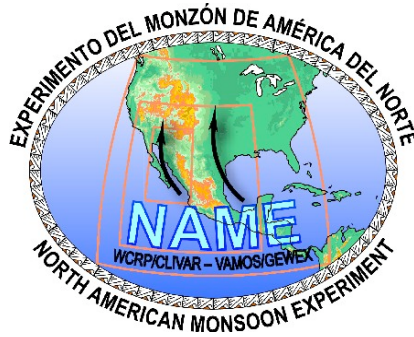


# **NAME Modeling and Data Assimilation: A Strategic Overview**



NAME Science Working Group\*

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## I. Introduction

This document presents a strategic overview of modeling and related data analysis and assimilation components of the North American Monsoon Experiment (NAME). Building on the NAME science plan, a strategy is outlined for accelerating progress on the fundamental modeling issues pertaining to NAME science goals. The strategy takes advantage of NAME enhanced observations, and should simultaneously provide model-based guidance to the evolving multi-tiered NAME observing program.

The overarching goal of NAME is to improve predictions of warm season precipitation over North America. Central to achieving this goal are enhanced observations, and improvements in the ability of models to simulate and predict the various components and time scales comprising the weather and climate of the North American Monsoon System (hereafter NAMS). The specific scientific goals outlined in the NAME Science Plan (<http://www.eol.ucar.edu/projects/name>) are to promote better understanding and prediction of:

- *warm season convective processes in complex terrain;*
- *intraseasonal variability of the monsoon;*
- *the response of warm season atmospheric circulation and precipitation patterns to slowly varying, potentially predictable oceanic and continental surface conditions;*
- *the life cycle of the North American monsoon system and its variability;*
- *extreme events, such as droughts and floods, during the monsoon season.*

In order to accomplish these goals NAME has adopted a multi-scale tiered approach with focused monitoring, diagnostic and modeling activities in the core monsoon region (Tier I), on the regional scale (Tier II) and on the continental scale (Tier III). *It should be emphasized that to be successful, NAME modeling activities must maintain a multi-tiered approach in which local processes are embedded in, and are fully coupled with, larger-scale dynamics.*

The NAME region represents a unique challenge for climate modeling and data assimilation. It is a region marked by complex terrain and characterized by a wide range of phenomena including, a strong diurnal cycle and associated land-sea breezes, low level moisture surges, low level jets, tropical easterly waves, intense monsoonal circulations, intraseasonal variability, and continental-scale variations that link the different components of the monsoon. In fact, the NAMS exhibits large-scale coherence in the form of several known phenomena that have an important impact on intraseasonal to decadal time scales. Hence there are building blocks to serve as the foundation for climate forecasting. The El Niño/Southern Oscillation (ENSO) phenomenon is the best understood of these phenomena, but previous research on the NAMS has also identified several others, including the Madden-Julian Oscillation (MJO) and the Pacific Decadal Oscillation (PDO). The relative influences of these phenomena on the warm season precipitation regime over North America are not well understood. Conversely, the large scale convective maximum associated with the monsoon affects circulation elsewhere, as shown by the relationship between the strength of deep convection and the amplitude and location of the summer subtropical High to the west. Similarly, intraseasonal and interannual fluctuations of monsoon rainfall in the Tier-1 region are often out-of-phase with summer rainfall across the central United States; at present the mechanisms for this feature remain unclear

Prospects for improved prediction on seasonal-to-interannual time scales hinge on the inherent predictability of the system, and our ability to quantify the initial states and forecast the evolution of the surface forcing variables (e.g. SST and soil moisture). In the NAME Tier 3 region, circulation anomalies are influenced by SSTs in the tropical Pacific associated with ENSO, as well as in the North Pacific and the tropical and North Atlantic. On decadal time scales, both the Pacific Decadal Oscillation and the tropical and North Atlantic SSTs have influences on monsoon rainfall. SSTs in the eastern Pacific influence tropical cyclone development, which in turn influence the frequency and intensity of moisture surges and attendant rainfall. SSTs in the Gulf of California and the Gulf of Mexico also play a role in modulating the low level circulations associated with the monsoon.

In addition to SST influences, the land surface has many memory mechanisms beyond soil moisture, especially over the western US. Snow extends surface moisture memory across winter and spring. Vegetation in semi-arid regions, which shows pronounced seasonal and interannual variability, acts as an atmospheric boundary condition that affects momentum transfer, radiation, heat and moisture fluxes.

Aerosols are an important atmospheric constituent in southwestern North America. Circulation is often weak and anthropogenic sources from urban areas attenuate and reflect shortwave radiation. Fires (both natural and man-made) and their associated particulates have pronounced seasonal and interannual variability. Dust is an important factor in the spring and early summer, when vegetation is sparse and surface winds are strong. Multi-year droughts may be triggered by SST anomalies, but they are likely to be sustained by land-atmosphere feedback processes that can alter the surface conditions for years and have a significant affect on interannual variability.

The NAME 2004 Field Campaign (Table 1) provided a comprehensive short term (one warm season) depiction of precipitation, circulation, and surface conditions in the core monsoon region. The EOP included enhanced networks of radiosondes, pilot balloons, raingauges, wind profilers, radars, and lightning detectors, as well as measurements of ocean fluxes, humidity, soil moisture, and vegetation. A principal goal of the EOP was to provide a sufficiently comprehensive data set to help guide the NAME modeling strategy aimed at improved warm season precipitation forecasts. The elements of the NAME modeling strategy include climate forecast system assessments, climate data assimilation, and climate model and forecast system development.

