Diagnosing the Climatology and Interannual Variability of North American Summer Climate with the Regional Atmospheric Modeling System (RAMS)

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1. Introduction

In recent years regional climate models (RCMs) have been increasingly used to study boreal summer climate in North America. To date, the majority of these efforts have been sensitivity studies. Typically one selected year is chosen for dynamical downscaling and the sensitivity to a particular surface parameter (soil moisture, vegetation, or sea surface temperature) or model physical parameterization scheme is evaluated (e.g. Small 2001; Gochis et al. 2002, 2003; Kanamitsu and Mo 2003). Though such studies can yield insight, they are necessarily limited because the lateral boundary forcing is fixed. Use of different lateral boundary forcing may change the conclusions.

Here we introduce an ensemble approach with a RCM in which the surface parameters and model parameterizations are fixed and the lateral boundary forcing varies for the warm season. A RCM used in this way is appropriate to investigate the warm season for two reasons. First, it adds value to its parent general circulation model (GCM) or global reanalysis. The global forcing data have long records (on the order of 50 years) and contain large-scale climate variability. However, because of their course resolution GCMs and atmospheric reanalyses poorly represent key details of summer climate, as forced by terrain and other surface effects, such as the diurnal cycle of convection, low-level jets (LLJ), and the seasonal maximum in precipitation associated with the North American monsoon. Second, a RCM approach is more advantageous than a purely statistically based approach. While statistical approaches can be used to determine spatial and temporal trends in surface data, like precipitation and temperature, atmospheric data at a scale of tens of kilometers is necessary to establish the physical linkages to large-scale climate variability. Moreover, there is no guarantee that the statistical relationships are invariant over time, as the surface conditions or large scale forcing change.

In this study, the RCM used is the Regional Atmospheric Modeling System (RAMS). To evaluate whether RAMS adds value beyond that of a GCM we consider the evolution of precipitation through the summer season and variation of atmospheric moisture at various timescales. After establishing that RAMS produces a reasonable representation of summer climate in North America, the interannual variability associated with changes in Pacific SSTs is investigated. The El Niño Southern Oscillation and Pacific Decadal Oscillation (PDO) are defined in terms of their sea surface temperature (SST) signatures. These two modes of variability are associated with distinct summer teleconnection responses that affect the distribution of atmospheric moisture and precipitation across the continent. In particular, the PDO generates the most statistically significant response.

2. The Regional Climate Model and Lateral Boundary Forcing Data

RAMS was originally developed at Colorado State University to facilitate research into predominantly mesoscale and cloud-scale atmospheric phenomena (Cotton et al. 2003; Pielke et al.

2002). It has also demonstrated its utility as a RCM (e.g. Eastman et al. 2001; Adegoke et al. 2003). The model domain is shown in Fig. 1. The length of all simulations is 15 May to 31 August. Grid spacing is 35 km. The surface boundary is prescribed with variable soil type according FAO classification; Reynolds and Smith (1994) SST and variable soil moisture from the Variable Infiltration Capacity (VIC) hydrologic model (Mauer et al. 2002) are defined at the beginning of each simulation. A modified Kain-Fritsch cumulus parameterization scheme is used for convective precipitation (Kain and Fritsch 1993). Non-convective precipitation is simulated by a simple dumpbucket scheme which considers the supersaturation of an air parcel. Other parameterizations for radiation and the boundary layer are standard for simulations of this type. The model uses three lateral boundary nudging points and weak internal nudging at a one day timescale. The internal nudging is necessary to maintain coherence of large-scale circulation features (Castro et al. 2004).

Two datasets are dynamically downscaled with RAMS. The NCEP-NCAR Reanalysis (Kalnay et al. 1996) is downscaled for nearly its entire length of record for the summer season (1950-2002). For these simulations, year specific soil moisture is provided by the VIC model. The reanalysis downscaling essentially constitutes a RAMS summer climatology from which to evaluate the existence of interannual variability during the past 53 years. The second dataset is GCM output from the NASA Seasonal to Interannual Prediction Project (NSIPP) model described in Schubert et al. (2002). These GCM ensemble simulations begin at 1 May with the same initial condition and end 31 August. The GCM is forced with idealized distributions of SST corresponding to 1980-1999 Reynolds SST climatology (40 realizations), and the two dominant SST rotated EOFs for the same period superimposed on climatology (40 realizations, 10 per sign of rotated EOF). The first two rotated EOFs are shown in Fig. 2. The first EOF is unquestionably associated with ENSO. Although the SST data only span 20 years, the second EOF bears resemblance to the PDO as defined by Zhang et al. (1997) among others.

