Investigation of the Summer Climate of North America: A Regional Atmospheric Modeling Study

Christopher L. Castro
Department of Atmospheric Science
Colorado State University

MMM Seminar
National Center for Atmospheric Research
October 20, 2005

Los Mochis, Mexico. NAME Field Campaign. Summer 2004
Photo by Peter Rogers

Acknowledgements

Collaborators and colleagues at Colorado State, particularly Dr. Roger A. Pielke, Sr.

Dr. Jimmy O. Adegoke, University of Missouri, Kansas City

Dr. Siegfried Schubert, Michael Kistler, and Phillip Pegion, NASA Goddard Space Flight Center

Funding Provided By

NOAA GEWEX Americas Prediction Project (GAPP) and Pan American Climate Studies (PACS), North American Warm Season Precipitation Initiative

NASA Earth System Science Fellowship Program

Department of Defense

Papers available on-line at Pielke group webpage at CSU

Seminar Outline

Introduction

Why is understanding summer climate important?
Challenges of Modeling North American Summer Climate
Dynamical Downscaling Types
North American Summer RCM studies to date
Relationship of North American summer climate to Pacific SST

Part I: RAMS and modification for use as a Regional Climate Model

Conclusions of RAMS sensitivity experiments evaluating the value retained and added by dynamical downscaling

Part II: A Summer Climatology of the Contiguous U.S. and Mexico

Part III: Diagnosing the effect of Pacific SST Associated Teleconnections on North American Summer Climate

Summary and Conclusions

Topics for Future Research

Importance of Understanding Summer Climate in North America

Phenomena

Sustained Flood or Drought

Wildfires

Severe Weather
- Rain
- Hail
- Tornadoes
- Flash Floods

Societal Impacts

Water resources

Energy consumption

Agriculture

Disaster response

Recreation

A GREATER sensitivity to climate and its variability as population has increased, particularly here in the western U.S. and Mexico

Dynamical Downscaling Types with a Limited Area Model

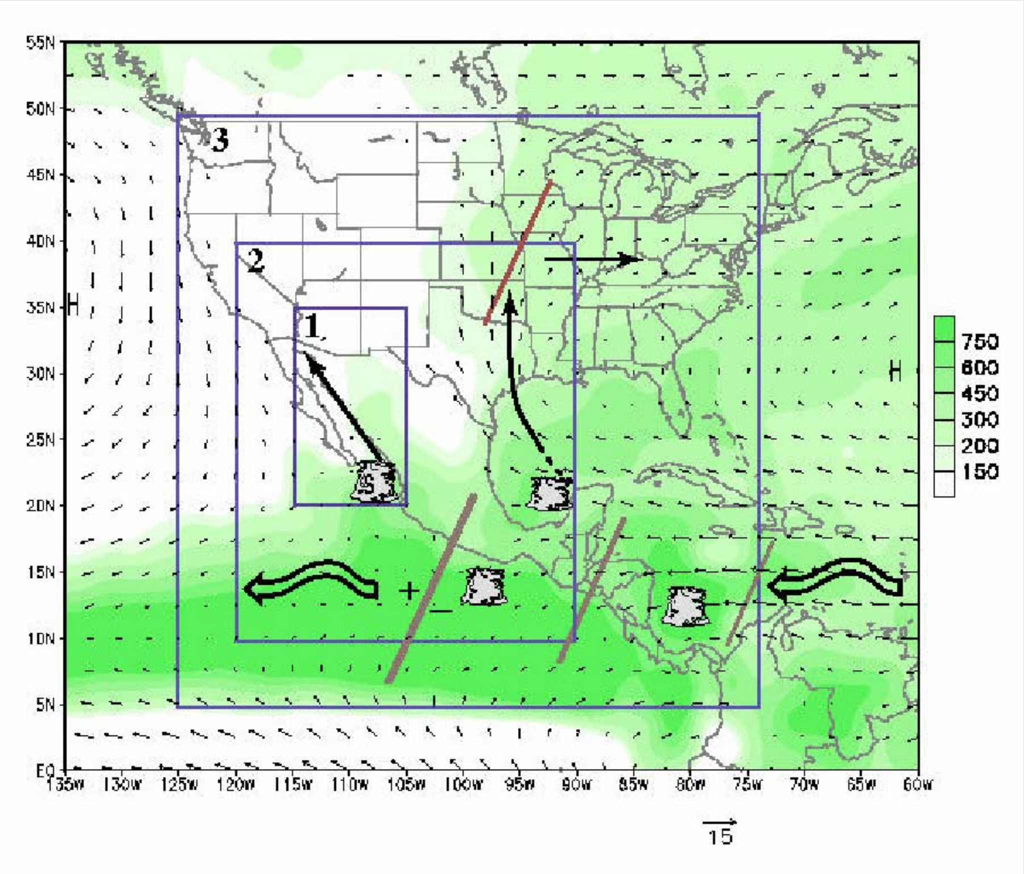
TYPE 1: Numerical Weather Prediction → short-term global forecast

TYPE 2: Seasonal Weather Simulation → Atmospheric Reanalysis

TYPE 3: Seasonal Weather Prediction → Global Model forced by SST

TYPE 4: Multiyear Climate Prediction → Coupled atmosphere-ocean global model

Major North American Summer Climate Modeling Challenges



From NAME documentation

Convective rainfall and its mechanisms

Great Plains and Baja low-level jets (LLJ)

Transient synoptic activity associated with passage of westerly troughs and tropical easterly waves

Large-scale circulation

Achieving a reasonable representation of North American summer climate requires all of these elements in a RCM.

RCM Diagnostic Studies

Emphasis is to produce mesoscale features of the summer climate missing in the reanalysis. **Typically focus on one season or a few in sequence for a given configuration of the RCM.**

ETA: Berbery et al. (2001)
RAMS: Saleeby and Cotton (2004)
NCEP RSM: Anderson et al. (2000, 2002, 2004), Mo and Berbery (2004)
MM5: Li et al. (2004), Xu et al. (2004)

RCMs have improved representation of:

Diurnal cycle of convection
Baja LLJ and associated gulf surges
Continental out-of-phase relationship in rainfall between core monsoon region and central U.S.
Precipitation, though typically more closely matches satellite observations
Timing of monsoon rains coincident with changes in the large-scale circulation (in a 22-year climatology)

In this study aim is to create a long-term RCM climatology, which has not been yet attempted, to investigate interannual variability.

RCM Sensitivity Studies

Change the surface boundary (snow cover, soil moisture, vegetation, or sea surface temperature) or the configuration of the RCM (model physical parameterizations, grid spacing, domain size, or nudging options)

RAMS: Castro et al. (2005), Miguez-Macho et al. (2005)
MM5: Liang et al. (2004), Gochis et al. (2002; 2003)
NCEP RSM: Kanamitsu and Mo (2003)

These studies have revealed:

LARGE sensitivities to the configuration of the RCM, particularly to the choice of convection scheme and nudging options. Can **drastically** affect the continental-scale distribution of rainfall.

Can be sensitivities to the surface boundary specification. Many studies have focused, for example, on the effect of soil moisture in the central U.S.

A necessary first step before attempting an RCM climatology is to quantify the sensitivity of the model to determine an appropriate experimental design.

Relationship of North American Summer Climate to Pacific SSTs

Castro et al. (2001, *J. Climate*): Using 50 years of NCEP Reanalysis data, showed statistically significant relationships between tropical and North Pacific SST and the evolution of the monsoon ridge over North America.

The teleconnection to Pacific SSTs **evolves in time** and is most apparent in early summer. This affects the onset of the North American monsoon and the end to the late spring wet period in the central U.S.

The SSTs reflect the El Niňo Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). These are the modes which will be used to guide investigation of the interannual variability of the RCM climatology.

Numerous other observational studies generally support an ENSO-PDO connection to North American summer climate and additionally note that ENSO is related to a shift in the climatological position of the ITCZ which affects precipitation in Mexico.

Mechanism of Rossby Wave Response

(Sardeshmukh and Hoskins 1988)

Rossby wave source in barotropic vorticity equation:

$$S = -v_\chi \bullet \nabla \zeta - D\zeta$$

Advection of vorticity gradient by divergent wind

Divergence term

Rapid changes in the climatological evolution of upper level jet streams will affect Rossby wave generation and propagation.

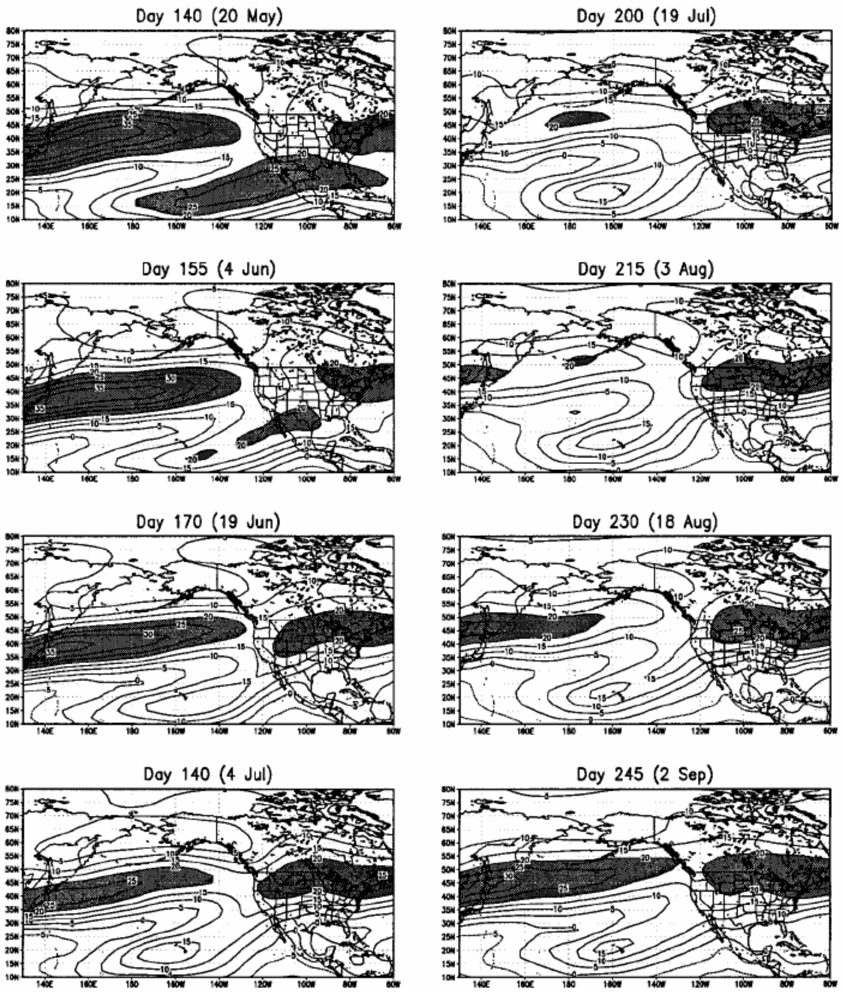


FIG. 5. Five-day running mean climatological evolution of 200-mb zonal wind over the Pacific and North America from Julian day 140 through Julian day 245. Contour interval is 5 m s^{-1}. Values greater than 20 m s^{-1} are shaded.

Castro et al. (2001)

Monsoon Ridge Position at Onset (Late June, July)

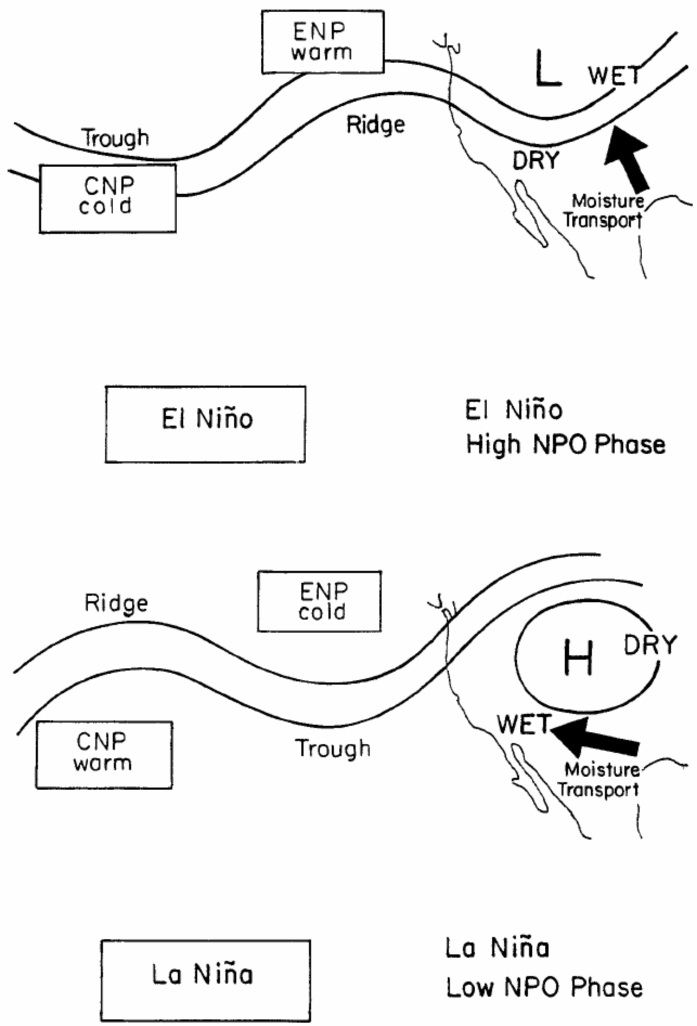


FIG. 14. Idealized relationship of monsoon ridge position and midlevel moisture transport to Pacific SSTs at monsoon onset.

Climatology delayed

Climatology accelerated

(Castro et al., 2001)

Modeling the Boreal Summer Teleconnection Response

Idealized modeling studies using baroclinic or barotropic models with prescribed tropical atmospheric heating suggest that the distribution of tropical Pacific SST can produce a boreal summer atmospheric teleconnection response, as in winter. **The teleconnection response is most apparent in late spring to early summer and is most likely related to forcing in the central and western tropical Pacific.**

References: Trenberth and Branstator (1992), Lau and Peng (1992), Newman and Sardeshmukh (1998)

Atmospheric GCMs have also been employed to investigate boreal summer climate and its relationship to sea surface temperature.

This study will use the GCM data from Schubert et al. (2002, J. Climate)

Observed SST Variability and Atmospheric Circulation

ENSO Mode

PDO-like Mode

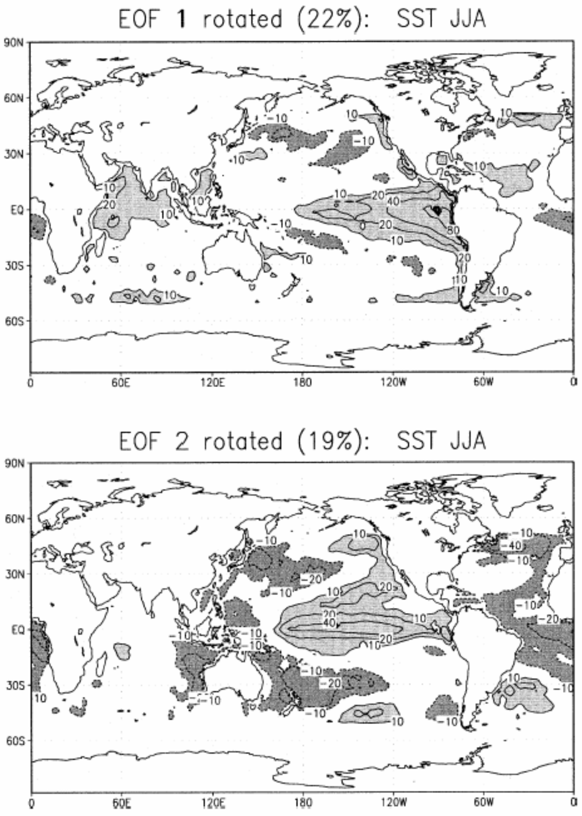


FIG. 6. The first two (of five) rotated EOFs of the JJA SST for 1980–99. Units are arbitrary.

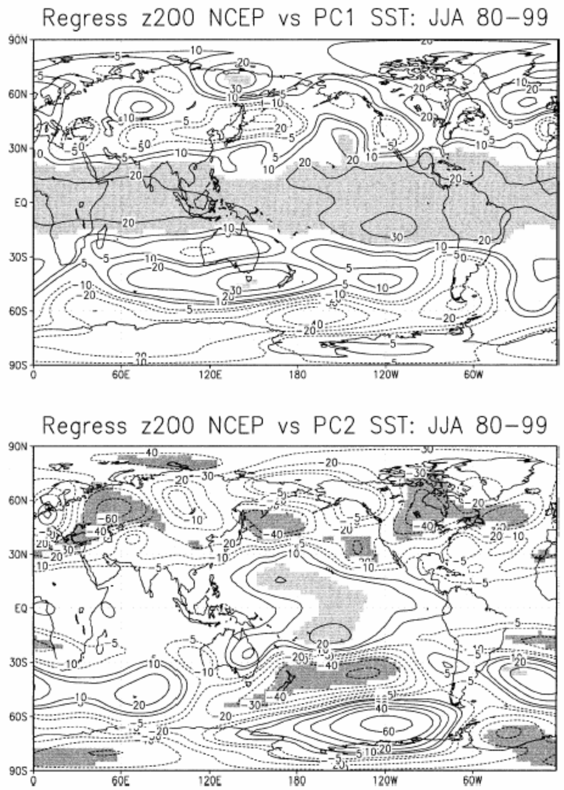


FIG. 10. Same as Fig. 9, except for the 200-mb height field from the NCEP–NCAR reanalysis.

Zonally symmetric response in the JJA average geopotential height field. The PDO-like mode has more significant variability in the midlatitudes.

Response of NSIPP GCM to Imposed SST Anomalies

ENSO Mode

PDO-like Mode

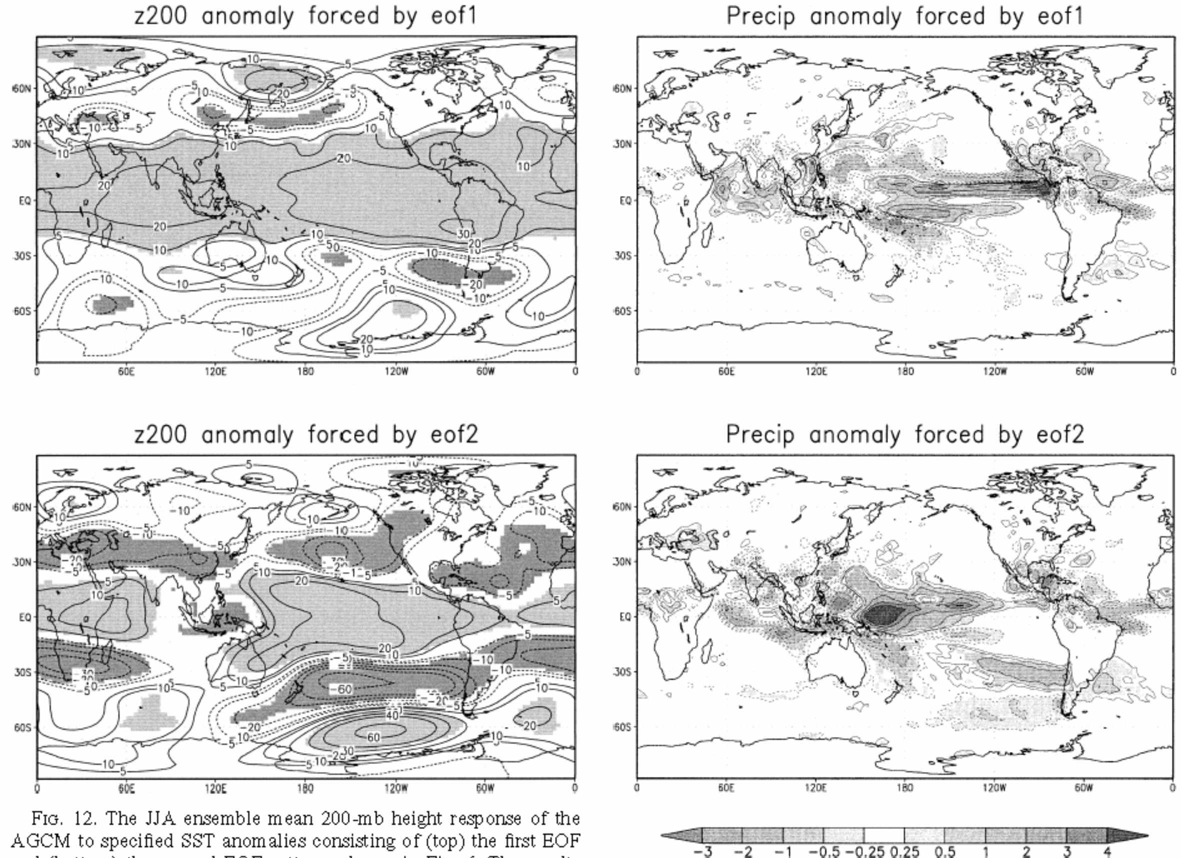


FIG. 12. The JJA ensemble mean 200-mb height response of the AGCM to specified SST anomalies consisting of (top) the first EOF and (bottom) the second EOF patterns shown in Fig. 6. The results shown are the differences of the responses to the two polarities of each SST EOF divided by 2. Shading indicates significance at the 5% level based on a *t* test. Units are in meters.

FIG. 13. Same as Fig. 12, except for precipitation. Units are millimeters per day.

Similar zonally symmetric response in geopotential height and longitudinal and latitudinal shifts in the distribution of precipitation in tropical Pacific and Indian oceans.

Part I
RAMS and Modification for Use as a Regional Climate Model

Regional Atmospheric Modeling System (RAMS) as a RCM

Parameterization Options:

Turbulent mixing: Mellor and Yamada (1974)
Land Surface: LEAF-2 Model (Walko et al. 2000)
Convective rainfall: Kain-Fritsch cumulus parameterization scheme (Kain 2004)
Non-convective rainfall: Dumpbucket scheme
Radiation: Chen and Cotton (1983)

Boundary Conditions:

Surface:
- Standard topography, soil type, and vegetation datasets
- NLDAS soil moisture from the VIC Model (Maurer et at. 2002)
- Reynolds and Smith (1994) sea surface temperature

Lateral Boundaries:
- NCEP Reanalysis (Kalnay et al. 1996)

RAMS Dynamical Downscaling Sensitivity Experiments (Castro et al. 2005)

Investigated the value retained and added by dynamical downscaling

Issues addressed:

1. **Underestimation of variability at large scales by the RCM**.
   As the grid spacing or domain size increases this worsens

2. **Influence of surface boundary forcing.**
   Dominant factor in generating atmospheric variability at the small-scale.
   Exerts greater control on the RCM solution as the influence of lateral boundary conditions diminish.

3. **Influence of model parameterizations**

Implications for Generating a RCM Climatology for North America

1. **Model domain size**
   A continental-scale, or smaller, domain is most appropriate so the lateral boundary forcing can affect solution.

2. **Interior nudging**
   Weak nudging (at a one-day timescale), forces the RCM solution to the reanalysis solution at the large-scale, while allowing the surface forcing to act on the small scale.