The strategy outlined in the following sections recognizes three distinct, but related, roles that observations play in model development and assessment. These are (1) to guide model development by providing constraints on model simulations at the process level (e.g. convection, land/atmosphere and ocean/atmosphere interactions); (2) to help assess the veracity of model simulations or forecasts of the various key NAMS phenomena (e.g. low level jets, land/sea breezes, tropical storms), and the linkages to regional and larger-scale climate variability; and (3) to provide initial and boundary conditions, and verification data for model predictions. Section II discusses the multi-scale model development strategy. Section III describes how data assimilation plays a vital role in addressing the larger-scale NAMS modeling issues, and section IV discusses the role of coupled ocean-atmosphere-land surface models in addressing the global-scale linkages and the NAMS prediction problem. A Roadmap that summarizes ongoing and planned NAME climate model assessment, climate data assimilation and climate forecast system development activities is given in section V.

## **II. Multi-scale Model Development**

The underlying premise of the NAME modeling strategy is that deficiencies in our ability to model "local" processes are among the leading factors limiting forecast skill in the NAME region. For the most

part, the source of the problem is in the simulation of deep convective processes and their organizing and maintaining mechanisms. While this problem is not unique to the NAME region, the presence of land/sea contrasts and complex terrain make this a particularly challenging problem for NAME. The anticipated Tier I observations are geared to addressing this problem with a specific focus on improving the treatment of:

- *moist convection in the presence of complex terrain and land/sea contrasts;*
- *land/atmosphere interactions in the presence of complex terrain;*
- *ocean/atmosphere interactions in coastal regions with complex terrain.*

The interactions with the surface provide, among other things, organization and memory to atmospheric convection so that the problems of modeling land/atmosphere and ocean/atmosphere interactions are intertwined with the deep convection problem. Improvements on these "process-level" issues will require both fundamental improvements to the physical parameterizations, *and improvements to how we model the interactions between the local processes and regional and larger scale variability in regional and global models. In short, model development efforts must take on a multi-scale approach.* As such, we require information about the NAMS and related variability that extends across all Tiers (I, II, III) and beyond to include global scales.

Development efforts are envisioned that simultaneously tackle these issues from both a "bottom-up" and a "top-down" approach. In the former, process-level modeling is advanced and scaled-up to address parameterization issues in regional and global modeling, while in the latter, regional and global models are scaled-down to address issues of resolution and the breakdown of assumptions that are the underpinnings of the physical parameterizations. The following expands on the specific issues that need to be addressed.

### **1) Moist convection in the presence of complex terrain and land/sea contrasts**

The key issue for organized convection concerns the difficulties that regional and global models encounter with the so-called scale-separation problem: parameterization schemes and grid-scale convection running concurrently. Parameterization schemes are not designed to cope with this multi-scale behavior. The problem has its roots in the principle of scale separation: the dynamical scale of the process being parameterized should be much smaller than the grid-resolution of the numerical model in which it is applied. In climate models, where the grid-resolution is typically hundreds of kilometers, the scale-separation assumption is sensibly valid. However, parameterizations are not designed to represent either the up-scale effects of convection or its organization. In global numerical weather prediction models the validity of the scale-separation assumption is directly challenged by the mesoscale organization of convection. Recent work shows that surrogate organization (aliased grid-scale circulations) can distort, or take over completely, convective parameterization in global models. This is a long-recognized problem in regional mesoscale models wherein organized convection clearly invalidates the scale-separation principle. A resounding message is that organized convection may occur for the wrong reasons in regional and global weather prediction models.

The violation of the scale separation principle is inevitable when model resolution increases while the convective parameterization remains the same. This is a clear indication that parameterization schemes must be designed for specific resolutions.

The approach taken to addressing this problem should involve a hierarchy of models including fully cloud-resolving models, single column land/atmosphere models, regional mesoscale models, and fully

coupled global atmosphere-land-ocean models. Numerical models that resolve convection and have computational domains large enough to explicitly represent interaction with the environment (to the extent practicable with present computers) set a path to basic understanding. Such a multi-scale/multi-model approach will necessarily require close collaboration between process (local), mesoscale and global modeling groups, together with the observational analysts.

These multiscale modeling efforts must be interlinked with the observational efforts of NAME. Tier I will provide detailed observational measurements and forcing. When interactively nested domains or high resolution global models are used, the multiscale models are capable of incorporating Tiers I, II, and III.

## **2) Land/atmosphere interactions in the presence of complex terrain and land/sea contrasts**

Observational studies have shown that certain monsoonal circulation regimes have strong persistence tendencies: once "monsoon onset" occurs, an identifiable monsoon regime is maintained for up to several months (depending on latitude). Understanding the mechanism(s) for this persistence is important for making credible seasonal forecasts of monsoon-related climate variables.

A positive surface moisture feedback process has been postulated as playing a critical role in maintaining the monsoon. Vegetation "greens up" dramatically and rapidly across a large portion of the monsoon region following the initiation of rainfall in early summer, providing (via evapotranspiration) a quick pathway for returning precipitation to the atmosphere. The spatial and temporal variations of the water and energy fluxes involved in this feedback are currently poorly measured and simulated. NAME modeling and diagnostic studies should strive to quantify this feedback. Recent improvements to coupled models with advanced land surface models and proper initialization may enhance the ability to simulate these feedbacks.