Schubert et al. (2002) note that these ENSO and PDO modes are related to two global teleconnection patterns which are symmetric with respect to the equator in both observations and their idealized GCM simulations. The first (ENSO) mode has maximum variance in the tropics, while the second (PDO) mode has a greater amount of variance in the mid-latitudes of both hemispheres. They further suggest that the second mode has the stronger link to wet and dry conditions in the central U.S. The question posed here is whether RAMS is able to add value to the NSIPP GCM representation of climate in North America and produce a statistically significant response in summer precipitation. Since a fixed VIC climatology of soil moisture is used at the beginning of each RAMS simulation, the NSIPP downscaling explicitly tests the hypothesis that summer climate evolution is significantly modulated by Pacific SST independent of local surface influences.

3. Climatology of Precipitation and Atmospheric Moisture

There are several a priori expectations as to where and when the enhanced surface boundary of the RCM should add value to the climatology of precipitation and atmospheric moisture. First, it should be expected that the RCM should yield a better representation of rainfall as the summer season progresses. Analysis of radar data shows rainfall becomes less dependent on large-scale synoptic weather systems and more dependent on diurnally-forced convection or propagating mesoscale convective systems (Carbone et al. 2002). Second, rainfall should be more realistically represented in locations where the diurnal cycle of convection is dominant, arising from complex topography and/or land sea contrast. These are also areas where periodic surges of moisture occur due to low-level jets. Finally, it should also be expected that precipitation should improve in areas where land surface feedback may be important, such as the central U.S.

Fig. 3 shows the summer precipitation in July as seen in NCEP 1° observations, the NCEP-NCAR Reanalysis, NCEP Reanalysis-RAMS downscaled, and NSIPP GCM-RAMS downscaled. June and August precipitation are shown in the corresponding PowerPoint presentation. Beginning in June, there is a late spring maximum in precipitation in the central U.S. The core North American monsoon region (northwest Mexico and Arizona) are dry. The NCEP Reanalysis tends to have a wet bias in the Southeast U.S. which persists throughout the summer. Dynamical downscaling with RAMS increases the precipitation along the Sierra Madre Occidental and in the central U.S. because of an enhanced diurnal cycle of rainfall. The NSIPP GCM downscaled precipitation shows a dry bias which worsens during the summer, likely because of a high temperature bias by the NSIPP model in North America. In July, observations show that the monsoon rains advance in the core monsoon region and the central U.S. rainfall decreases. In the NCEP reanalysis, the advance of the monsoon is not captured and the central U.S. rainfall is underestimated. The Reanalysis-RAMS downscaled precipitation correctly shows the advance of the monsoon northwestward and has more precipitation in the central U.S. The monsoon also appears to advance in the NSIPP GCM-RAMS downscaled case, though it is weaker. The monsoon reaches its furthest northward extent in August, and this is correctly represented in both downscaling cases.

The climatology of moisture flux (MF) and moisture flux convergence (MFC) are next evaluated for the month of July. These variables were selected for analysis because they are related to rainfall via the water balance equation and reflect features for which the regional climate model should add value. Conventional Fourier analysis techniques were used to spectrally decompose both variables for the thirty day period about the date. Spectra are then averaged for all of the years in a given set of downscaling experiments. Four distinct frequency bands were determined: a synoptic mode (4-10 days); a sub-synoptic mode (2-3 days), a semidiurnal mode (1.5 days) and a diurnal mode (1 day). The spectral power was computed as the average of the power spectrum in the given frequency band. This quantity is then multiplied by the fraction of spectral power above the 95% confidence level in the band, with a value of zero meaning there is no statistically significant power in the band and a value of one meaning all the spectral power in the band is significant. This weighting ensures that the most statistically significant features are emphasized.

