

## Synthesis of Results from the North American Monsoon Experiment (NAME) Process Study

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### ABSTRACT

An international team of scientists from the United States, Mexico, and Central America carried out a major field campaign during the summer of 2004 to develop an improved understanding of the North American monsoon system leading to improved precipitation forecasts. Results from this campaign, which is the centerpiece of the North American Monsoon Experiment (NAME) Process Study, are reported in this issue of the *Journal of Climate*. In addition to a synthesis of key findings, this brief overview article also raises some important unresolved issues that require further attention. More detailed background information on NAME, including motivating science questions, where NAME 2004 was conducted, when, and the experimental design, was published previously by Higgins et al.

### 1. The NAME Process Study

The North American Monsoon Experiment (NAME) is an internationally coordinated process study aimed at determining the sources and limits of predictability of warm season precipitation over North America. The NAME program is jointly sponsored by the Climate Variability and Predictability (CLIVAR) and Global Energy and Water Cycle Experiment (GEWEX) interdisciplinary research efforts. 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 toward improved prediction is the clear documentation of the major elements of the monsoon system and their variability within the context of the evolving OAL annual cycle. NAME employs a multiscale (tiered) approach with focused monitoring, and diagnostic and modeling activities in the core monsoon region, on the regional and continental scales (Fig. 1).

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An international team of NAME scientists from the United States, Mexico, and Central America carried out a major field campaign during the summer of 2004 to develop improved North American monsoon forecasts. NAME 2004 was an unprecedented opportunity to gather an extensive set of atmospheric, oceanic, and land surface observations in the core region of the North American monsoon, including northwestern Mexico, the southwestern United States, and adjacent oceanic areas. The campaign involved scientists from more than 30 universities, government laboratories, and federal agencies, including more than 30 weather forecasters from the National Oceanic and Atmospheric Administration (NOAA)/National Weather Service and the Mexican National Weather Service (Servicio Meteorológico Nacional, SMN).

NAME 2004 produced immediate benefits, including enhanced (and sustained) observations for monitoring the monsoon, and a two-way exchange of information, technology, and training between NOAA/National Weather Service and the SMN. NAME empirical and modeling studies are leveraging the NAME 2004 enhanced observations to accelerate improvements in warm season precipitation forecasts, products, and applications. A comprehensive NAME Web site (<http://www.eol.ucar.edu/projects/name/>) covers all aspects of

