1.2 MULTI-SCALE INTERACTIONS DURING THE NORTH AMERICAN MONSOON

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ABSTRACT

Some multi-scale interactions of key phenomena affecting the North American summer monsoon are examined. Emphasis is placed on a synthesis of early results from the North American Monsoon Experiment (NAME) 2004 Field Campaign. Several topics are briefly addressed including terrain influences on the diurnal cycle of convection, up-scale organization of convection, tropical cyclone-Gulf surge-precipitation relationships, influences of the Madden-Julian Oscillation on the timing and frequency of tropical cyclones and Gulf surges, and the role of the land surface in modulating monsoon precipitation from diurnal to inter-seasonal timescales.

1.0 INTRODUCTION

Improved warm season precipitation forecasts over North America are of tremendous interest and value, especially in areas where water is relatively scarce such as southwestern North America. However our ability to predict warm season anomalies is currently very limited. The international North American Monsoon Experiment (NAME) was organized to improve our understanding and ability to predict warm season precipitation fluctuations in the monsoon region of southwest North America (see section 2). A driving hypothesis is that we need to improve simulations of the diurnal cycle of convection and the organization, upscale growth and propagation of convective events in the core of the continental monsoon precipitation maximum in northwestern Mexico.

The NAME Model Assessment Project (NAMAP; Gutzler et al. 2005) was carried out in advance of the NAME 2004 field campaign to determine the state-of-the-art of warm season climate modeling and to provide benchmark simulations for testing the NAME hypothesis. NAMAP included 6 participating groups (4 regional models / 2 global models), all of which simulated a single common warm season (1990) that exhibited high summer rainfall. The NAMAP analysis identified several important problems with current model simulations, including delayed monsoon onset (August instead of July) in global models, incorrect amplitude and phase of the diurnal cycle of convection, poorly constrained surface quantities (temperature, latent and sensible heat fluxes), and weak linkages between low-level jets and precipitation. The NAMAP analysis also highlighted several key multi-scale issues that need to be addressed in models:

- Weak coupling between the diurnal cycle, propagating convection and large-scale circulation / waves;
- Improper representation of coastal effects (e.g. sea/land breeze effects on diurnal cycle of precipitation;
- Ineffective generation of precipitating systems over complex terrain (e.g. frequency; intensity);
- Absence/weaknessof mesoscale systems (e.g. convective parameterizations are scale separated);
- Missing effects of transients (e.g. easterly waves; synoptic-scale waves) on organized convection;
- Difficulties with regime transitions (e.g. onset / demise of MJO and influence on active/break periods and transients);
- Poor constraint on the magnitude of surface fluxes (e.g. large inter-model variability on sensible and latent heat fluxes).

The NAME 2004 observations offer a unique opportunity to improve our understanding of multi-scale variability in the monsoon region as an important prerequisite to improving our model simulations and predictions. Several studies in the special issue of the *Journal of Climate* on NAME have used the NAME 2004 data sets for this purpose (e.g. Lang et al. 2007; Johnson et al. 2007). In this brief review paper we highlight three examples from those studies to help direct future modeling studies focused on these issues. The three examples are: (i) the

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diurnal heating cycle and monsoon precipitation; (ii) tropical cyclone -gulf surge - precipitation relationships; and (iii) land-atmosphere interactions and local-regional feedbacks/forcing to the atmosphere. Prior to presenting the examples in section 3, we provide a bit of background on the NAME program (section 2).

2.0 NAME PROGRAM

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. 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 (OAL) models. 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). The NAME program is overseen and directed by a Science Working Group (SWG) that is charged with developing and leading the cooperative international research to achieve NAME objectives. Recently the SWG organized and implemented an international (United States, Mexico, Belize, Costa Rica), multi-agency (NOAA, NASA, NSF, USDA, DOD) field campaign during the summer (June-September) of 2004. 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, which is northwestern Mexico, the southwestern United States, and adjacent oceanic areas. During the campaign data were gathered from more than 20 different types of instrument platforms, including surface meteorological stations, radars, aircraft, research vessels, satellites, windprofilers, rawinsondes and raingauge networks. The campaign involved scientists from more than 30 universities, government laboratories and federal agencies, including more than 30 weather forecasters. At least 15 U.S. National Weather Service / Weather Forecast Offices and 4 of the National Centers for Environmental Prediction (NCEP) (Hydrologic Prediction Center, the Tropical Prediction Center, the Storm Prediction Center, and Climate Prediction Center) participated in the campaign.