Shown in Fig. 4 is the significant spectral power for the moisture flux and moisture flux convergence for the reanalysis and NSIPP downscaled simulations in the synoptic mode. In the synoptic mode, the moisture flux has a connection to tropical moisture sources. The strongest fluxes are in the eastern U.S. associated with variations in moisture transport from the Gulf of Mexico. Also present, but weaker, is a flux of moisture from the Gulf of California into the interior Southwest U.S. The variation of the Baja LLJ at these timescales is related to periodic (Gulf) surges of moisture. The Gulf surges are related to a significant variation in the moisture flux convergence in the core monsoon region at the synoptic timescale, particularly at lower elevations. These surge events provide moisture for thunderstorms propagating westward off the Sierra Madre Occidental or the Mogollon Rim. The sub-synoptic and semidiurnal modes show no connection of moisture transport from the tropics. The variation of moisture flux convergence for these modes is due to rainfall from synoptic weather systems or eastward propagating mesoscale convective systems (see PowerPoint slides).

MF and MFC in the diurnal mode (Fig. 5), not surprisingly, are statistically significant everywhere and have large spectral power in areas of terrain gradients and land sea contrast. In particular, the diurnal cycle of convection is the principal mechanism for rainfall along the Sierra Madre Occidental and the Rocky Mountains, where the spectral power of MFC exceeds 10 mm^2 day^{-2}. The NCEP Reanalysis itself yields spectral power which is about an order of magnitude less than what the regional model produces in these regions (not shown).

4. Interannual Variability Associated with ENSO and the PDO

Using the NCEP Renalysis, Castro et al. (2001) established that different and distinct teleconnection relationships exist in the boreal summer season related to ENSO and the PDO. To investigate this further an EOF analysis was performed on the 500-mb height field for classified ENSO and PDO years in observations, as defined by Castro et al. (2001), and the NSIPP EOF1 and EOF2-forced NSIPP GCM ensembles. Shown in Fig. 6 is the correlation of the 500-mb height with either the first or second principal component as obtained by EOF analysis of the subsets of years. The teleconnection pattern for ENSO-EOF1 is for the period of monsoon onset (late June, early July). For the PDO-EOF2 forced composite the period considered is monsoon peak (late July, early August). Thus, the teleconnections are not only distinctive to each mode, but have a time-evolving character, such that the ENSO mode appears in the early part of the summer and the PDO mode appears later. These teleconnections tend to accelerate (low PDO, low ENSO) or delay (high PDO, low ENSO) the evolution of the North American Monsoon. The regions which exhibit the strongest responses in MFC and precipitation in the summer are the Southwest U.S. and central U.S. The two questions posed here are: 1) Can dynamical downscaling of the reanalysis improve the statistical significance of precipitation anomalies associated with SST variability; and 2) do similar and significant precipitation responses occur in RAMS-downscaled NSIPP simulations.

Observed ENSO and PDO-type years from the 53 year record were categorized according to thresholds in Pacific SST indices similar to Castro et al. (2001). The statistical significance of each subset of reanalysis RAMS-downscaled years is determined by evaluating each selected set of composite years against all others using a two-tailed t-test. For the NSIPP-RAMS downscaling, the statistical significance of each ten year EOF-forced ensemble is evaluated by a two-tailed t-test against 20 years of SST climatology and the other 30 EOF-forced runs. In the following figures, statistical significance is plotted at the 80% level and above to show the continental scale pattern of the precipitation anomalies.

Fig. 7 shows the July precipitation anomaly for the positive PDO years. As suggested by Schubert et al. (2002), this grouping of years is the most statistically significant. There is a positive precipitation anomaly in the central U.S. which reflects an extended late spring wet period there. With RAMS downscaling the wet anomaly is closer to observations in terms of spatial extent and magnitude. The maximum precipitation difference of 40-60 mm occurs in the central U.S. in approximately the same location as where the 1993 Flood occurred. Monsoon onset is delayed and it is drier than average in the core monsoon region, including northwest Mexico. This dry anomaly becomes statistically significant with RAMS downscaling. Though the NSIPP downscaling places a weaker wet anomaly to the north and east of where it is found in observations, there is still a significant dry anomaly in the core monsoon region. The July precipitation anomaly for the negative PDO years is approximately the reverse signal of the positive PDO years, though the dry anomaly in the central U.S. is not as significant or non-existent. The wet anomaly in the core monsoon region is stronger and more significant in the RAMS simulations (see PowerPoint slides). Similar composites were constructed for the ENSO years (not shown), but these were not as significant or spatially coherent as the PDO-type years.

