Modeling Mesoscale Convective Systems

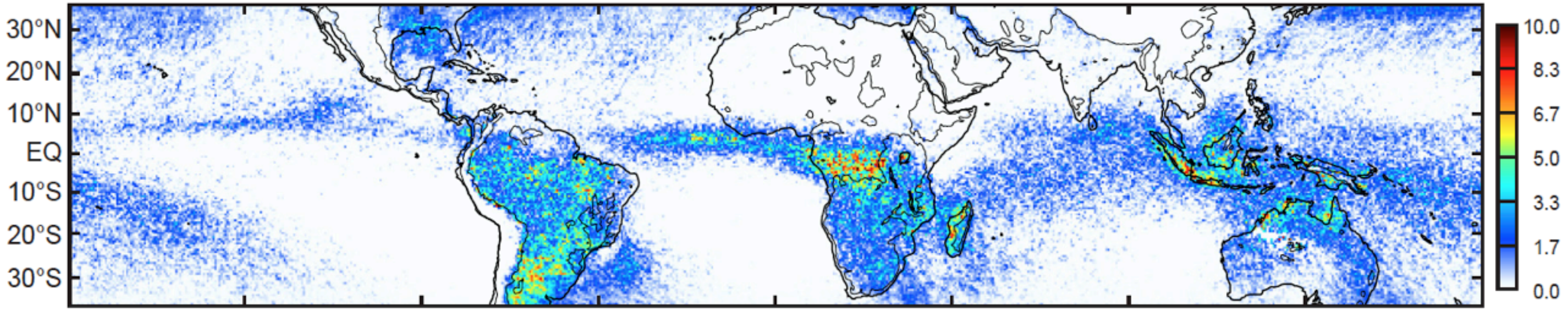
L. Ruby Leung
Pacific Northwest National Laboratory, Richland, WA

GEWEX SSG meeting, 25-28 February, 2019, Geneva, Switzerland

MCSs are ubiquitous in the global tropics

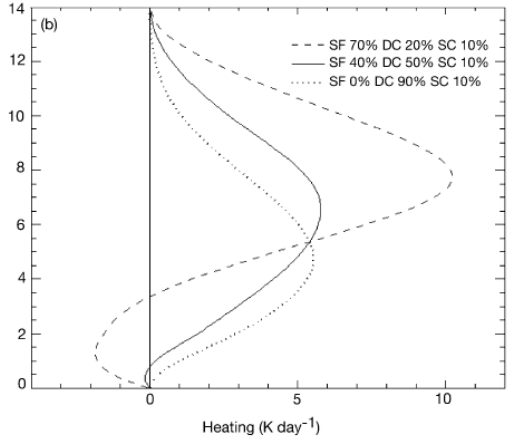
- Mesoscale convective systems (MCSs) account for ~ 50-60% of tropical rainfall
- The top heavy heating profile of MCSs produces robust upper-level circulation

Frequency of occurrence of proxy of mature MCSs in DJF

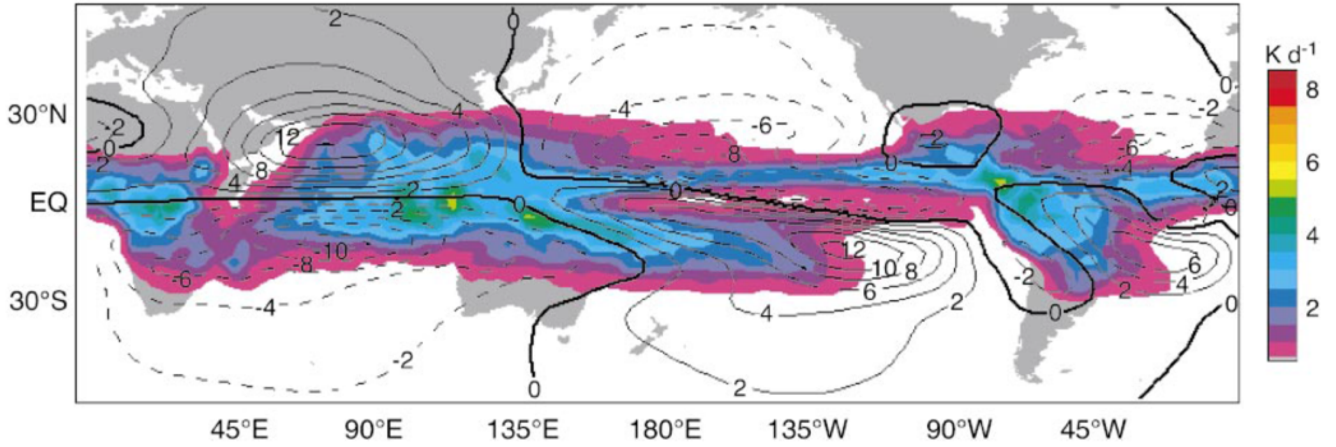


(Houze et al. 2015 Rev. Geophys.)

Latent heating profiles



400-hPa latent heating and 250-hPa streamfunction anomalies



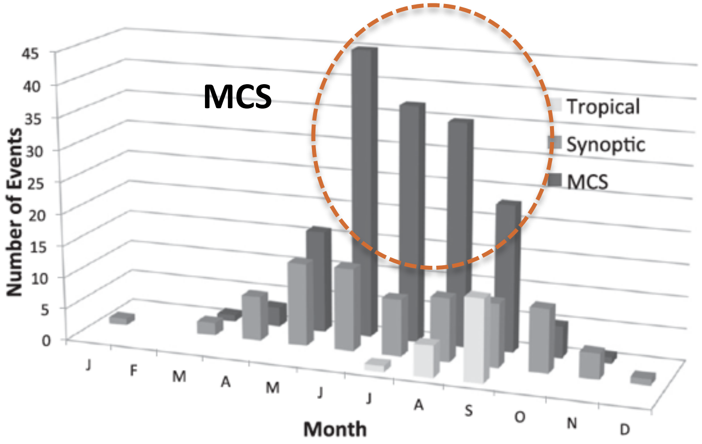
(Schumacher et al. 2004 JAS)

MCSs produce severe weather and flooding over the US

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

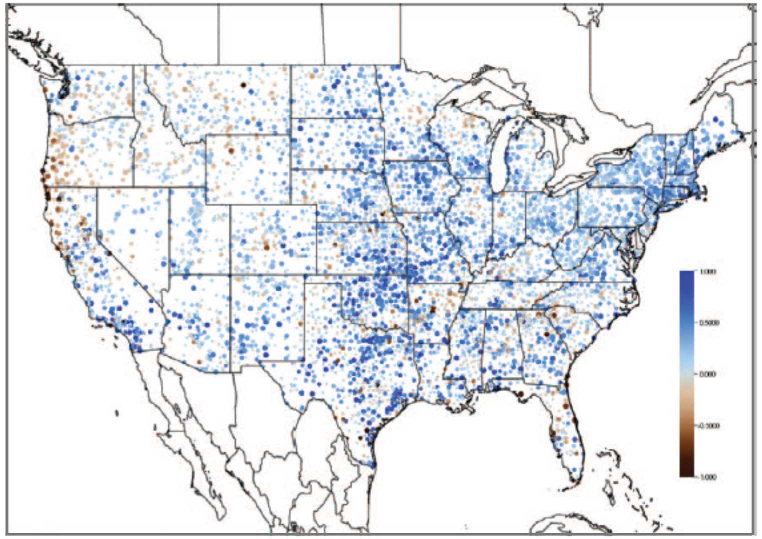
- MCSs produce 30-70% warm season rainfall and over half of the extreme daily rainfall in the US Great Plains
- Observed extreme rainfall in central U.S. has been increasing in the past several decades
- Have MCSs changed in the past, and how will they change in the future?

