



- Simulations are less sensitive to model resolution in the subbasin representation than the grid representation
  - Rainfall / snowfall ratio
  - Topographic parameter for runoff
- Spatial structure that takes advantage of the emergent patterns and scaling properties of atmospheric, hydrologic, and vegetation processes may improve model scalability

Different shades of land-atmosphere interactions

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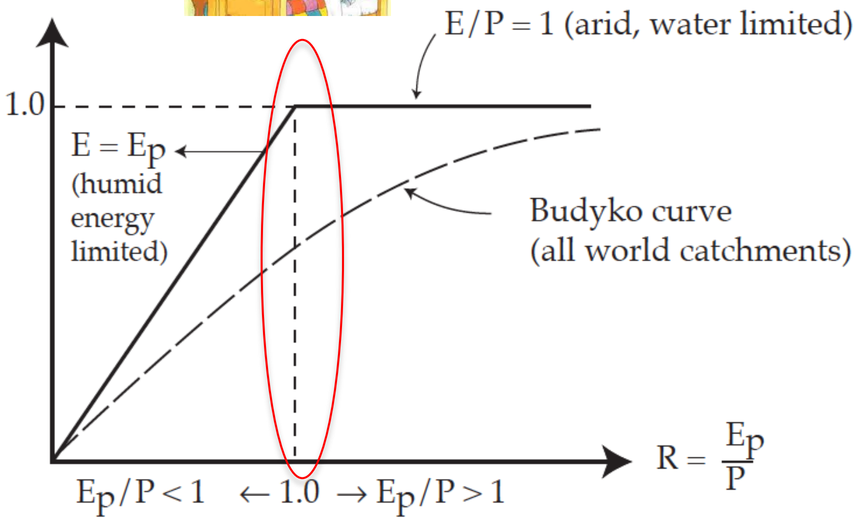
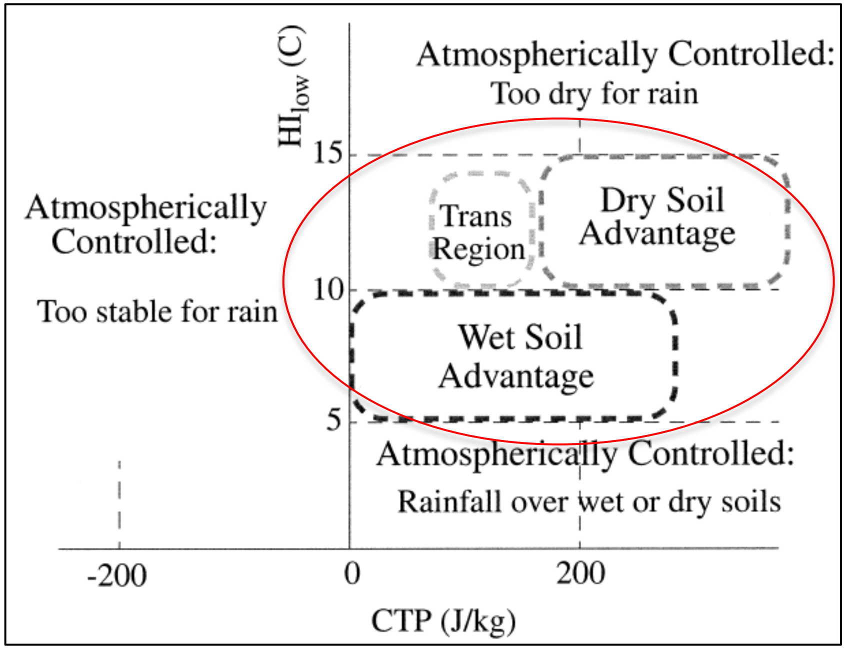
- Strength of land-atmosphere interactions (soil moisture - precipitation feedback) is different in:
  - Energy vs. moisture limited regimes
  - Atmosphere vs. land controlled precipitation regimes



Climate Aridity



(Findell and Eltahir 2003 JHM)

Dynamical convergence: local precipitation recycling

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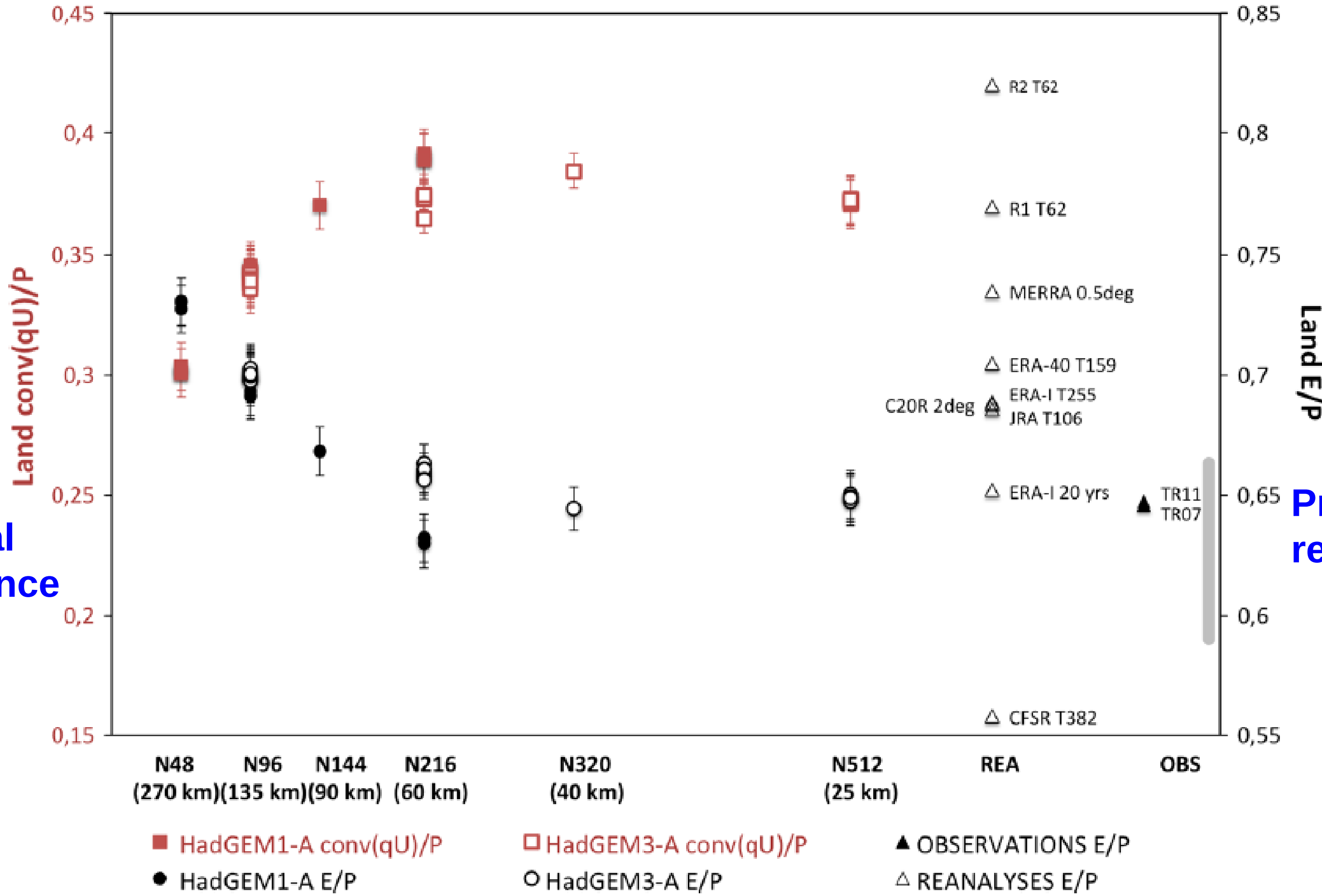
- Decreasing E/P over land with resolution and convergence at ~50km resolution

