Simulation of the North American Monsoon in Different Pacific SST Regimes Using RAMS

Christopher L. Castro*, Roger A. Pielke, Sr., and Glen E. Liston
Department of Atmospheric Science
Colorado State University, Fort Collins, CO

1. Background and Modeling Issues

The North American Monsoon System (NAMS) is a principal feature of summer climate in the western U.S. and Mexico. Castro et al. (2001) showed that different time evolving teleconnection patterns related to tropical and North Pacific SSTs exist during the NAMS onset period in the Southwest U.S. (late June, early July). At this time, the Pacific Transition and East Pacific patterns govern monsoon ridge position and modulate the climatological transition period from the pre-monsoon to monsoon regimes. El Niño (La Niña) and a high (low) phase of the North Pacific (or Pacific Decadal) Oscillation are associated with a late (early) monsoon onset in the Southwest and protracted (shortened) late spring wet period in the Great Plains. These features are seen in reanalysis atmospheric moisture and coop station precipitation.

The most archetypal years in the past two decades illustrating these idealized climatological relationships in different Pacific SST regimes are 1988 and 1993, respectively. These were years of severe drought or flooding conditions in the Great Plains and very early (late June) or late (early August) NAMS onset in the Southwest. These years have already been extensively studied from both modeling and observational perspectives, and so are the most logical years to test whether a regional model can reproduce the differences in NAMS evolution.

The earlier observational NAMS studies by Castro et al. (2001) and others pose two important unresolved questions. First, what are the controls on NAMS evolution and how do these influences vary with time? Pacific SST forcing via teleconnection patterns seems to govern NAMS onset, but what about the land surface forcing factors of snow cover, soil moisture, and vegetation? It has been suggested that antecedent snow cover in the Southwest affects the subsequent summer surface energy budget, and hence NAMS onset (Gutzler and Preston 1997). Soil moisture sensitivity experiments with the MM5 model seem to confirm this hypothesis and also suggest that local soil moisture anomalies may have a positive feedback with NAMS rainfall (Small 2001). Do these land surface factors become the dominant controls on monsoon evolution in the latter part of NAMS (late July, August)? Second, do the teleconnection patterns affect regional hydrometeorological features responsible for NAMS rainfall, such as low-level jets (LLJ) and local convection? While the observational studies hint that this is indeed the case, atmospheric reanalyses are too poorly resolved to capture these critical monsoon features. A regional forecast model run in a retrospective seasonal weather simulation mode is essential to investigate such questions and provide sound physical bases for data gathering and observational validation.

* Corresponding author address: Christopher L. Castro, Department of Atmospheric Science, Colorado State University, Fort Collins, CO 80523
E-mail: chris@atmos.colostate.edu

2. Model Description

In this work, we use the Regional Atmospheric Modeling System (RAMS), Version 4.3.0, originally developed at Colorado State University (Pielke et al. 1992). The pertinent features of RAMS include telescoping two-way interactive nested grids, the LEAF-2 land surface energy balance submodel, explicit microphysics which resolve liquid and ice processes related to clouds and precipitation, and the Chen and Cotton radiation scheme which accounts for liquid water in clouds. RAMS has been extensively used to simulate mesoscale atmospheric phenomena primarily on short time scales, though it has also demonstrated success in a retrospective seasonal weather simulation mode (Liston and Pielke 2001).

Several modifications to RAMS have been made for seasonal weather simulation over large domains and coarse grid spacing. For the land surface, we use variable soil types according the FAO classification and variable soil moisture initialization using a climatology derived from the Global Soil Wetness Project. Year-specific Reynolds SSTs replace the standard RAMS SST climatology. The Kain-Fritsch (KF) cumulus parameterization scheme (Kain and Fritsch 1993) has been added as a new alternative to the Kuo scheme, which was previously the only deep cumulus convection scheme available in the model. The KF module is the same as that used in the experimental version of the ETA forecast model at the National Severe Storms Laboratory.

3. Simulation Design

The RAMS NAMS simulations were performed on two grids, each with 30 vertical levels (Fig. 1). The course grid has 100 km grid spacing and the nested grid, which covers all of Mexico and most of the western U.S., has 33 km grid spacing. Two sets of simulations were performed. The first set is retrospective seasonal weather simulations of 1988 and 1993 using KF and full microphysics. These simulations are three months in length, from June through August. These simulations should ideally be about six months or more in length to obtain a realistic soil moisture distribution, but the model run time was limited by computing constraints. The second set is one-month simulations of July 1988 comparing the KF and Kuo cumulus parameterization schemes. All the simulations use the NCEP-NCAR reanalysis as the lateral boundary condition.