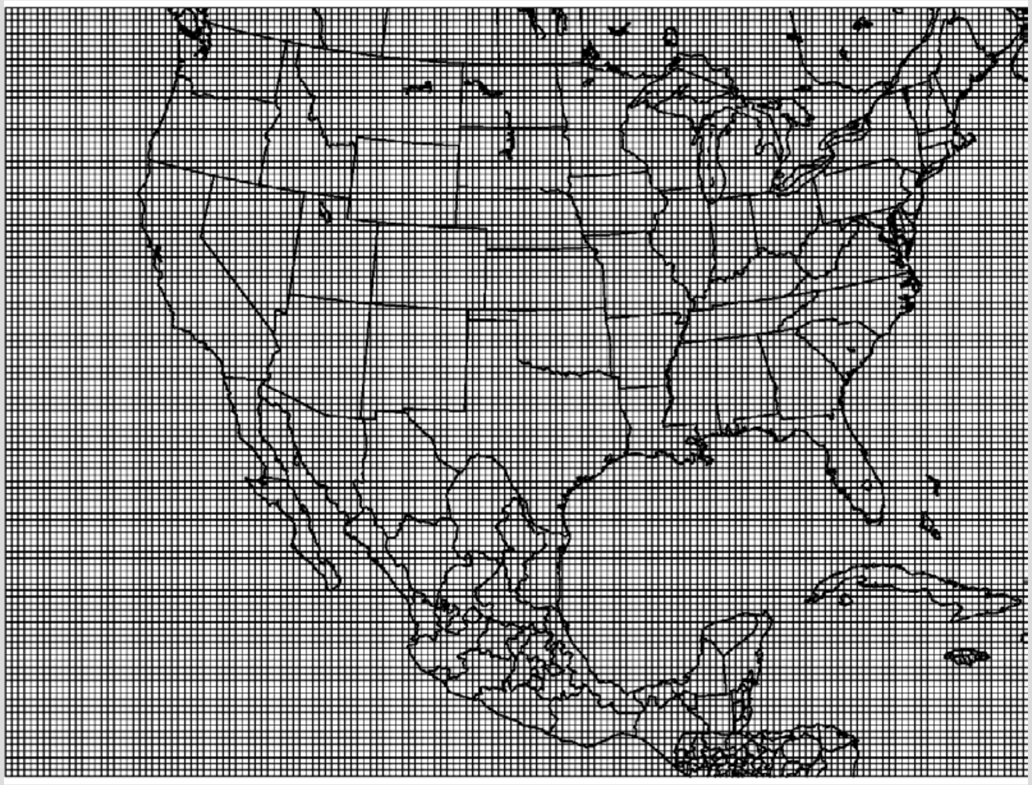
3. **Cumulus parameterization**
   Kain-Fritsch scheme is most appropriate for the warm season because it is more sensitive to the surface forcing and yields a better representation of precipitation

4. **Single or multiple nesting?**
   A single grid approach is most desirable for RCM simulation.

Part II

A Summer RCM Climatology of the Contiguous U.S. and Mexico

RCM Setup for Summer Climatology



Grid spacing: 35 km

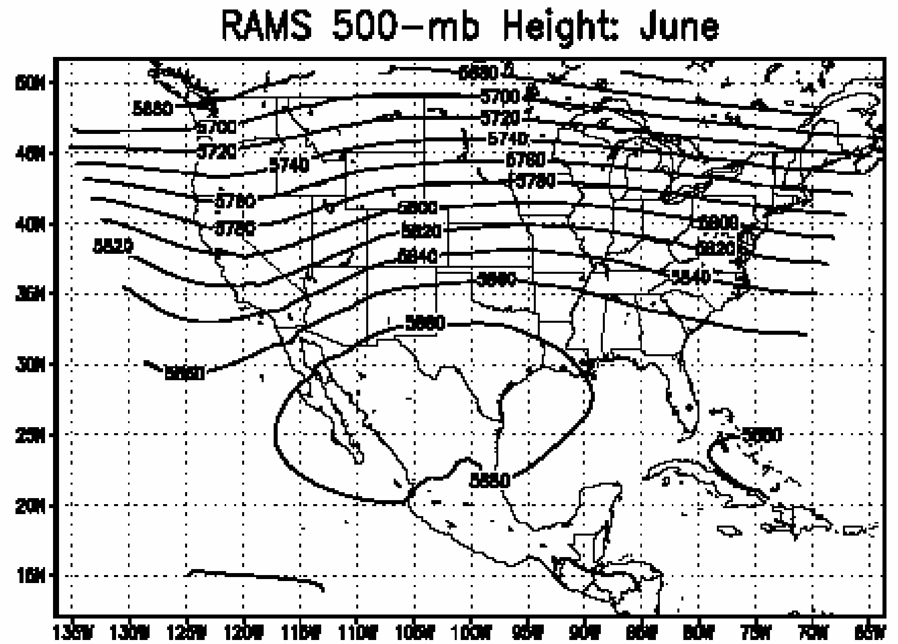
160 x 120 grid points horizontal
30 grid points vertical

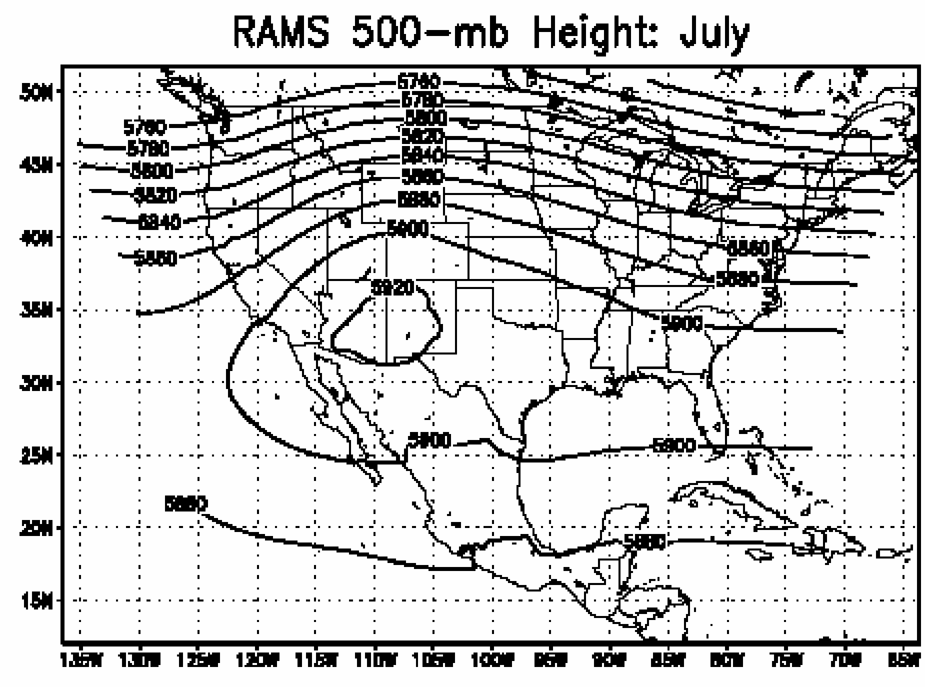
Simulation length:
15 May – 31 August

Years downscaled:
1950-2002

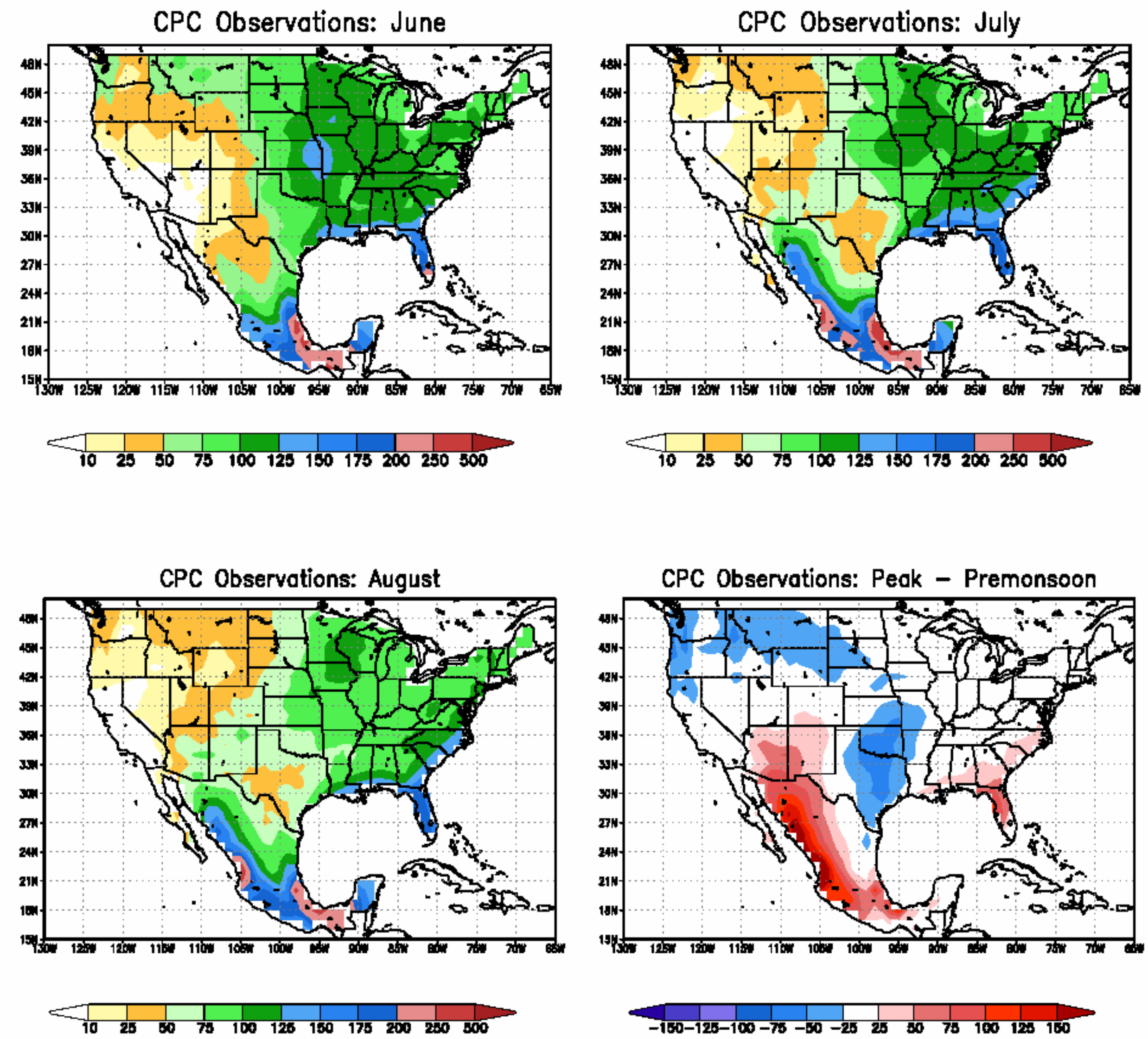
Premonsoon: 15 May – 15 June
Onset: 15 June – 15 July
Peak: 15 July – 15 August

Evolution of RAMS Average 500-mb Height





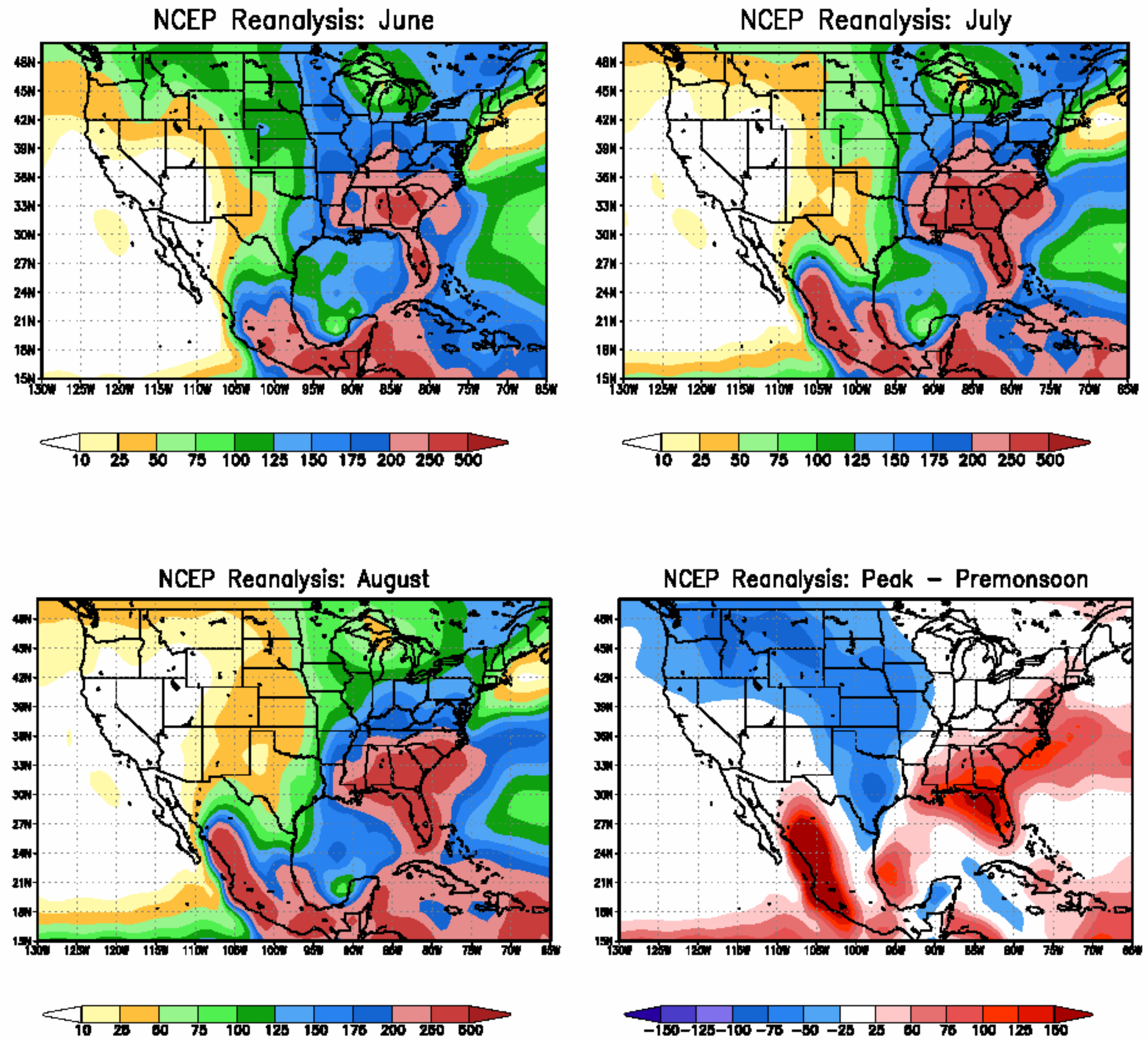
Observed Gauge Average Precipitation (mm)



Late spring to early summer maximum in the central U.S.

Mid to late summer maximum in the core monsoon region

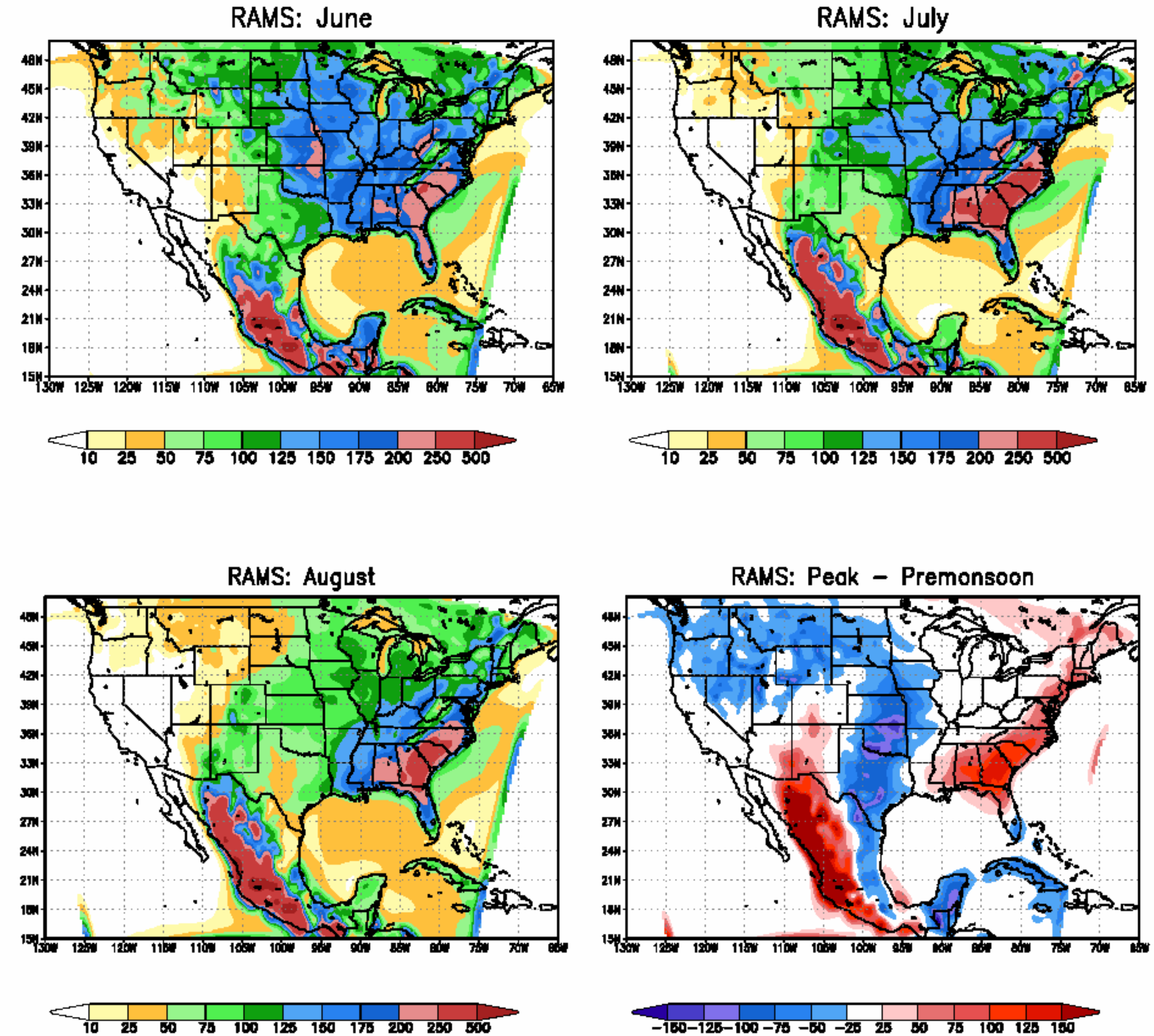
NCEP Reanalysis Average Precipitation (mm)



Overestimates in southern Mexico and southeast U.S.

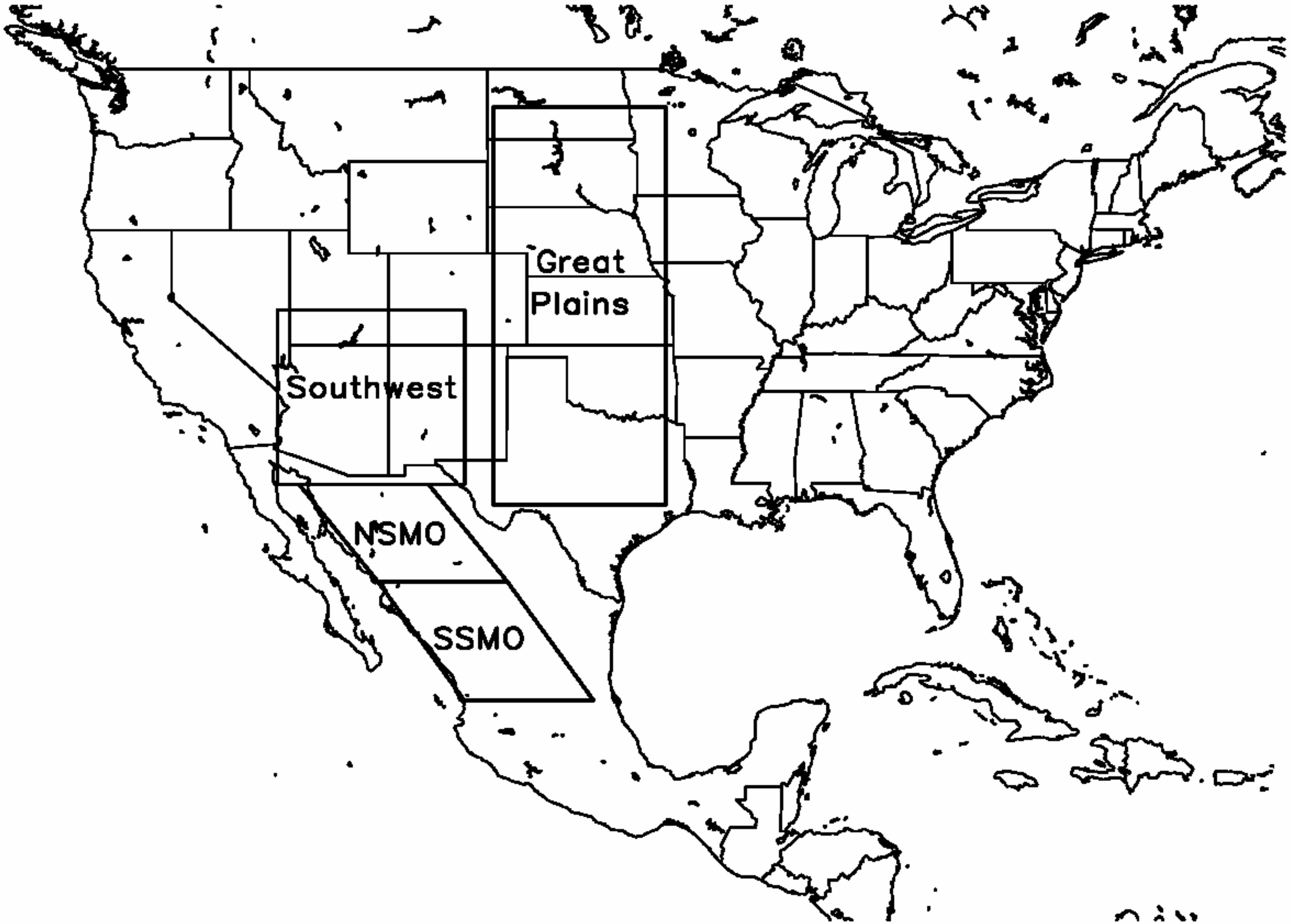
Underestimates in core monsoon region and central U.S.