Given that RAMS downscaling yields significant and spatially coherent precipitation anomalies for the PDO years, the percentage change in variance of the components of MF and MFC can be evaluated. Here we focus attention to the high PDO years, since those exhibited the most statistically significant signal. Fig. 8 shows the percentage change in the variance of synoptic MFC. There is decreased moisture flux into the Southwest U.S. associated with weaker and less frequent Gulf of California surge events. Decreased Gulf surge events lead to decreases in rainfall in the core monsoon region, particularly at lower elevations which receive their rainfall from westward propagating MCSs which form on the Mogollon Rim or Sierra Madre Occidental. The propagating MCSs that affect rainfall in the Midwest are stronger and more frequent. Most important, there is a stronger diurnal cycle in the Great Plains and weaker diurnal cycle in the core monsoon region (Fig. 9). The demarcation between wet and dry signals associated with Pacific SST variability is roughly the continental divide.

5. Conclusions

In this study a regional climate model (RAMS) has been used to dynamically downscale the NCEP Reanalysis and NSIPP GCM data for the summer season. More than 100 summer seasons were simulated, which allows for statistical analysis of the RCM data. A RCM adds value by capturing key hydrometeorological features a GCM cannot resolve, namely the diurnal cycle of convection and low-level jets which transport moisture into the continental interior. The largest precipitation differences from the reanalysis occur in central and western North America where these factors largely govern summer rainfall. RAMS can successfully capture the observed coherent and continental scale pattern of precipitation anomalies associated with ENSO and PDO. The teleconnection patterns either delay or accelerate the evolution of the summer synoptic climatology in North America. Downscaling from the NSIPP GCM shows these anomalies occur even the absence of local surface forcing. The PDO yields the most statistically significant pattern of summer precipitation anomalies in North America, and its variability likely affects the occurrence of long-term wet or dry periods in the western and central U.S. Further work is necessary to quantify how local surface influences may modulate the effect of remote SST forcing, but it is clear from this work that the latter sets the large scale circulation pattern that defines monsoon evolution and summer climate in North America.

6. Acknowledgements

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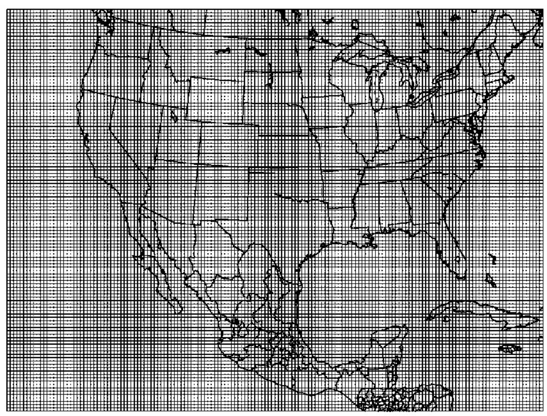

Figure 1: RAMS domain for dynamical downscaling.

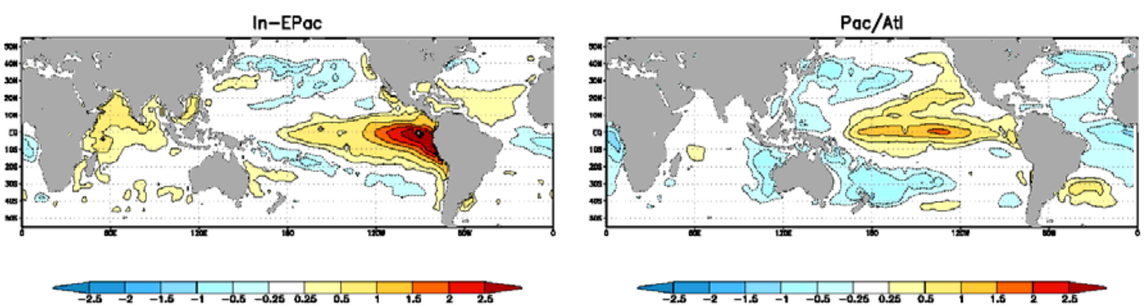

Figure 2: Prescribed SST anomalies used as forcing for NSIPP GCM ensemble experiments. The pattern on the left corresponds to rotated EOF1 (ENSO mode) and the pattern on the right corresponds to rotated EOF2 (PDO mode). Figure courtesy of Sigfried Schubert and Michael Kistler, NASA GSFC.

