

The Path to Improving Predictions of the North American Monsoon

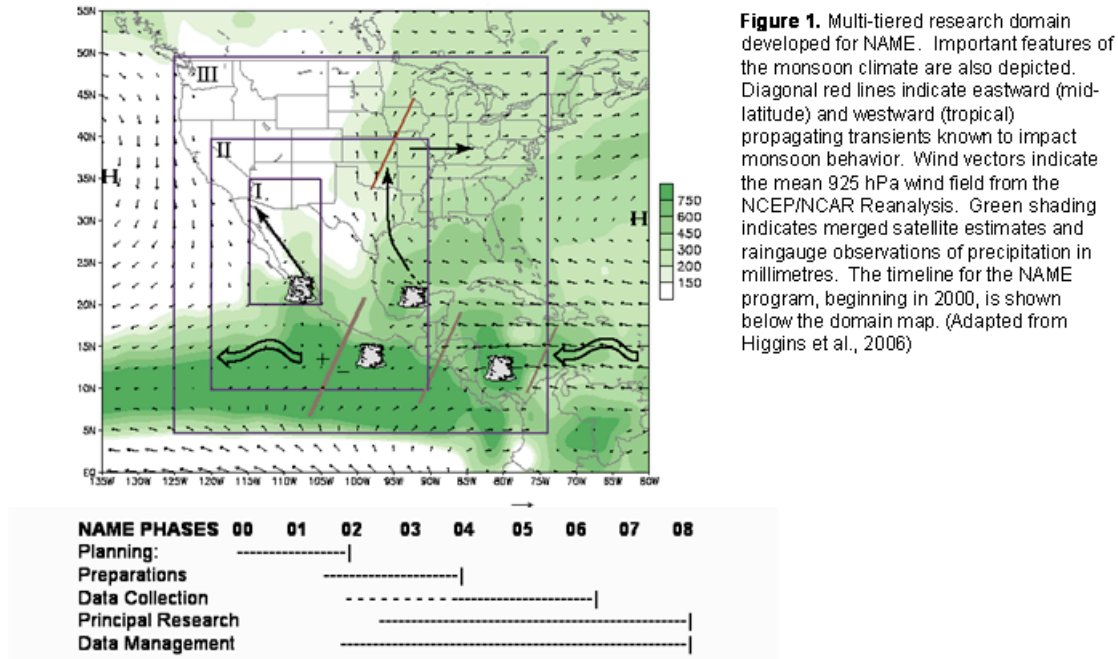
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The North American Monsoon System (NAMS) is considered to be the principle organizing structure for the warm season climate of southwestern North America. Like its global, though often larger, counterparts in Asia, Australia, Africa and South America, the NAMS exhibits marked seasonal reversals in land-ocean thermal contrasts, low and mid-tropospheric wind fields, atmospheric moisture convergence patterns, atmospheric stability and, consequently, precipitation. The seasonal onset, intensity and decay of summer rains drive a host of ecological and societal dependencies ranging from water resources to wildland fire threat to rangeland forage production to energy supply and demand to estuarine fisheries (*cf* Ray et al., 2007; Aragón and García, 2002; Gochis et al., 2006, 2007a). However, also like its global counterparts, prediction skill of warm season rainfall on seasonal to interannual timescales remains critically low. This lack of skill translates into a persistent vulnerability of the aforementioned dependencies that directly impacts the livelihoods and welfare of inhabitants of the monsoon region. The 2006 summer monsoon, which brought persistent heavy rainfall to the U.S.-México border region (Sonora, Chihuahua, Arizona and New Mexico) and tens of millions of dollars in damages, served as a timely reminder of this vulnerability (*cf* FEMA, 2007, CLIMAS, 2006).

