THE NORTH AMERICAN MONSOON SYSTEM

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Abstract

This paper examines major features of the North American Monsoon System (NAMS). The summertime circulation shows upper-level anticyclone/low-level heat low structures. In a companion papers Mechoso et al., (2005) compare the North and South American monsoons and Grimm et al., (2005) discuss the South American monsoon. This paper reviews recent research on the NAMS and summarizes hypothesized mechanisms associated with NAMS rainfall and sources of moisture for this rainfall. No single rainfall mechanism is seen to be dominant. Numerical model simulations indicate modest potential predictability when forced by observed sea surface temperature. We suggest that the large scale boundary forcing provides some degree of “conditioning” to all or the majority of these precipitation mechanisms. From this perspective the large-scale boundary forcing associated with SST anomalies can provide some modest shifts to the probability distribution of the occurrence or effectiveness of the phenomena related to NAMS rainfall. The hemisphere-scale aspects of the NAMS and possible relationships to the South American Monsoon require further study.

1. Introduction

The North American Monsoon System (NAMS) contains all of the elements of the much larger and stronger Asian Monsoon system, Mechoso et al. (2005), but on a smaller scale. Other major seasonal circulation features, primarily the evolution of the Bermuda high and its westward extension, also vie for importance in shaping the character of summer precipitation in the North America. Nonetheless the NAMS is a critical feature of the climate in western Mexico and parts of the southwestern United States. The monsoon accounts for at least 50% of the summer rainfall for much of western Mexico from near 20°N through the states of Nayarit, Sinaloa and Sanora, Adams and Comrie (1997), and nearly 40% of seasonal rainfall in southern Arizona and New Mexico in the United States, Fig 1. Some locations in Mexico receive as much as 70% or their annual rainfall associated with the NAMS during July, August and September (e.g. Douglas et al 1993).
While the bulk of the monsoon rains fall from July through September agriculture in southwestern Mexico is sensitive to the onset of the monsoon rains in June. The NAMS region has experienced a dramatic population growth over the past 20 years along with an increase in manufacturing and land under cultivation making the entire area more sensitive to year-to-year variations in monsoon rainfall and more vulnerable to monsoon failures. Variability in the NAMS rains have also been related to variations in the threat of wildfires as well as being a factor in public health including Valley Fever and more recently dengue, Ray et al. (2003). Thus NAMS, like its larger and stronger counterparts, has a profound impact over a substantial population influenced by its evolution.

Fig 1. Percent of annual rainfall falling in the heart of the North American Monsoon season (July, August, September). The 50% level is shown in dark green, CAMS_OPI data, Xie and Arkin (1997).

2. Characteristics of the North American Monsoon System (NAMS)

The NAMS shares many of the characteristics of its larger and more powerful monsoonal siblings in Asia and Africa and its Western Hemisphere counterpart in South America. On each of these continents the monsoon rainfall occurs during the summer season, has a distinct onset and a less distinct demise, and is accompanied by significant changes in large-scale atmospheric circulation fields. While the NAMS rains are not as impressive as those associated with the monsoons in Africa and Asia (accounting for only 50% to 70% of the annual total rainfall compared to large areas that experience 80% of the seasonal totals in the latter regions) the NAMS rains are indeed important. Some earlier monsoon studies (e.g. Ramage 1971) did not include NAMS and its South American counterpart (see Grimm et al., 2005). However, both have many circulation components in common with the Asian and African monsoon systems and many researchers include the North and South American monsoons in their definitions of the phenomenon. Most notably each of the monsoon areas are, to first approximation, a manifestation of the reversals of low level temperature gradients generally associated with the seasonal shifts in insolation i.e. for the most part they are initiated by the changes in differential heating between a land mass and adjacent oceans associated with the changes in seasons. The concomitant development of a surface low-pressure system is also accompanied by the development of an upper level monsoon anticyclone and seasonal summer rainfall.