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 Mexican National Weather Service (Servicio Meteorólógico Nacional or SMN). NAME empirical and modeling studies are leveraging the NAME 2004 data to accelerate improvements in warm season precipitation forecasts, products and applications over North America. A comprehensive NAME webpage (www.joss.ucar.edu/name) covers all aspects of the project, including a science and implementation plan (NAME Science Working Group 2004), data, and documentation. A special issue of the *Journal of Climate* containing over 20 articles on NAME will be available in the spring of 2007.

3.0 MULTI-SCALE INTERACTIONS IN THE CONTEXT OF NAME

3.1 THE DIURNAL HEATING CYCLE AND MONSOON PRECIPITATION

During the monsoon season (typically June-September in the core monsoon region) daytime heating leads to afternoon and evening showers and thunderstorms that fire along the Sierra Madre Occidental (SMO), shift to the west and, less so, to the east, and gradually die off during the night. Mesoscale circulations (e.g. between land and sea or between mountains and plains) help to initiate and sustain propagating convective systems (lines or complexes) that tend to last well into the night. Convective systems sometimes develop during the night in regions affected by low-level jets, most notably in the U.S. Great Plains).

Satellite estimates of the mean diurnal cycle of precipitation departures from average (Fig. 2) show that rainfall begins along the upper west slopes of the SMO and then propagates both westward (primarily) and eastward (secondarily). Consistent with this, results from the NAME Event Raingauge Network (NERN) show a lagging of the diurnal cycle of rainfall intensity with elevation (Fig. 3). In particular, precipitation intensity peaks along the upper slopes of the SMO (2500-3000 m) in the early afternoon and along the Coastal Plain (0-500 m) in the late afternoon. In addition, the peak intensities increase in magnitude with lower elevation, with the strongest average intensities (roughly 5.5 mm hr^{-1}) along the Coastal Plain (0-500m). There is also increased intensity in the nocturnal signal in the 0-500 m band compared to that at higher elevations.

Lang et al. (2007) used the multi-radar network operated in the southern Gulf of California (GoC) region during NAME 2004 to analyze the spatial and temporal variability of local precipitation. They found that terrain played a key role in the diurnal cycle, which was dominated by convective triggering during the afternoon over the peaks of the SMO. They identified two disturbed regimes. During Regime A, precipitation moves off the mountains towards the GOC, with significant "refiring"along the sea-breeze front. During non-Regime days any organized features are confined to higher terrain. During Regime B, there is significant coast-parallel movement of systems towards the north. Regimes A and B often overlap in time. In these cases convection has the capability to organize, scale upwards, propagate and produce more rainfall. A preliminary look at reanalysis data suggested links between disturbed regimes and tropical easterly waves, though additional analysis is needed because of the limited number of cases. While Lang et al. (2007) were able to show that the diurnal cycle is very different between regime and non-regime days, significant uncertainty exists as to the dynamical and thermodynamical factors that are contributing to the organization, upscale growth and propagation of convective events in the NAM region.

The results above are synthesized into a conceptual model of monsoon storm development (Fig. 4), with frequent light precipitation events over high terrain from comparatively shallow clouds with relatively warm tops and less frequent initiation of organized deep convection (lines, clusters) with colder cloud tops and heavy precipitation (Hong et al., 2006). It is worth noting that IR-based satellite precipitation estimates underestimate the frequency of light precipitation events and overestimate the frequency of heavy precipitation events, and that posterior correction with additional gauge data provides significant benefit (Wei Shi, personal communication).