RAMS Average Precipitation (mm)

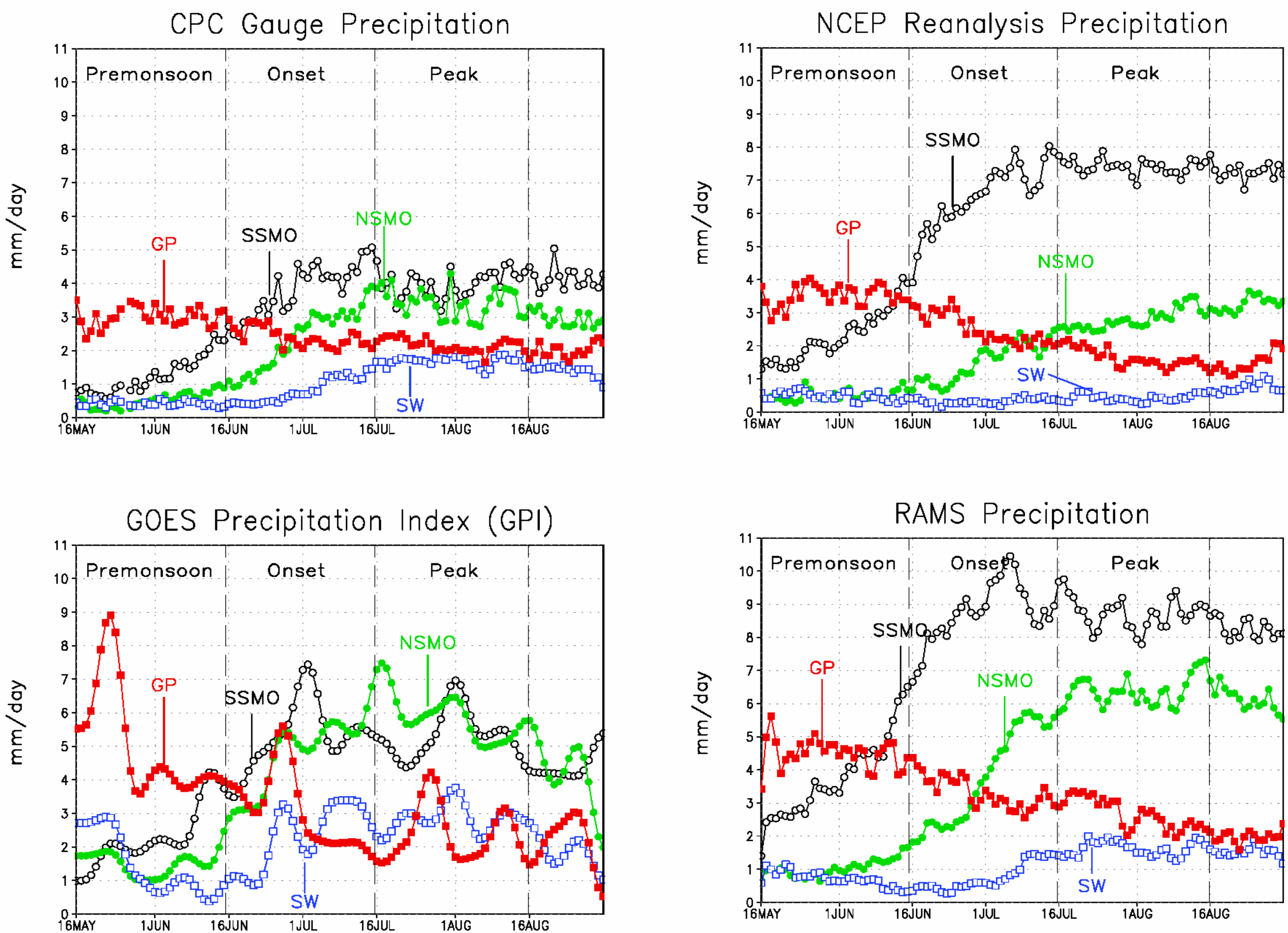


More precipitation in the core monsoon region and central U.S.

Precipitation still overestimated in areas where NCEP Reanalysis overestimates

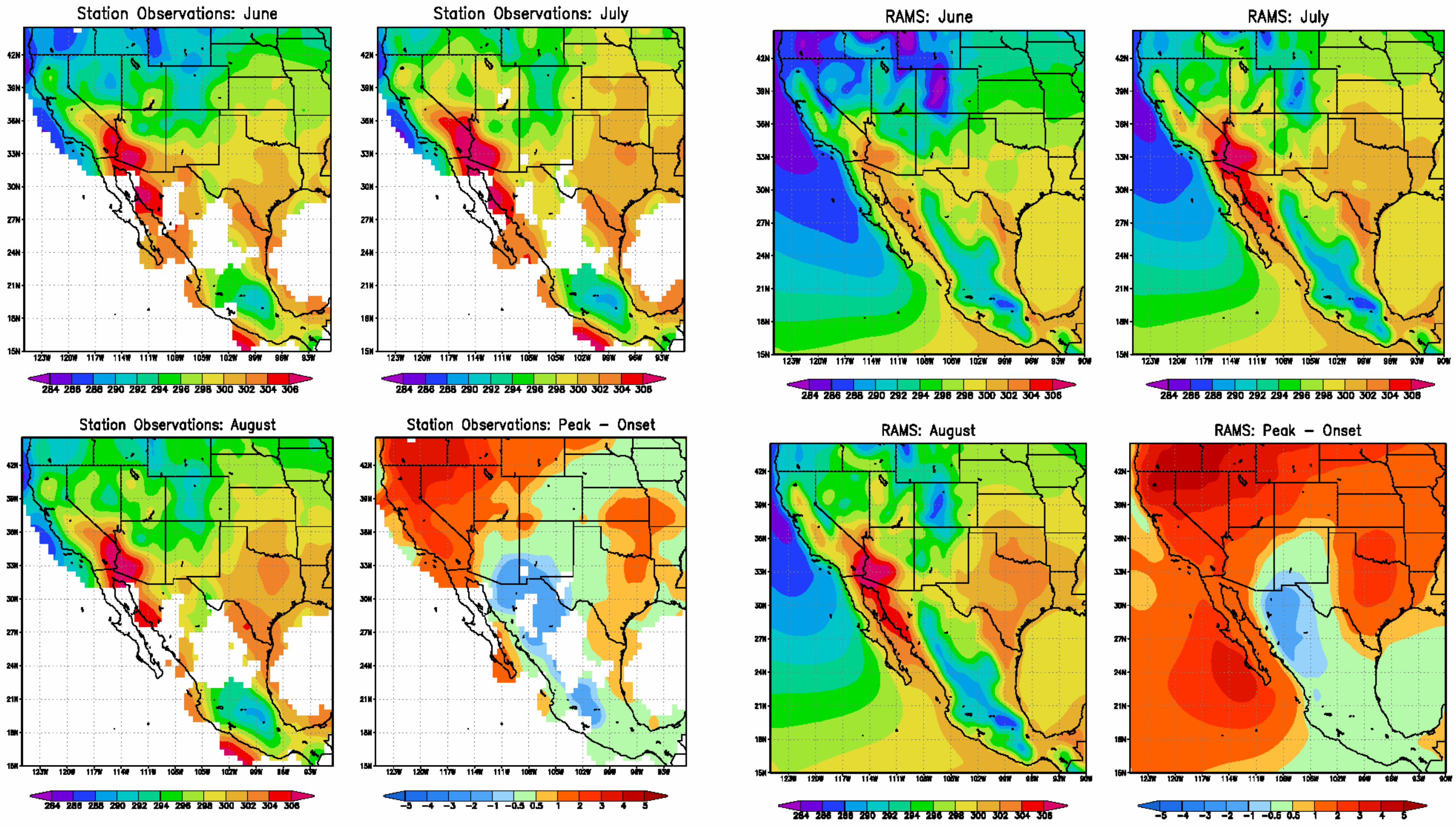


Great
Plains
Southwest
NSMO
SSMO



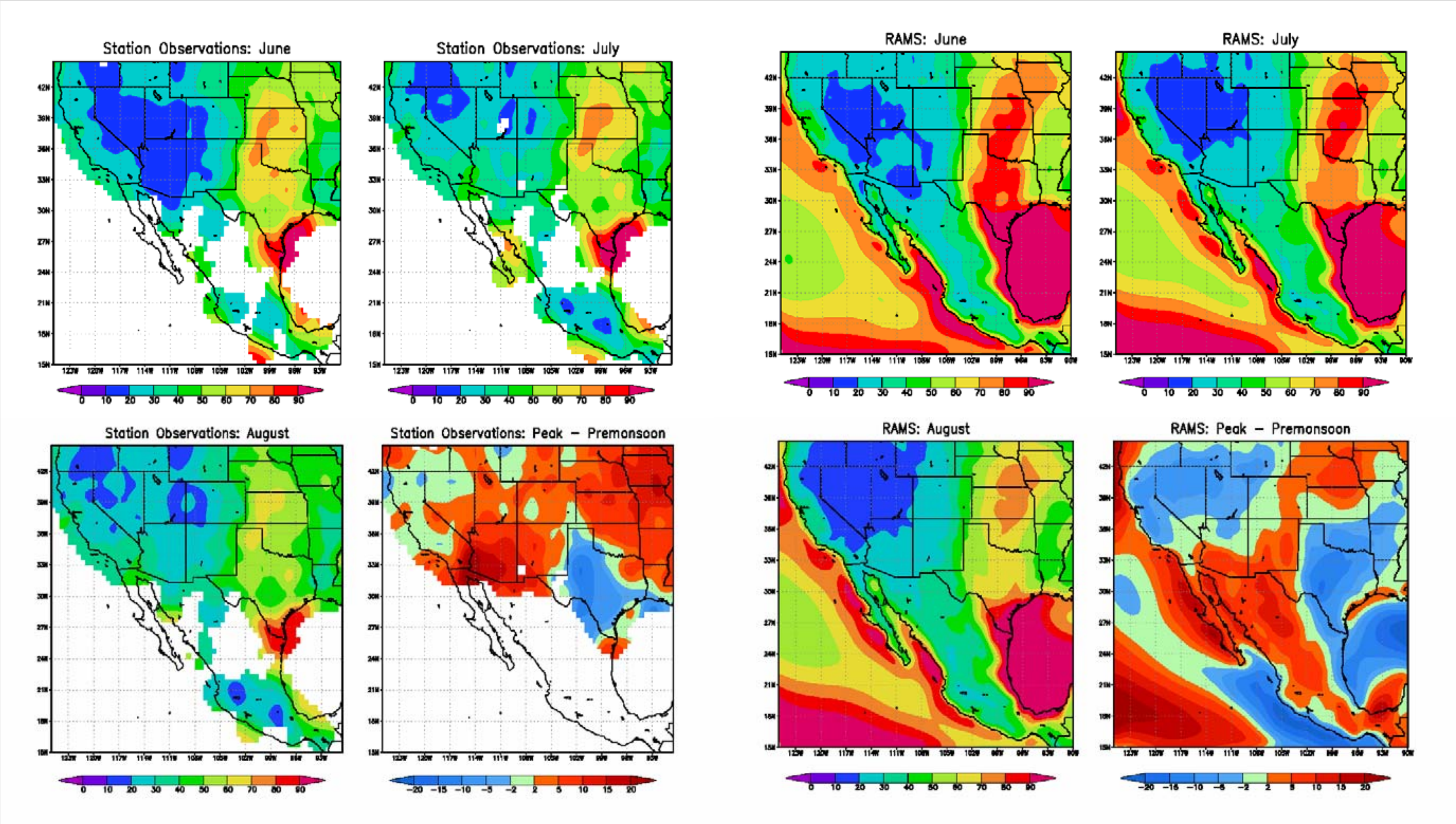
RAMS precipitation more closely matches satellite-estimated precipitation and captures the abrupt transition associated with monsoon onset

Surface Temperature (K)



A temperature maximum in the Colorado River Valley. Temperatures decrease in the core monsoon region after monsoon onset, and generally increase elsewhere.

Surface Moisture Flux (m s^{-1} g kg^{-1})



Great Plains and Baja low-level jets appear in RAMS simulations and evolve in time. Baja LLJ, however, is weaker than observed.

Spectral Analysis of Integrated Moisture Flux Convergence (MFC)

Procedure:

For a given thirty day period about the date, perform a Fourier analysis on MFC and determine red noise spectrum. Do this for all the years and average the spectra to compute a climatology.

Determine the spectral power in the following bands:

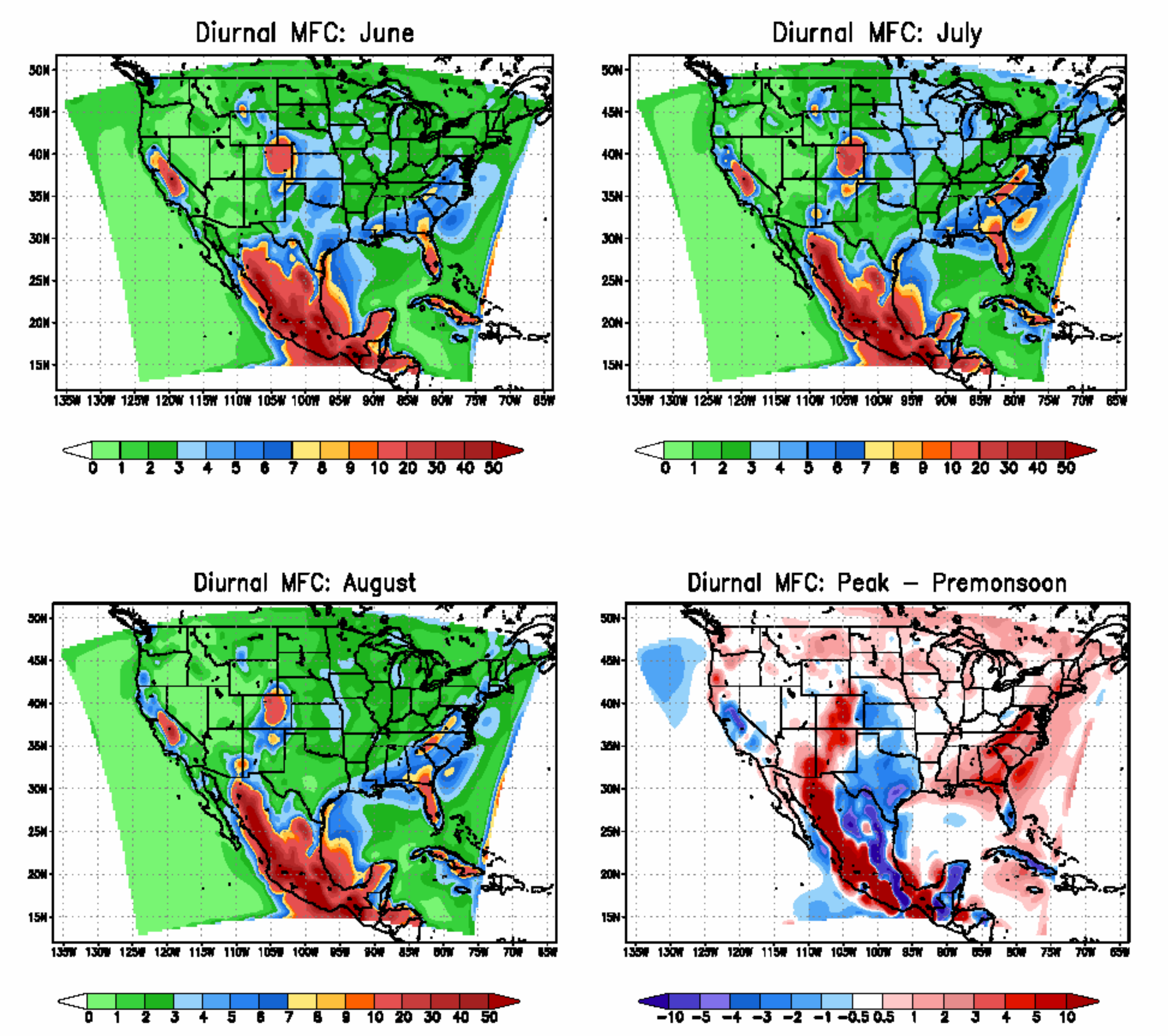
- Diurnal: 1 day
- Sub-synoptic: 1.5 – 3 days
- Synoptic: 4 – 15 days

Multiply the spectral power in a given band by a weighting factor that accounts for the area above the red noise spectrum. Ensures the most physically relevant features are emphasized.

Analyze the integrated moisture flux convergence because it is a proxy for convective activity.

Weighted Spectral Power of MFC Diurnal Band

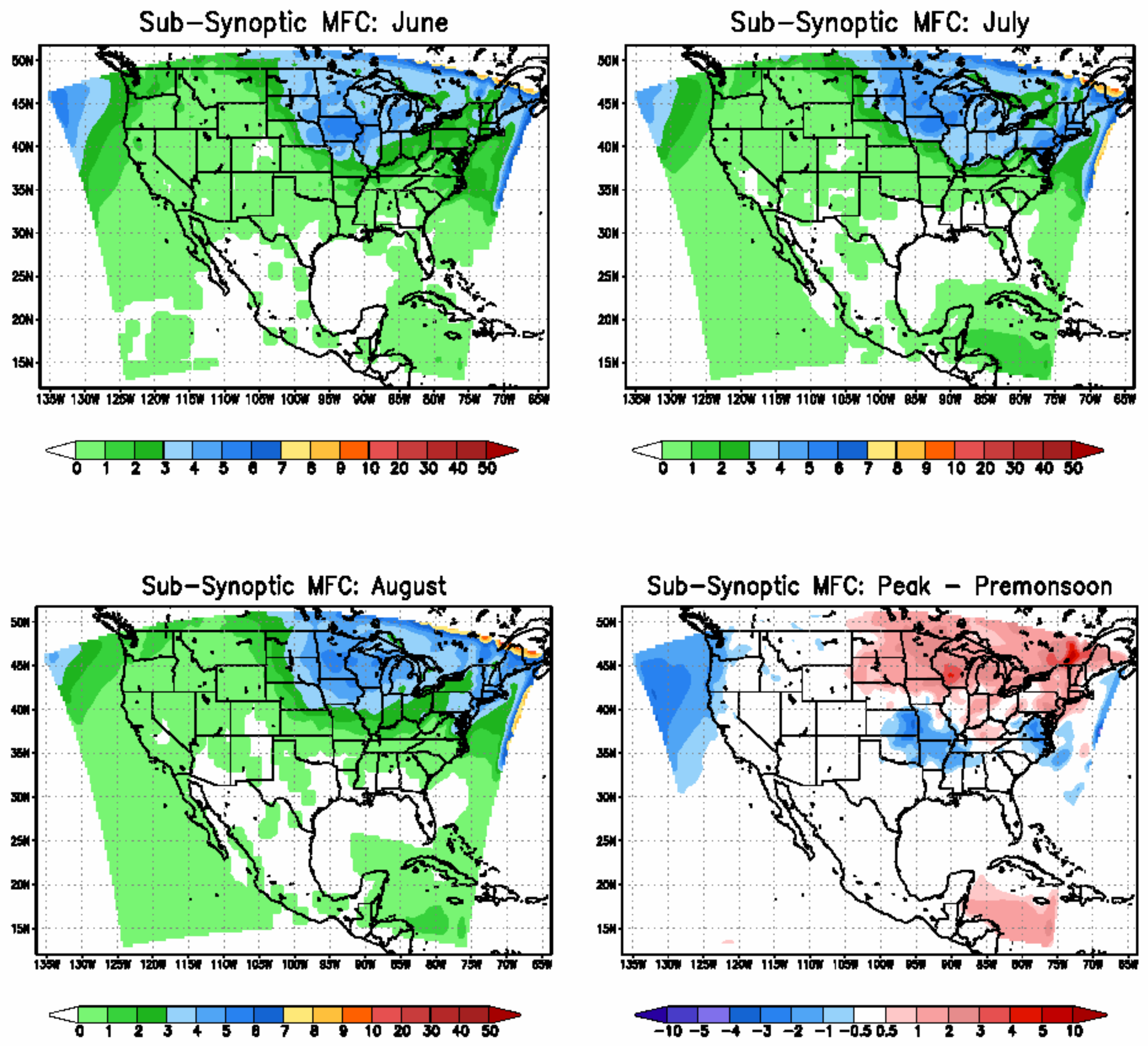
Units : $mm^2\ day^{-2}$



Diurnal cycle of convection is physically important everywhere. Strongest where there are terrain gradients and land-sea contrast. Reanalysis rainfall is impacted in areas where the diurnal cycle is underestimated.

Weighted Spectral Power of MFC Sub-synoptic (1.5 – 3 day) Band

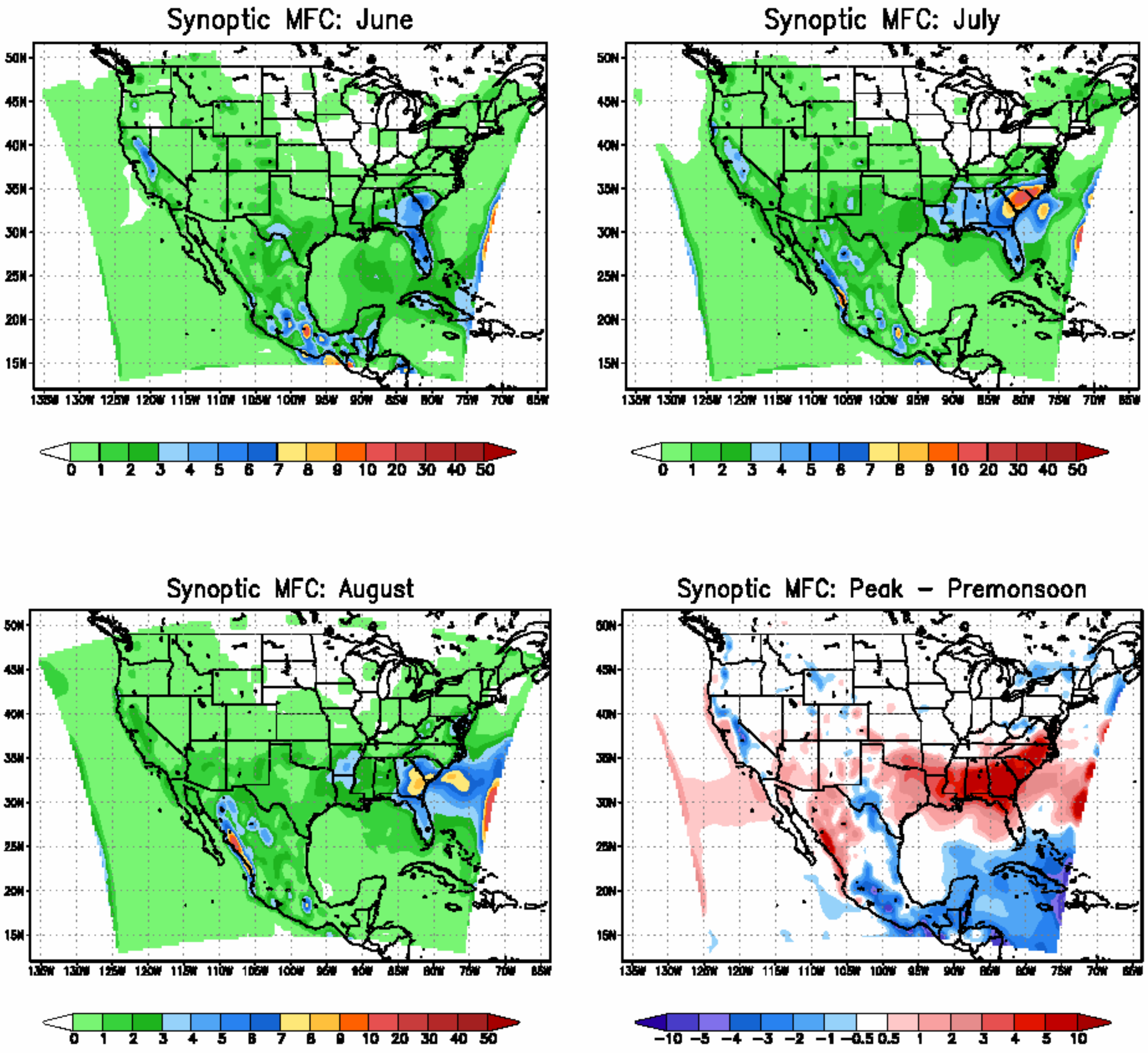
Units : mm^2 day^{-2}



Reflects fast moving synoptic weather systems or MCSs propagating around the periphery of the monsoon ridge which originate as diurnal convection over the Rockies. Just as important as the diurnal cycle in generating rainfall in the Midwest.