While there are numerous similarities among Earth’s monsoonal climate regimes, plate tectonics have provided climate scientists with a set of four very different land-sea configurations, which can be viewed as interesting natural experiments, to help develop our understanding of monsoon systems. Both the African and Asian Monsoon systems have water to the south and land to the north, with no
significant elevated heat source (mountains) in the former case and the largest mountains on earth in the latter. In the Western Hemisphere monsoon systems the mountains are oriented primarily north-south. Moisture for the South American monsoon has its origins in easterly trade wind circulations rooted in the Atlantic Ocean (Grimm et al. 2005). The oceanic pole of the North American monsoon circulation is by comparison extremely complex, with important roles played by the Gulf of Mexico, Pacific Ocean, and much smaller Gulf of California. This complexity is associated with an unresolved debate over the oceanic sources of atmospheric moisture for the NAMS, as discussed below. Study of the similarities and differences among the monsoon systems can provide clues to the physical mechanisms associated with monsoon generation, demise and interannual variability.

A. Evolution of the NAMS Mean Circulation Features

1.) The Upper Level Circulation

The evolution of the NAMS atmospheric circulation patterns is influenced by the complex topography over the region, Fig 2. Prominent geographic features include: the Gulf of California, defined to the west by the Baja California peninsula, and to the east by the Mexican mainland and Sierra Madre mountains which rise to above 2000m throughout much of central Mexico. The western slopes of the Sierra Madre Occidental effectively channel and confine low-level flow from the south-southeast up the Gulf of California towards the north-northwest into the southwest United States. The eastern mountain slopes (Sierra Madre Oriental) provide a barrier to low-level flow and direct low level moisture transport from the Gulf of Mexico into the monsoon region. The high topography of central Mexico also promotes vertical transport of moisture into the middle troposphere via the deep convective mixing associated with orographically triggered thunderstorms.

![Digital elevation map for the North American Monsoon system region. Based on data from the GLOBE data set, Hastings and Dunbar (1998).](image)

Because of the complex terrain in the land areas under the influence of the NAMS the evolution of the monsoon is most evident in the 200-hPa circulation. Prior to the start of the monsoon the flow is primarily zonal. During late May to early June the zonal flow begins to evolve with the formation of a monsoon-like anticyclone, centered near 15°N just to the south of Mexico, Fig 3a. Even at these early stages the 200-hPa ridge axis, though weak, extends northward into Canada. By July the mean position of the anticyclone migrates north and is centered over the Sonora desert near the border of
Mexico and the United States, Fig 3b. In a 500 hPa composite analysis Higgins et al (1997) suggest that the formation of a downstream trough to the lee of the Rocky Mountains and extending into the central United States is a part of the NAMS. During August the monsoon anticyclone continues to strengthen, in the mean, with a stronger ridge to the north and a suggestion of upper-level confluent flow northward to the Canadian border, Fig 3c. By August the mean 200-hPa anticyclone dominates the climatological circulation pattern from the Pacific Coast eastward through the Gulf of Mexico. In September the 200-hPa anticyclone moves southward and diminishes in size signaling the demise of the monsoon, Fig 3d. By October (not shown) the mean flow becomes essentially zonal over the NAMS region and remains so until the beginning of the next monsoon season. While these features are quite evident in the mean 200-hPa circulation, the evolution of the NAMS for a particular individual year shows considerable interannual variability.

2.) Mean Low-level Circulation

As mentioned above, Baja California to the west, the Sierra Madres to the east and the Rockies, the Sierra Nevadas and Colorado Plateau to the north complicate the low-level circulation patterns over much of the NAMS region (see Fig. 2). This string of mountain ranges and the high plateau form barriers to circulation features below 700 hPa where most of the atmospheric moisture resides. This has led to some debate, summarized in Adams and Comrie (1997), as to the source of the moisture for the NAMS rainfall. We will return to this question below. In this section we simply describe the mean circulation features of the lower atmosphere.

