Predicting Extreme Climate with Earth System Models

A Top-Down Look at the Southern Great Plains

Minghua Zhang

Stony Brook University

1. **Introduction on extremes**
2. **Multi-scale interactions as sources of uncertainties**
3. **The Southern Great Plains**
4. **Uncertainties in future projections**
5. **Summary**

Definition of Extremes:

1. **Absolute indices, e.g., hottest or coldest temperature of a year, maximum 1 day or 5-day precipitation rates**
2. **Threshold indices, e.g. number of days when a fixed temperature or precipitation threshold is exceeded**
3. **Duration indices, e.g., length of wet and dry spells, or warm and cold spells**
4. **Percentile-based threshold indices, e.g., exceedance rates above or below a the 10th or 90th percentile in a reference base period**

Examples Extreme Indices (ETCCD)

Indicator name	Abbrev.	Definition
Frost days	FD	Number of days with $T_{min} < 0$ °C
Icing days	ID	Number of days with $T_{max} < 0$ °C
Summer days	SU	Number of days with $T_{max} > 25$ °C
Tropical nights	TR	Number of days with $T_{min} > 20$ °C
Cool nights	TN10p	% of days with $T_{min} <$ the historical 10th percentile value
Warm nights	TN90p	% of days with $T_{min} >$ the historical 90th percentile value
Cool days	TX10p	% of days with $T_{max} <$ the historical 10th percentile value
Warm days	TX90p	% of days with $T_{max} >$ the historical 90th percentile value
Maximum T_{min}	TNx	Monthly maximum value of T_{min}
Minimum T_{min}	TNn	Monthly minimum value of T_{min}
Maximum T_{max}	TXx	Monthly maximum value of T_{max}
Minimum T_{max}	TXn	Monthly minimum value of T_{max}
Diurnal range	DTR	Monthly mean difference between daily T_{max} and T_{min}
Growing season length	GSL	Number of days between the first 6-day span with daily mean temperature above 5 °C and the first span after July 1 (in NH) with daily mean temperature below 5 °C
Warm spell duration index	WSDI	Annual count of at least six consecutive days with $T_{max} >$ the historical 90th percentile value
Cold spell duration index	CSDI	Annual count of at least six consecutive days with $T_{min} <$ the historical 10th percentile value
Maximum 1-day precipitation	RX1day	Monthly maximum 1-day precipitation (mm)
Maximum 5-day precipitation	RX5day	Monthly maximum consecutive 5-day precipitation amount (mm)
Simple daily intensity index	SDII	Mean precipitation amount on wet days (mm)
Number of heavy precipitation events	R10	Annual count of days with precipitation > 10 mm
Number of very have precipitation days	R20	Annual count of days with precipitation > 20 mm
Consecutive dry days	CDD	Maximum number of consecutive days with precipitation < 1 mm
Consecutive wet days	CWD	Maximum number of consecutive days with precipitation > 1 mm
Very wet days	R95p	Annual total precipitation derived from days > 95th percentile
Extremely wet days	R99p	Annual total precipitation derived from days > 99th percentile
Annual total precipitation	PRCPTOT	Annual total precipitation on all days.

(Schoof et al. 2016)

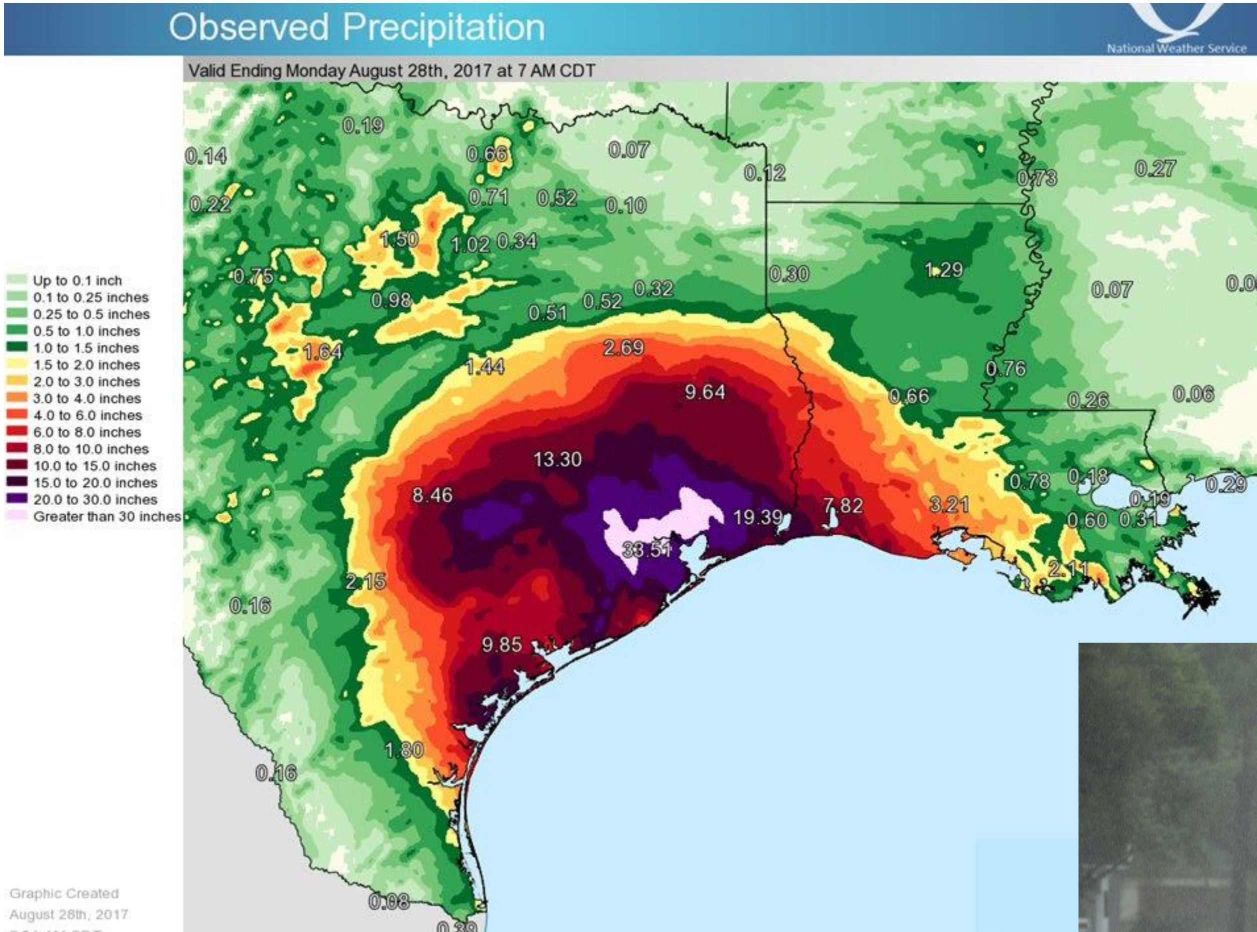
- **Extremes are often driven by interactions of systems with different temporal and spatial scales**

- **Extremes are application-specific**

All these require ESM


U.S. HURRICANE LANDFALLS
2017
HARVEY (CAT. 4)
ROCKPORT, TEXAS
AUG. 25
NATE (CAT. 1)
LA/MS
OCT. 7-8
IRMA (CAT. 4)
SOUTH FLORIDA
SEP. 10
MARIA (CAT. 4)
PUERTO RICO
SEP. 20
The Weather Channel

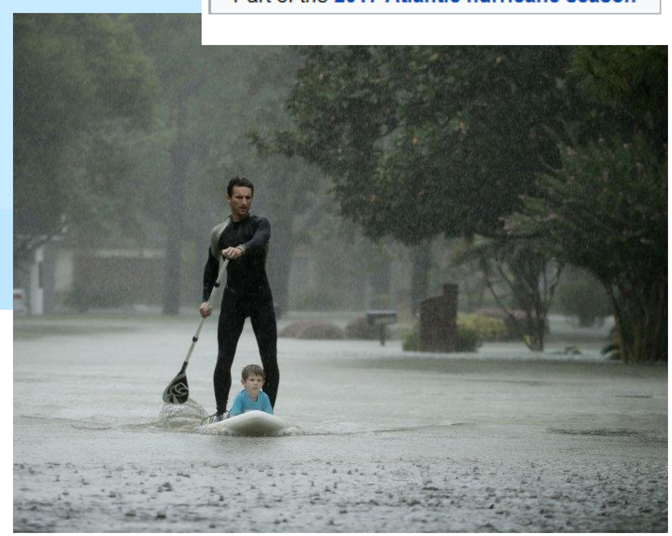
Hurricane Harvey



Hurricane Harvey at peak intensity, prior to landfall in southern Texas on August 25

Formed	August 17, 2017
Dissipated	September 3, 2017 (Extratropical after September 1)
Highest winds	*1-minute sustained*: 130 mph (215 km/h)
Lowest pressure	938 mbar (hPa)
Fatalities	83 confirmed
Damage	≥ $70 billion (2017 USD) (Preliminary total; unofficially third-costliest tropical cyclone in U.S. history)
Areas affected	Windward Islands, Suriname, Guyana, Nicaragua, Honduras, Belize, Yucatán Peninsula, Southern and Eastern United States (especially Texas, Louisiana)

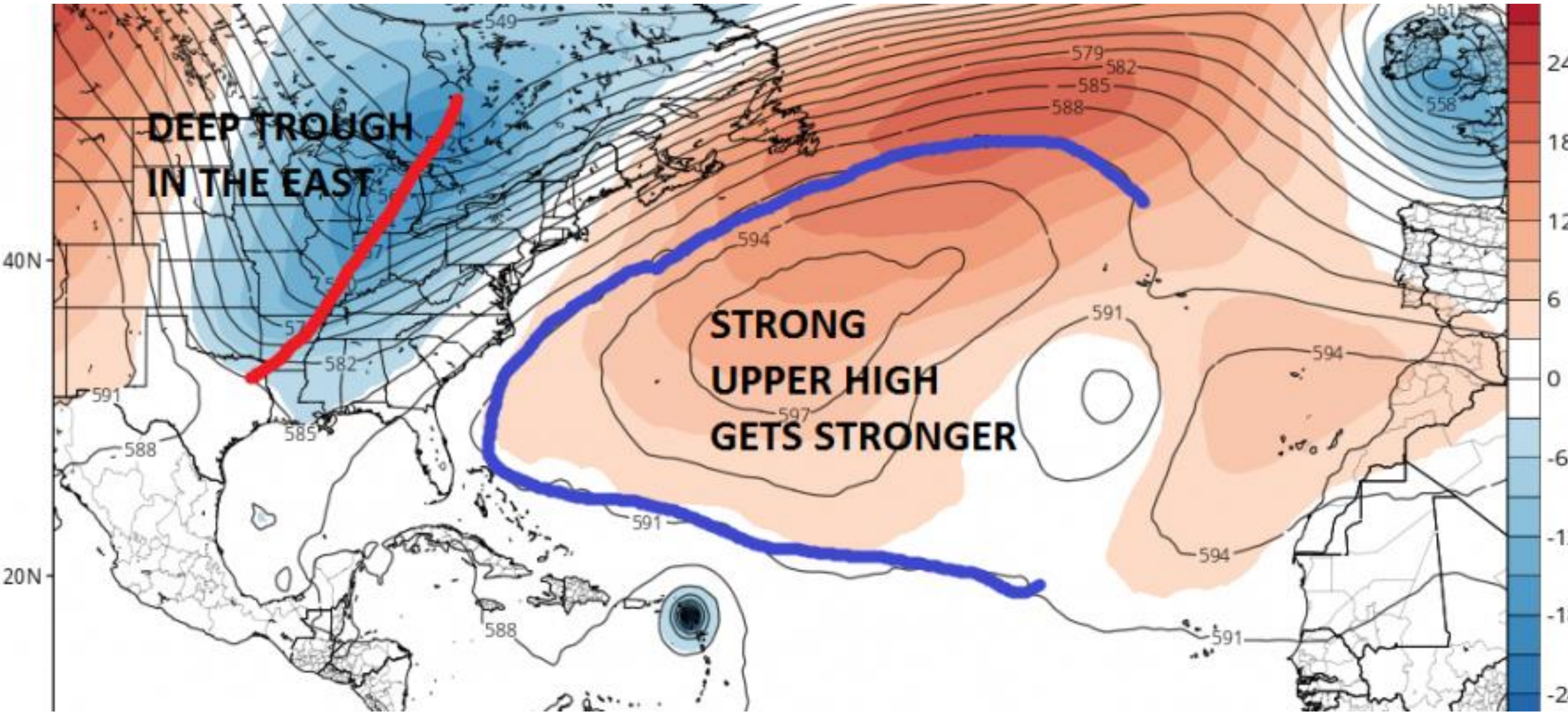
Part of the **2017 Atlantic hurricane season**