Weighted Spectral Power of MFC Synoptic (4 – 15 day) Band

Units : mm^2 day^{-2}

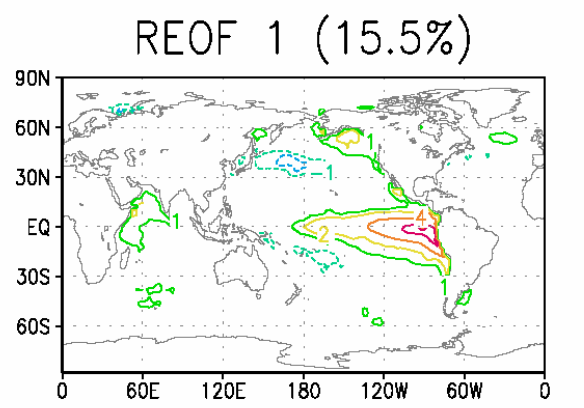


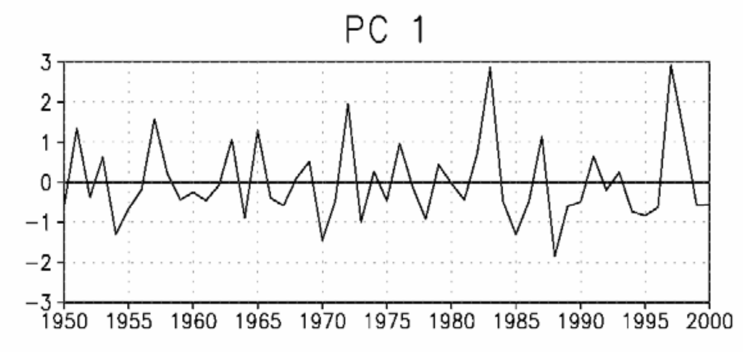
Mode reflects passage of tropical easterly waves around the southern periphery of the monsoon ridge. These enhance the diurnally forced convection and allow it to more readily organize into MCSs– may trigger gulf surges in the Gulf of California.

PART III
Diagnosing the Effect of Pacific SST Associated Teleconnections on North American Summer Climate

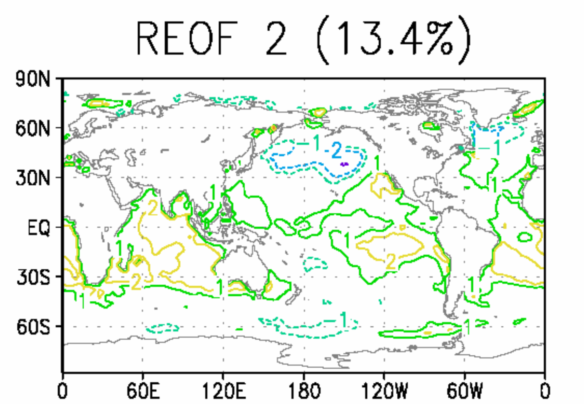
Boreal Summer Global SST Modes (1950-2000)

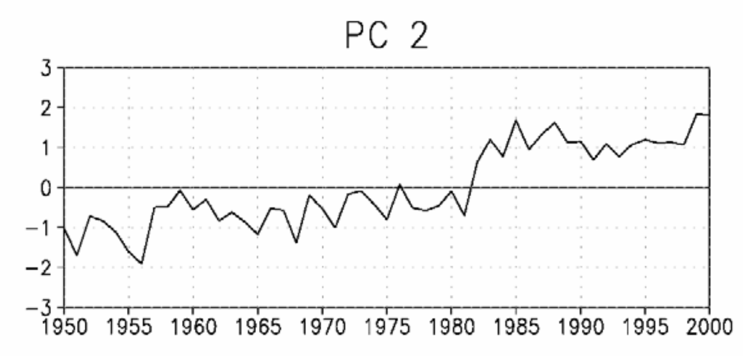
ENSO Mode



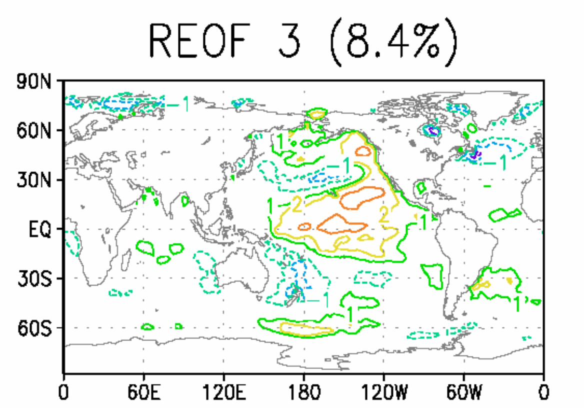


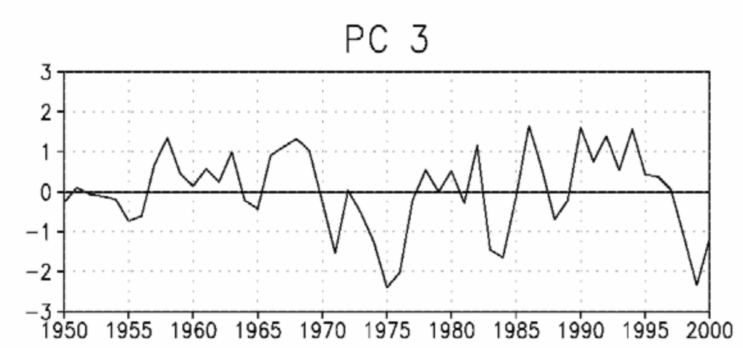
SST Regime Shift Mode (new in longer record)





PDO-like Mode





Composite Analysis Technique

Consider years above or below a half standard deviation of a particular PC time series to generate a positive and negative composite.

2001 and 2002 are considered PC 3 negative and PC 2 positive because of their SST pattern.

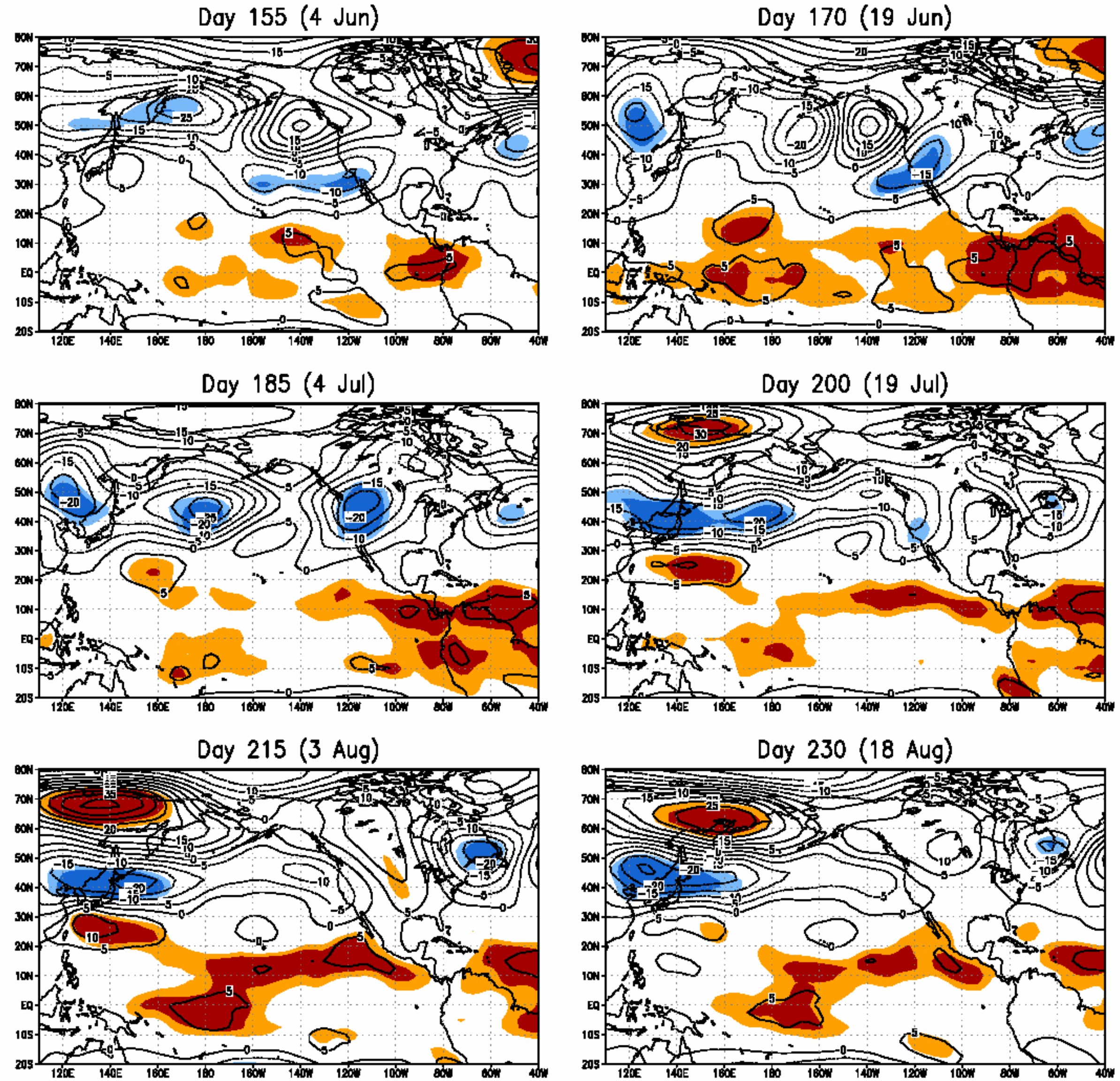
Determine the statistical significance by a two-tailed t-test which considers the anomaly of a given composite against the rest of the years. Significance shown at the 90% level and above.

Shown is the anomaly of the positive composite minus the negative composite divided by two.

Observed 30 Day Average 500-mb Height Anomalies (m)

PC 1 Composites

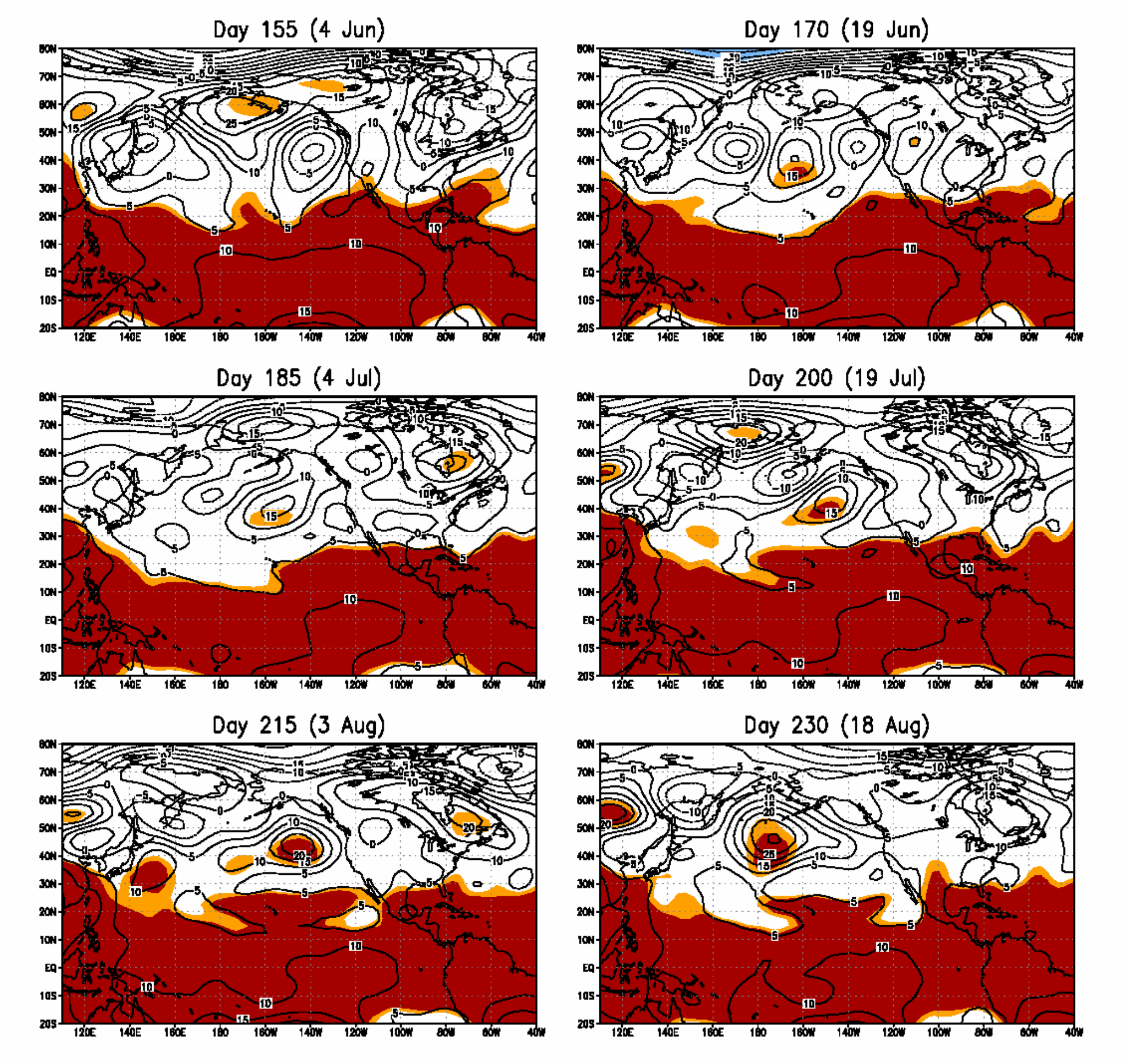
ENSO mode



Observed 30 Day Average 500-mb Height Anomalies (m)

PC 2 Composites

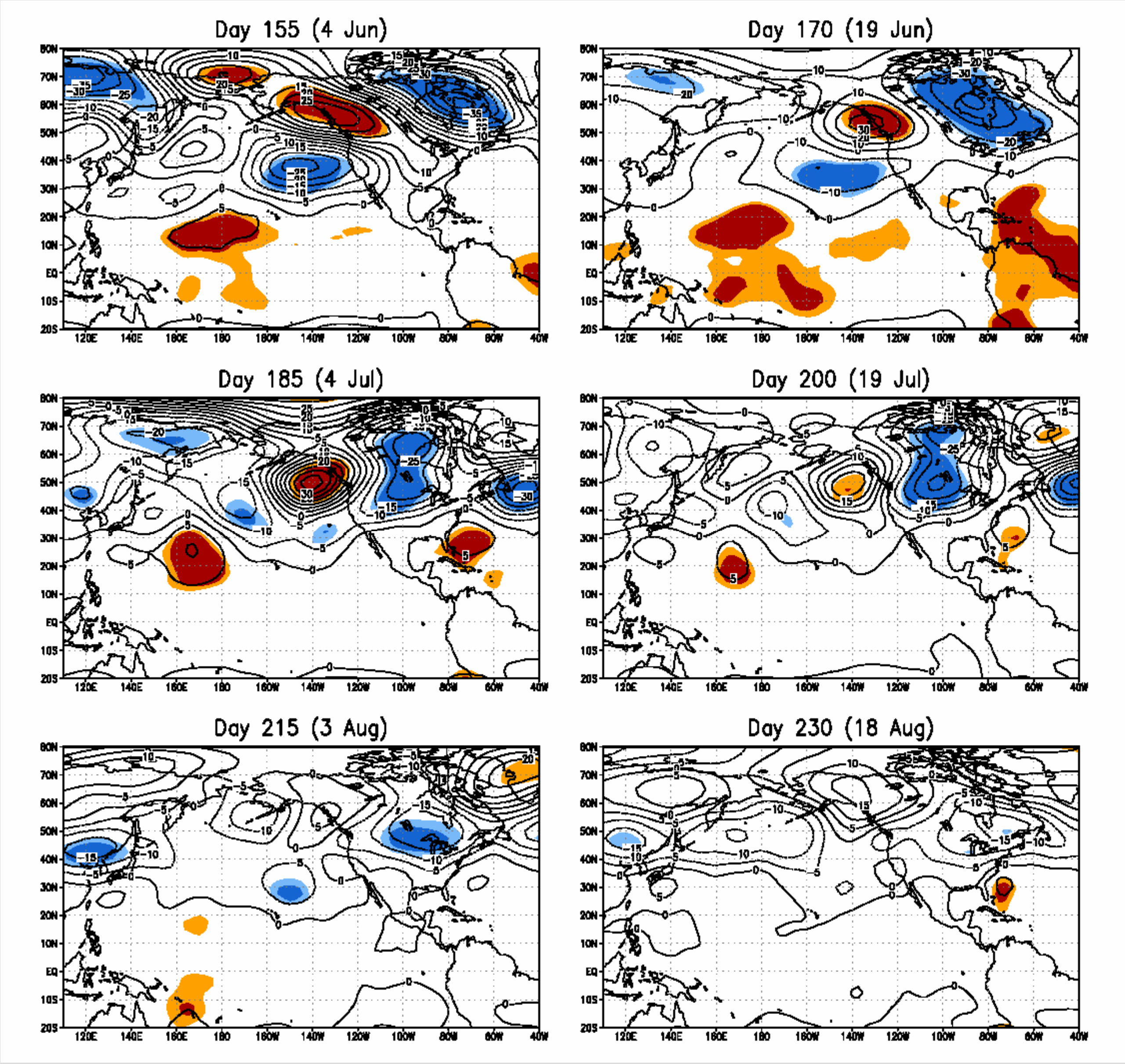
SST Regime Shift Mode



Observed 30 Day Average 500-mb Height Anomalies (m)