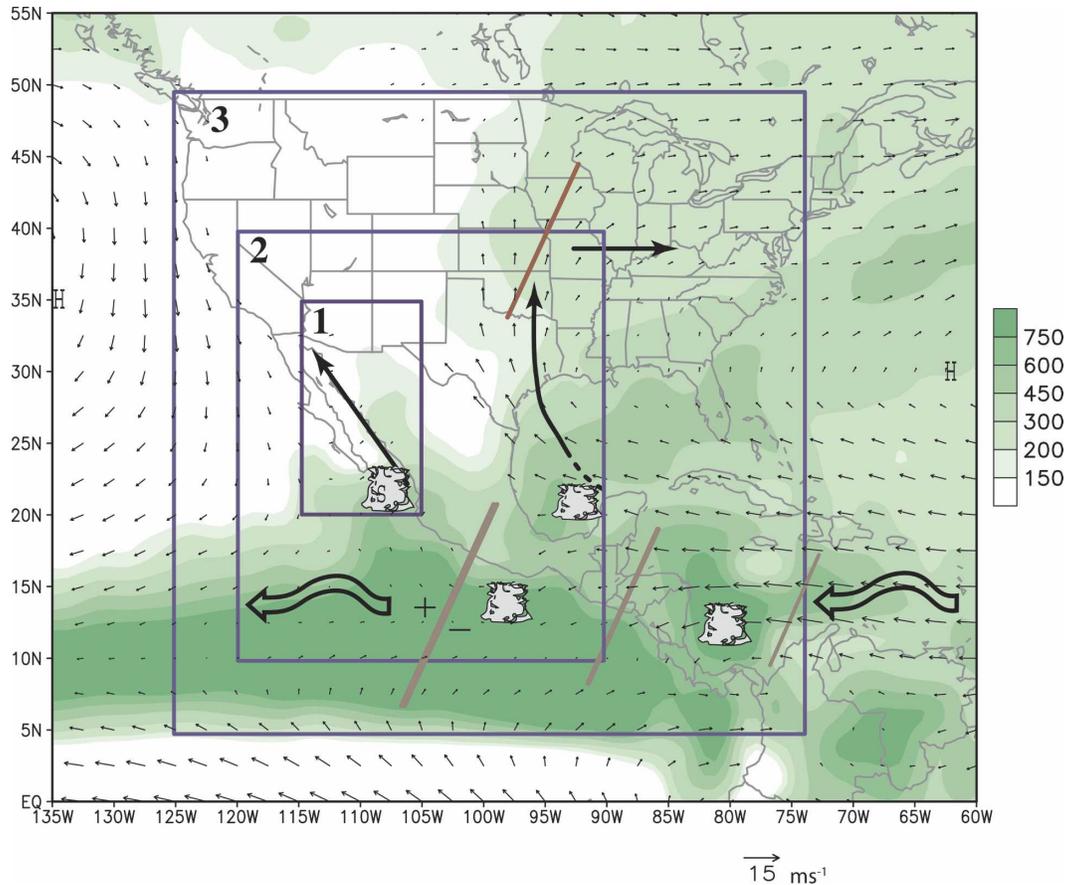


FIG. 1. Schematic illustrating the multitiered approach of the North American Monsoon Experiment (NAME). The schematic also shows mean (July–September 1979–95) 925-hPa vector wind ( $\text{m s}^{-1}$ ) and merged satellite estimates and rain gauge observations of precipitation (shading; mm). Circulation data are taken from the NCEP–NCAR reanalysis archive. The Gulf of California (Great Plains) low-level jet is indicated by the straight (curved) arrow in the GOC (southern plains). Schematic includes transient lines near  $10^{\circ}$ – $15^{\circ}\text{N}$  ( $40^{\circ}\text{N}$ ) to indicate westward (eastward) propagation of disturbances such as easterly waves (midlatitude fronts).

the project, including information on data access and program documentation. More detailed background information on NAME than that presented in this overview, including motivating science questions, where and when NAME 2004 was conducted, and the experimental design are found in Higgins et al. (2006).

This issue of the *Journal of Climate* presents a set of articles that report preliminary findings from analysis of the NAME 2004 datasets and related modeling studies. Many of the results are new, while some are confirmatory of previous studies. The full impact of NAME 2004 on monsoon prediction and applications will not be realized until a thorough integration of analysis and modeling studies has been completed, a process that will take a number of years. This issue is organized to report upon several areas, including precipitation characteristics, circulation and transient observations/analyses, ocean observations/analyses, land–atmosphere inter-

actions and hydrology, modeling studies, and societal applications; a brief synthesis of some of the key findings is given in section 4. The set of papers is necessarily diverse to illustrate the scope of the program.

## 2. NAME timeline

NAME planning began in the spring of 2000 at the request of the Climate Variability and Predictability (CLIVAR)/Variability of the American Monsoons (VAMOS) Panel, which endorsed the formation of a science working group (SWG) to develop cooperative international research to investigate the North American monsoon system. The SWG identified enhanced monitoring and field studies of the low-level circulation features and diurnal cycle of precipitation in the core monsoon region as key priorities. These priorities were subsequently endorsed in the U.S. arena by the U.S.

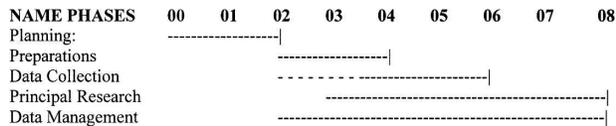


FIG. 2. The NAME timeline.

CLIVAR Pan American Panel (July 2000) and the first NAME Planning Workshop was held (October 2000) to discuss and coordinate plans for NAME implementation. Subsequent meetings of the NAME SWG were held to refine the NAME 2004 implementation plan and to organize modeling and data assimilation activities in advance of the field activities [e.g., Gutzler et al. (2005) discusses results from the North American Monsoon Model Assessment Project (NAMAP)]. NAME activities have included planning, preparations, data collection, research, and data management phases during an eight-year “life cycle” (Fig. 2). The NAME research phase is on going and will continue for the next several years. During this phase the coordinated and cooperative research efforts, which were the principal drivers of NAME field activities, will continue to provide input to the data management efforts of the Earth Observing Laboratory at the National Center for Atmospheric Research (NCAR/EOL) (see section 3). This will ensure that the datasets resulting from NAME are widely available and archived in a manner that is most useful for future studies.

### 3. NAME data

During the NAME 2004 field campaign, data were gathered from 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 antennas among others. NAME data are managed by the NCAR/EOL [formerly the Field Operations and Data Management Group of the University Corporation for Atmospheric Research’s (UCAR) Joint Office for Science Support]. EOL has established and maintains the NAME project Web site (<http://www.eol.ucar.edu/projects/name/>), including the data management pages and final project archive. These Web pages provide access to the archive through a distributed “master list” of all NAME datasets (<http://www.eol.ucar.edu/projects/name/dm/archive/>), NAME program-relevant documents, and links to other related project data.

