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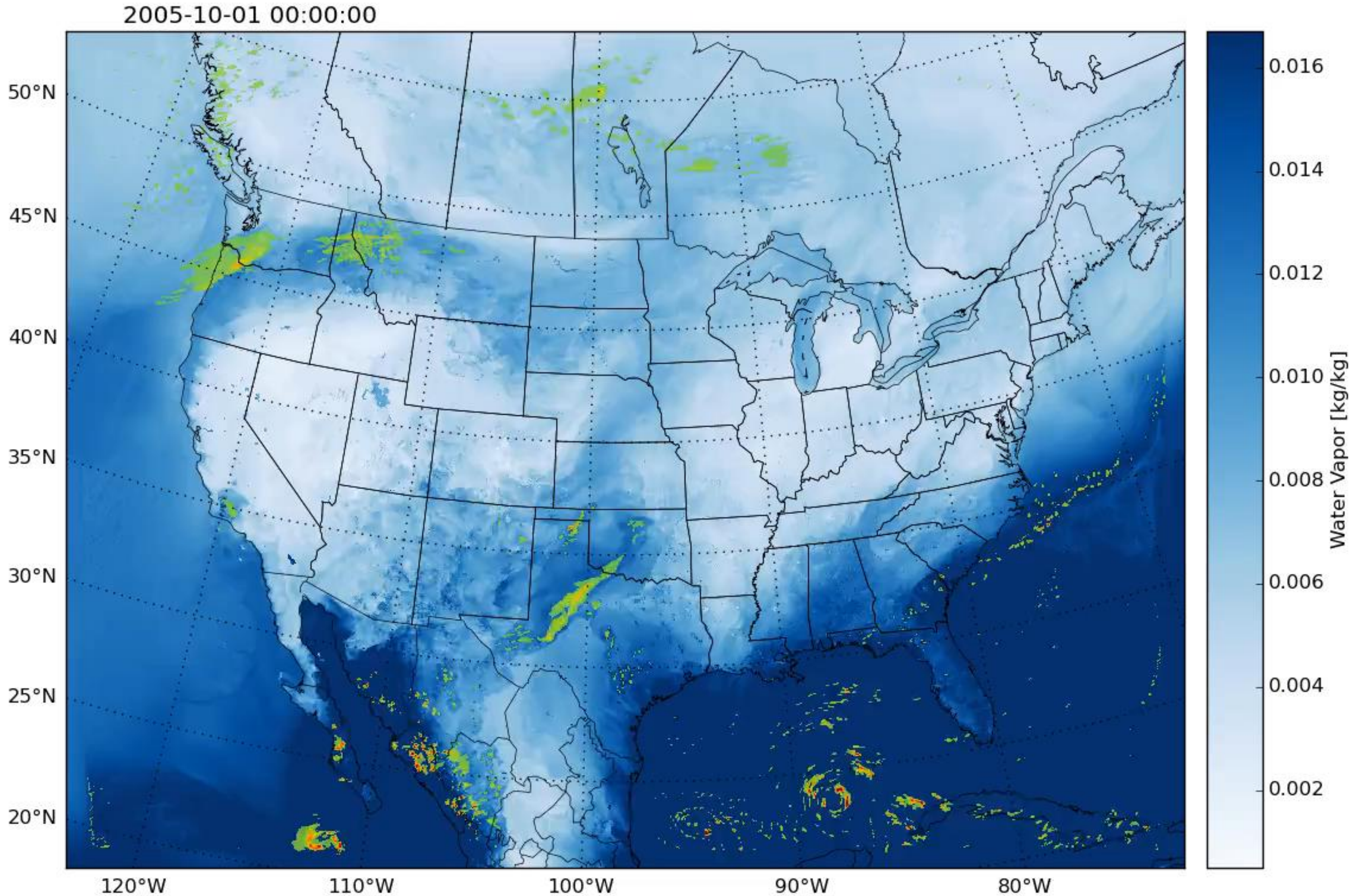
Dynamical Downscaling (convective permitting scales): Is it worth it?

Roy Rasmussen, Ethan Gutmann and Andreas Prein, NCAR

Presentation at the International Workshop on Climate Downscaling Studies

October 2017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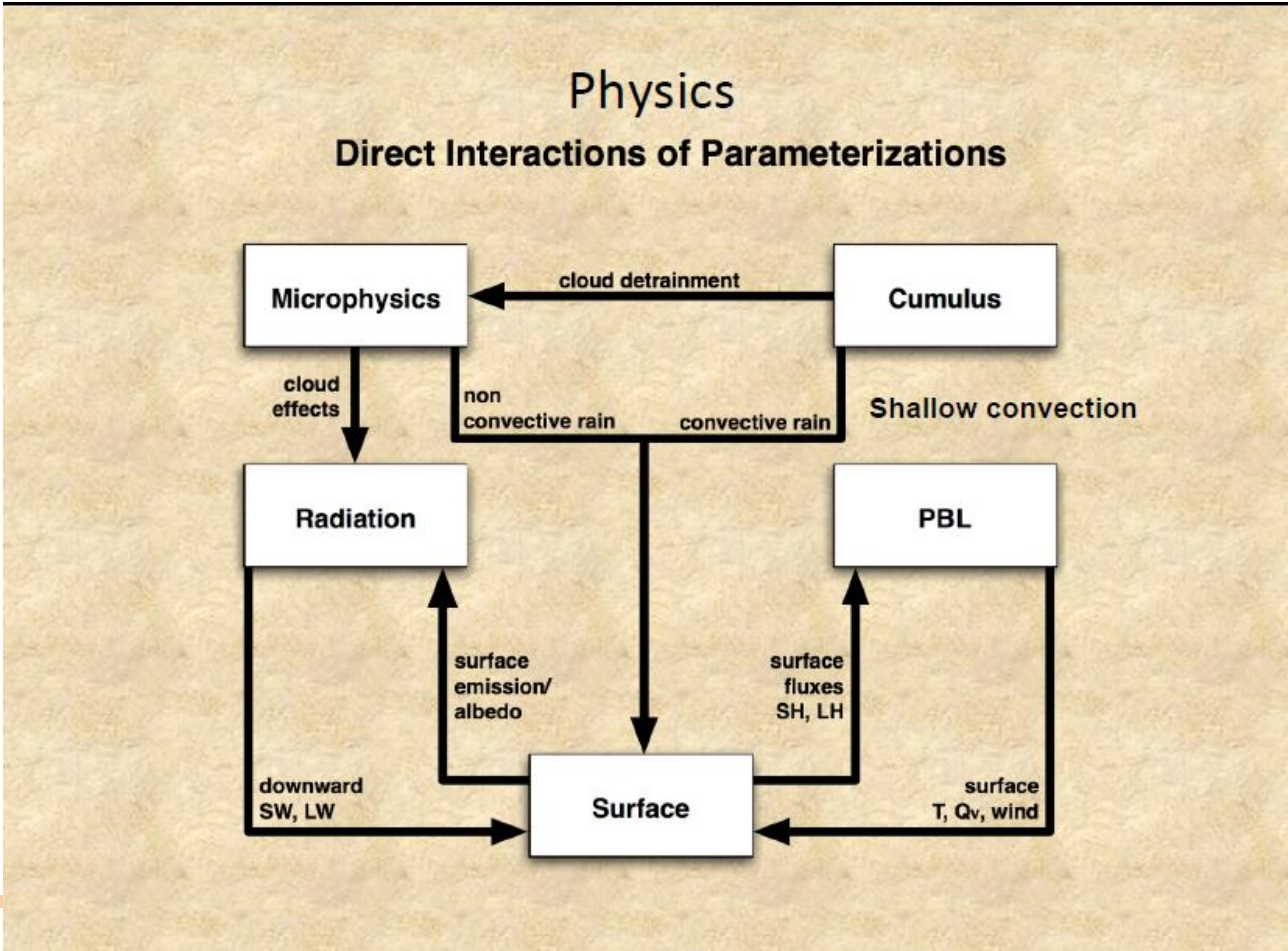
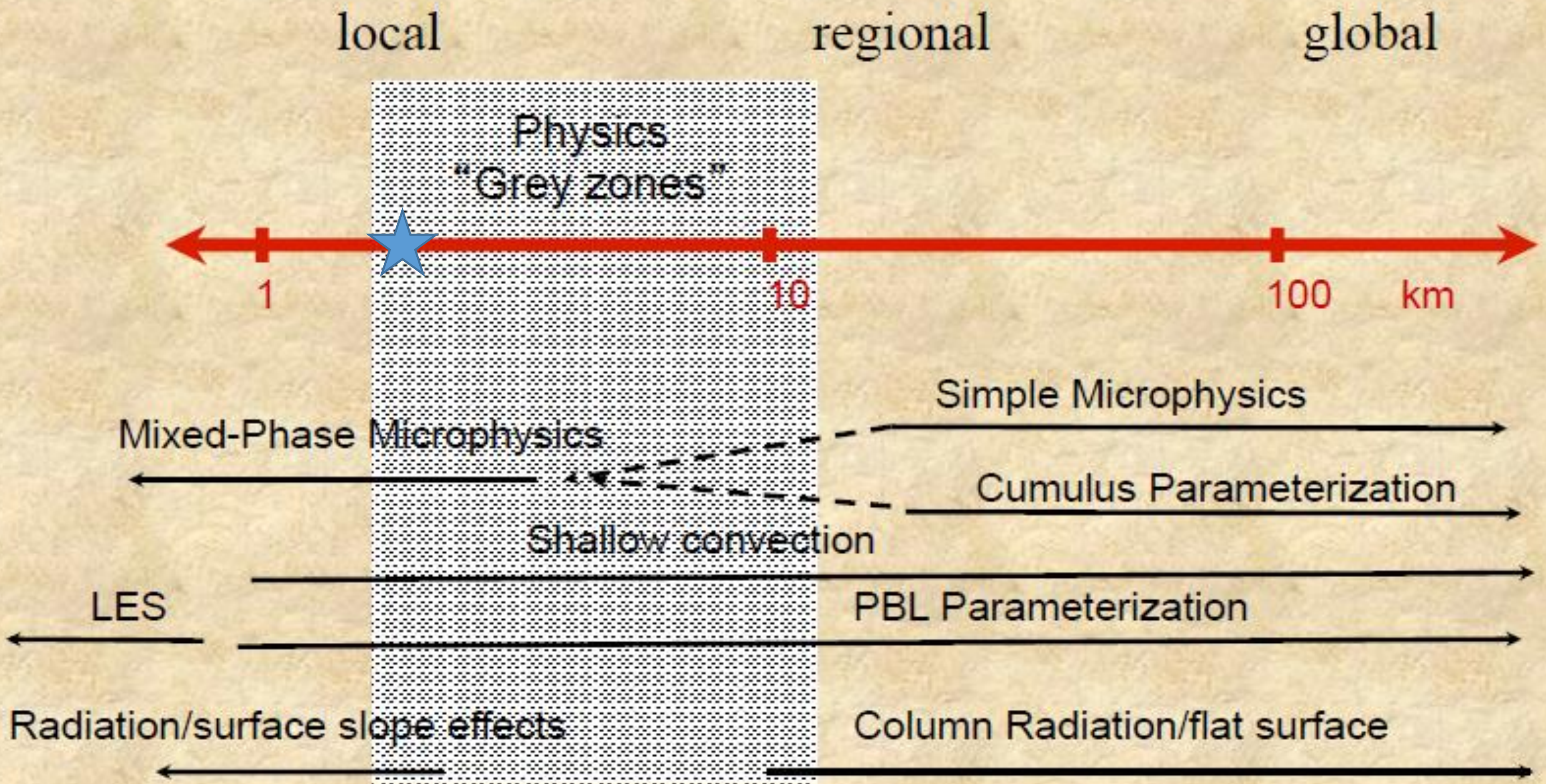
Water Vapor [kg/kg]

Schematic of WRF Physics Parameterization Interactions



Physics in Multiscale Model



Key issues for all models and scales:

- **Are precipitation intensity, frequency, duration, sequence and phase right?**

  These aspects all have implications for soil moisture, runoff and surface hydrology and thus for surface feedbacks.

Can we create a convective parameterization to capture the observed precipitation dynamics or should we move to convective permitting resolution (> 4km)?

Can we capture the benefits of convective permitting through statistical or hybrid downscaling?

Are global climate models good enough for regional and convective permitting climate models to downscale water related quantities? What about the CIMP5 model runs?