The persistence of the monsoon is presumably also dependent on large-scale heat sources and sinks, as in the Asian summer monsoon, where onset and maintenance depends on surface sensible heat fluxes over elevated terrain (the Tibetan Plateau). The timing of the monsoon onset and demise is an important issue for the NAMS, as it is for the Asian monsoon. Modeling studies are required to explore the mechanisms controlling the timing of the onset and the demise.

In addition to their theoretical importance, there will be immediate and important social and economic applications of better information on the variability of land surface and hydrologic characteristics in the NAME region. Improvements in understanding the mechanisms that control vegetation, groundwater infiltration and surface runoff are critically important to both U.S. and Mexican efforts to foster sustainable economies and ecosystems in the arid Southwest.

## **3) Ocean/atmosphere interactions in coastal regions with complex terrain**

Monsoons are air-sea-land interaction phenomena, but it is not straightforward to separate out a purely air-sea interaction component because the air-sea interactions are strongly mediated by air-land processes. The predictability of intraseasonal variability of the NAM is heavily tied up in predictions of sea surface temperature (SST) and land soil/vegetation moisture reservoirs - both extreme challenges for today's models. Field campaigns (e.g., PACJET) on the US West Coast have shown that the dynamical influence of steep coastal terrain extends as much as 100 km out to sea for mid-latitude fronts.

Monsoons, however, are primarily powered by the land-sea temperature contrast: land has a strong seasonal and diurnal variation while the ocean has a moderate seasonal variation and a relatively small

diurnal variation. Furthermore, CAPE is very sensitive to PBL moisture and a 1°C change in SST produces 2.5 times the moisture in the Gulf of California than off the coast of California. Deep convection over the steep terrain has a strong effect on fluxes over the Tier-I ocean, which in turn influences the evolution of SST. At night, land convection tends to propagate westward over the eastern Pacific. Because the convective clouds block incoming solar radiation and produce cold pool outflows with resulting enhancement of mixing processes, the diurnal timing is critical in determining their cooling effect on the ocean. Models must produce the strength and timing correctly or feedbacks from the nearby oceans will further deteriorate the forecasts. For climate models this is a formidable problem because the land-sea interface is often poorly resolved.

The primary Tier-I air-sea interaction issues for NAME are:

- *the ocean as a source of moisture (the balance of local vs large scale sources);*
- *the interaction of the flat ocean with surrounding steep topography in generating the structure of the Gulf moisture surges and low-level jets;*
- *the strong effect of the land-sea temperature contrast in the dynamics of deep convection; and*
- *the coupling of deep convection to changes in ocean fluxes and resulting effects on the SST.*

To assess and improve model treatment of these issues, NAME 2004 gathered ship-based observations near the mouth of and along the Gulf of California. The mix of observations gathered by the Mexican Navy Research Vessel Altair, the University of Mexico El Puma and the CICESE Research Vessel Ulloa (see the NAME data catalog at <http://www.eol.ucar.edu/projects/name>) include 4-times daily rawinsonde launches with enhanced launch frequency during IOPs, high resolution wind and precipitation profiler to provide continuous measurements of the wind and drop size distribution characteristics, direct turbulent and radiative flux measurements, and near-surface bulk variables. The principal strategy of this suite of observations is to provide detailed time series of surface fluxes and bulk meteorology combined with profiles of wind, thermodynamics, and precipitation structure for direct comparisons with model output. The air sea interaction observations also allow *single-column* investigations of model physics, and provide critical validation for convective parameterization schemes. The ships also provide the only continuous high-quality soundings over the local ocean, which are important in defining the time series of mesoscale forcing.

Direct observations and turbulent and radiative fluxes will allow us to examine the efficacy of standard bulk flux routines in a coast zone. Present operational routines are tuned to the open ocean where there is typically an approximate balance between the wind and wave fields. Coastal regions (and particularly semi-enclosed bodies such as the Gulf) are hypothesized to have higher fluxes because the wave field is suppressed. Observations of covariance fluxes, bulk variables, and ocean surface wave fields will allow us to examine this issue (relevant to local sources of moisture and the acceleration of Gulf surges over the water). Finally, very accurate measurements of the surface heat budget and the SST will shed light on the relative roles of surface forcing and oceanic processes (advection and entrainment) in the predictability of SST in the Gulf of California.

In addition to the data taken during NAME 2004, several NAME "Value Added"

products will be produced:

- SSTs over the Gulf of California and nearby ocean obtained from both satellite and in situ ship measurements;
- Soil moisture from SMEX04;
- Surface sensible and latent heat fluxes;
- LCL of the surface air to compare with observed cloud base height;
- Surface drag or friction velocity.

These products will be useful for verification and calibration of models and can be used to enhance our understanding of physical processes.

#### 4) The diurnal cycle as a prototype multi-scale problem

A key focus of the NAME modeling effort will be on improving the representation of the diurnal cycle. The diurnal cycle is important to the NAME region for the following reasons:

- There are strong diurnal signals in many key variables such as precipitation and convection, low-level winds, moisture transport, and surface temperature, etc.
- Many physical processes crucial to the NAMS operate on the diurnal timescale, such as sea/land breezes, and land-atmosphere interactions through surface evaporation, vertical transport of water vapor by deep convection, etc.
- The diurnal cycle is modulated by processes on local scales (surface conditions), regional scales (coastal land-sea contrast), and the large scale (the circulation), and thus is a universal problem for all three NAME tiers. The presence of complex terrain further complicates the mechanisms for the diurnal cycle.

