The potential for improved sub-seasonal to seasonal (S2S) forecasts of the North American monsoon in the Southwest U.S.

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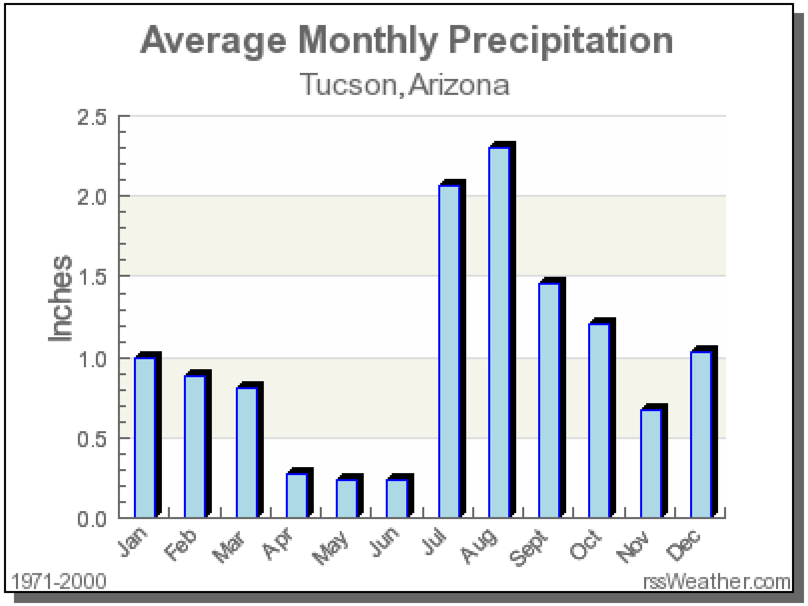
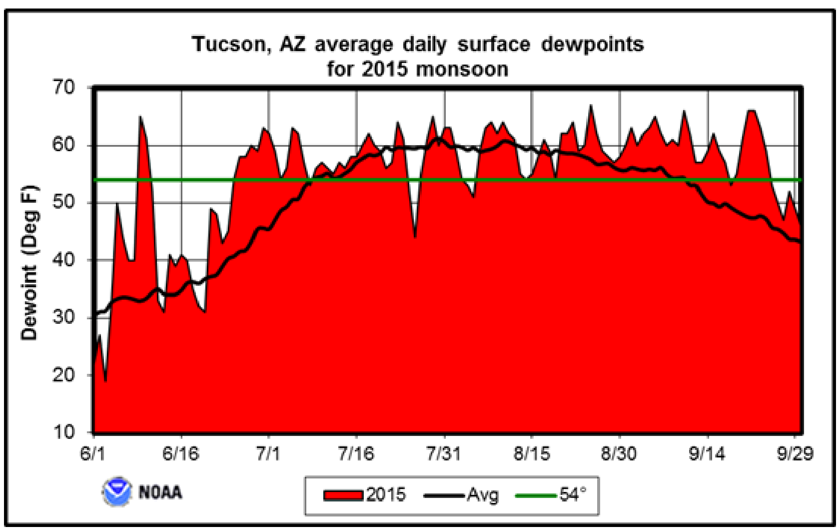
Presentation Outline

- Brief review of North American monsoon and its associated severe weather hazards in Arizona
- Factors controlling monsoon S2S variability
- Current state of operational S2S forecasts
- Potential for forecast improvement using regional atmospheric modeling
- Concluding thoughts

The monsoon in Tucson, Arizona





It is a ‘monsoon’ from the standpoint of a rapid increase in moisture and precipitation that occurs at about the same time every year.

Average monsoon precipitation in Tucson is about 6”

Old NWS definition of monsoon onset: Dew point 54°F or above for three consecutive days. Average onset date 4 July.

Monsoon Thunderstorms in Arizona

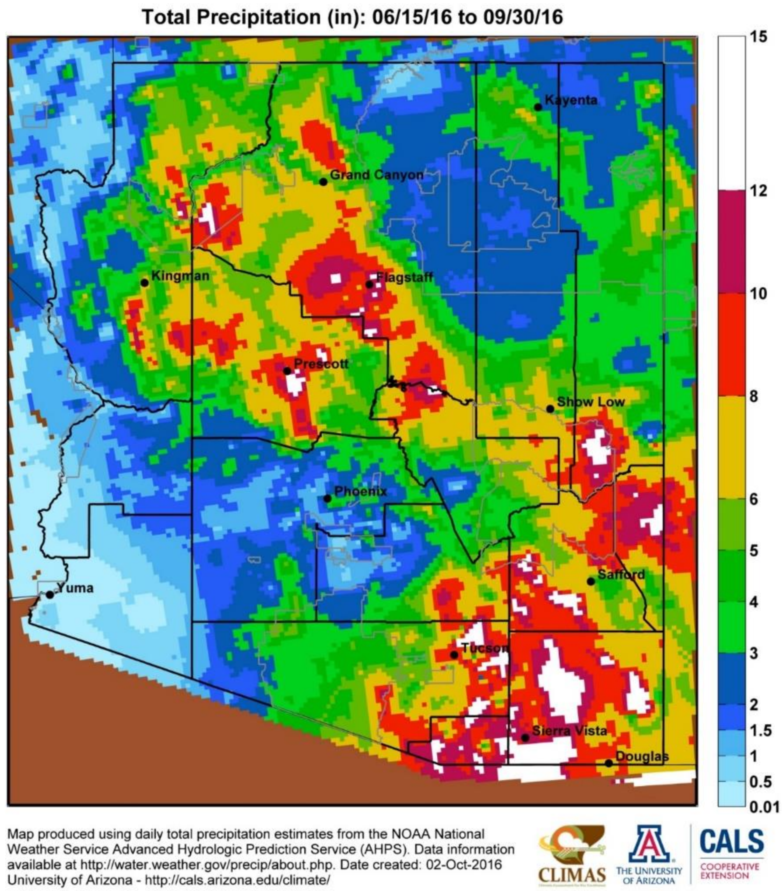
Monsoon thunderstorms at Kitt Peak at mature stage with gust fronts.

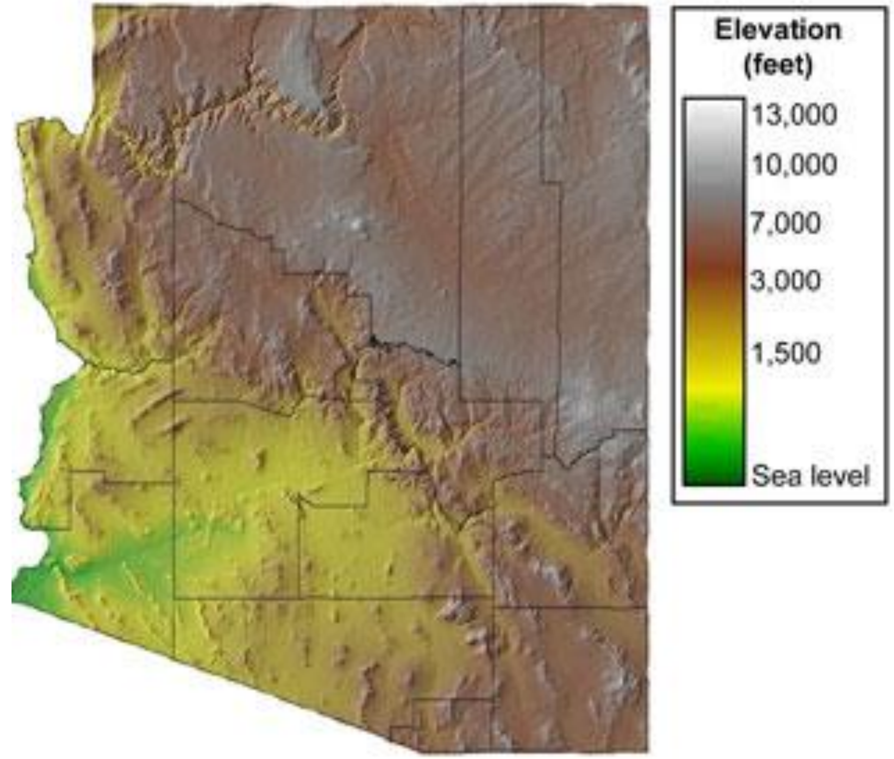
Forced by the diurnal mountain valley circulation

Air-mass type thunderstorms form over the mountains during late morning to early afternoon

Reach mature stage by about mid-afternoon.