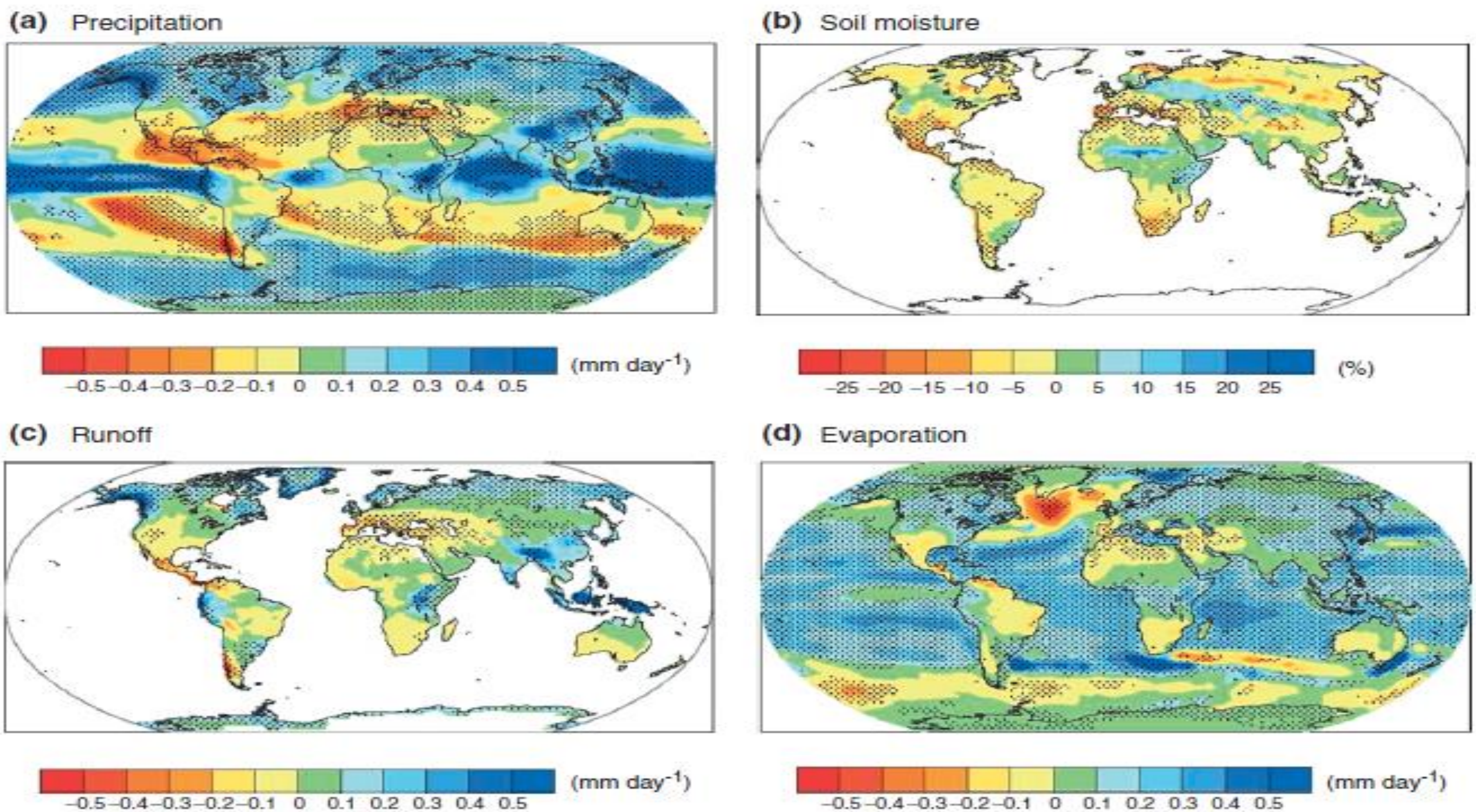


FIGURE 10 | Multi-model mean changes from 1980–1999 to 2080–2099 under the SRES A1B scenario in annual (a) precipitation (mm/day), (b) soil moisture (%), (c) runoff (mm/day), and (d) evaporation (mm/day). The stippling indicates where at least 80% of the models agree on the s of the mean change. (Reprinted with permission from Ref 114. Copyright 2007 Cambridge University Press.)

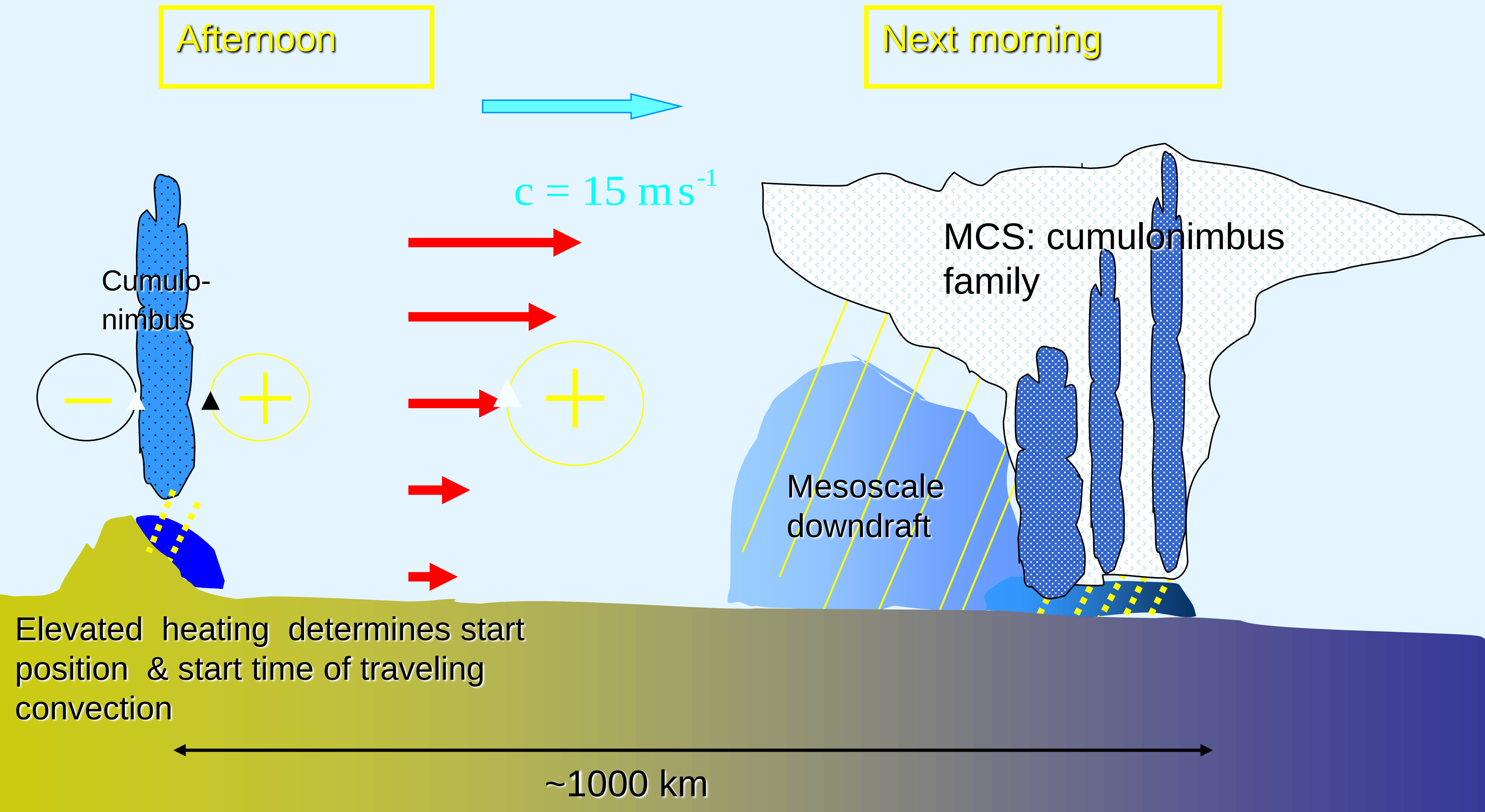
Key issues for all models and scales:

- **Are precipitation intensity, frequency, duration, sequence and phase right?**

  These aspects all have implications for soil moisture, runoff and surface hydrology and thus for surface feedbacks.

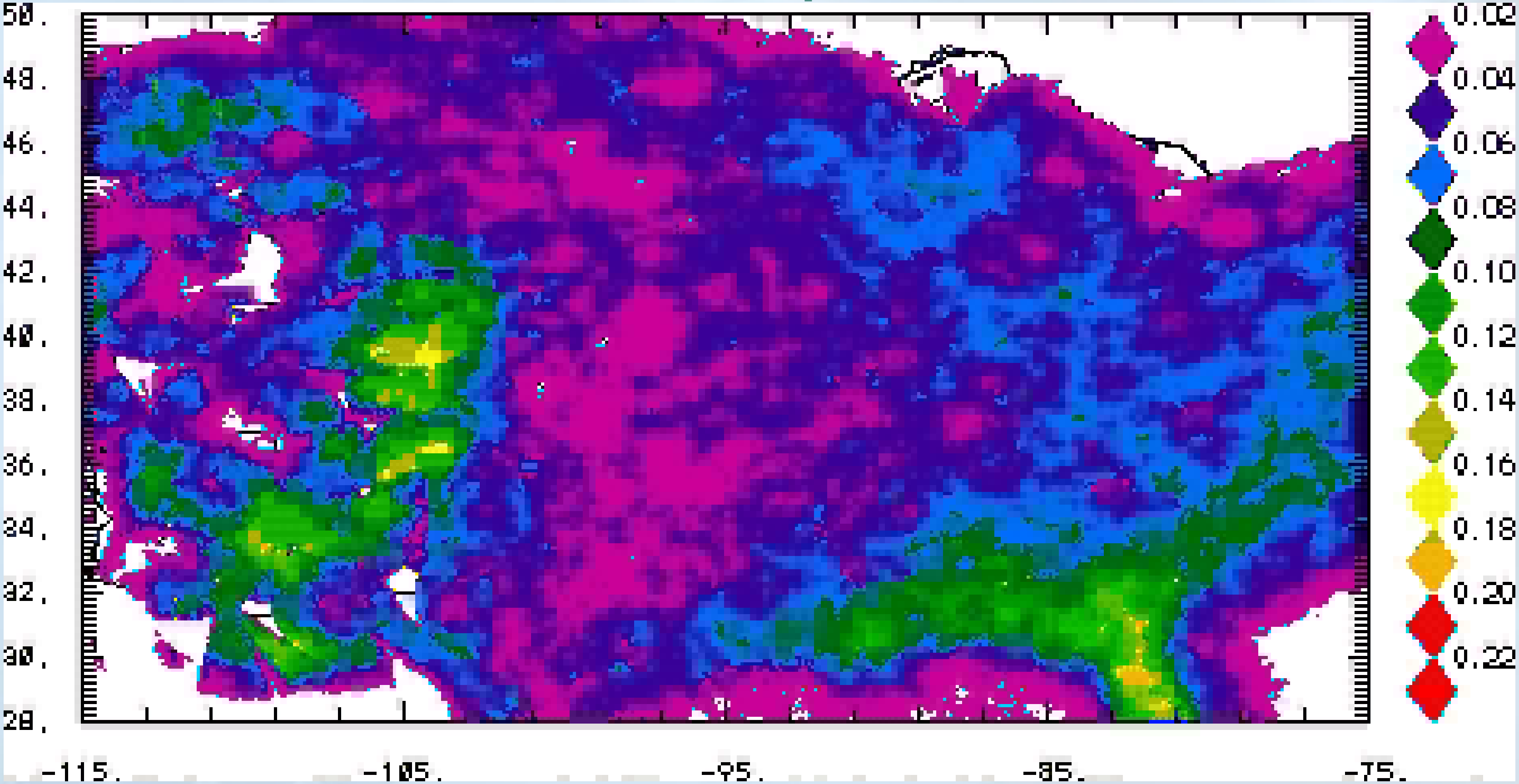
- **The timing and duration of precipitation events can be examined systematically by exploiting the diurnal cycle of precipitation in the warm season over North America and extending results to other continents.**