Dynamical convergence

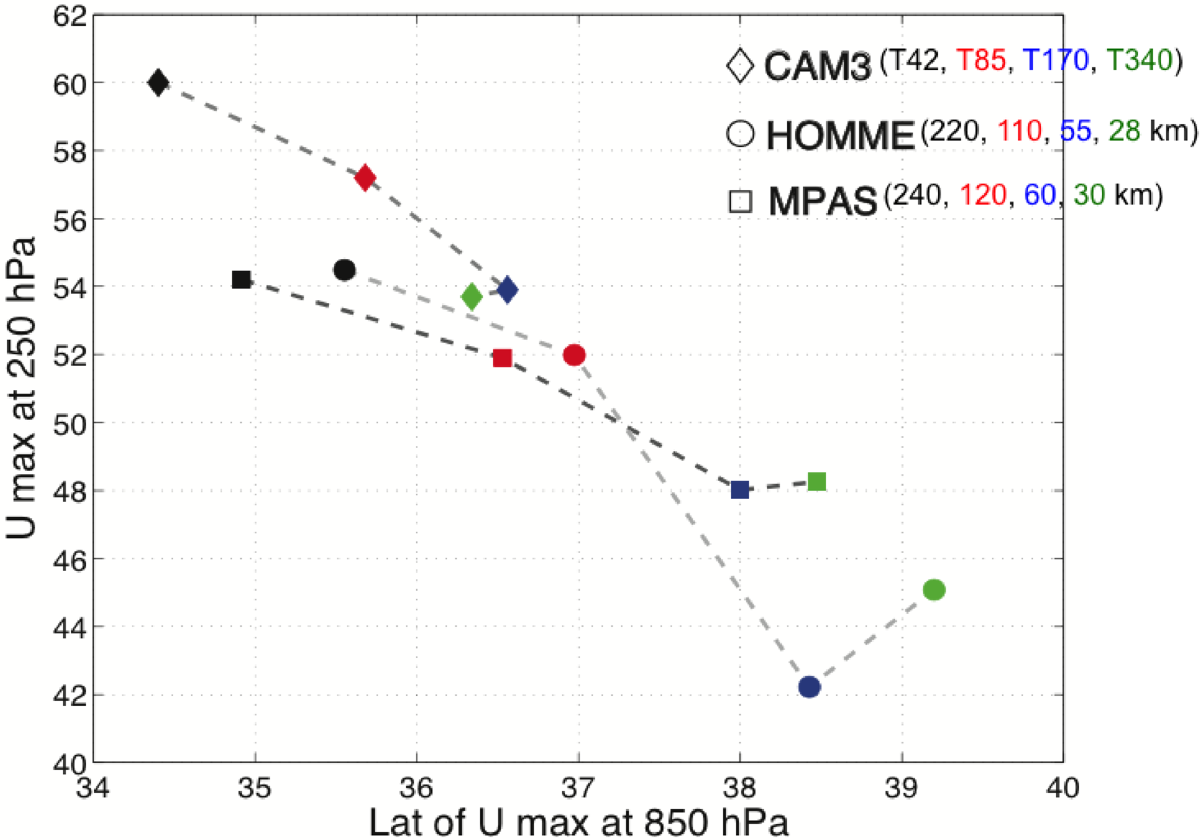


Precipitation recycling

(Demory et al. 2014 CD)

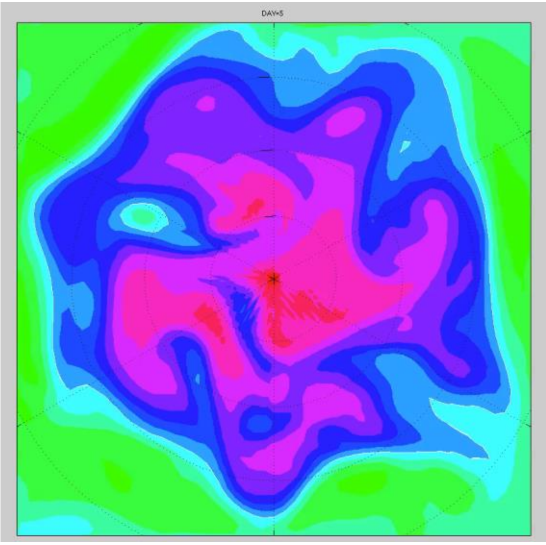
Dynamical convergence: eddy-driven jet

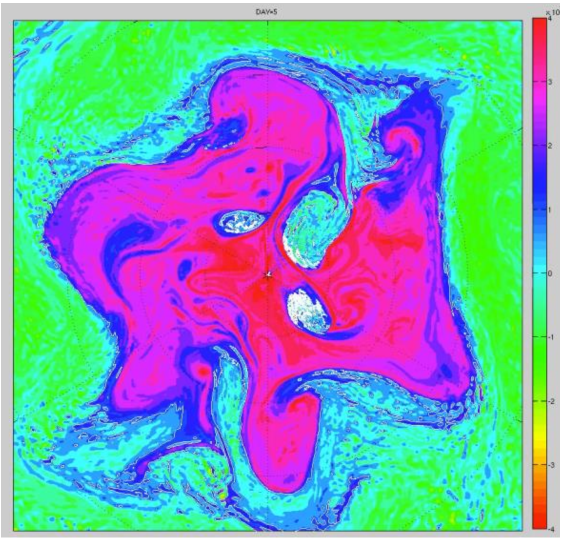
- Eddy-driven jet stream dynamically converged at ~50km resolution ➔ atmospheric rivers that transport moisture from ocean to land
- Model diffusivity approaches the asymptotic effective diffusivity of the Batchelor turbulence



(Lu et al. 2015 JC)