(*Photo taken around 3pm)*



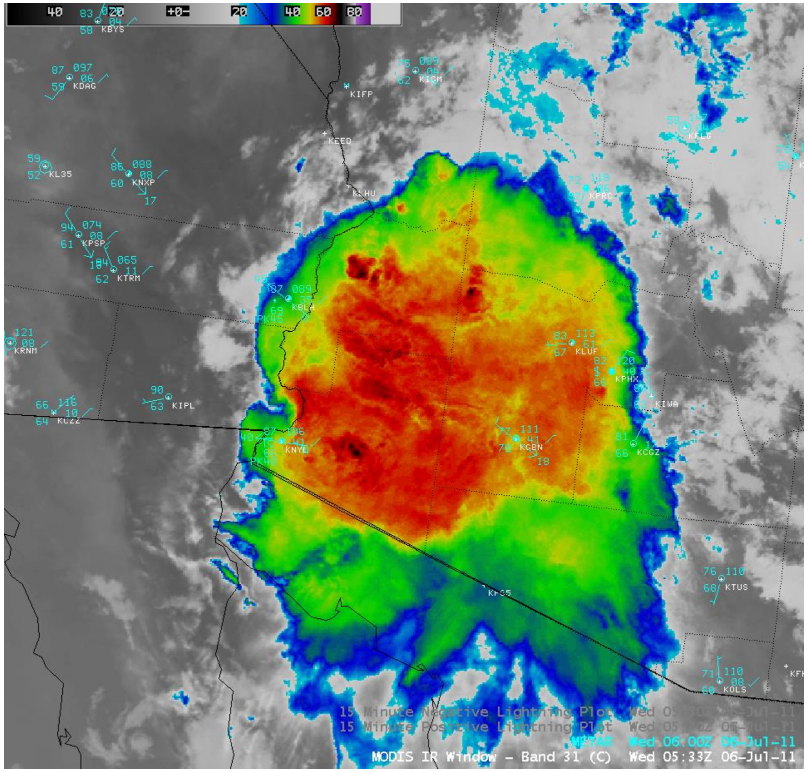


Monsoon precipitation is a strong function of elevation. Most occurs over highest mountain ranges where storms occur about every day.

Only rains a handful of times per year in the low southwest desert part of the state

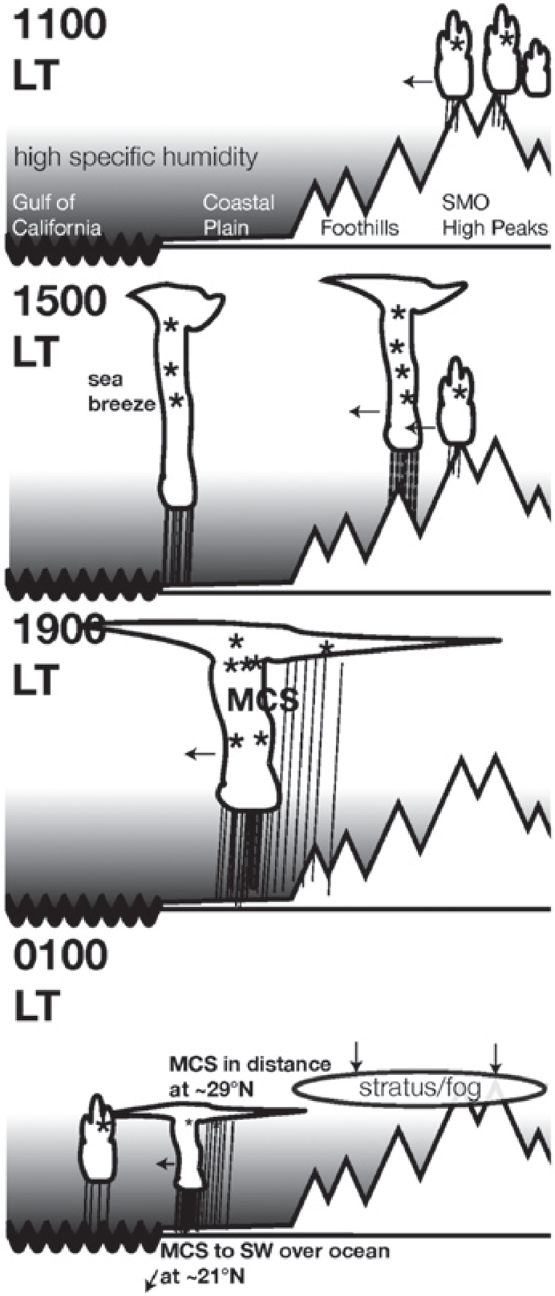
Phoenix Dust Storm Event: July 5, 2011

Dust storm outside Phoenix NWS



Resultant MCS in southwest Arizona

BUT…the few times does rain in the southwestern deserts of Arizona, it is likely to be associated with severe, organized convection!



Nesbitt et al. (2008)

Convective organization and propagation

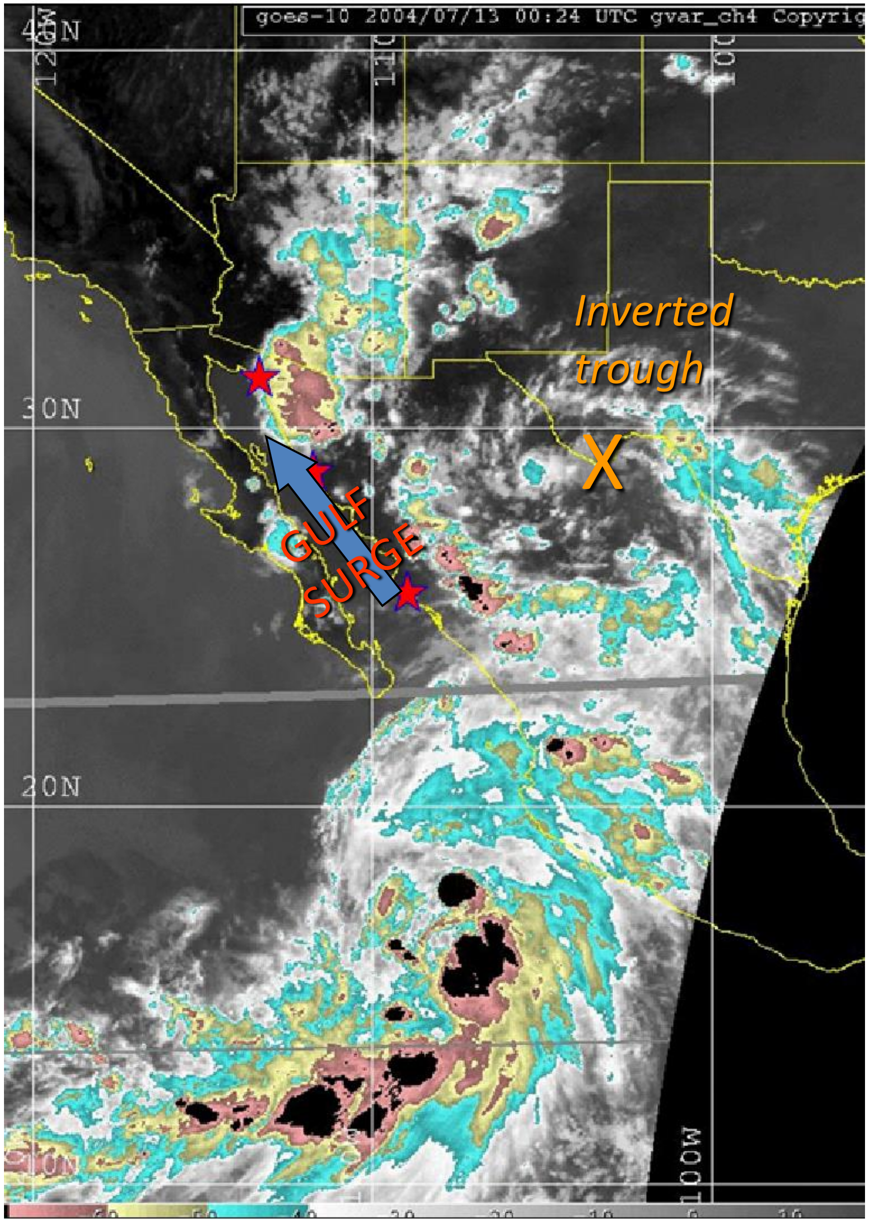
Convective clouds form over the mountains in the morning.

By afternoon and evening storms propagate to the west where they can organize into mesoscale convective systems if there is sufficient moisture and instability.

Convective-permitting resolution necessary to represent this process correctly in regional models.

Monsoon weather hazards in Southwest U.S.

Can S2S forecast guidance help to quantify the level of risk to extremes?