Mesoscale Convective Systems (MCS) downstream of mountains



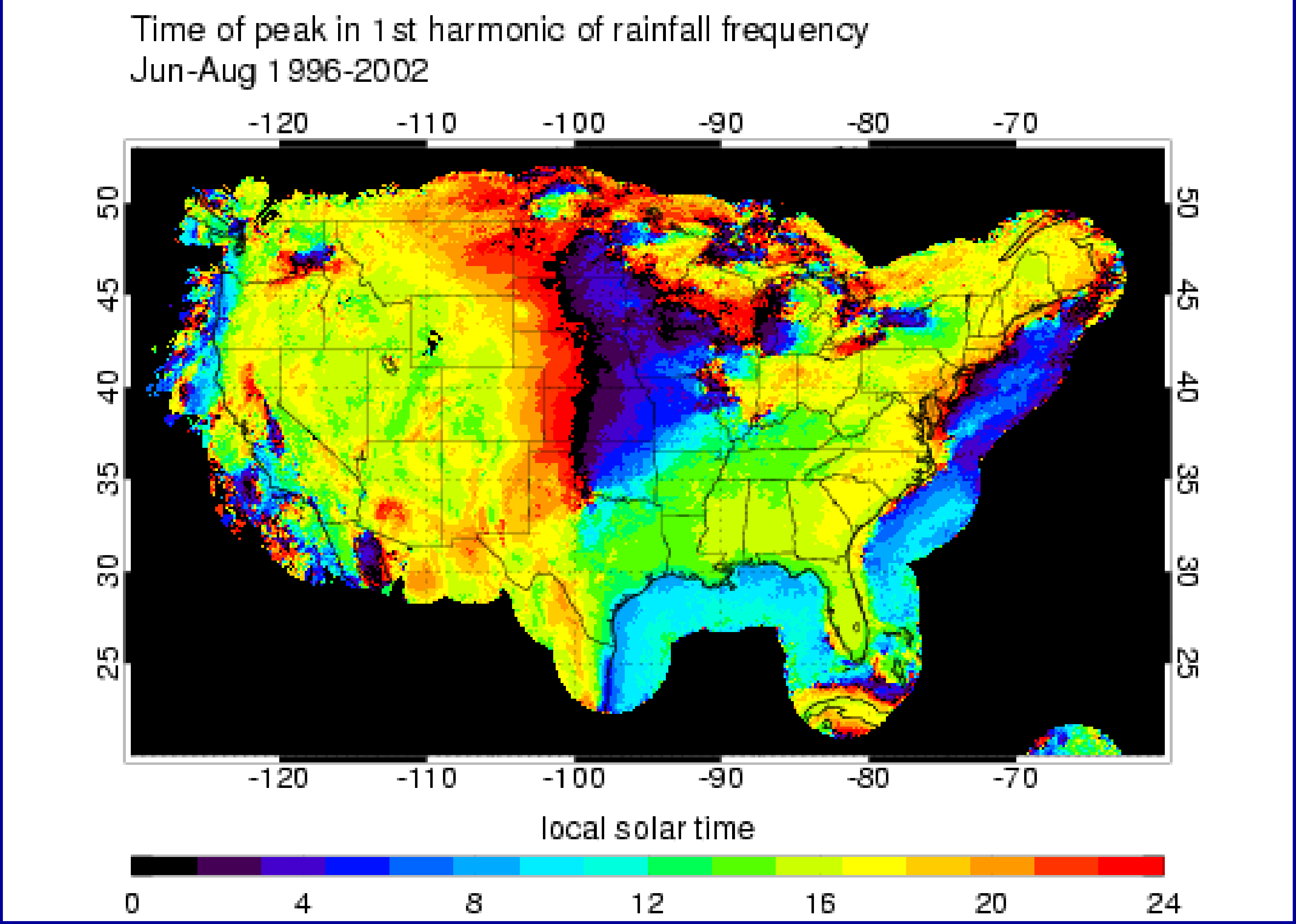
JJA 1996 - 2002

% Time Radar Precipitation Echo



Carbone and colleagues

Phase of diurnal cycle

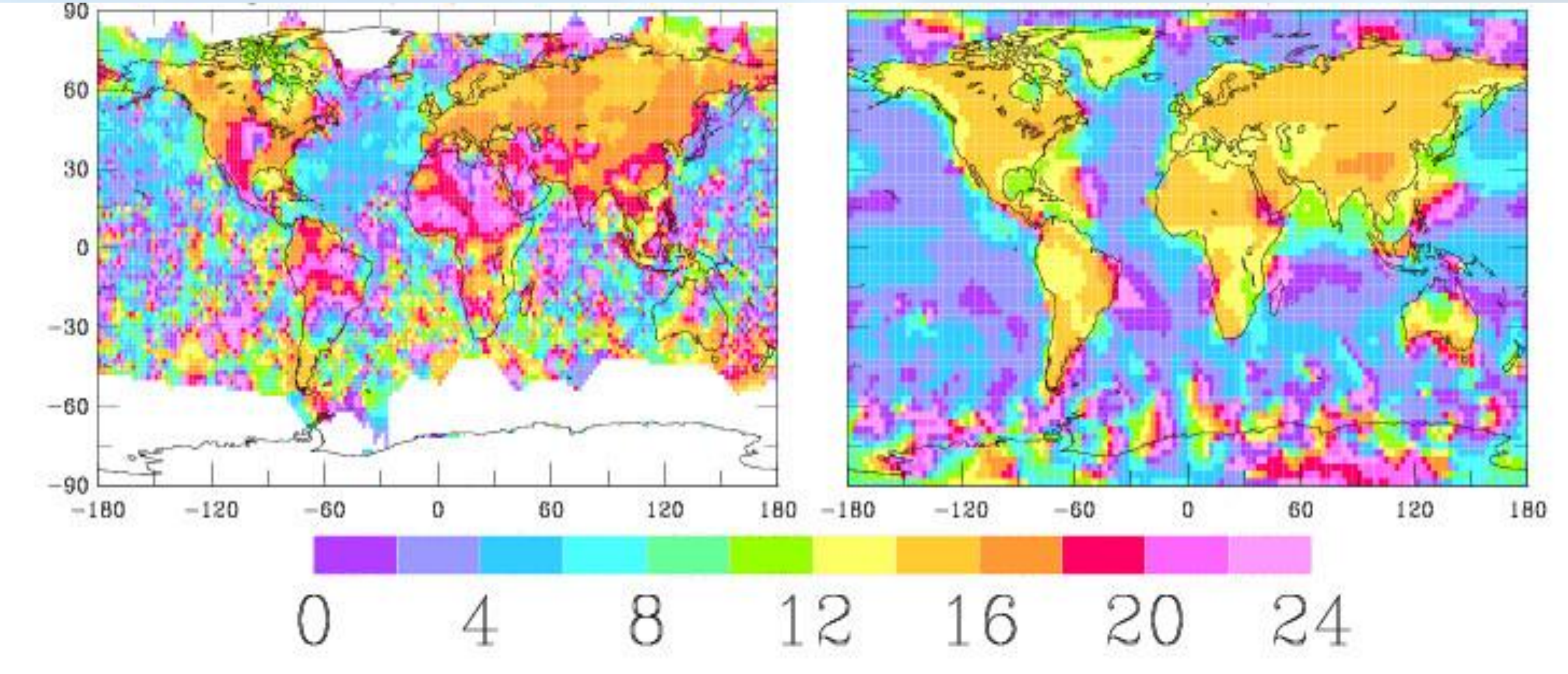


Knievel et al. (2004)

Diurnal Cycle of Convective Precipitation for JJA

Observed Frequency 1976-97
Time of maximum

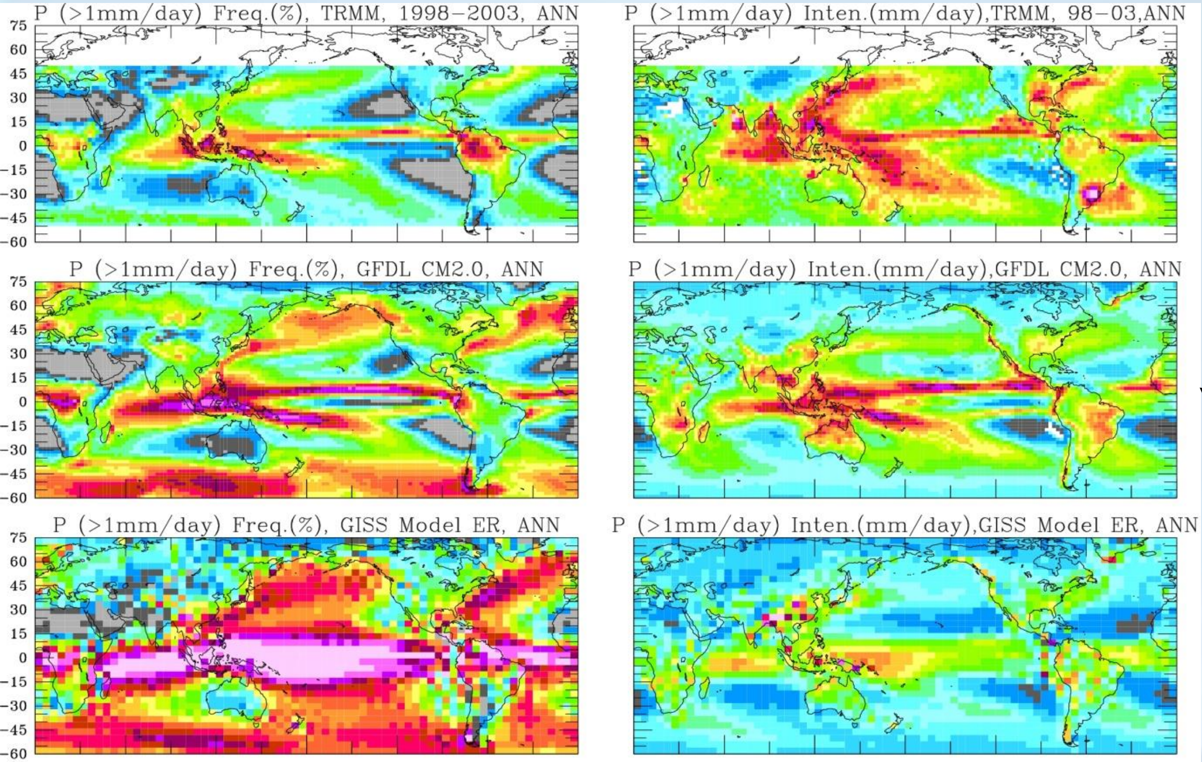
CCSM Frequency 1983-88
Time of maximum



Modeled frequency occurs about 2 hours earlier than observed

Dai and Trenberth 2004

% of time precipitating   Intensity (mm/day)



← TRMM Satellite

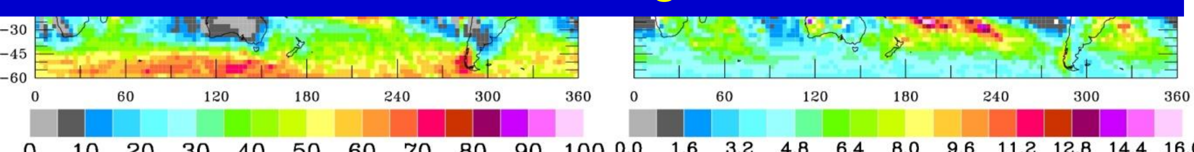
Dai, *J. Climate*, Precipitation Characteristics in 18 Coupled Climate Models, 2006

GCM Model

Recent paper by Stephens et al. (2010) entitled:

"Dreary state of precipitation in global models"

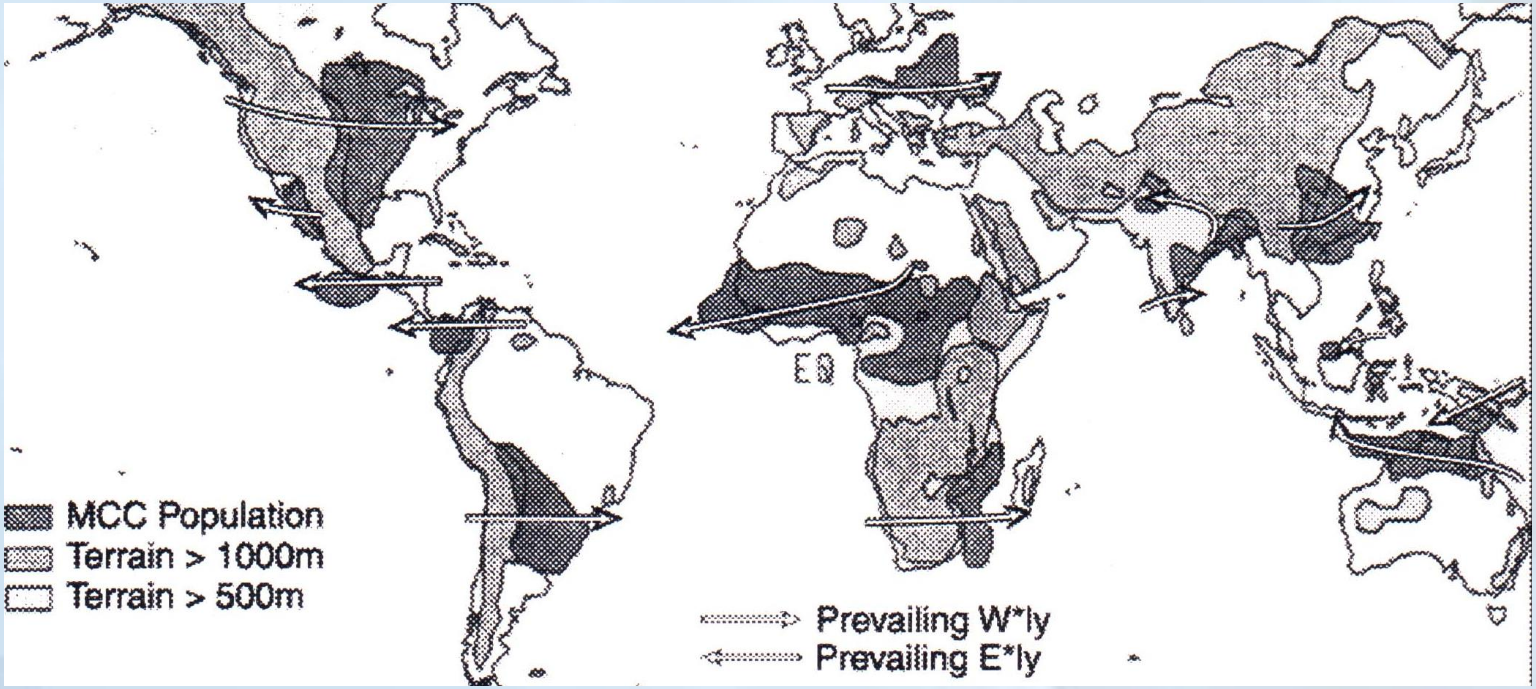
confirms these results using CloudSat data.



Annual-mean frequency (% of time, left column) and intensity (mm/day, right column) of daily precipitation (>1 mm/day) events from TRMM satellite observations (top panels, 3B42 data set, 1998-2003 mean) and four different coupled models (1991-2000 mean).

Note the underestimates of intensity and overestimates of frequency of precip. in the models.