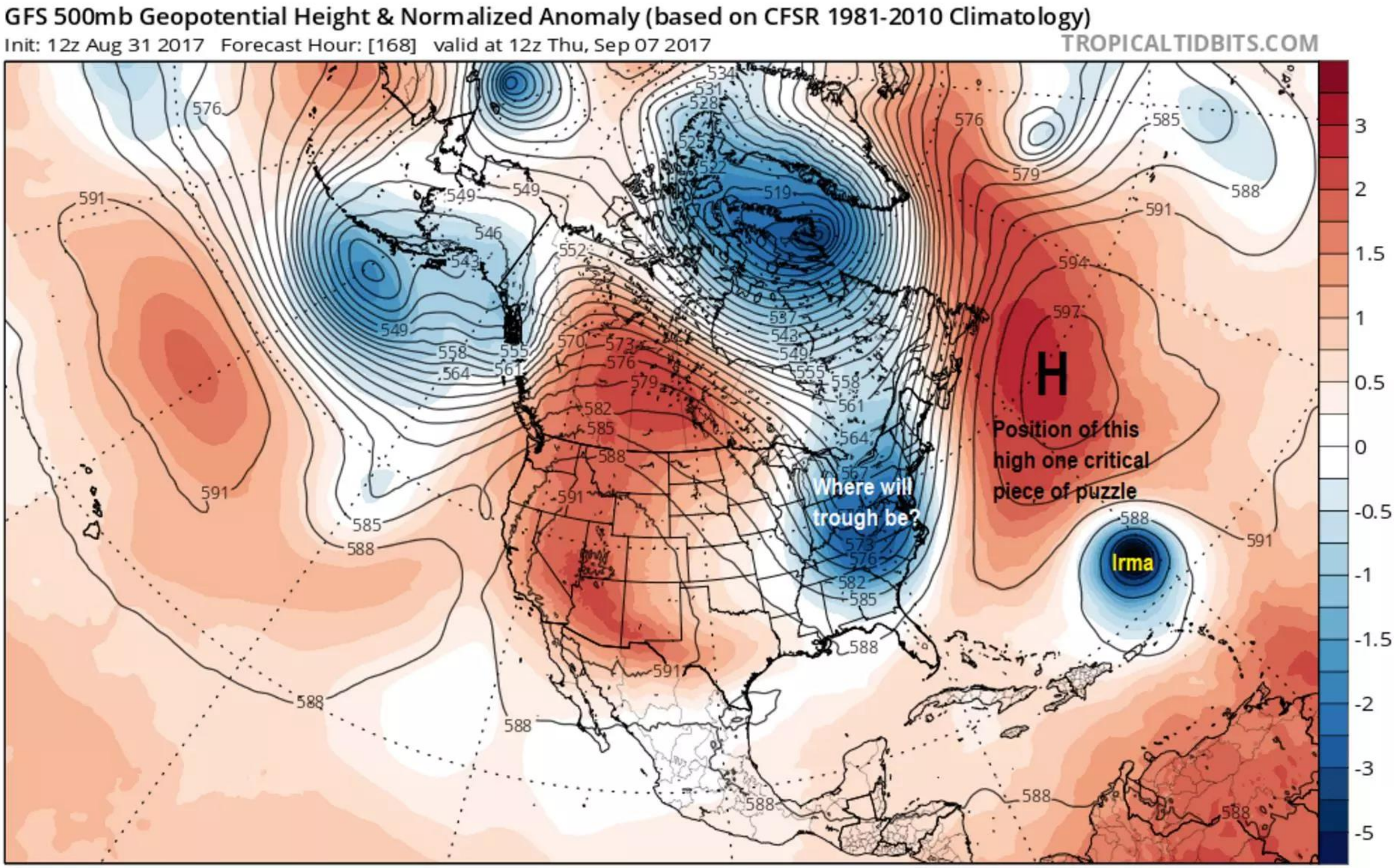
Maximum rainfall for a 4-day period > 1000 mm

Wettest tropical hurricane brought heavy Rain and caused catastrophic flooding

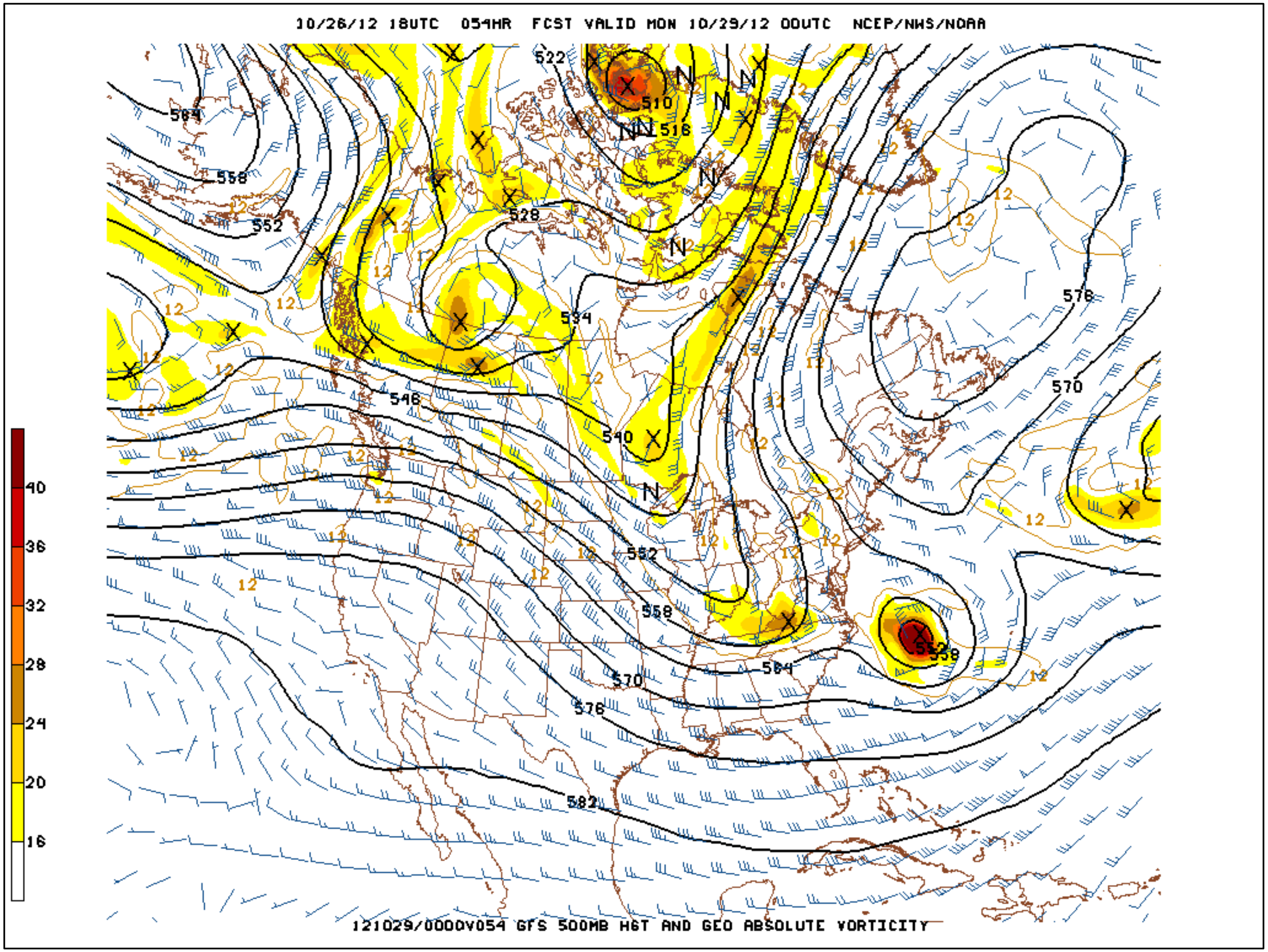
(Xia 2017)


DEEP TROUGH
IN THE EAST
STRONG
UPPER HIGH
GETS STRONGER
549
579
582
585
588
594
591
597
588
585
582
591
588
588
591
594
594
591
561
558
40N
20N
24
18
12
6
0
-6
-12
-18
-24

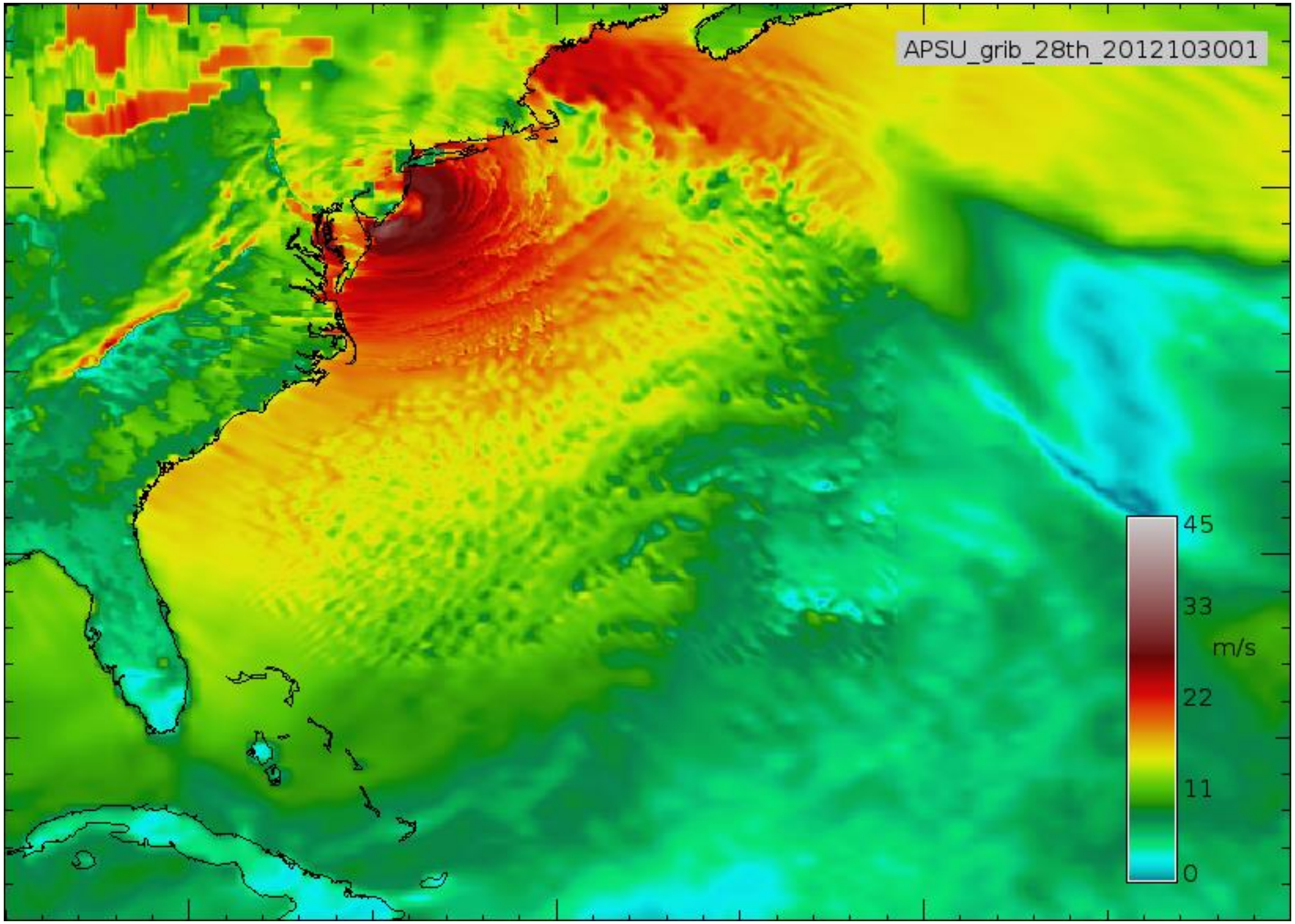
Hurricane Irma



Hurricane Sandy

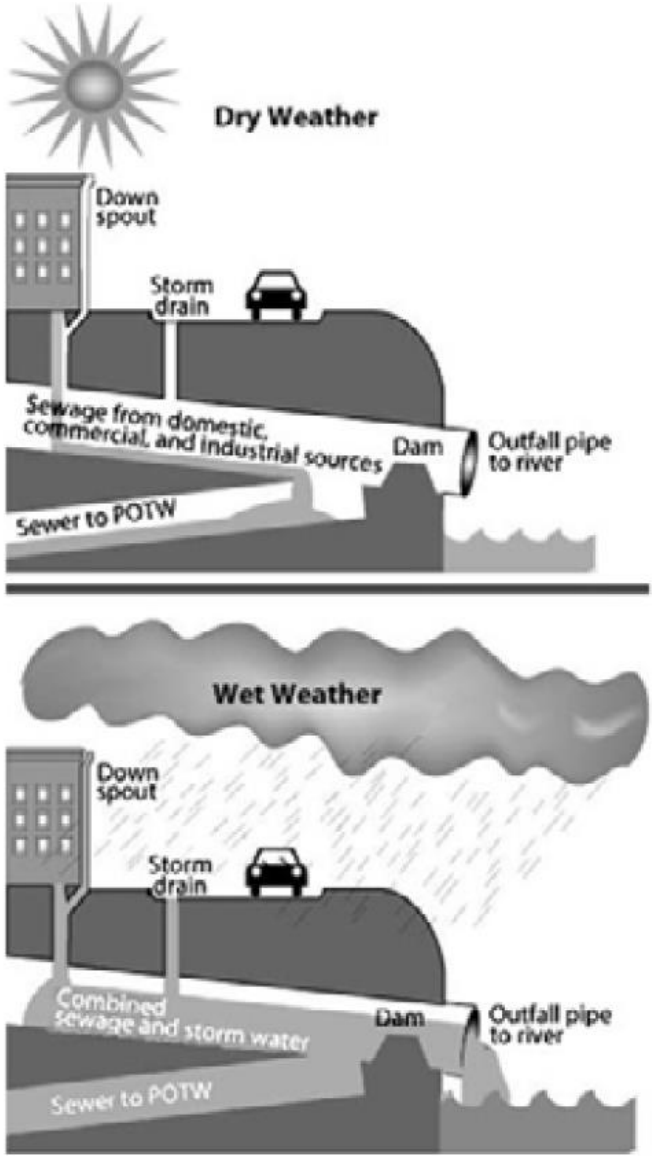


Hurricane Sandy Surface Wind Speed



Extremes are application specific

Sewage treatment plant as an example



(Kenward et al. 2013)