The NAME data archive consists of 266 datasets and the NAME map server tool and field catalog, which will

continue to be available online. The field catalog (reports, maps, imagery, and other “browse-able” products) currently consists of approximately 500 000 files totaling 26 MB. Surface precipitation and upper-air “composite” datasets have also been prepared. The surface precipitation composite datasets (hourly and daily) involves the collection of all operational/research surface network precipitation data from available sources, geographical and time subsetting, integration of data to a common time scale, resolution of duplicate data conflicts, conversion of all data to a common format, compilation of metadata with station data, provision of uniform quality control, and generation of final composite datasets at respective time resolutions. Two upper-air composites are available from operational and research rawinsonde data, including all soundings at the highest vertical resolution, and all soundings interpolated to 5-hPa levels.

Several other NAME value-added data products have been delivered or are forthcoming, including radar composites, NAME atmospheric analyses, merged rain gauge datasets, merged atmospheric sounding composites, multisensor sea surface temperature products, and land surface datasets. Many of these datasets will provide essential initialization, forcing, and validation data for future NAME modeling studies, including NAMAP-2 (<http://www.eol.ucar.edu/projects/name/namap2/>), which has been organized to simultaneously quantify the impact of the NAME special observations on numerical model forecasts, and to measure progress in simulation quality since NAMAP.

### 4. Synthesis of results from NAME 2004

The 2004 North American monsoon (NAM) season was characterized by a climatologically late start and early retreat and a relatively poorly developed subtropical ridge (Douglas and Englehart). On a longer time scale, the 2004 NAM lies within an extended period of drought, which has resulted in decreased summer precipitation across parts of Sonora, Mexico, and southern Arizona (Watkins et al.). Monsoon onset in extreme northwestern Mexico and the southwestern United States was coincident with a strong surge around 12–13 July induced by Tropical Storm Blas. Analyses of atmospheric soundings and profilers (Johnson et al.) and shipboard measurements (Zuidema et al.) indicate that onset was associated with strong southeasterly flow and the advection of warm water into the Gulf of California (GOC).

Time-mean analyses of NAME 2004 observations show strong low-level convergence (upper-level divergence) along the crest of the Sierra Madre Occidental

(SMO) (Johnson et al.). However, significant uncertainty in humidity structure over the complex terrain exists due to the lack of surface meteorological and atmospheric observations there. 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., Zuidema et al.). 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. Easterlies tend to persist at middle and upper levels in the GOC region, fostering a light to moderately sheared environment. Divergence, vertical motion, heating, and moistening profiles derived from analyses of the special observations are all consistent with a convectively dominated dynamical system, but stratiform precipitation structures frequently observed during nighttime hours also play an important role in modifying the regional thermodynamic structure over and around the GOC (Johnson et al., Zuidema et al., Williams et al.).

Climatologically, inverted troughs and other synoptic transients are critical features of the NAM (Douglas and Englehart). Inverted troughs help advect moisture and provide dynamical support by means of large-scale ascent and orographic lift in dry regions such as the central Mexican Plateau. Additionally, moisture surge activity appears to be enhanced during active phases of the Madden-Julian oscillation (Johnson et al.). Synoptic variability during 2004 was characterized by a reduced number of inverted troughs and nearly twice the climatological number of midlatitude westerly troughs (Douglas and Englehart). The westerly troughs during 2004 were implicated in drier-than-normal conditions in Arizona and northern Sonora. On interannual time scales the dominance of a particular transient regime can also influence summer rainfall patterns (Douglas and Englehart). Furthermore, Mestas-Nunez et al. show that variability in the transport from the key moisture source region of the intra-Americas Seas is linked to changes in summertime precipitation patterns over the central and eastern United States.

Since the initiation of monsoon convection is often aided by terrain-induced circulations, precipitation character (e.g., frequency, intensity, and duration) is often related to variations in local ( $O \sim 1\text{--}10$  km) and regional ( $O \sim 10\text{--}100$  km) terrain features, land-sea contrasts, and access to abundant atmospheric moisture (Gebremichael et al., Gochis et al., Janowiak et al., Lang et al., Vivoni et al.). During 2004, NAM convective precipitation storm length scales typically ranged from approximately 15 to 23 km (Mekkonen et al., Lang et al.). Organized, propagating precipitation