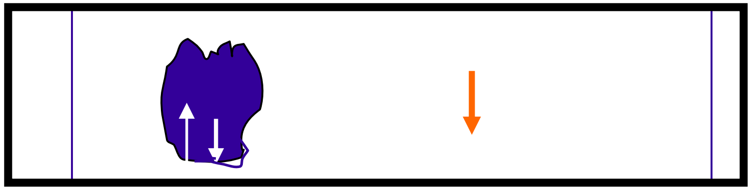
Orogenic MCS downstream of mountain ranges



Laing & Fritsch (1997)

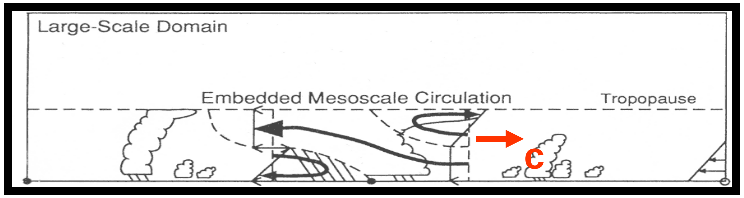
Organized convection parameterization challenge:

'Ordinary' deep convection
(conventional paradigm)



Single grid volume

Organized deep convection
(new paradigm)



Spans many grid volumes

- **Entraining ('mixing') plume model**
- **Shear not taken into account**
- **Propagation not considered**
- **Closed system (mass compensation within grid volume)**
- **Weak interaction with environment**

- **Organized quasi-laminar-flow models**
- **Shear affects organization, transport**
- **Propagation integral part of organization**
- **Open system (environment and far-field an integral part of system)**
- **Strong interaction with environment**

Organized *and* ordinary convection may occur in the same grid volume

Why Convection-Permitting Climate Modeling?

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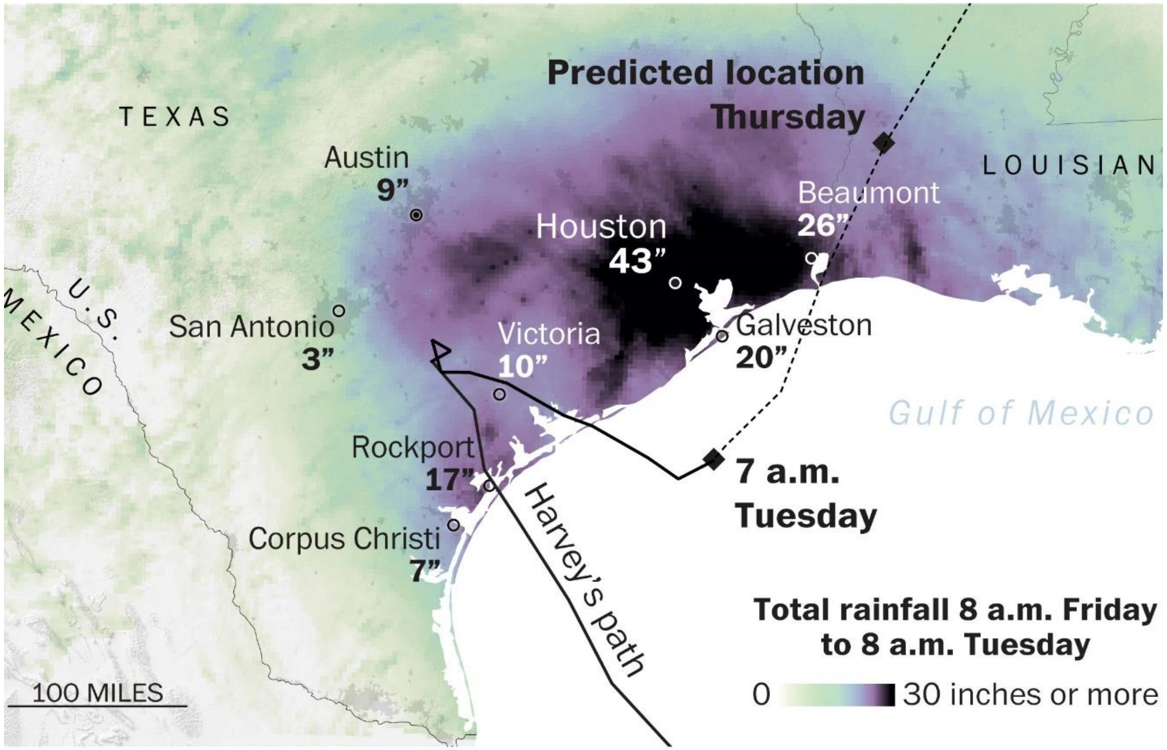
4-day rain accumulation from Hurricane Harvey



[The Washington Post]

Simulation Domain and Setup

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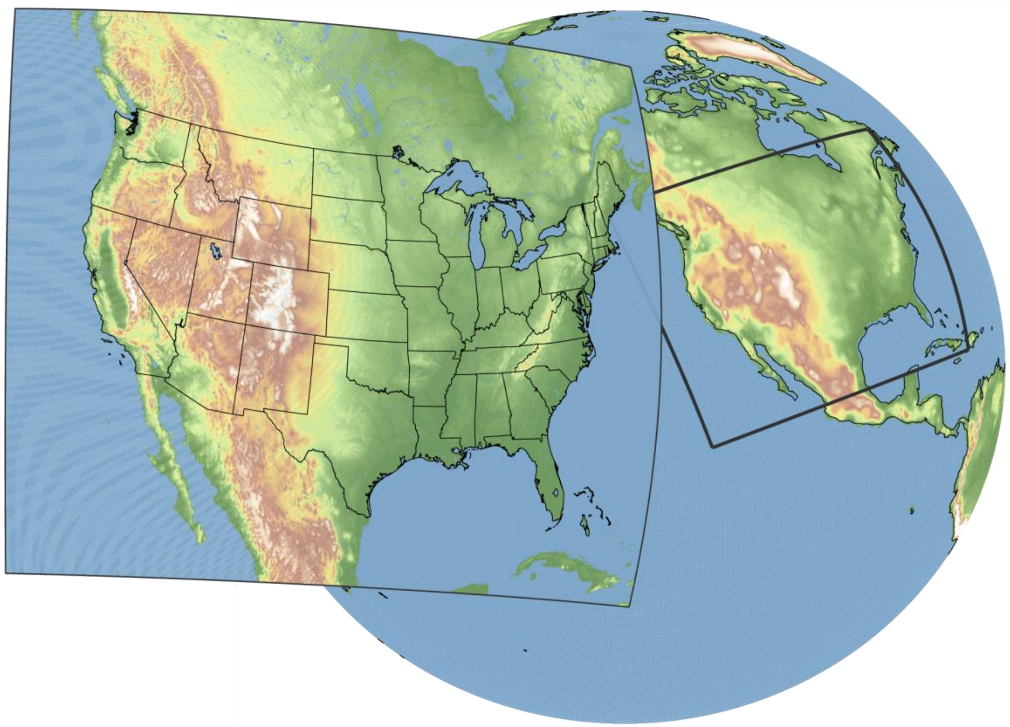
WRF 4 km | 1359 x 1015 grid cells

13 years (2001-13)

ERA-Interim



Liu et al. 2016, Clim. Dyn.

Physics

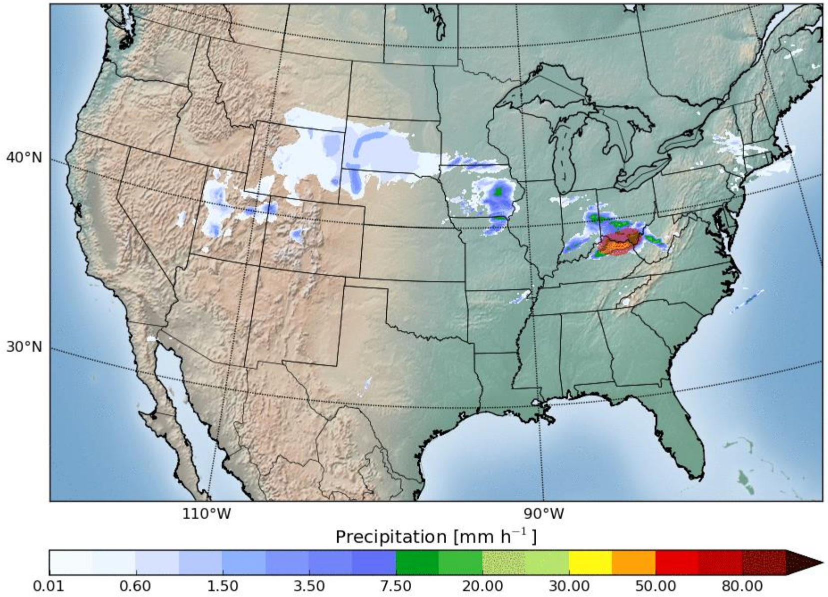
- Microphysics
  Thompson aerosol-aware
  [Thompson and Eidhammer 2014]
- Radiation RRTMG [Iacono et al. 2008]
- Land-surface model NOAH-MP
- Boundary layer YSU [Hong et al. 2006]

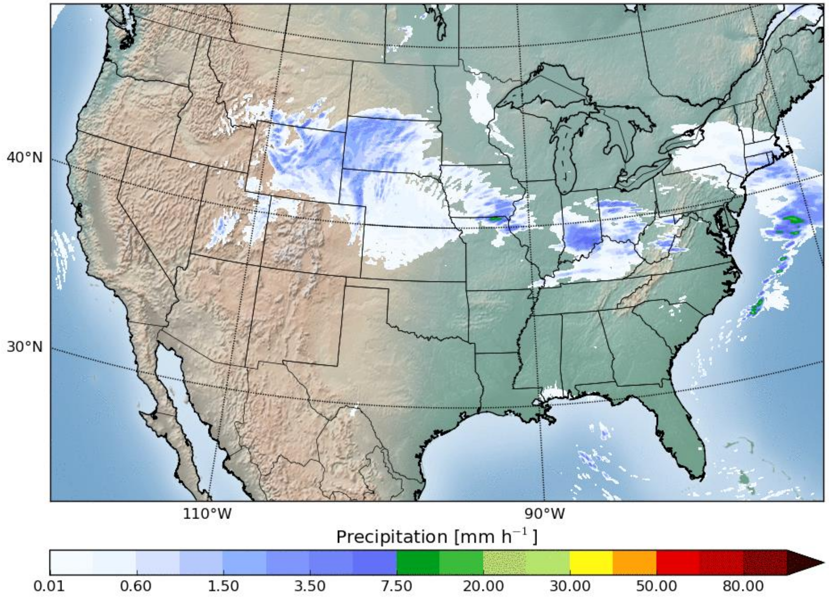
Spectral Nudging

U, V, T, and ZG above the PBL

Simulating on the Storm-scale

Convective outbreak in May 2010





- Objective based analysis allows to evaluate model on the storm scale

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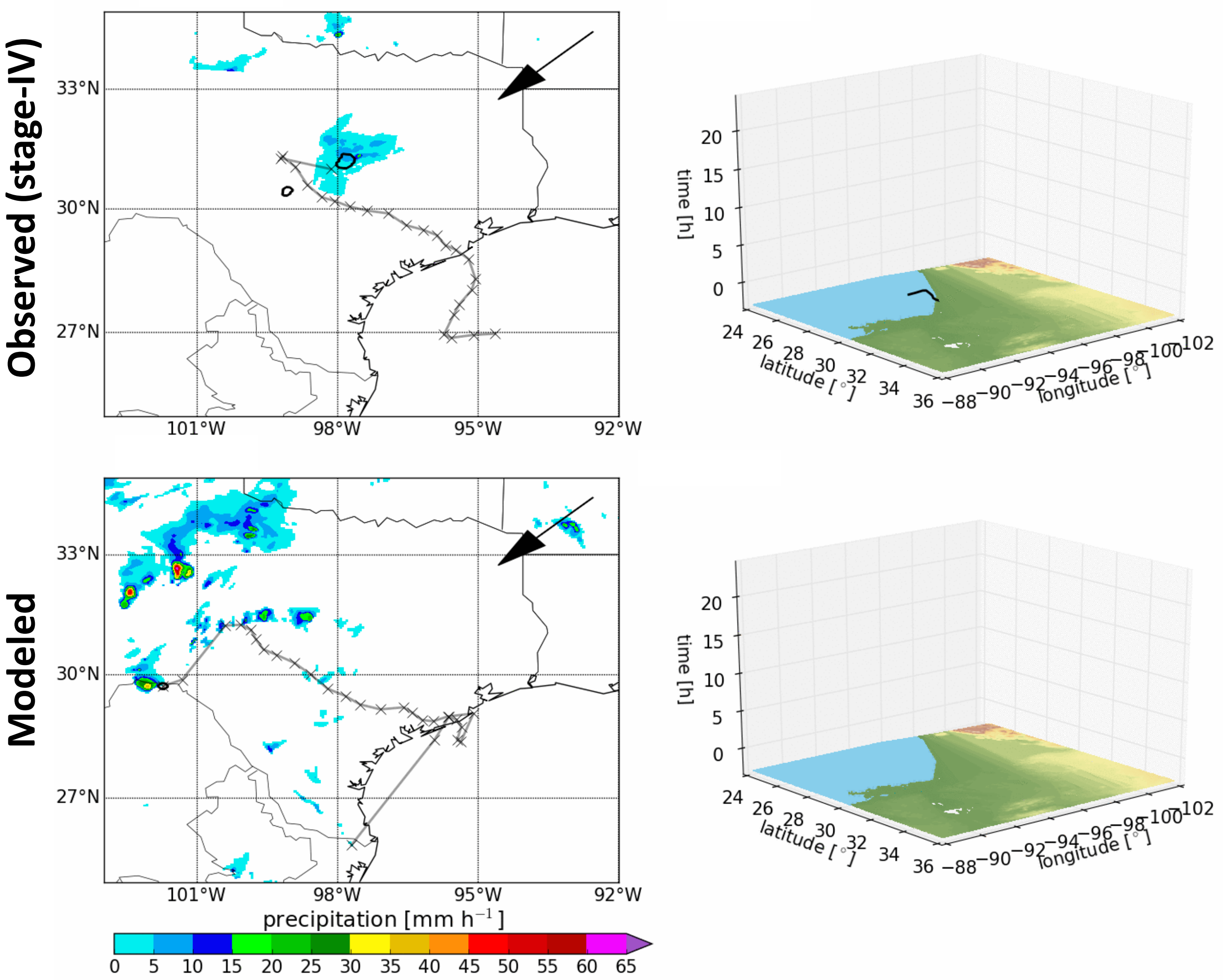
MCSs in current climate simulation