A vertical cross section of the mean (1 July – 15 August) flow perpendicular to the SMO over the southern Gulf shows that the daily heating cycle is associated with westward advection of moisture from the SMO centered near 600-hPa, moist onshore flow at low levels west of the SMO, mean subsidence over the Gulf and convergence over the crest of the SMO with divergence aloft near 200-hPa (Johnson et al. 2007). These features are associated with a deep land-sea breeze circulation in the vicinity of the central Gulf region. The afternoon sea breeze circulation peaks near 1800 LT, while there are offshore flow maxima near 600-hPa and 150-hPa during the afternoon and evening. The boundary layer along the coastal plains dries out in the afternoon due to surface heating. The nocturnal land breeze circulation peaks near 0600 LT, with onshore flow maxima near 600 and 150 hPa during the morning. The boundary layer along the coast and over the Gulf moistens during the night due to surface evaporation and offshore flow bringing moisture westward from the SMO. A vertical cross section of the mean (1 July – 15 August) flow along the axis of the Gulf of California reveals 3 moist layers with strong SE flow (Johnson et al. 2007): a shallow layer near 950-hPa associated with the nocturnal low-level jet (LLJ), a layer near 600-hPa associated with the westward extension of the Bermuda high, and a layer near the tropopause associated with the monsoon high aloft.

Examination of westward and eastward propagating transients and their relationship to precipitation continues to show that synoptic scale transient structures act as significant modulators of the time-mean circulation and are often responsible for episodic pulses of moisture to regions peripheral to the primary monsoon region of western Mexico (Douglas and Englehart, 2007). Rainfall attributed to synoptic scale transients such as tropical easterly waves, inverted troughs and backdoor cold fronts can often constitute a significant fraction of the seasonal rainfall for a particular region. In fact the 2004 NAME field campaign was heavily influenced by backdoor cold fronts. Additionally, the frequency of these features show marked interannual variance in response to large scale forcing. Further work on the multi-scale interaction of synoptic disturbances on the monsoon regional circulation is needed to improve our understanding and prediction of rainfall variability in monsoon affected regions.

3.2 TROPICAL CYCLONE-GULF SURGE-PRECIPITATION RELATIONSHIPS

During the monsoon season tropical easterly waves frequently pass through the monsoon domain, often culminating in eastern Pacific tropical cyclones (hereafter TCs). Aside from their direct impacts on precipitation, TCs often trigger propagating disturbances, such as moisture surges, that have important remote influences on the monsoon precipitation patterns (e.g. Higgins and Shi 2006; Johnson et al. 2007). Thus, TCs, moisture surges, and their multi-scale interactions are important features of the North American monsoon system that must be understood in order to improve simulations and predictions of warm season precipitation with climate models.

Gulf surge activity can influence the monsoon at any stage of the monsoon life-cycle. For example, during NAME 2004 the first major pulse of moisture into the Southwest US associated with the onset of the monsoon occurred on 13 July in association with a strong Gulf surge. This surge was linked to the westward passage of Tropical Storm Blas to the south of the Gulf of California. The development of Blas appeared to be associated with an easterly wave that moved westward into the eastern Pacific during the active phase of a Madden-Julian Oscillation. The evolution of the observed precipitation and anomalies relative to the onset of this surge (defined as day 0) at Yuma, AZ is shown in Fig. 5. The progression of enhanced precipitation along the west coast of Mexico and into the Southwest is clearly evident. Atmospheric soundings and profilers and shipboard measurements indicated that onset was associated with strong SE flow along the Gulf (Johnson et al. 2007) and the advection of warm water into the Gulf (Zuidema et al. 2007).