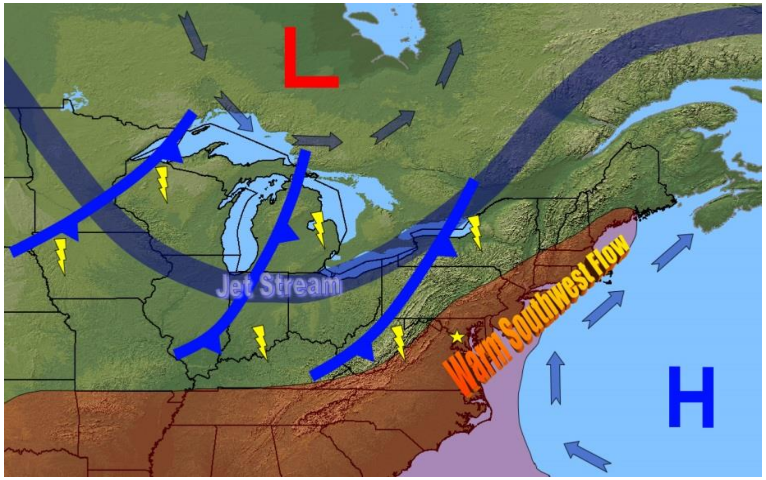
Overflow

Flooding

Multi-scale Interactions as Sources of Uncertainties

Multi-scale interactions

Planetary scale

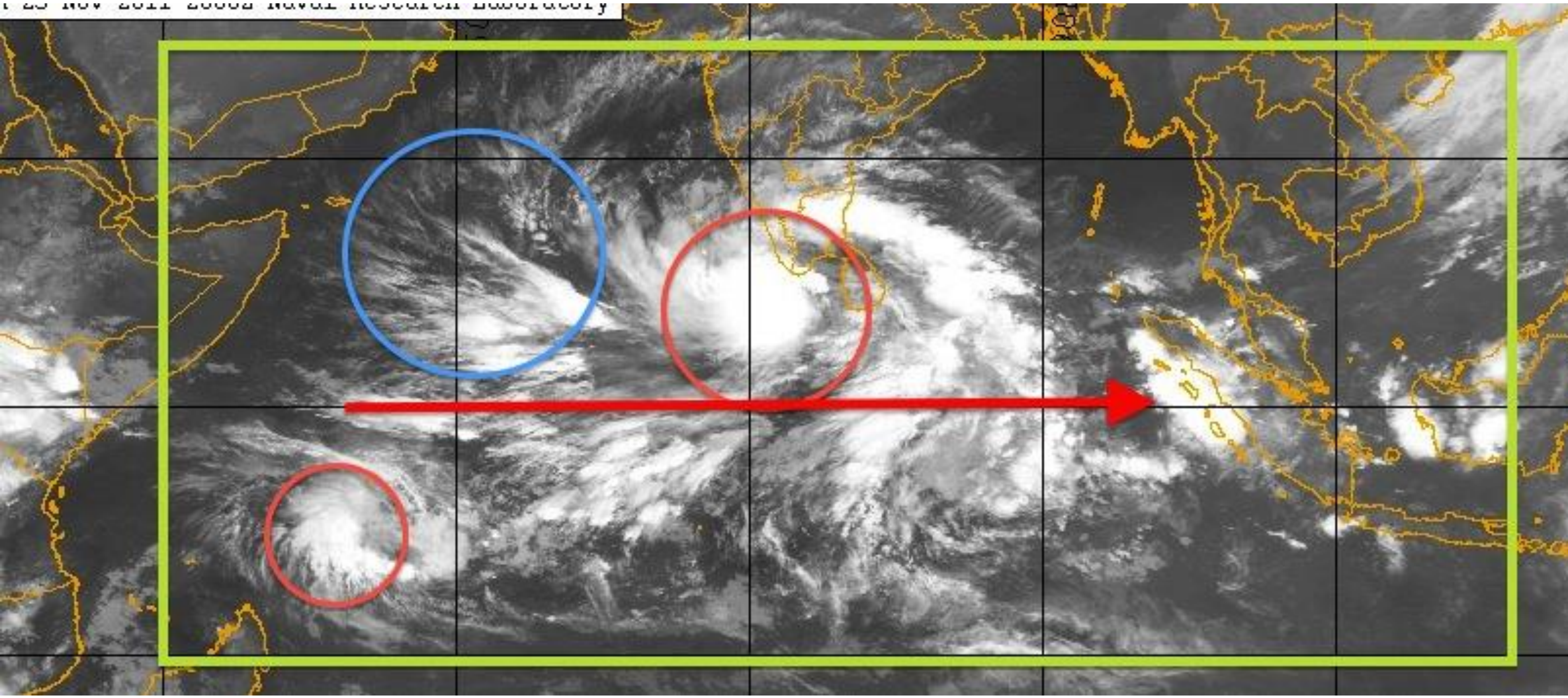


Synoptic scale

Cloud scale

Microphysical Scale

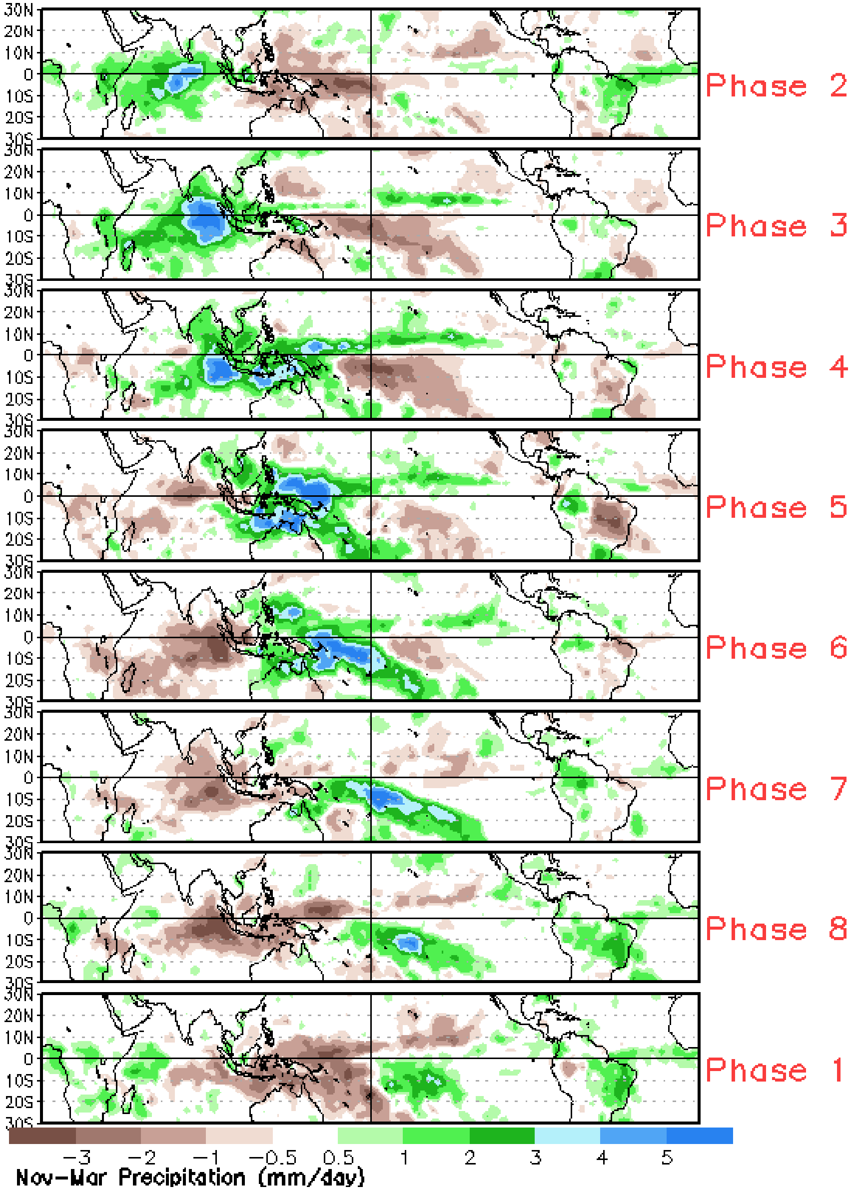
An example of multi-scale interactions
The Madden-Julian Oscillation MJO



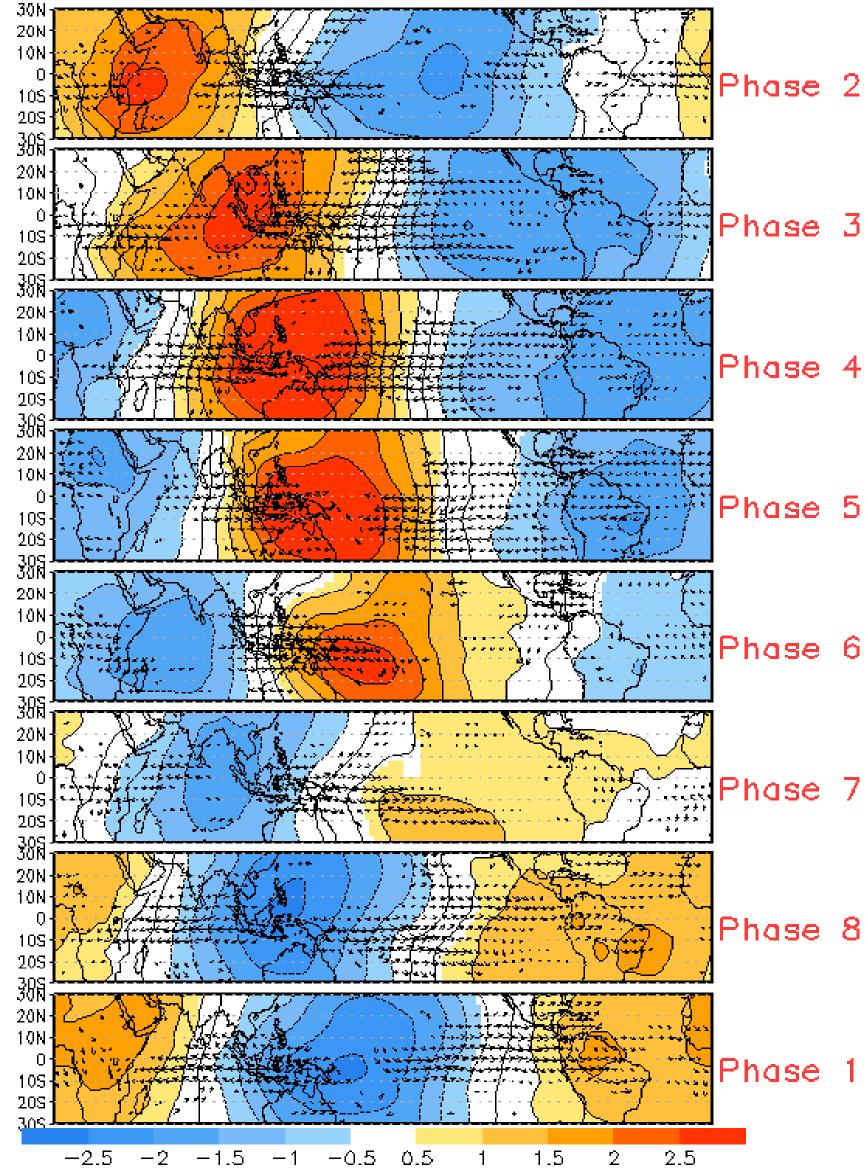
Courtesy of Adames

MJO

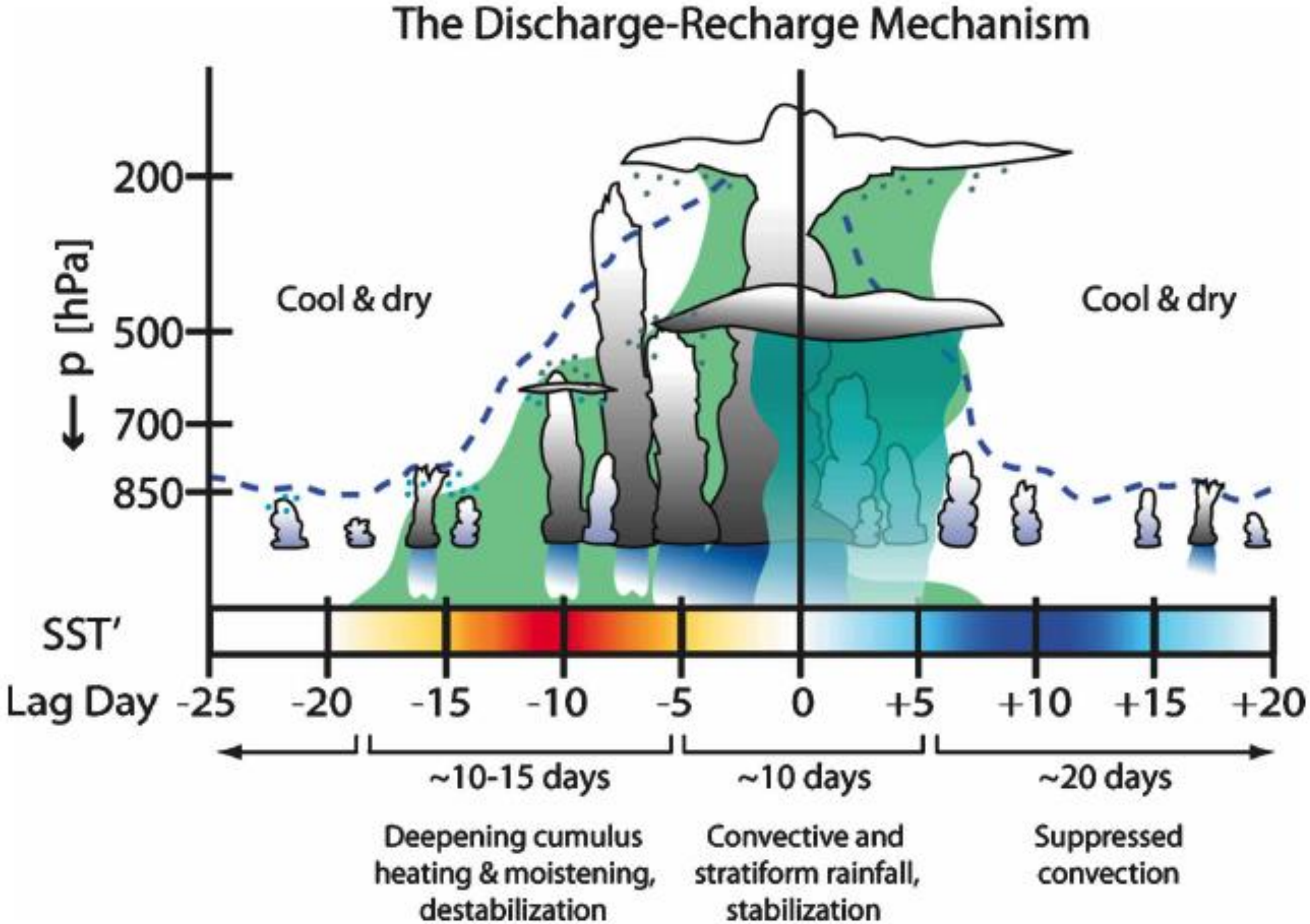
Precipitation (40 days)