The area of the Pacific Ocean immediately to the west of the NAMS region is generally characterized by high pressure and anticyclonic circulation that form part of the mean summer subtropical high pressure belt. Sinking motion to the west of the NAMS precipitation may enhance the strength of the high pressure as discussed in Mechoso et al. (2005). Northerly winds on the eastern flank of the anticyclonic mid-latitude circulation are associated with coastal upwelling along western
North America. The northerly flow extends to Baja California through the Northern Hemisphere winter but diminishes in strength during the spring and summer. By June the mean northerlies are well off the coast and the low level mean circulation becomes relatively weak along the Mexican coast for the remainder of the summer, Fig 4a through 4d. Conversely, in the Gulf of Mexico strong low-level easterly and southeasterly flow develops during the spring, feeding moisture into the low level jet over the Great Plains to the lee of the Rockies, Fig 4a. During the late spring and early summer a relative low pressure area develops under the 200-hPa anticyclone discussed above. This is manifest in the NCEP/NCAR Reanalysis pressure fields by a col over the Sonora Desert (not shown) and by light and variable winds at 850 hPa, Fig 4a.

The mean 850-hPa wind and moisture fields illustrate some of the fundamental challenges in understanding the moisture transport mechanisms associated with NAMS rainfall. The strongest low level winds and by implication the strongest low level moisture transports are to the east of the main NAMS monsoon rain areas. The mean low level winds are strongest in regions of relatively weak moisture gradients i.e. to the east of the Sierra Madre mountains and, in contrast, strong low level moisture gradients appear along the west coast of Mexico in a region where the NCEP/NCAR Reanalysis shows the mean wind fields to be near zero during each month of the monsoon season, Figs 4a-d. If the moisture for monsoon rainfall comes from the Pacific this suggests that the NAMS precipitation results primarily from transients. (We note that some analyses suggest a strong mean low level southerly jet extending along the entire length of the Gulf of California but there is not a strong observational consensus with respect to the detailed spatial extent and temporal variability of this low level jet. This feature is the subject of ongoing research.)

A close look at the topography, moisture gradients and winds in northern Mexico lends support to the view that some portion of the NAMS precipitation may be fed by moisture from the east. (Note,
however, that only a relatively small area is below 2000m along the Mexico-United States border in Figs 4a-d). Schmitz and Mullen (1996) using ECMWF analyses and Higgins et al. (1997) using NCEP/NCAR Reanalysis suggest that moisture enters into the NAMS region from the east i.e., from the Gulf of Mexico above 850 hPa. On the other hand, given the sparseness of input data and the scale of the NCEP/NCAR and ECMWF analyses the details of the wind and moisture fields may be somewhat uncertain. Current mesoscale modeling efforts are expected to help better define the source regions of the moisture needed to sustain the monsoon rains.

B. Mean Evolution of NAMS Monsoon Rainfall

The bulk of the summer (July to September) rainfall in the region falls over the ocean with maximum amounts centered near 10°N and 105°W, Yu and Wallace (2000), Higgins and Shi (2001). This rainfall is associated with the northward progression of the Inter-Tropical Convergence Zone (ITCZ) and can be viewed in that context. However, an argument can be made that the contrast between the relatively high sea surface temperatures (SSTs), coinciding with the areas of maximum rainfall, and the relatively cold waters to the south, constitute a “classic” thermally direct monsoon system, but with a major component over water. Presumably the associated subsidence region(s) would be on the northern flank of precipitation maximum, over the stratus decks off of the California coast and/or on the southern flank of the precipitation maximum off of the west coast of South America. Most studies of NAMS precipitation concentrate on the precipitation that falls over the land areas of North America while acknowledging that the continental rainfall is a relatively small portion of the total rainfall regime in the NAMS. The description below follows this convention.