Northward propagating surges of relatively cool, moist, maritime air from the eastern tropical Pacific into the southwestern United States via the Gulf of California (GOC) are common during the North American monsoon season. These events are associated with episodic increases in wind speed along the Gulf, in most cases originating at the southern end of the Gulf of California and subsequently propagating northward (Johnson et al. 2007). The majority of these wind increases (Gulf surges) are accompanied by increases in the north-to-south pressure gradient along the Gulf, with pressure rises in the south preceding those in the north within the desert heat low. Cases in which the southerly flow extends to the south of the Gulf are typically linked to TCs (Johnson et al. 2007). Surges connected to the northern half of the Gulf are generally attributed to downdraft outflows from mesoscale convective systems along the SMO.

Higgins and Shi (2006) examined relationships between Gulf surges and TCs in the eastern North Pacific basin during the period July-August 1977-2001. They found that roughly half of all Gulf surges are related to TCs (Table 1). The response to the surge in NW Mexico and the SW United States is strongly discriminated by the presence or absence of TCs. Surges that are related to TCs tend to be associated with much stronger and deeper low-level southerly flow, deeper plumes of tropical moisture, and wetter conditions over the core monsoon region than surges that are unrelated to TCs (Fig. 6). The response to the surge is also strongly influenced by the proximity of the TC to the Gulf of California region. TCs that track in close proximity to the Gulf region exert a stronger, more direct influence on Gulf surges than those that track away from the Gulf. Roughly 6 in 10 of the TC-related Gulf surges have a direct relationship, while the remaining ones are indirect (Table 1).

Even when influenced by a TC, the response to the surge in the southwestern U.S. also depends strongly on the location of the upper-level monsoon anticyclone in midlatitudes at the time of the surge (Higgins et al. 2004). During wet surges the axis of the monsoon anticyclone was typically located to the east of the Four-Corners region, permitting a deep layer of tropical moisture to be advected into Arizona and New Mexico from the south and east. During dry surges, the axis of the monsoon anticyclone was located near the west coast, permitting midtropospheric northerly flow around the east side of the monsoon anticyclone to cap the atmosphere, inhibiting convective development even when a shallow, moist southerly flow was present near the surface.

Work is underway to investigate the influence of the Madden-Julian Oscillation (MJO) on TC-surge-precipitation relationships. The MJO is an intraseasonal fluctuation or "wave" that modulates the pattern of tropical rainfall with a period of roughly 30-60 days. During the NH warm season the MJO modulates the occurrence of TCs in the Atlantic and Pacific basins (Fig. 7; from Higgins and Shi 2001). For the period July-August 1977-2001 there was a 40% increase in Gulf surge frequency during periods when the MJO favored enhanced convection in the Western Hemisphere over periods when the MJO was inactive. When the MJO is active in the Western Hemisphere and there is a TC in close proximity to the southern Gulf of California, it is likely that any surge activity will be strong. The effect of MJO activity on monsoon rainfall also exhibits significant spatial variations such that precipitation in Arizona and NW Mexico shows a relationship to MJO phase while precipitation in New Mexico does not (Lorenz and Hartmann, 2006). Though these events are relatively rare, this is a potentially useful forecast tool. No statistically significant relationship between ENSO phase and the frequency of surge events has been identified, though this may be due to the insufficient number of ENSO events in the period 1977-2001.

3.3 LAND-ATMOSPHERE INTERACTIONS

The role of the land surface, vegetation-dynamics and moisture recycling within various monsoon-affected regions remain poorly understood. Several recent studies have focused on the role of antecedent , cold-season precipitation and soil moisture as forcing mechanisms modulating monsoon onset and intensity. Correlations between winter and summer precipitation in the Rocky Mountains, southwest Mexico and northwest Mexico are transient as they tend to exhibit variability on interdecadal timescales (e.g. Gutlzer and Preston 1997; Zhu et al., 2007; Hu and Feng, 2004). Historical evidence suggests that this relationship is best characterized as a tendency for wet winters to be followed by dry summers with delayed monsoon onset and vice versa, though this relationship does not always hold. The physical hypothesis for an inverse relationship in seasonal precipitation is that wet winters yield comparatively cool, moist land surface conditions during the following spring and that this land surface state reduces the regional scale land-sea temperature contrast thereby weakening or delaying the formation of the summertime thermal low and monsoon anticyclone. Hu and Feng (2004) suggest that the influence of the land surface in modulating the monsoon regional climate may be important, but only in epics where large scale teleconnective forcing is relatively diminished. Other studies have suggested that El Niño-Southern Oscillation (ENSO) variability on inter-annual timescales is a significant driver of this inter-seasonal linkage but that ENSO's influence on the monsoon varies over time and can be somewhat regionally-specific (Brito-Castillo et al., 2003; Gochis et al., 2006b; Higgins and Shi, 2001; Hu and Feng, 2002). Further modeling work is required in order to better characterize the physical linkages between local and remote forcing mechanisms.