850 hPa wind velocity potential



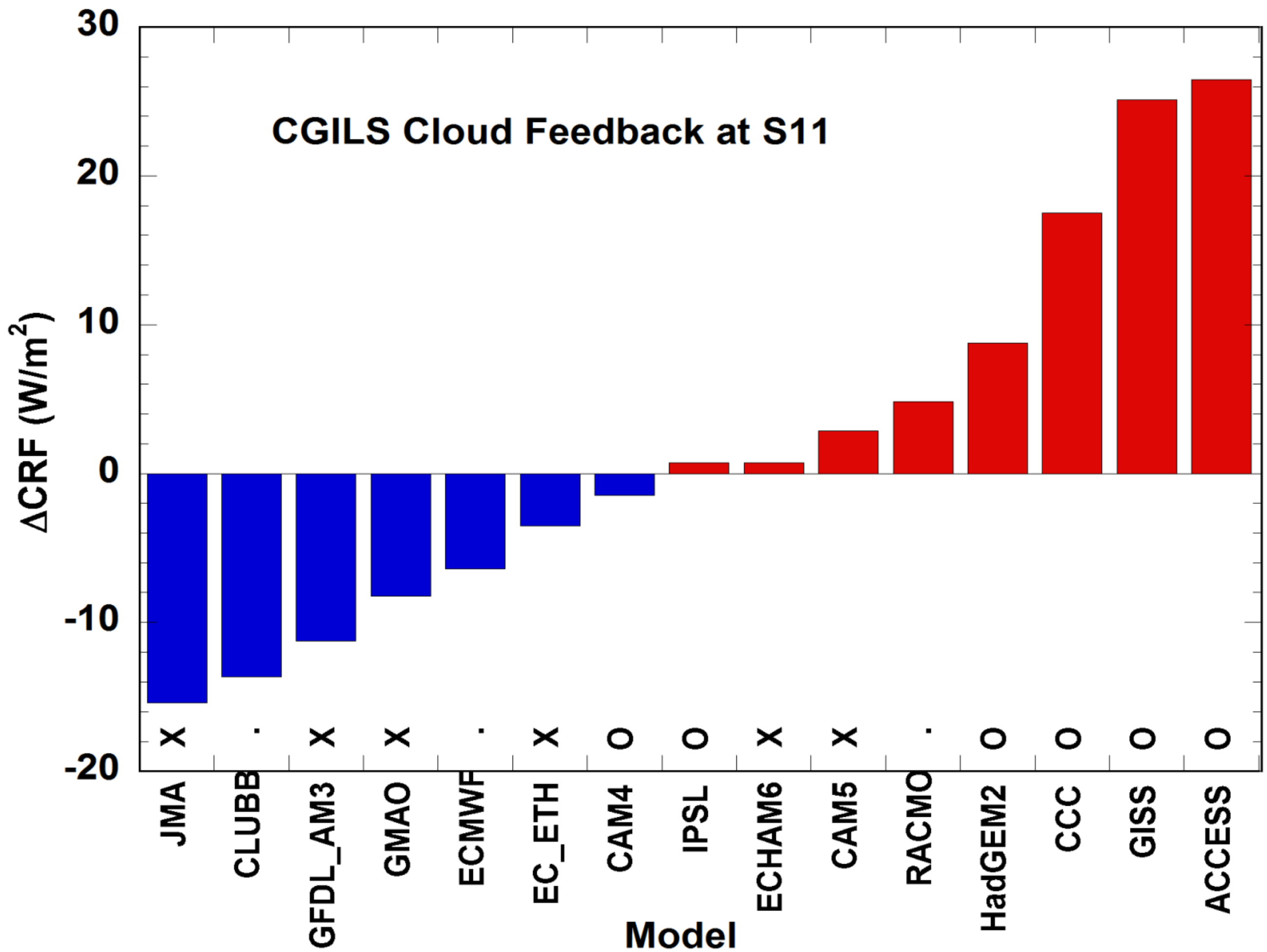
NOAA



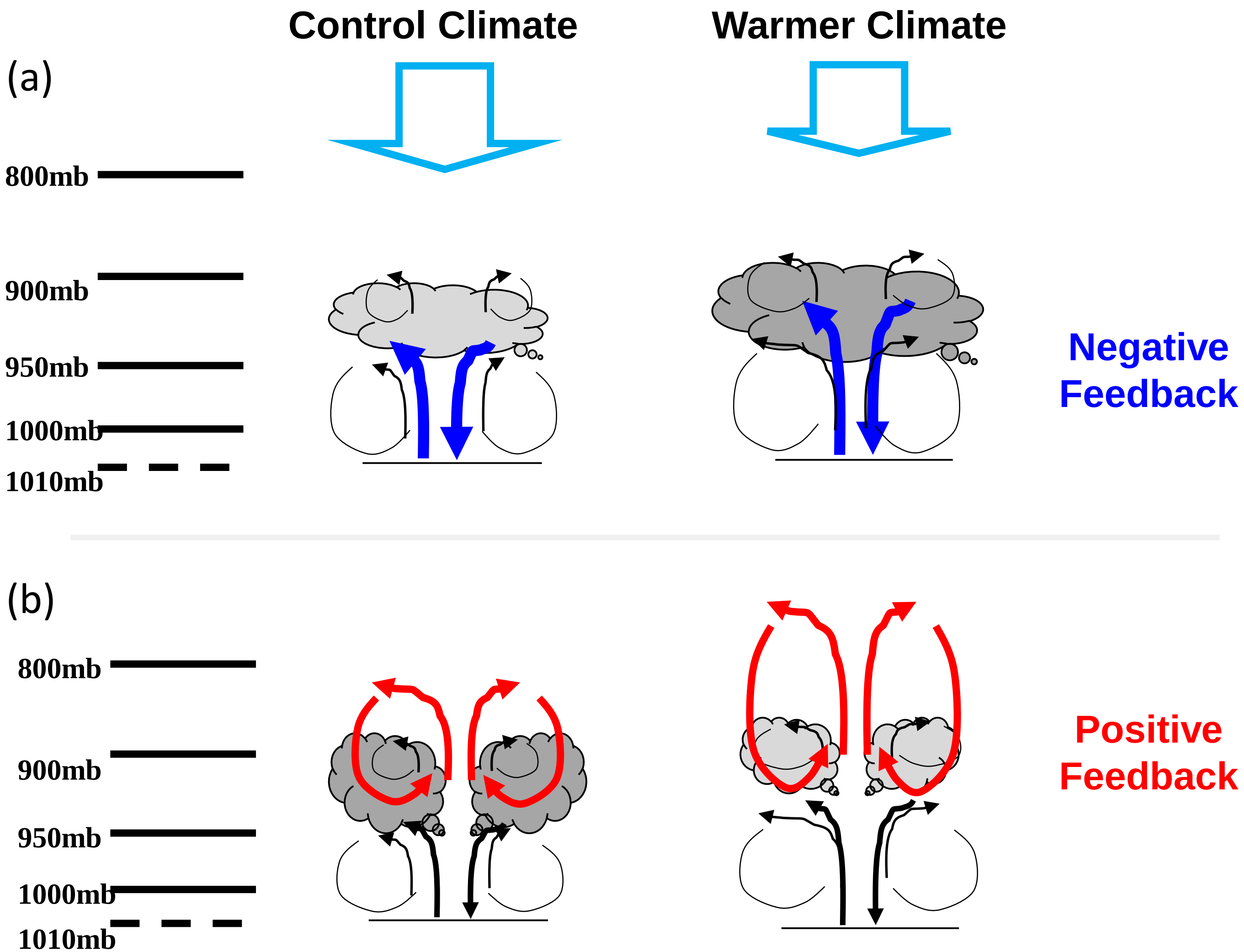
Boundary-layer turbulence, shallow convection, and cumulus congestus pre-condition deep convections

(Benedict and Randall 2007)

Cloud radiative feedbacks from low clouds



(Zhang et al., 2013 JAMES)



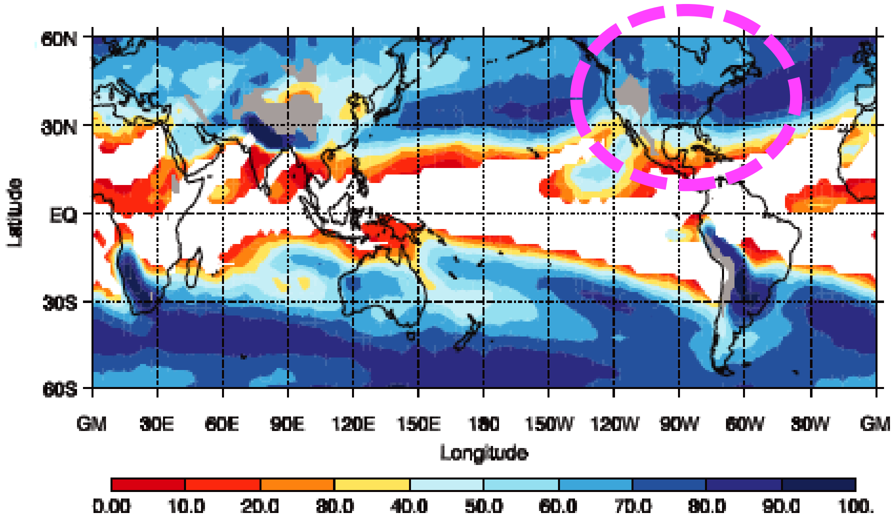
The "NESTS-SCOPE" Mechanism

(Zhang et al., 2013 JAMES)

Special About the Southern Great Plains

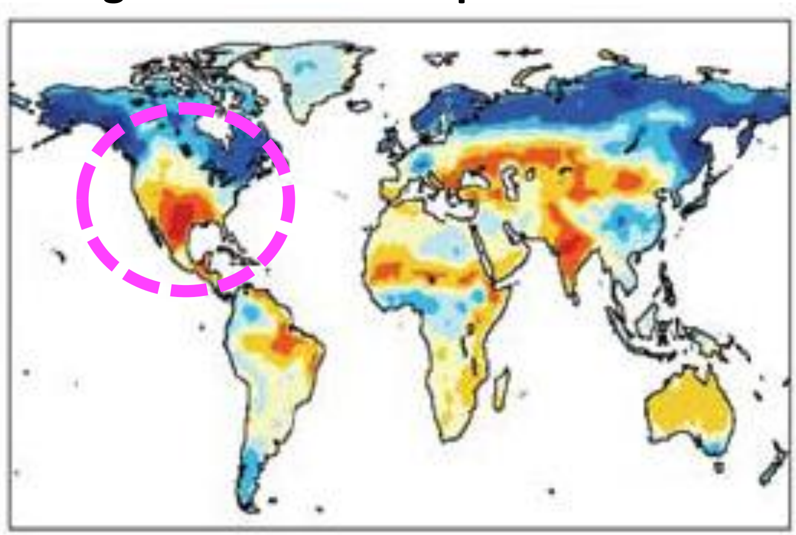
- Fronts
- Low-level jet
- Thunderstorms
- Land-atmosphere coupling

Percentage of precipitation associated with fronts



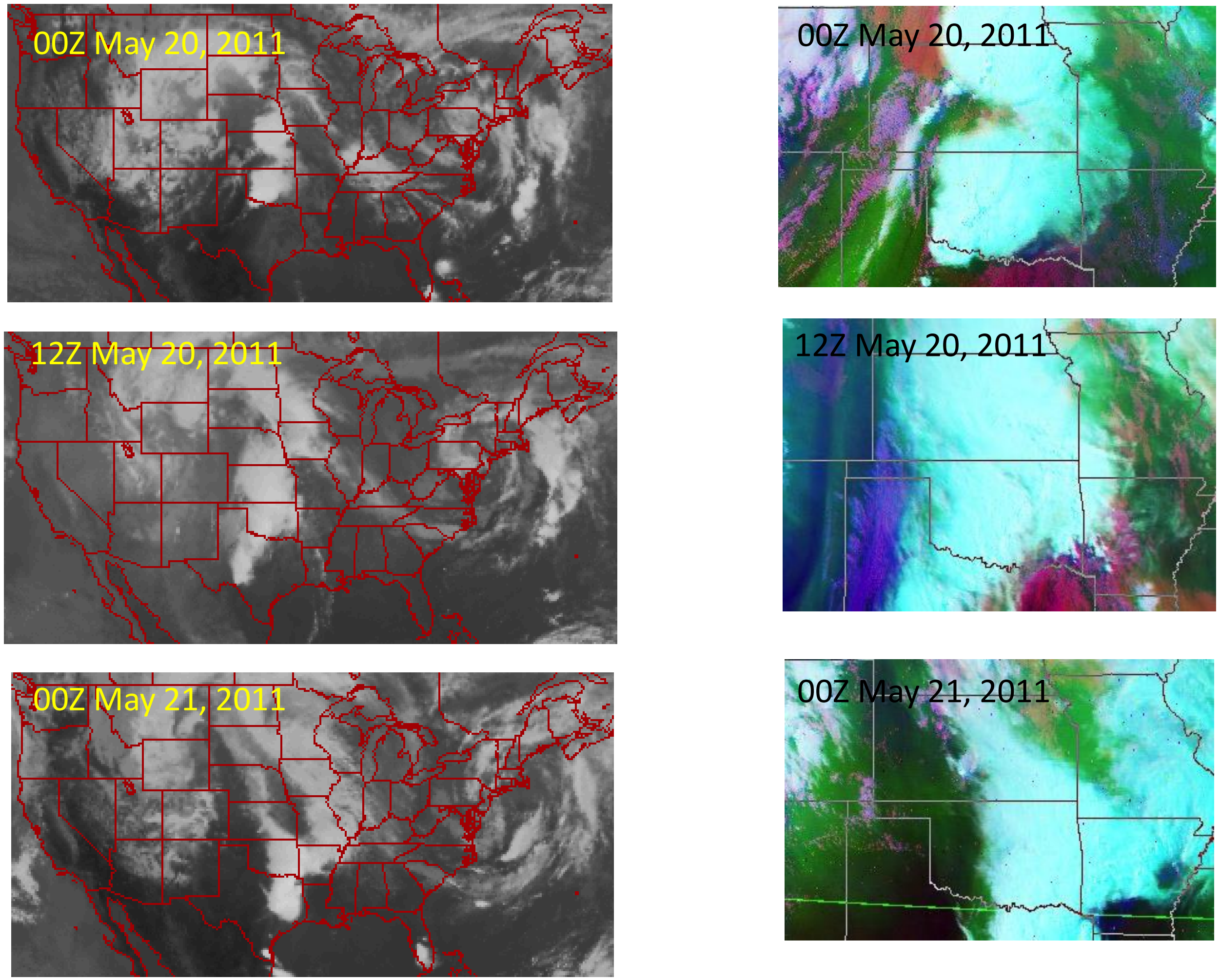
(Catto and Pfahl, JGR 2013)