4. Comparison of Convection Schemes

Fig. 2 shows the comparison of KF and Kuo cumulus parameterization schemes to the NCEP coop observed 0.25° gridded precipitation dataset for July 1988. The Kuo scheme has significant problems in the simulation of summer precipitation in the U.S. In areas of steep terrain gradients, such as Arizona and New Mexico, the scheme overpredicts convective precipitation. It underpredicts precipitation in the central U.S. Similar simulations of the South American monsoon have revealed the same behavior (A. Beltran, personal communication). The KF scheme precipitation amount and distribution is much closer to observations. The combination of KF and microphysics, however, appears to overestimate NAMS precipitation in Mexico, particularly along the Sierra Madre Occidental with over 100 cm of rainfall in July (not shown). The overestimation of Mexican precipitation may reflect that KF is tuned for convection in the mid-latitudes or that RAMS is overestimating the vertical motion associated with the topographic barrier. Possible adjustments to KF to decrease Mexican monsoon precipitation include decreasing the sensitivity to the convective trigger function, modification of downdraft parameters, a decrease in the assumed cloud radius, and/or an increase in entrainment values (J. Kain and B. Mapes, personal communication).

5. Seasonal simulation results

Here we focus the discussion on the United States, since that region appears to be the most influenced by the Pacific SST associated teleconnection patterns. Fig. 3 shows the diurnal cycle of the integrated moisture flux and convergence over the western and central U.S. for July 1988 and July 1993, respectively. The evolution of moisture flux convergence reflects a diurnal cycle of convection. Convection originates over the regions of elevated terrain during the day (18Z), then propagates toward lowland regions, principally the Great Plains, into the evening and nighttime (0Z to 12Z). In 1993, a strong Great Plains LLJ, associated with a negative phase of the Pacific Transition Pattern, allows the topographically forced convection to propagate into the Great Plains and Midwest as mesoscale convective systems or complexes. By contrast, in 1988, the topographically forced convection still exists, but the thunderstorms weaken as they propagate eastward because a diminished low-level moisture source and unfavorable convective environment.

Because of its proximity near the surface and narrow width, the Baja LLJ and its diurnal cycle are difficult to simulate in an atmospheric model. Current long-term reanalyses and GCMs are unable to resolve this feature. Fig. 4 shows the diurnal cycle of low-level (lowest seven sigma levels) moisture flux for July 1988 . There is an 18Z jet maximum in the northern Gulf of California. The particular location and time of the jet maximum is somewhat consistent with the limited observational data from the previous SWAMP field campaign (Douglas et al. 1995) and simulations from other mesoscale models (Berbery 2001) which project the jet maximum further west in the Gulf and occurring earlier in the day. Subtle differences such as these provide impetus for a more accurate description of the Baja LLJ by observations.

Even given the possible errors in simulation of the Baja LLJ, RAMS does seem able to capture a relationship of the Baja LLJ to large-scale synoptic features. Fig. 5 shows the upper level zonal moisture flux over the Southwest and the corresponding 18Z low level moisture flux in the Colorado River Valley, as a proxy for LLJ activity, for 1988 vs. 1993. Enhanced low level moisture transport into the Southwest U.S. is coincident with easterlies at upper levels, consistent with enhanced easterly wave activity and a strong monsoon ridge. Favorable easterly wave activity leads to an early monsoon onset in 1988, with probable gulf surge events in late June and mid-July. Between 1988 and 1993, the interannual differences in easterly wave activity and low-level moisture transport are most apparent at monsoon onset, in agreement with observations.

Though RAMS demonstrates a good ability to capture NAMS atmospheric circulation features, the model-generated precipitation is sensitive to the initial soil moisture specification. Fig. 6 shows the RAMS simulated vs. NCEP-coop observed precipitation for the monsoon onset period 15 June to 15 July for 1988 and 1993, respectively. The RAMS simulated precipitation is fairly accurate for 1988, and RAMS is able to capture an early monsoon onset in the Southwest U.S. The spatial pattern of precipitation in 1993 is roughly correct in that monsoon onset is delayed in the Southwest and there is a high amount (>25 cm) of precipitation in the central U.S. However, RAMS underestimates the precipitation associated with the Flood of 1993, most likely because of the dry initial soil moisture assumption used.