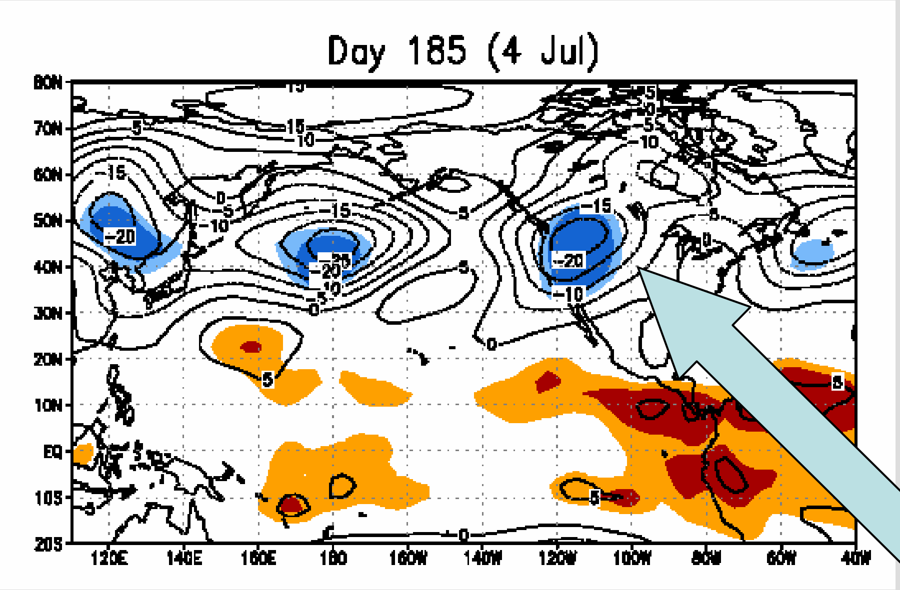
PC 3 Composites

PDO-like Mode



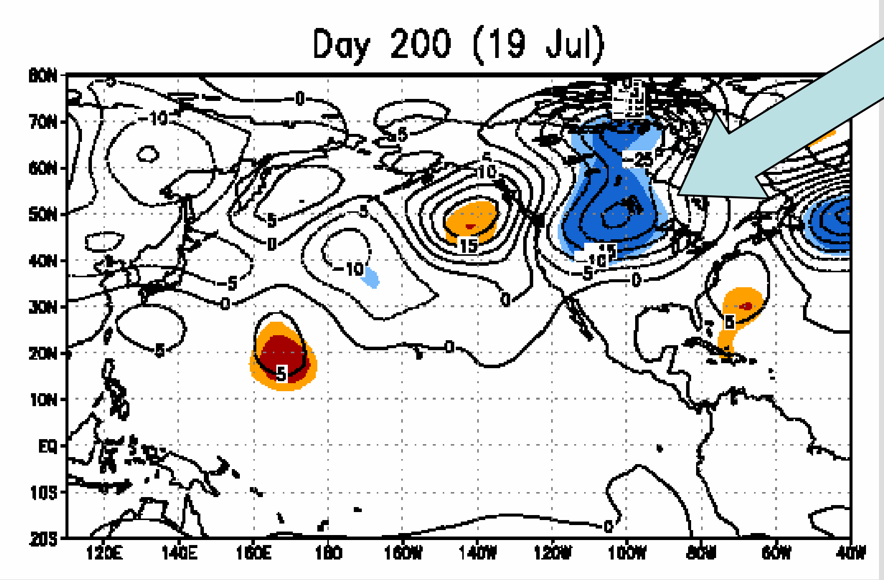
ENSO Mode Teleconnection

Peaks late June, early July



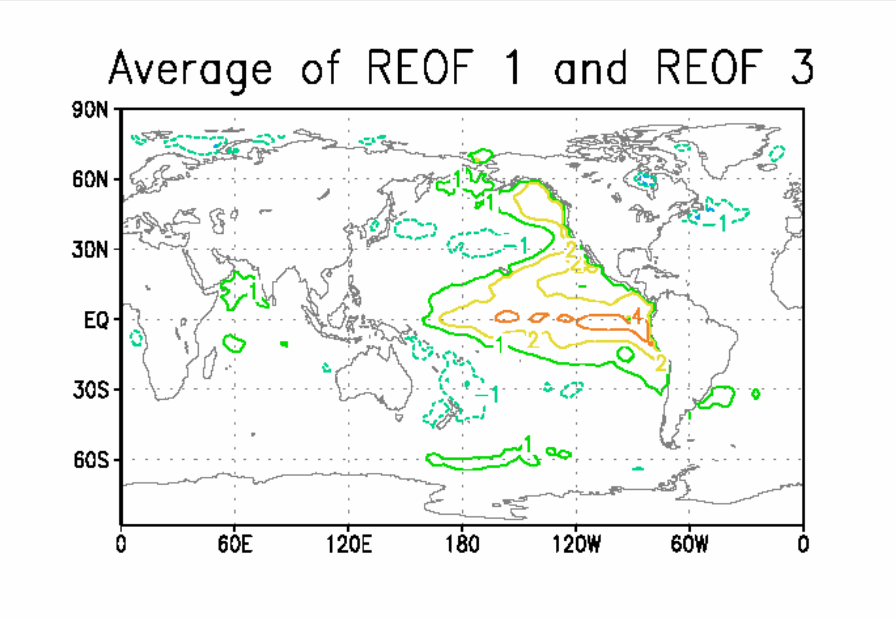
PDO-like Mode Teleconnection

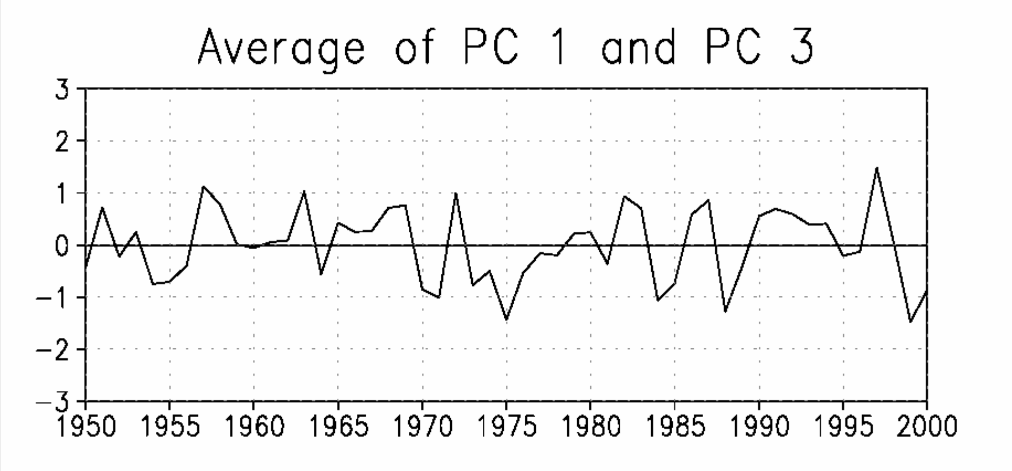
Peaks July



At time of "maximum teleconnectivity" the anomalies are in quadrature

Pacific SST Variability Mode





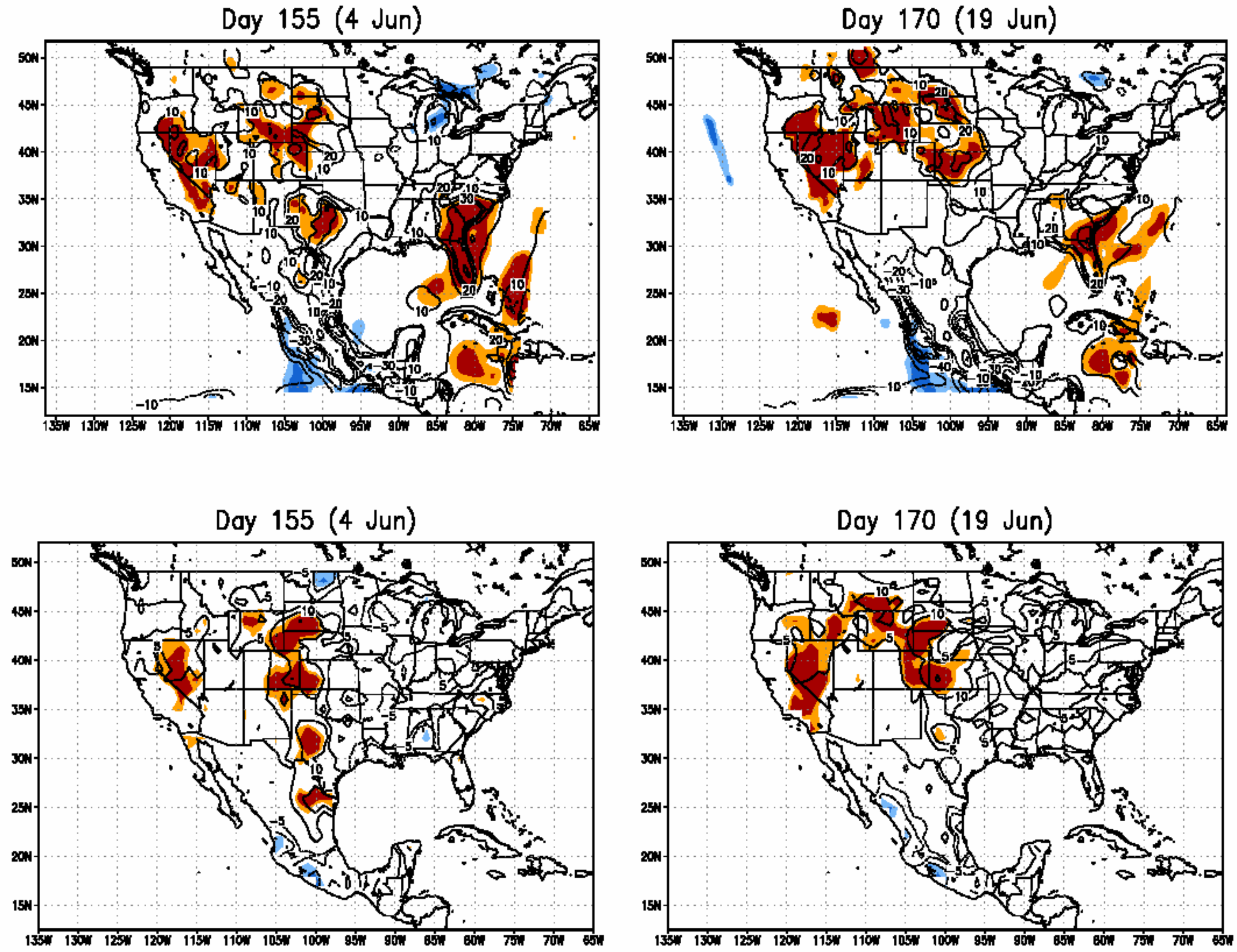
Given the different teleconnection relationships associated with each mode, should expect that climate anomalies would occur over a wider geographic area with a combined index of ENSO and PDO-like SST REOF modes.

Perform a similar composite analysis on this mode.