PV





Land-atmosphere feedback changes sign in convection permitting simulations

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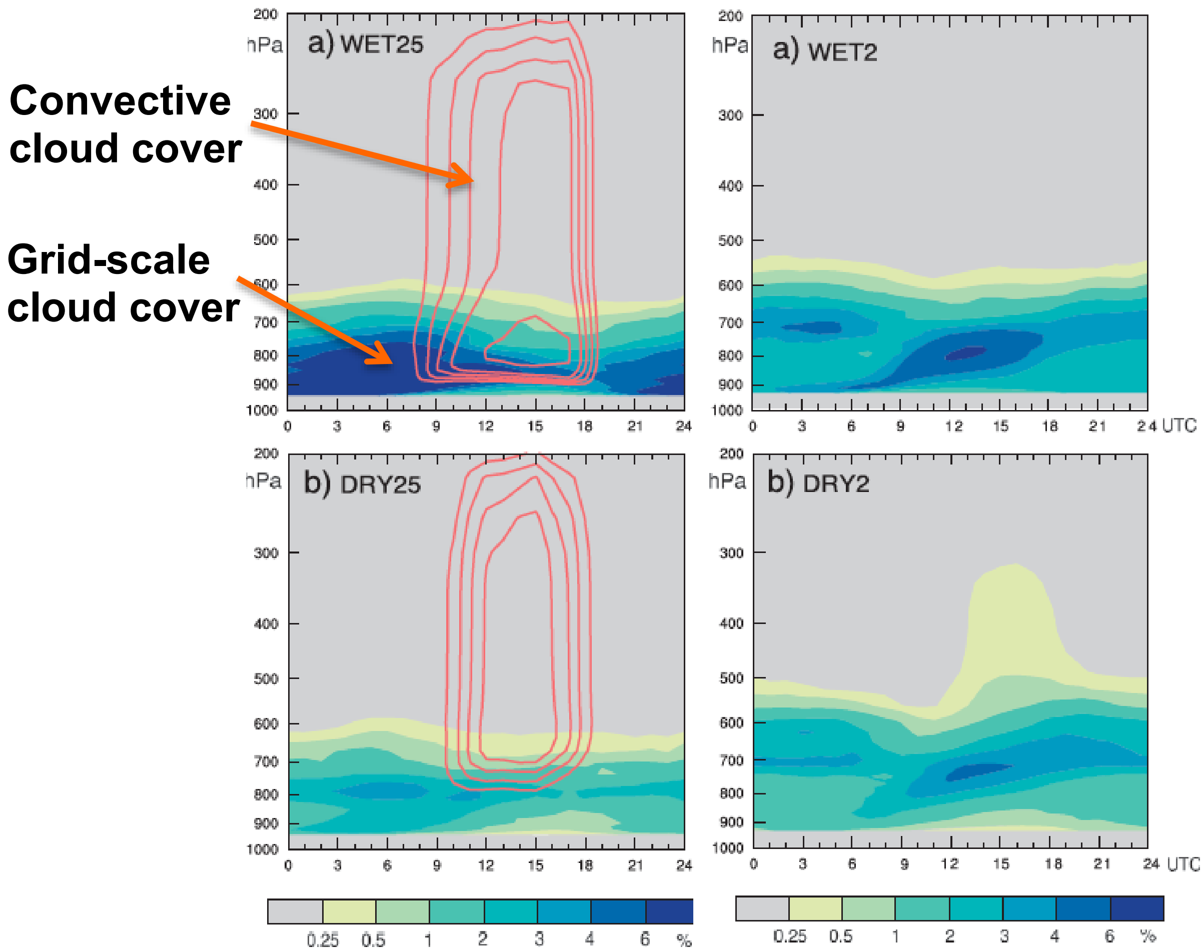
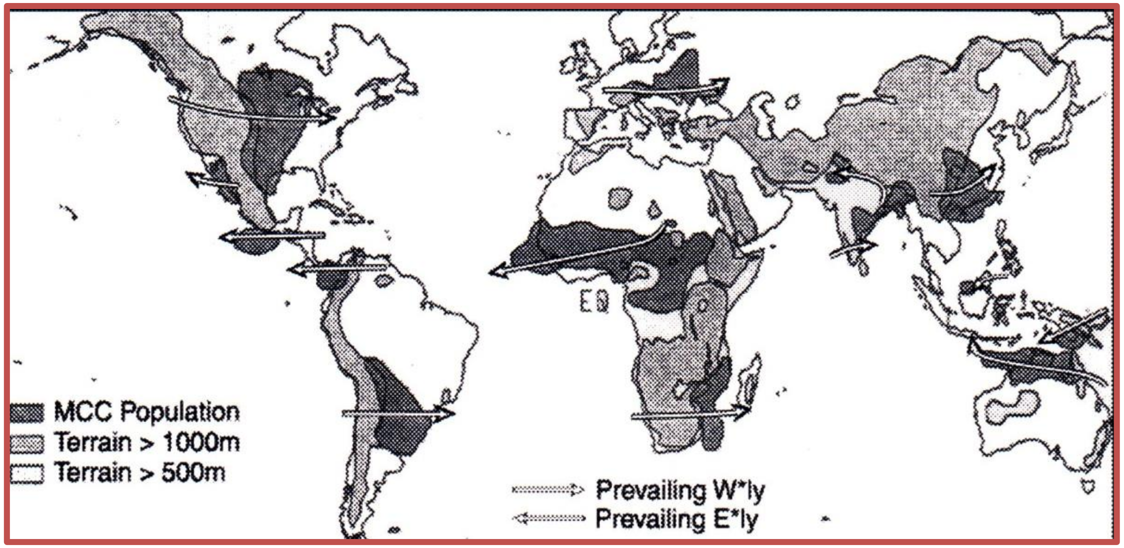
- Clouds transition from shallow to deep in the 2 km resolution simulation under dry condition. At 25 km resolution, parameterized convection is triggered over both wet and dry soils



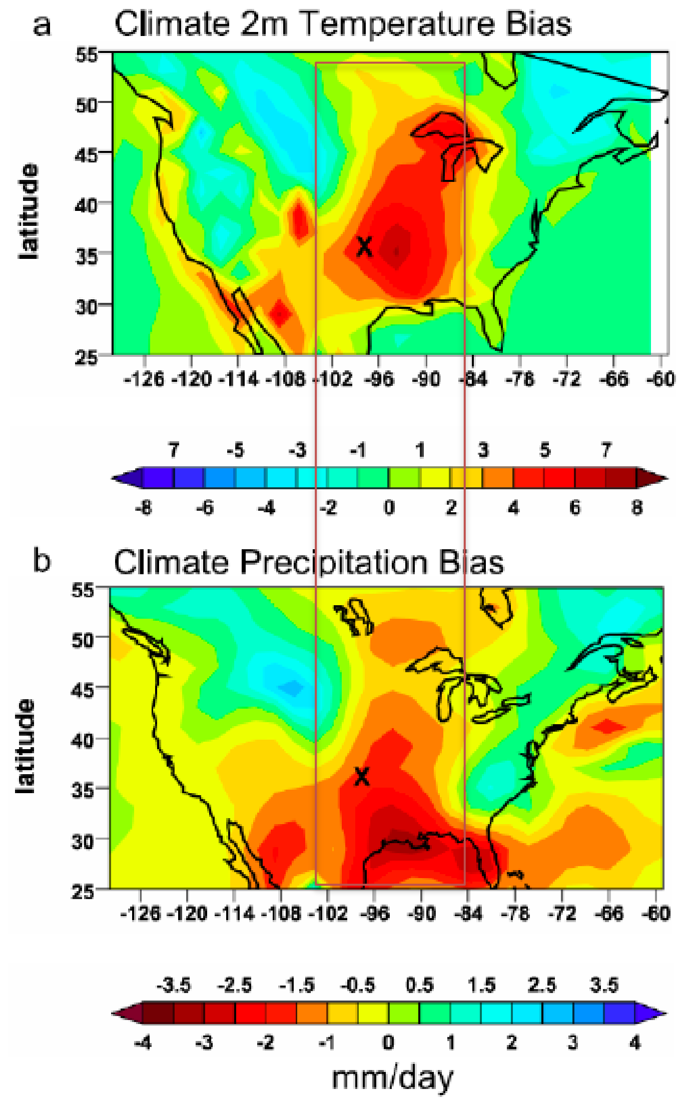
(Hohenegger et al. 2009 JCLIM)

Mesoscale organized convection may represent an even bigger challenge



(Laing and Fritsch 1997 QJRMS)

(Klein et al. 2006 GRL)



- Mesoscale organized convection is a ubiquitous mechanism for generating large rain amounts in many regions worldwide
- Model limitations in simulating convection are linked to biases in diurnal cycle of rainfall, surface temperature, land-atmosphere interactions, etc.

Testing a scale-aware convective parameterization

Scale-aware parameterization (Grell and Freitas, 2014, ACP)

- Stochastic approach from Grell and Devenyi, 2002.