Current models have difficulty simulating the diurnal cycle so it is an important problem for multi-scale modeling. The NAME 2004 enhanced observations and NAME "Value Added" Products (including mixed layer depth and its diurnal cycle; diurnal evolution of specific humidity, winds, and surface fluxes) can be used to calibrate the satellite measurements, verify model output and increase the general understanding of the diurnal cycle.

As we move beyond Tier I, we need to consider the large regional differences within the broader-scale NAM region including differences in terrain, land surface conditions, and the basic climatology. In particular, efforts should be geared to understanding and improved modeling of the differences between the representation of organized convection in the coastal terrain of NAME, its representation over the Great Plains in the presence of a strong low-level jet, and its representation over the relatively wet land surface conditions of the eastern United States. Here too the diurnal cycle will likely play a central role, especially in terms of its interaction with topography, the land surface, and with the large-scale flow.

Over NAME Tier II the influence of soil moisture and surface fluxes on circulation patterns and precipitation is particularly strong. Models with appropriate land-surface subcomponents and proper initialization are critical. Addressing and verifying such large-scale interactions and regional differences



will require that the NAME Tier I observations are put in the context of other in situ and remote observations. This is best accomplished through data assimilation (including land data assimilation) as discussed in the next section.

### **III. Multi-tier Synthesis and Data assimilation**

The observations obtained from the NAME 2004 field campaign should provide valuable new insights into the mechanisms and phenomena of the monsoon in the Tier I region and, as outlined in the previous section, help to improve the representation of key physical processes in models. Nevertheless, in order to pursue a true multi-scale modeling strategy, we require information about the monsoon that extends well beyond the Tier I region. In this section, we discuss the role of data assimilation in enhancing the value and extending the impact of the Tier I observations to allow addressing issues of model quality and monsoon variability on scales that extend across the greater NAM region. In addition, data assimilation can provide an important framework for quantifying the impact of observations, and for assessing and understanding model deficiencies.

The basic goal is the creation of the best possible research quality assimilated data sets for studying the NAM region and its interactions with the large-scale environment. It is expected that this effort will rely primarily on regional data assimilation systems with some limited work done with global systems. The former have the potential to provide high resolution, and spatially and temporally coherent (compared with the Tier I observations alone) estimates of the various NAMS phenomena such as Gulf surges, low level jets, and tropical easterly waves, while the latter provide information (at a somewhat lower resolution) about linkages between the greater NAMS and global-scale climate variability and the role of remote boundary forcing, and will be discussed more in section IV. Additionally, we anticipate that off-line land data assimilation systems, as well as, simplified 1-dimensional land/atmosphere and ocean/atmosphere data assimilation systems will provide invaluable "controlled" environments for addressing issues of land-atmosphere and ocean-atmosphere interactions and model errors.

Specific examples of data sets to be generated include a series of assimilations for North America covering the EOP both with and without the NAME 2004 enhanced observations. Since the data assimilation products are model dependent and coarse resolution models will not resolve the Gulf of California, the data impact studies will be performed using high resolution global models and regional models. If observations are found to improve monsoon forecasts or simulations, recommendations will be made to continue such data collection beyond 2004. Parallel simulations, obtained by nesting regional models in the analyses both with and without the NAME 2004 enhanced observations will also be performed. Here efforts should also take advantage of existing operational and special reanalysis data assimilation products.

**Some specific objectives of these studies are:**

**1) To better understand and simulate the various components of the NAM and their interactions:**

- *Gulf of California moisture surges and precipitation in Tier I;*
- *tropical easterly wave / moisture surge relationships;*

- *moisture budget and sources (Gulf of Mexico vs. Gulf of California);*
- *tropical easterly wave / midlatitude (westerly) wave relationships;*
- *the diurnal cycle of convection over Southwest North America and the east Pacific ITCZ;*
- *relationships between low-level jets in the Gulf of California and U.S. Great Plains;*

These components are crucial to our understanding of the seasonal evolution of the monsoon. They may also help explain the out of phase relationship between precipitation in SW North America and that in the US Great Plain.

## 2) To quantify the impact of the NAME observations

Specifically, the aim is to assess the impact of the NAME observations on the quality of the analyses. The impact on predictions is one measure of quality, though that will be addressed in the next section. Improvements to the analyses can come about directly through the assimilation of the observations, or indirectly through improvements in the models used in the assimilation systems. As such, it is also important to understand the extent to which model errors impact the quality of the assimilated data.

To a large extent quantifying improvements will require comparisons with independent data that has not been assimilated. For this purpose, the NAME community has compiled additional precipitation products and satellite products that cover the period of the NAME 2004 field campaign. All of the products are in a useful format for quantitative applications (as opposed to .gif files, pointers, or raw measurements). Many of the products are subsets for the NAME domain at high spatial and temporal resolution. The precipitation products include:

- Gauge analyses (0.25° horizontal resolution and finer)
  - CPC merged US and Mexico daily precipitation analysis (0.25°, daily and hourly)
    - NAME Event Raingauge Network (NERN) (as fine as 5 minutes)
    - SMN Automated Weather Stations (10 min)
    - AGROSON automated agricultural weather stations
- Satellite analyses (0.25° horizontal resolution and finer)
  - CPC Morphing Technique ("CMORPH") (daily, hourly)
  - Naval Research Laboratory/GEO (daily)
  - US-Irvine/PERSIANN (daily)
  - NASA/GSFC/3B42RT (daily, 3 hourly)
  - NESDIS/Merged AMSU-B Estimates (daily hourly)
  - NESDIS/"Hydro-Estimator" Estimates (daily)
  - NESDIS/GOES Multi-spectral Rainfall Algorithm (GMSRA) (daily)