30 Day Average Precipitation Anomalies (mm) Pacific SST Variability Mode Composites: June

RAMS Simulated

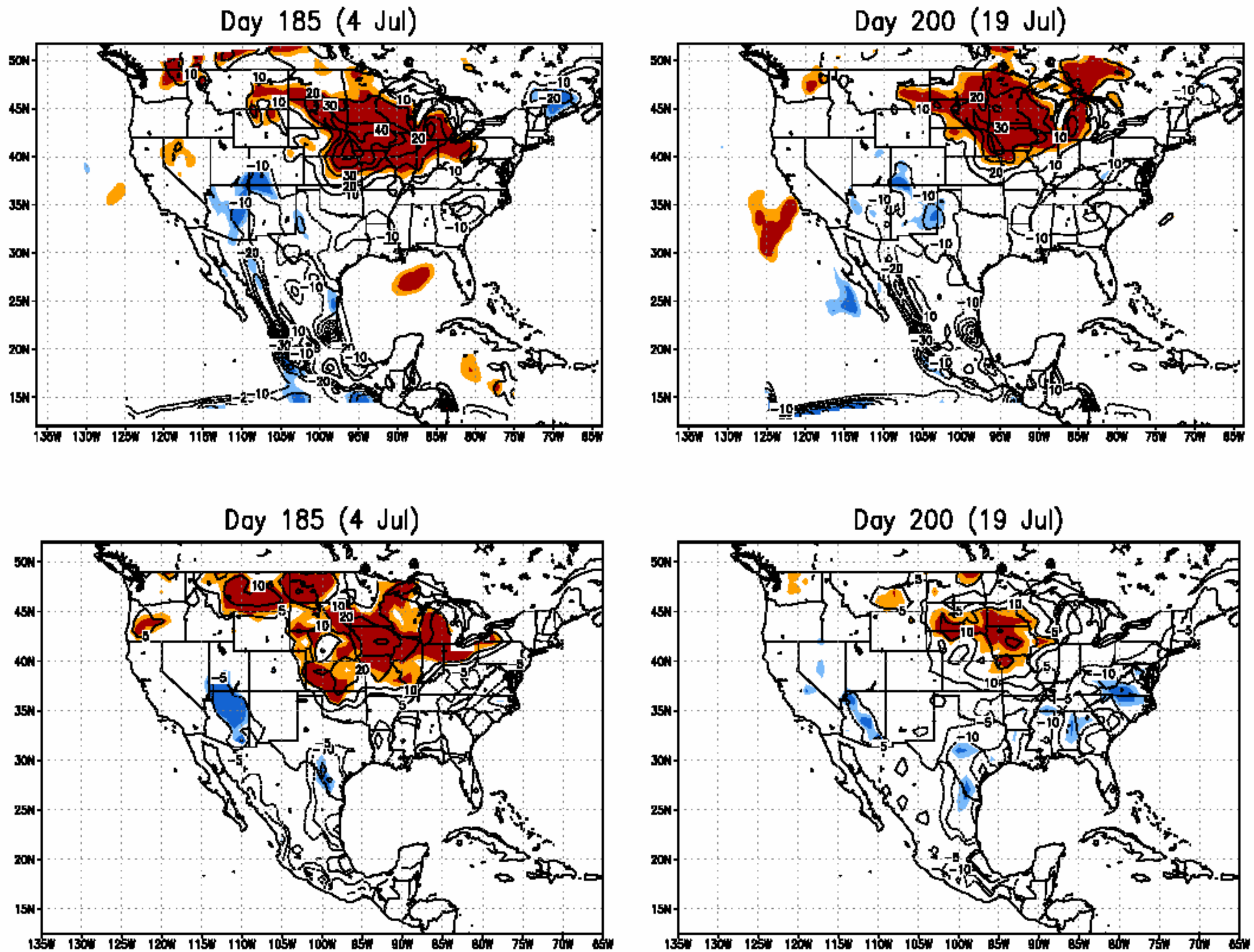
NCEP U.S.-Mexico Observations



30 Day Average Precipitation Anomalies (mm) Pacific SST Variability Mode Composites: July

RAMS Simulated

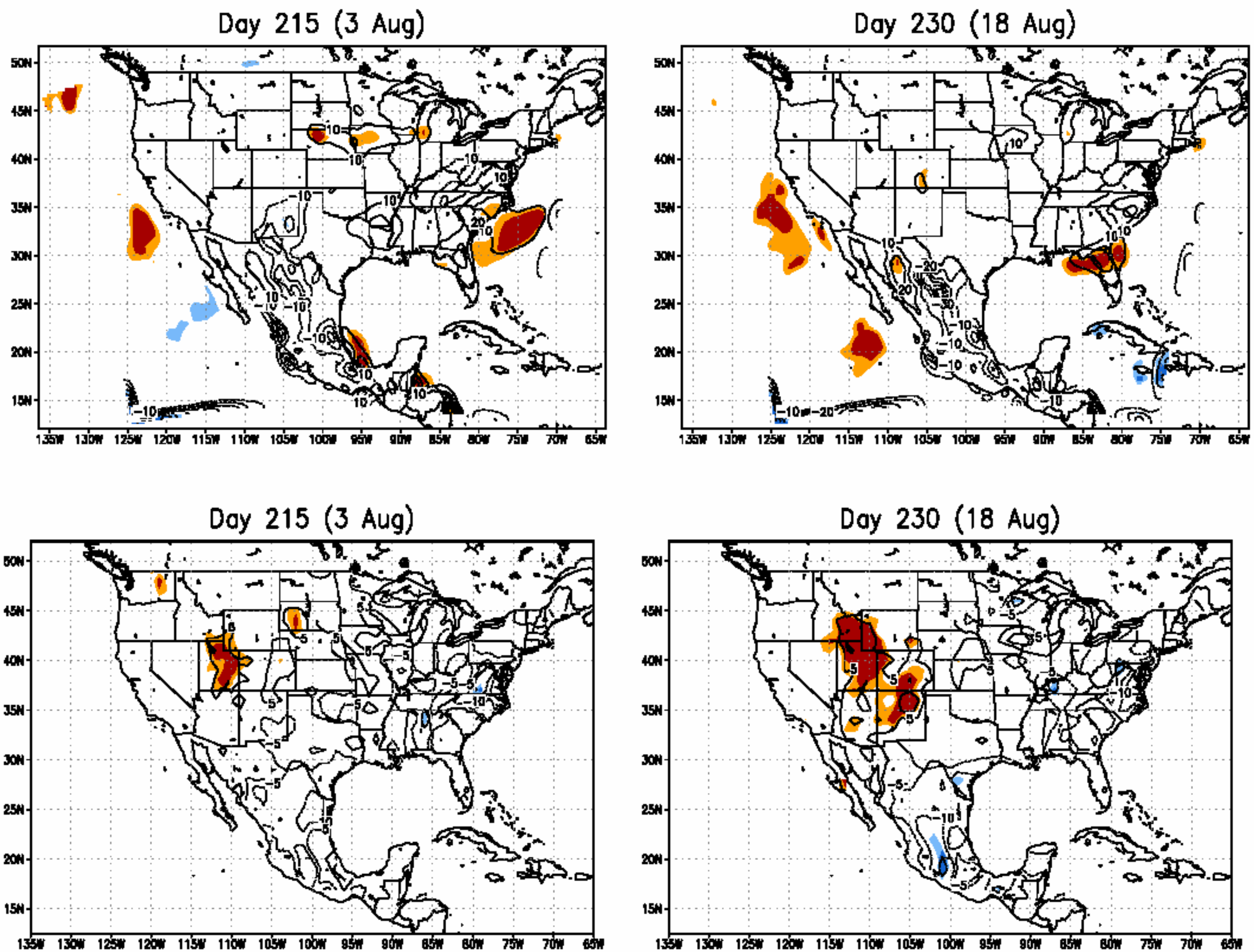
NCEP U.S.-Mexico Observations



30 Day Average Precipitation Anomalies (mm)
Pacific SST Variability Mode Composites: August

RAMS Simulated

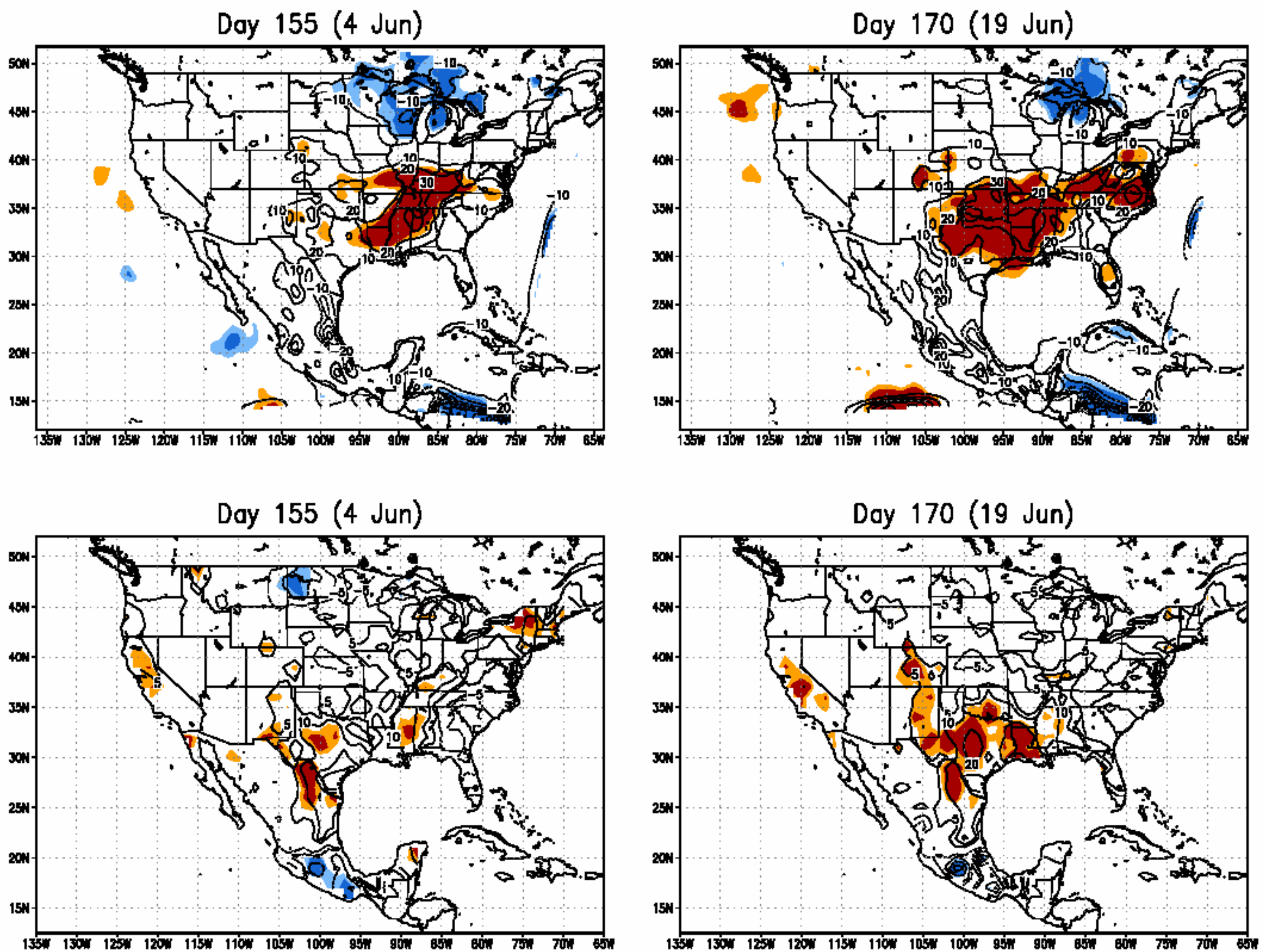
NCEP U.S.-Mexico Observations



30 Day Average Precipitation Anomalies (mm)
SST Regime Shift Mode Composites: June

RAMS Simulated

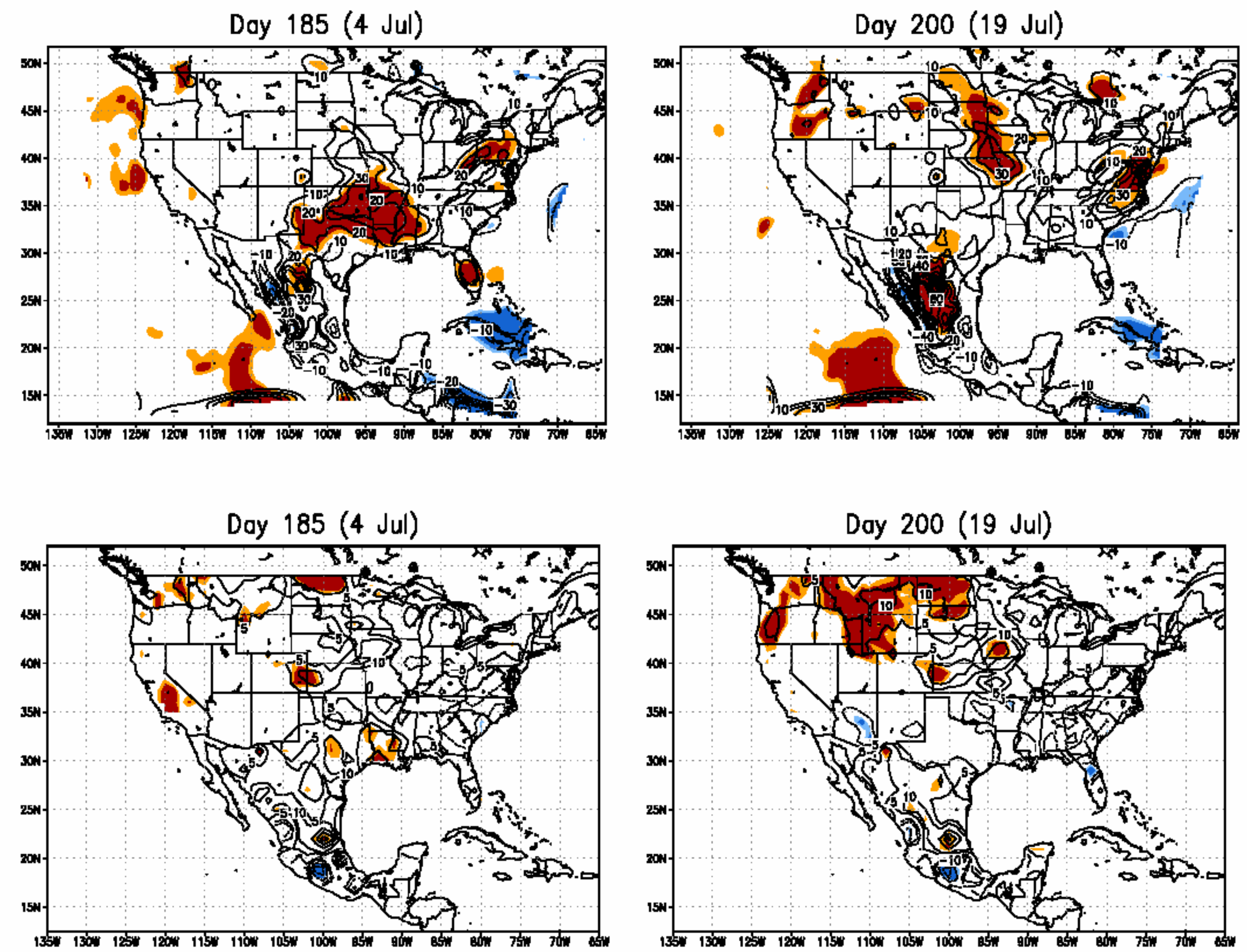
NCEP U.S.-Mexico Observations



30 Day Average Precipitation Anomalies (mm)
SST Regime Shift Mode Composites: July

RAMS Simulated

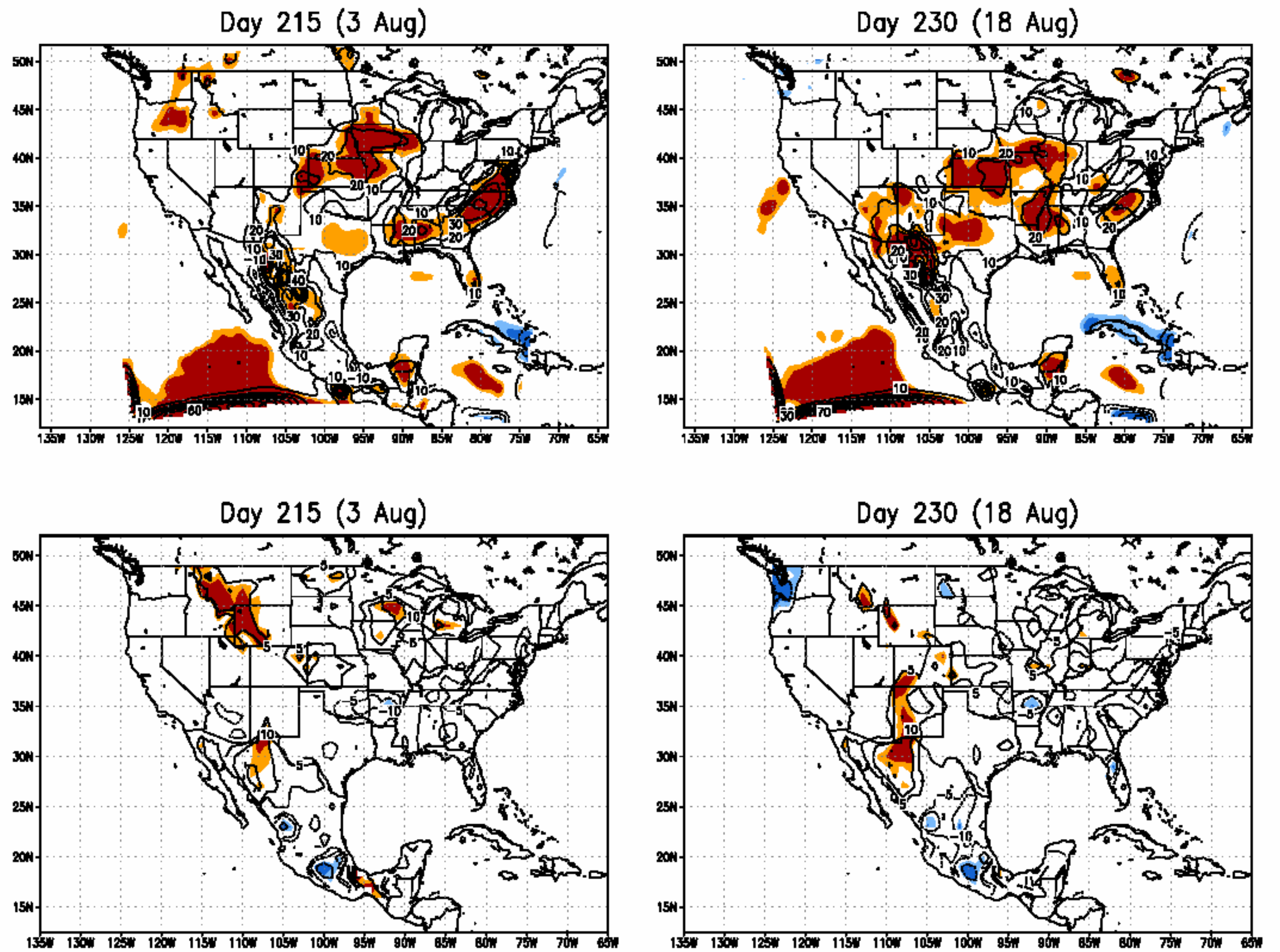
NCEP U.S.-Mexico Observations



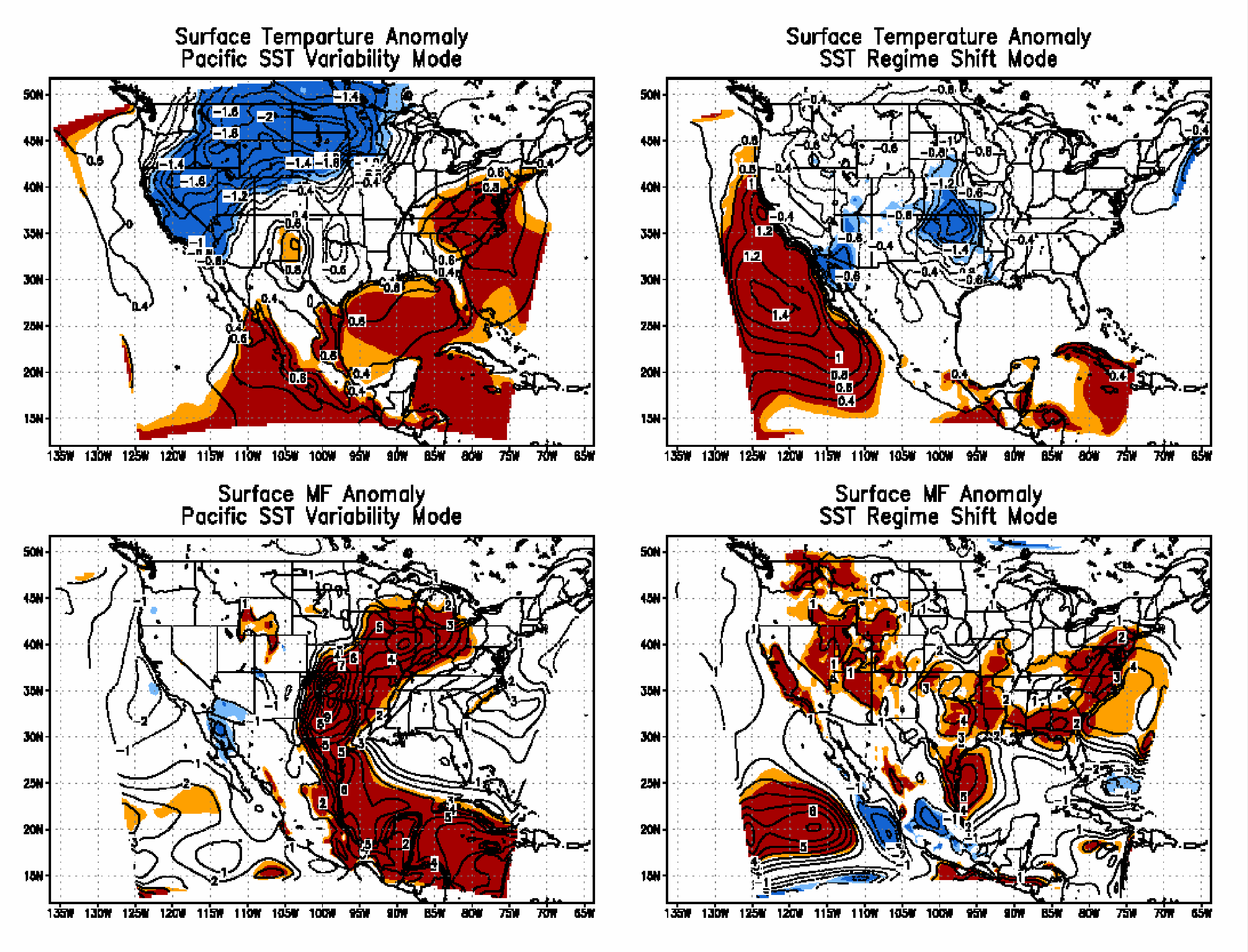
30 Day Average Precipitation Anomalies (mm)
SST Regime Shift Mode Composites: August

RAMS Simulated

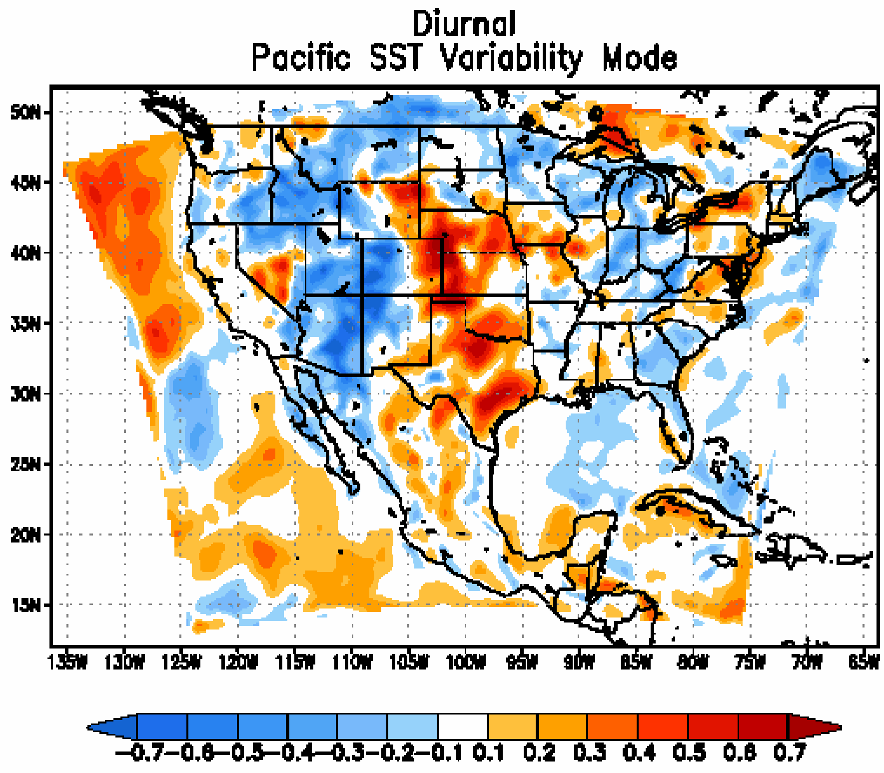
NCEP U.S.-Mexico Observations

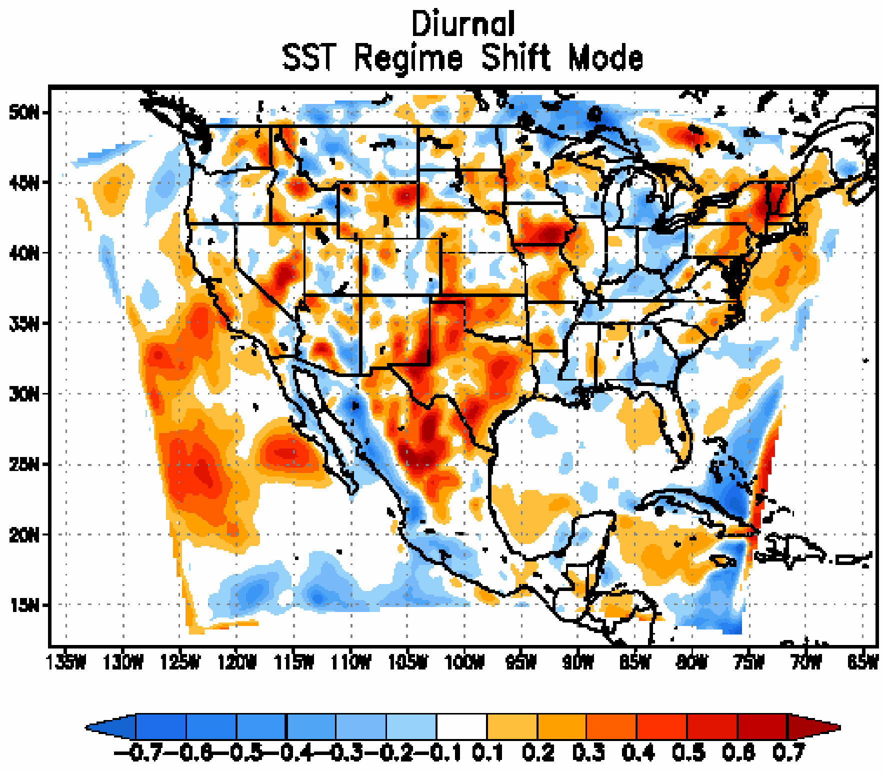


Surface T (K), MF ($m\ s^{-1}\ g\ kg^{-1}$) Anomalies Time of Maximum Teleconnectivity (15 July)



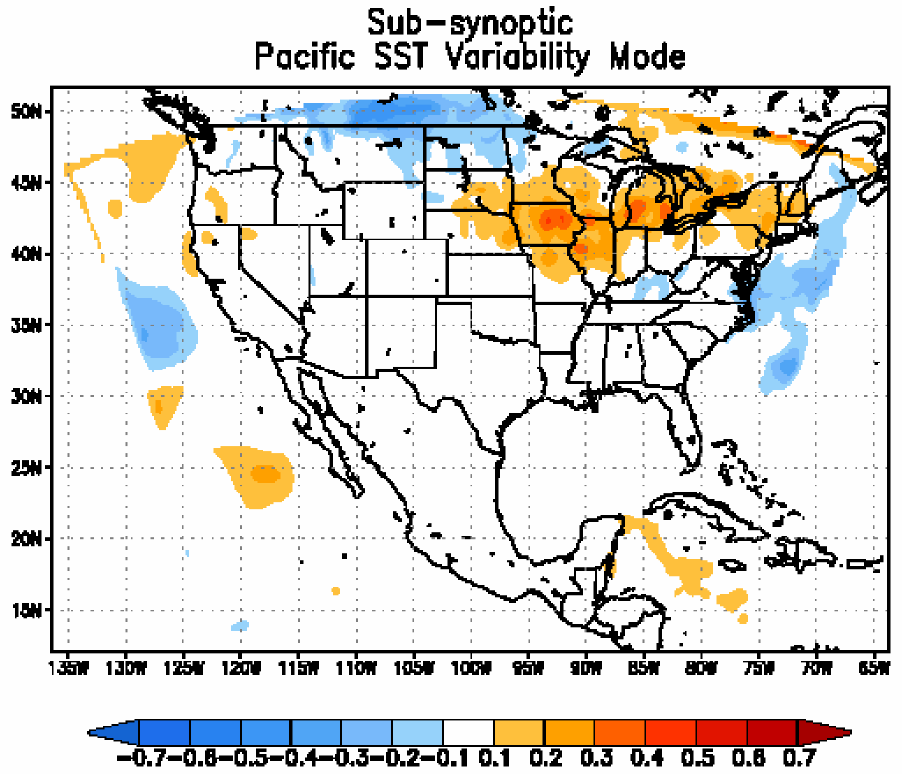
Change in Magnitude of Diurnal Band of MFC at Time of Maximum Teleconnectivity

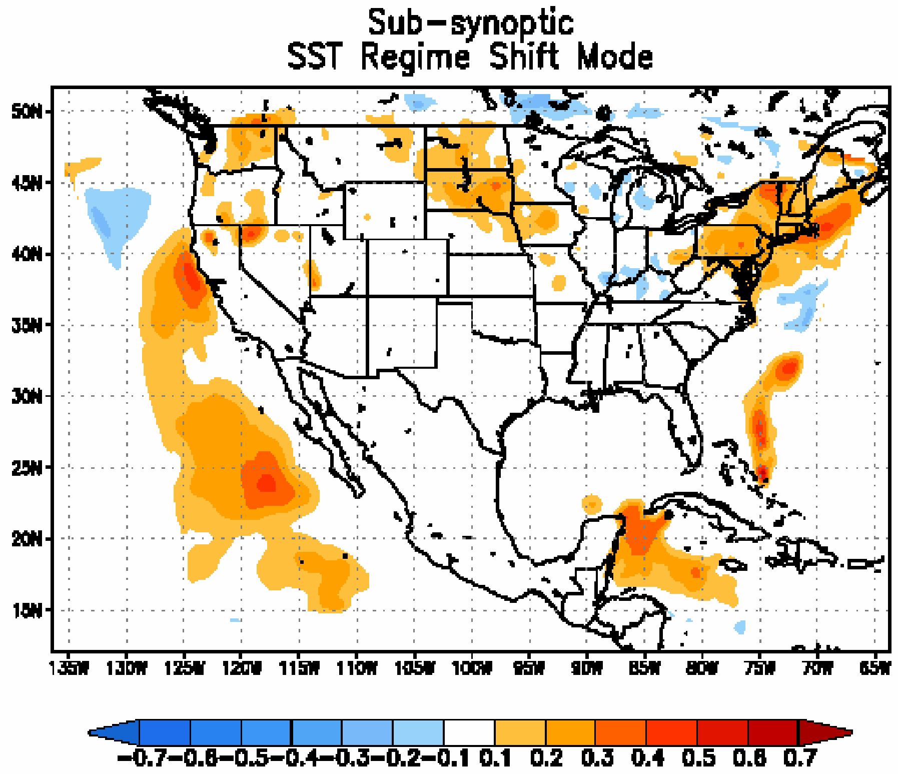




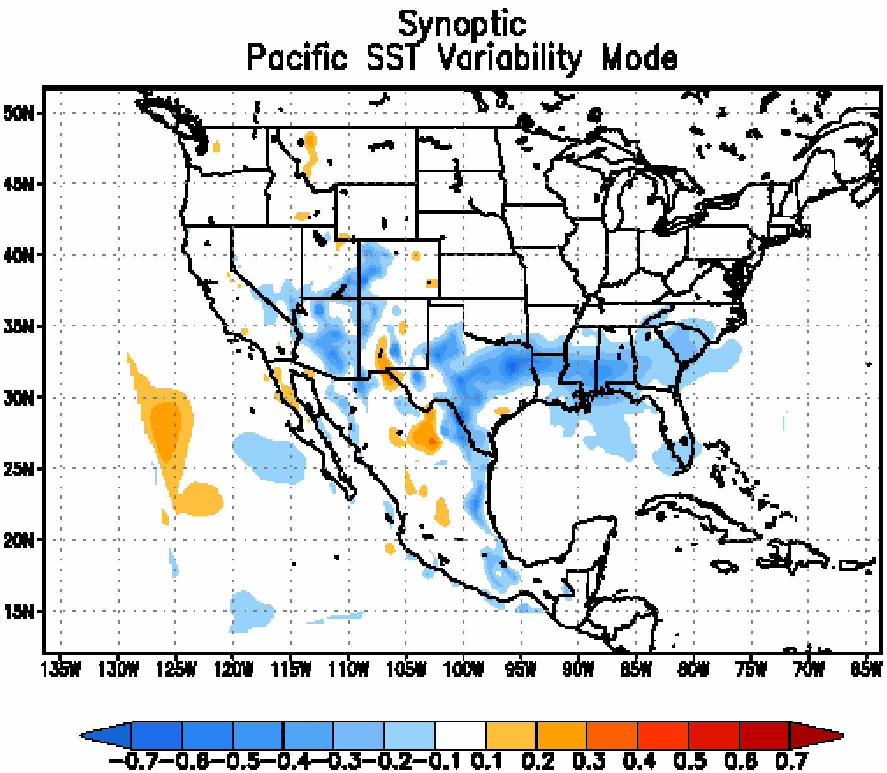
Continental divide is a physical barrier to low-level moisture transport by Great Plains and Baja LLJ. Geographic separation point between regions with opposite signals in interannual variability of diurnal convection.

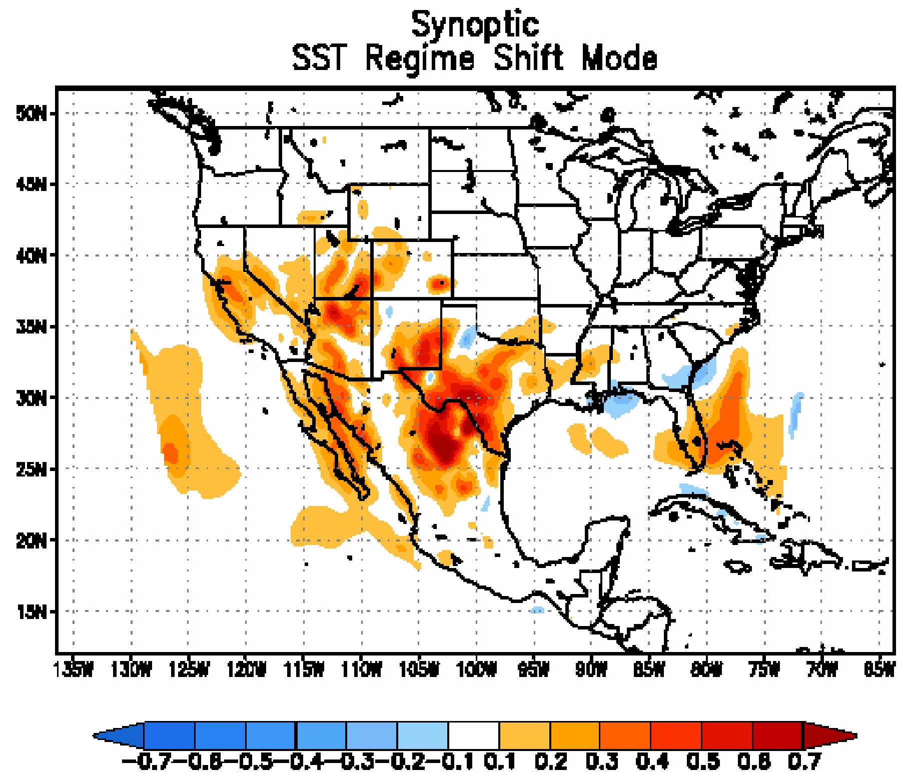
Change in Magnitude of Sub-Synoptic Band of MFC at Time of Maximum Teleconnectivity





Change in Magnitude of Synoptic Band of MFC at Time of Maximum Teleconnectivity





Westward propagating convection off the Mogollon Rim and Sierra Madre Occidental associated with gulf surges is affected.

NSIPP GCM Downscaling

Can it be shown in a *seasonal weather prediction mode* (Type 3) that Pacific SSTs cause the observed climate anomalies?

Using the same methodology as for the reanalysis, dynamically downscale the NSIPP GCM summer simulations of Schubert et al. (2002).

SST perturbed conditions (40): 10 per sign of ENSO, PDO-like REOFs
SST climatology (40)

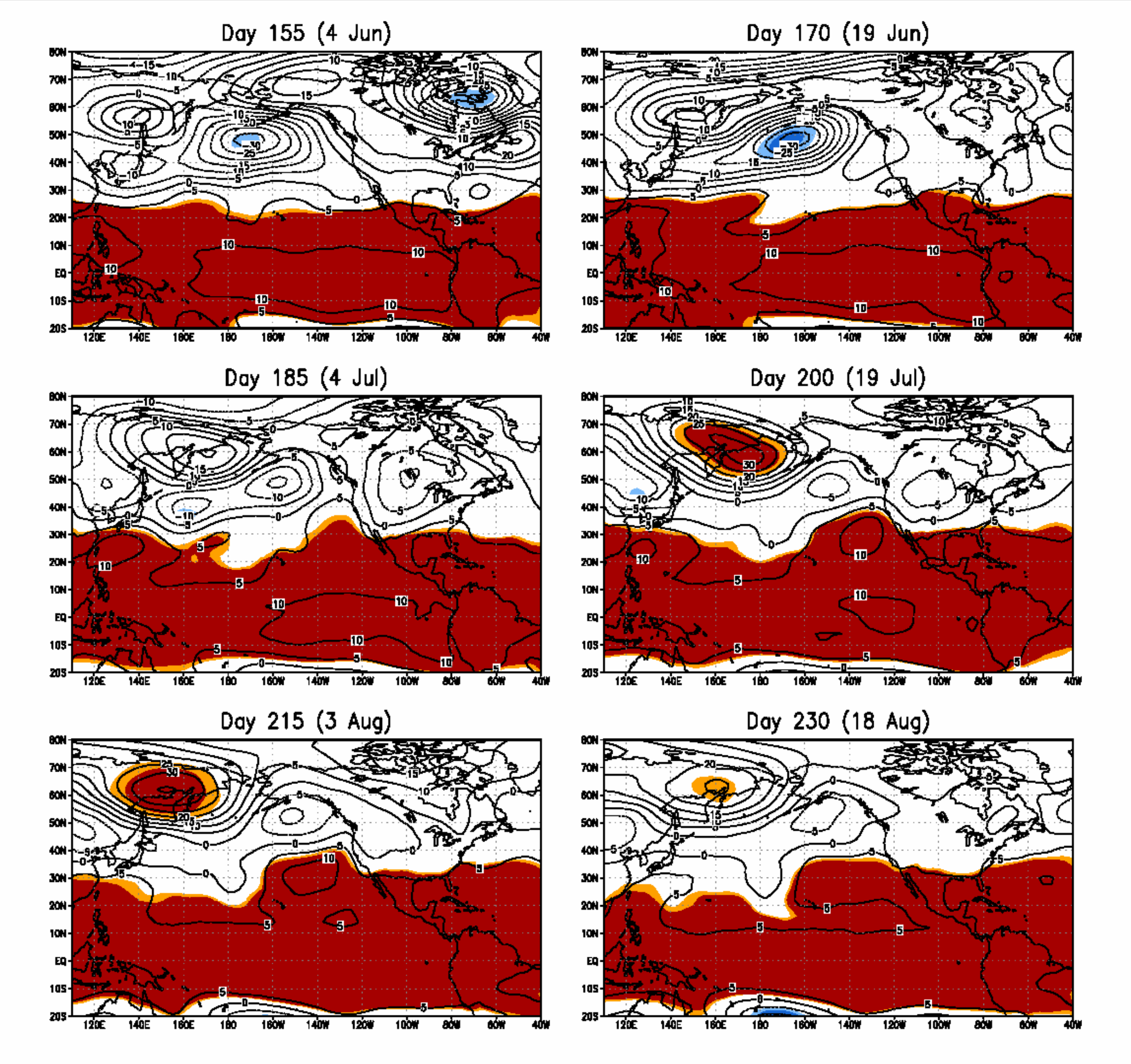
In these cases, the initial soil moisture is specified as the 50 year NLDAS climatology, **so there is no sensitivity to the initial land state.**

The anomalies are computed as the difference between the SST-EOF forced runs and the SST climatology runs. Approximately the same number of degrees of freedom in determining the statistical significance.