Following monsoon onset the land surface in the semi-arid regions of southwestern North America undergo a dramatic transformation (Fig. 8). The replenishment of soil moisture and reduction in extreme aridity from monsoon moisture contribute to a rapid greening of the deciduous tropical forests along the western and eastern slopes of the SMO (Watts et al., 2007). Although the broadband albedo of the region has been shown not to change greatly, there is a marked difference in the thermal and moisture state of the land surface following onset. Depending on location in western Mexico about 15-30% of the monsoon rainfall is converted into streamflow (Gochis et al., 2006a). Assuming a comparatively small fraction of the remainder percolates to recharge regional aquifers, a significant fraction of monsoon rainfall is evaporated back to the atmosphere. This recycling of moisture is thought to help drive, and in some cases stabilize, the regional precipitation regime (Dominguez et al., 2006). In particular, recycling of moisture appears to be particularly important after onset in drier regions along the U.S.-Mexico border and into Arizona / New Mexico. In these regions episodic moisture flux inputs are also critical in replenishing moisture for evaporation and thermodynamic instability (Becker and Berbery, 2006). However, since relatively few PBL observations were collected during NAME it remains unclear how the land surface fluxes interact with regional scale features such as the land-sea and mountain-valley circulations to initiate convection (Vivoni et al., 2007).

4.0 SUMMARY

A brief overview of the flow on multiple scales ranging from the large scale (e.g. MJO) down to the mesoscale (e.g. MCS's) in association with the North American monsoon was presented. Convection, Gulf surges, and other regional-scale and local phenomena are modulated by and interact with flows over this wide range of scales.

Many of the basic features of the monsoon precipitation climatology, its diurnal cycle, and its association to topography have been documented and confirmed during NAME. However significant uncertainty exists as to what the dynamical and thermodynamical factors are contributing to the organization, upscale growth and propagation of convective events in the monsoon region. Additionally, large discrepancies between operational products pose significant challenges to model verification efforts, as well as basic diagnostic analyses. Posterior correction of monitoring and forecast products with additional station data appears to provide significant benefit in removing biases in the operational products.

Transient features in the monsoon region (tropical easterly waves, TCs, inverted troughs, and Gulf surges) are documented in unprecedented detail within the NAME 2004 data set. Although only a small portion of the findings are reported here (see the NAME issue of the Journal of Climate for additional results), the full complement of NAME observations reveals the multiscale characteristics of these phenomena. Eastward and westward propagating transients, including tropical easterly waves and TCs, act as significant modulators of the time-mean circulation, and are often responsible for episodic pulses of moisture (Gulf surges) and changes in the precipitation patterns in the monsoon region. In a large-scale context, the timing and frequency of TCs and Gulf surges are linked to the arrival in the eastern Pacific of the active phase of the MJO. On a regional scale, the strong southerly surface wind accelerations associated with Gulf surges are in response to increasing pressure gradients along the Gulf. Improved understanding of the possible role of these moisture flux patterns in modulating the large-scale subtropical circulation connecting the Atlantic and Pacific Oceans remains a key research need. Renewed interest in the role of the Intra-America-Seas (Gulf of Mexico, Caribbean, tropical North Atlantic), and the partitioning of the moisture budget into northward (Great Plains) and westward (Central American) components should be pursued.