The satellite products include:

- SST

- AMSR, GOES, MODIS, TRMM
  - Hourly observations from GOES over clear sky; up to 4x daily from microwave instruments of AMSR and TRMM over clear sky and most cloudy regions
- Surface Wind
  - QuikSCAT over oceans; 2x daily
- Soil Moisture
  - AMSR (new product); 2x daily
- Temperature / moisture profiles
  - AIRS (new product); up to 2x daily
- Clouds
  - AIRS, AMSR, GOES, MODIS, TRMM
  - Cloudiness / cloud top temperature from GOES
  - Total column cloud liquid water from AIRS, AMSR and MODIS
  - 3-D structure of cloud liquid water from TRMM
- Precipitation / Radar Reflectivity
  - AMSR, TRMM
  - Surface precipitation from AMSR, TRMM/TMI and TRMM/Precipitation Radar (PR)
    - 3-D structure of precipitation and Radar Reflectivity from TRMM / Precipitation Radar (PR)
    - TRMM Radar Reflectivity useful for comparison with ground radar observations
- Aerosol
  - MODIS; Up to 4x daily

Here the Coordinated Enhanced Observing Period (CEOP) will play a key role in providing independent data for verification (e.g. Model Output Location Time Series (MOLTS) at the locations of the NAME upper air soundings). Another way to quantify the impact of data is to compare short range rainfall or circulation forecasts from 24-96 hr initialized from the analyses with and without the NAME 2004 enhanced observations. Improvements in the models ability to capture monsoon onset, precipitation amounts, monsoon breaks and / or the associated circulation changes would indicate the impact of the enhanced observations.

Another measure to quantify the impact of the NAME 2004 enhanced observations is to perform short range forecasts initialized from analyses with and without the NAME data. After the spin up period, the forecasts made from more accurate initial conditions should have better forecast skill.

Another approach is to withhold certain components of the NAME observations to assess their impact on the assimilation. Again, the primary tools used here would consist of regional data assimilation systems and models that are capable of resolving the key local features of the

monsoon, and are most likely to extend and enhance the Tier I NAME observations.

The impact of model deficiencies can be determined in a relative sense by comparing assimilations with different models, though here it will be difficult to produce completely clean comparisons without actually swapping different models into and out of the same data assimilation system. The recent Earth System Modeling Framework (ESMF 2001) development efforts could potentially provide such a capability. Another approach to identifying the impact of model errors is to compare assimilations and simulations carried out with the same model.

### **3) To identify model errors and attribute them to the underlying model deficiencies**

In many ways data assimilation provides one of the most direct ways of addressing model errors. One of the underlying assumptions of climate data assimilation is that a model forced (via data insertion) to remain close to the observed prognostic fields will produce more realistic forcing fields after a brief spin up or down period (e.g. radiation, latent and sensible fluxes) compared with the same model run in simulation mode. To the extent that the parameterizations are given the "right" input during an assimilation, yet still produce the wrong output (as measured for example by the systematic differences between model first guess and analysis fields), data assimilation provides a mechanism for diagnosing errors early, before they have a chance to grow and interact with other components of the flow. As such, the "analysis increments" obtained during an assimilation can provide valuable information about basic model deficiencies.

This approach to addressing model errors relies on having the models of interest run in data-assimilation mode. While this currently limits the analysis to just a few (mainly numerical weather prediction) models, we again expect that ESMF can facilitate carrying out such an analysis on a wider range of climate models.

In summary, the specific goals to be addressed through data assimilation are to assess the impact of the NAME observations, better understand the nature of model errors, and to obtain a better understanding and improved simulation of the full range of phenomena comprising the NAMS.

### **4) To identify model deficiencies in the representation of moist processes**

As discussed earlier, regional and global models have a difficult time representing moist convective processes. Cloud-resolving models can represent convection explicitly, but there is still the question of the realism of the results. Direct measurements of moist convective processes in Tier I offer the opportunity for direct comparison and validation of model results and their convective parameterizations. Specific items to be investigated are:

- *the structure, location, and timing of precipitation systems in the Tier I region;*
- *surface fluxes over the ocean and their modification by precipitation systems;*
- *divergence and vertical motion in convective regions;*
- *statistics of cloud fields;*
- *microphysical properties of convection*

Key measurements will be radar (including polarimetric) data, sounding data through the entire troposphere, surface flux measurements from ships, and boundary-layer wind and thermodynamic profiles.

#### IV. Prediction and Global-scale Linkages

One of the key measures of success of the NAME program will be the extent to which warm season precipitation prediction over the North American monsoon region is improved. Over the Tier 3 region the prediction problem for NAME is rather broad and includes time scales ranging from diurnal to interannual. While regional models will play an important role, dynamical predictions beyond more than a few days are potentially influenced by (and interact with) global climate variability, so that global models and data assimilation become increasingly important. In fact, it is likely that global-scale variability and the slower components of the boundary forcing (e.g. SST and soil moisture) will provide the main sources of predictive skill in this region on subseasonal and longer time scales.