Strength of land-atmosphere interaction

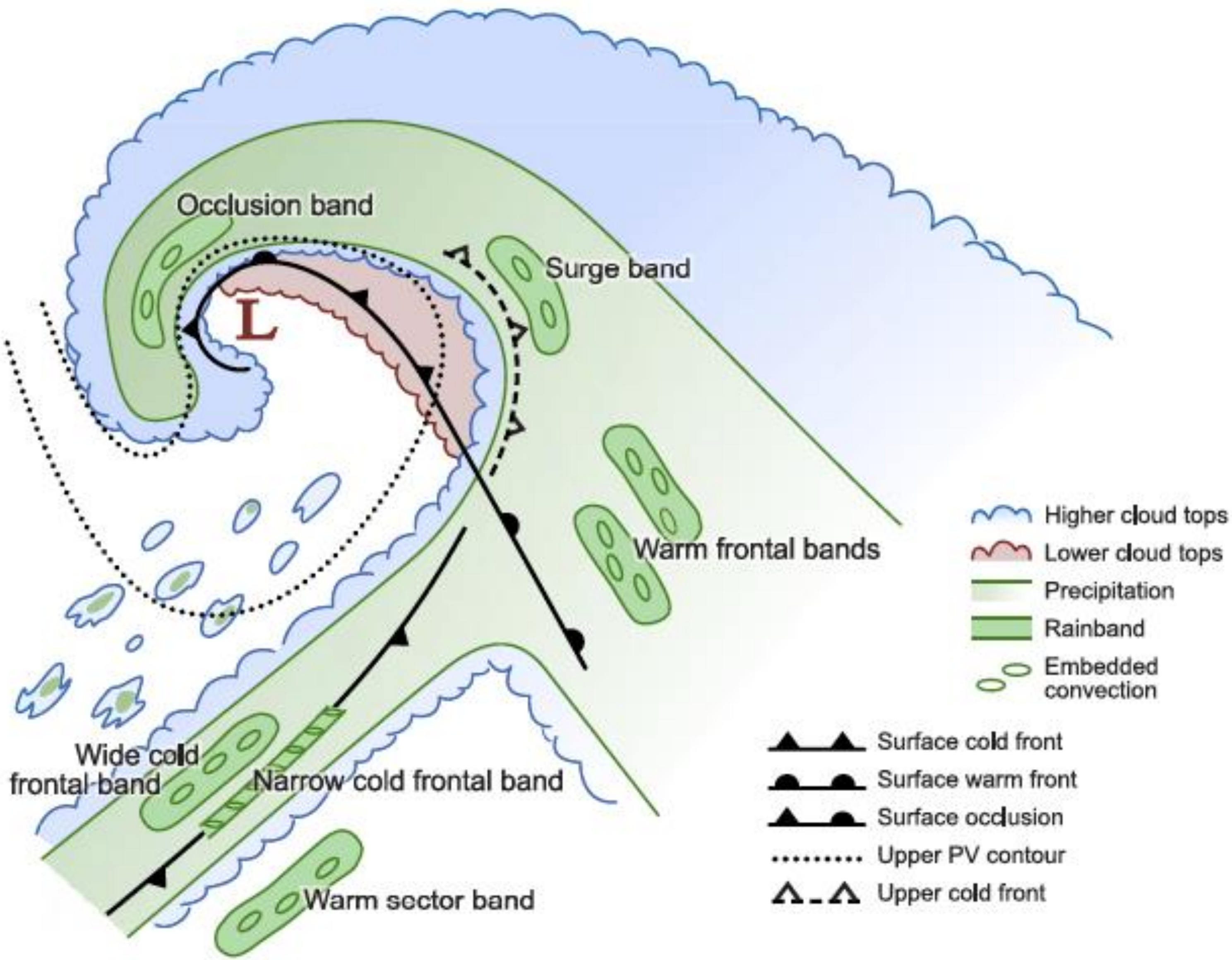


(Seneviratne et al. Nature, 2006)

A strong precipitation event during the ARM MC3E Field Campaign

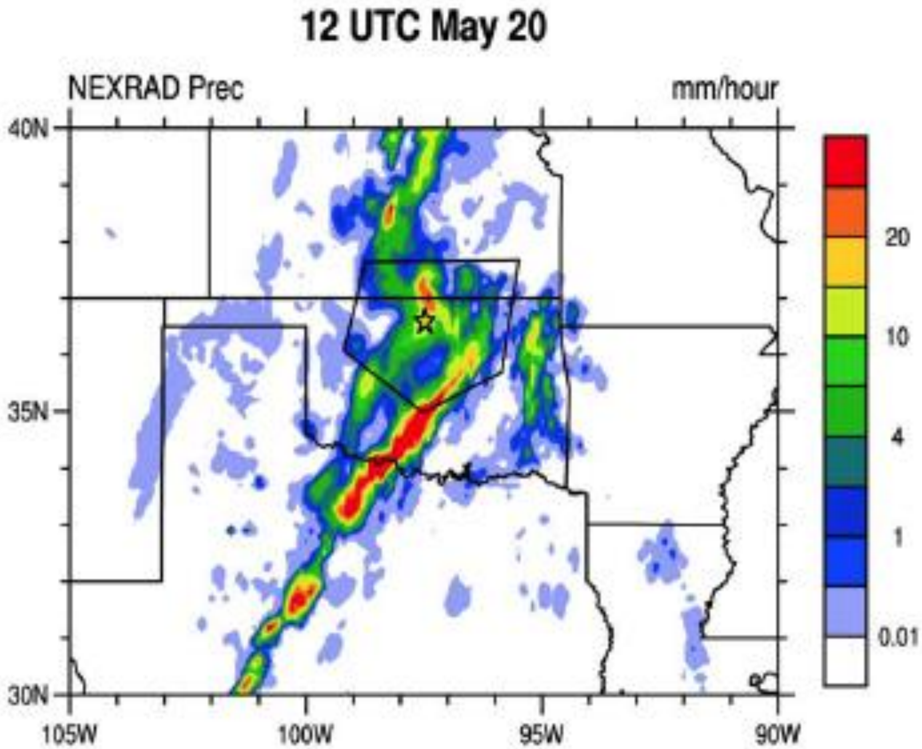


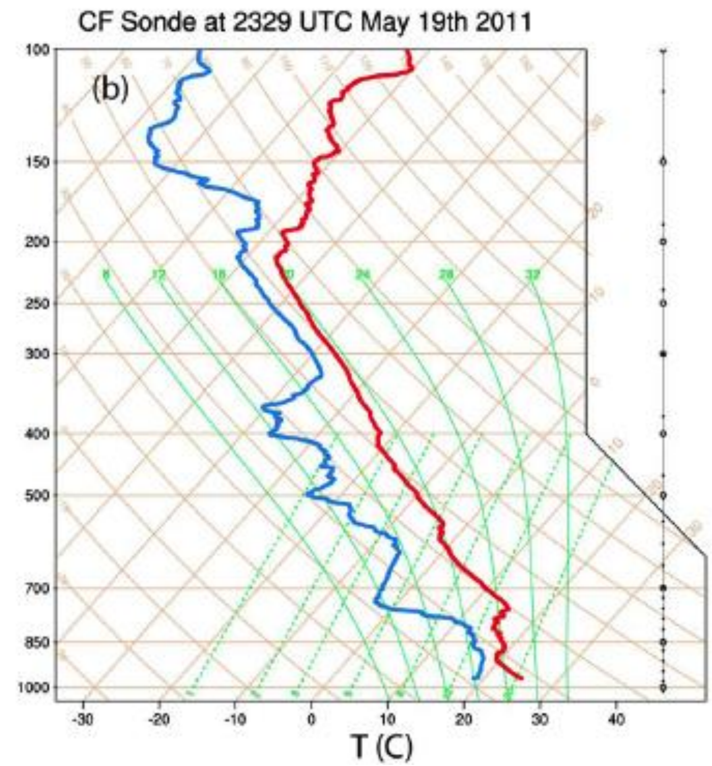
(Wang et al. 2017)



Occlusion band
L
Surge band
Warm frontal bands
Wide cold
frontal band
Narrow cold frontal band
Warm sector band
Higher cloud tops
Lower cloud tops
Precipitation
Rainband
Embedded
convection
Surface cold front
Surface warm front
Surface occlusion
Upper PV contour
Upper cold front

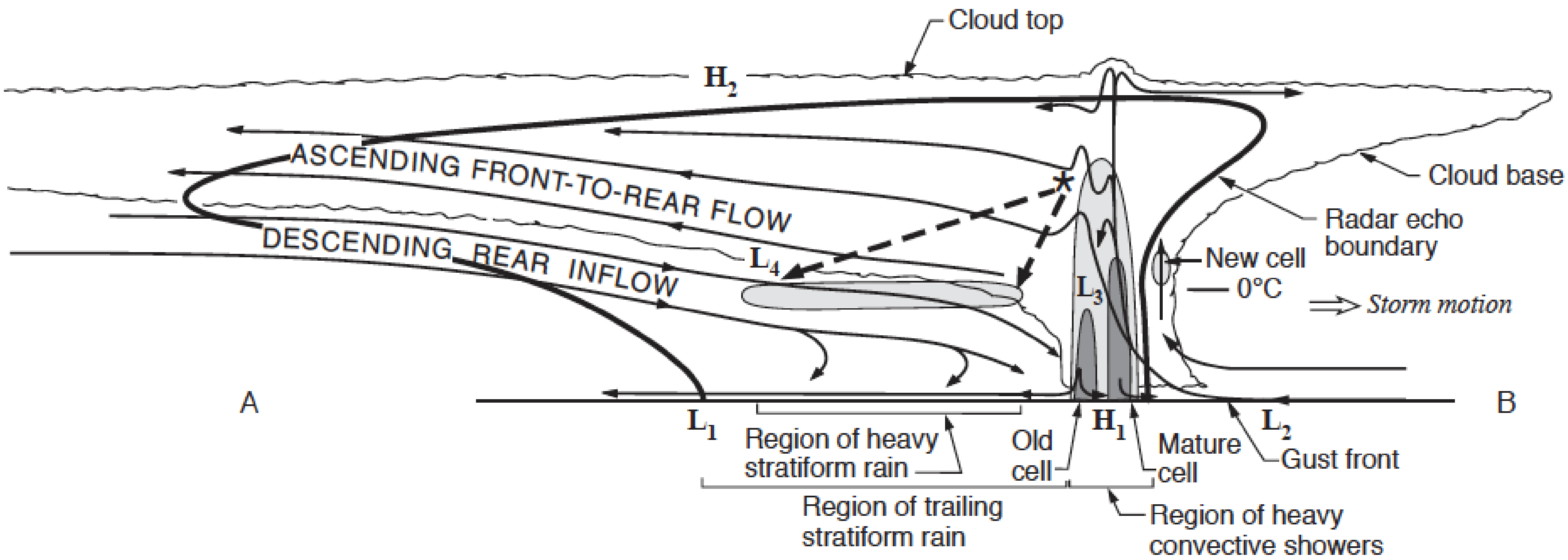
(Houze 2014)





(Xie et al. 2014)

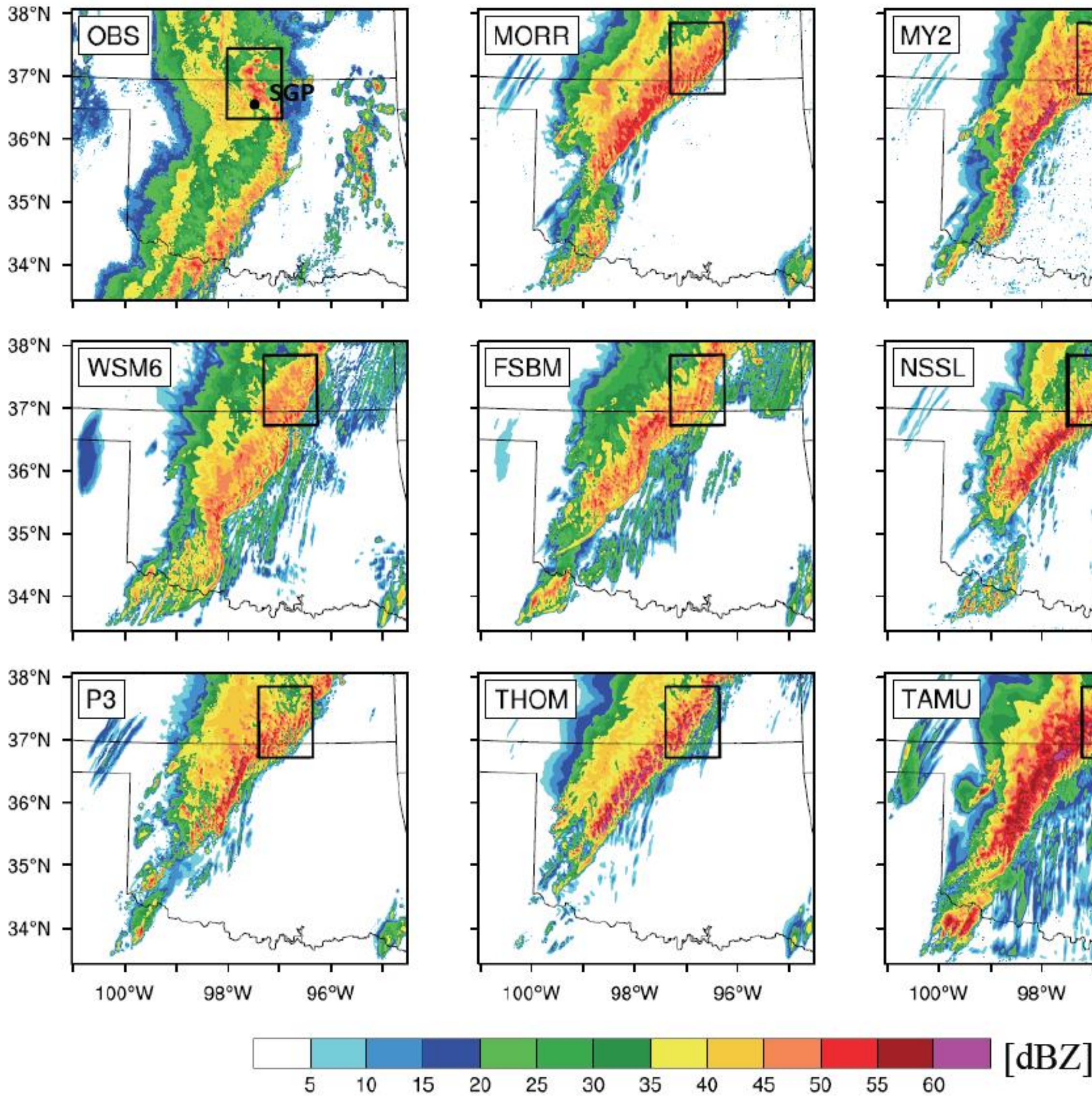
Mesoscale convective systems
Not resolved in current climate models