6. Conclusions

In a regional domain seasonal weather simulation mode, RAMS is a practical tool to investigate the variability of NAMS features, such as low-level jets, diurnal cycles of moisture flux and convergence, the evolution of the monsoon ridge, and convective rainfall (at least in the U.S.). RAMS successfully captures differences between different monsoon-type years associated with Pacific SSTs in a way consistent with observations. The KF scheme improves model-simulated precipitation for mid-latitude regions. Further modifications to KF are required, however, to accurately simulate tropical rainfall. RAMS generated precipitation is sensitive to the initial soil moisture specification, particularly in the summertime.

7. Acknowledgments

Current regional modeling simulations of the NAMS with RAMS are funded by NOAA grant NA67RJ0152, Amendment 31, and NASA grant NGT5-30344. The NAMS observational study was partially funded through the Significant Opportunities in Atmospheric Research and Science Program (SOARS) through the University Corporation for Atmospheric Research and the National Science Foundation.

8. Selected References

Castro, C.L., T.B. McKee, and R.A. Pielke, Sr., 2001. The Relationship of the North American Monsoon to Tropical and North Pacific Sea Surface Temperatures as Revealed by Observational Analyses, *J. Climate*, **14**, 4449-4473.

Berbery, E.H., 2001. Mesoscale moisture analysis of the North American Monsoon. *J. Climate*, **14**, 121-137.

Douglas, M.W., 1995. The Summertime Low-Level Jet Over the Gulf of California. *Mon. Wea. Rev.*, **123**, 2234-2347.

Gutlzer, D.S., and J.W. Preston, 1997. Evidence for a relationship between spring snow cover in North America and summer rainfall in New Mexico. *Geophys. Res. Lett.*, **24**, 2207-2210.

Kain, J.S., and J.M. Fritsch, 1993. Convective parameterization for mesoscale models: The Kain-Fritsch scheme. *The representation of cumulus convection in numerical models*. Meteor. Monogr., No. 24., Amer. Meteor. Soc., 165-170.

Liston, G.E., and R.A. Pielke, Sr., 2001. A Climate Version of the Regional Atmospheric Modeling System. *Theor. And Appl. Climatol.*, **68**, 155-173.

Pielke, R.A., et al., 1992. A Comprehensive meteorological modeling system—RAMS. *Meteor. Atmos. Phys.*, **49**, 69-91.

Small, E.E., 2001. The influence of soil moisture anomalies on variability of the North American Monsoon system. *Geophys. Res. Lett.*, **28**, 139-142

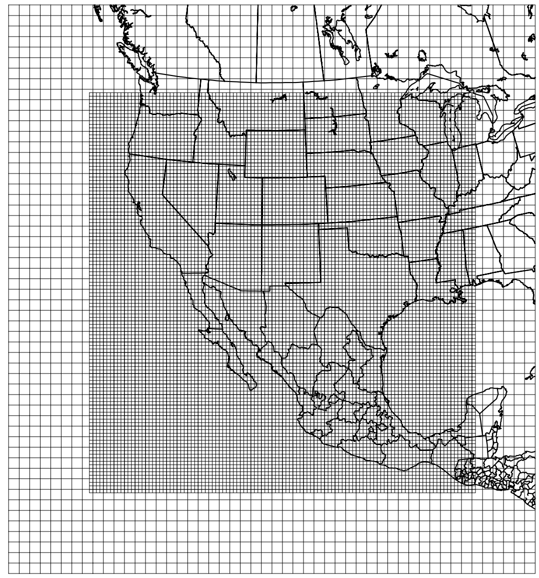

Figure 1: RAMS domain for NAMS simulations. The course grid spacing is 100 km and the nested grid is 33 km.