Given the importance of SST and soil moisture initial conditions, it is clear that a fully coupled ocean-atmosphere-land surface forecast system will be required. The atmosphere-ocean coupled model should be used to forecast SSTs, not only in the tropical Pacific, but elsewhere (e.g. the North Pacific and the North and tropical Atlantic). The importance of soil moisture suggests that a land data assimilation system is needed to provide realistic soil conditions and surface fluxes to initialize the forecasts.

In seasonal simulations, the key issues to be addressed include the extent to which model improvements made at the process level (e.g. convection, land/atmospheric interaction), and associated improvements made in the simulation of regional-scale phenomena (diurnal cycle, basic monsoon evolution, low level jets, moisture surges etc), validated against improved data sets, ultimately translate into improved dynamical predictions. Additionally, we must determine the impact on predictions of the improved initial and boundary conditions, though this is limited to the period of the NAMEE 2004 field campaign. Still, we can examine how sensitive model simulations of NAMS precipitation (and the components of the large scale circulation driven by monsoonal convection) are to accurate specification of SSTs in the Gulf of California, Gulf of Mexico, or eastern Pacific.

We envision a number of "hindcast" experiments with fully coupled models, and utilizing existing regional and global assimilated data sets. The NAME 2004 enhanced observing period serves as an important case study to assess the direct impact of the enhanced observing system for initializing and forcing the models.

Some specific objectives of NAME predictability research are:

- *to examine whether the observed connections between the leading patterns of global climate variability (e.g. ENSO, MJO) and the NAMS are captured in global models;*
- *to determine the predictability and prediction skill over the NAMS region associated with the leading patterns of climate variability;*
- *to investigate the impacts of anomalous continental and oceanic conditions in regional and global models;*
- *to determine the impact of land-atmosphere interactions (e.g. due to soil moisture) and*

*vegetation changes during the monsoon;*

- *to compare the relative influences of local and remote SST forcing on predictive skill in the NAME region;*
- *to assess the advantage for NAME region predictions of increased resolution (either global or locally enhanced - for example by embedding regional high-resolution models in global models).*
- *to utilize satellite measurements directly or indirectly through data assimilation to improve forecasts.*
- *to assess and correct errors in SSTs predicted from a coupled model and to estimate land forcing such as soil moisture or vegetation types or coverage.*

Several broader cross-cutting themes also warrant attention. These include studies that examine the relative importance of oceanic and land-surface boundary forcing, and studies to quantify error growth due to model errors and those due to the uncertainties in analyses and boundary conditions.

Model development and testing requires computer resources as well as system and science support and expertise. Recently, NOAA established the Climate Test Bed (CTB) facility to accelerate research advances into improved NOAA operational climate forecasts, products and applications. It is anticipated that many of the NAME modeling and data assimilation activities, including the NAME Climate Process and modeling Team (CPT), will establish strong linkages to the CTB as improvements in warm season precipitation prediction are realized.

## **V. A Roadmap**

Results from the NAME 2004 Field Campaign are being used to address climate issues aimed at improved seasonal-to-interannual precipitation prediction. Some of the critical questions include:

- Can we understand and simulate variations in the North American Monsoon?
- What are the influences of the core monsoon region on the larger scales (e.g. relationship between precipitation variability in the SW and Great Plains)?
  - What are the relative roles of oceanic (e.g. SST) and continental (e.g. soil moisture) boundary forcing on the predictability of the monsoon?
  - What is the current forecast skill of monsoon rainfall on seasonal to interannual time scales in a coupled model? Does the model have skill in non-ENSO years? Can the model forecast skill be improved by using the two- tier approach (e.g. force a high resolution atmospheric model with statistically corrected SSTs from a coupled model)?

In order to address these questions, the NAME has organized and is pursuing a series of climate

model assessment, climate data assimilation and climate model and forecast system development activities that collectively take the form of a "Roadmap":

### **I. Climate Model Assessments**

- North American Monsoon Assessment Project (NAMAP)
- North American Monsoon Assessment Project 2 (NAMAP2)
- Diurnal Cycle Experiments
- Impact of Resolution on Warm Season Precipitation Forecasts
- High Frequency Features of North American Summer Climate
- Precipitation Assessment Project (PAP)

### **II. Climate Data Assimilation**

- NCEP High Resolution North American Climate Analysis System
  - NAME 2004 Data Impact Studies

### **III. Climate Model and Forecast System Development**

- NAME Climate Process and modeling Team (CPT)
- End-to-End Forecast System

The Roadmap has been developed to ensure the synchronization of the observing program (e.g. NAME 04) with the modeling and data assimilation efforts. In particular, the objective is to facilitate a timely two-way flow of information so that the modeling and data assimilation activities provide guidance to the evolving observing program, and that the observations provide information for advancing model development

Brief summaries of a few of the major activities in the Roadmap are given below:

#### **I. Climate Model Assessments**

- **North American Monsoon Assessment Project (NAMAP)**

The North American Monsoon Model Assessment Project (NAMAP) provided an indication of the ability of numerical models to simulate atmospheric variability across southwestern North

America during the summer season. The activity was designed by the NAME research community as an attempt to engage the broader modeling community in advance of NAME 2004. The simulations were carried out independently by six modeling groups (two global models, four regional models) for a single summer season (1990). Examination of the cross-model variability, together with comparisons to available observations, provided motivation for enhanced observations in data-poor areas during the NAME 2004 Field Campaign. The NAMAP analysis also motivated metrics to quantify model simulation quality and improvement to be followed in modeling activities in this proposal. An online Atlas (Gutzler et al. 2003), found on the NAME webpage, documents the performance of the NAMAP models in simulating several key variables (precipitation, temperature, low-level winds and moisture transport). Emphasis is placed on the diurnal cycles of these fields, motivated by the NAME working hypotheses regarding the importance of understanding the diurnal cycle and the seasonal evolution of the North American monsoon. The main NAMAP web page hosted by NCAR/EOL (<http://www.eol.ucar.edu/projects/name/namap/index.html>) contains links to the modeling protocols, brief descriptions of each model, and an online order form for obtaining output via anonymous ftp.