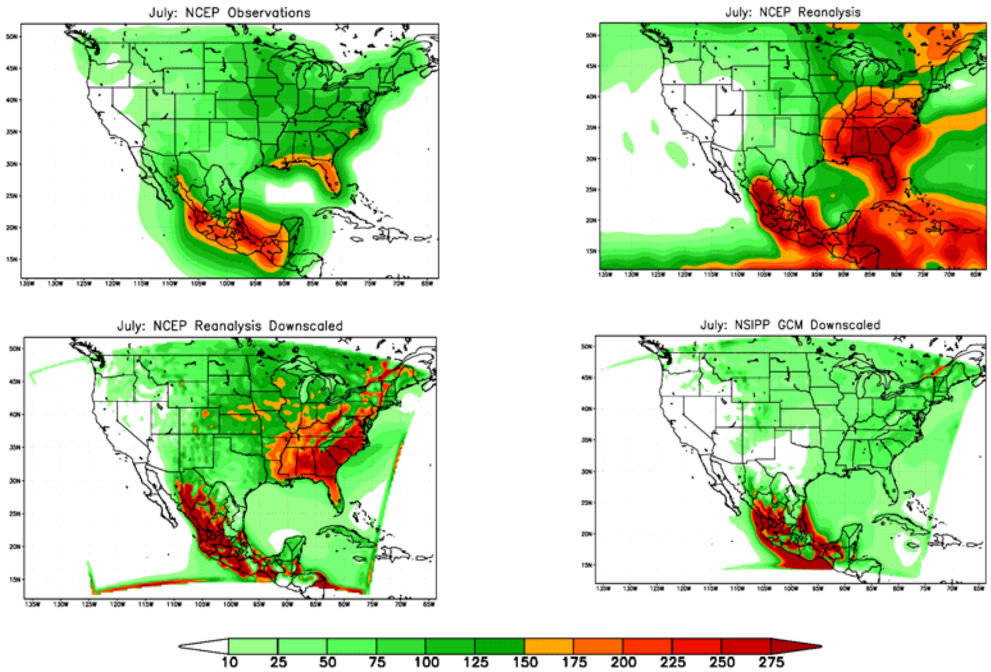

Figure 3: Average July precipitation in mm (1950-2002) from NCEP observations, NCEP Reanalysis, NCEP Reanalysis-RAMS downscaled and NSIPP GCM-RAMS downscaled simulations.

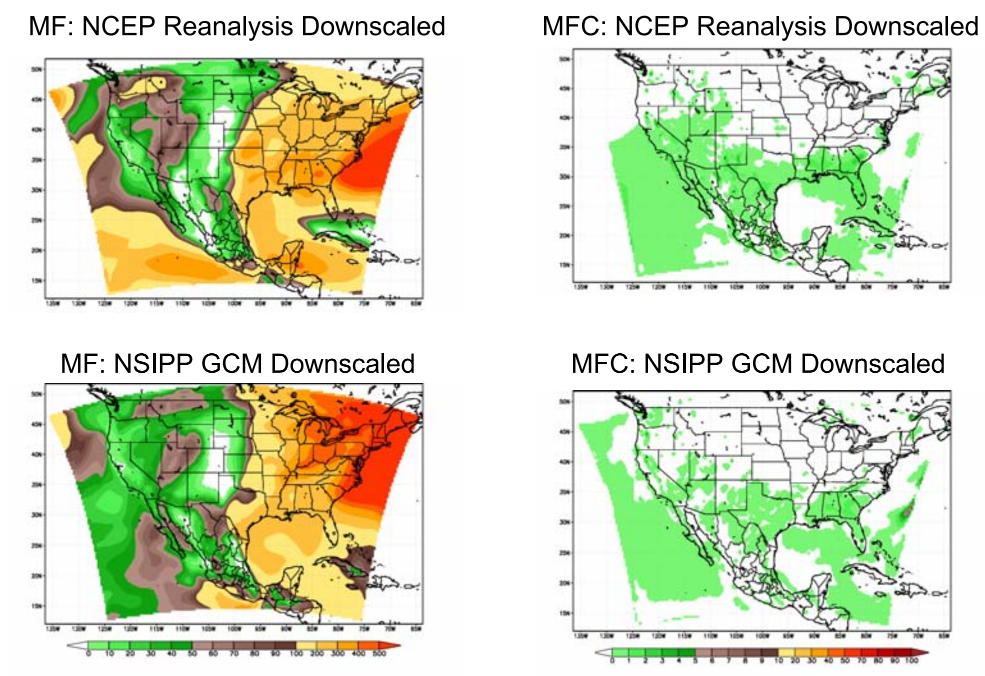

Figure 4: Significant spectral power for the synoptic component of moisture flux ($kg^2\ m^2\ s^{-2}$) and moisture flux convergence ($mm^2\ day^{-2}$). July average for NCEP Reanalysis-RAMS downscaled and NSIPP GCM-RAMS downscaled simulations.