Monsoon thunderstorms during 'burst' periods

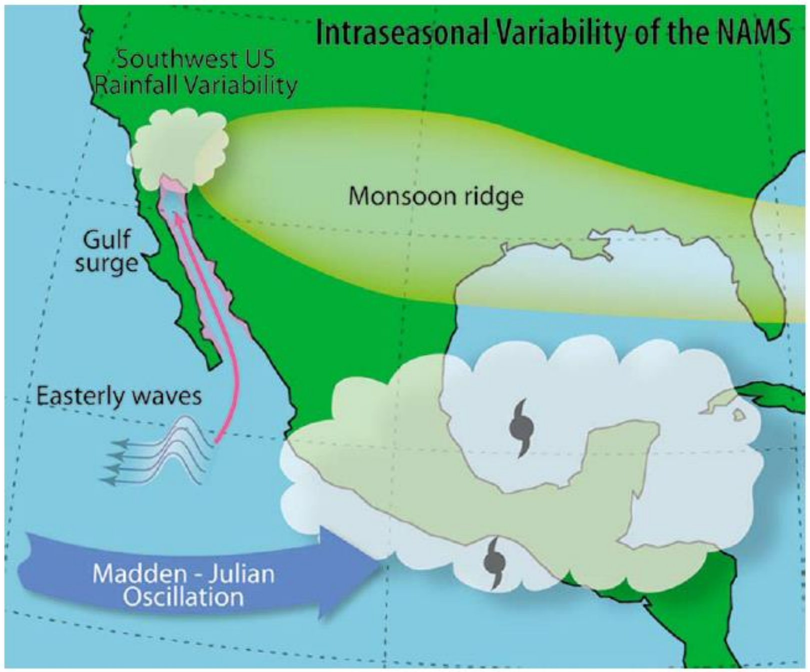
An inverted trough (X) traveling around the monsoon ridge.

Low level-moisture surging up the Gulf of California

RESULT

Thunderstorms which originate on the Mogollon Rim intensify and move westward toward low deserts and the Colorado River Valley.

Monsoon Intraseasonal variability



Moloney et al. (2008)

Factors Include:

- Easterly waves
- Tropical cyclones
- Low level moisture surges
- Upper level disturbances
- Madden Julian Oscillation

All these factors can help convection organize and intensify.

Will focus more on mechanisms relevant to longer timescales (> 1 month) for seasonal prediction.

Variation in North American monsoon ridge

Carleton et al. (1990, *J. Climate*)

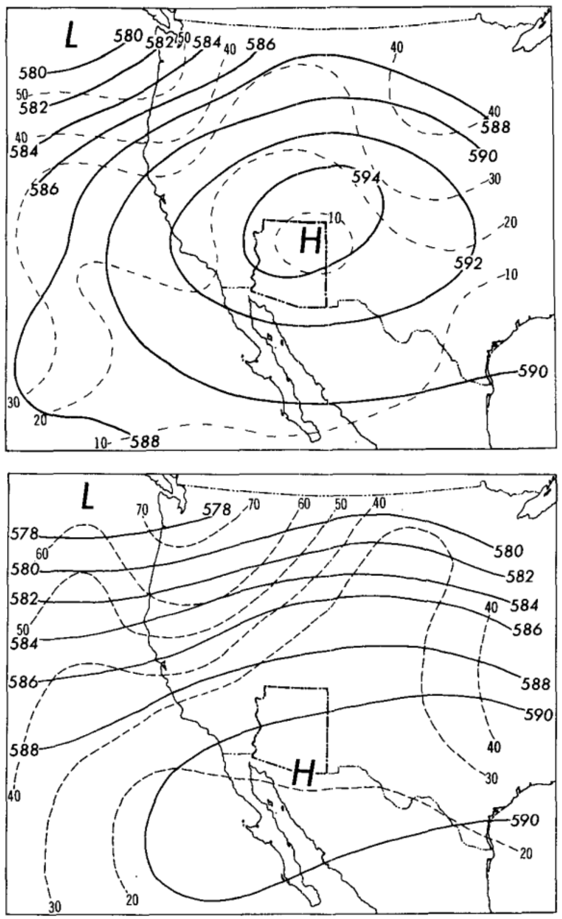


FIG. 1. Composite daily 500 mb height patterns (in gpdm) for (a) "four corners high", or northward-displaced STR, and (b) southward-displaced STR. These are based upon strong differences in 3-day averaged satellite-observed total cloud cover over the Southwest for summers 1980–82 (see Carleton 1986). Standard deviations associated with each type (in m) are shown dashed (From Carleton 1987).

Monsoon precipitation in Arizona is climatologically related to the strength and positioning of an upper-level ridge of high pressure over the western United States in summer.

Controls the flow of upper-level moisture into the NAMS. Monsoon typically starts in southern Arizona once the ridge moves toward the Four Corners region.

Interannual variability: Teleconnections at monsoon onset (late June, early July)

e.g. Castro et al. (2001, *J. Climate*)

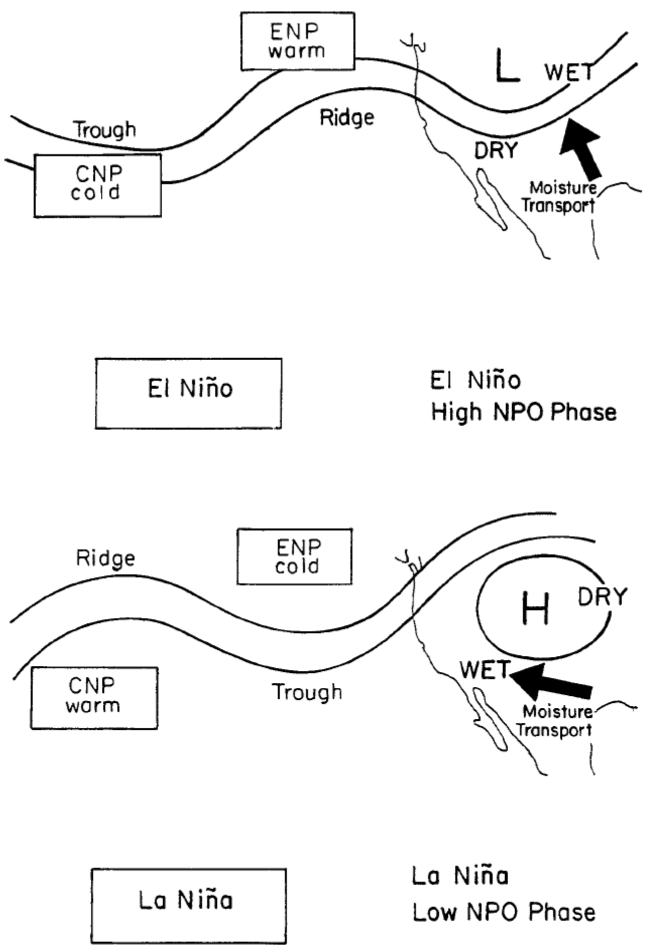
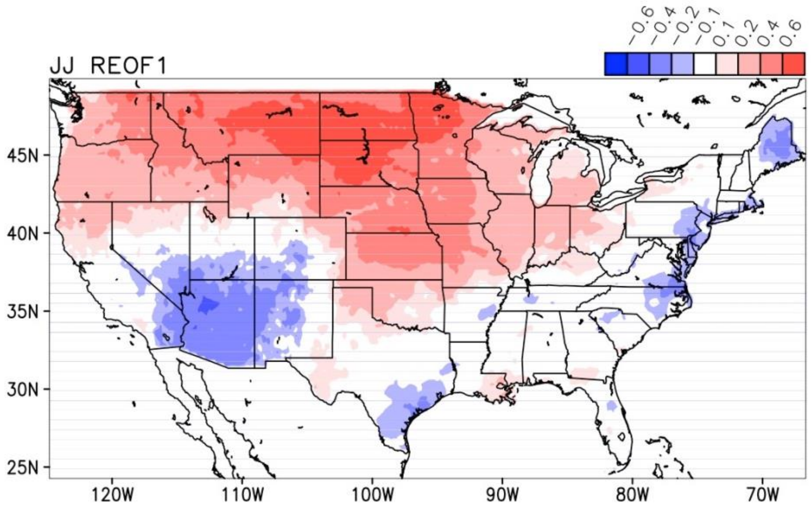


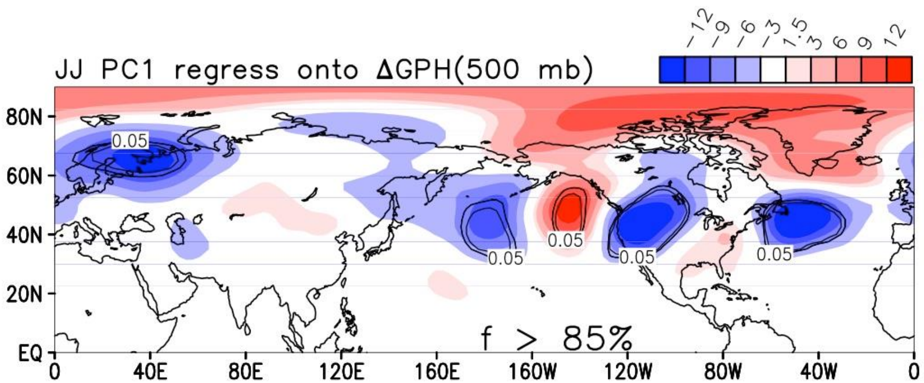
FIG. 14. Idealized relationship of monsoon ridge position and midlevel moisture transport to Pacific SSTs at monsoon onset.