The NAME Program:

The North American Monsoon Experiment (NAME) is a continental-scale process study now in its seventh year that was conceived to directly address the issue of improving predictions of warm season precipitation in North America. The NAME program is jointly sponsored by Climate Variability and Predictability (CLIVAR) and Global Energy and Water Cycle Experiment (GEWEX) research efforts. The underlying hypothesis of NAME is that the structure and evolution of the NAMS provides a physical basis for determining the degree of predictability warm season precipitation over much of North America. In particular, NAME seeks improved understanding of the key physical processes that must be parameterized for more realistic simulations and accurate predictions with coupled Ocean-Atmosphere-Land (O-A-L) models. A fundamental first step towards improved prediction is the clear documentation of the major elements of the monsoon system and their variability within the context of the evolving O-A-L annual cycle (Higgins and Gochis, 2007). To achieve this NAME employs a multi-scale (tiered) approach with focused monitoring, diagnostic and modeling activities in the core monsoon region, on the regional-scale and on the continental-scale (Fig. 1). (Additional detail on NAME background information and motivating science questions can be found in Higgins et al., 2006 and NAME-SWG, 2007).



Central to the NAME research effort is a list of science questions posed on the three tiers of the NAME study domain. These questions are aimed at improving the understanding and simulation of 1) warm season convective processes over complex terrain (Tier I), 2) the modes and drivers of intra-seasonal variability (Tier II) and, 3) the response of the NAMS to oceanic and continental boundary conditions (Tier III). The timeline for NAME activities (Fig. 1) encompasses planning, data collection and principle research phases. A progressive aspect of NAME has been that modeling and data assimilation activities were engaged early in planning process in order to guide the observational strategy of a large Enhanced Observing Period (EOP) or, field campaign, which was conducted during the summer of 2004. This coordination insured that the field data collected not only would serve as valuable data for conducting exploratory and diagnostic analysis, but would also directly address problematic modeling issues that had arisen through numerous prior modeling studies. These issues included the structure and evolution of regional moisture flux patterns over the Gulf of California (GoC), air-sea interactions over the GoC and Eastern Pacific, the diurnal cycle of precipitation, upscale organization and propagation of convection, the influence of low-and mid-latitude transients on precipitation episodes and coupling between the land-surface and the atmosphere. The NAME 2004 EOP was organized and conducted by an international coalition of university and agency scientists, and forecasters from México, the U.S. and central America. More than 20 different types of instrument platforms, including surface meteorological stations, radars, aircraft, research vessels, satellites, wind profilers, rawinsondes, pibals, rain gauge networks, soil moisture sensors and GPS integrated water vapor retrieval antennae were deployed within the Tier I and II regions in Figure 1. (Higgins and Gochis, 2007)

The remainder of this article provides a brief overview of the key findings from the 2004 EOP as well as a discussion on current activities aimed at improving predictions of warm

season precipitation over North America. Given the brevity of this summary only a few topics are highlighted. These topics include: Regional circulation around the Gulf of California, Characteristics of NAM Precipitation, and Ocean-Land-Atmosphere Coupling. The summary provided below along with much of the work cited is contained in a forthcoming special issue in the Journal of Climate on NAME due to be published during the late-spring of 2007, and in meeting reports from the NAME SWG from 2005 and 2006 available through the official NAME website. (<http://www.eol.ucar.edu/projects/name/>)

Key Findings from 2004 EOP:

Regional circulation structures around the GoC:

Owing to marked deficiencies in the pre-existing operational sounding network over the NAMS region, characterization of the atmospheric circulation in the Gulf of California region was greatly enhanced during the 2004 NAME EOP. Time mean analyses of NAME 2004 observations, conceptualized in Figure 2, show strong low-level convergence and upper-level divergence along the crest of the Sierra Madre Occidental (SMO) (Johnson et al., 2007). This direct circulation structure, centered over western México, is considered to be the principle driver of the NAMS. Peripherally, strong subsidence was found to persist over the Gulf of California as a result of return flow from sea-breeze/terrain circulation and from flow descending over the SMO (Johnson et al., 2007; Zuidema et al., 2007). Despite the enhanced observing network present during 2004, significant uncertainty in the vertical humidity structure over the complex terrain exists due to lack of surface meteorological and atmospheric observations there.