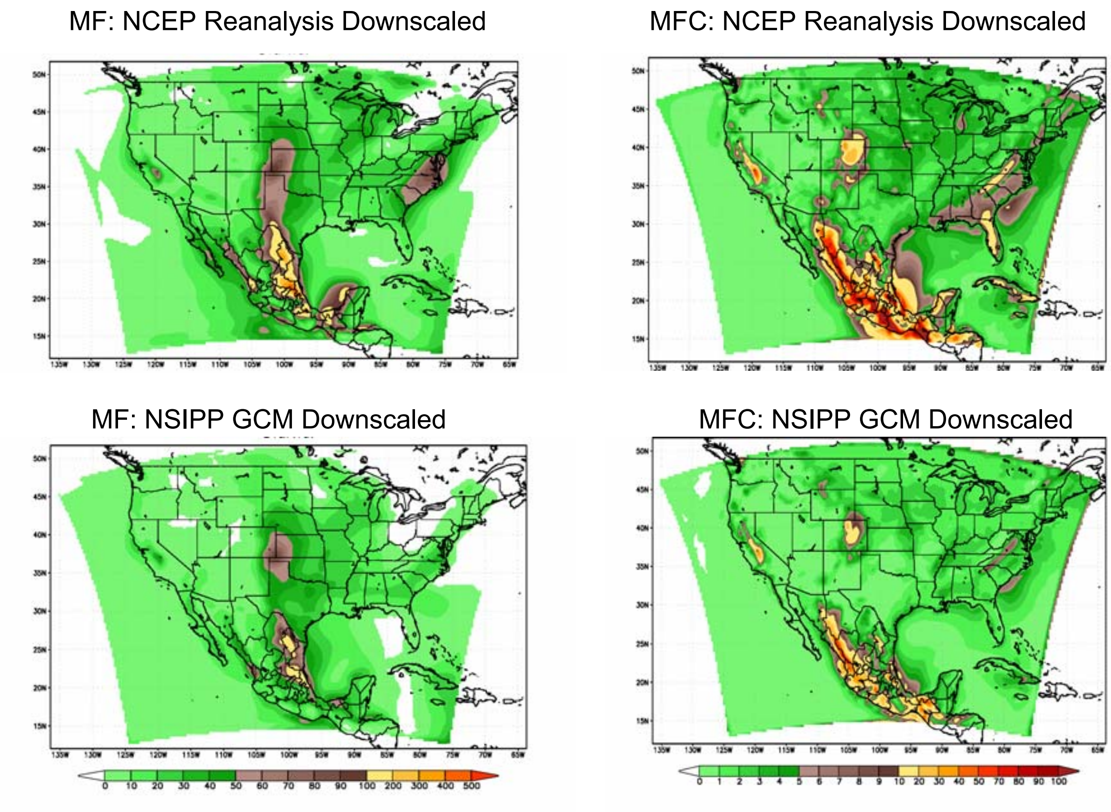

Figure 5: Same as Fig. 4 for the diurnal mode

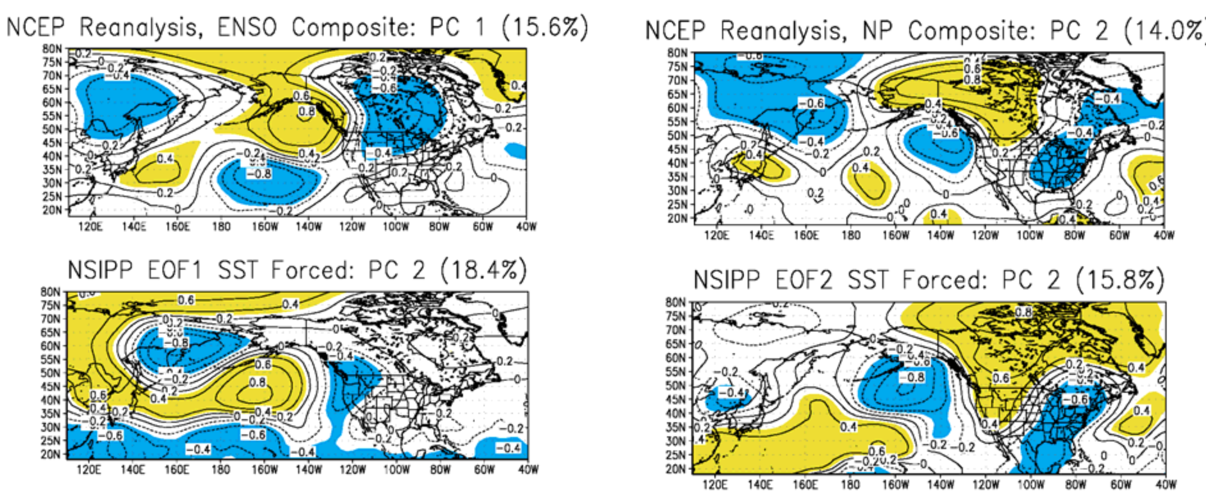

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Figure 6: Correlation of the 500-mb height field with either the first or second principal component obtained by EOF analysis of the given subset of observed and NSIPP-GCM ensemble years. The ENSO-EOF1 patterns are for the period