- Scale aware by adapting the Arakawa et al approach (2011).
  - Arakawa et al (2011): developed a relation between vertical convective eddy transport and convective updraft/downdraft fraction s:

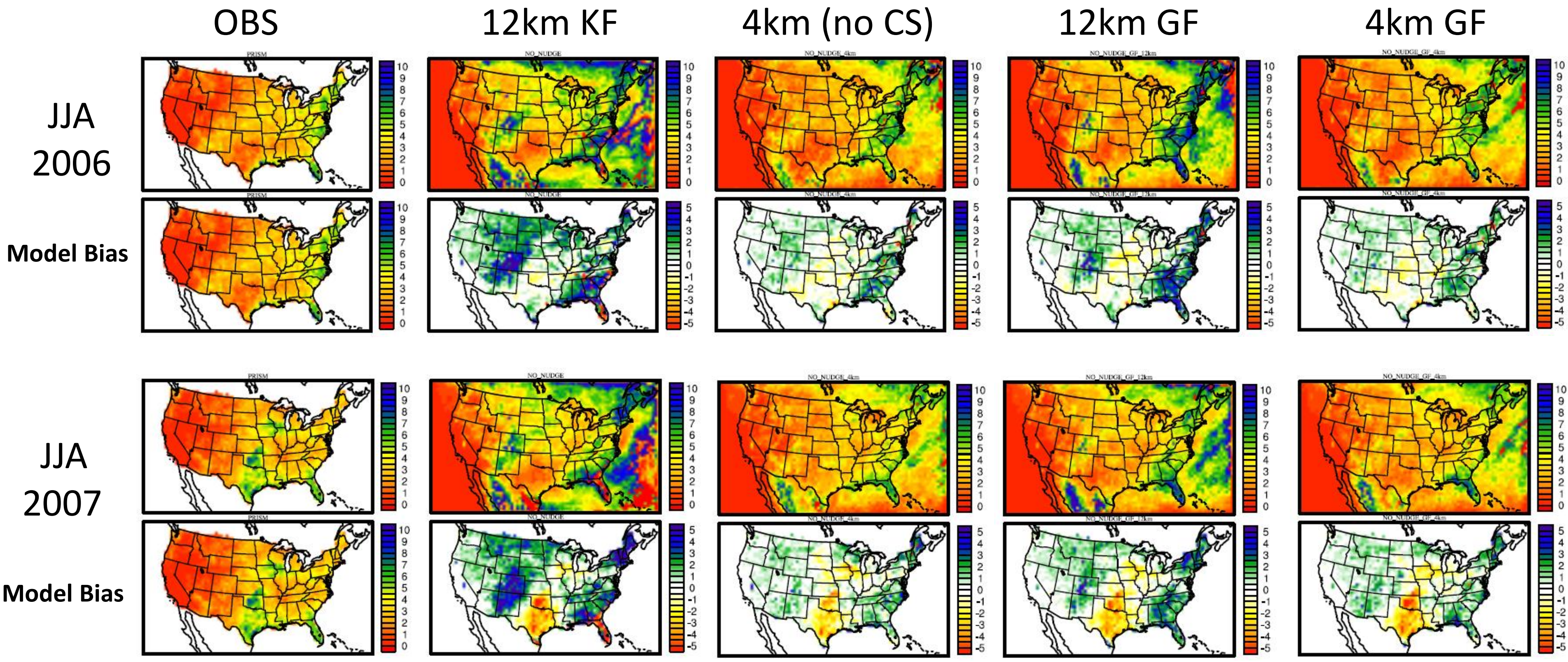
$$\rho\overline{w\psi} = (1-\sigma)^2 M_c(\psi_c - \bar{\psi}) \quad \text{with} \quad M_c \equiv \rho\sigma w_c$$

  - GF: σ is the area covered by active updraft and downdraft plume.
  - GF closure uses a simple relationship between σ and the entrainment rate (related to radius of plume).

- Transitions to precipitating shallow scheme as grid spacing decreases.
  - At very high resolution (dx < 3km) parameterized convection becomes much shallower – cloud tops near 800 mb (down from 200-300 mb).
  - Temperature & moisture tendencies decrease as resolution increases.

Effects of model resolution on summer precipitation

- Smaller JJA mean precipitation bias at 4 km than 12 km
- Smaller sensitivity to resolution using the GF scale-aware parameterization



Diurnal precipitation in the Great Plains

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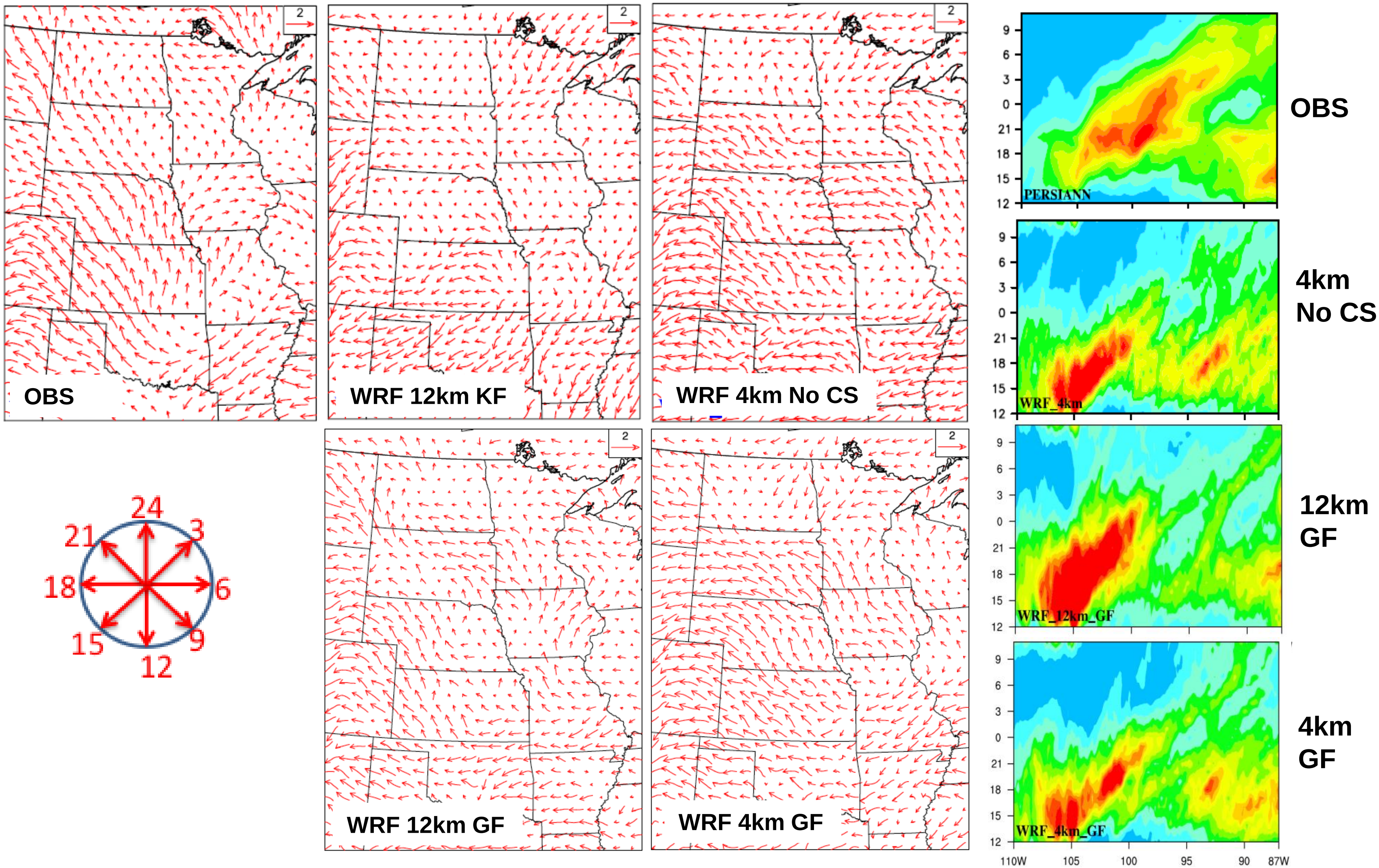
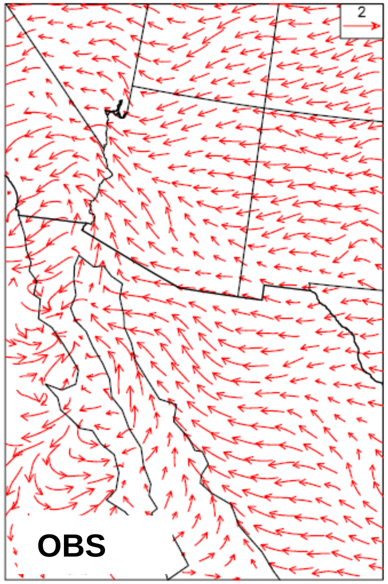
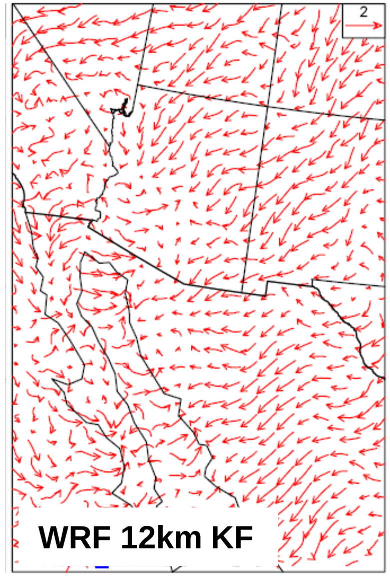
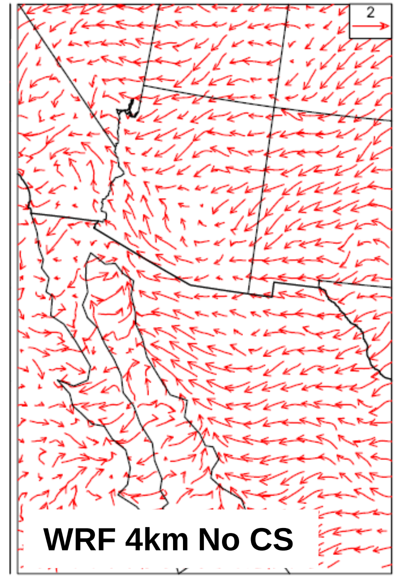
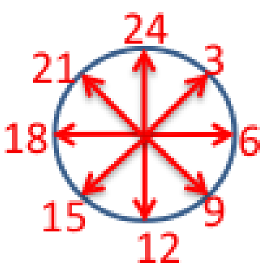