Extreme event types in Central and Eastern US



(Stevenson & Schumacher 2014 *MWR*)

Changes in observed 20-yr return value of daily precipitation (1948-2010)

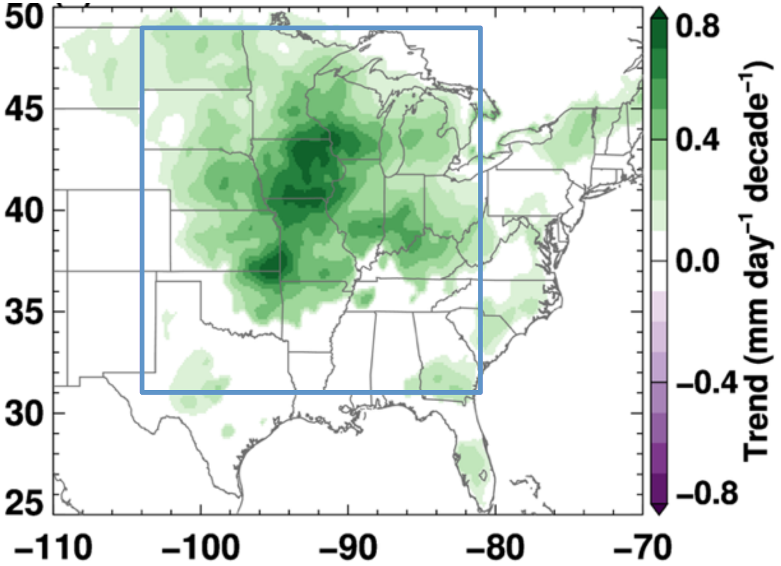


(Kunkel et al. 2013 *BAMS*)

Changes in MCS rainfall and characteristics in the past decades

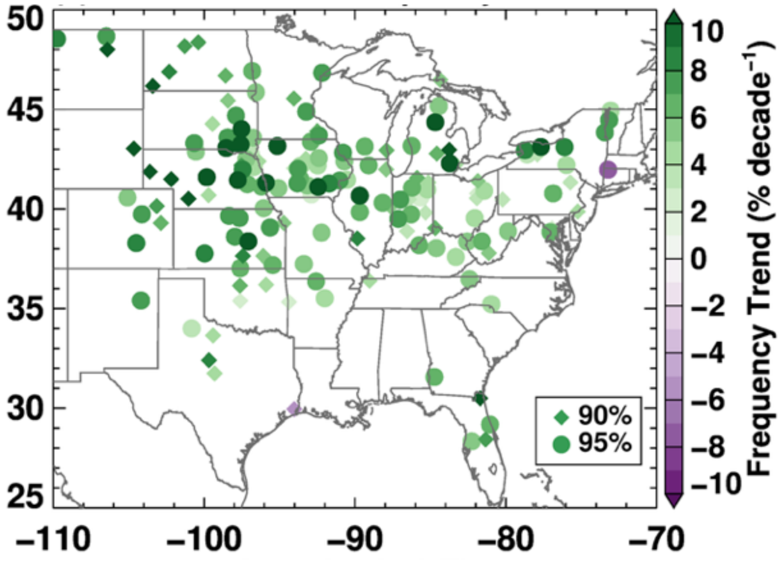
Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Trend in MCS mean rainfall in spring



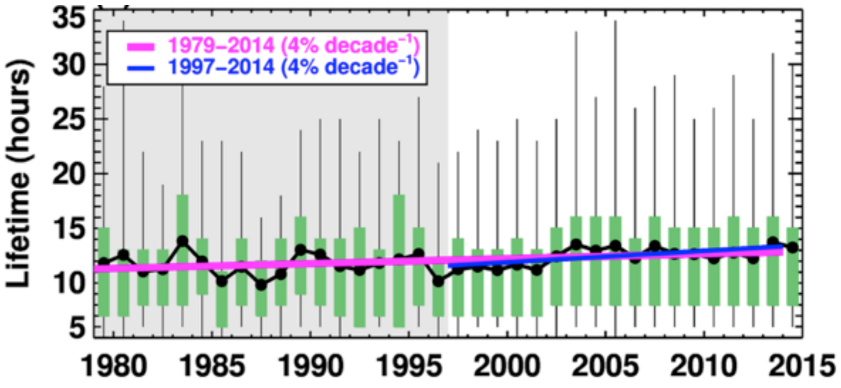
- Some regions in Midwest experienced 0.4-0.8 mm day^{-1} per decade (20-40%) increase in MCS precipitation between 1979-2014

Trend in 95% exceedance frequency



- 95th percentile MCS hourly rain-rate increased

Trend in MCS lifetime



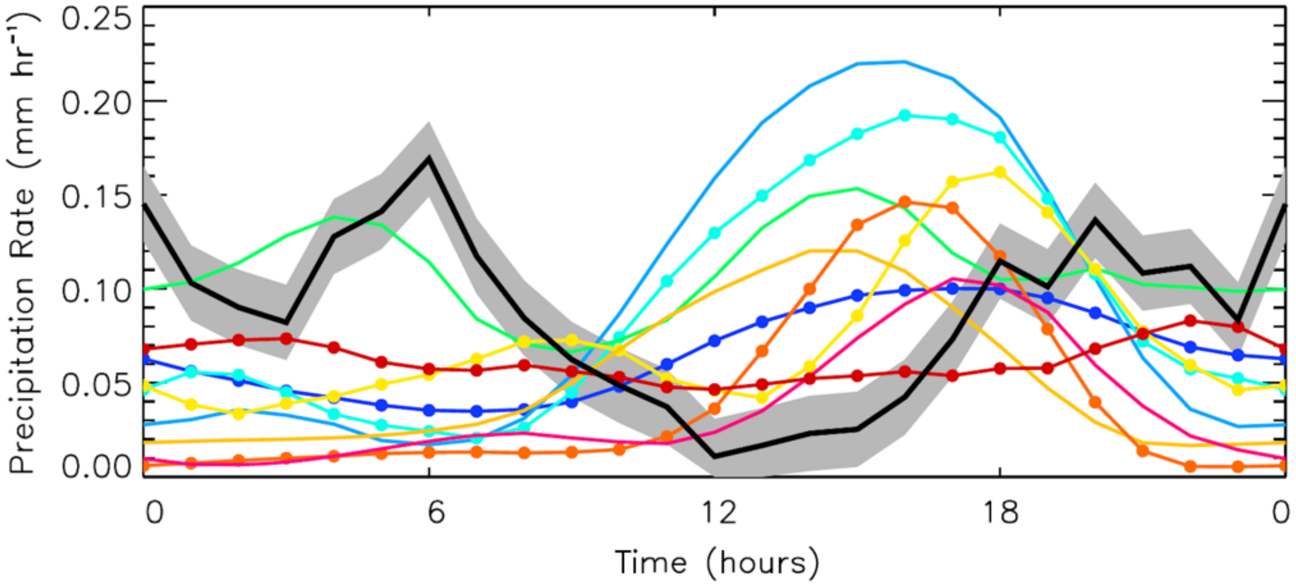
- Averaged MCS lifetime increases by 4% per decade, long-lasting MCS increases by 7% per decade

(Feng et al. 2016 *Nat. Commun.*)

Challenges for climate modeling

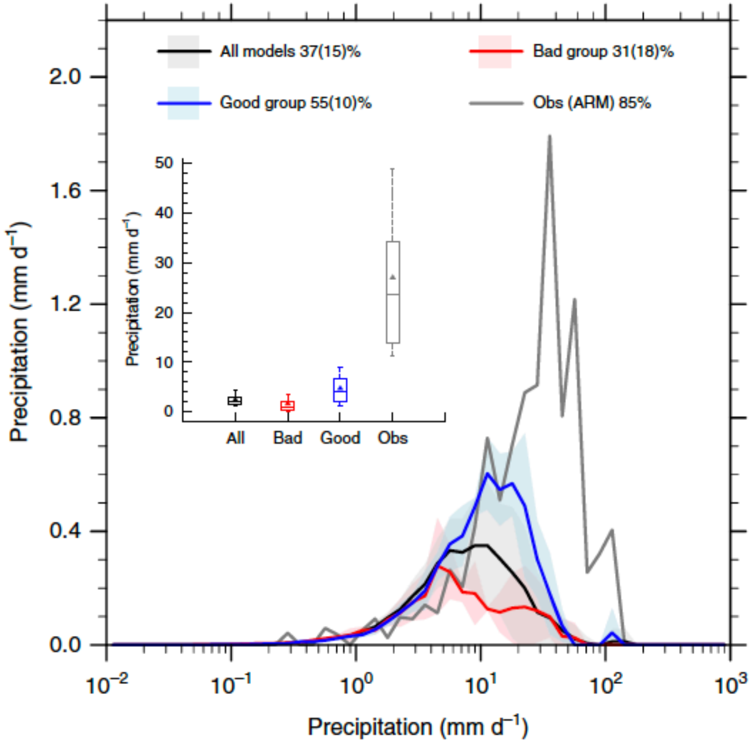
- Climate models with parameterized convection exhibit significant biases in simulating precipitation (mean, diurnal cycle, intensity) and surface temperature

Diurnal cycle of precipitation in central U.S.