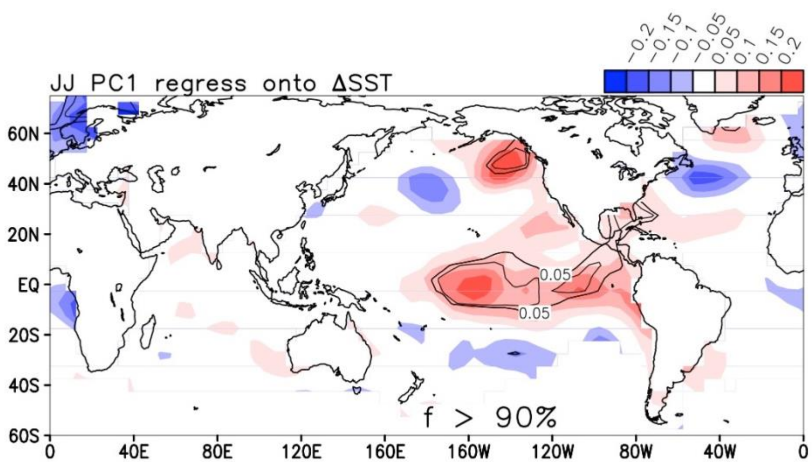
The onset and variability of North American Monsoon System (NAMS) is partly controlled by warm season atmospheric teleconnections

Teleconnections driven El Niño Southern Oscillation (ENSO) and Pacific Decadal Variability (PDV)

Influence monsoon ridge positioning in early summer.







Dominant mode of early summer precipitation (1950-2000) PRISM-based JJ SPI

Antiphase relationship in early summer rainfall between Southwest U.S. and central U.S

Relationship to atmospheric circulation anomalies

Teleconnection response Quasi-stationary Rossby wave train

Relationship to sea surface temperature anomalies

ENSO, Pacific decadal variability drive variation in tropical convection

Ciancarelli et al. (2013, *Int. J. Climatol.*)

Dominant warm season teleconnections related to precipitation variability principally in western and central U.S.

Western Pacific North America Pattern (WPNA)
More likely external mode

(a) **ENSO/PDV Forced: Early summer (JJ)**
Probably most seasonally predictable

(b) **Indian monsoon forced: Late summer (JAS)**

Figure 14. (a) Idealized atmospheric teleconnection pattern associated with JJ REOF 1 (ENSO/PDV forcing dominant). (b) Idealized atmospheric teleconnection pattern associated with AS REOF1 (likely dependent on Asian monsoon convection). Wet/dry areas over the United States indicated by blue/red.

Circumglobal Teleconnection (CGT)
Either external or internal mode

(a) **CGT Mode 1**

(b) **CGT Mode 2**

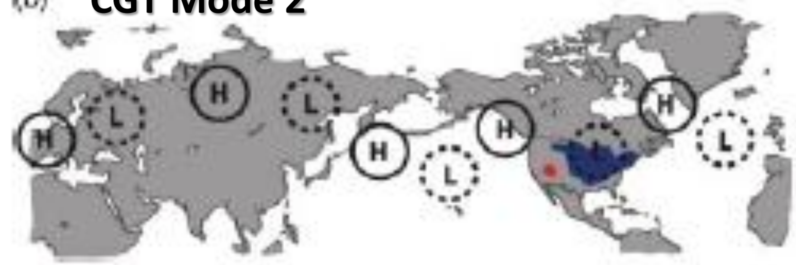


Figure 15. (a) Cartoon illustrating the CGT atmospheric teleconnection pattern associated with JJ REOF 2 (likely associated with the CGT). (b) Cartoon illustrating the CGT atmospheric teleconnection pattern associated with JJ REOF 5 (likely associated with the CGT). Wet/dry areas over the United States indicated by blue/red.

Ciancarelli et al. (2013)

Influence of Atlantic Multidecadal Oscillation

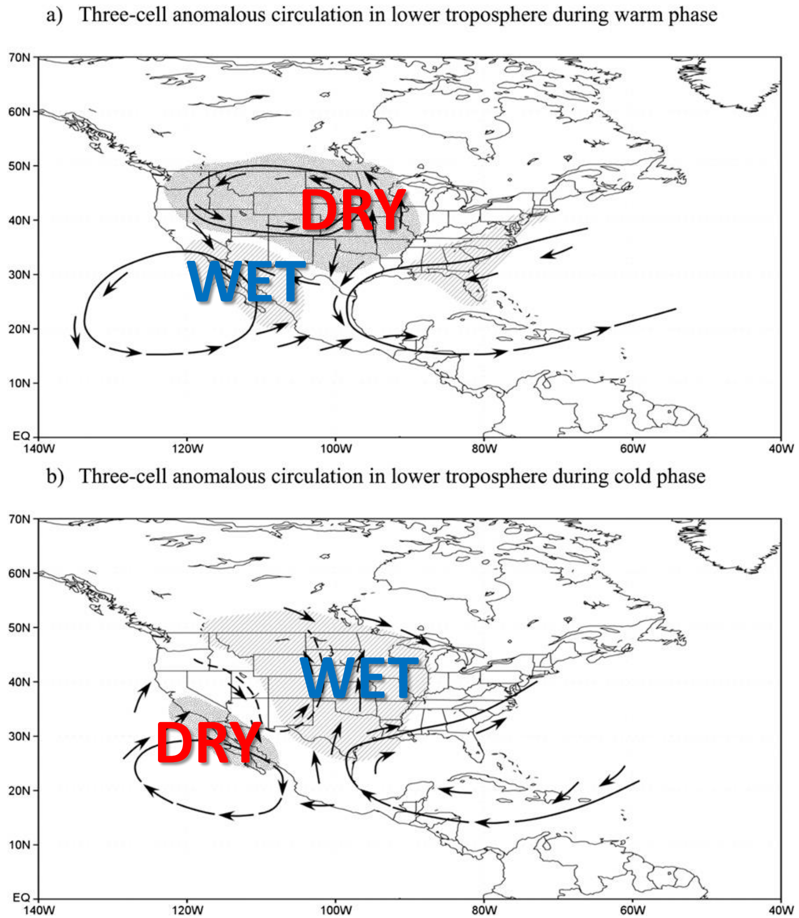


FIG. 7. Schematic summary of pressure and flow anomalies (the three-cell anomalous circulation) in the lower troposphere during the (a) warm and (b) cold phase of the AMO and in the upper troposphere during the (c) warm and (d) cold phase of the AMO. The hatched areas have above average summer (JJA) precipitation and the dotted areas have below-average summer precipitation. The double line in (c),(d) indicates the upper-troposphere front.

Hu and Feng (2011, *J. Climate*)

Warm phase: Weaker North Atlantic subtropical high, weaker Great Plains low-level jet.

Dry in central U.S., wet in Southwest U.S.

Cold phase: Stronger North Atlantic subtropical high, stronger Great Plains low-level jet.

Wet in central U.S., dry in Southwest U.S.

Probably also reflects variability associated with aforementioned CGT, WPNA patterns

Improving monsoon S2S forecasts: Atmospheric teleconnections are large-scale orchestrator

Idea: Warm season atmospheric teleconnections organize the continental-scale patterns of temperature and precipitation anomalies. **Principally WPNA and CGT patterns.**

Some likely sources of S2S predictability for **externally** forced modes:

- ENSO-Pacific Decadal variability: Basically SST, tropical convection in the western tropical Pacific
- Indian, SE Asian monsoon variability
- Atlantic Multidecadal Oscillation
- Madden Julian Oscillation

One key to skillful S2S monsoon forecasts:

1) **Dominant warm season teleconnection modes and their forcing mechanisms exist as statistical features within global S2S models.**
2) **The modes are deterministically predictable at S2S timescales.**

Antecedent Land Surface Conditions

e.g. Zhu et al. (2007, *J. Climate*)

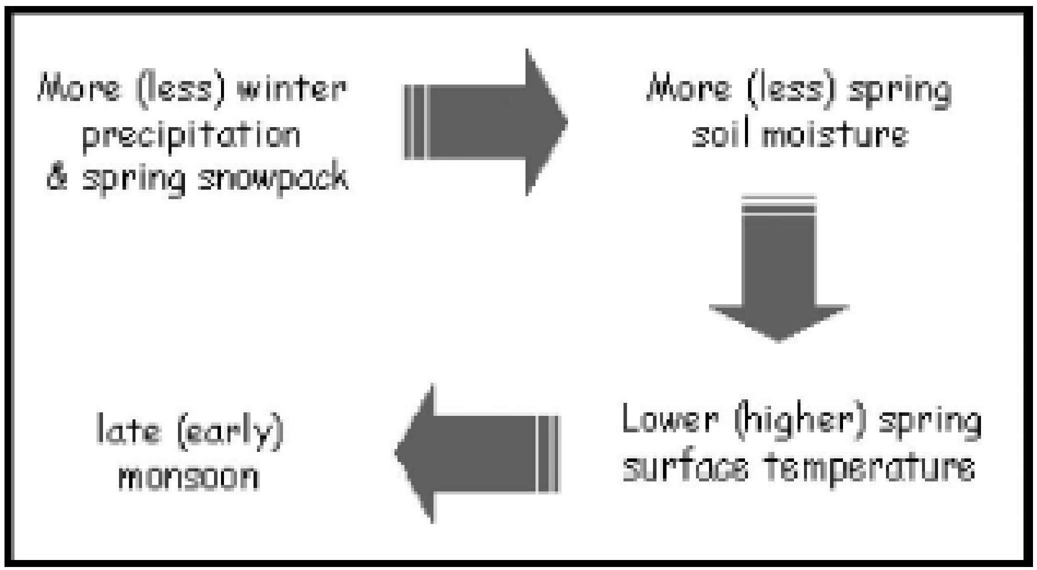


Fig. 1. Proposed winter–summer land surface–atmosphere feedback hypothesis for the North American monsoon.