- **North American Monsoon Assessment Project 2 (NAMAP2)**

This project involves systematic evaluation of model performance in the NAME domain, including several global and regional models, and testing different convective parameterization schemes (Relaxed Arakawa Schubert, Grell, Kain-Fritsch, etc.) in one or more of the models. Simulations will be performed for the 2004 summer (coinciding with the NAME 2004 Enhanced Observing Period). Large-scale evaluation will focus on metrics identified by NAMAP (Gutzler et al. 2004), including simulations of monsoon onset to within 1 week of the observed onset and simulations of the monthly mean diurnal cycle of precipitation to within 20% of the observed diurnal cycle over the core region of the North American monsoon. More detailed local evaluations will also be performed, guided by the availability of NAME 2004 data, especially soundings and convection observations.

- **Diurnal Cycle Experiments**

NAME is evaluating the diurnal cycle in three global AGCMS (NCEP, GFDL and GMAO). An initial comparison of the seasonal means from coarse resolution runs (approx. 2 deg) has been completed. The comparison indicates that the models have remarkable similarities in their bias with a generally wet bias over northwestern Canada and Alaska, and a dry bias over the central and southwestern United States. All three models produce realistic diurnal variations in the Great Plains low level jet. On the other hand the models have difficulty in reproducing the diurnal cycle of precipitation, including over the heart of the North American monsoon region. Both the NASA and GFDL models fail to capture the nocturnal maximum in the Great Plains, while the NCEP



model produces a more realistic diurnal variation. Initial attempts to link the differences in the precipitation to differences in CAPE suggest a complicated relationship in which it is important to understand the details of the convection schemes (e.g. inhibition and trigger functions) as well as how the schemes interact with the boundary layer schemes. Current efforts center on developing more detailed diagnostics of the performance of the convection and boundary layer schemes, and carrying out sensitivity studies including runs with enhanced resolution.

- **Impact of Resolution on Warm Season Precipitation Forecasts**

Experiments were designed to determine the horizontal resolution needed in the NCEP Global Forecast System (GFS) to forecast realistic North American monsoon precipitation. Summer season simulations for selected years were performed at high resolution [T126L28] and low resolution [T62L28] with 28-levels in the vertical in each case. Experiments were performed with prescribed observed sea surface temperatures to assure that simulation errors come from model deficiencies (Mo et al. 2004).

- **High Frequency Features of North American Summer Climate**

NAME has been analyzing the North American monsoon in the broader context of the global annual cycle (e.g. Mapes et al. 2004). The Annual Cycle Explorer (ACE) (Mapes et al. 2004) has been developed to depict high-frequency features, such as monsoon onsets. Comparisons of observations and output from a dozen global climate models are planned.

- **Precipitation Assessment Project (PAP)**

During the build-up phase of the NAME program, the NAME community developed a comprehensive archive of satellite and gauge precipitation estimates for use during the NAME 2004 field campaign and in subsequent diagnostic and modeling studies aimed at improved understanding, simulations and ultimately predictions of warm season precipitation over North America. This NAME "Precipitation Assessment Project" or PAP, was a no-cost contribution of data by various groups in support of NAME. All precipitation products were subset for the NAME domain at the highest spatial and temporal resolution available (for later temporal averaging) and put into a common format. The NCAR Earth Observing Laboratory (EOL) currently maintains a master list of all NAME-related precipitation datasets ([www.eol.ucar.edu/projects/name/](http://www.eol.ucar.edu/projects/name/)), including those gathered for the NAME PAP. Some of the gauge and satellite estimates available to the NAME community were listed in section III, part 2.

## **II. Climate Data Assimilation**

## **NCEP High Resolution North American Climate Analysis System and NAME 2004 Data Impact Studies**

A series of global and regional data assimilation and forecast experiments are underway at NCEP to explicitly test the impact of NAME 2004 enhanced observations on analysis quality, and to provide real time monitoring and assessment products to NAME. For the global experiments we exploit the NCEP operational Climate Data Assimilation System (CDAS) II , which is also used to provide the boundary conditions for the regional analyses. For the regional experiments we are implementing the NCEP Regional Reanalysis (RR) assimilation system so that the RR climatology can be used to put current anomalies in the proper historical context. Because of the regional aspect of the monsoon, a fine resolution regional analysis may be needed to capture small-scale regional features. The data impact study will also be performed using the operational EDAS of January 2005 with the 12 km Eta model. Analyses both with and without NAME 2004 data are underway and forecasts based on the initial conditions from the analyses with and without the NAME data will be made to examine the impact of the enhanced observations on analyses and forecasts. In addition, these analyses will provide verification data for global model experiments, and serve as benchmarks for other data impact studies.