(VanWeverberg et al. 2017 *JGR-A*)

Daily precipitation distribution



(Lin et al. 2017 *Nat. Commun.*)

A fundamental challenge

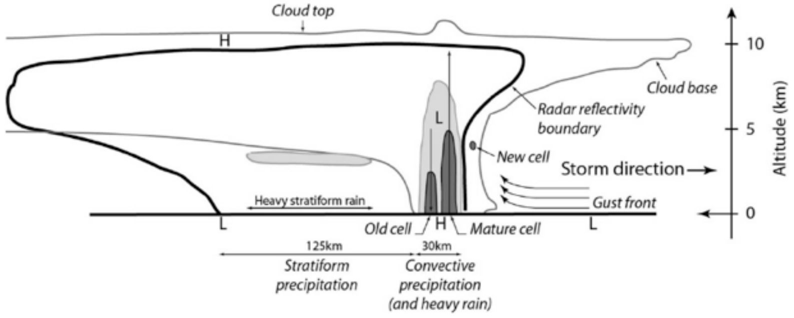
Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Resolving storm structures and two-way interactions may be key to modeling precipitation and circulation in the tropics and mid-latitude during warm season

Cloud microphysics and convection parameterizations

Large-scale circulation

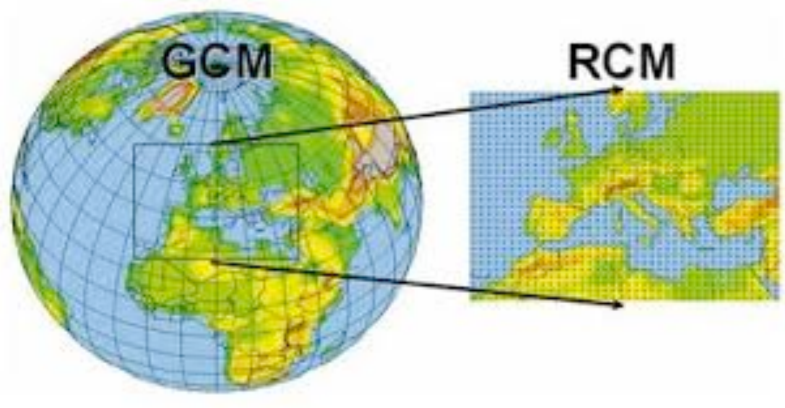
Precipitation



Modeling MCSs in climate models

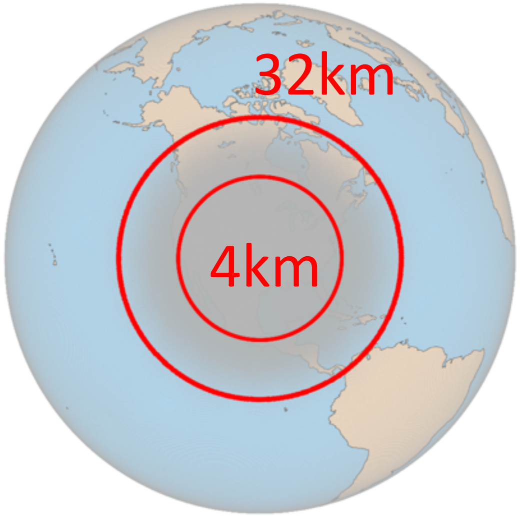
- Three modeling approaches with computational requirements within reach for climate simulations:

Limited area models



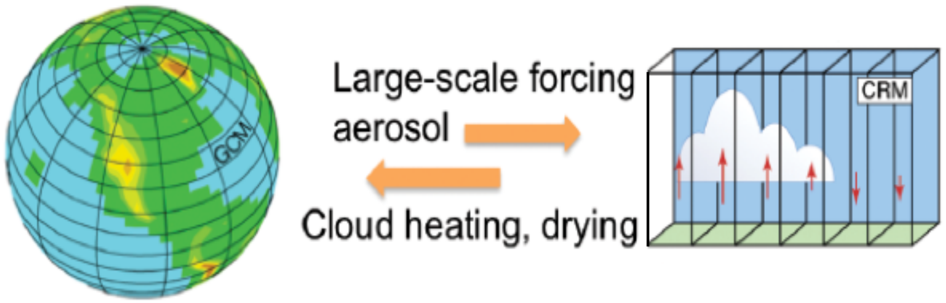
Weather Research and Forecasting (WRF)

Global variable resolution models



Model for Prediction Across Scales (MPAS)

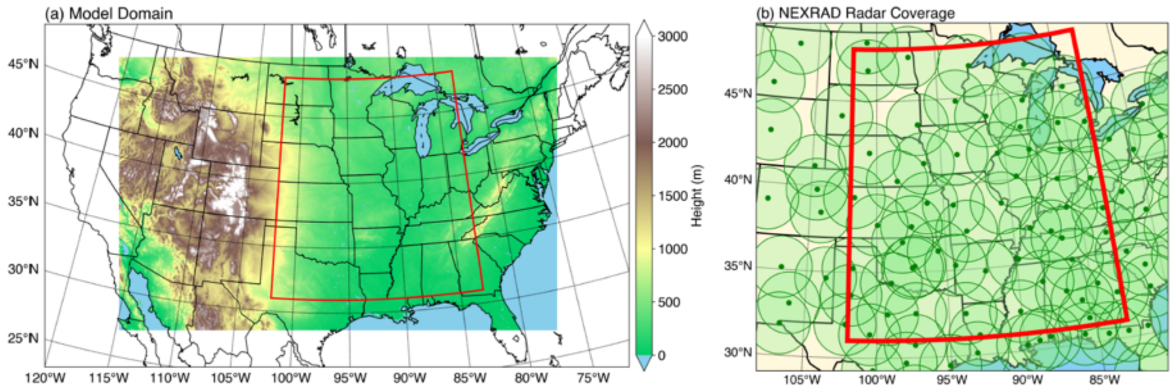
Multiscale Modeling Framework



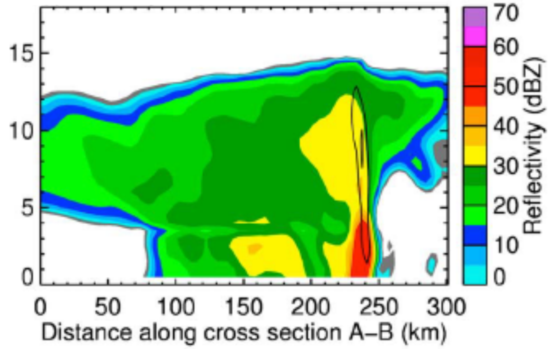
Superparameterized Energy Exascale Earth System Model (SP-E3SM)

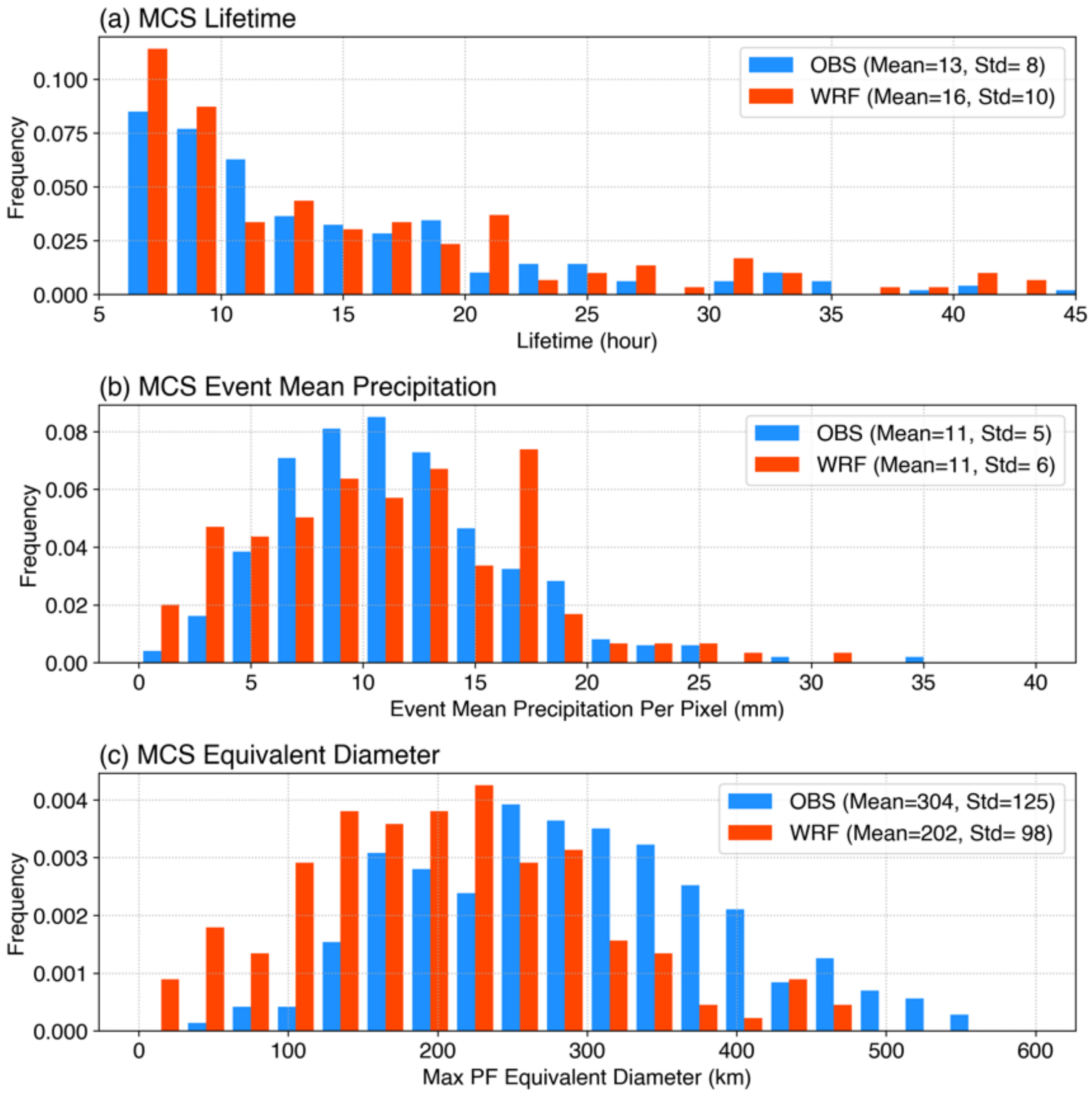
MCS characteristics reasonably simulated