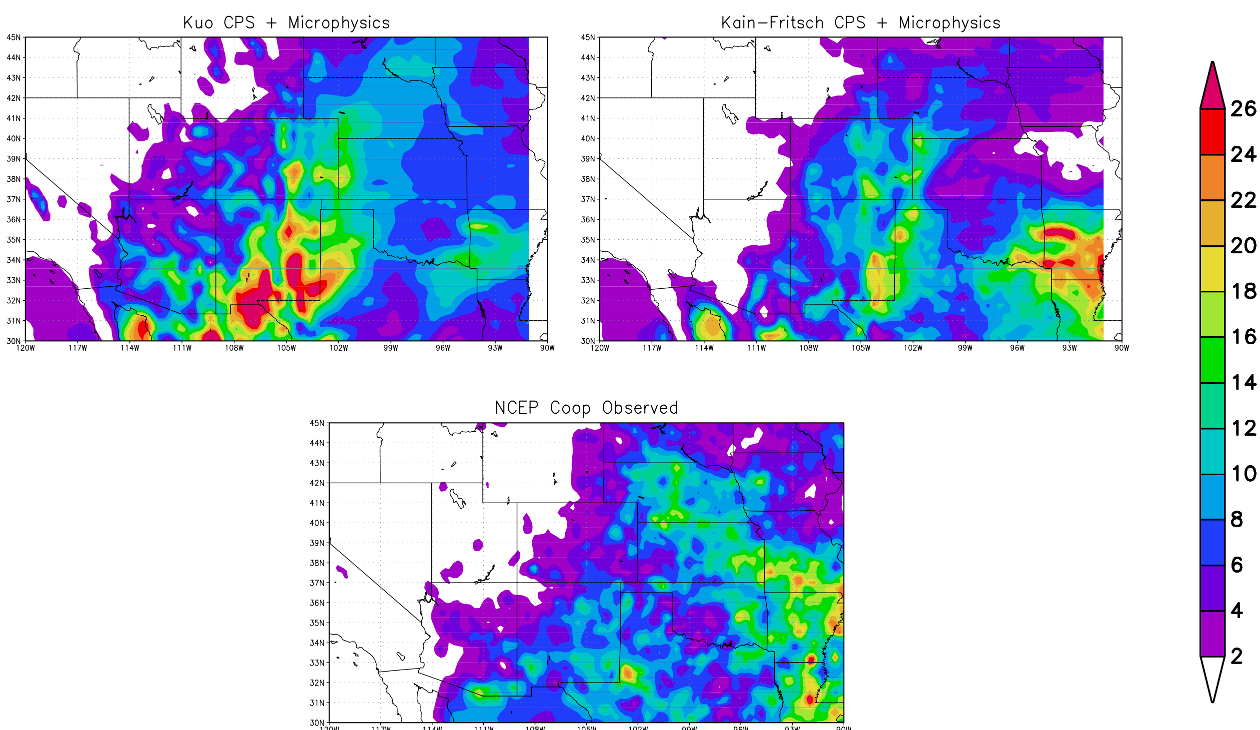

Figure 2: Kuo versus Kain-Fritsch cumulus parameterization schemes in RAMS as compared to NCEP quarter-degree coop observations over western and central U.S. Precipitation totals (cm) for July, 1988.