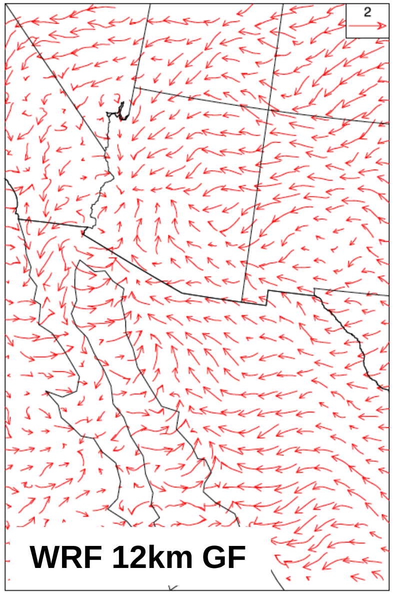
Diurnal precipitation in monsoon region

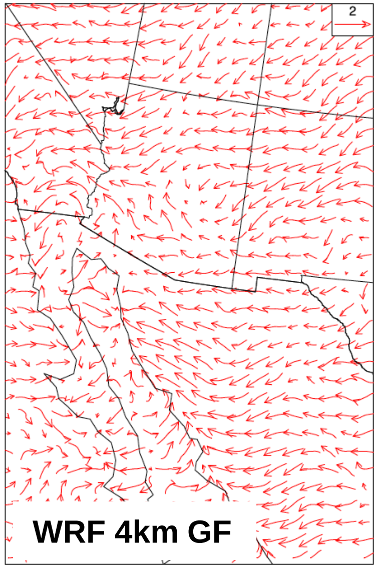






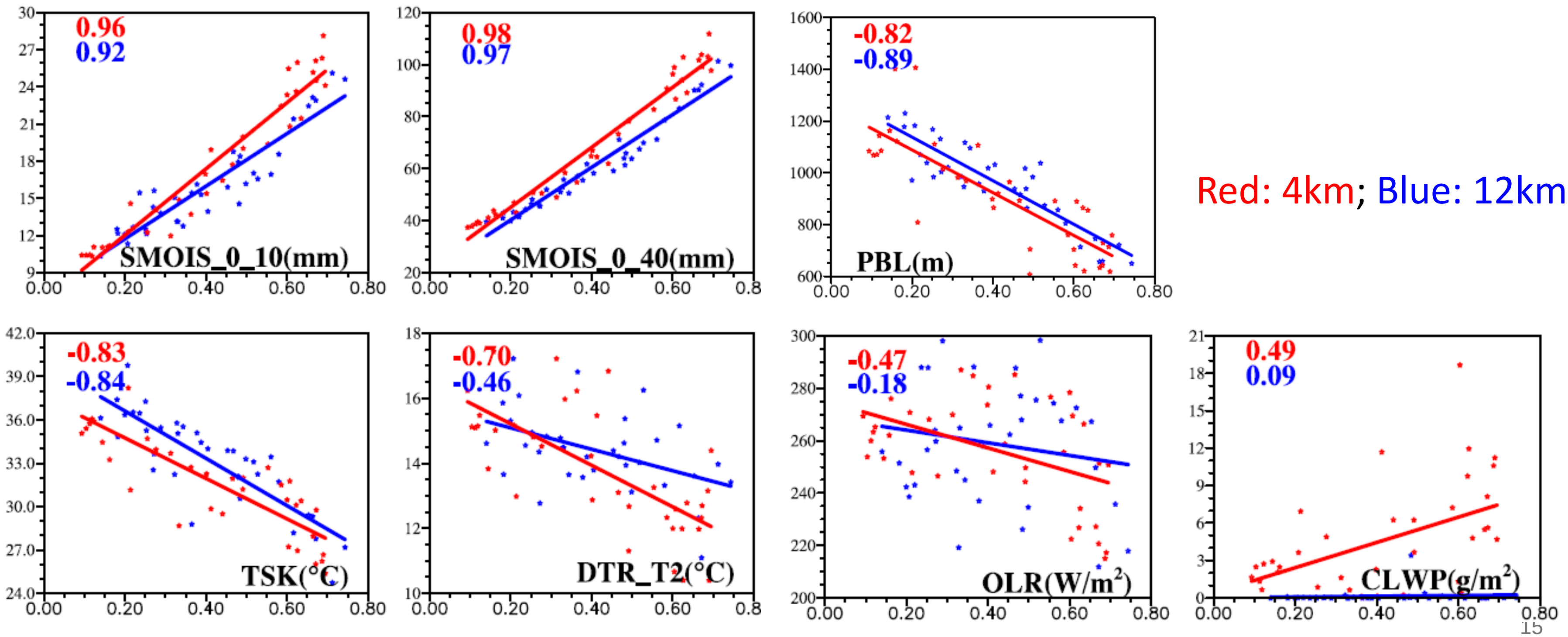






Land-atmosphere coupling strength

- Changing soil moisture alters the partitioning of SH and LH (EF = LH / (SH + LH))
- Changing EF alters PBL height, cloud top height, cloud water content, and temperature
- Stronger relationships or coupling at 4 km than 12 km resolutions