- WRF convection permitting simulations at 4 km grid spacing for two warm seasons without convection parameterization
- Simulations reproduced observed MCS statistics



Radar reflectivity





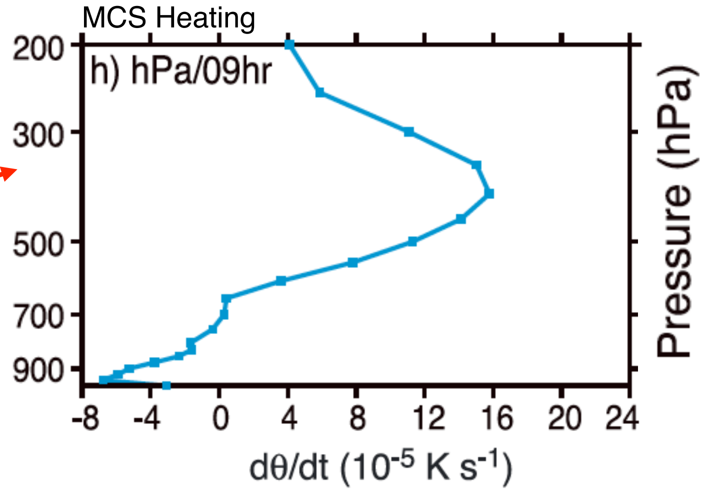
(Yang et al. 2017 *JGR*)

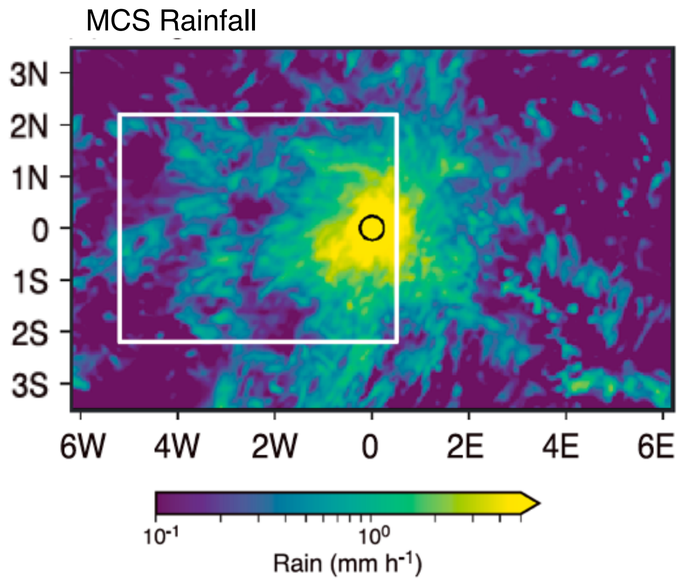
Positive feedback from long-lived MCSs to the environment supports their longevity

Interactions between MCSs and their large-scale environment

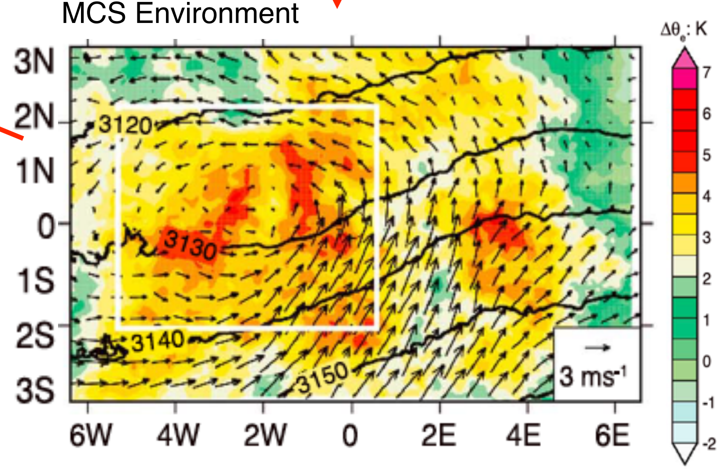
- Long-lived MCSs produce a midlevel circulation anomaly that maintains the MCSs and strengthens the environmental trough

MCS precipitation generates top-heavy heating profile





Top-heavy heating strengthens the mesoscale vortex

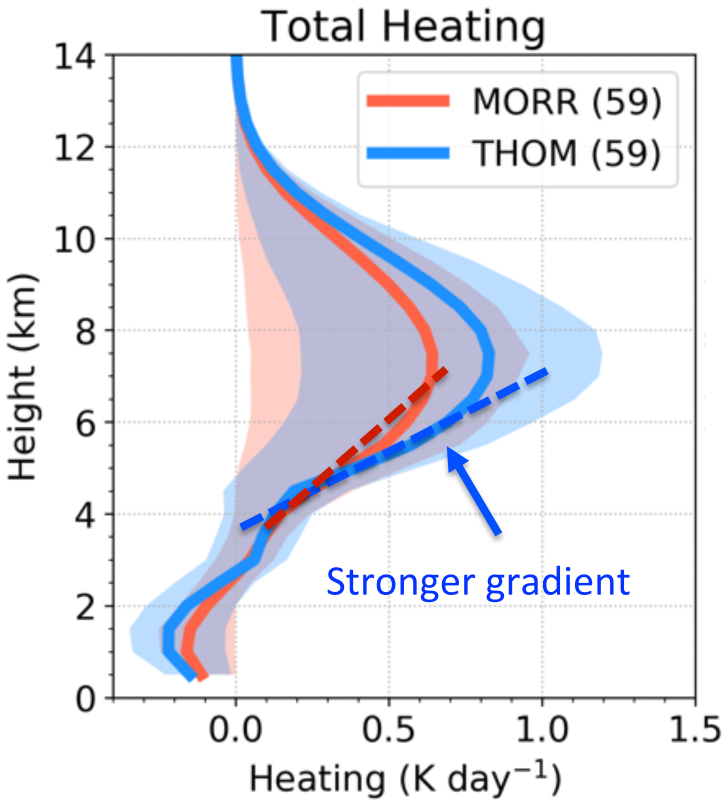


Mesoscale vortex feeds dry, cooler air that enhances evaporative cooling and prolongs the lifetime of MCS

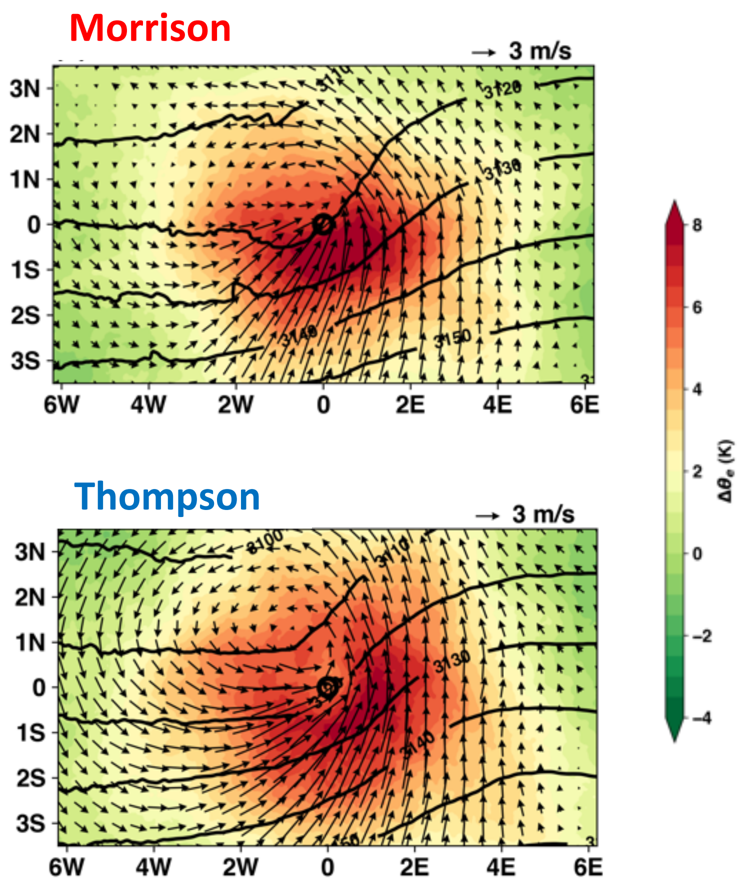
(Yang et al. 2017 *JGR*)

Microphysical influence on MCS evolution

- Comparing WRF convection permitting simulations with Morrison vs. Thompson microphysics schemes