~ 100 km

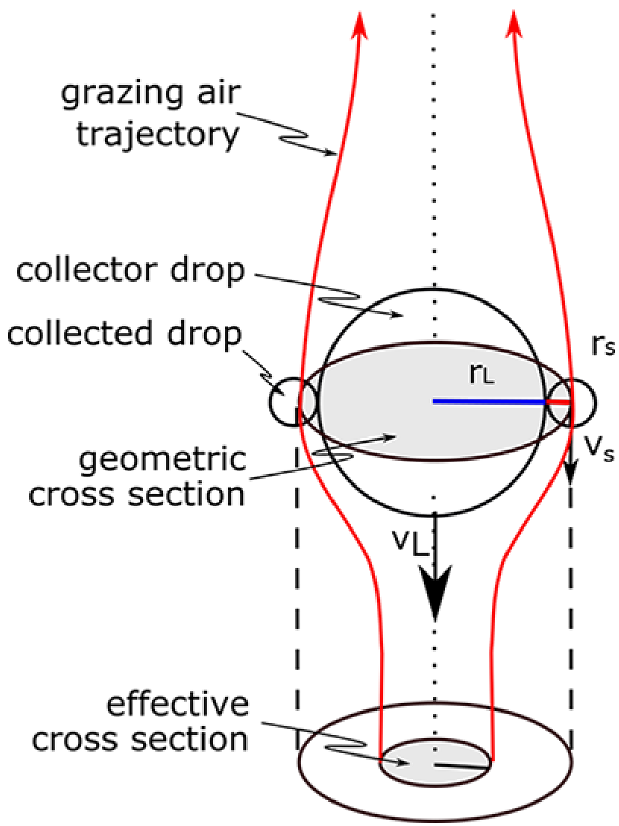
(Houze 2014)

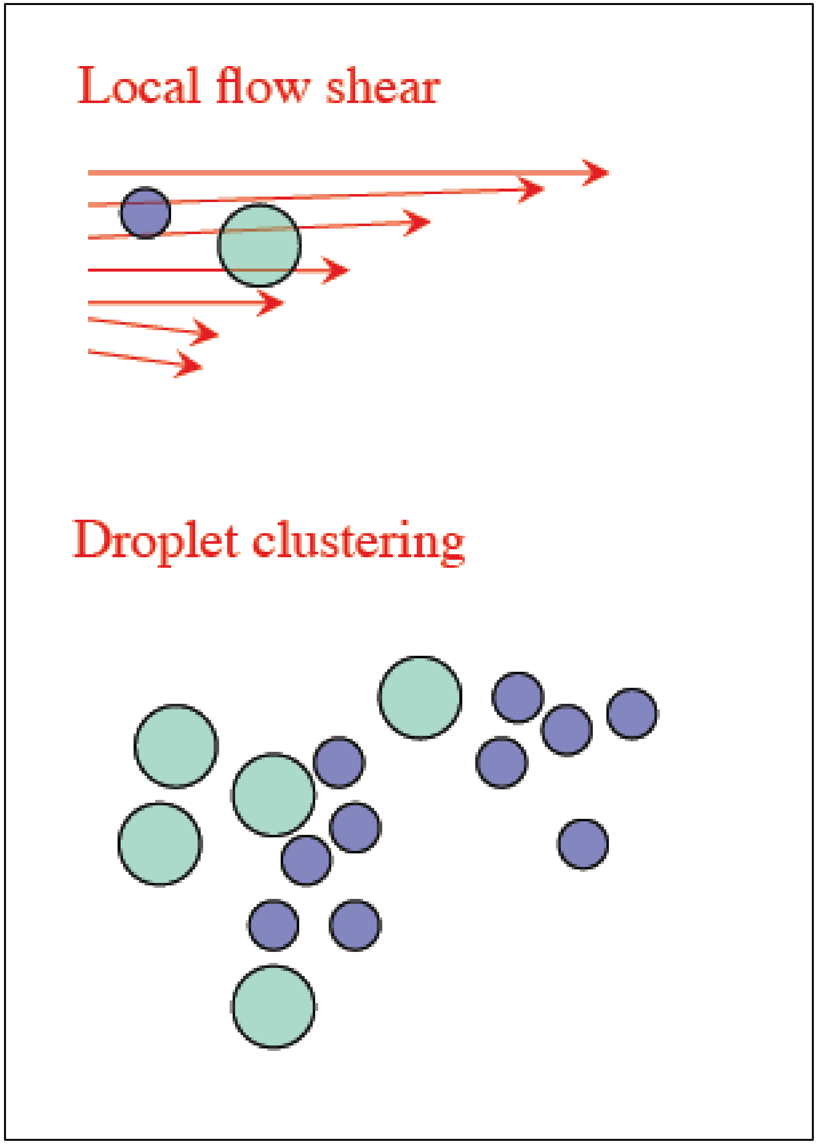
Resolution alone is necessary, but not sufficient
Sensitivity of MCS reflectivity on cloud microphysics (An ARM MC3E Event)



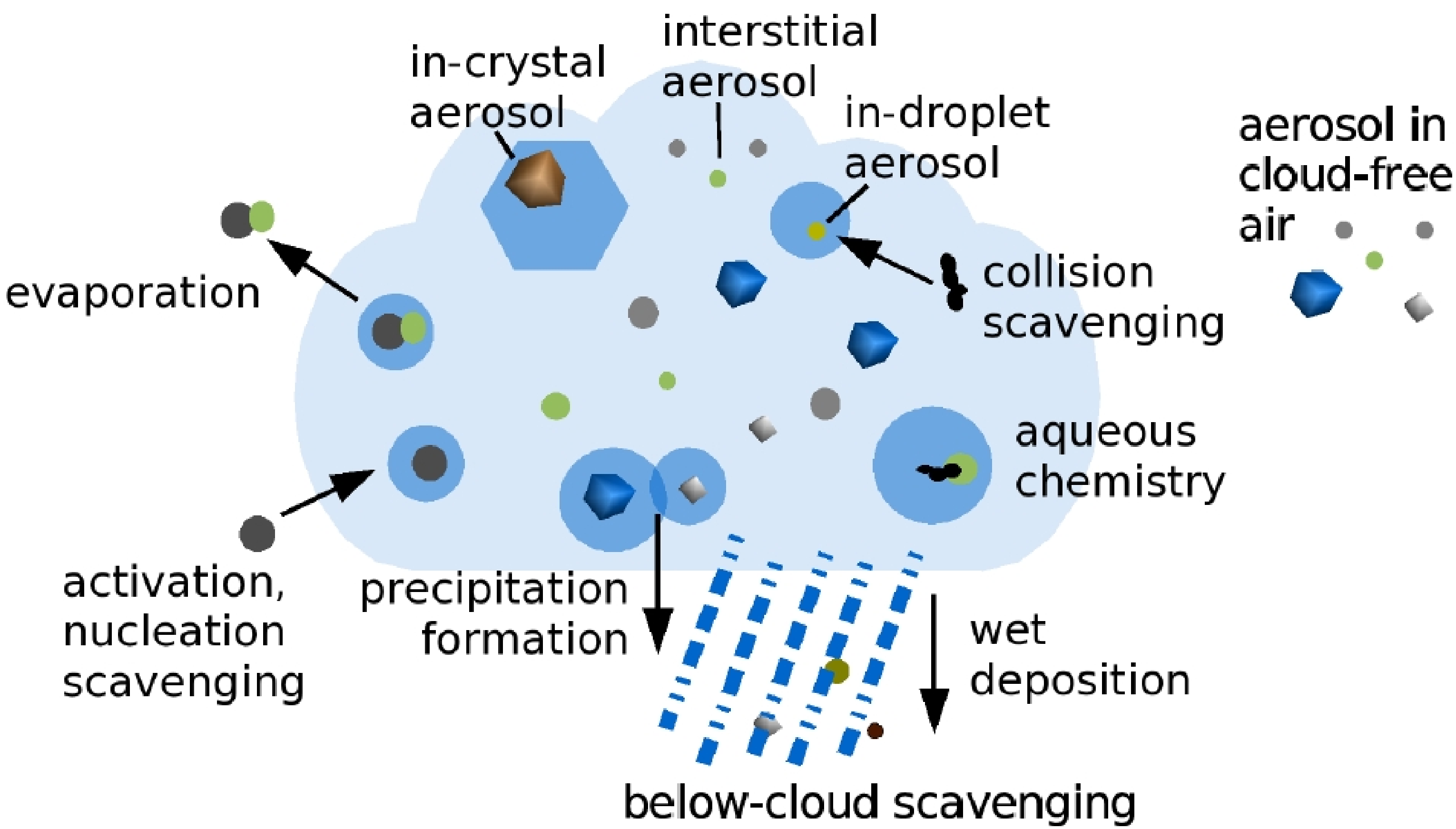
(Fan et al. 2017)