[accepted in Climate Dynamics]

MCS in Texas during March 2007

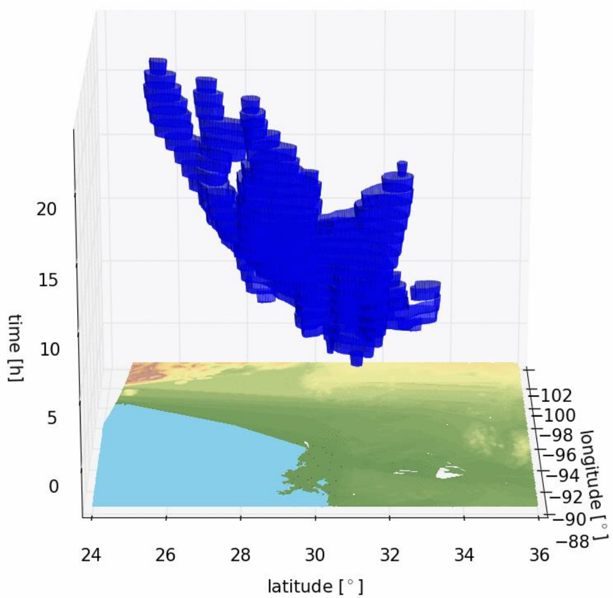


Method for Object-Based Diagnostic Evaluation (*MODE*) Time Domain (MTD)

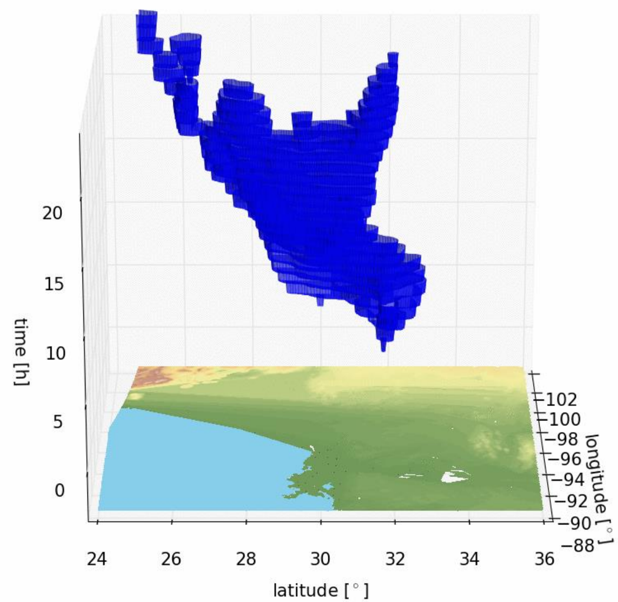
Under the supervision and support of Randy Bullock

MCS in Texas during March 2007

Observed (stage-IV)



Modeled



4 km WRF model is able to simulate the precipitation form MCSs realistically

MCS Characteristics

- Speed
- Lifetime
- Size
- Maximum Intensity
- Total Precipitation
- ...

MCS attributes – JJA Central U.S.

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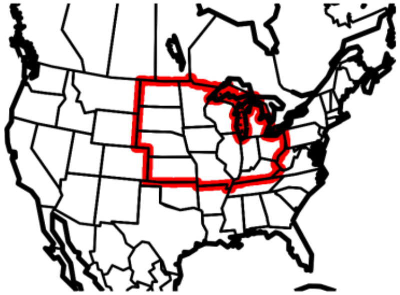
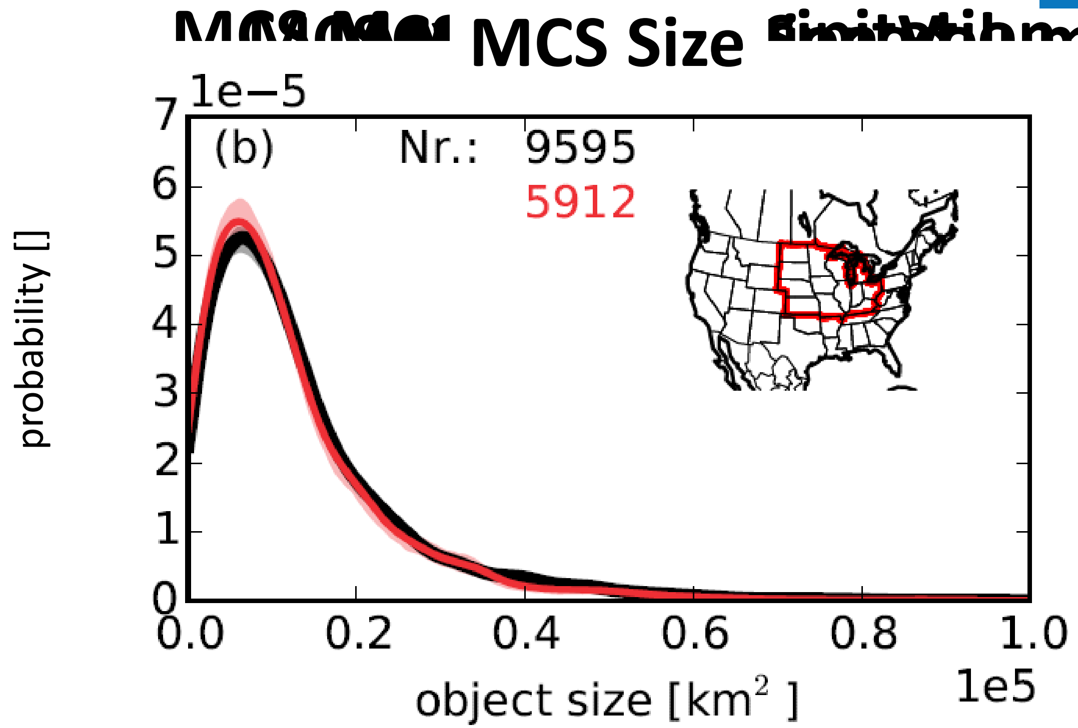
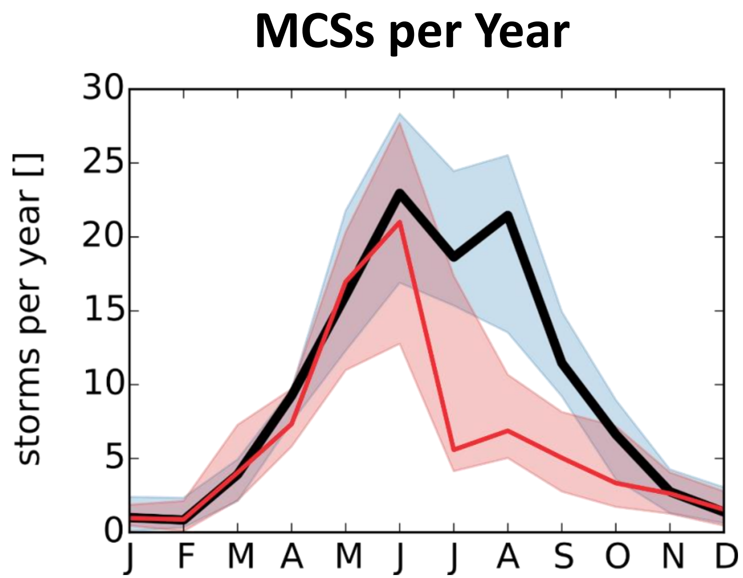
Observation

Model



- Realistic representation of MCS attributes
- But underestimation of MCS frequency

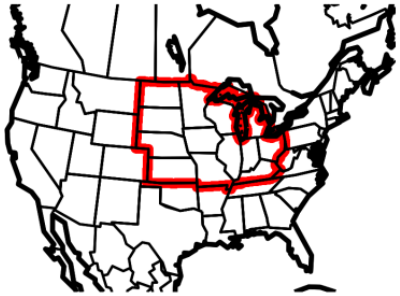




MCS attributes – JJA Central U.S.