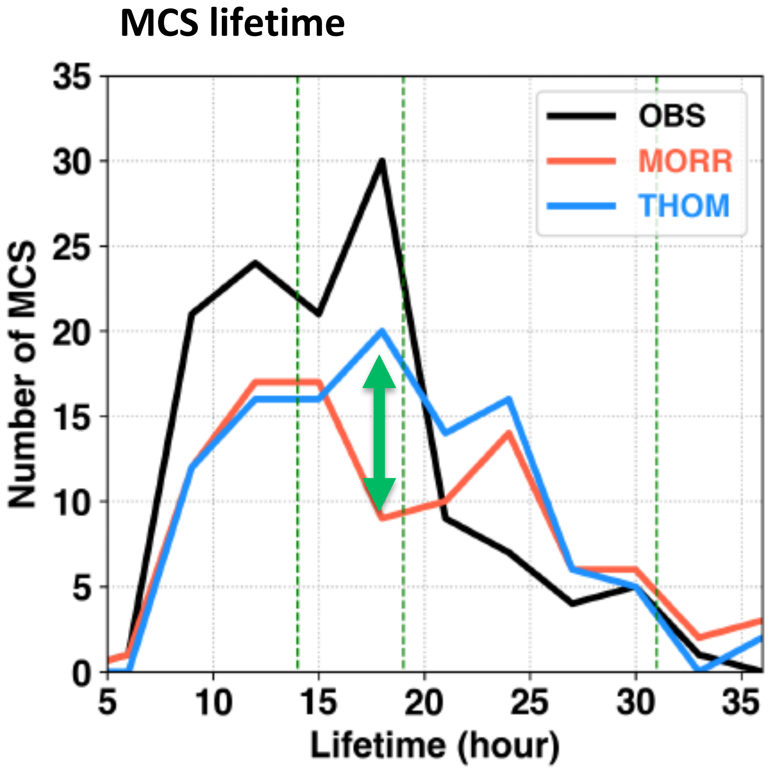


(Feng et al. 2018 *JAMES*)



700 hPa winds and equivalent potential temperature anomalies

Thompson produced more longer-lived MCSs that produced more precipitation



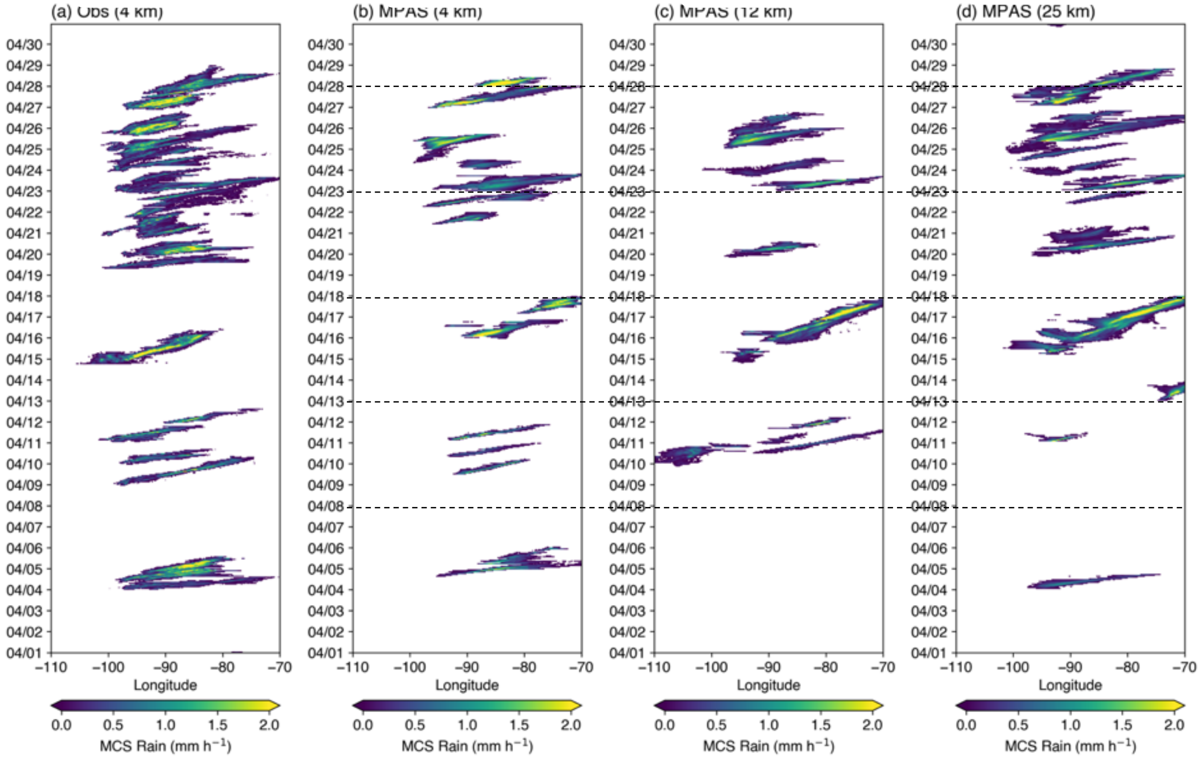
MCSs in April and August

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

- Model evaluation using initialized forecasts: 4 km (no CP), 12 and 25 km (with CP)