Figure 5. Mean North American Monsoon onset date based on 5-day satellite estimated rainfall, from Janowiak and Xie (2003). The shading represents the standard deviation of the onset dates in days.
Figure 6. Evolution of the North American Monsoon rainfall based on CMAP, Janowiak and Xie (1999) range 0 to 10 mm/day.

Figure 7. Mean Diurnal cycle of rainfall June to August 2003, Joyce et al. 2004.
By mid-to-late June the continental monsoon rain is generally evident near 20°N in Nayarit State in Mexico and proceeds fairly rapidly to the north. Satellite-based precipitation analysis suggests that once underway the monsoon precipitation progresses from the east along the Sierra Madre Occidental, towards the west, Fig 5, Janowiak and Xie (2003). The same analysis suggests that the monsoon rainy season has about a 100-day duration, lasting essentially from late June through September, over much of the core monsoon region over land. The June monsoon rainfall is relatively modest even in Mexico, Fig 6a, but by July the rainfall has lined up from west central Mexico northward into the United States, Fig 6b. August is the rainiest monsoon month over much of the region, Fig 6c, but by September the rains have substantially retreated to the south, Fig 6d. Generally drier conditions return to the region by October (not shown). Barlow et al (1998) note that the rapid June to July increase in monsoon rainfall is coincident with dramatic decreases in the U.S. central plains. This suggests that the influence of the NAMS may extend into the central U.S., beyond the areas directly involved in evolution of the monsoon rainfall.

The monsoon rainfall has a large diurnal component over the Sierra Madre Occidental, Fig 7. Satellite estimates suggests that rainfall amounts peak in the mountains in late afternoon with the time of maximum rainfall becoming later to the west and a tendency for late evening to near midnight local maxima for locations on the Gulf of California. The diurnal variability is not completely understood and is likely related to the rainfall mechanisms discussed in the following section.

C. Rainfall Mechanisms

Studies of the continental monsoon rainfall have suggested several dynamical mechanisms that may modulate rainfall, including pressure “surges”, easterly waves, tropical storms, and intra-seasonal variability associated with the Madden-Julian Oscillation (MJO). No one of these mechanisms appears, by itself, to explain the bulk of the monsoon rainfall and its variability. There is an emerging consensus that rainfall over the continental portions of the monsoon regions is associated with transients rather than the mean flow. Berbery (2001) analyzed the Eta Model’s seasonal mean and transient moisture flux at 950 hPa and suggested that the mean flow may actually be northerly along the southern half of the Gulf of California while the transients, though weaker, show northward transports of moisture flux into the monsoon rainfall regions. If the transients are the primary NAMS rainfall producers, the relative climatological contributions of various transient phenomena (Gulf surges, easterly waves, tropical storms, intraseasonal variability like the MJO) are still not clear. Further discussions of mesoscale processes in Monsoons can be found in Johnson (2005).

Tropical storms are one transient rainfall phenomenon that certainly brings abundant rainfall to the region (Englehart and Douglas 2001). There is no doubt that substantial amounts of summer monsoon rainfall in western Mexico and into the southwest United States is associated with tropical storms during some years. However, these storms are episodic and do not affect the entire NAMS region during every monsoon season.

Gulf surges are pulses of southerly winds that transport moisture up the Gulf of California. While the surge phenomenon is well documented (Stensrud et al. 1997), the link between Gulf surges and rainfall, particularly along the northern extent of the monsoon is not strong e.g. Mechoso et al., (2005). It has been hypothesized that the surges may be related to the occurrence of easterly waves propagating across the Gulf of Mexico. Fuller and Stensrud (2000) further suggest that the easterly waves are most effective in producing surges if they are properly in phase with the passage of mid-latitude troughs. While their study suggests that this mechanism may account for some of the monsoon rainfall, the required phasing of all of the elements suggests that it can’t be the sole, or even primary, mechanism.