Observation

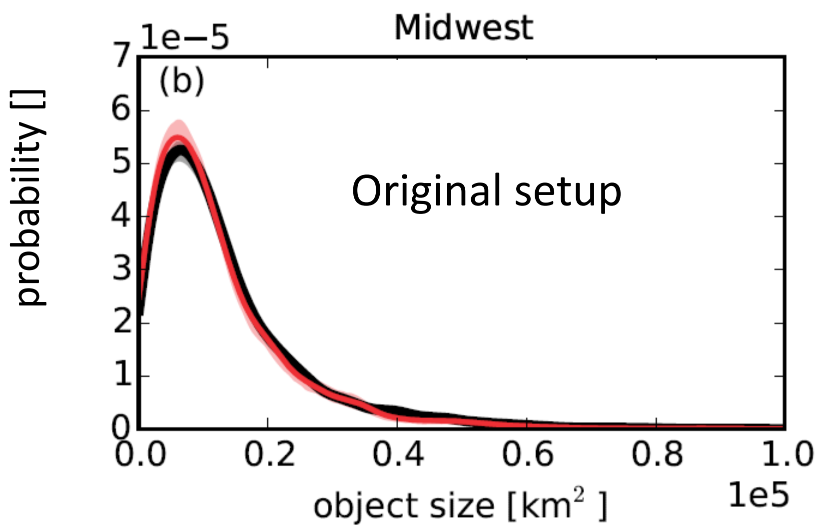
Model

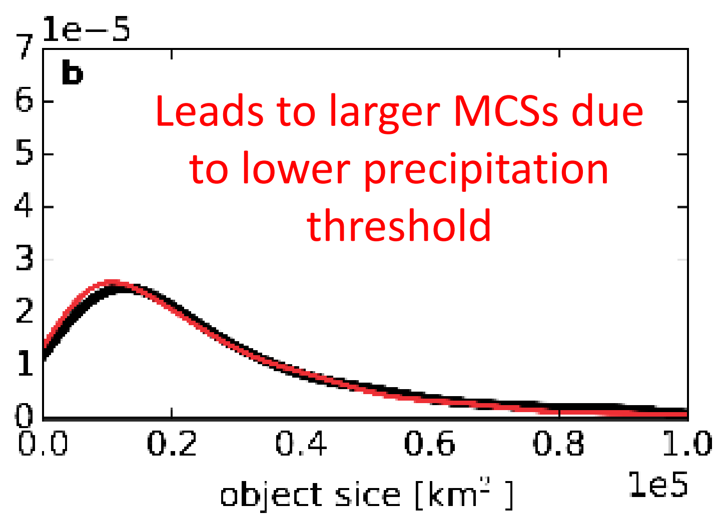


Similar good results for variety of feature tracking setups

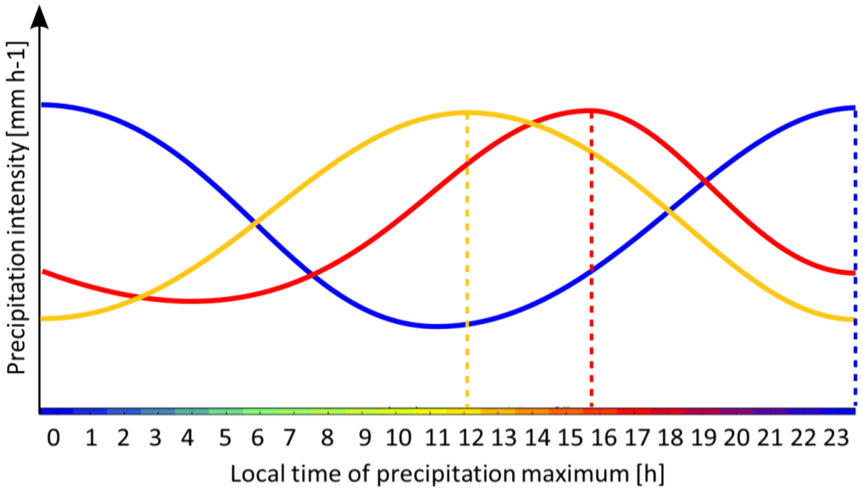
MCS Size

Precipitation Threshold:	5 mm/h	2.5 mm/h
Smoothing Radius:	32 km	64 km





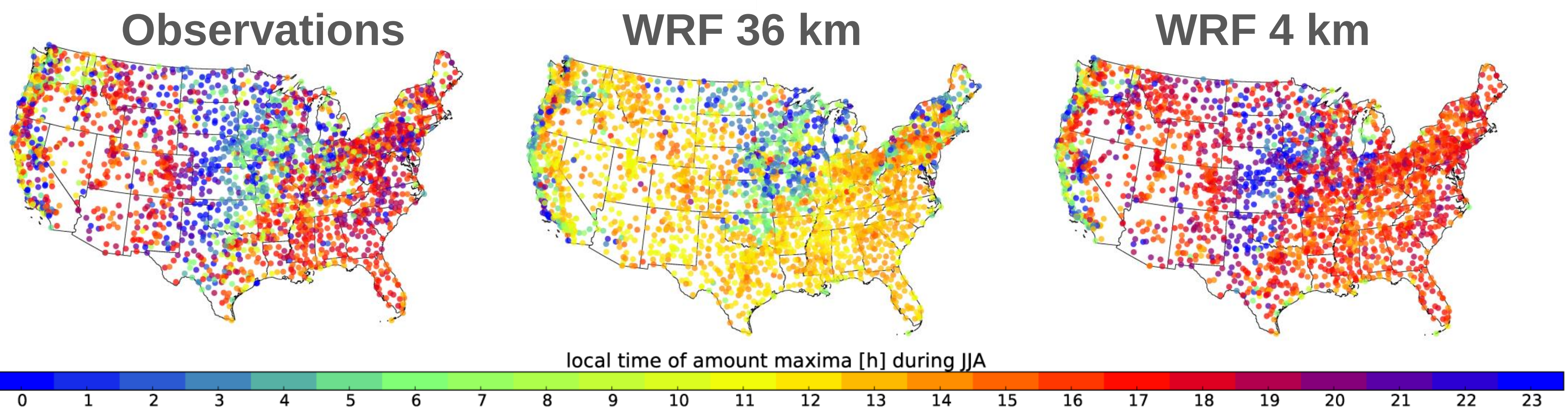
Convective Diurnal Cycle



Afternoon Peak

Noon Peak

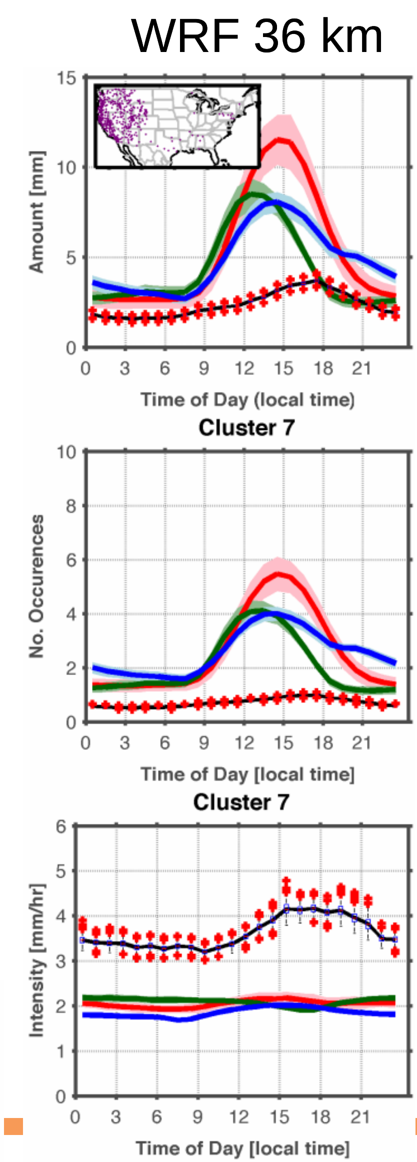
Nighttime Peak

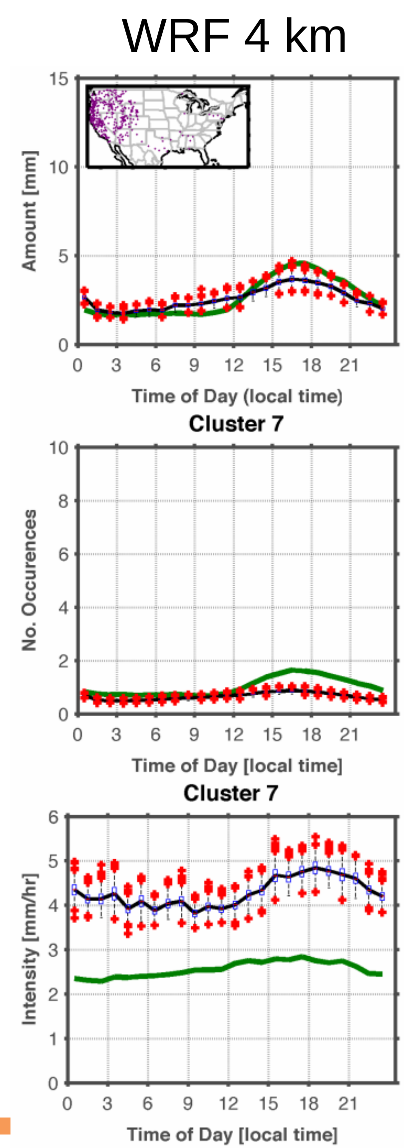


Improved simulation of diurnal cycle of of the amount, intensity, and frequency of precipitation at 4 km compared to 36 km with convective parameterization

[Scaff et al. submitted]

Summertime rainfall diurnal cycle in Western U.S.

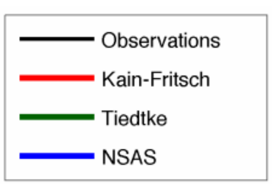


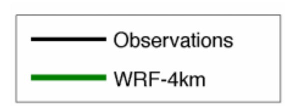


Amount

Frequency

Intensity





Non-MCS precipitation well simulated at 4 km (convective permitting) but poorly handled in **regional models (36 km)**!

[Mooney et al. 2016]

Future MCSs

[submitted to Nature Climate Change]

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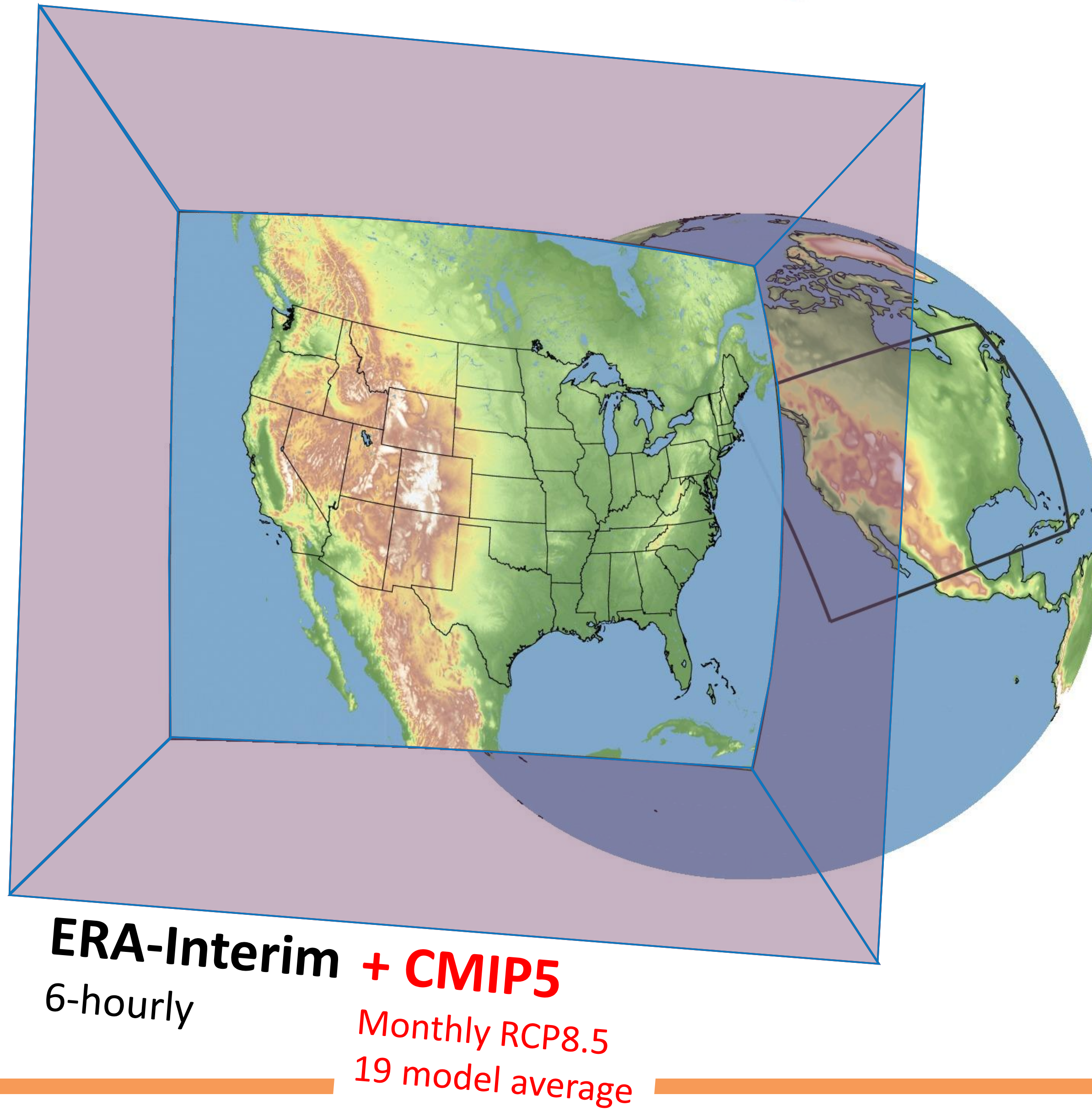
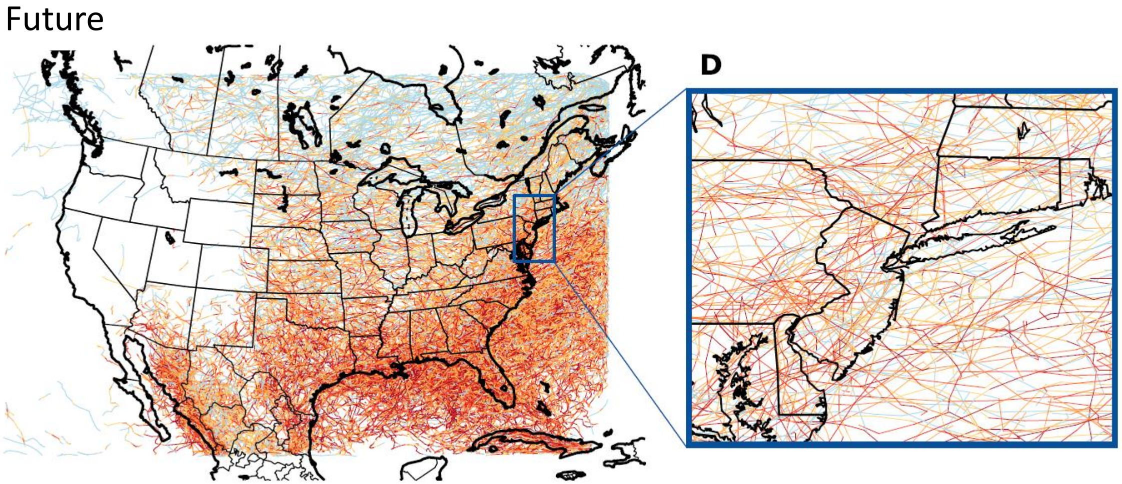
Pseudo Global Warming (PGW) [Schär et al. 1996, Rasmussen et al. 2011]

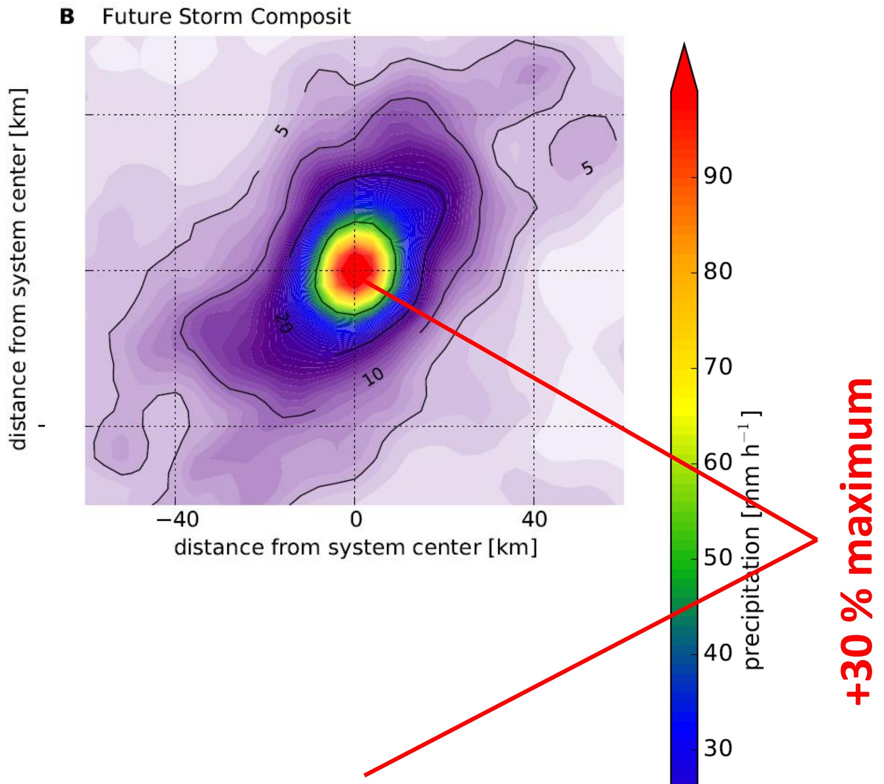
- Monthly averaged climate change perturbations from **19 CMIP5 GCMs**
- Delta 2071 to 2100 – 1976 to 2005 → RCP8.5
- Thermodynamic response of climate change
- No changes in weather patterns / moisture convergence
- No issues with internal variability