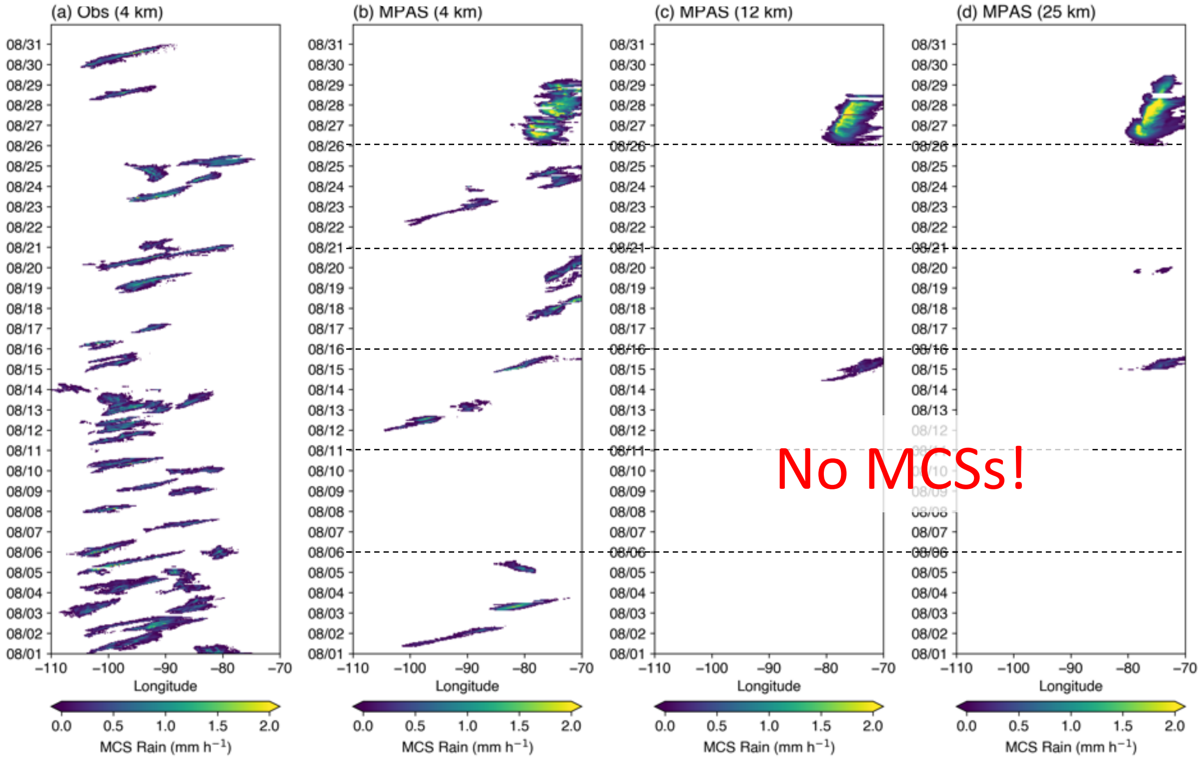
MCS precipitation in April

OBS | 4 km | 12 km | 25 km



MCS precipitation in August

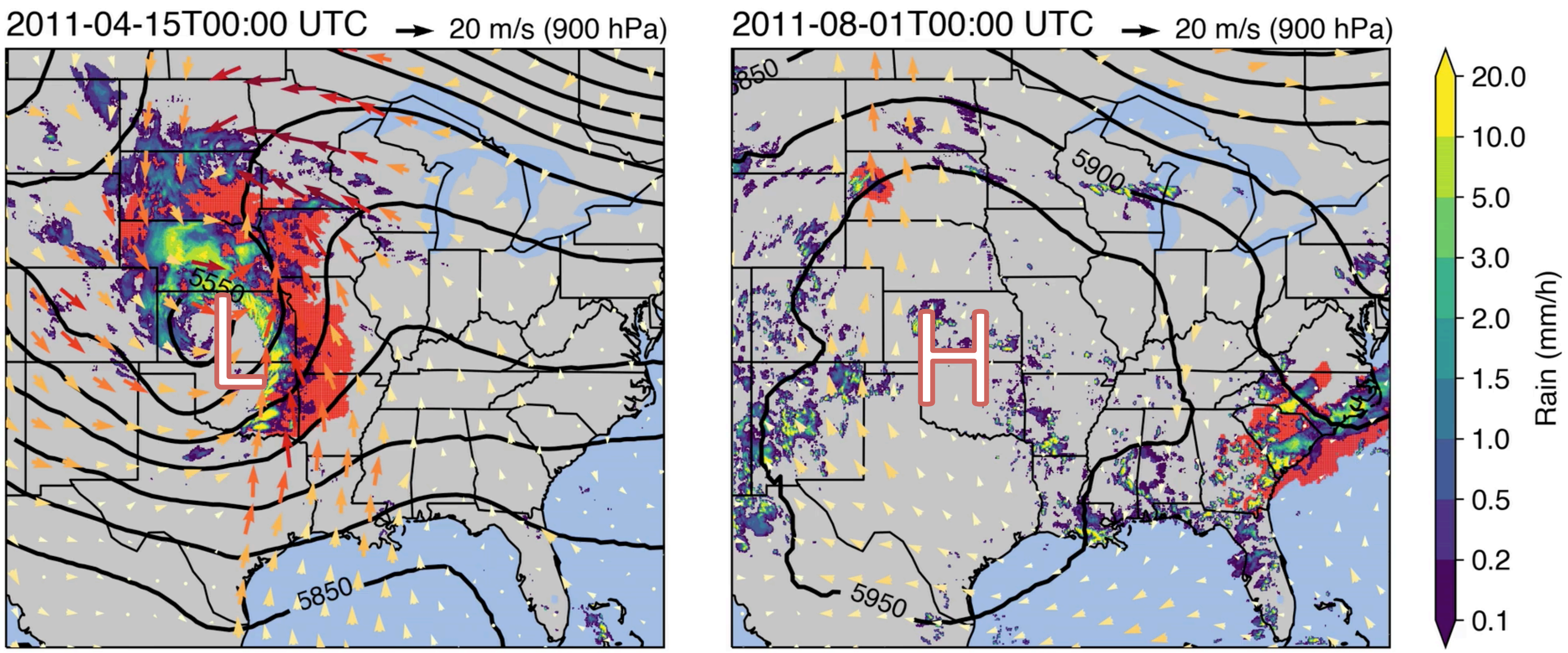
OBS | 4 km | 12 km | 25 km



MCS large-scale environment

- Strong baroclinic forcing and low level jet support MCS development in spring
- Only weak forcing such as mid-tropospheric perturbations is enough to support MCS development in a thermodynamically favorable environment in summer
- Limitations in GCM microphysics parameterizations may also be responsible for the biases

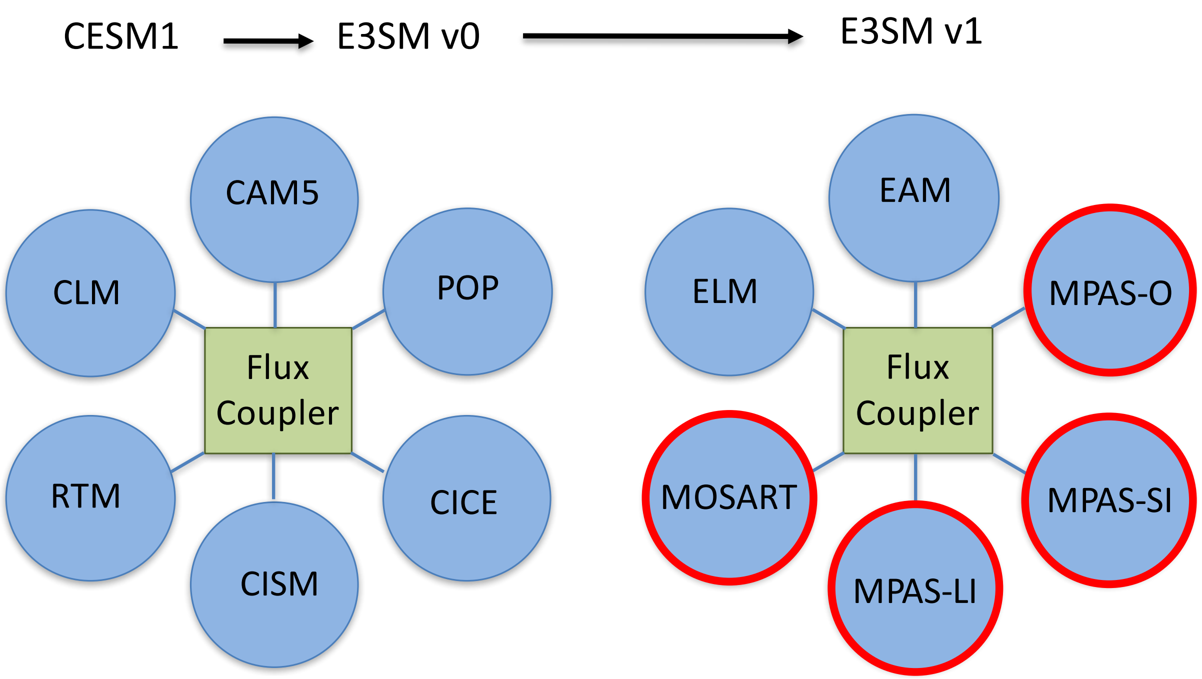
Strong synoptic forcing for an MCS in April **High pressure system and an MCS in August**



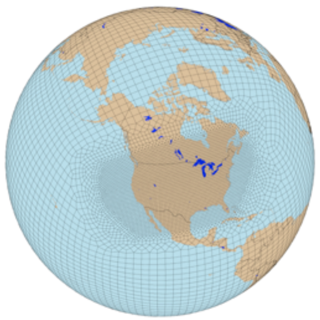
Energy Exascale Earth System Model (E3SM)

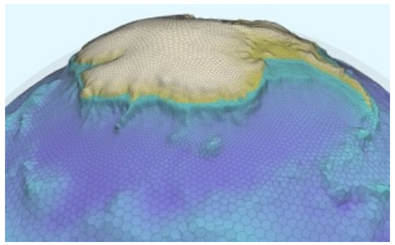
- E3SM v1 includes a low resolution (LR ~ 100 km) and a high resolution (HR ~ 25 km) configuration
- A “proof-of-concept” regional refinement model (RRM) with 25 km over North America and 100 km outside has been tested, but improvements are minimal in the Great Plains