GF reduces coupling strength sensitivity to resolution

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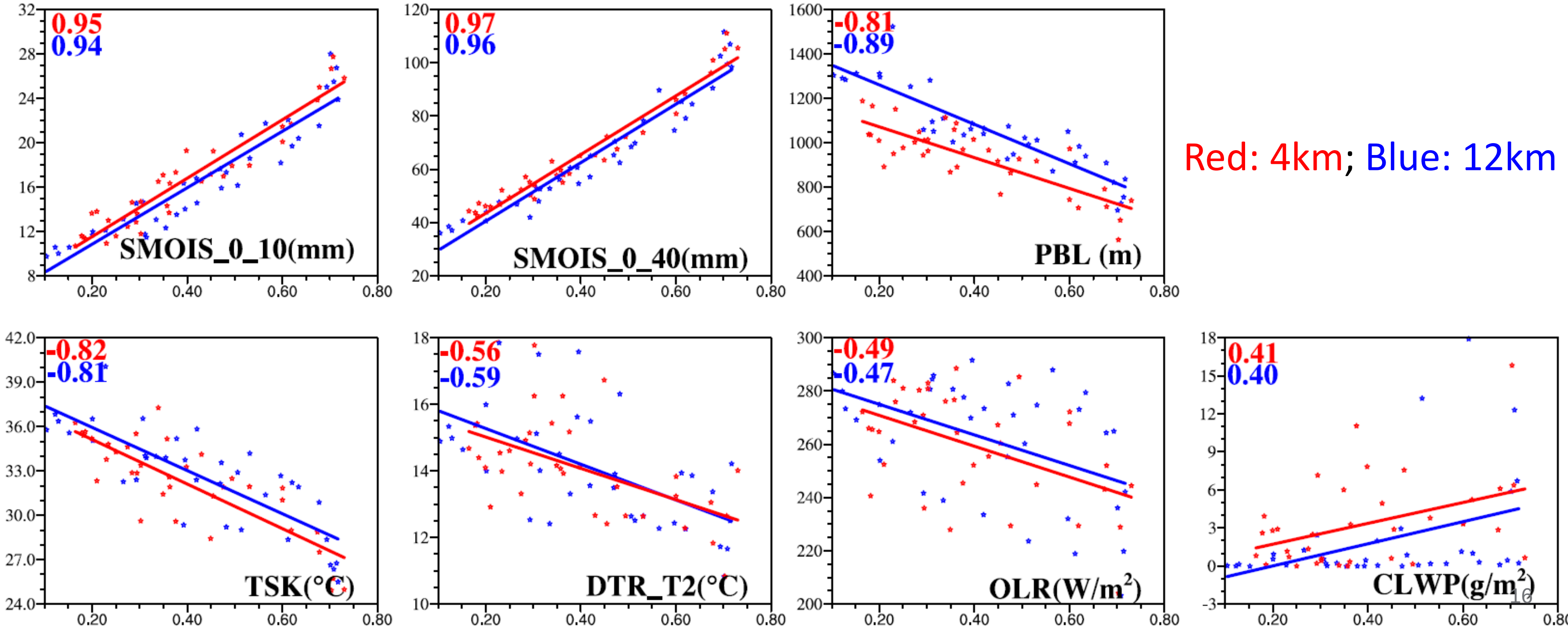
- Slightly more comparable coupling strength between 4 km and 12 km when the scale-aware cumulus (GF) scheme is used



Red: 4km; Blue: 12km

Afternoon rainfall occurs preferentially over dry soil

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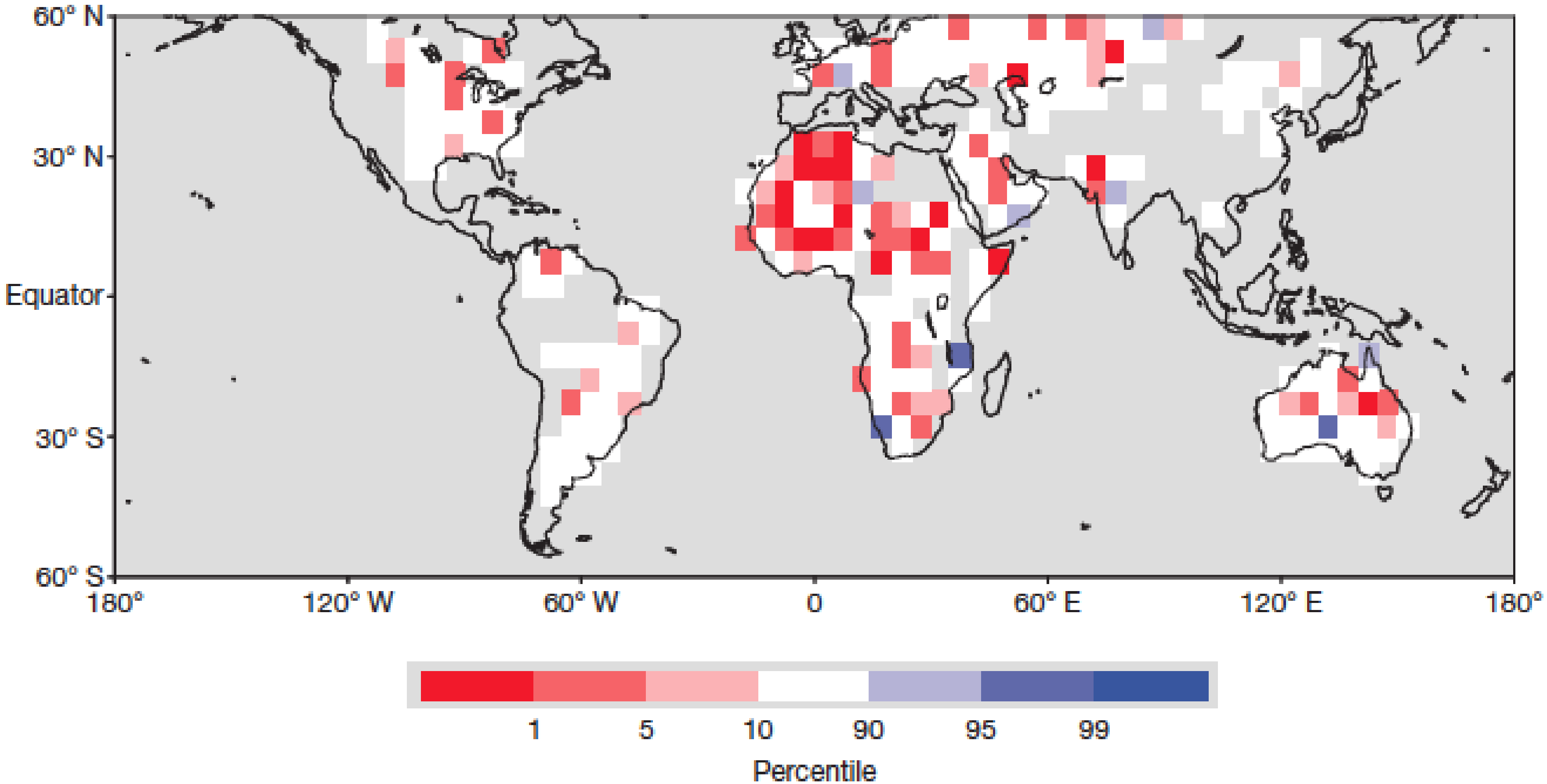
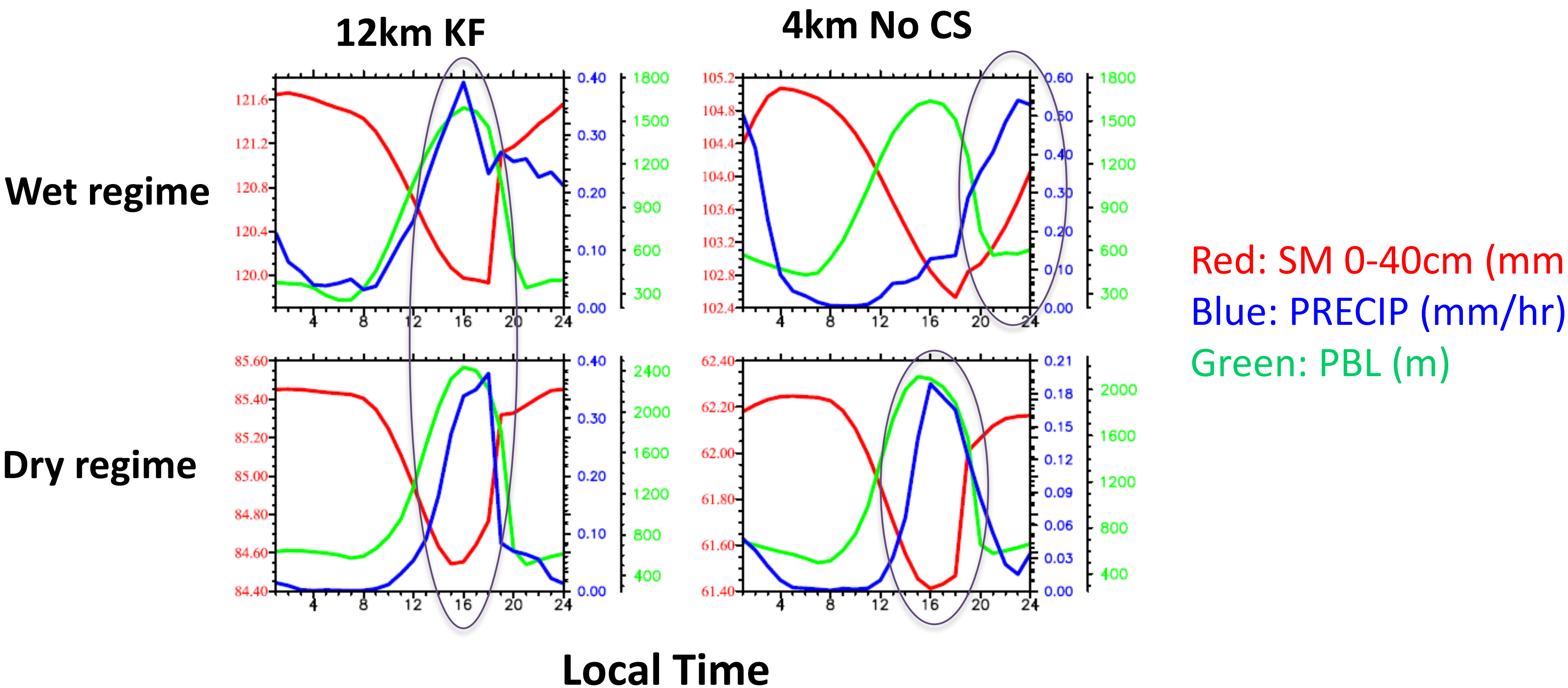
- Soil moisture from ASCAT and AMSR-E; precip from CMORPH
- Areas over mountains and tropical forest are excluded