of late June and early July. The PDO-EOF2 patterns are for the period of late July and early August. Explained variance of each EOF included.

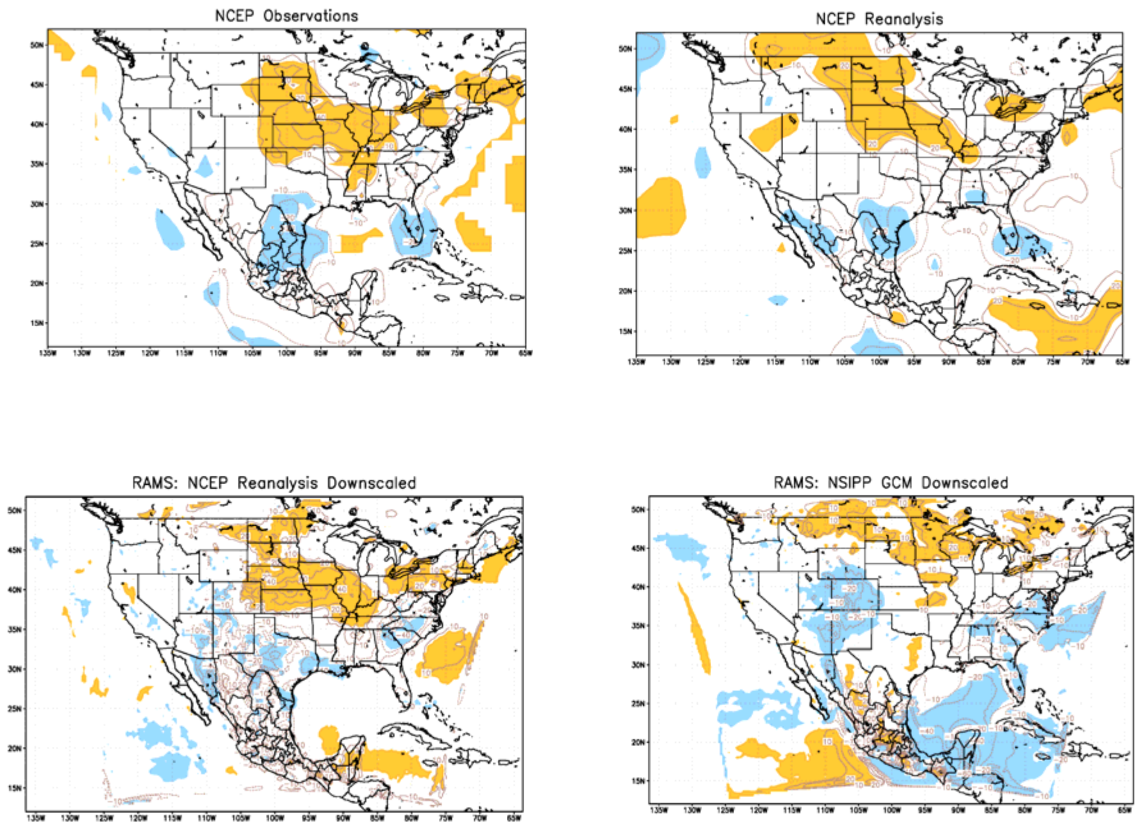

Figure 7: July precipitation anomaly (mm) for positive PDO years in NCEP observations, NCEP Reanalysis, and RAMS downscaling simulations. Blue and orange shading indicate statistical significance at the 80% level and above.

