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IMPACT OF TROPICAL EASTERLY WAVES ON GULF SURGES DURING THE NORTH AMERICAN MONSOON

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1. INTRODUCTION

During the warm season, there is a distinct maximum in rainfall over the southwestern United States and northwestern Mexico. This yearly maximum in rainfall is associated with the North American Monsoon (NAM) and it accounts for 60-80% of the annual rainfall in northwestern Mexico and nearly 40% of the yearly precipitation in Arizona (Douglas et al. 1993). Monsoon onset is characterized by a distinct shift in winds to a more southerly direction below 700 hPa as well as a sharp, marked increase in rainfall, which usually first occurs in July with a gradual decrease in rainfall beginning in September (Barlow et al. 1998). Throughout this time period, several areas in Mexico receive greater than 300mm of rain, and along the slopes of the Sierra Madre Occidental, the ground cover changes from desert-like to tropical in a matter of weeks (Douglas 1993).

The rainfall over the NAM region is typically produced by deep convection, and in the deserts of the southwestern United States, severe weather is known to occur during the monsoon season. Thunderstorms with strong downbursts, heavy rain and flash flooding, intense cloud-to-ground lightning, hail and occasionally small tornadoes have generated hazards to both humans and their property (McCollum et al. 1995).

The source of moisture for these monsoon thunderstorms has been the subject of debate over the past several decades. Earlier studies indicate that the main supply of water vapor originates over the Gulf of Mexico (Bryson and Lowry 1955; Green and Sellers 1964; Jurwitz 1953). Rasmusson (1967) disputes this theory by noticing moisture fluxes that are inconsistent with the Gulf of Mexico being the major source of water vapor. In addition, Reitan (1957) observes that 80% of the precipitable water in Phoenix, Arizona, is between the surface and 800 hPa. Hales (1974) agrees with Reitan (1957) and Rasmusson (1967), suggesting that the Gulf of Mexico could not be responsible for the significant increase in lower level moisture over the NAM region. This is due to the high peaks of the Sierra Madre Occidental in western Mexico acting as a formidable barrier to the progression of low-level Gulf of Mexico moisture westward. Douglas et al. (1993) concurs that the Gulf of Mexico does not supply the water vapor needed for the NAM. They argue that if the Gulf of Mexico is in fact the main moisture source for western Mexico and the southwest portion of the United States, topographically forced convection would be present across eastern and central Mexico, which it is not. Hales (1972) recognizes that the Gulf of California has been neglected as a possible source of moisture for the NAM and suggests that "gulf surges", induced by the passage of tropical easterly waves, supply the needed moisture for these events. This previous work leads to the current consensus that at the lower levels, moisture predominantly comes from the Gulf of California, whereas at mid-levels, moisture originates over the Gulf of Mexico (Schmitz and Mullen 1996; Higgins et al. 1998; Berbery 2001).

One explanation for the transport of NAM low-level moisture northward is the "gulf surge". The gulf surge hypothesis has grown to become a widely accepted idea in recent years (Hales 1972; Brenner 1974; Hales 1974; Douglas et al. 1993; Douglas 1995; McCollum et al. 1995; Stensrud et al. 1995; Schmitz and Mullen 1996; Stensrud et al. 1997; Douglas et al. 1998; Fuller and Stensrud 2000; Berbery 2001; Berbery and Fox-Rabinovitz 2003; Douglas and Leal 2003; Saleeby and Cotton 2004). Generally, gulf surges appear to be initiated by the passage of a tropical easterly wave across the southern end of the Gulf of California (Hales 1972; Brenner 1974; Stensrud et al. 1997). These events are characterized by a net transport of cool, moist air northward using the Gulf of California as a natural channel, bounded by Baja California to the west and the Sierra Madre Occidental to the east. As the surges move to the north along the gulf, they have several effects on the surrounding environment. Hales (1972) and Brenner (1974) observe the following characteristics of gulf surges:

(1) Cooler temperatures, increased dewpoints, a rise in pressure, decreased visibility, increased cloud cover, and strong southerly winds.

(2) A distinct increase in thunderstorm activity in Arizona.

(3) Shallow vertical extent, with the most noticeable effects near the surface.

(4) Low-level cooling decrease and loss of surge definition as the surge moves into the desert and spreads out over Arizona.

Reed et al. (1977) study the structure and properties of tropical easterly waves (TEWs) over western Africa and the eastern Atlantic Ocean. Many of the TEWs that originate in these areas eventually impact the NAM region by potentially inducing a gulf surge. The waves in this study occur during the GARP Atlantic Tropical Experiment (GATE) in the summer of 1974. From August 23 to September 19, eight wave disturbances pass over the region. Reed et al. determine that these waves have an average wavelength of 2500 km, a period of approximately 3.5 days, and an easterly propagation speed of 8 m/s using a compositing method. Thus, at most eight TEWs can pass across Mexico during a one month period, although months with no TEW passages also are observed. In addition, TEWs are most pronounced in the horizontal wind field at 700hPa, where there is a cyclonic circulation with a distinct northeast-southwest tilt. Fuller and Stensrud (2000) show that nearly three-fourths of gulf surges are associated with TEWs by examining 14 years of European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis data.