### **III. Climate Model and Forecast System Development**

- **NAME Climate Process and modeling Team**

The NAME Climate Process and Modeling Team builds on NAMAP (Gutzler et al. 2004) and the diurnal cycle experiments (Schubert et al.) discussed above. The NAME CPT is organizing and implementing NAMAP2, which will re-examine the metrics proposed by NAMAP, extend the NAMAP analysis to transient variability, and exploit the extensive observational database provided by NAME 2004 to analyze simulation targets of special interest. Vertical column analysis will bring local NAME observations and model outputs together in a context where key physical processes in the models can be evaluated and improved. In addition, the NAME CPT build on the current NAME-related modeling effort focused on the diurnal cycle of precipitation in several global models, including those implemented at NCEP, NASA and GFDL. Activities focus on the ability of the operational NCEP Global Forecast System (GFS) to simulate the diurnal and seasonal evolution of warm season precipitation during the NAME 2004 EOP, and on changes to the treatment of deep convection in the complicated terrain of the NAMS domain that are necessary to improve the simulations, and ultimately predictions of warm season precipitation. The findings and recommendations from both the NAME Diurnal Cycle Experiments and NAMAP2 will be tested at NCEP to ensure maximum development and improvement of the NCEP operational model.

#### ***End-to-End Climate Forecast System***

The NAME End-to-End Forecast System is aimed at improving the skill of warm season precipitation forecasts using a fully coupled atmosphere-ocean-land surface forecast system. This activity has the following components: (i) Predict global SSTs using fully coupled ocean-atmosphere-land surface forecast system; (ii) Forecast large scale atmospheric circulation anomalies on the continental scale directly from the global atmospheric model (Tier III); (iii) Forecast precipitation and circulation anomalies on the regional scale (Tier II) using the high resolution global model or a regional model with downscaling; (iv) Model moist convection, land breeze / sea breeze interactions, and land / atmosphere interactions in the core monsoon region (Tier 1) using high resolution regional models or explicit cloud resolving models; and (v) Hydrometeorological Applications from regional models with downscaling. Strong links to the NOAA CTB are required to accelerate the transition of improved warm season precipitation forecasts into NOAA climate forecast operations. Some specific examples of activities to be carried out in the context of the End-to-End forecast system include:

### ***Sensitivity to Boundary Conditions (SST, soil moisture, vegetation)***

NAME will conduct special model experiments in addition to "control runs" for the 2004 warm season, to examine model sensitivity to anomalous surface boundary values. These experiments will involve versions of the NCEP coupled forecast system (CFS) or the associated atmospheric model (GFS). The experiments will include studies of the response of the models to several prescriptions of Gulf of California SST, equatorial Pacific SST, and land surface sensitivity experiments. Land surface conditions, soil moisture in particular, have been shown to have a large impact on warm season climate prediction in many observational and numerical studies. For example, in the NCEP GFS the prediction skill of surface temperature increases considerably over the core monsoon region with initialized soil moisture. Overall, these experiments emphasize that a proper description of the land surface is required to improve warm season climate prediction.

### ***Dynamical Seasonal Prediction of warm season precipitation***

For real time warm season forecasts of precipitation and surface temperature, the boundary conditions are unknown. The best SST estimates come from ocean atmosphere coupled models. Current coupled models can forecast SST anomalies in the Nino 3.4 area with an anomaly correlation near 0.85, indicating that they are able to forecast ENSO. However, there are still large errors in portions of the Tropics and in the extratropics. The skill of coupled model forecasts must be assessed to establish a baseline for improvements. Some experiments to be performed using the two tier approach include: (a) seasonal forecasts with error corrected SSTs, (b) seasonal forecasts performed by a high resolution atmospheric model with error corrected SSTs, (c) seasonal forecasts performed using a high resolution atmosphere-ocean coupled model, and (d) seasonal forecasts with an ocean-atmosphere-land surface coupled model and proper initialization.

### ***Drought monitoring and prediction***

Over the past several years western North America has endured drought conditions. A Drought Early Warning System (DEWS) for North America would help to mitigate the impacts of drought, including human suffering and property losses. A DEWS system is under development utilizing a real-time observational data base, operational global and regional analyses, the NCEP

North American Land Data Assimilation System (NLDAS) and the NCEP fully Coupled Forecast System (CFS). The DEWS enhances the drought monitoring and forecasting capabilities for North America. The drought monitoring and forecast products developed for DEWS will forge strong ties between NAME, the GAPP core project, the NOAA CTB, and the external user community.

### *Hydrometeorological applications*

The NAME Hydrometeorological Working Group (NHWG) was formed to address critical issues pertaining to hydrometeorology, hydroclimatology and water resources throughout the NAME region. From recent analyses, it is clearly evident that there exists an increasing warm season influence on hydrologic systems, in general, and streamflow, in particular, as one proceeds southward from the southern Rocky Mountain region into the core region of the North American Monsoon (NAM) in western Mexico. Catchments within the core region of the NAM exhibit, on average, maximum precipitation and runoff during the summer and early fall months from July through October. While the North American Monsoon Experiment (NAME) Science Plan acknowledges surface hydrologic processes as important elements in the generation and sustenance of the NAM climate system and its associated variability, many key issues related to the generation of streamflow, soil moisture and, more broadly, water resources are not specifically addressed. It is the intent of the of the NAME Hydrometeorology Working Group (NHWG) to define such critical issues and provide, in the context of NAME, process critical data and research which address current uncertainties in hydrologic understanding in the NAM region. The synthesis of such findings is aimed at the underlying goal of NAME itself, which is to increase predictability in warm season hydroclimatic processes. For more information, see the NAME Hydrometeorological Working Group Homepage <http://www.eol.ucar.edu/projects/name/hydromet/index.html>

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