This hypothesis has been mostly explored only in a statistical framework.

Land Sea Thermal Contrast

e.g. Turrent and Cavazos (2009, *Geophys. Res. Lett.*)

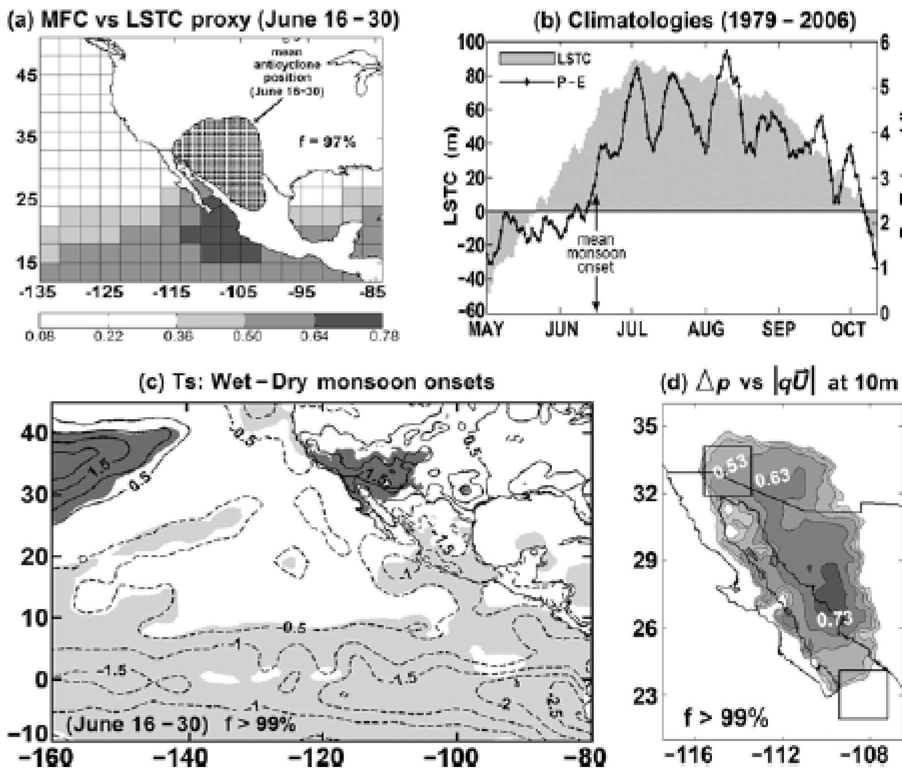


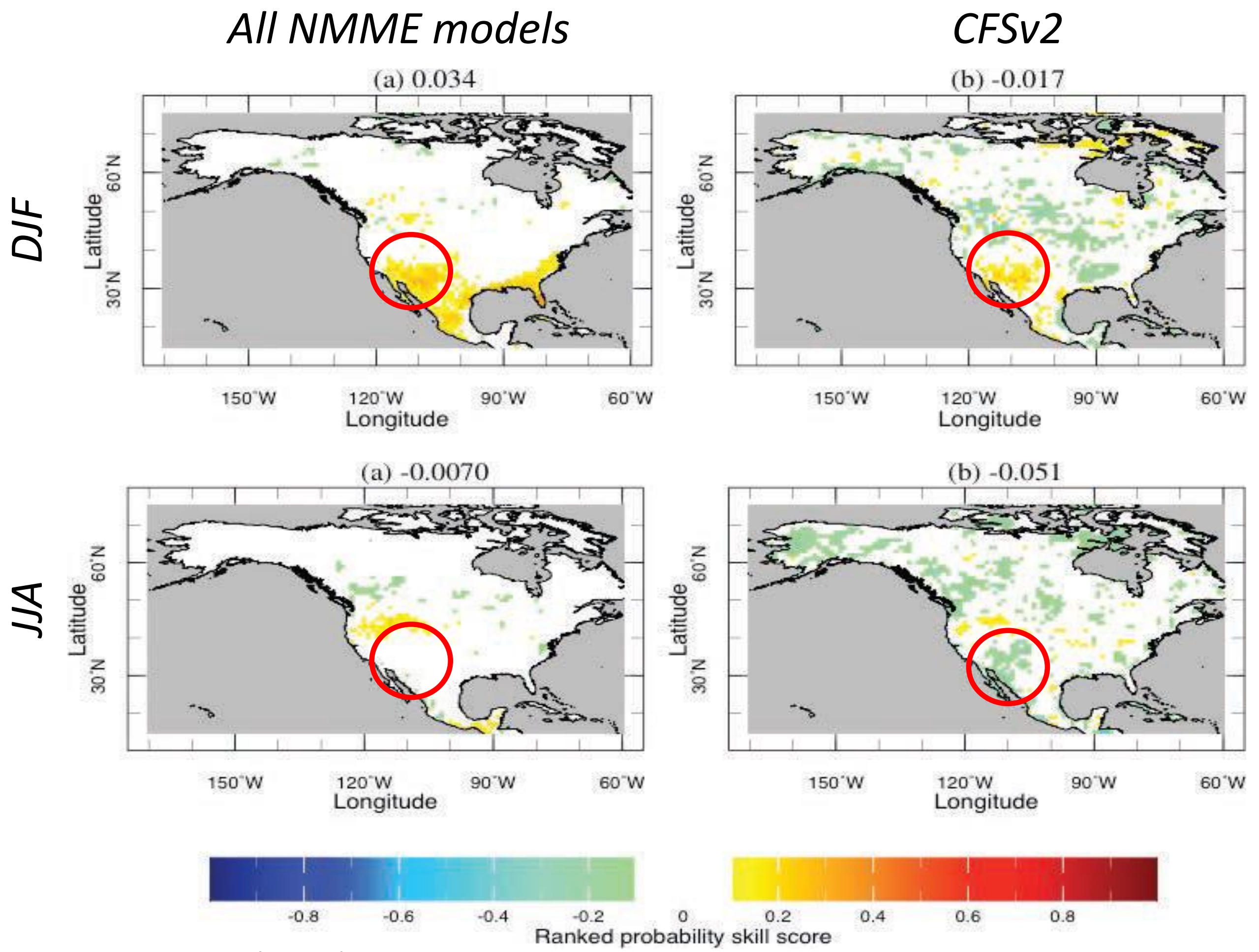
Figure 3. (a) Correlation of the MFC index vs. horizontal differences of the area average of ΔZ over the continental dotted region and each of the individual oceanic boxes. (b) Daily NARR climatologies of the monsoon LSTC, and P - E area-averaged over the core region, based on the period 1979–2006. (c) Wet – Dry NAM onsets surface temperature composite (June 16–30); statistically significant positive (negative) difference regions ($p < 0.05$) are shaded in dark (light) gray; contour interval is 0.5°C over sea and 1.0°C over land; SST data from OISST-V2 dataset [*Reynolds et al.*, 2002], LST data from NARR. (d) Correlation of the Gulf of California surface pressure gradient index (Δp) vs. mean surface moisture flux magnitude ($|qU|$ at 10 m); both quantities are averaged over June 16–30, and contour interval is 0.1. Only significant contours ($p < 0.05$) are plotted; f indicates the level of field significance.

Basic idea: Temperature contrasts (measured by thickness) between land and ocean have a strong positive relationship to monsoon onset and total monsoon precipitation.

Probably more important for monsoon precipitation in Mexico, as opposed to teleconnective influences.