Released April 2018

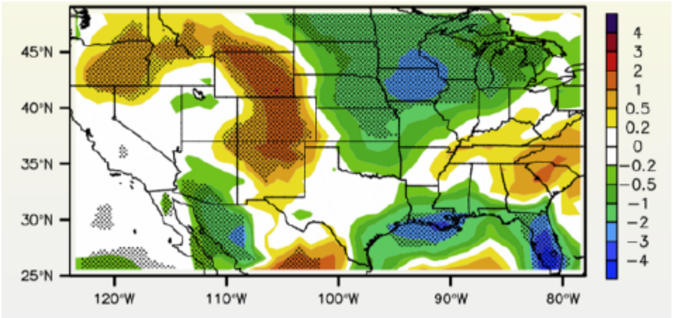


Unstructured grids allowing regional refinement in all model components

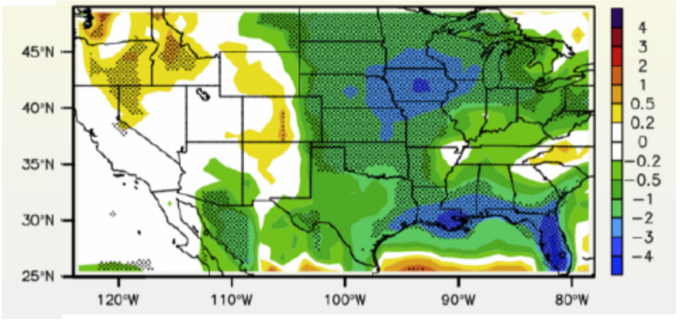




LR - GPCP   mm/day



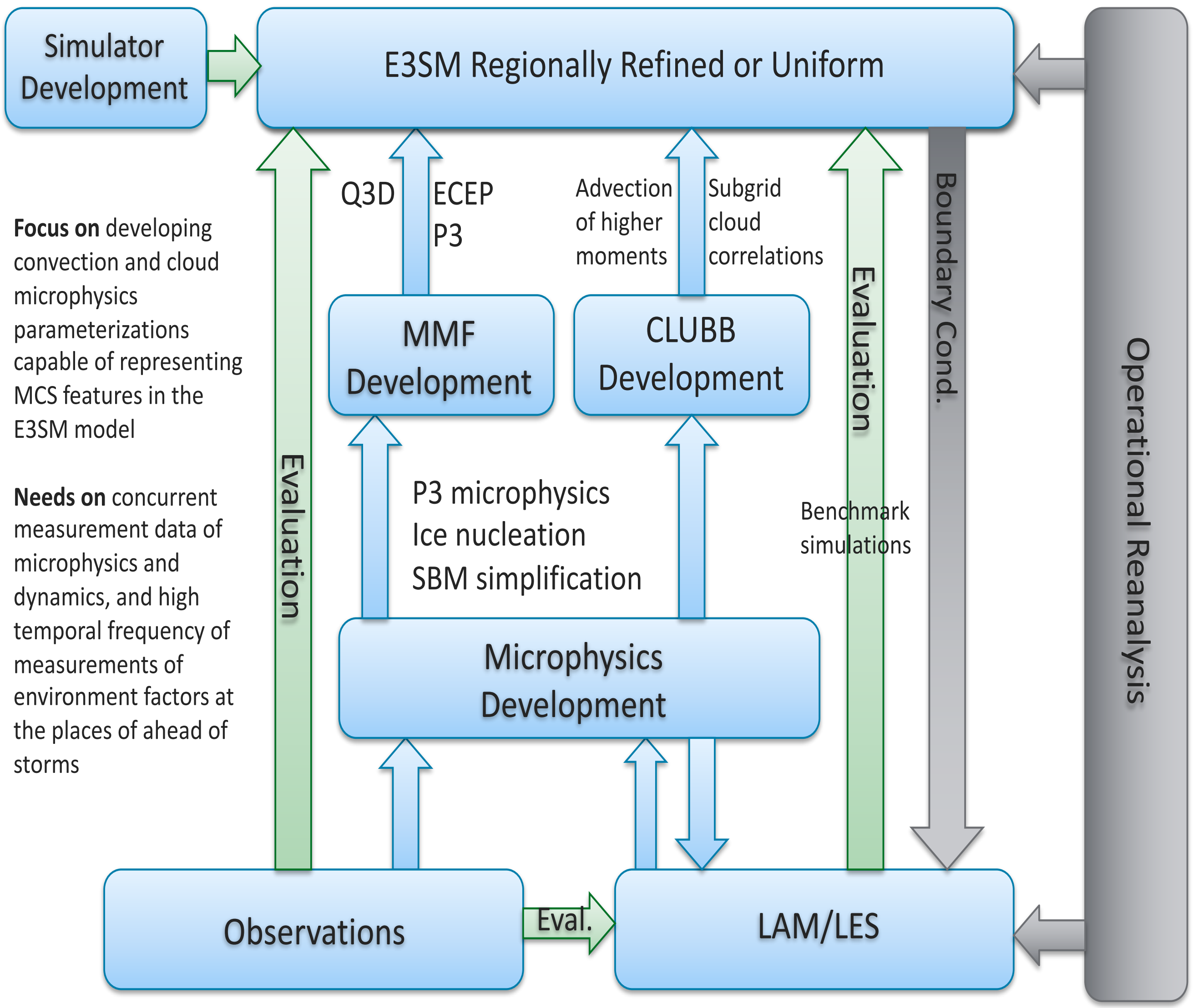
RRM - GPCP   mm/day



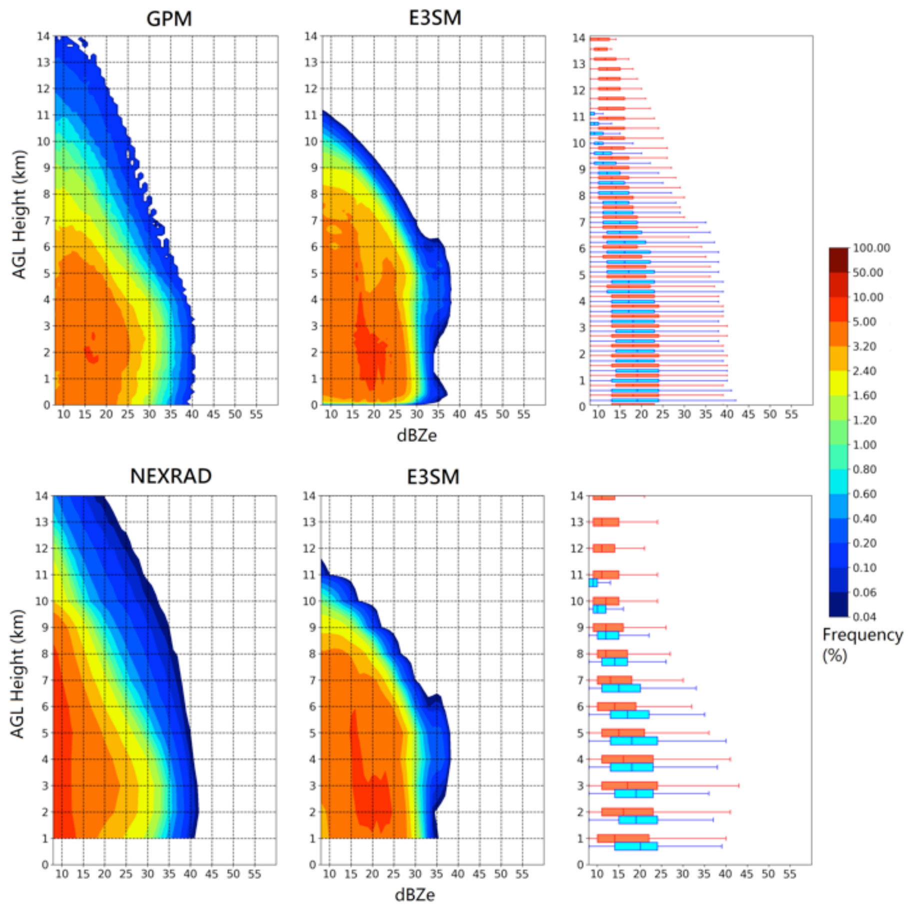
Climate Model Development and Validation (CMDV-MCS) project

Focus on developing convection and cloud microphysics parameterizations capable of representing MCS features in the E3SM model

Needs on concurrent measurement data of microphysics and dynamics, and high temporal frequency of measurements of environment factors at the places of ahead of storms



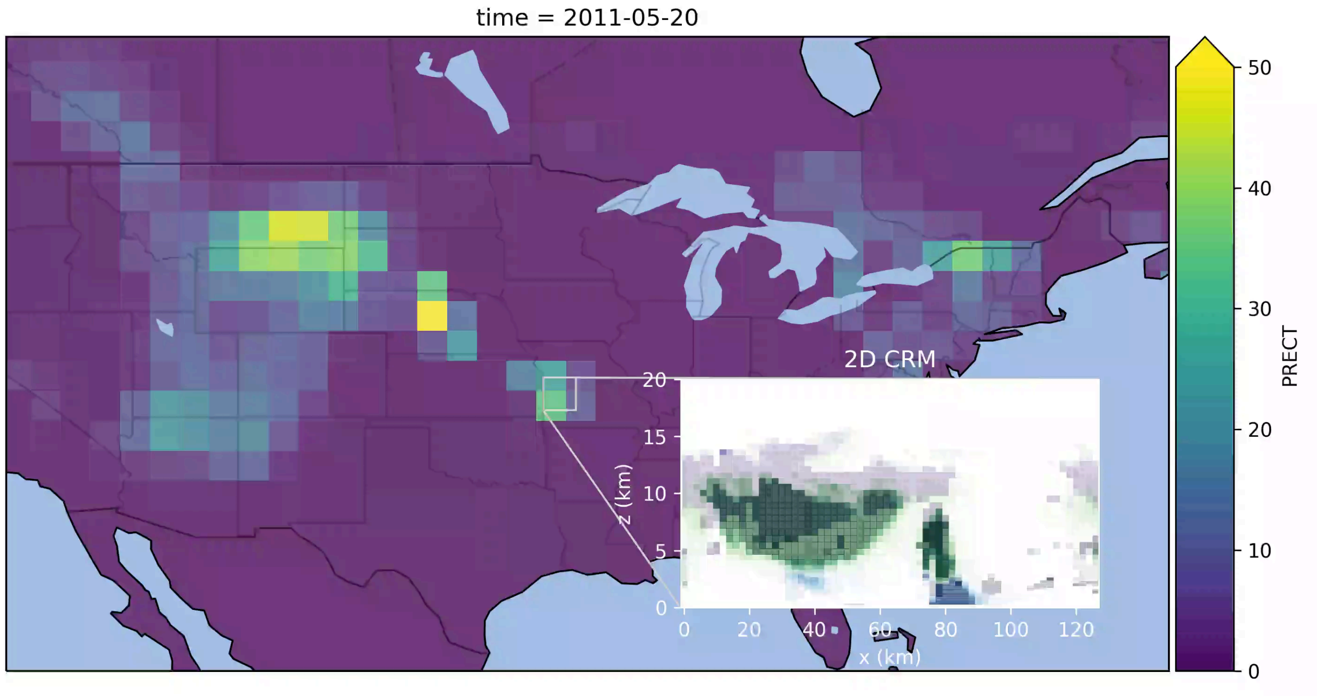
Evaluation of E3SM using GPM and NexRAD



(Source: Steve Ghan and Jiwen Fan)