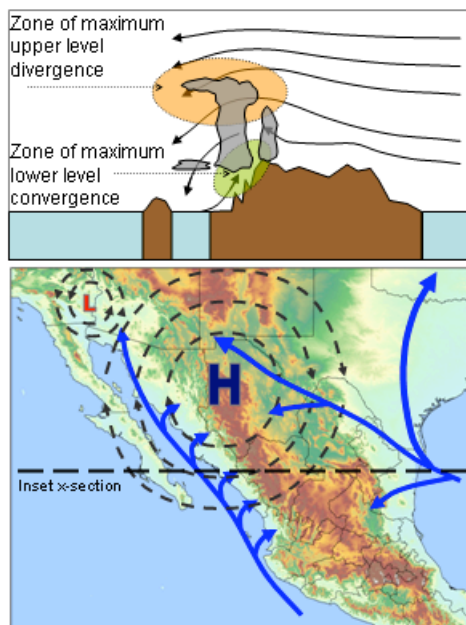


Figure 2. Schematic of regional circulation features of the North American Monsoon. Heavy blue lines in plan view designate principle moisture pathways. 'H' and 'L' indicate climatological positions of the upper-level monsoon anticyclone and the low-level desert thermal low, respectively. Cross-section in top figure is approximated from heavy black dotted line on map. Cloud structures in grey shading approximate those structures diagnosed from various precipitation studies conducted as part of NAME. (Adapted from Johnson et al., 2007, Higgins et al., 2006, Nesbitt and Gochis, 2007)

Flow over the GoC and the western coast of the Mexican mainland was typified by nocturnal low level southeasterly flow and daytime low-level westerly flow inland

towards the SMO. Easterlies tend to persist at middle and upper levels fostering a light to moderately sheared environment over the principle convective region of the western slope of the SMO. Divergence, vertical motion, heating and moistening profiles derived from analyses of the special observations are all consistent with a convectively-dominated dynamical system. (Johnson et al., 2007) Nevertheless, stratiform precipitation structures were frequently observed during nighttime hours and are assumed to play an important role in modifying the regional thermodynamic structure over and around the GOC (Johnson et al., 2007; Zuidema et al., 2007; Williams et al., 2007).

Climatologically, inverted troughs and other synoptic transients such as tropical easterly waves, and westerly mid-latitude troughs are critical features of the NAM (Douglas and Englehart, 2007). Inverted troughs, propagating along the southern limb of the summertime subtropical anticyclone, help advect moisture and provide dynamical support by means of large scale ascent and orographic lift in otherwise dry regions such as the central Mexican Plateau. In addition to having a late onset, synoptic variability during 2004 summer monsoon was characterized by a reduced number of inverted troughs and nearly twice the climatological number of midlatitude westerly troughs (Douglas and Englehart, 2007). The westerly troughs during 2004 were implicated in drier-than-normal conditions in Arizona and northern Sonora but wetter than normal conditions in eastern New Mexico. On interannual timescales the dominance of a particular transient regime significantly influences summer rainfall patterns (Douglas and Englehart, 2007).

Characteristics of Precipitation:

Forcing of the diurnal cycle of winds is supplied by land-sea contrasts and the heating of elevated terrain and these circulations significantly influence the diurnal cycle of precipitation. As a result, precipitation character (e.g. frequency, intensity and duration) is often related to variations in local (O~1-10 km) and regional (O~10-100 km) terrain features, land-sea contrasts and access to abundant atmospheric moisture (Gebremichael et al., 2007; Gochis et al., 2007b; Janowiak et al., 2007; Lang et al., 2007; Vivoni et al., 2007). Numerous studies now confirm a precipitation climatology in which precipitation forms most frequently and earliest in the afternoon over the highest terrain, albeit with comparatively light intensity, and less frequently and later during the evening but with heavier intensities over the low elevation coastal regions. While a large fraction of the regional precipitation climatology is dominated by events whose entire life cycles occur over the complex terrain of the SMO, a secondary, 'disturbed' regime is now recognized under which organized, propagating precipitation events move away from topography (Lang et al., 2007). Radar composite products collected during 2004 also capture the complex interactions between the regional circulation, the land-sea breeze and propagating organized precipitation events over the GoC. Notably, precipitation over the GoC is about 12 hours out of phase with precipitation occurring over the SMO (Lang et al., 2007; Zuidema et al., 2007). Long-lived stratiform precipitation structures, characterized by strong brightband signatures in radar and vertically-pointing profilers, are very significant and, at times, a dominant mechanism for precipitation (Lang et al., 2007; Williams et al., 2007). Retrievals from NOAA wind profilers and space-borne radar show a relatively strong dependence on microphysical structures, in particular

brightbanding (Williams et al., 2007). Strong spatial and temporal variations in cloud thermal and microphysical characteristics present significant challenges in estimating precipitation from remote sensing platforms (Nesbitt and Gochis, 2007).