Need for improved S2S forecasts of warm season: Current skill of NMME seasonal forecasts

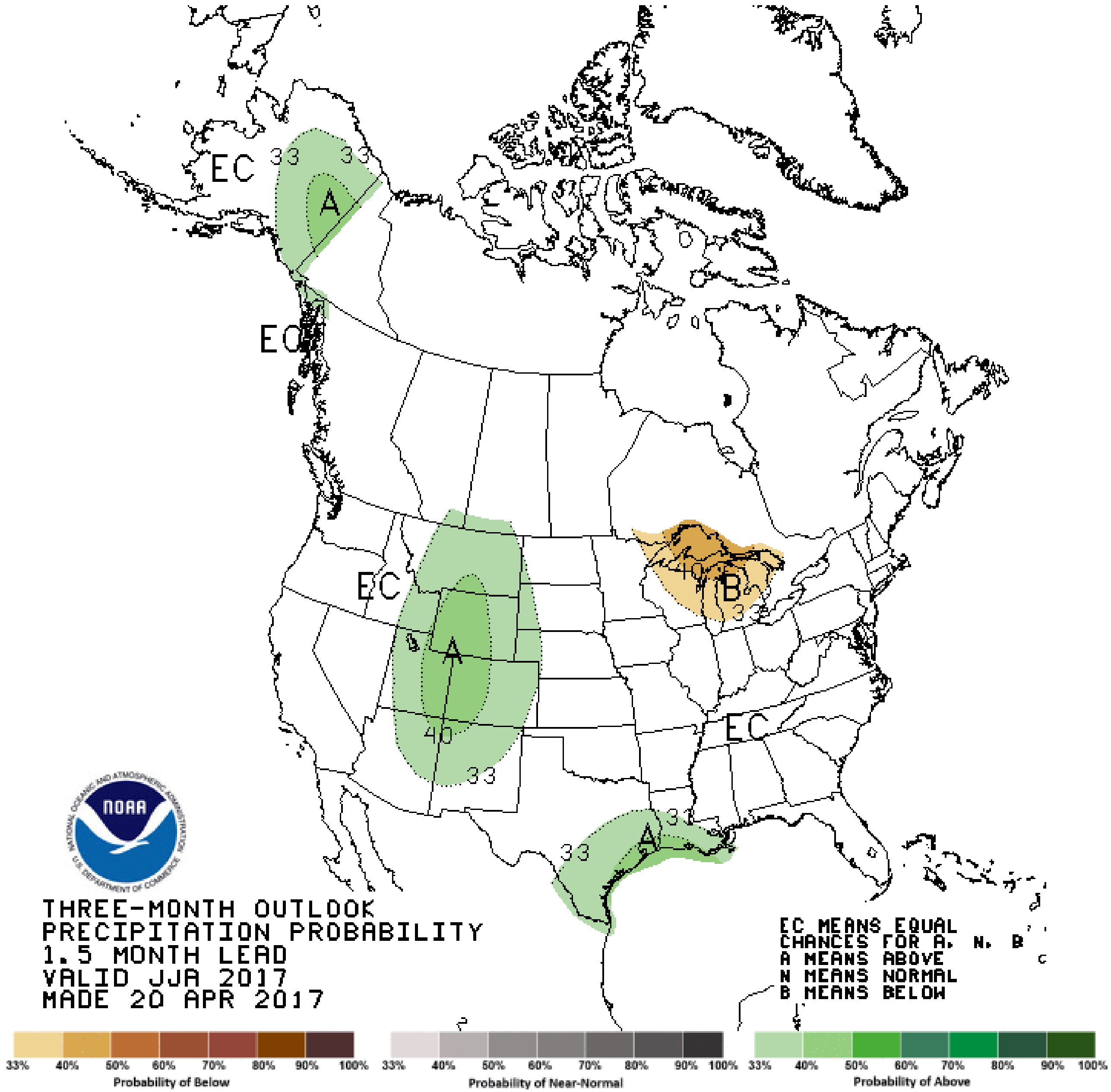
Rank probability skill score of 6-month precipitation forecast



NMME models have greatest forecast skill for precipitation in cool season, especially in Southwest

Comparatively much poorer skill in warm season. Basically no skill to forecast monsoon precipitation.

Kirtman et al. (2014)

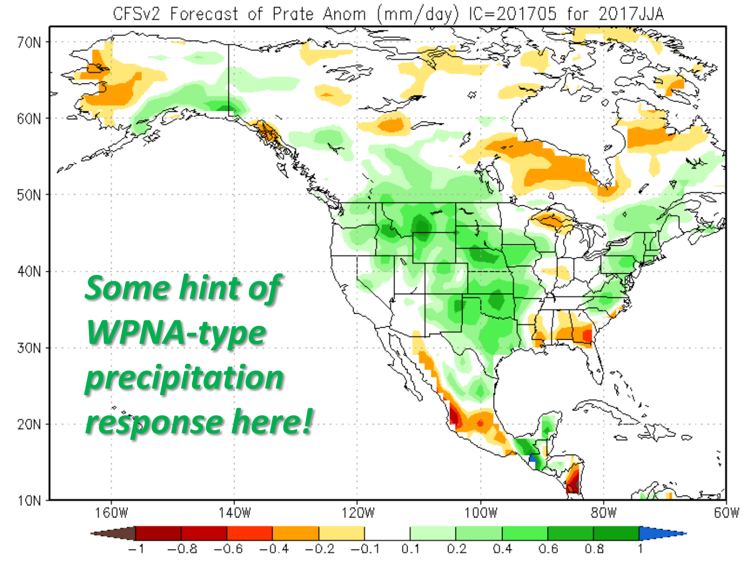

THREE-MONTH OUTLOOK
PRECIPITATION PROBABILITY
1.5 MONTH LEAD
VALID JJA 2017
MADE 20 APR 2017
EC MEANS EQUAL
CHANCES FOR A, N, B
A MEANS ABOVE
N MEANS NORMAL
B MEANS BELOW
EC
A
B
33
40
33% 40% 50% 60% 70% 80% 90% 100%
Probability of Below
33% 40% 50% 60% 70% 80% 90% 100%
Probability of Near-Normal
33% 40% 50% 60% 70% 80% 90% 100%
Probability of Above

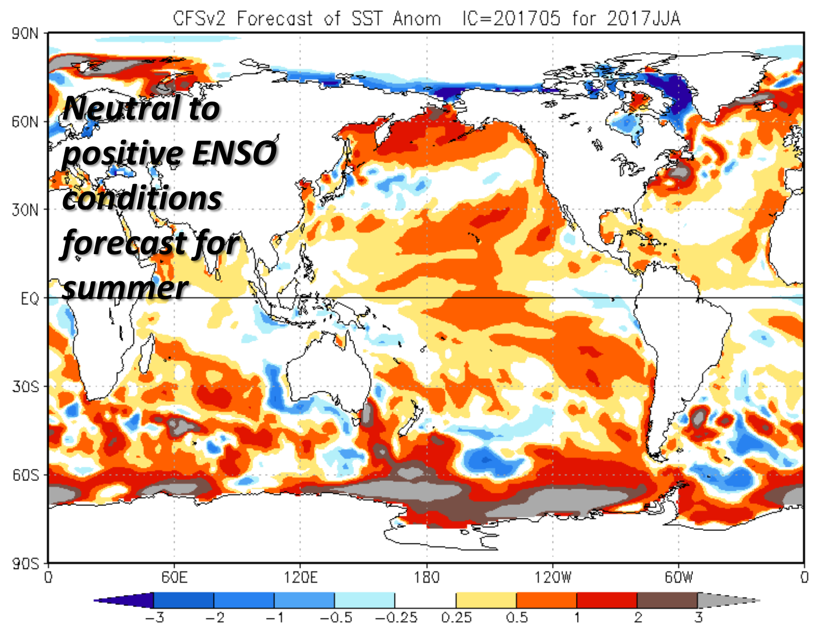
2017 JJA CFSv2 Forecast

Two possibilities for lack of monsoon skill :

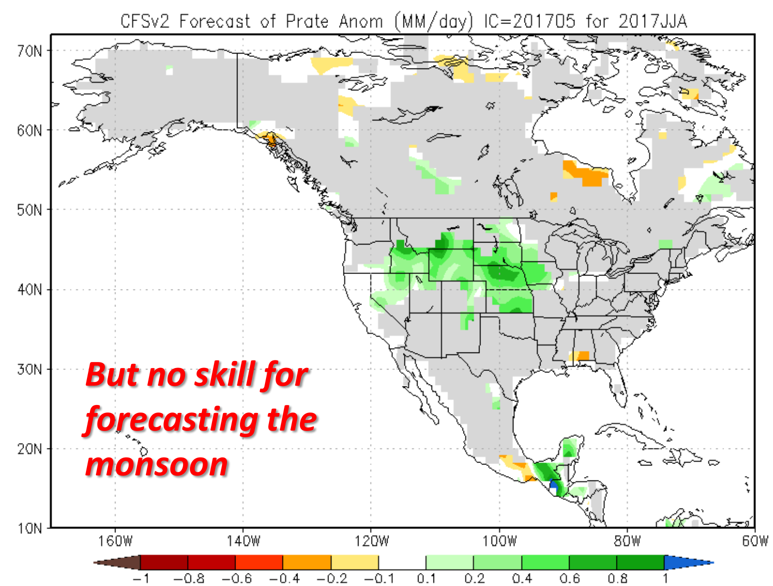
- Cannot predict warm season teleconnections: **fundamental deterministic predictability limit**
- Poor representation of convective precipitation, land surface feedbacks: **higher resolution, parameterized physics could maybe fix?**