One element of microphysical process: collision-coalescences



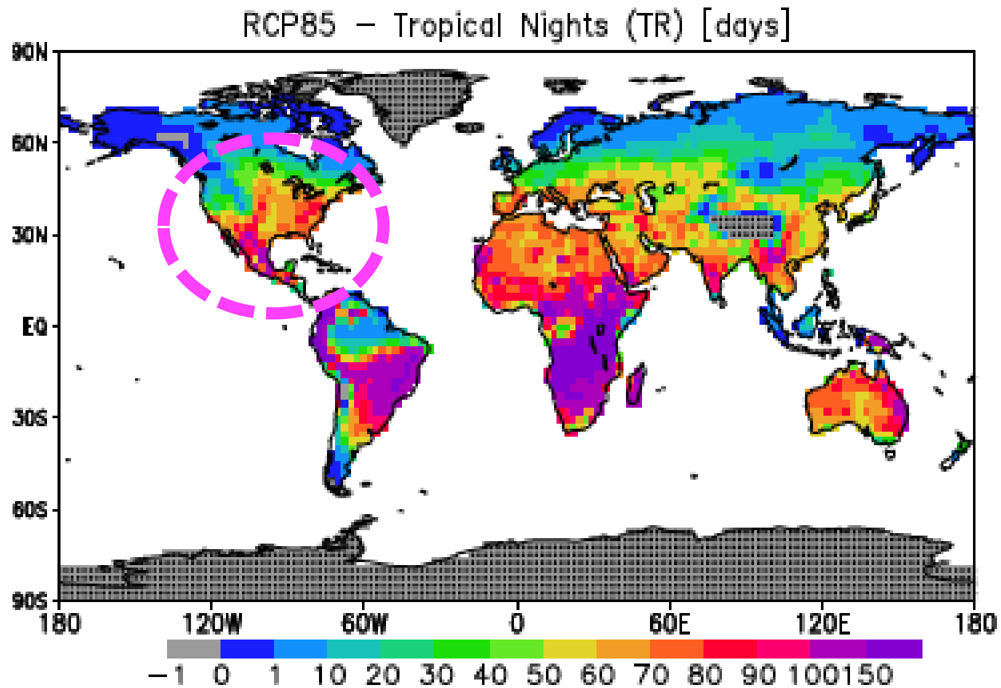


Complexity of cloud microphysics



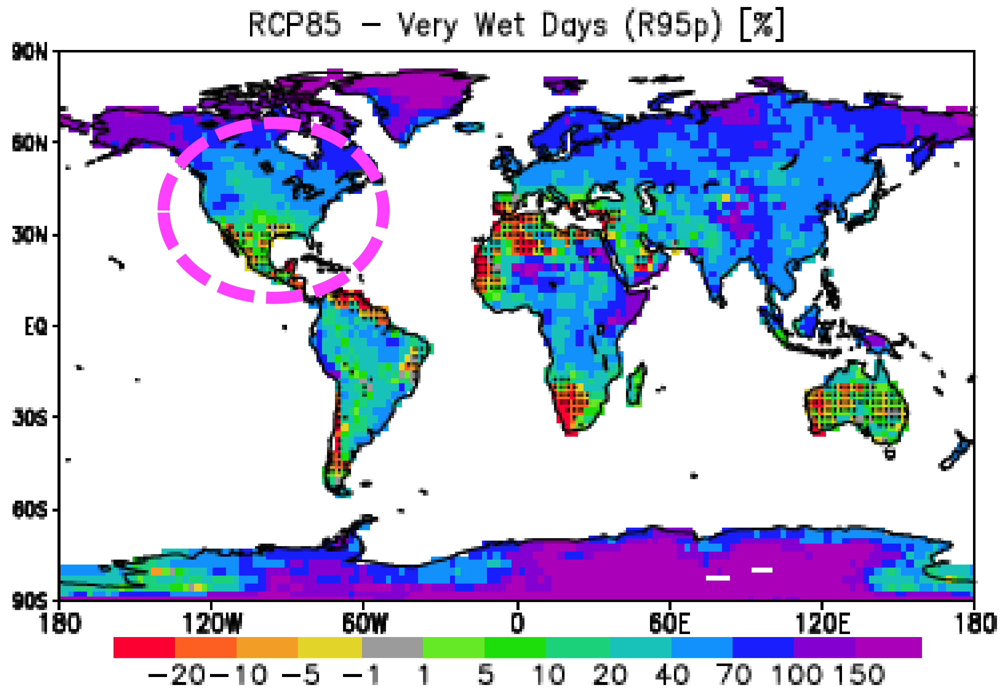
Future Projections and

Uncertainties over the SGP



RCP8.5

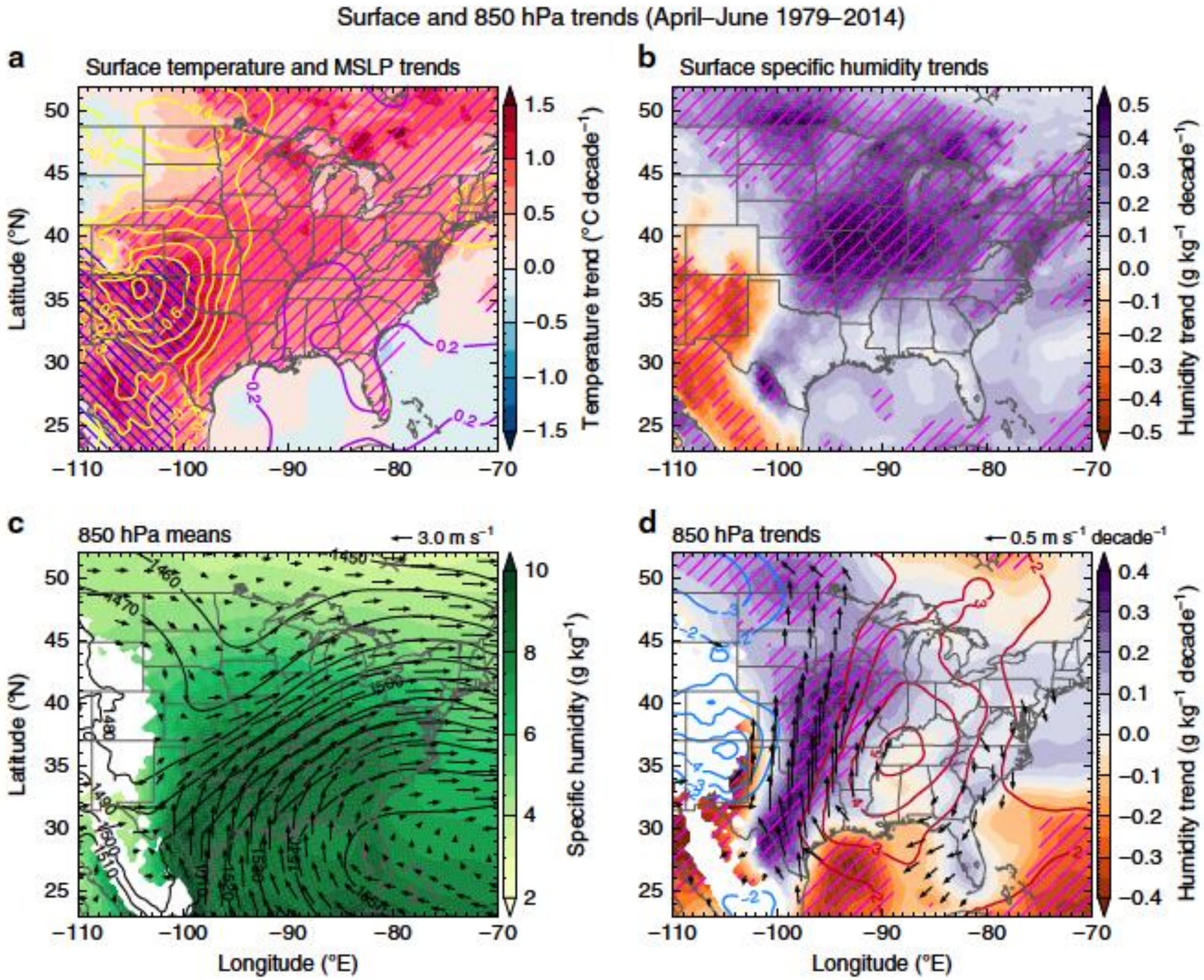
Changes of Tropical Night Days (T_{min}>20°C)



RCP8.5

Changes of Very Wet Days (P> 95th percentile)%

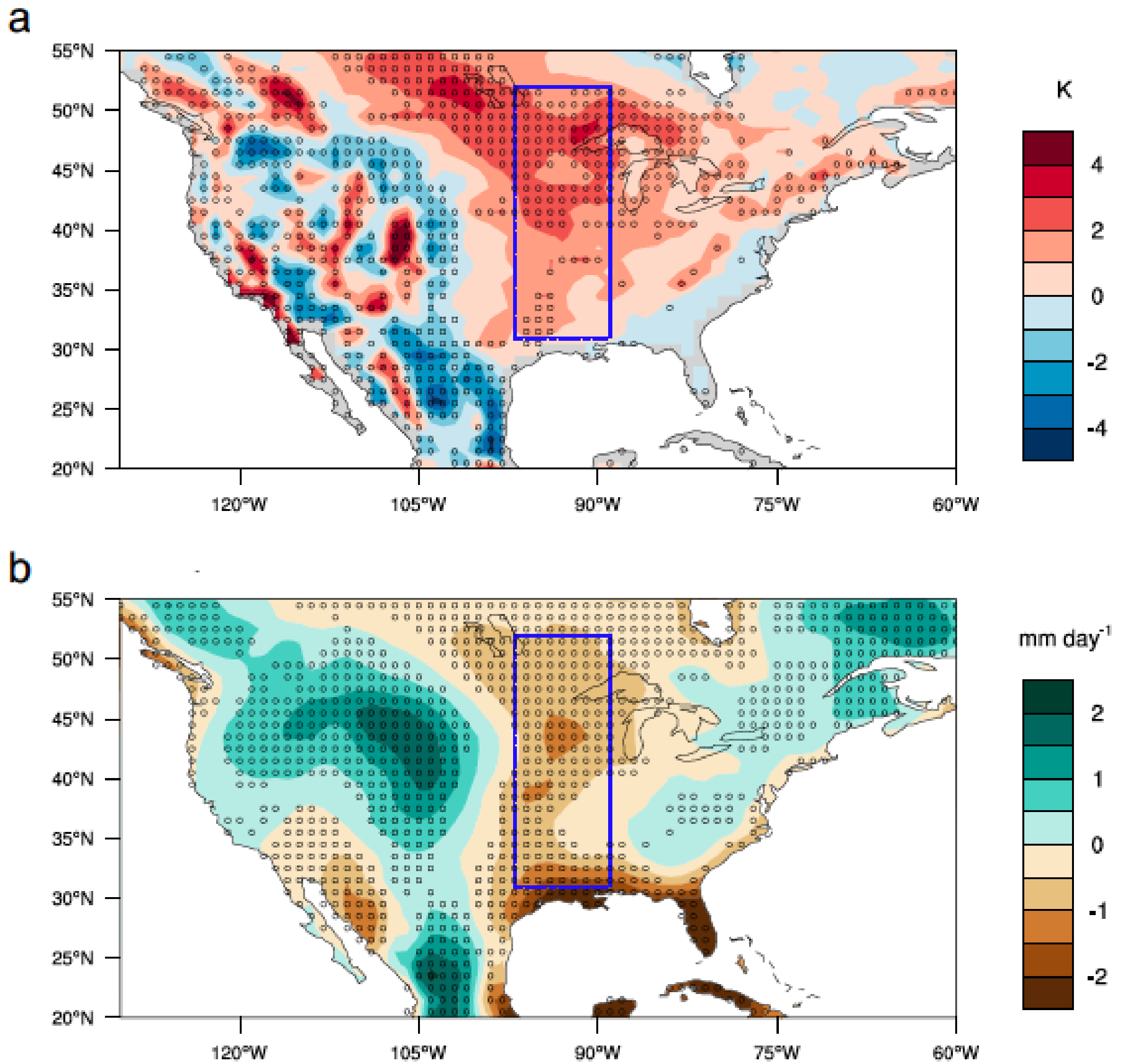
Changes of LLJ and Precipitation

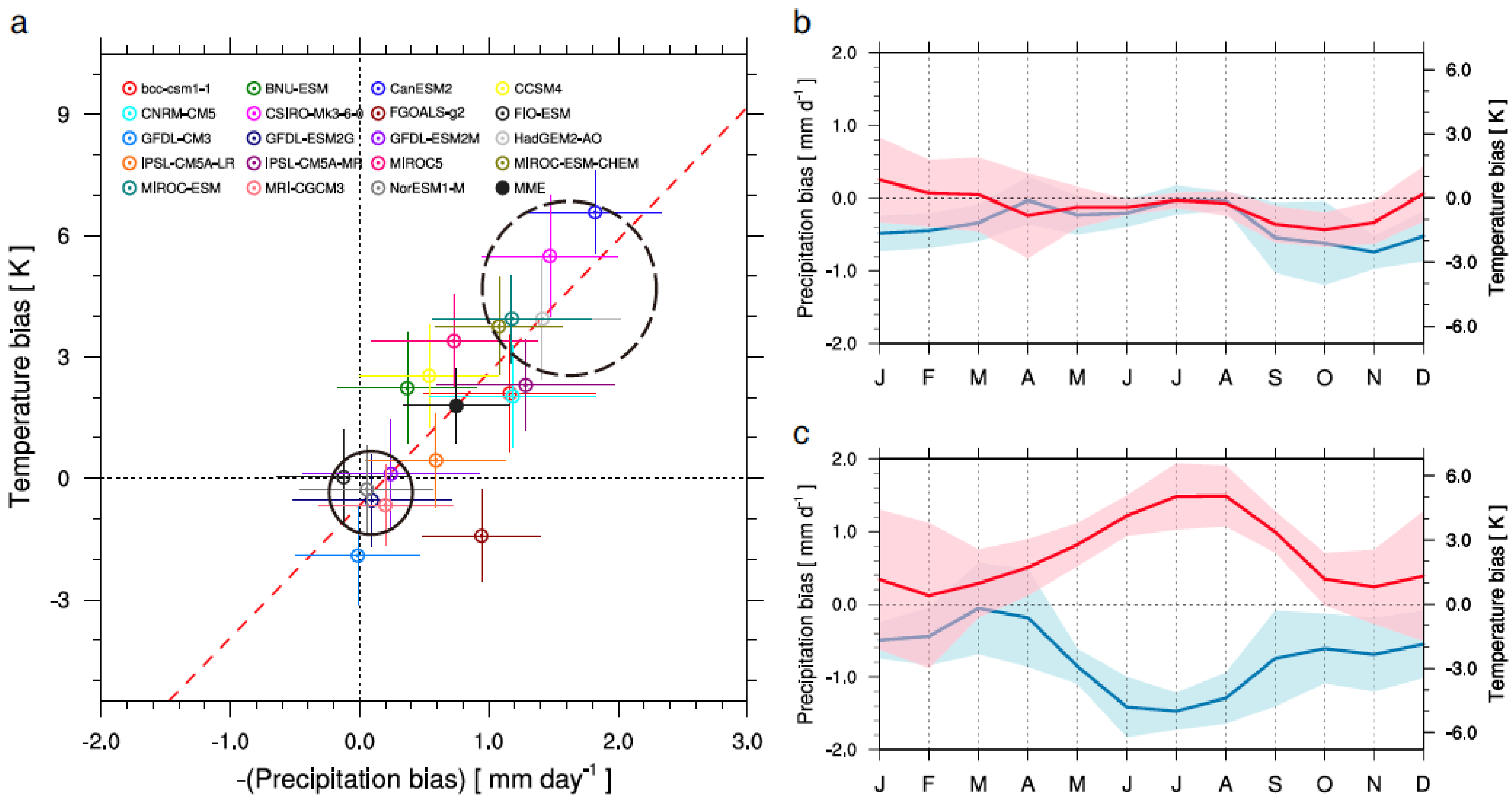


(Feng, Leung et al. Nature Communications 2016)