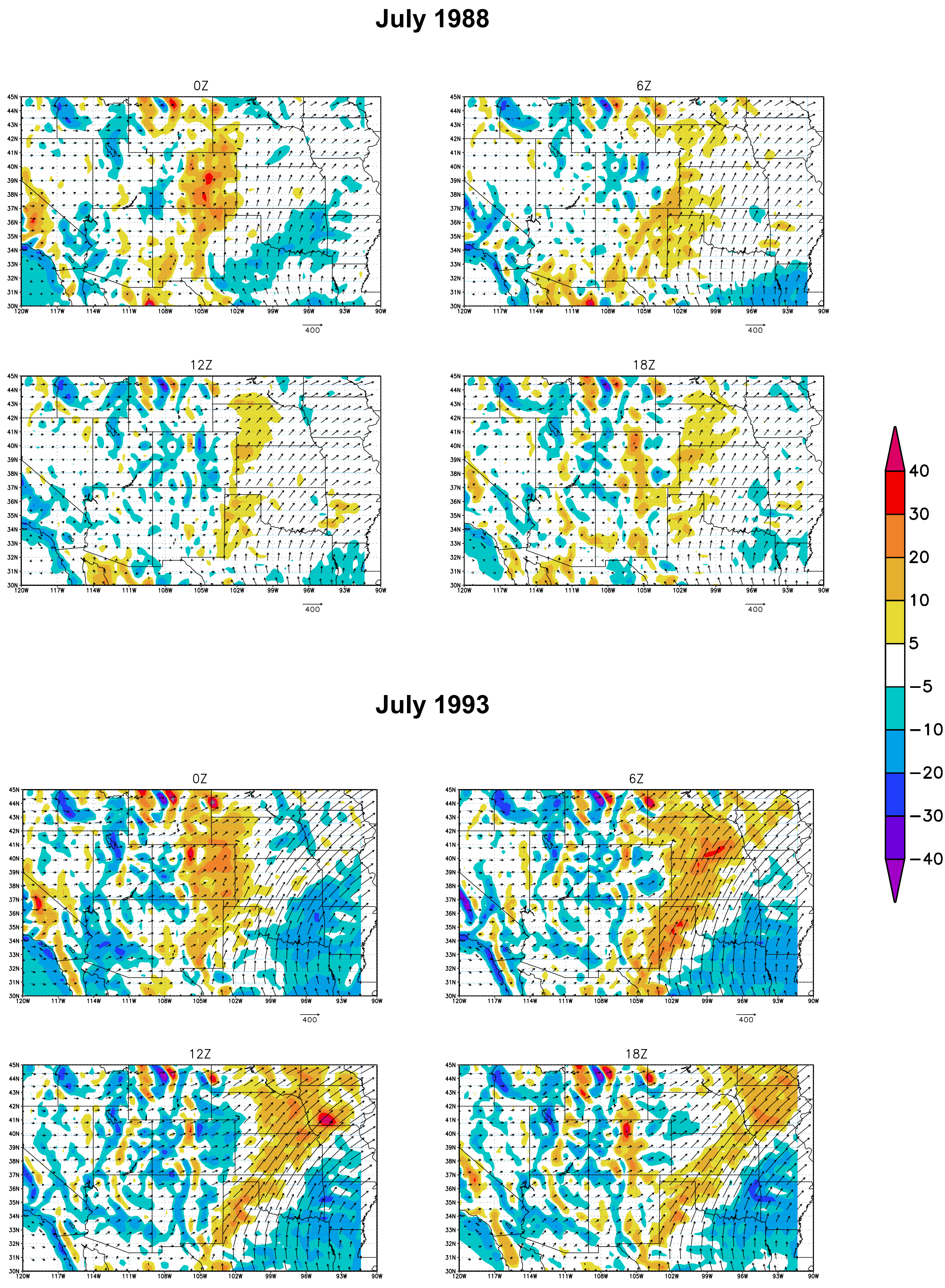

Figure 3: Diurnal cycle of integrated moisture flux (kg m s^{-1})and convergence (mm day^{-1}) for July 1988 and July 1993 RAMS simulations. Standard synoptic analysis times shown. Vector length is 400 kg m s^{-1}.

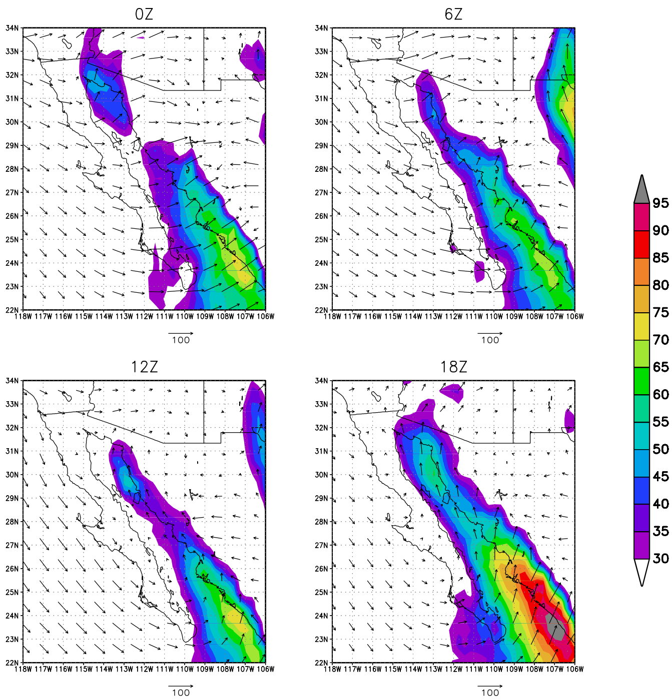

Figure 4: RAMS-simulated diurnal cycle of low-level integrated moisture flux (kg m s^{-1}) in the Gulf of California for standard synoptic analysis times. Meridional component shaded.