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Table 1. Number (fraction in percent) of total surge events at Yuma, AZ that were TC-related and not TC-related during the period July-August 1979-2001. Yuma surges are further subdivided into those with direct (indirect) relationships to TCs. (Higgins and Shi 2006)

Category	Number of Events
All	132
TC-Related	65 (49%)
Not Related to TCs	67 (51%)
Direct	38 (58% of TC-related)
Indirect	27 (42% of TC-related)

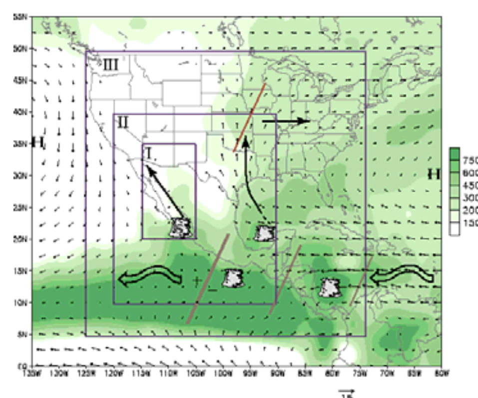


Figure 1. Schematic Illustrating the multi-tiered approach of the North American Monsoon Experiment (NAME). The schematic also shows mean (July-September 1979-1995) 925-hPa vector wind (m s^{-1}) and merged satellite estimates and raingauge observations of precipitation (shading) in millimeters. Circulation 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°-15°N (40°N) to indicate westward (eastward) propagation of disturbances such as easterly waves (midlatitude fronts).

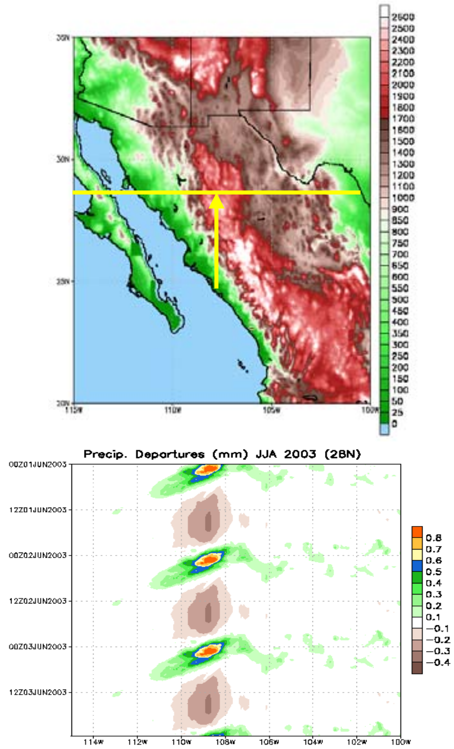


Figure 2. Mean diurnal cycle of precipitation departures from average (28°) for June-August 2003. Results are from CMORPH (CPC Morphing Technique), which uses IR data along with passive microwave data to create global rainfall analyses (60°N-60°S) at high spatial and temporal resolution. (Janowiak et al. 2007)

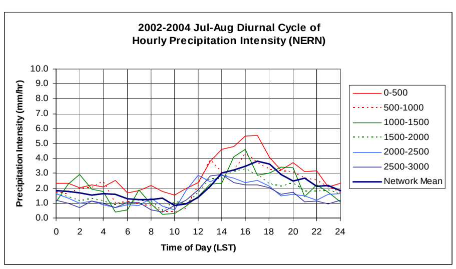


Figure 3. Diurnal cycle of hourly precipitation intensity for July-August 2002-2004 based on data from the NAME Event Raingauge Network (NERN). Results are expressed in mm hr^{-1} for eleveation bands given in the key. (Gochis et al. 2007)

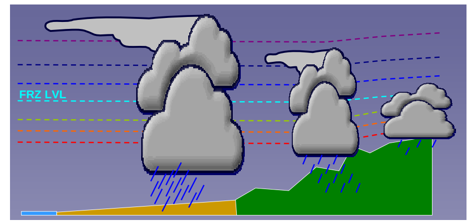


Figure 4. Conceptual model of monsoon storm development.