Thus there is no strong evidence for the dominance of any of these transient phenomena in producing NAMS rainfall. It is possible that there is no overall dominant transient rainfall mechanism
but that each mechanism contributes to the rainfall and the relative contributions for any particular season is random.

As mentioned above the continental component of the monsoon rains is a relatively small fraction of the total rainfall associated with this phenomenon. Studies that include the portion of the NAMS rainfall over oceans suggest that both the El Nino/Southern Oscillation and the Madden-Julian Oscillation (MJO) i.e., intraseasonal variability may influence rainfall over the NAMS region. Higgins and Shi (2001) show correlations between seasonal monsoon rainfall and ENSO as well as with intraseasonal variability. On the other hand, in an analysis based on monthly data, Yu and Wallace (2000) could find no strong link between the oceanic component of the rainfall and ENSO (the El Nino/Southern Oscillation) phenomenon except for a tendency towards broadening of the principal rainfall band during warm, El Nino, conditions and contraction or sharpening of that band during cold, La Nina, conditions. To the extent that ENSO has some influence over the NAMS precipitation, its influence appears to be very modest over continental regions, confined to the southern portion of the NAMS domain (Gutzler 2004).

3. Modeling Studies

As mentioned above, the North American Monsoon System (NAMS) is modest in the extent and amplitude of its precipitation maximum, and exhibits a much less pronounced seasonal wind reversal, compared to Earth's other monsoons. Nevertheless the seasonal evolution of the NAMS serves to organize warm season precipitation across the entire North American continent including areas not usually associated with the core monsoon development such as the U. S. Great Plains. The continental geometry of North America, featuring distinct oceanic moisture sources both to the east and west of the monsoon precipitation maximum with steep, high topography in between, forces extremely sharp gradients of precipitation around the periphery of the NAMS domain. The Gulf of Mexico on the eastern side of the domain feeds moisture both into the highly elevated southwestern region of the North American continent (the monsoonal domain), as well northward into the heartland of the United States, where the continent is quite flat and the seasonal precipitation maximum occurs in springtime.

Capturing these climatological features poses an extreme challenge for dynamical models. Proper simulation of the warm season precipitation regime across North America must:

1) Include a realistic description of the seasonal evolution and spatial distribution of precipitation in the core of the monsoon region in northwestern Mexico. The presence of high topography very close to the coastline tends to generate circulations with an extremely high-amplitude diurnal cycle.

2) Capture the observed evolution of continental scale features around the periphery of the NAMS domain. These include the diminution of moisture transport and precipitation in the central U.S. (associated with shifts in the Atlantic subtropical High), and the shifting and strengthening of the Pacific subtropical High, as the NAMS ramps up.

3) Reproduce the proper linkages to synoptic and large-scale tropical features to the south and east of the monsoon domain, including interannual shifts in the amplitude and position of the Pacific ITCZ, and synoptic-scale circulation anomalies such as the Madden-Julian Oscillation (MJO), easterly waves and tropical cyclones.

Regarding point (1), the sharp spatial gradients in precipitation associated with the NAMS have proven especially difficult to model (Gutzler et al. 2004). In the core of the monsoon region, the summer precipitation maximum occurs along the slopes of the Sierra Madre Occidental, on the eastern side of the Sea of Cortes (the Gulf of California). The interaction of steep orography, diurnal land-ocean circulations, and atmospheric buoyancy is quite complicated and generally not well simulated by existing treatments of deep convection in models. On the western side of the Gulf of California, not much more than 100 km away, summer precipitation is very sparse, the Pacific
subtropical High dominates the circulation, and most precipitation falls in winter. Simulated precipitation rates in the core of the NAMS domain have been shown to be sensitive to choice of convective parameterization and boundary layer treatment in atmospheric models, as well as being very sensitive to both land surface treatment and SST in the Gulf of California (e.g. Mitchell et al. 2002; Gochis et al. 2002; Matsui et al. 2003; Kanamitsu and Mo 2003)

Large-scale models have demonstrated some fidelity in simulating the continental features listed in point (2), but these features are sensitive to the precipitation rates (hence tropospheric heating) in the monsoon core. Improvements in continental-scale simulation, and thereby dynamical seasonal-interannual climate prediction, would therefore seem to hinge on getting the core monsoon precipitation modeled properly.