Taylor et al. 2012 Nature

Diurnal differences in wet vs dry regimes



- Rainfall peaks in afternoon in both wet and dry regimes at 12km resolution
- Rainfall peaks in afternoon in dry regime and at night in wet regime at 4km resolution

Convection Permitting Simulations in a Global Variable Resolution Modeling Framework

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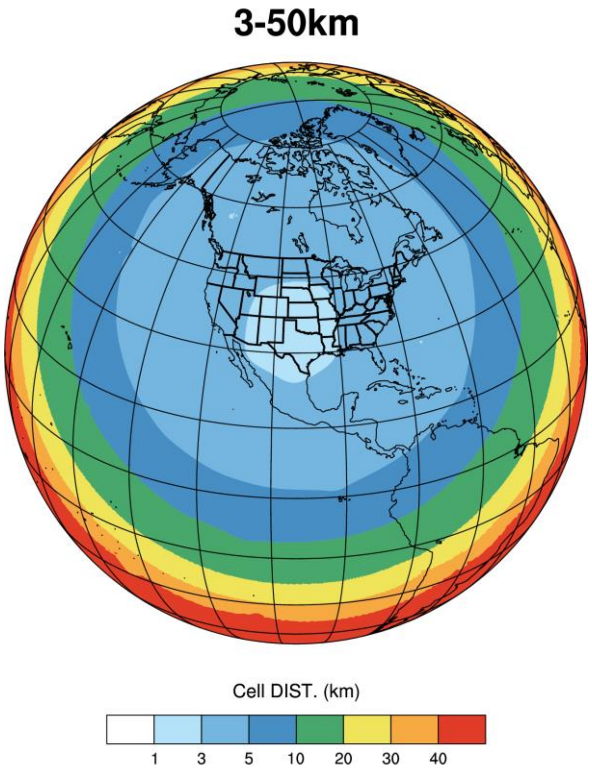
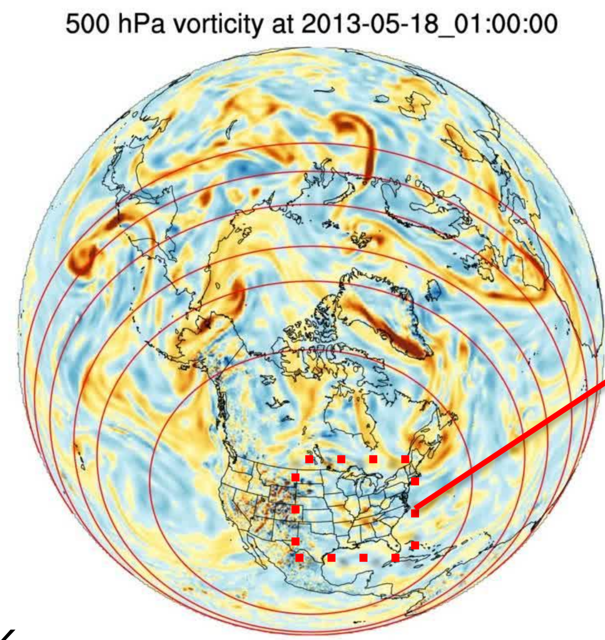
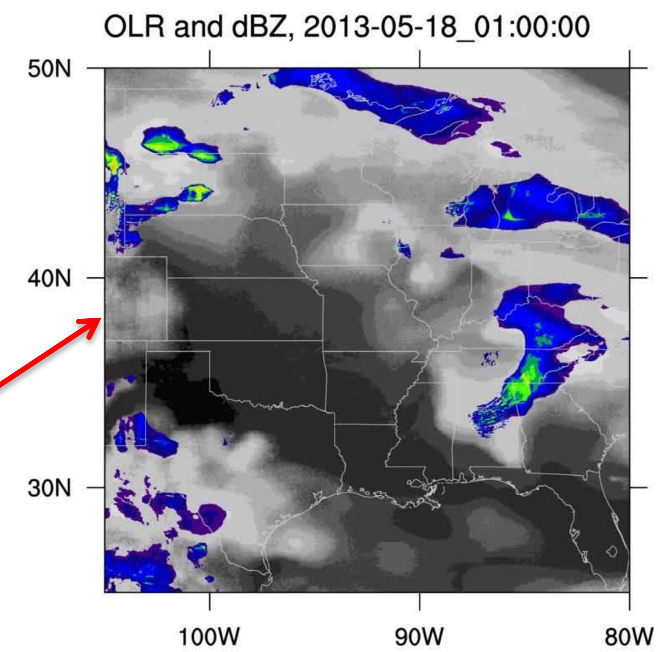
- MPAS (Model for Prediction Across Scales) with WSM6 microphysics and the scale-aware Grell-Freitas convection scheme
- Variable resolution forecast for 0 UTC 18 May – 12 UTC 21 May 2013







Source: Bill Skamarock

Partitioning between convective and resolved precipitation

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MPAS 50-3 km mesh,
Grell-Freitas convection scheme
3 day 12h forecast valid at
2013-05-21_12:00