Raw precipitation anomaly forecast



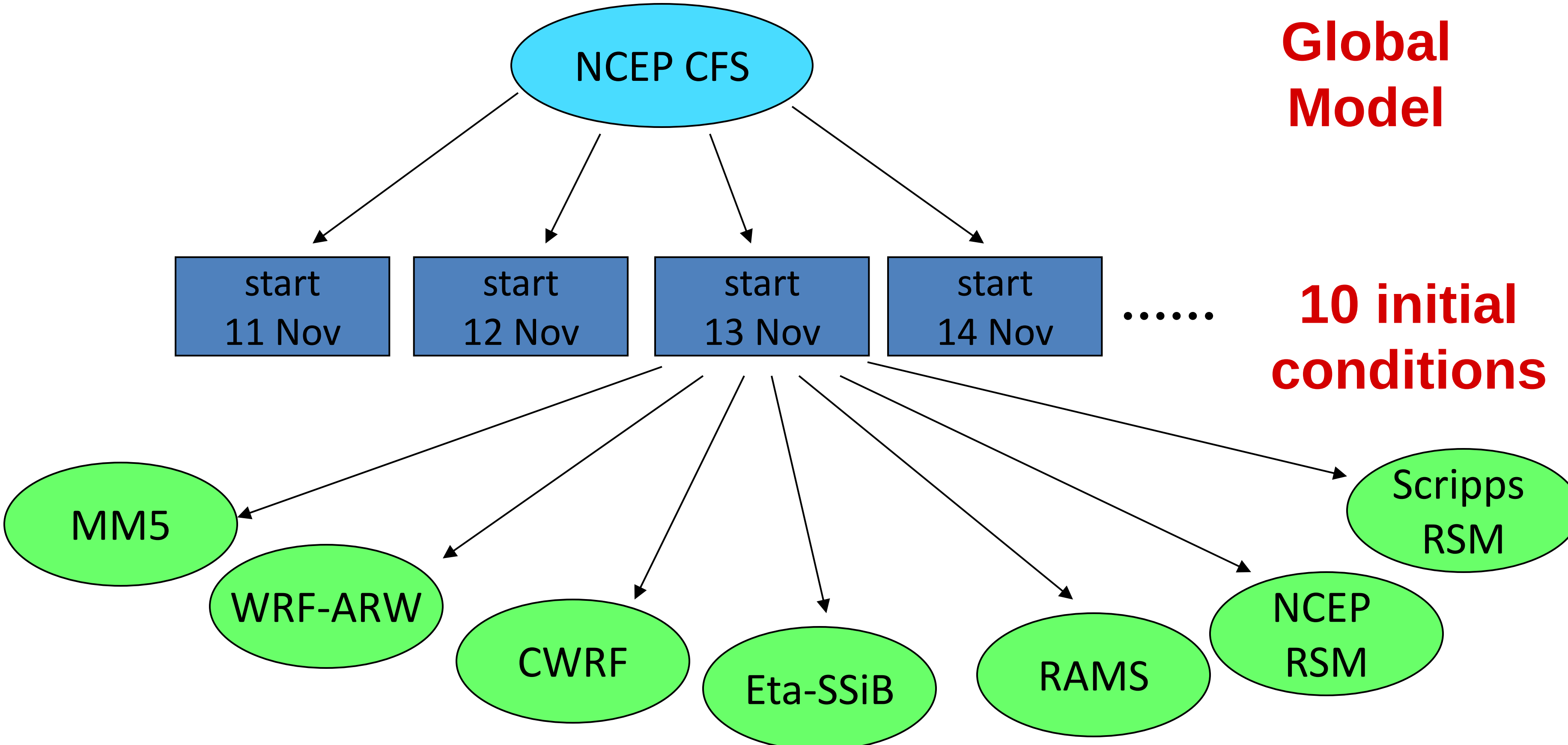


With skill mask applied



MRED = Multi-Regional Ensemble Downscaling

Downscaled 23 years of CFSv1 reforecasts



Regional Models

Courtesy Prof. Ray Arritt, Iowa State

Are skillful seasonal NAMS forecast possible?

Castro et al. (2012, *J. Climate*)

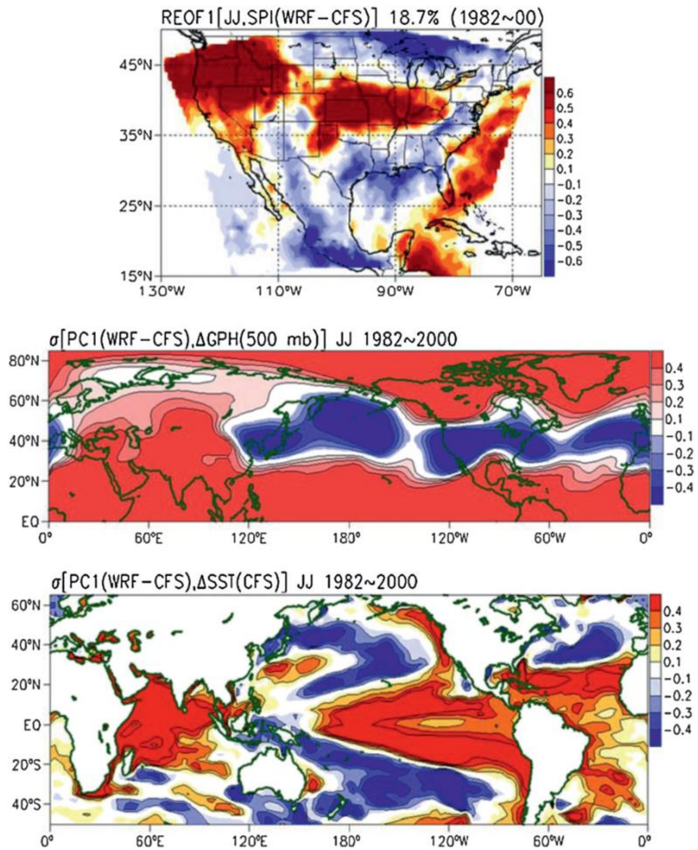


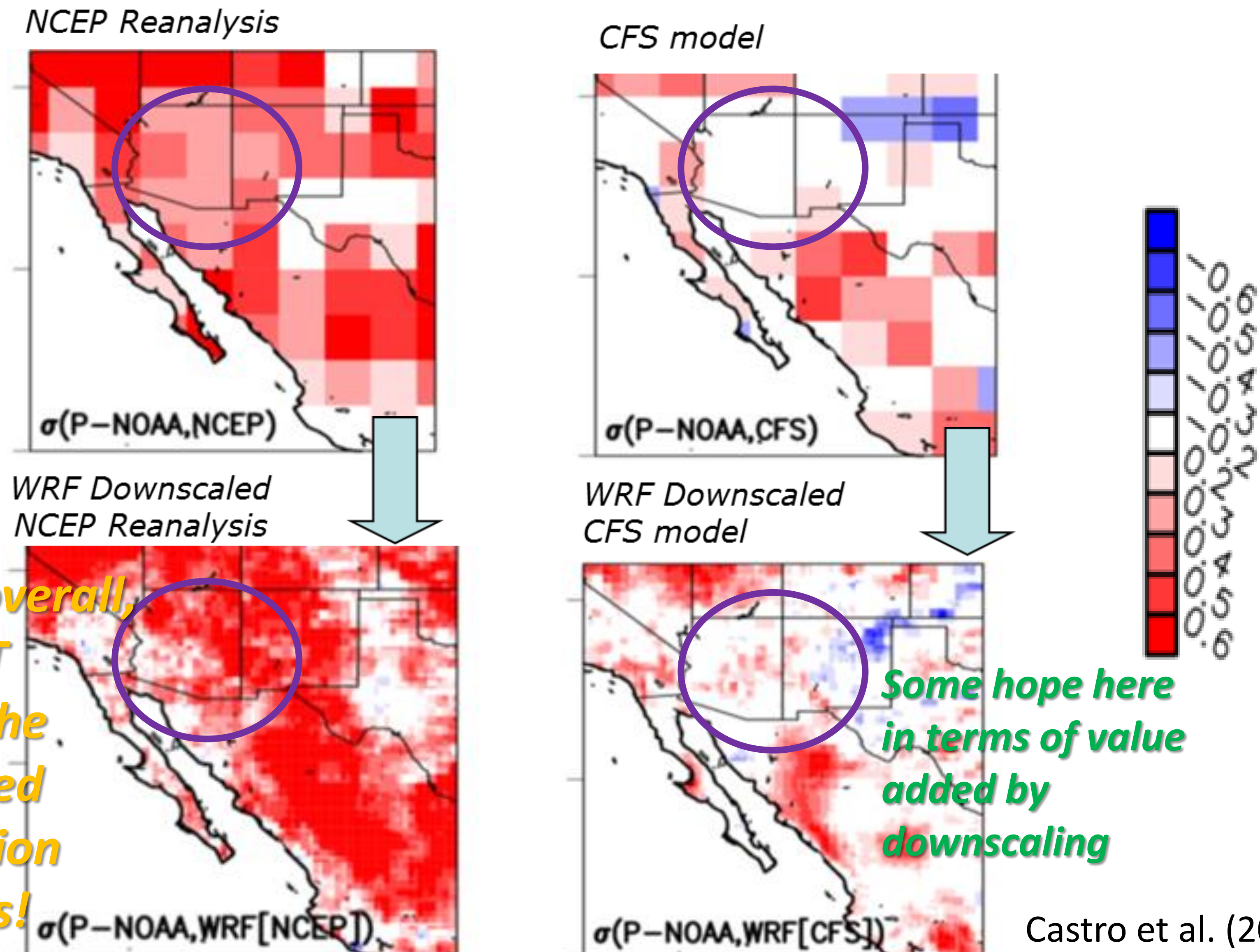
FIG. 18. (top) Most highly correlated mode of early warm season (JJ) SPI in WRF-CFS in comparison to first three REOF early warm season SPI modes from WRF-NCEP, shown as the regression on the principal component with variance explained. Specifically, this mode is most highly correlated with the second REOF from WRF-NCEP at a value of 0.44 with significance exceeding the 95% level. (middle) Corresponding PC correlation on normalized 500-mb geopotential height anomalies from CFS. (bottom) Corresponding PC correlation on CFS SSTA.