Ocean-Land-Atmosphere Coupling:

Onset of the 2004 monsoon was associated with the southeasterly advection of warm water from the tropical East Pacific Ocean into the GoC (Zuidema et al., 2007). Throughout the summer, oceanographic observations made aboard a research vessel deployed near the mouth of the GoC documented that strong solar heating, ocean heat advection and nighttime cloudiness over the Gulf provide a positive feedback resulting in net surface heating despite a large evaporation component. Furthermore, periodic, strong advection of warm water from the southeast during atmospheric moisture surge events also appears contribute to a surge-memory effect as the recently advected water contributes to the latent and sensible fluxes within the Gulf region. Capturing the complex, transient behavior of the GoC heat and moisture source will be essential for improving model simulations and highlights the importance of resolving the Gulf in free running climate models.

Strong latitudinal and terrestrial gradients in terrestrial hydrology and ecology are found throughout the monsoon region. These variations act as a dynamic assimilator of atmospheric processes yet their influence as an atmospheric driver (*ie* the nature of the land-atmosphere feedback) remains uncertain (Vivoni et al., 2007; Watts et al., 2007; Zhu et al., 2007). During 2004, tower flux and soil moisture measurements were made in a variety of ecotones. From a vegetation biome perspective tropical deciduous forests respond much more quickly and strongly to precipitation than other semi-arid communities (Watts et al., 2007). Notably, the tropical deciduous forests exhibit slower decay of evapotranspiration fluxes under moisture stress than many other communities effectively resulting in a ‘quick learning-long forgetting’ behavior. On seasonal and interannual timescales antecedent land surface conditions across southwestern North America affect the timing of the onset of monsoon precipitation by modulating the land-sea thermal contrast (Grantz et al., 2007, Zhu et al., 2007). These anomalies are largely established in response to antecedent cold-season precipitation anomalies which vary greatly from year to year. This regional forcing acts in concert or competition with large-scale teleconnective forcing provided by remote and near shore sea surface temperatures (Grantz et al., 2007, Gochis et al., 2007a).

Towards Improving Predictions:

Transferring this emerging understanding of the NAMS into improved predictions of warm season precipitation will not be easy. Fundamental limitations still exist in the observing system over parts of México, in particular the SMO, the intra-America Seas region, and the tropical oceans in general. Poor treatment of convection in models and limited understanding of role of terrestrial forcing will continue to inhibit rapid increases in seasonal and inter-annual forecast skill from dynamic models. However, as part of NAME, progress is being made on defining which observations are critical to improving model initializations and forecasts. Assimilation of NAME 2004 special soundings into

NCEP model-based data assimilation systems indicates that impacts of the soundings are most pronounced at low levels in the atmosphere and mainly in the core monsoon region of northwestern México and the southwestern U.S. where the sounding data were collected (Mo et al., 2007). Enhanced sounding observations also had a significant and beneficial impact on depicting the structure of the Gulf of California low-level jet. However, additional data impact studies of the NAME 2004 enhanced observations, such as sea surface temperatures, rain gauge observations, and soil moisture measurements, on atmospheric analyses are needed. These studies will, over time, contribute to the development of an observing system design for the NAMS which is key deliverable from the NAME program.

Comparatively less progress has been made in addressing NAME research questions in Tiers II and III compared to Tier I. While this is understandable, given the focus of NAME 2004, the research issues in Tiers II and III need to have greater priority in the future in order to make progress on warm season precipitation forecasts. The 2004 monsoon highlighted the significant dependence of monsoon precipitation, in many regions, on transient synoptic features. For instance, moisture surge activity appears to be enhanced during active phases of the Madden Julian Oscillation (Johnson et al., 2007; Lorenz and Hartmann, 2006). Similarly, Mestas-Nunez et al. (2007) show that variability in the transport from the key moisture source region of the intra-America Seas is linked to changes in summertime precipitation patterns over the central and eastern U.S. It has become clear that there are complex interactions between tropical easterly waves, upper-level inverted troughs, cold fronts, cut-off lows, open troughs, and GoC moisture surges that are not well understood despite the fact that they are critically important in the prediction of warm season precipitation.