With regard to point (3), model improvements and empirical research must be linked, as the relationships between tropical ocean anomalies and the NAMS are still being explored in observations. Robust links between interannual ENSO-related anomalies (and associated meridional shifts in the eastern Pacific ITCZ) and the NAMS are still elusive, as discussed further in the following section. Low frequency intraseasonal variability in the NAMS is very pronounced; some of this variability has tentatively been identified with coherent tropical synoptic variability associated with either the MJO (propagating eastward) and/or easterly waves (propagating westward). Recent empirical studies suggest that tropical cyclones imprint a significant signal on coastal precipitation, especially late in the monsoon season (Englehart and Douglas 2001).

4. Predictability

Even though ENSO tends to be primary source of climate predictability over many regions of the world it does not seem to offer much to predictability over the continental regions of the NAMS domain during the summer, Yu and Wallace (2000), Higgins and Shi (2001), Gutzler (2004). Nevertheless, several numerical models forced by observed sea surface temperatures show modest correlation skill between “forecast” and observed rainfall over the NAMS domain during the July to September season. In particular, the ECHAM3.6, NCEP-MRF9, CCM3.2 and the NASA/Goddard NSIPP models each show NAMS regions with correlations in the order of 0.4 and greater for the 33-year period 1965 to 1997 (on the web, http://iri.columbia.edu/forecast/climate/skill/SkillMap.html). The sources of this modest potential predictability has not been diagnosed but the consistency among the numerical models suggest that at least a part of this predictability is real.

Empirical studies have explored possible relationships between sea surface temperatures in the Gulf of California e.g., Mitchell et al. (2002). In general, these studies rely on sea surface temperature analyses that resolve smaller spatial scales for shorter duration than analyses that are typically available for global models, and thus are limited to a few samples or case studies.

Empirical studies have also suggested that some predictability over portions of the NAMS domain may be associated with winter and spring snow cover, Gutzler and Preston (1997), Gutzler (2000), Lo and Clark (2001) and Matsui et al., (2003). These studies suggest some very limited predictability of NAMS summer precipitation in New Mexico and Arizona associated with snow water equivalent or proxies for this variable. However, these studies relate only to the relatively modest monsoon precipitation on the very northern boundaries on the overall NAMS precipitation regime.

In the absence of any single dominant mechanism associated with NAMS precipitation, but faced with indications of modest potential predictability from models forced by observed sea surface temperature, one might conclude that the large scale boundary forcing provides some degree of “conditioning” to all or the majority of these mechanisms. From this perspective the large-scale boundary forcing associated with SST anomalies can provide some modest shifts to the probability distribution of the occurrence or effectiveness of these phenomena related to NAMS rainfall.
5. Final Remarks

To accelerate progress on the issues outlined above, an international process study called the North American Monsoon Experiment (NAME) has been organized. NAME seeks to improve understanding and predictability of warm season precipitation fluctuations across the continent. The NAME field campaign was held in summer 2004 to make enhanced observations in the heart of the NAMS across Southwest North America. A primary goal of the experiment and the field campaign is to reach better understanding of NAMS rainfall mechanisms and their predictability. In addition, in conjunction with the NAME observational campaign, a focused set of modeling activities is being undertaken to address the simulation challenges outlined above.

A series of complementary activities are also being conducted to better understand the South American Monsoon System (SAMS), e.g., see Grimm et al., 2005. Coordinated study of the similarities and differences between these two monsoon systems may provide insights into the nature of monsoons that could not be obtained through study of either in isolation.

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