Dynamically downscaled CFSv1 warm season seasonal forecasts at 35 km grid spacing for about 20 years

Global seasonal forecast models do have an ability to statistically represent WPNA response

More problematic is representing WPNA response in a deterministic sense for a skillful seasonal forecast.

Early summer (JJ) precipitation anomaly correlation for NAME Tier 2 Region



Better overall, but NOT where the organized convection happens!

Some hope here in terms of value added by downscaling

Castro et al. (2012)

Lessons Learned from MRED project and our similar work for the warm season

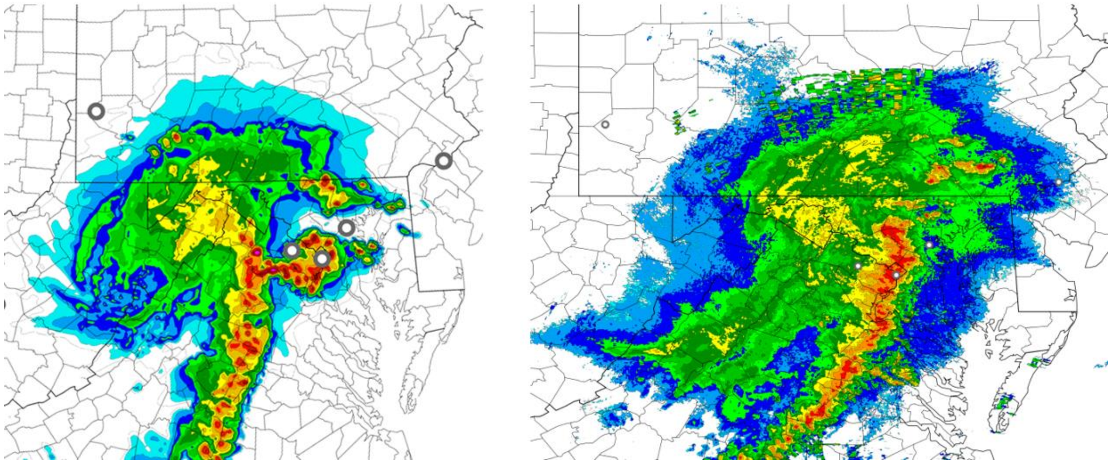
Dynamical downscaling of seasonal forecast models mostly improves forecast skill in regions where the global models already demonstrate some appreciable skill, ultimately tied to deterministic representation of natural climate variability.

Greatest value added obtained by downscaling to be expected where large-scale climate modes project strongly on regional precipitation (e.g. ENSO).

Therefore, western and central U.S. would be the a priori target areas where CPMs would be expected to add most value at S2S timescales during warm season.

Improving warm season S2S forecasts: Convective-permitting modeling (CPM)

3 km HRRR model forecast   Radar observation



12-h HRRR forecast simulation of East Coast derecho event that occurred 29 June 2012 (2300 LT).

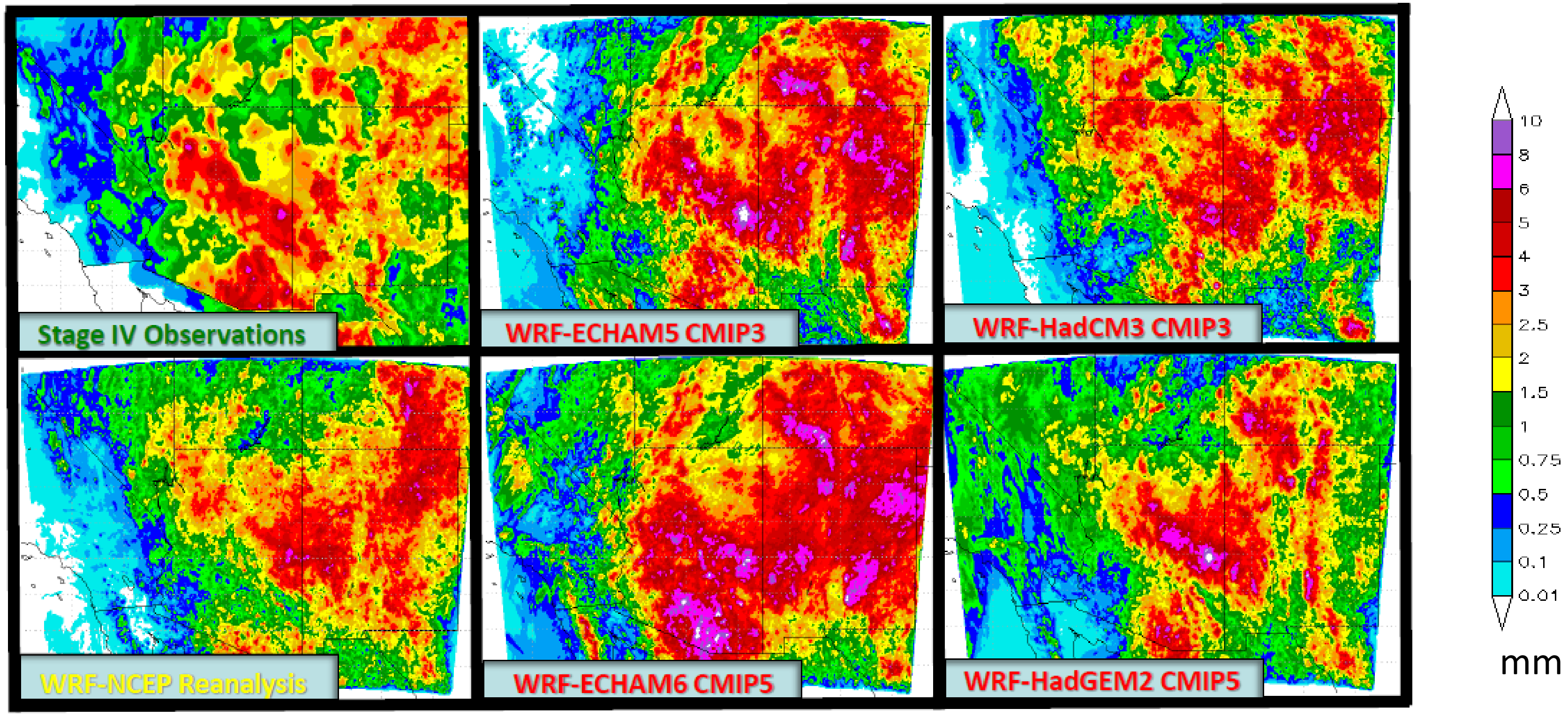
Image from: UCAR AtmosNews (24 September 2011)

Atmospheric models with meso-β scale resolution (~10 km) with parameterized convection have poorer representation of warm season precipitation, as compared to cool season.

Convective permitting modeling (<5 km) at meso-γ scale results in better physical representation of storm-scale structures, timing, propagation. Also better statistical characterization of convective precipitation extremes.

Presently <u>little to no application</u> of CPMs to address warm season S2S predictability.

Daily averaged modeled precipitation in comparison to observations for thermodynamically favorable severe weather event days All modeling paradigms (period of Stage IV record 2002-2010)



Precipitation across the Southwest U.S., with maximum values centered on mountains. CMIP paradigms behave well in comparison to Stage IV product. Diurnal cycle is reasonable too.

Luong et al. (2016, J. Appl. Meteor. Climatol., submitted)

The way forward:
Feasibility of addressing warm season S2S challenge and improved monsoon forecasts

A robust methodological approach to investigate warm season S2S problem, based on dynamical modeling should:

1. Incorporate use of multiple S2S global forecast models and/or ensembles across a continuum of S2S timescales to assess deterministic predictability of warm season atmospheric teleconnections, using data from NMME S2S reforecasts.

1. Use one or more limited area models to perform dynamical downscaling of global S2S model ensemble data at convective-permitting scale.

A MRED-type approach is probably what is needed here…