As NAME enters into its modeling and prediction phase many significant challenges remain. Some of these are ‘grand challenge’ issues, such as the representation of convection in models or land-ocean-atmosphere coupling, that extend well beyond NAME and thus NAME will only make measured contributions to their ultimate resolution. More importantly, in order to improve predictions of warm season precipitation, NAME will need to engage a variety of strategies aimed at detecting critical environmental processes that modulate the warm season circulation and improving the representation of these processes in empirical and dynamical prediction models. One way forward, as mentioned previously, is to design and maintain a robust climate observing system across the southern North American cordillera, the GoC and the intra-America Seas regions. Such a climate observing system will provide critical information on fast and slow memory processes within the coupled climate system necessary for improved system diagnosis, modulation by teleconnective forcing as well as improved dynamical model initialization. This need has also been identified in the context of other climate variability and climate change research efforts recently articulated by Diaz et al. (2006) and Diamond and Helfert (2007).

Second, NAME must also engage efforts to provide added value to existing forecast methodologies in order to create more usable warm season forecast products. One way NAME is addressing this issue is by developing the NAME Forecast Forum which will

consolidate a variety of operational and experimental forecast products of monsoon activity. This new effort will build upon the success of the NAME Model Assessment Project (NAMAP see Gutzler et al., 2006 for details), which has documented the attributes and shortcomings of several leading global and regional models in the simulation of monsoon circulation and precipitation features. More detail on this effort will be forthcoming in the coming months though interested parties are encouraged to contact the authors directly. Another way for NAME to add value to existing forecasts is by improving the application of dynamical and statistical-dynamical downscaling techniques in seasonal forecasts. While such approaches clearly can not correct for erroneously forecasted climatic structures, they can serve to better transfer information captured in forecasted climate modes to smaller scale, regional climate processes such as variable precipitation characteristics across complex terrain. As has been the case from the beginning of NAME, it will be through a synthesis of multi-disciplinary activities that measured progress in improved understanding of the monsoon system will be transferred into improved prediction capabilities.

REFERENCES:

- Aragón, E.A. and A. García, 2002: Postlarvae recruitment of blue shrimp *Litopenaeus stylirostris* (Stimpson, 1871) in antiestuarine conditions due to anthropogenic activities. *Hidrobiológica*, **12**(1), 37-46.
- CLIMAS, 2007: Southwest climate outlook – August 2006. *Online climate Outlook published by the Climate Assessment for the Southwest (CLIMAS) project. Tucson, Arizona.* Available online at:
<http://www.ispe.arizona.edu/climas/forecasts/archive/aug2006/swoutlook.html>
- Diamond, H.J. and M.R. Helfert, 2007: The U.S. Global Climate Observing System (GCOS) Program: Plans for high elevation GCOS surface network sites based on the benchmark U.S. Climate Reference Network (CRN) System. *Mountain Views, Newsletter of the Consortium for Integrated Climate Research in Western Mountains (CIRMOUNT)*, **1**, 16-19.
- Diaz, H.F., R. Villalba, G. Greenwood and R.S. Bradley, 2006: The impact of climate change in the American Cordillera. *Eos, Transactions of the American Geophysical Union*, **87**(32), August, 2006, p. 315.
- Douglas, A.V. and P.J. Englehart, 2007: A climatological perspective of transient synoptic features during NAME 2004. In press, *J. Climate*.
- FEMA, 2007: New Mexico severe storms and flooding. *Federal Emergency Management Agency (FEMA) Disaster Information web page.* Available online at:
<http://www.fema.gov/news/event.fema?id=6925>

Gebremichael, M., E.R. Vivoni, C.J. Watts, and J.C. Rodriguez, 2007: Local-scale spatio-temporal variability of North American monsoon rainfall over complex terrain. In press, *J. Climate*.

Gochis, D.J., L. Brito-Castillo, W.J. Shuttleworth, 2006: Hydroclimatology of the North American Monsoon region of northwest México. *J. Hydrology*, **316**, 53-70.