events, which moved away from topography under “disturbed regimes,” represented a comparatively smaller fraction of the climatology than those events whose entire life cycle occurred over terrain (Lang et al.). Forcing of the diurnal cycle of winds (Johnson et al., Zuidema et al.) is supplied by land-sea contrasts and the heating of elevated terrain and these circulations significantly influence the diurnal cycle of precipitation. Notably, GOC precipitation is about 12 h out of phase with precipitation occurring over the SMO (Lang et al., Zuidema et al.) while precipitation at higher elevations tends to occur several hours earlier in the day ( $\sim 1400$  LT) compared to precipitation at lower elevations ( $\sim 1800$  LT). Given the strong dependence on terrain forcing for modulating hydrometeorological fluxes (e.g., precipitation and evapotranspiration) and responses (e.g., infiltration and runoff), and the complexity of terrain, coherent climatic regions in the NAME tier I domain are relatively small, compared to cooler seasons and other regions (Douglas and Englehart, Gochis et al., Vivoni et al.).

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., Williams et al.). Retrievals from NOAA wind profilers and space-borne radar show a relatively strong dependence on microphysical structures, in particular brightbanding (Williams et al.).

The land surface acts as an important, but spatially heterogeneous, assimilator of atmospheric processes (Vivoni et al., Watts et al., Zhu et al.). From a vegetation biome perspective tropical deciduous forests respond much more quickly and strongly to precipitation than other semiarid communities (Watts et al.). 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. Interestingly, albedo changes in response to monsoon onset are notably small in nearly all biomes. At local spatial scales (order 1–10s of km) the terrain is a dominant control in modulating the land surface response to precipitation (Vivoni et al.), and therefore elevation and ecosystem type play a large role in modulating land-atmosphere coupling (Vivoni et al., Watts et al.). On seasonal and interannual time scales, 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., Zhu et al.). These anomalies are largely established in response to antecedent cold-season precipitation anomalies. This regional forcing acts in concert or com-

petition with large-scale teleconnective forcing provided by remote and nearshore sea surface temperatures (Grantz et al.).

Over the Gulf of California strong solar heating, ocean heat advection, and nighttime cloudiness provide a positive feedback resulting in net surface heating despite a large evaporation component (Zuidema et al.). Additionally, strong advection of warm water from the southeast during surge events may contribute to a surge-memory effect as the recently advected water contributes to the latent and sensible fluxes within the gulf region.

Assessment of the impact of enhanced observations on atmospheric analyses and forecasts is a key activity of the NAME research program. Assimilation of NAME 2004 special soundings into National Centers for Environmental Prediction (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 Mexico and the southwestern United States where the sounding data were collected (Mo et al.). Enhanced sounding observations also had a significant and beneficial impact on depicting the structure of the Gulf of California low-level jet. Additional studies of the impacts of the NAME 2004 enhanced observations (e.g., rain gauge, SSTs, and various combinations thereof) on atmospheric analyses are needed to determine if NAME science has the potential to improve large-scale simulations and predictions of North American climate variability.

To achieve its goals, NAME will need to improve numerical simulations of the monsoon circulation and its large-scale effects. A driving hypothesis of NAME is that the community must develop proper simulations of the relatively small (spatial and temporal) scale climate variability, especially the diurnal cycle, in the core of the continental monsoon precipitation maximum in northwestern Mexico. The timing of diurnal precipitation over the core NAM region in the NCEP Global Forecast System (GFS) was found to be about 3 h earlier than was observed from a merged satellite-gauge product (Janowiak et al.). GFS model-derived precipitation character appeared to have longer decorrelation length than observed precipitation. In general, global and regional models continue to produce light and moderate rainfall too frequently and heavy rainfall too infrequently. Similarly, while rainfall detection (rain versus no rain) over NAME tier 1 was found to be reasonable, moderate precipitation events were overpredicted and heavy events were underforecast (Janowiak et al.).

Simulations of precipitation in the core monsoon re-

gion tend to improve with increases in horizontal resolution in both global and regional models, but key processes, such as the diurnal cycle of convection, are phase-shifted relative to observations in part due to the influences of prominent terrain features (Collier and Zhang, Lee et al.). Alternately, regions peripheral to the core monsoon region, such as the U.S. Great Plains and northeastern Mexico, tend to exhibit little or no improvement due to an overestimation of subsidence. Increased horizontal resolution in global models does appear to positively impact the depiction of low-level moisture transport, land-sea breezes, and nearshore precipitation structures. In multiyear climate configurations, the NCAR Community Atmosphere Model (CAM) exhibits an erroneous phase shift in the annual cycle of precipitation with peak values occurring in August and September as opposed to July (Collier and Zhang). The fifth-generation Pennsylvania State University-National Center for Atmospheric Research Mesoscale Model (MM5) regional weather and climate model, operating at a horizontal resolution requiring convective parameterization, showed marked improvement in depicting the spatial and temporal distributions of precipitation compared to global models but still suffered from inadequate evolution of the diurnal cycle of precipitation (Gao et al.). Deficiencies in simulating the precipitation-terrain relationship are attributed to a continued misrepresentation of parameterized convective dynamics. However, MM5 showed a reasonable depiction of intraseasonal variance attributed to surge events.