NSIPP GCM 30 Day Average 500-mb Height Anomalies (m)

PC1 Composites

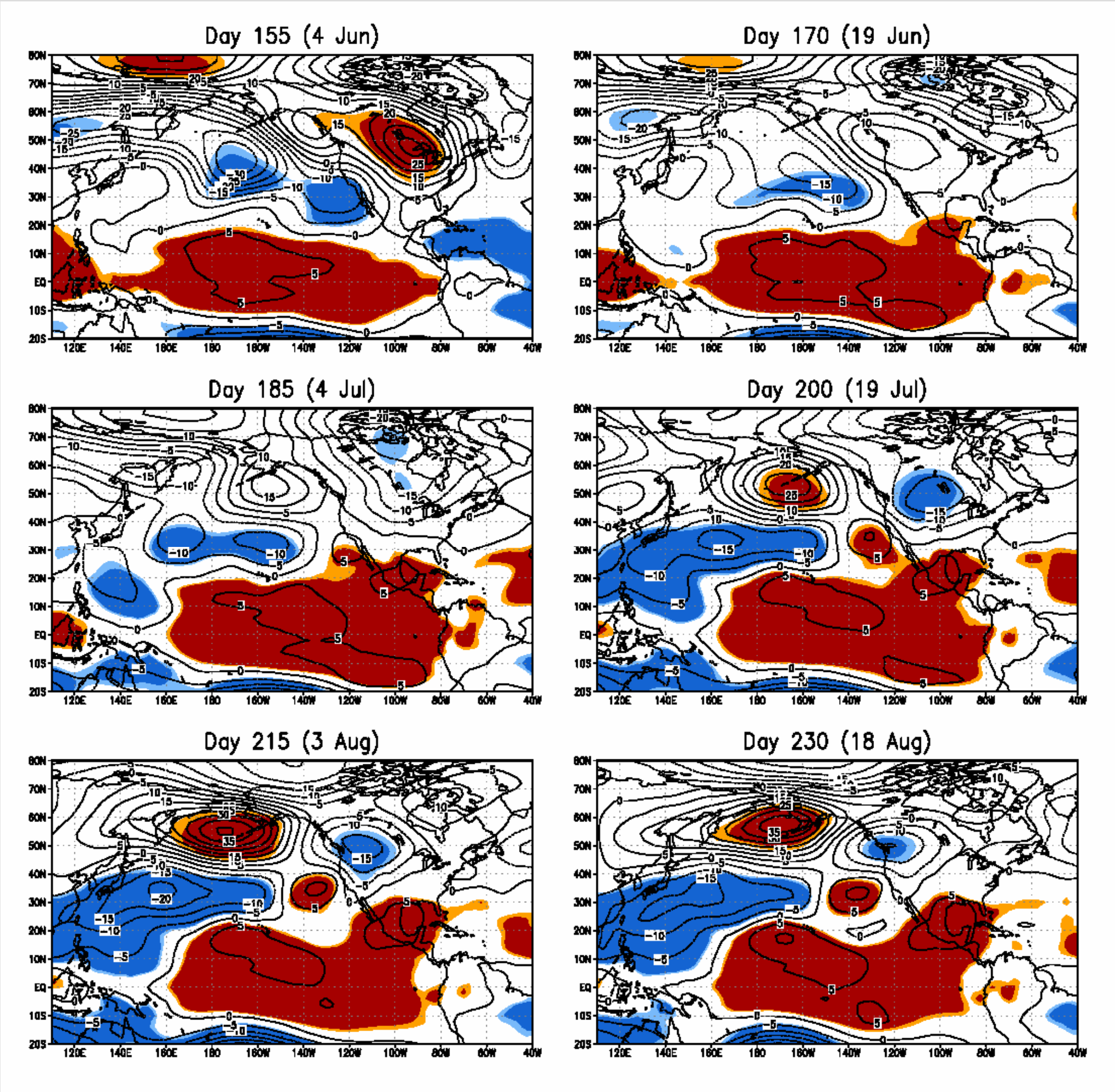
ENSO Mode



NSIPP GCM 30 Day Average 500-mb Height Anomalies (m)

PC 2 Composites

PDO-like Mode

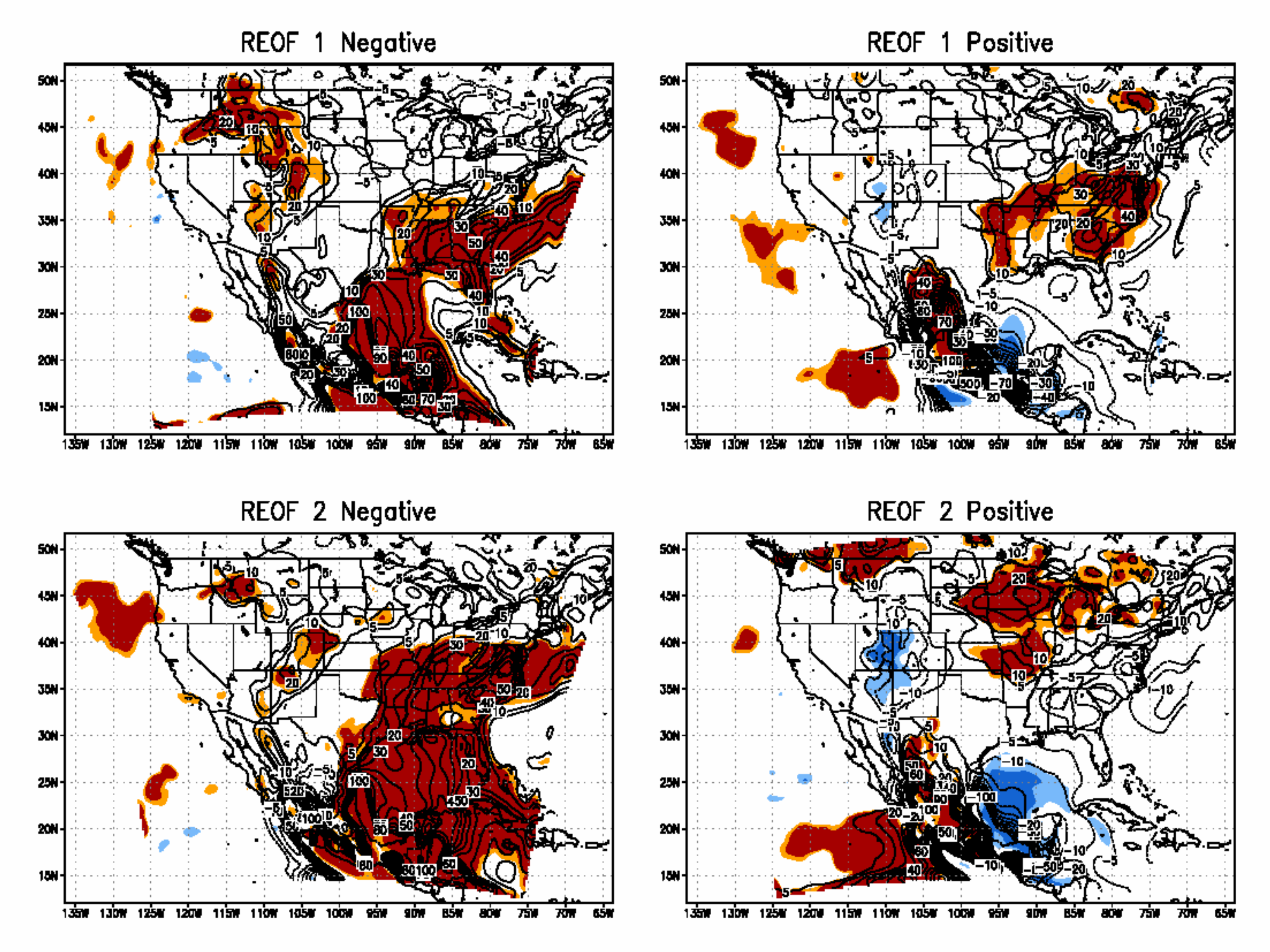


The height anomalies in the contiguous U.S. are due mainly to positive phase.

RAMS-NSIPP Precipitation Anomalies (mm) at Time of Maximum Teleconnectivity

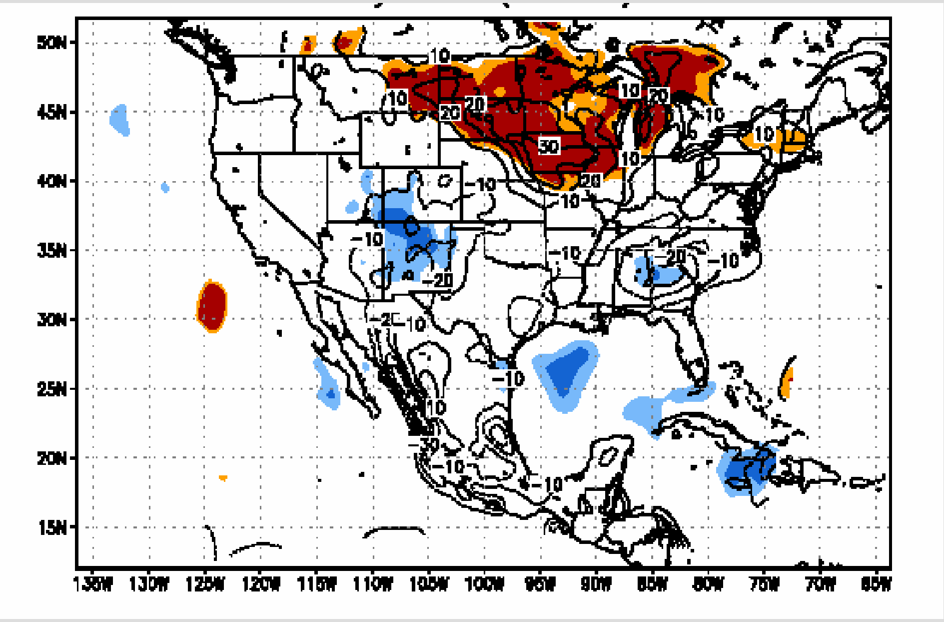
ENSO Mode

PDO-like Mode

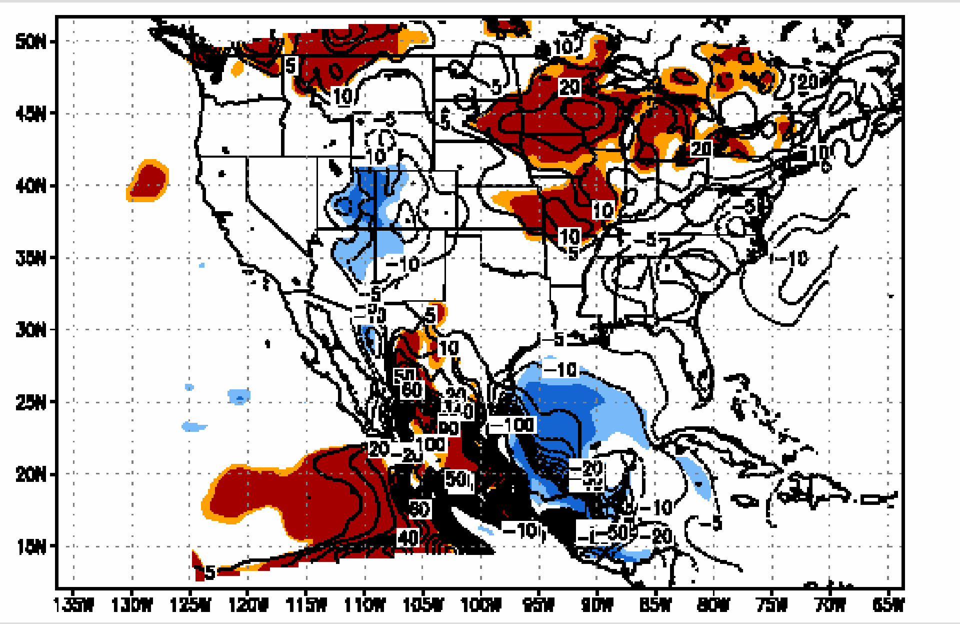


RAMS Precipitation Anomalies (mm) at Time of Maximum Teleconnectivity for Positive PDO-like Mode Composites

Type 2: Simulation mode
RAMS-NCEP Reanalysis



Type 3: Prediction Mode
RAMS-NSIPP GCM

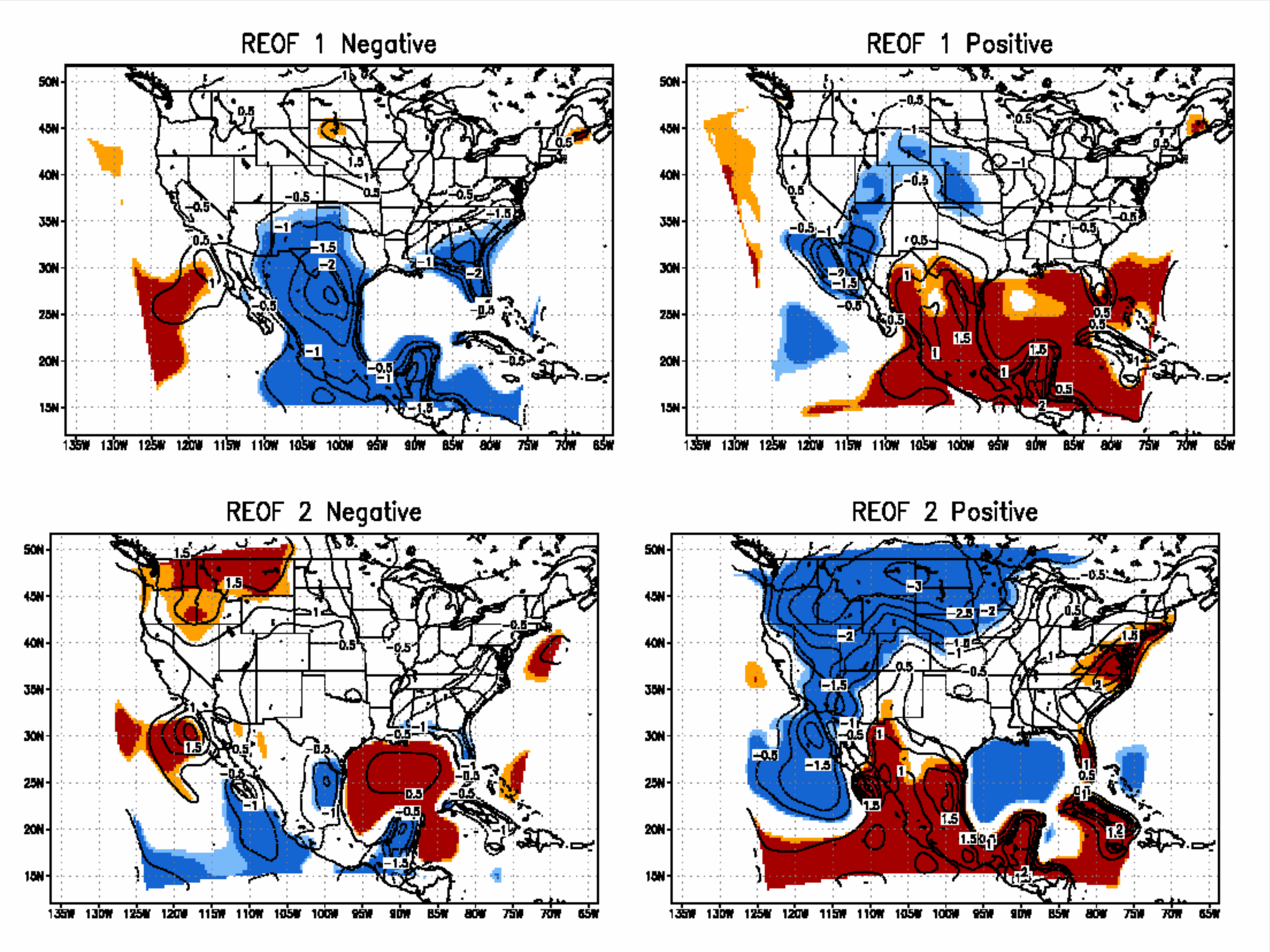


In the case where the NSIPP GCM most faithfully reproduced the large-scale teleconnection response, the precipitation anomaly pattern produced in seasonal weather simulation mode is nearly identical to that of a seasonal weather prediction mode.

RAMS-NSIPP Surface Temperature Anomalies (K) at Time of Maximum Teleconnectivity

ENSO Mode

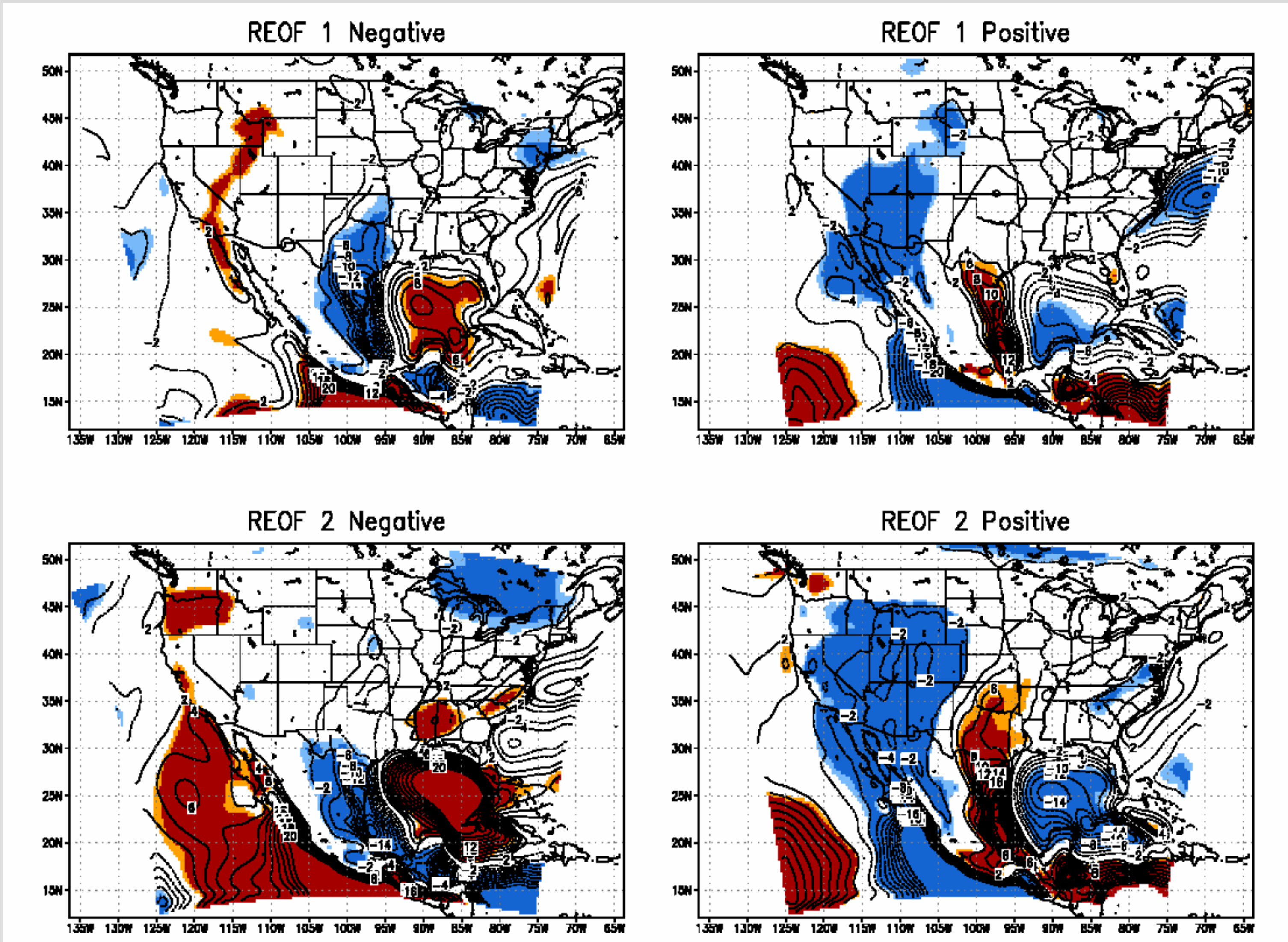
PDO-like Mode



RAMS-NSIPP Sfc. MF Anomalies (m s^{-1} g kg^{-1}) at Time of Maximum Teleconnectivity

ENSO Mode

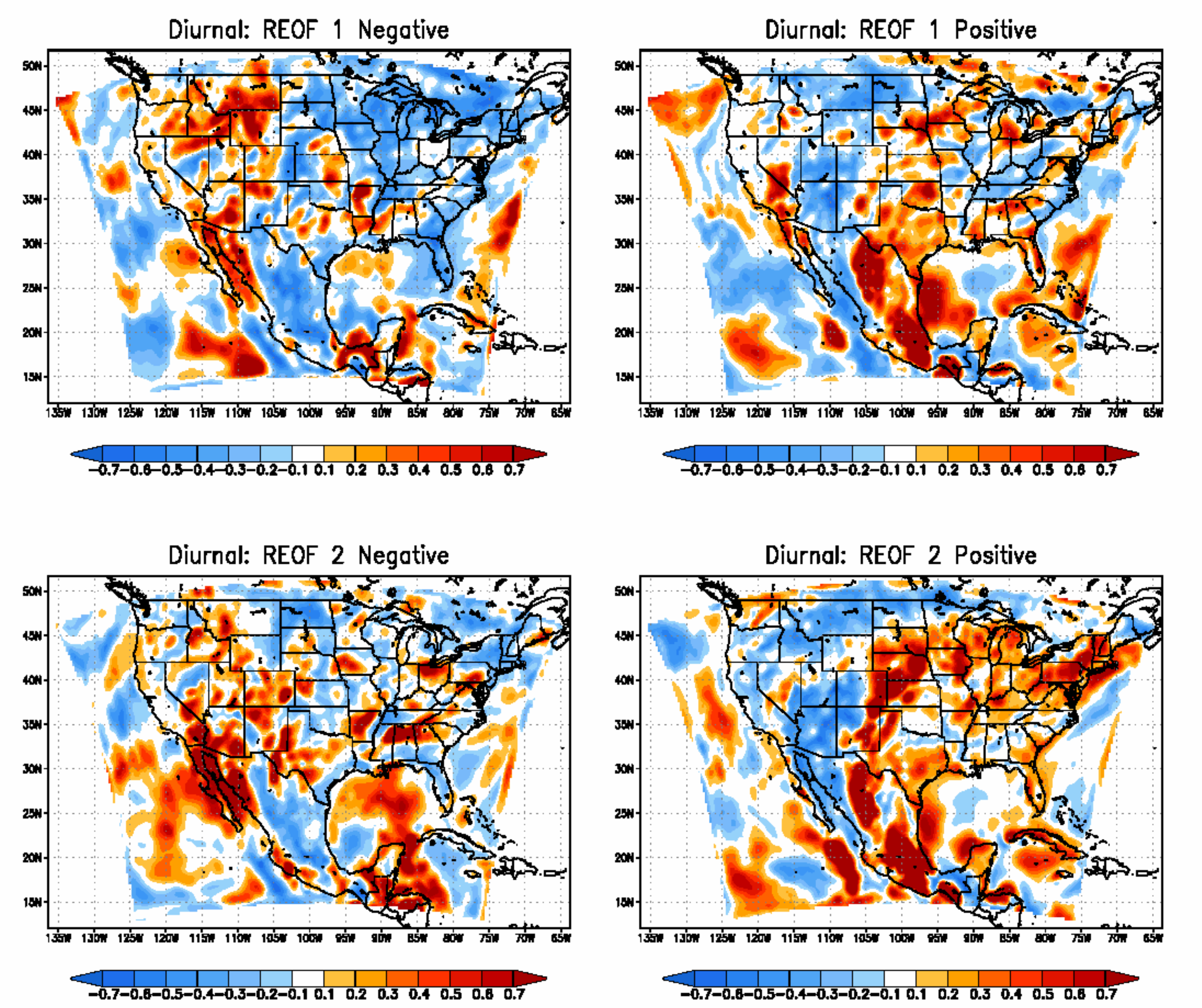
PDO-like Mode



RAMS-NSIPP Change in Magnitude of Diurnal MFC at Time of Maximum Teleconnectivity

ENSO Mode

PDO-like Mode



Summary and Conclusions
RAMS Simulation Design and Goals

TYPE 2, Seasonal Weather Simulation Mode

NCEP Reanalysis used to downscale 53 summer seasons (1950-2002) over North America

Construct a RCM summer climatology and use this to further explore the statistical relationship of North American summer climate to global SST modes.