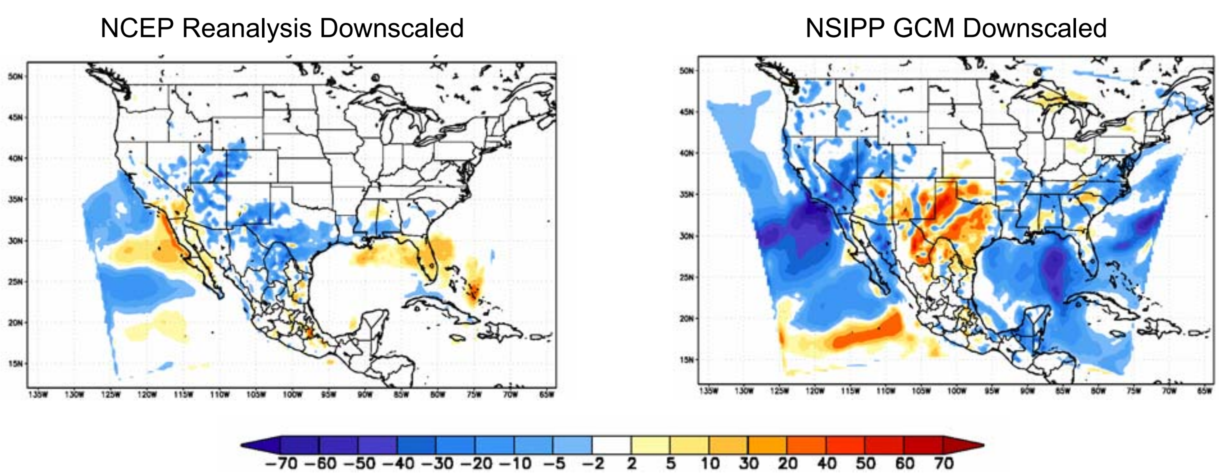

Figure 8: Percentage change in variance of July synoptic component of moisture flux convergence, high PDO years.

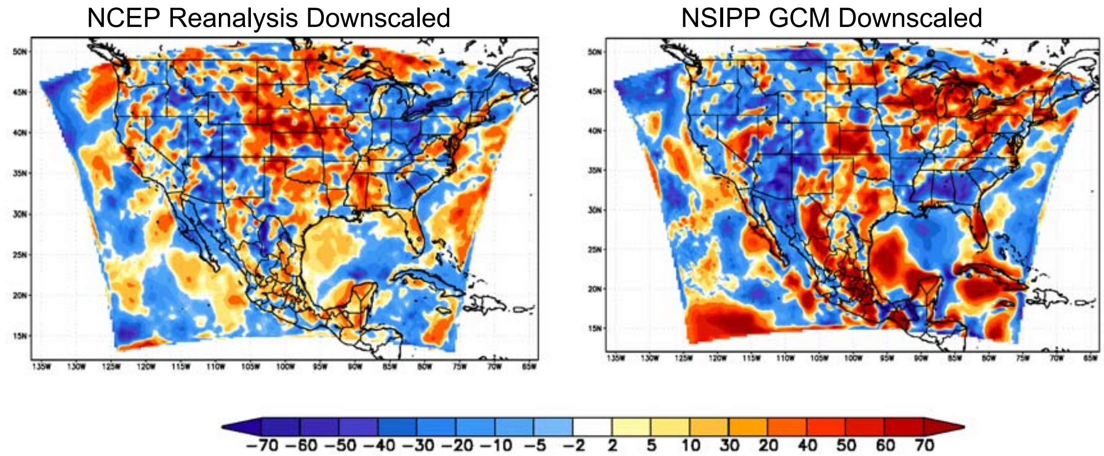

Figure 9: Same as Fig. 8 for diurnal component of moisture flux convergence.