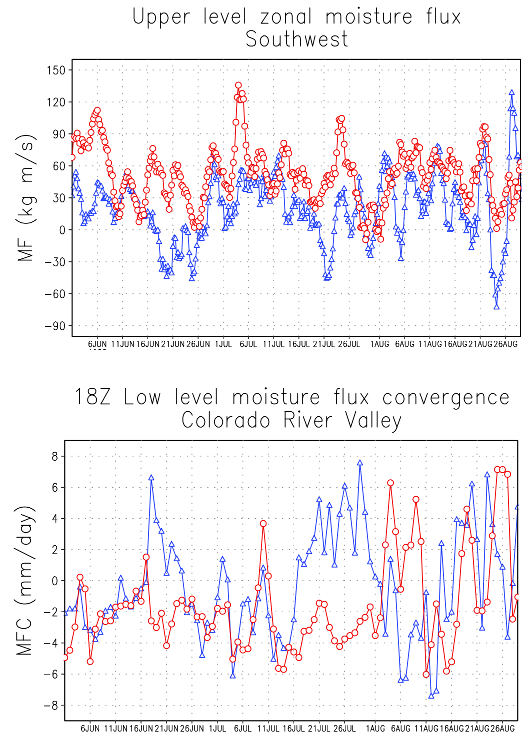

Figure 5: Evolution of upper level zonal moisture flux (kg m s^{-1}) over the Southwest and 18Z low-level moisture flux convergence (mm day^{-1}) in the Colorado River Valley for 1988 (blue) and 1993 (red) simulations.

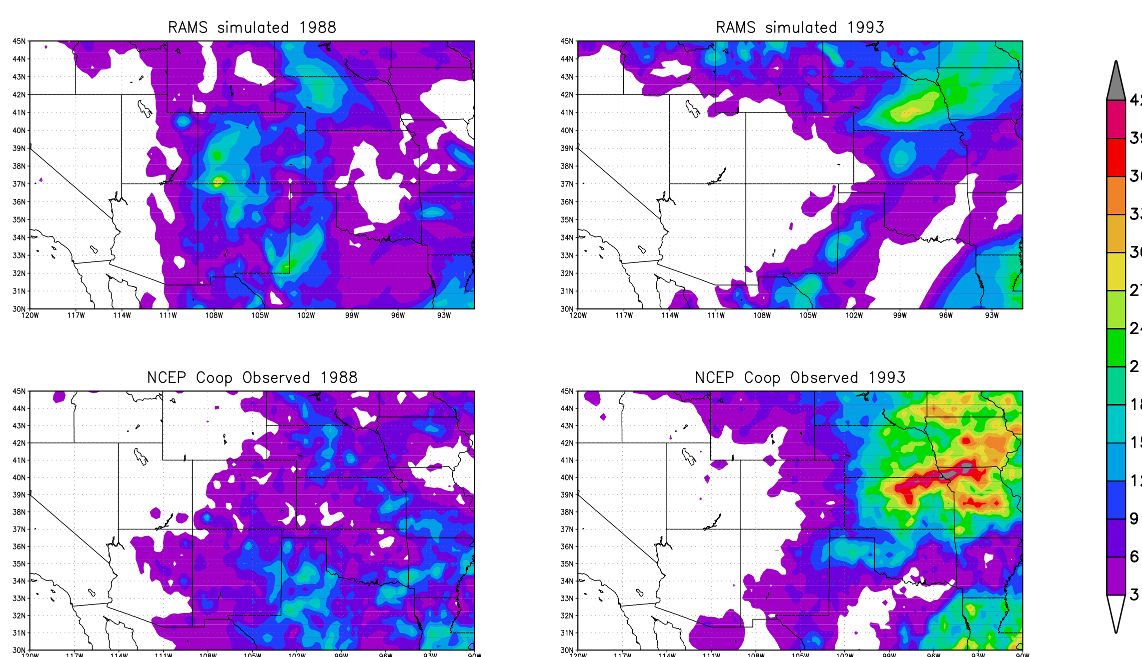

Figure 6: RAMS-simulated precipitation (cm) for monsoon onset period 15 June – 15 July, 1988 and 1993, versus NCEP quarter-degree observations.