Additional NAME research is under way to understand the interactions between the North American monsoon and society, in order to develop appropriate applications for monsoon research in a diverse, multicultural, and binational region (Ray et al.). Four principal stakeholder sectors have been identified in which there is an opportunity for monsoon science to benefit society: natural hazards, agriculture, public health, and water management. There continues to be a significant need to deliberately link monsoon research to integrated assessments involving scientists and stakeholders in the region. A NAME hydrometeorological working group has been organized as a useful step toward developing these linkages.

## 5. Progress and emerging issues

While the results documented within this issue offer measurable progress on understanding many key elements of the North American monsoon, much work remains. The following paragraphs synthesize, by tier, the current state of our understanding of the monsoon

and also point out some emerging issues for future monsoon research.

#### *a. Tier I research*

NAME 2004 provided a much improved observational dataset from which the lower-atmospheric circulations along the Gulf of California coastline can be studied. Continued analysis of these measurements is under way and many results are discussed in this issue or are forthcoming. It is increasingly evident that the atmospheric flow structure around the Gulf of California is strongly modulated by the diurnal cycle and by the passing of synoptic-scale transients. Improved understanding of this modulating behavior should remain a priority of NAME research.

Comparatively less progress has been made on our understanding of the daytime evolution of the atmospheric boundary layer and moisture fluxes over the foothill region and high terrain of the Sierra Madre Occidental. The nature of the interaction between the land and marine boundary layer regimes also remains unclear. Most of the atmospheric observing systems deployed during NAME 2004 were within 50 km of the coastline of the Gulf of California and, therefore, only sampled the low-elevation topographic regime of the monsoon. Improved documentation of structure and diurnal variation of the atmospheric boundary layer over land and ocean are critical to improving our understanding of convective initiation and organization mechanisms.

Several investigators collected surface flux data during NAME 2004. It is hoped that these measurements will improve our understanding of the nature of land-atmosphere coupling in the core monsoon region. In particular, improved understanding of the vegetation response to and control of soil moisture is needed in order to better constrain estimates of moisture recycling to the atmosphere. A key challenge is to develop appropriate methods to scale local measurements across large ecoregions. Improved or sustained precipitation observations and soil moisture observations would help address these uncertainties.

Progress on the diurnal cycle of convection, its initiation, and the dominant moisture sources for the monsoon has been substantial. NAME 2004 data are resolving some of the key mechanisms of the diurnal cycle, including the role of heating over land in producing the late afternoon/early evening precipitation maximum, and the nature of convective systems over high terrain that are subsequently advected by the mean wind into regions well removed from the origin of the systems. Additional work is needed to determine contributions of rainfall-producing systems (e.g., mesoscale

convective systems, organized sea-breeze convection lines, etc.) to the mean diurnal cycle of precipitation, including documentation of the frequency of occurrence of rainfall-producing systems. Results from these studies can be used to improve the ability of models to simulate the diurnal cycle toward achieving more accurate precipitation forecasts.

#### *b. Tiers II and III research*

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 forecasts of the monsoon. The 2004 monsoon highlighted the significant dependence of monsoon precipitation, in many regions, on transient features. It has become clear that there are complex interactions between tropical easterly waves, upper-level inverted troughs, cold fronts, cutoff lows, open troughs, and Gulf of California moisture surges that are not well understood despite the fact that they are likely to be important in the prediction of monsoon precipitation.

Recent work has suggested that portions of the region encompassed by NAME tiers II and III are “hot spots” for warm season land-atmosphere coupling (e.g., the southern Great Plains) (Koster et al. 2004). Improved diagnostics for evaluating this complex feedback process and its relationship to regional climate anomalies are needed. Additional understanding of the coupling mechanisms between the ocean and atmosphere is also required. This uncertainty is impeding our understanding of the relative roles of the leading patterns of climate variability [e.g., El Niño–Southern Oscillation (ENSO) on interannual time scales and the Madden–Julian oscillation (MJO) on intraseasonal time scales] in modulating monsoon precipitation. To improve predictions on these time scales, emphasis must be placed on improving the representation of ocean–atmosphere interactions in coupled prediction models.

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