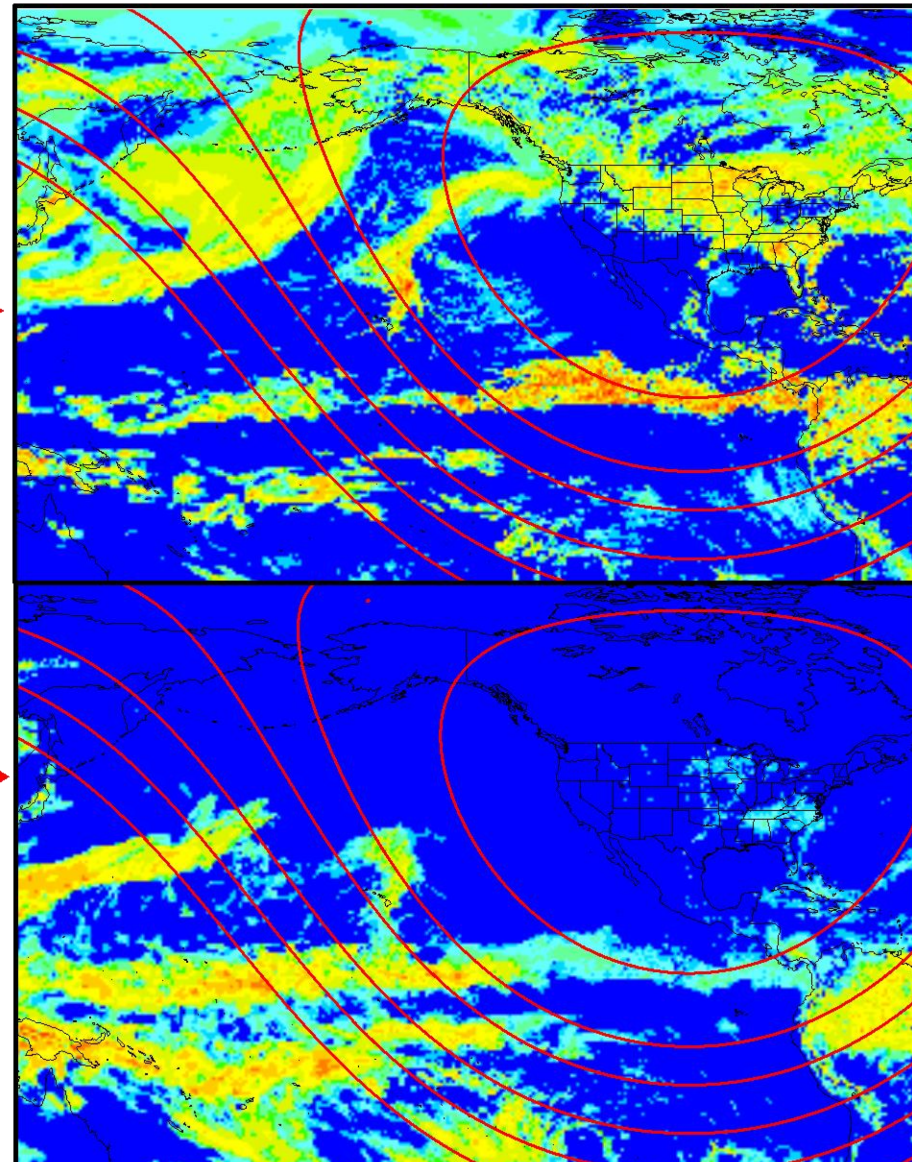
Explicit precipitation
(resolved on the mesh)

Mesh spacing
(4, 8, 12, 20, 30 40 km)

Accumulated precipitation (mm)

Convective precipitation
(from the convection scheme)

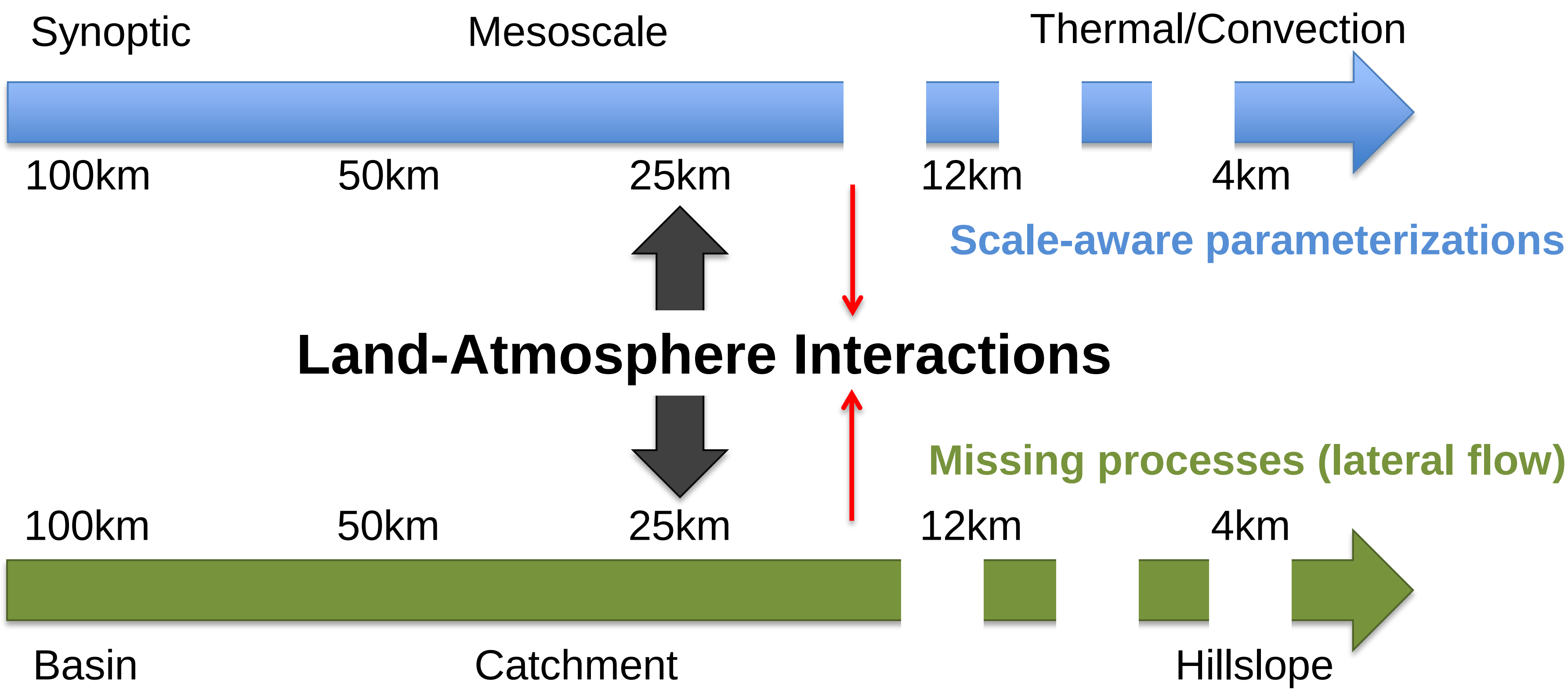
GF convection scheme gradually turns off as mesh spacing transitions to convection-permitting scales.



Framing the resolution challenge

Atmosphere

3D Navier Stokes equation + physical processes
(e.g., moist processes, turbulence)



1D Richards equation + physical processes
(e.g., topography/gravity, surface properties, lapse rates)

Land

Summary and discussion

- Land surface processes are strongly influenced by small scale heterogeneities in surface properties
  - LSMs can benefit from high resolution modeling if the subgrid parameterizations account for the dominant processes
  - Impacts of resolution seem more prominent at ~1km resolution
- How much land-atmosphere interactions benefit from increasing resolution depends partly on the relative control of atmosphere vs. land
- Large-scale atmospheric features may converge at ~50km due to the dominance of dynamics, with implications for land-atmosphere interactions
- But the converged solution may or may not resemble the solution from convection permitting simulations
- Scale-aware parameterizations hold some promises for bridging the two