TYPE 3, Seasonal Weather Prediction Mode

80 realizations of NSIPP GCM data downscaled for forcing corresponding to SST climatology and ENSO, PDO-like SST modes.

Establish a causal link of North American summer climate variability to remote sea surface temperature forcing.

Summary and Conclusions
RAMS RCM Summer Climatology

The RCM summer climatology for North America was reasonable, in light of observations. Important features captured included:

- Seasonal transitions in precipitation and temperature
- Baja and Great Plains LLJ
- Development of the monsoon ridge
- Modes of variability in convection, particularly the diurnal cycle

Summary and Conclusions
Climate Variability

Time-evolving teleconnections associated with Pacific SST variability accelerate or delay evolution of the North American Monsoon.

The strongest climate response occurs in late June and July.

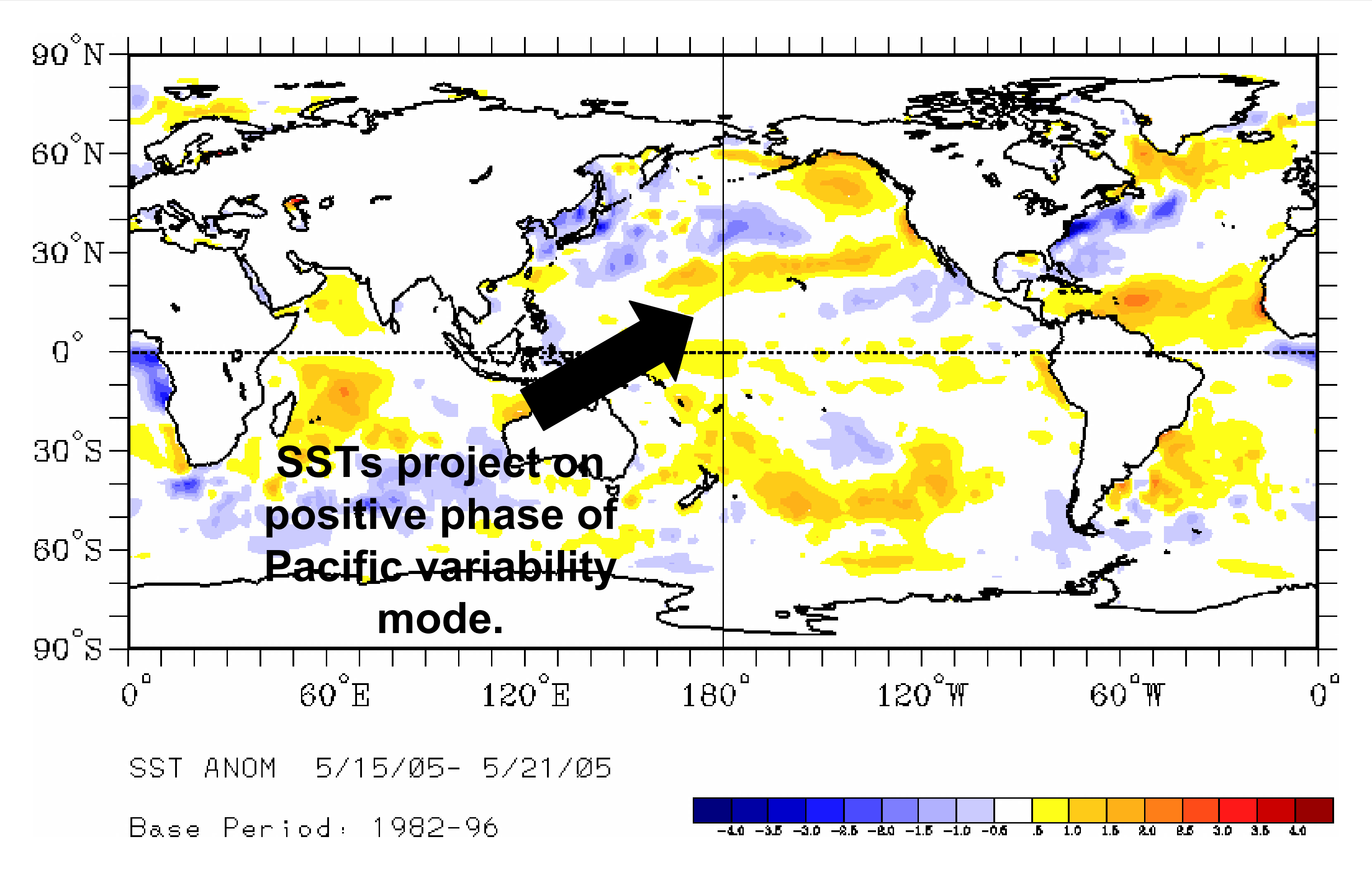
At this time, Pacific SSTs are most significantly related to precipitation in the central U.S. and core monsoon region.

The teleconnections affect the strength of the Great Plains and Baja LLJs in opposite ways.

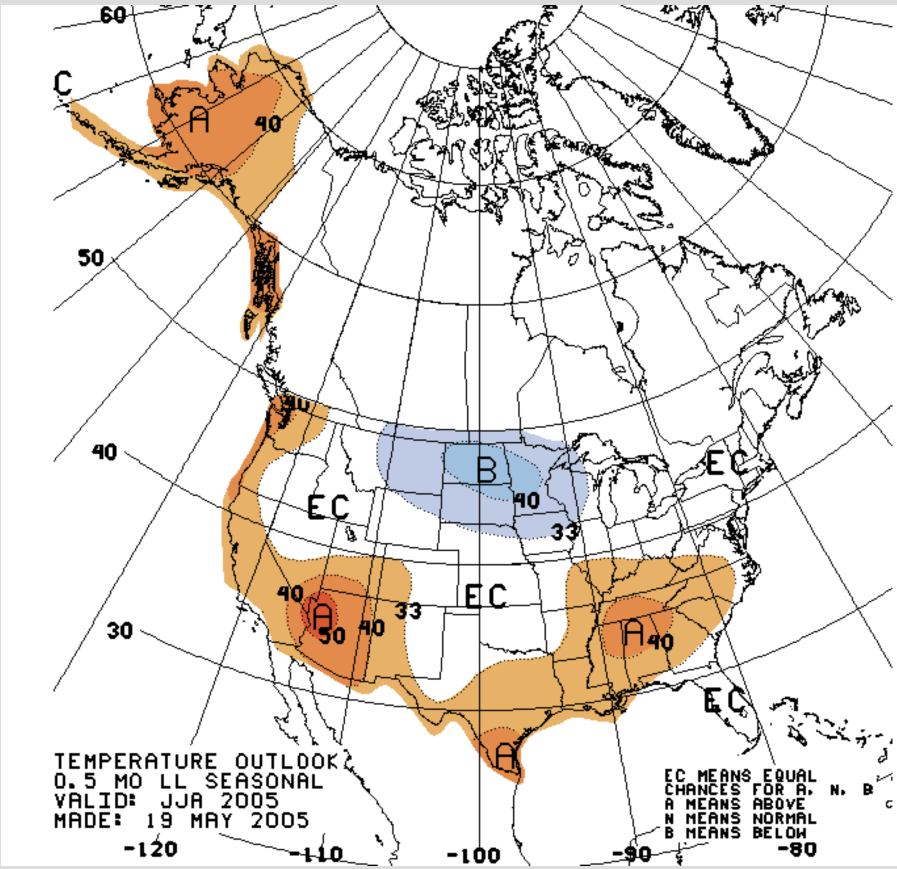
The changes in low-level moisture transport influence the magnitude of the diurnal cycle of convection, as well as the lower frequency modes of convection.

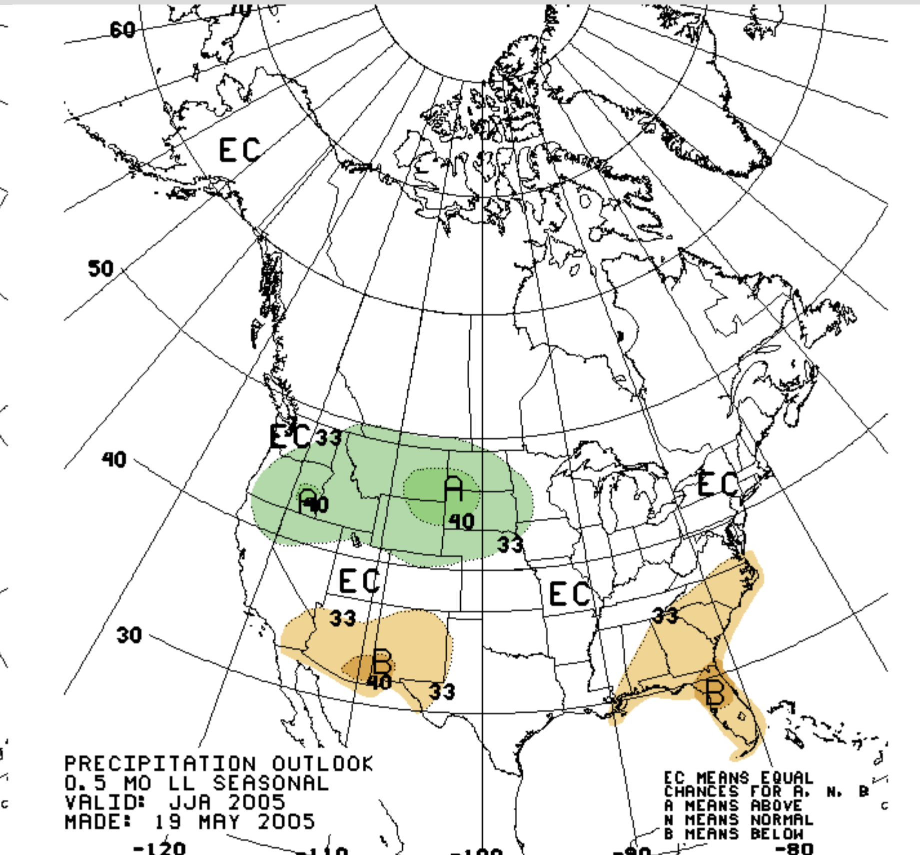
Regime shift in tropical SST associated with general increase in simulated precipitation, except in western Mexico.

May 2005 Sea Surface Temperature Anomalies



Climate Prediction Center
Summer 2005 Forecast

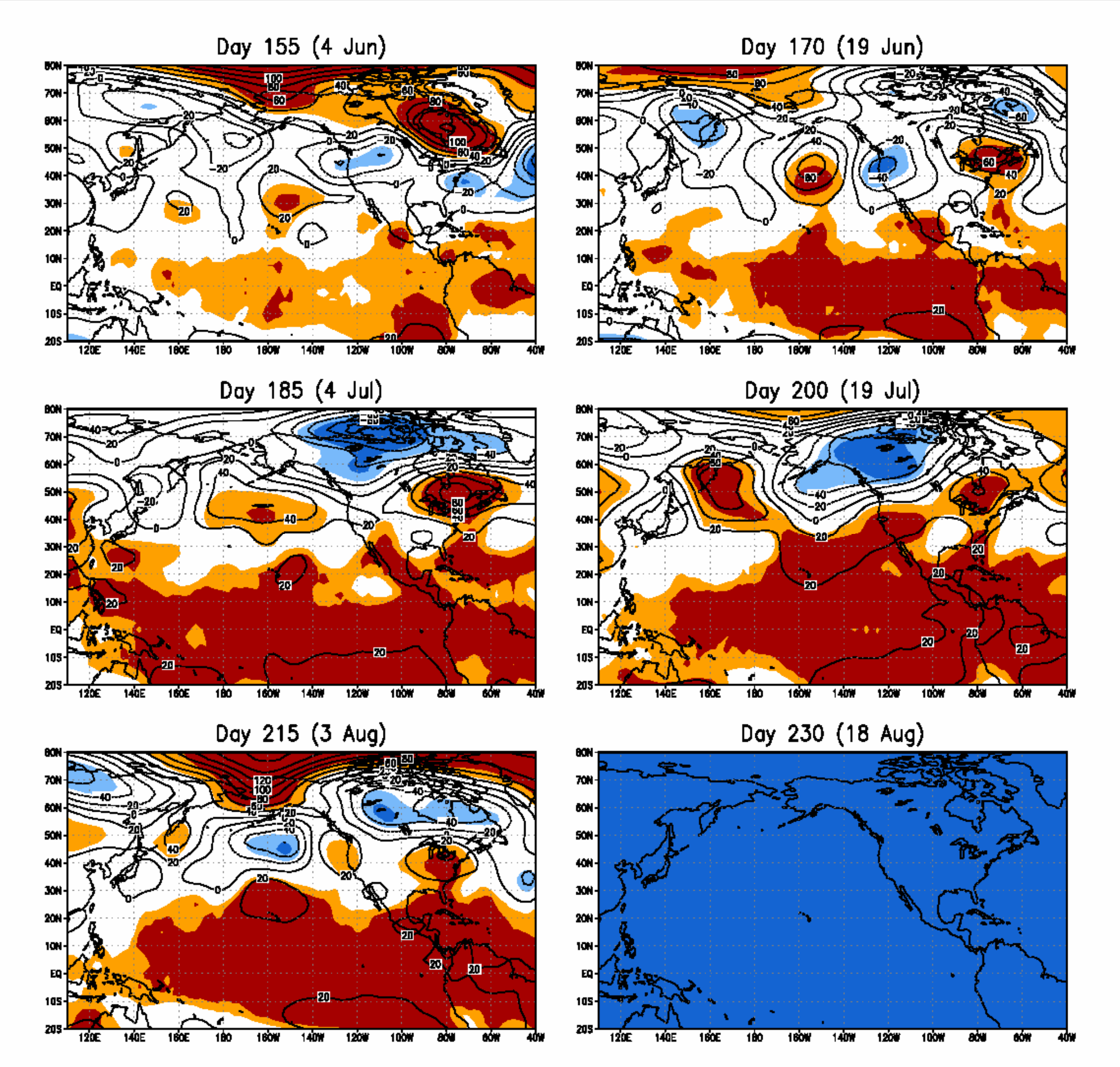


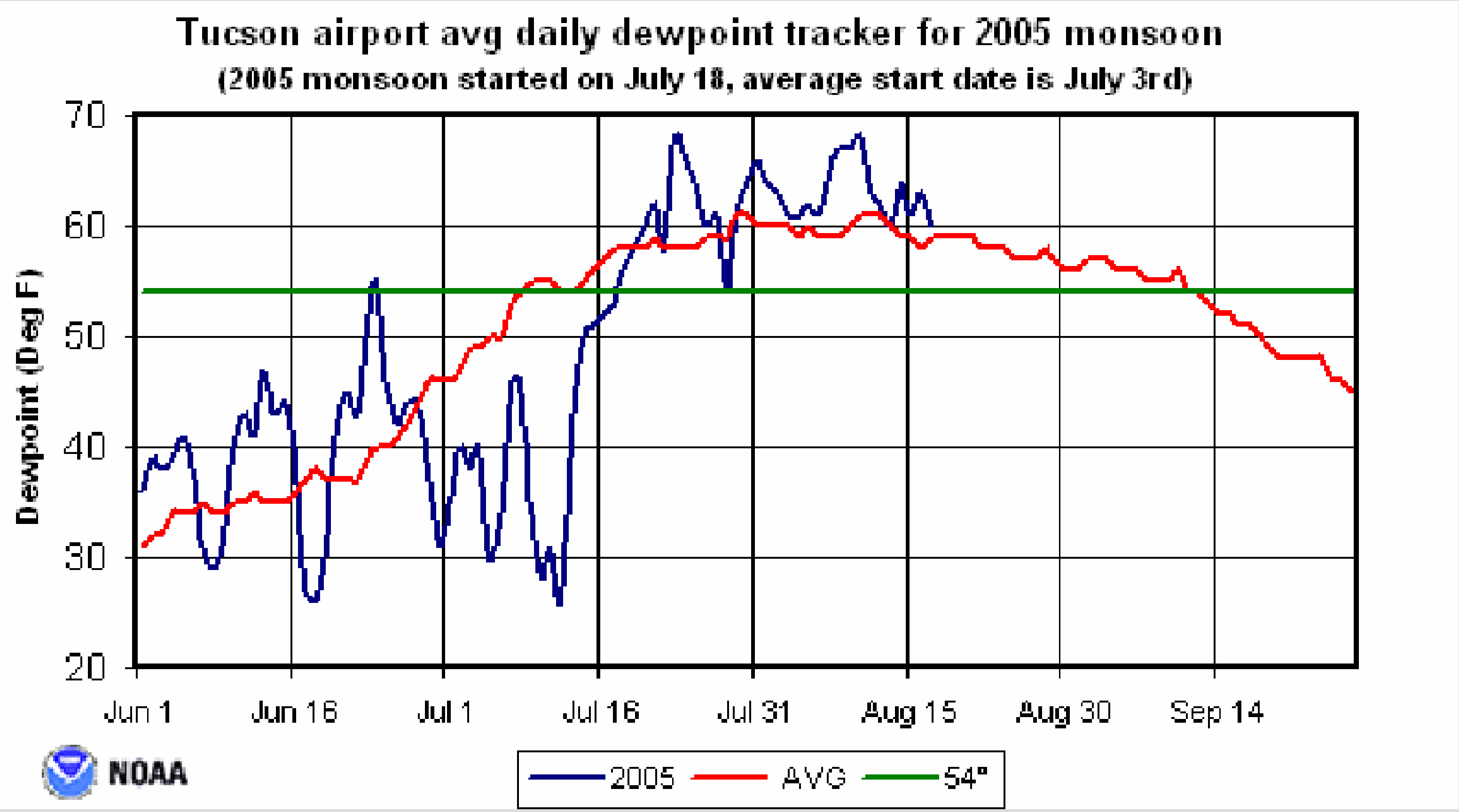


30-day Average 500-mb Height Anomaly

Summer 2005

Shading at 0.5 and 1 standard deviation based on 1950-2002 record



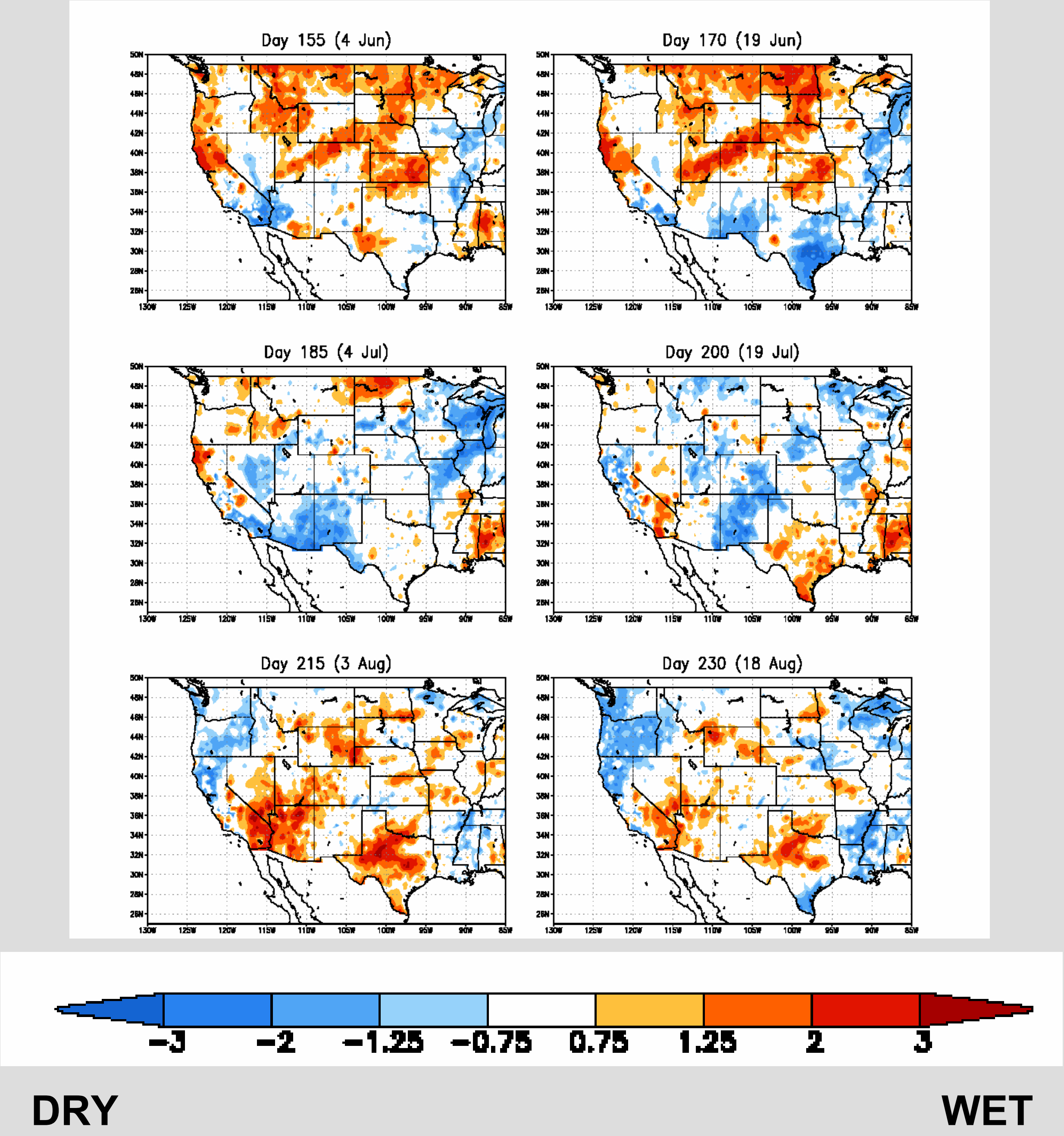


Summer 2005 was the second latest monsoon onset on record!

30-day Standardized Precipitation Index (SPI)

Summer 2005

Based on 1950-2002 CPC U.S. precipitation record



Topics For Future Research

The impact of the land surface state. Not considered in this study. How do snow cover, vegetation, and soil moisture interact with the climate forcing by Pacific SSTs? Is there a positive feedback? **Future work with RAMS aims to investigate this issue.**

Could the present set of simulations be used to drive **finer resolution simulations**?

The GCM SST-forced simulations need to be repeated with a variety of GCMs to confirm the robustness of the time-evolving teleconnection response in boreal summer and impact of warmer tropical SSTs.

If the boreal summer teleconnection response is truly global in nature, then it could be expected that similar relationships exist in other parts of the world, like East Asia and Europe. Dynamical downscaling in the same vein as the present study may also yield significant results.

Multi-year climate prediction (Type 4) requires an accurate representation of ENSO and PDO-like modes in a coupled ocean-atmosphere GCM. Still don’t know the physical mechanisms of the latter.


THANK YOU!