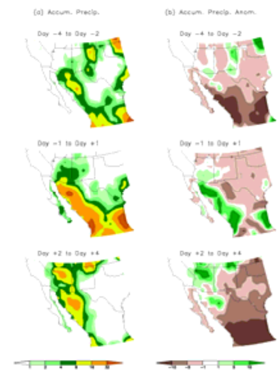


Figure 5. Evolution of (a) accumulated precipitation (mm) and (b) accumulated precipitation anomalies (mm) for the 13 July 2004 surge at Yuma, AZ. Day 0 is the onset date of the surge at Yuma. The accumulation period relative to onset is indicated on each panel. The shading intervals are given by the colorbar. (Higgins and Shi 2006).

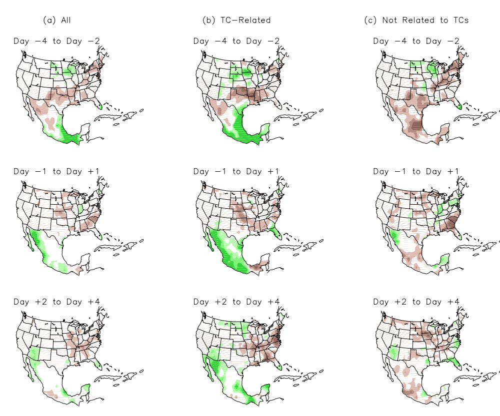


Figure 6. Composite evolution of accumulated precipitation anomalies (mm) for (a) all surges, (b) TC-related surges and (c) surges not related to TCs. Surges are keyed to Yuma, AZ. Day 0 is the onset date of the surges at Yuma. The accumulation period relative to onset is indicated on each panel. The shading interval is 1 mm $day^{-1}$and values greater than 1 mm day^{-1} (less than -1 mm day^{-1}) are shaded dark (light). (Higgins and Shi 2006)

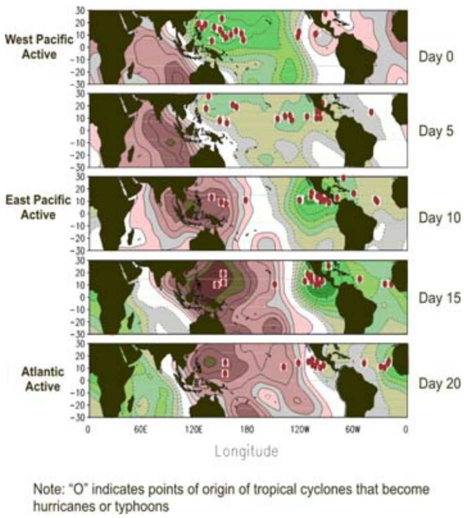
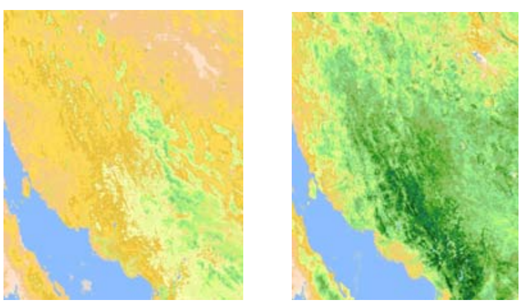


Figure 7. Velocity potential composites for different phases of the MJO cycle with hurricane/typhoon origin locations. Green shading indicates upper level divergence (favoring enhanced precipitation) and brown shading indicates upper level convergence (favoring suppressed precipitation). Open circles indicate hurricane/typhoon origin centers. (Higgins and Shi 2001)



a) 15 May, 2006 b) 10 Sept., 2006

Figure 8. MODIS derived NDVI from northwest Mexico a) before monsoon onset and b) during the mature phase of the monsoon (Images provided courtesy NASA , http://rapidfire.sci.gsfc.nasa.gov)