Gochis, D.J., L. Brito-Castillo, W.J. Shuttleworth, 2007a: Correlations between sea-surface temperatures and warm season streamflow in northwest México. In press, *Int'l. J. Climatol.*

Gochis, D.J., C.J. Watts, J. Garatuza-Payan, and J.C. Rodriguez, 2007b: Spatial and temporal patterns of precipitation intensity as observed by the NAME event rain gauge network from 2002 to 2004. In press, *J. Climate*.

Gutzler, D. S, H.-K. Kim, R. W. Higgins, et al., 2005: The North American monsoon Model Assessment Project (NAMAP): Integrating numerical modeling into a field-based process study. *Bull. Amer. Met. Soc.*, **86**, 1423-1430.

Lorenz, D.J. and D.L. Hartmann, 2006: The effect of the MJO on the North American Monsoon. *J. Climate*, **19**, 334-343.

Higgins, R. W. and co-authors, 2006: The North American Monsoon Experiment (NAME) 2004 Field Campaign and Modeling Strategy. *Bull. Amer. Meteor. Soc.*, **87**, 79-94.

Higgins, R.W. and D.J Gochis, 2007: Synthesis of results from the North American Monsoon Experiment (NAME) process study. In press, *J. Climate*.

Janowiak, J.E., V.J. Dagostaro, V.E. Kousky and R.J. Joyce, 2007: An examination of precipitation in observations and model forecasts during NAME with emphasis on the diurnal cycle. In press, *J. Climate*.

Johnson, R.H., P.E. Ciesielski, B.D. McNoldy, P.J. Rogers and R.J. Taft, 2007: Multiscale variability of the flow during the North American Monsoon Experiment. In press., *J. Climate*.

Lang, T.J., D.A. Ahijevych, S.W. Nesbitt, R.E. Carbone, S.A. Rutledge and R. Cifelli, 2007: Radar-observed characteristics of precipitating systems during NAME 2004. In press, *J. Climate*.

Mestas-Nuñez, A., D.B. Enfield and C. Zhang, 2007: Water vapor fluxes over the Intra-Americas Sea: Seasonal and interannual variability associated with rainfall. In press, *J. Climate*.

NAME Science Working Group, cited 2007: North American Monsoon Experiment Science and Implementation Plan. [Available online at <http://www.cpc.ncep.noaa.gov/products/monsoon/NAME.html>.]

Nesbitt, S.W. and D.J. Gochis, 2007: Characteristics of convection along the Sierra Madre Occidental observed during NAME-2004: Implications for warm season precipitation estimation in complex terrain. Manuscript in preparation.

Ray, A.J., G.M. Garfin, M. Wilder, M. Vasquez-Leon, M. Lenart and A.C. Comrie, 2007: Applications of monsoon research: Opportunities to inform decision making and reduce regional vulnerability. In press, *J. Climate*.

Vivoni, E.R., H.A. Gutierrez-Jurado, C.A. Aragon, L.A. Mendez-Barrozo, A.J. Rinehart, R.L. Wycoff, J.C. Rodriguez, C.J. Watts, J.D. Bolten, V. Lakshmi and T.J. Jackson, 2007: Variation of hydrometeorological conditions along a topographic transect in northwestern México during the North American monsoon. In press, *J. Climate*.

Watts, C.J., R.L. Scott, J. Garatuza-Payan, J.C. Rodriguez, J.H. Prueger, W.P. Kustas and M. Douglas, 2007: Changes in vegetation condition and surface fluxes during NAME 2004. In press, *J. Climate*.

Williams, C.R., A.B. White, K.S. Gage and F.M. Ralph, 2007: Vertical structure of precipitation and related microphysics observed by NOAA profilers and TRMM during NAME 2004. In press, *J. Climate*.

Zhu, C., T. Cavazos and D.P. Lettenmaier, 2007: Role of antecedent land surface conditions in warm season precipitation over northwestern México. In press, *J. Climate*.

Zuidema, P. C. Fairall, L.M. Hartten, J.E. Hare and D. Wolfe, 2007: On air-sea interaction at the mouth of the Gulf of California. In press, *J. Climate*.