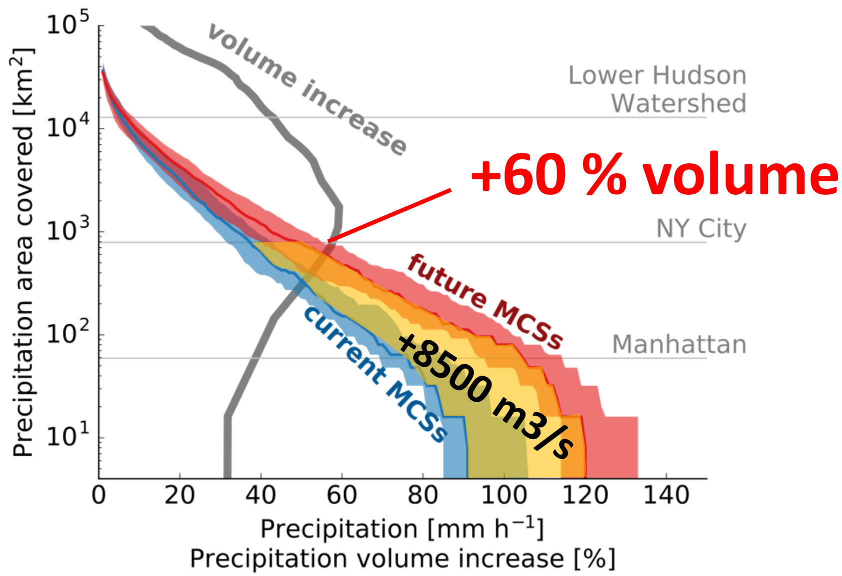


MCS Tracks & Intensities

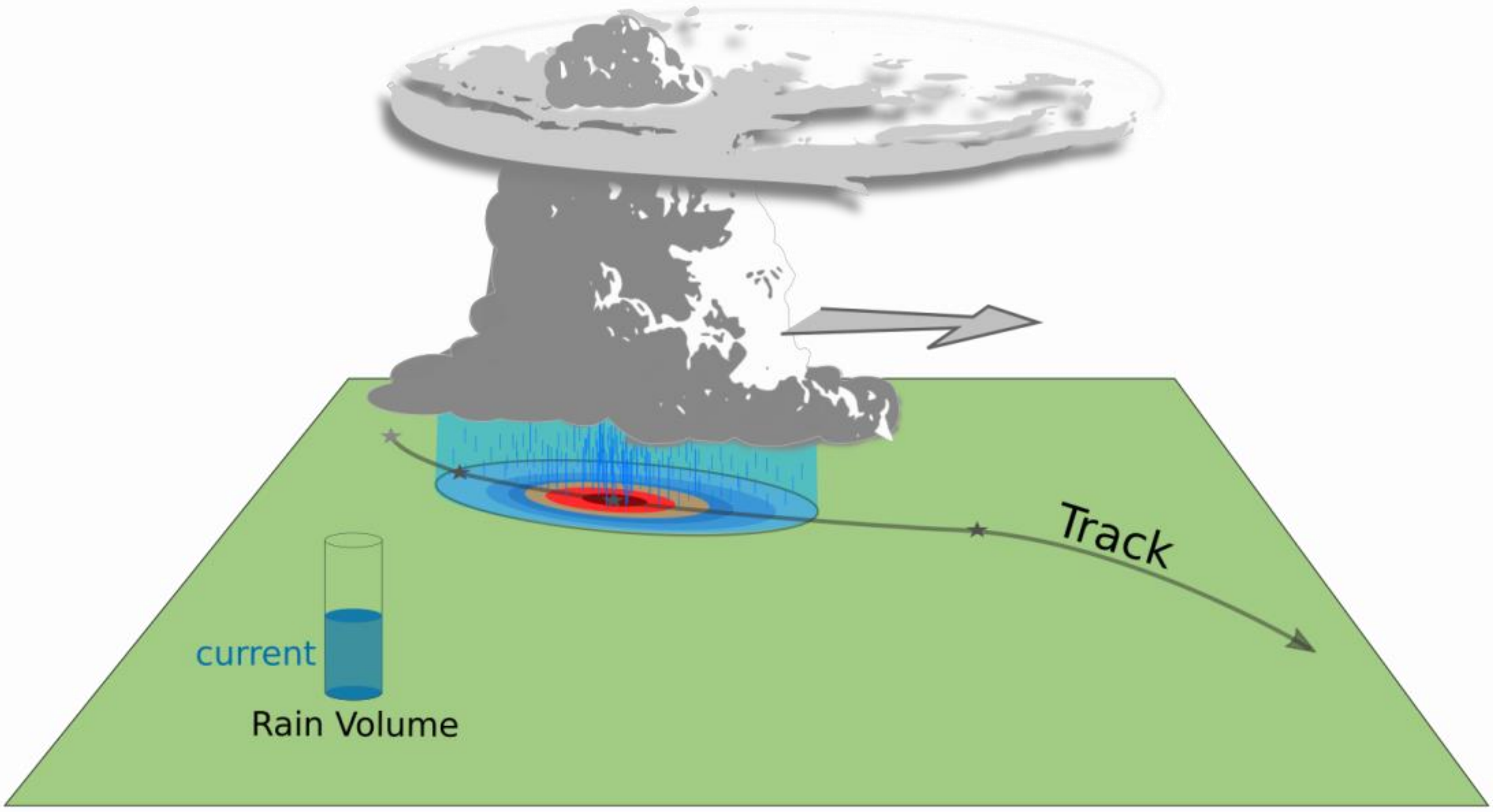


MCS total precipitation – Mid Atlantic





Conclusion



Can statistical or hybrid downscaling capture this behavior?

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- Statistical:
  - Correlates GCM large scale fields with observations
  - GCM typically uses 1-D cloud parameterization that does not capture movement of convective clouds from cell to cell.
  - If fundamental diurnal cycle of convection not captured in the GCM, large scale fields incorrect and not necessarily correlated with the physical processes producing the precipitation over the central U.S. (~70% due to propagating MCS systems).
  - While winter precipitation over the continental U.S. captured by statistical downscaling, summer convection poorly handled.
  - Not possible to deal with changes in MCS frequency, intensity and size.

Changes in MCS Dynamics and Thermodynamics – Mid Atlantic

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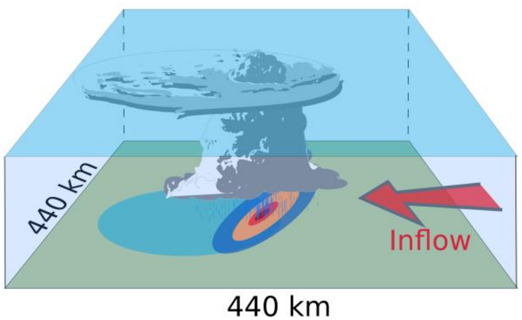
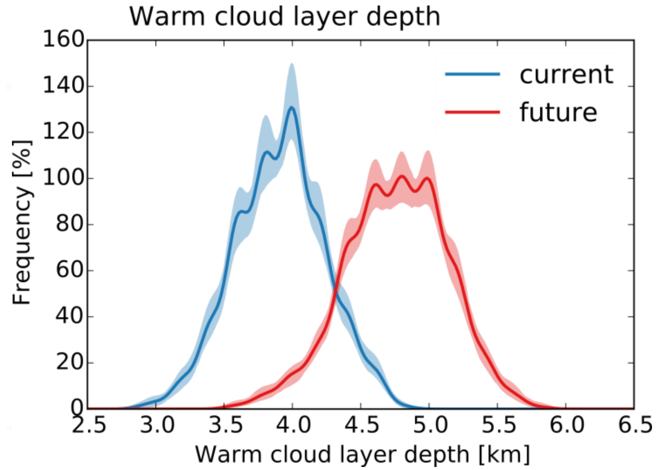
Rotated MCS environments



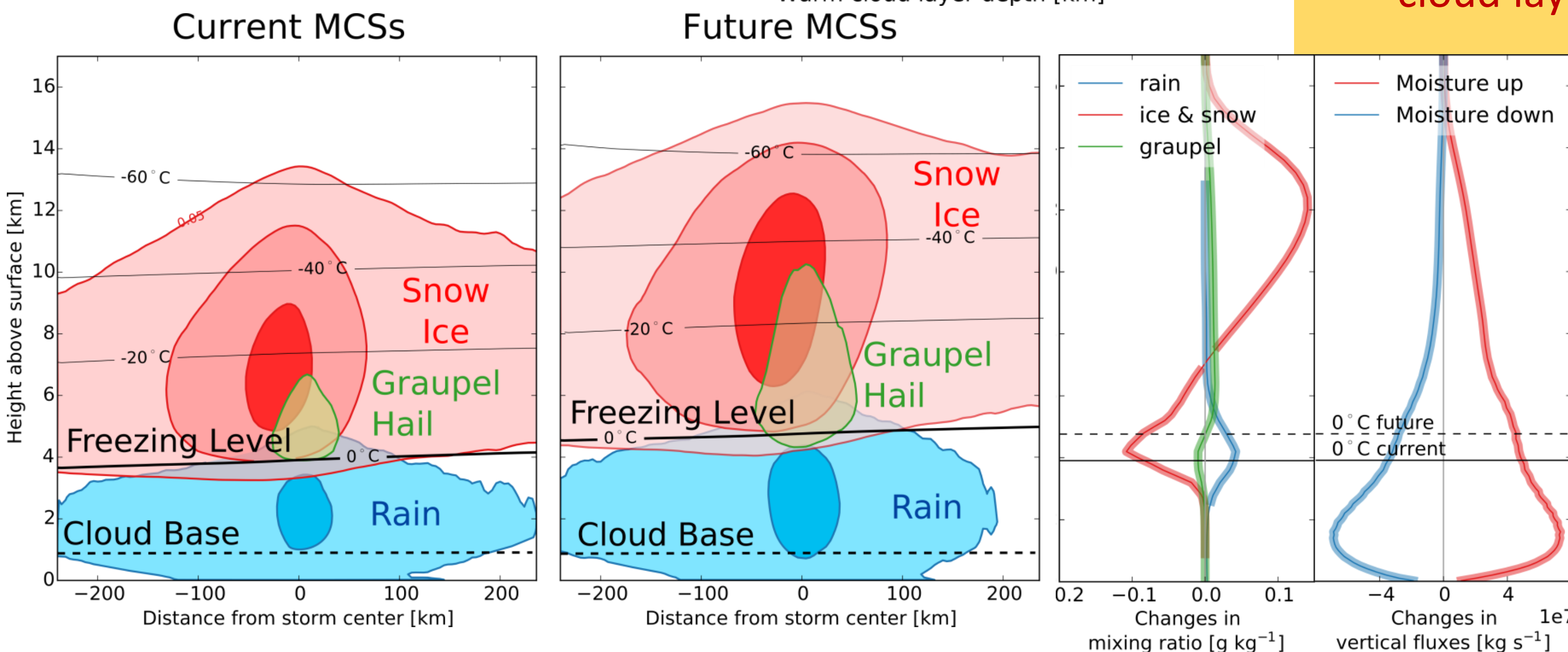


More Favorable

- + Increased CAPE
- + Higher cloud top
- + Increased vertical moisture transport
- + Deeper warm cloud layer

le

g stability
Humidity



Can statistical or hybrid downscaling capture this behavior?

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- Can Hybrid downscaling provide some of the advantages of dynamical downscaling without the large cost?
  - ICAR system (Gutmann et al. 2016) uses linear solution of flow field driven by the GCM large scale variables
  - Allows for high resolution simulations similar to dynamical downscaling spatial resolution used for Colorado Headwaters (4 km, Rasmussen et al. 2011) but 100 times faster due to the simplified dynamics.
  - Shows promise in capturing orographic precipitation that is largely driven by large scale flow interaction with local topography
    - Limitations: Blocked flow not well captured. Thus, weak flow and/or steep topography are situations that may not be well simulated

    .
  - Current weakness: Convection.
    - Research to date has shown poor performance in capturing convection storms, especially MCS type systems.

    1. GCM typically uses 1-D cloud parameterization that does not capture movement of convective clouds from cell to cell and thus does not capture the likely adjustments to the large scale flow that occurs with large MCSs. Diurnal cycle of precipitation incorrect over the continental U.S., keyed to local noon and not delayed as observed.

    2. If fundamental diurnal cycle of convection not captured in the GCM, large scale fields incorrect and not necessarily correlated with the physical process producing the precipitation over the central U.S. (~70% due to propagating MCS systems).

What about regional modeling?

- Regional modeling at 25-50 km horizontal resolution nests driven by GCM or reanalysis boundary conditions has shown skill in capturing mesoscale features such as land/sea breezes and hurricanes at significantly less expensive that convective permitting models. Can this model be used to provide improved large scale fields to perform statistical or hybrid downscaling? Can it be used by itself to answer key climate change questions?
  - Depends:
    - Can be used to examine changes in frequency of large scale mesoscale systems such as hurricanes, however, the tradeoff is that the frequency of hurricanes formed in both the current and future climate sensitive to the convective parameterization used. Thus, another uncertainty is introduced.
    - As shown in this talk, a 36 km regional model is unable to capture the dynamics and physics of MCS type convective systems, so convective permitting simulations required to examine future changes in intensity, size, storm speed, and frequency.