E3SM-MMF and global cloud resolving modeling

E3SM-MMF (ongoing testing of MMF embedded in E3SM at 30km grid spacing)

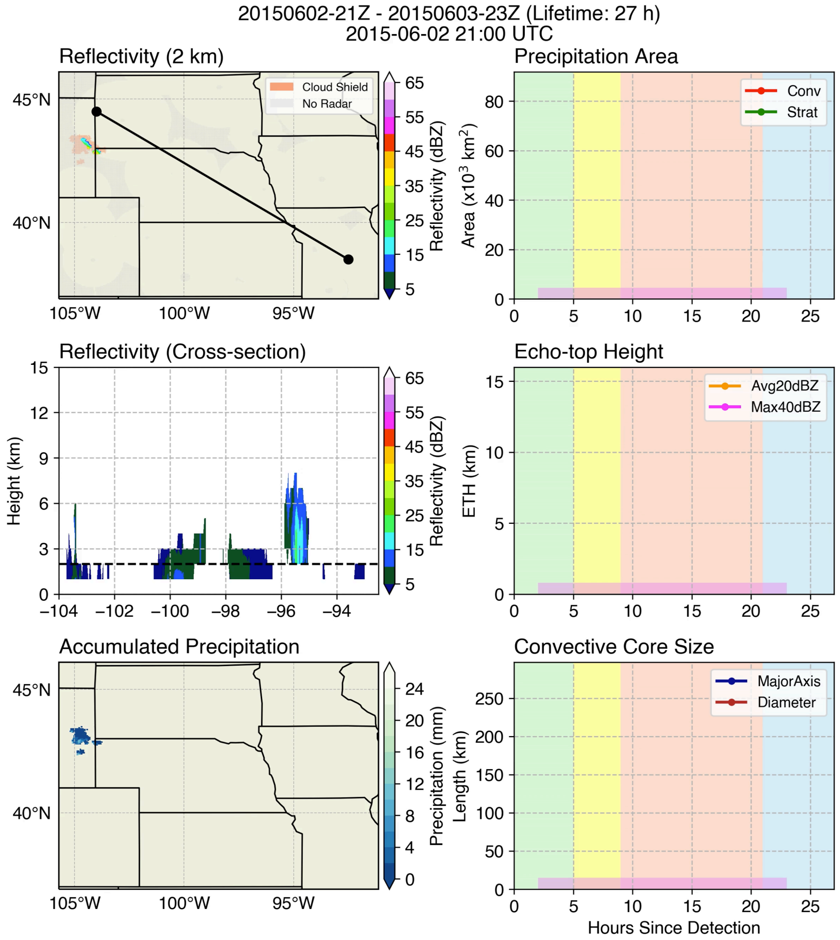


Development of a global cloud resolving model with RRM for testing

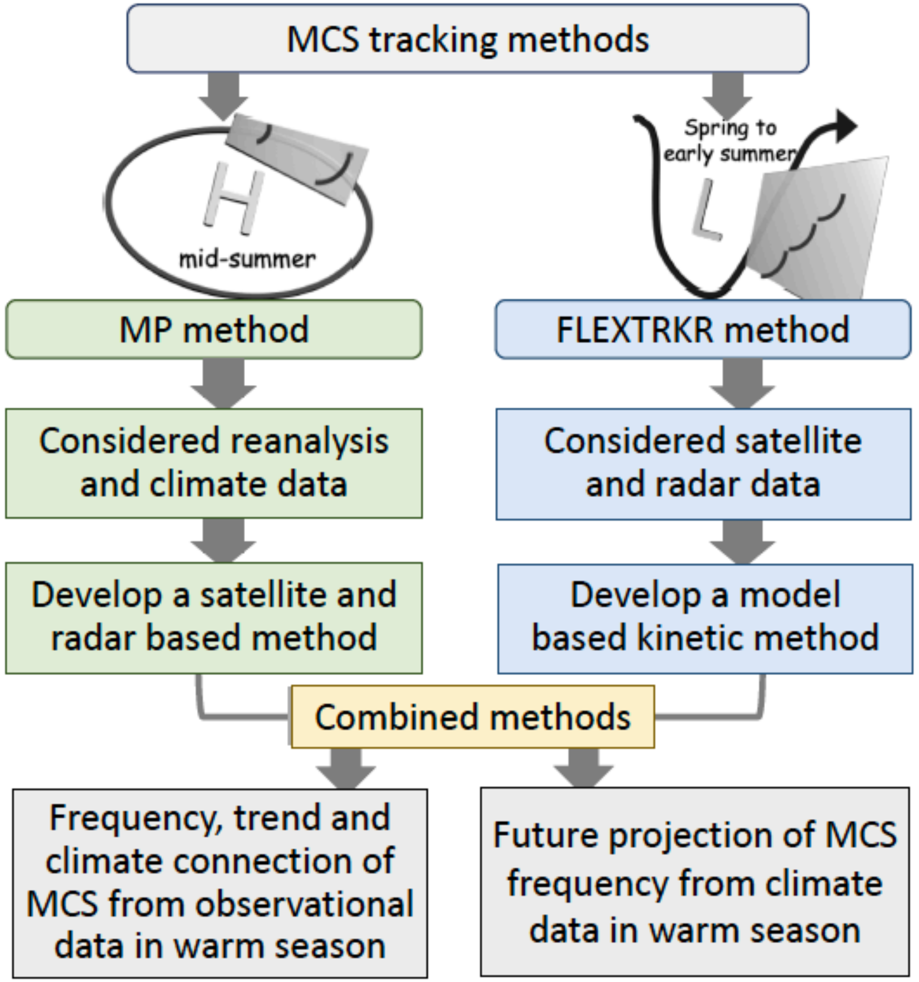
- Nonhydrostatic spectral element dynamical core at 3 km grid spacing
- Dynamical core being ported to GPU and rewritten in C++
- Coupled with existing physics parameterizations
- Development of new physics parameterization more suitable for cloud resolving applications

Ongoing work: Characterizing MCSs globally

- Track MCSs using global geostationary data and GPM dual-frequency precipitation radar (DPR) overpass data to construct a global "hybrid tracking-overpass" MCS database



- Development of MCS tracking and metrics



Ongoing work: Characterizing impacts of MCSs on surface water budgets and flooding in the U.S.

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

- Use water tagging combined with the U.S. MCS database to trace MCS precipitation through surface and subsurface processes in land surface models
- Use coupled models to quantify the impacts of MCSs on the terrestrial water balance and land-atmosphere interactions
- Relate MCS characteristics and antecedent soil moisture to flooding

Recipe of flash flooding

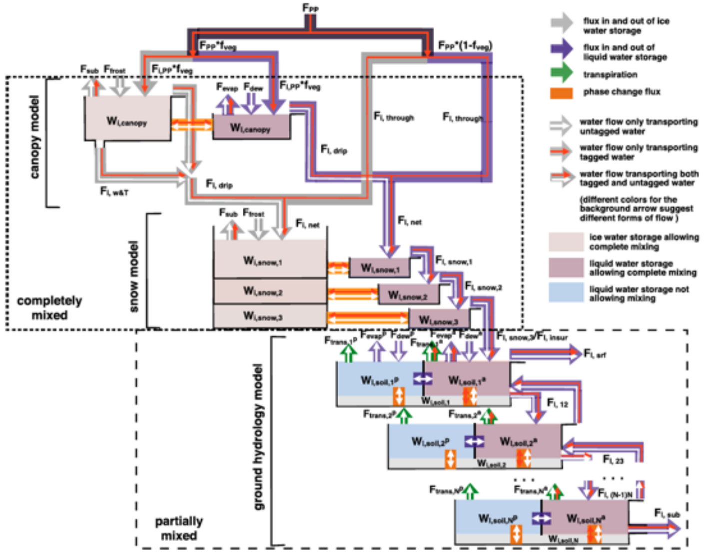
Ingredients:

- Heavy precipitation
- Deep moist convection
- System movement and size
- Storm types

(Doswell et al. 1996 *WAF*)

A land surface hydrological view is missing

Water tagging in a land surface model



(Hu et al. 2018 *JHM*)

Summary

- MCSs are ubiquitous and play important roles in precipitation and large-scale circulation
- Most climate models do not simulate MCSs, as evidenced by their dry/warm biases and erroneous diurnal cycle of precipitation
- Convection permitting modeling holds some promises to simulate MCS cloud structures – important connections between large-scale circulation and precipitation
- Different approaches are being developed and tested
- MCS tracking, MCS data base, and MCS metrics are being developed to support analysis and modeling