Uncertainties from GCM can be large and systematic

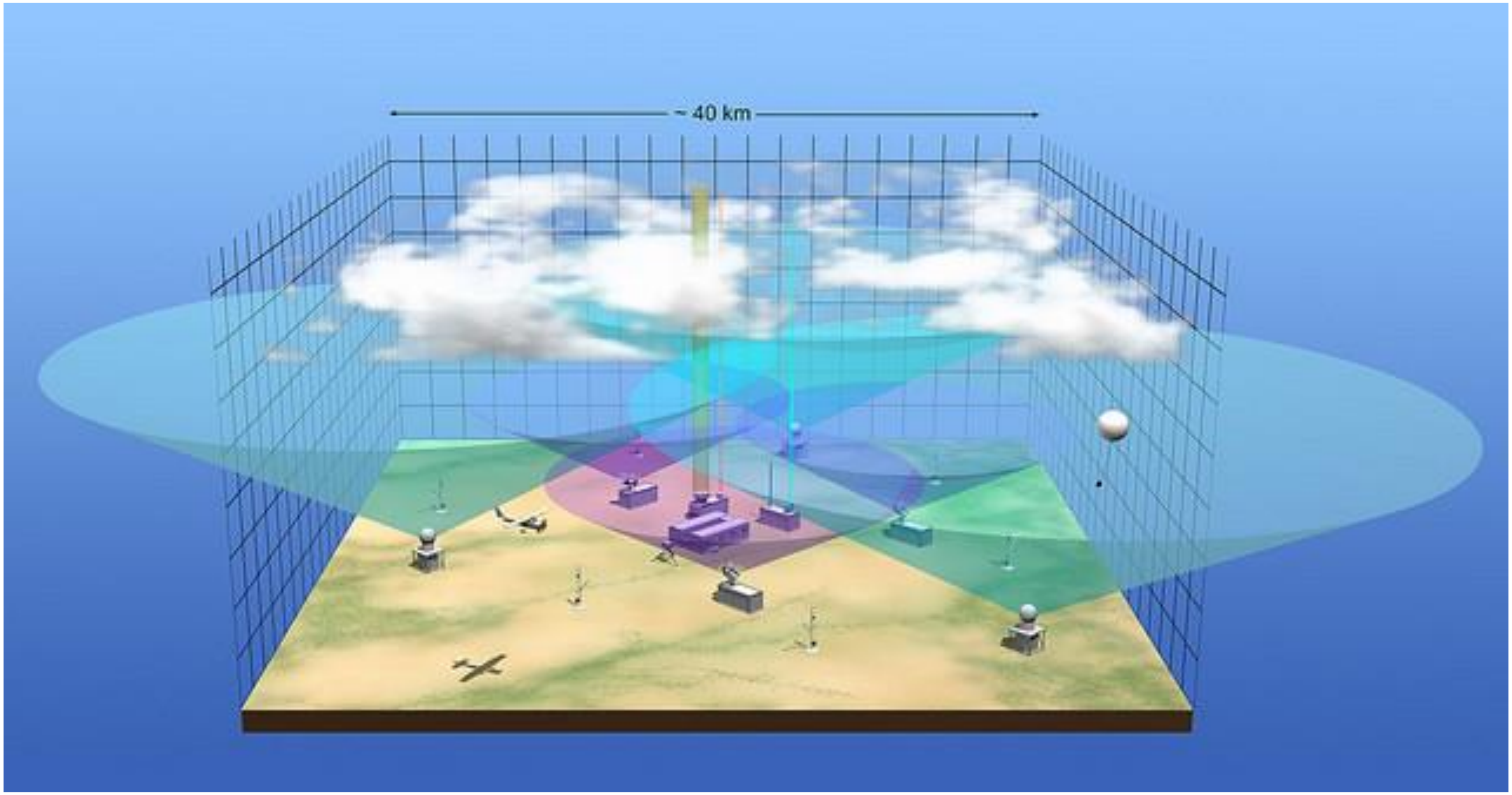
CMIP5 Model biases



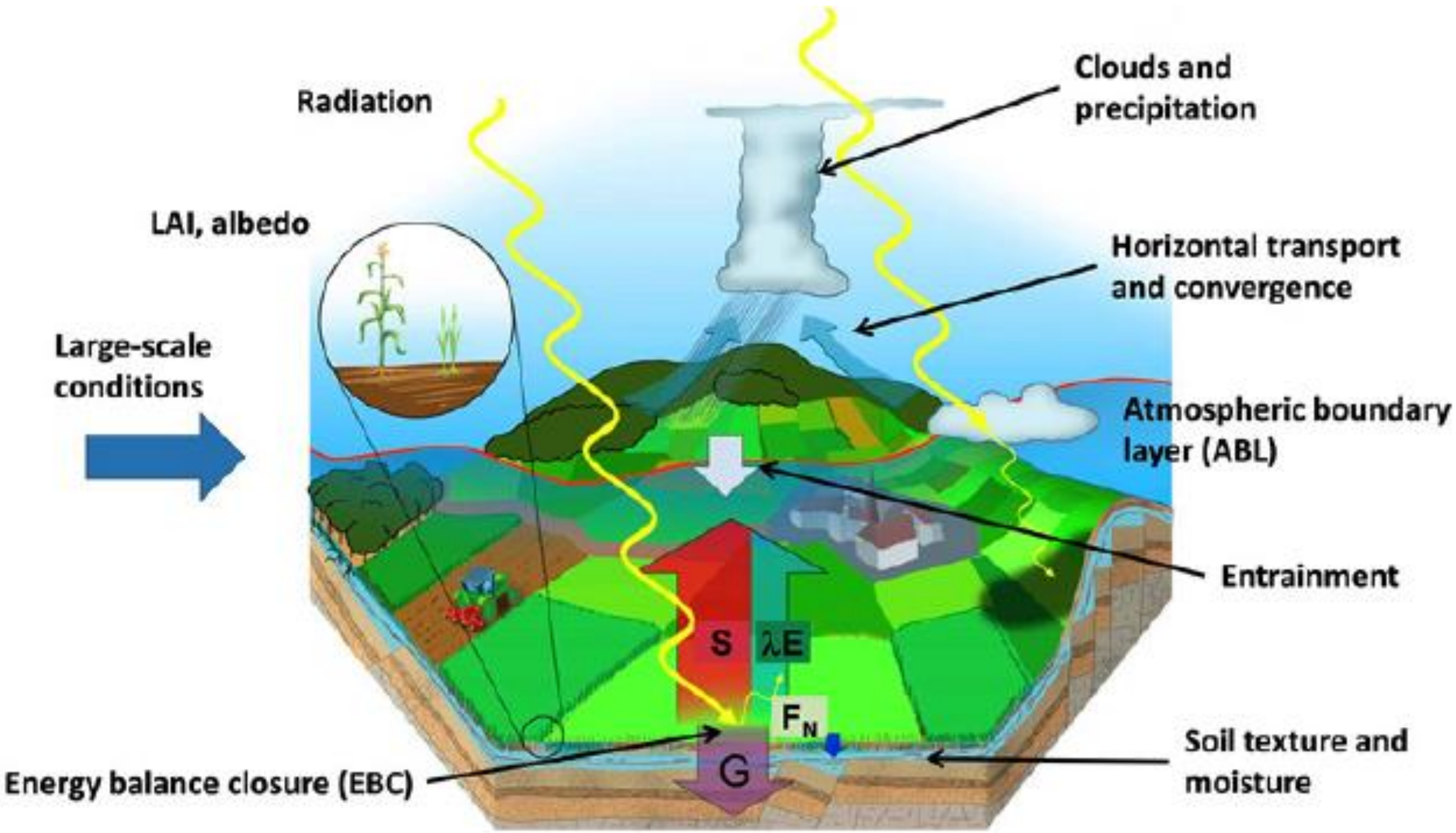


(Lin et al. 2017 Nature Communications)

Artistic Schematics of the ARM SGP Facility



Land-atmosphere coupling



(Wulfmeyer et al., 2016)

Heavy rain

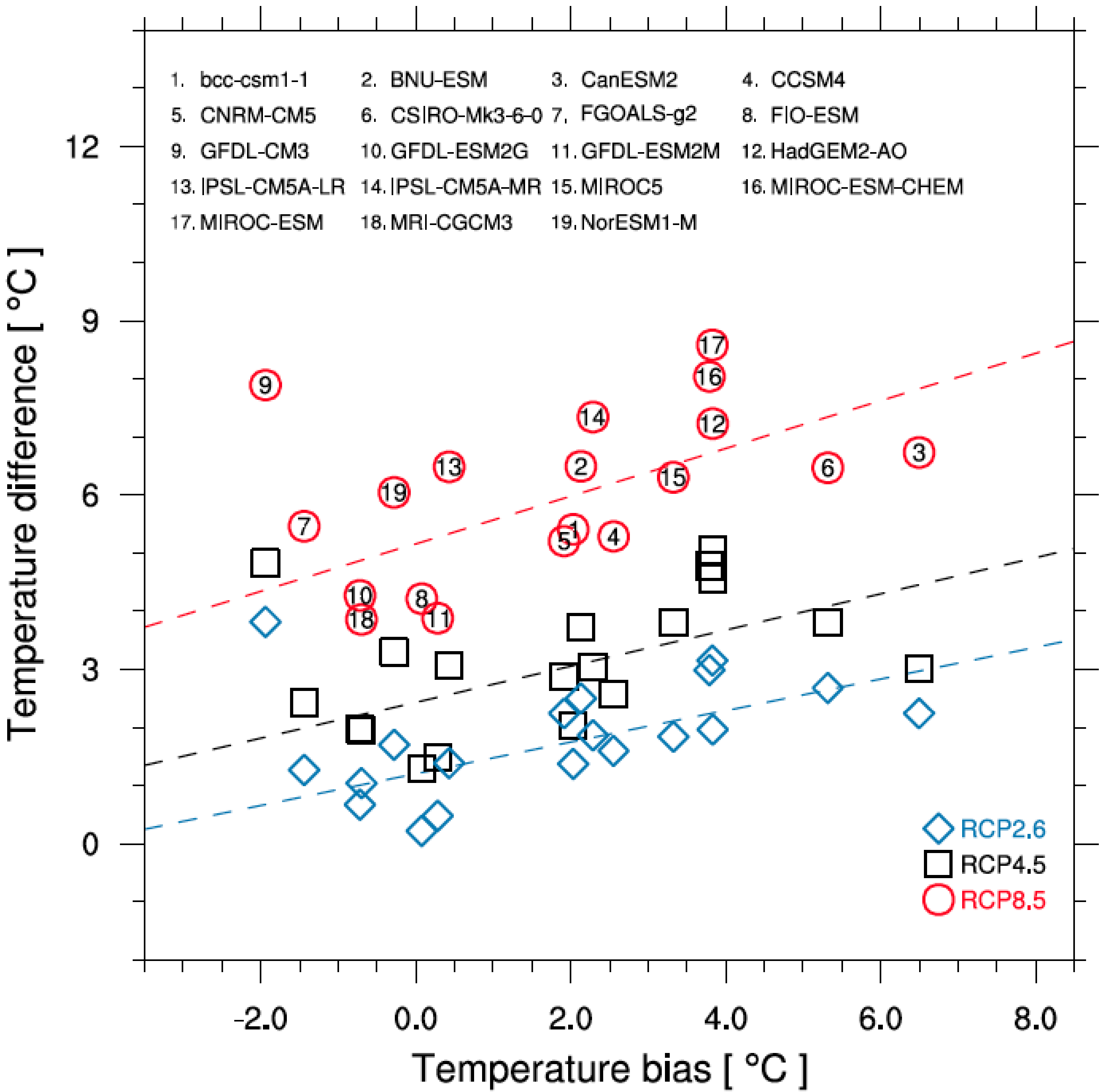
In subsequent no-rain days

Less solar radiation & lower temperature

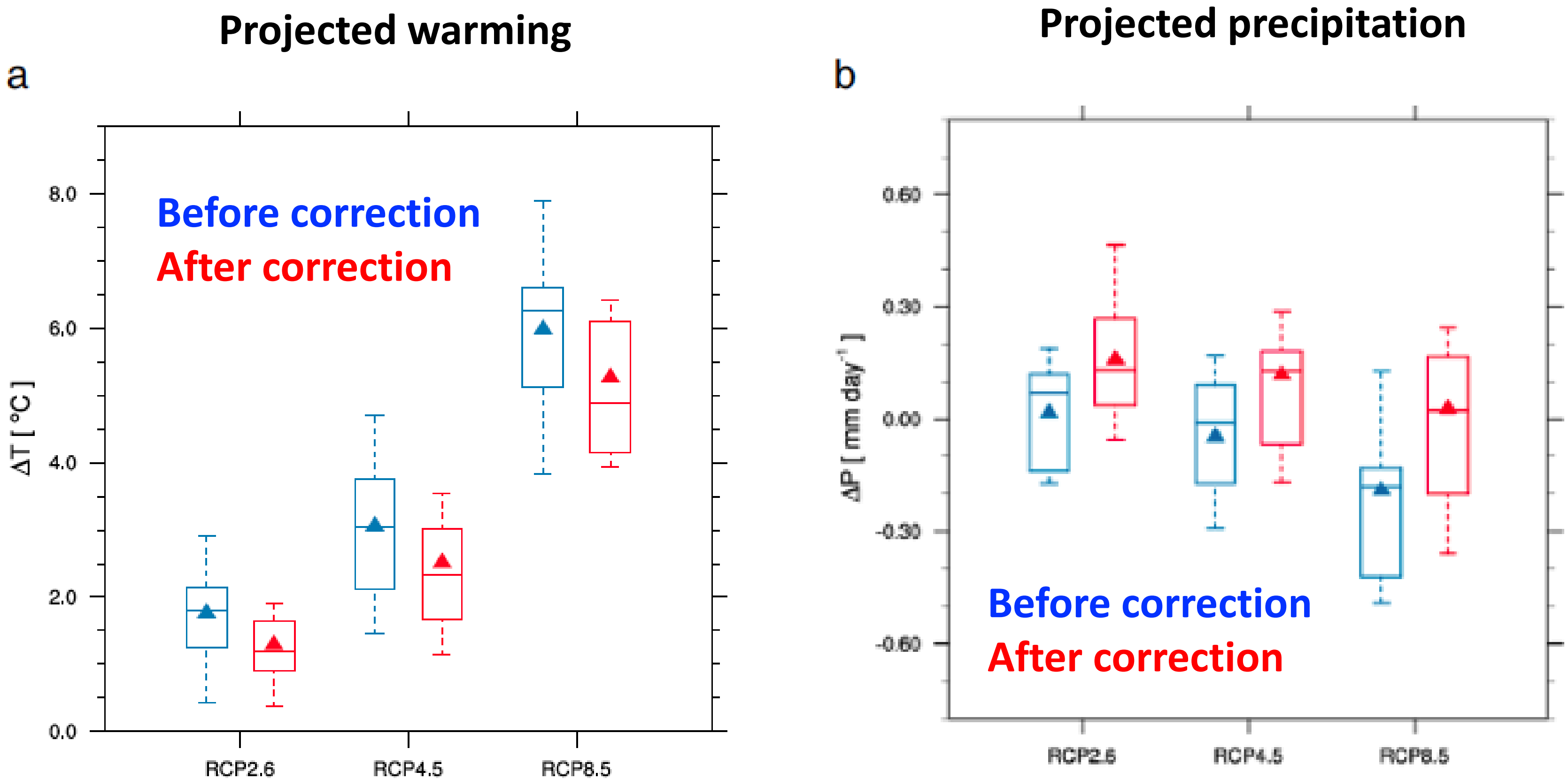
More solar radiation & Higher temperature

Light rain

In subsequent no-rain days



1. bcc-csm1-1
2. BNU-ESM
3. CanESM2
4. CCSM4
5. CNRM-CM5
6. CSIRO-Mk3-6-0
7. FGOALS-g2
8. FIO-ESM
9. GFDL-CM3
10. GFDL-ESM2G
11. GFDL-ESM2M
12. HadGEM2-AO
13. IPSL-CM5A-LR
14. IPSL-CM5A-MR
15. MIROC5
16. MIROC-ESM-CHEM
17. MIROC-ESM
18. MRI-CGCM3
19. NorESM1-M
RCP2.6
RCP4.5
RCP8.5
Temperature difference [°C]
Temperature bias [°C]


Projected warming
a
Before correction
After correction
ΔT [°C]
8.0
6.0
4.0
2.0
0.0
RCP2.6
RCP4.5
RCP8.5
Projected precipitation
b
ΔP [mm day⁻¹]
0.60
0.30
0.00
-0.30
-0.60
Before correction
After correction
RCP2.6
RCP4.5
RCP8.5

Summary

- **Extreme events often arise from a combination of systems on multiple scales. Simulations of their correct spatial-temporal relations are needed to capture their combined impact for specific applications.**

- **Upscale feedbacks cause large uncertainties in extremes from unresolved processes of scales ranging from cloud-aerosol microphysics, shallow convection, and cloud systems.**

- **Over the SGP, most current ESMs miss strong convective events, leading to underestimation of the subsequent shallow convective clouds and overestimation of downward shortwave radiation, thus warm and dry biases**