Sensitivity of hurricane frequency at 36 km to model physics

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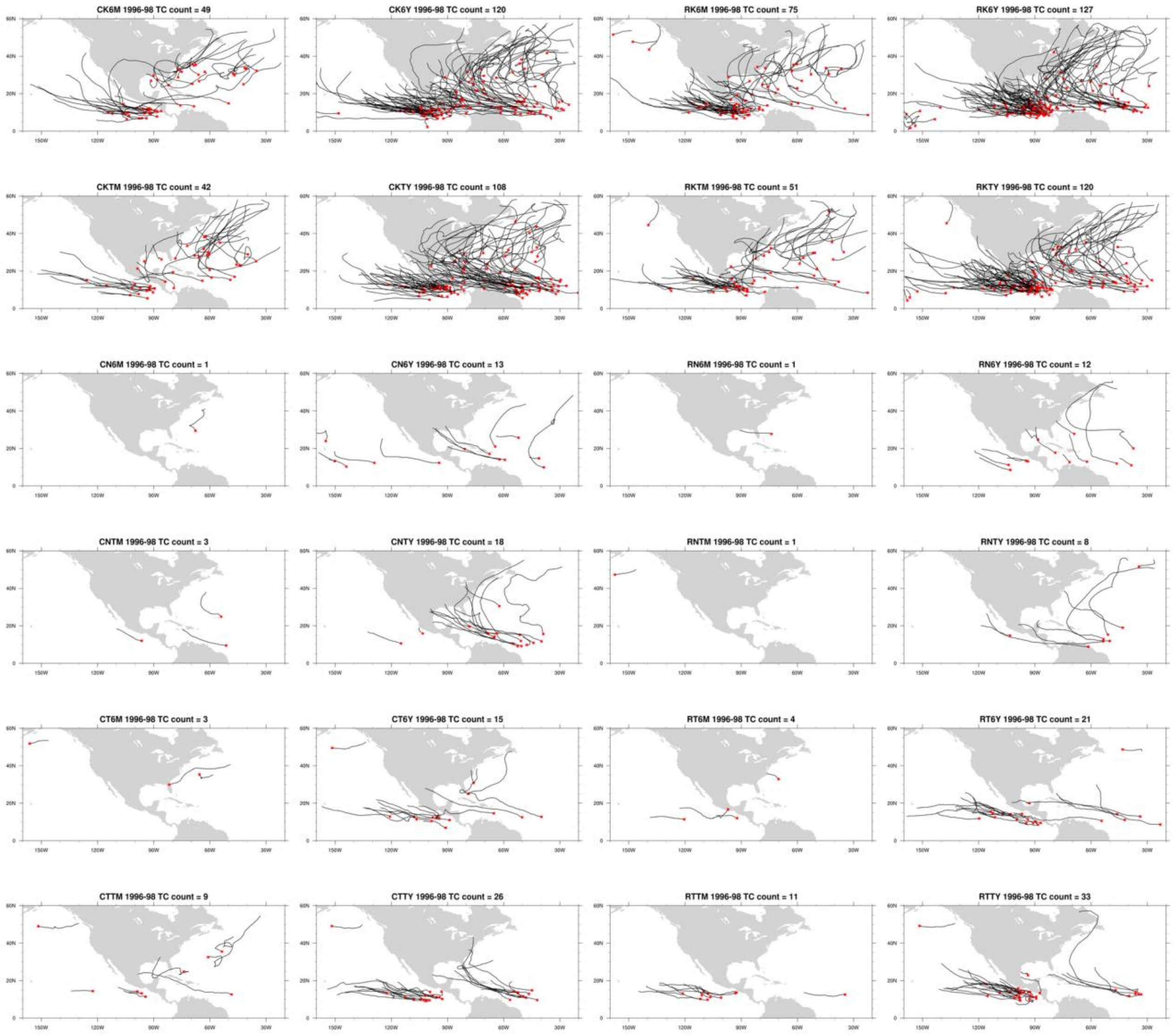

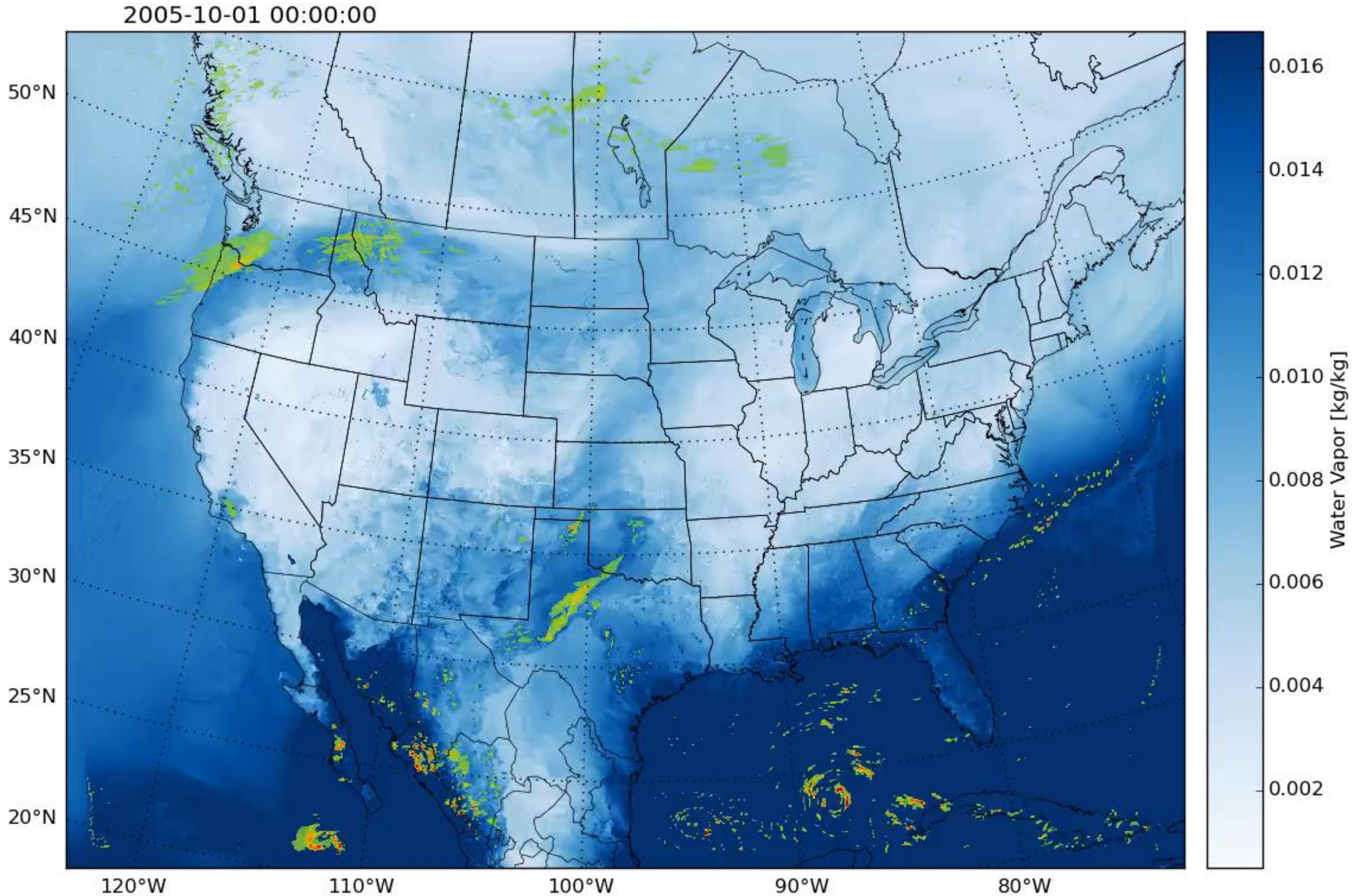
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0.002
Water Vapor [kg/kg]

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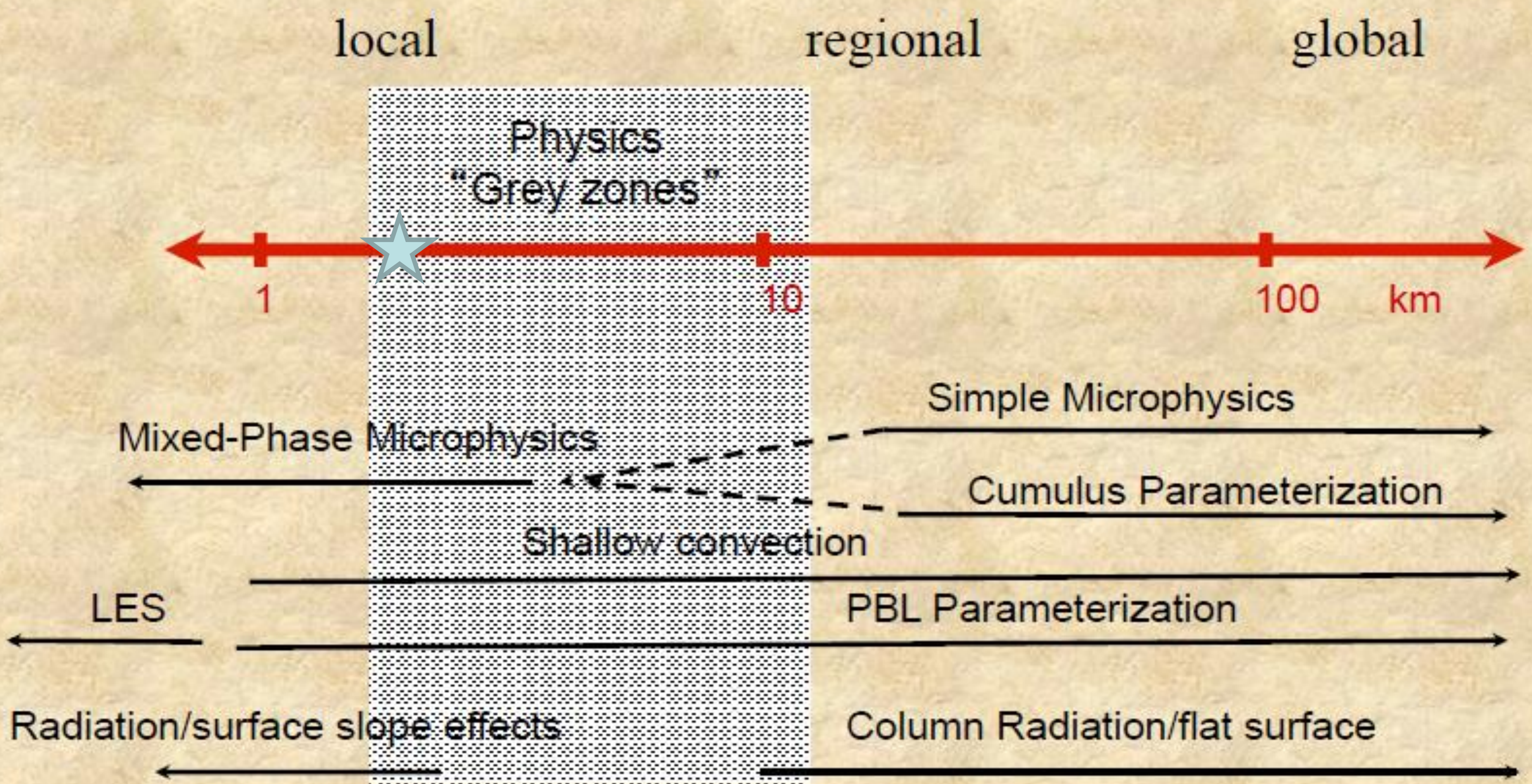
Physics in Multiscale Model



Summary

- Is dynamical downscaling worth it?
  - Depends on the region, the driving model and the problem asking.

  - Region:
    - Regions dominated by convection systems should consider dynamical downscaling as simpler techniques such as ICAR not able to capture convection well yet. Phd student??

    - Examples of regions that could benefit from dynamical downscaling include regions subject to hurricanes and summer convection downstream of significant orography.

  - Driving model
    - GCM or Regional model
    - Need to bias correct large scale model before using to drive dynamical downscaling model.

  - Problem:
    - Temperature or precipitation? Mean or extreme weather? Hard to simulate many years with dynamical downscaling.
    - Local? High resolution simulations provide more accurate local effects and better estimate of physical processes including future climate changes.
    - Need to estimate uncertainty? ICAR or statistical downscaling may be the method of choice. Able to downscale many GCM ensemble members. If use dynamical downscaling, consider using stochastic physics to get at likely physics uncertainty.

Challenges to address regarding downscaling:

1. Appropriate representation of the land surface, including soil structure and moisture
2. Approprate representation of convection
3. Appropriate representation of extremes (hourly precipitation, etc.)
4. Limitations of the data that global models are downscaled to.
5. Appropriate representation of sub-grid scale cloud and radiation feedbacks (even at cloud permitting scales).
6. Appropriate representation of precipitation phase (terrain smoothing)
7. Representation of vertical motion
8. Representation of microphysical processes
9. Appropriate representation of snow melting due to slope and aspect considerations

Thank You!

[rasmus@ucar.edu]

The high resolution WRF simulation data for the current and future climate over CONUS produced by our NCAR group is now available for download via NCAR's Research Data Archive website. https://rda.ucar.edu/datasets/ds612.0/. To download, sign in first (top of the page on the url). Each variable from hourly 2D and 3-hrly 3D data are archived separately.

How to site this dataset:

Rasmussen, R., and C. Liu. 2017. *High Resolution WRF Simulations of the Current and Future Climate of North America*. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D6V40SXP. Accessed† dd mmm yyyy.