While observing the highly localized monsoon rainfall is challenging, Stensrud et al. (1995) prove that a suitably constructed and initialized mesoscale model can accurately depict the large-scale and mesoscale features of the NAM. By conducting 32 successive 24 hour simulations, they find that such a model can detect southerly low-level flow over the Gulf of California, upslope flow along the western slopes of the Sierra Madre Occidental during the day, the diurnal cycle of convection, and a low-level jet that forms over the northern gulf and intensifies during surge events. This differs significantly from the work of Dunn and Horel (1994) that shows the operational 81-km ETA model to have serious difficulties in reproducing signatures of the monsoon. Dunn and Horel feel the errors originate from the unsatisfactory resolution of important topographical features over the region. In addition, gulf surges, which supply much of the moisture for the NAM, are a mesoscale phenomenon and are not resolved well in models with a larger grid spacing (Stensrud et al. 1997).

In this study, the effects of tropical easterly waves on gulf surges and the NAM are examined through use of the Fifth-Generation National Center for Atmospheric Research/Pennsylvania State University Mesoscale Model (MM5). A control run is compared to a simulation in which TEWs are removed from the boundary conditions to determine the impacts on fields such as meridional moisture flux, rainfall totals, and surge occurrences.

2. MODEL AND METHODS

The number of grid points used in the MM5 domain (x,y,σ) are 350x180x23 with a horizontal grid spacing of 25 km (Figure 1). The Kain-Fritsch convective parameterization scheme (Kain and Fritsch 1990) is implemented as well as a simple ice convective scheme (Dudhia 1989) and the MRF planetary boundary layer scheme (Hong and Pan 1996). The MM5 is initialized using the National Center for

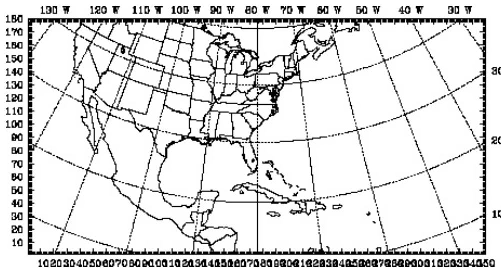

Figure 1. MM5 domain used in this study.

Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data. The data is interpolated onto the mesoscale model grid at the initial analysis time and each subsequent six hour interval. Sea surface temperature (SST) analyses are obtained from NCEP operational analysis, with further modification to capture the significant warming of the Gulf of California during the summer monsoon season.

To determine the importance of TEWs to surge events, a control run is compared to a model simulation where tropical easterly waves have been dampened or removed through harmonic analysis of the MM5 boundary conditions. Harmonic analysis allows the amplitude and phase of each harmonic to be determined. Since the data is both equally spaced in time and contains no missing values, the model data can be represented exactly given a series of n points by summing a series of n/2 harmonic functions (Wilks 1995)

$$y_t = \bar{y} + \sum_{k=1}^{n/2} \{A_k \cos[\frac{2\pi kt}{n}] + B_k \sin[\frac{2\pi kt}{n}]\}$$

where

$$A_k = \frac{2}{n}\sum_{t=1}^{n} y_t \cos(\frac{2\pi kt}{n})$$

and

$$B_k = \frac{2}{n}\sum_{t=1}^{n} y_t \sin(\frac{2\pi kt}{n})$$

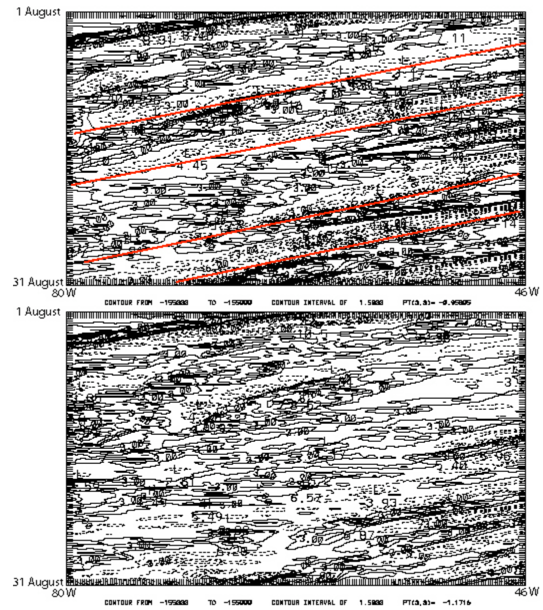

Figure 2. Hövmoller diagram of the 700 hPa meridional wind component along 20° N in August 1988 **(top)** control run and **(bottom)** simulation without TEWs. Red lines in top panel indicate location of TEW troughs.

For the model data series, the harmonic analysis is done within 10 points of the eastern, western, and southern boundaries of the model domain. Based on Reed et al. (1977), waves with periods of approximately 3.5 to 7.5 days are removed from the model simulation. This is achieved by replacing the amplitudes of waves representing TEWs with a value of zero south of 30˚N and then linearly increasing the amplitudes back to their original values between 30˚N and 35˚N. Hövmoller diagrams of the meridional wind component at 20˚N provide evidence of wave removal (Figures 2a-b). The waves show up as features that move from the upper right to lower left in the figures, in zones where the wind shifts from northerly to southerly. Since harmonic analysis is done only on the boundary conditions, it is important to note that if a TEW is contained in the initial conditions, the wave will be present in both model simulations.

3. RESULTS

While simulations were done for four different one-month periods, only the results from August 1988 are discussed here. The

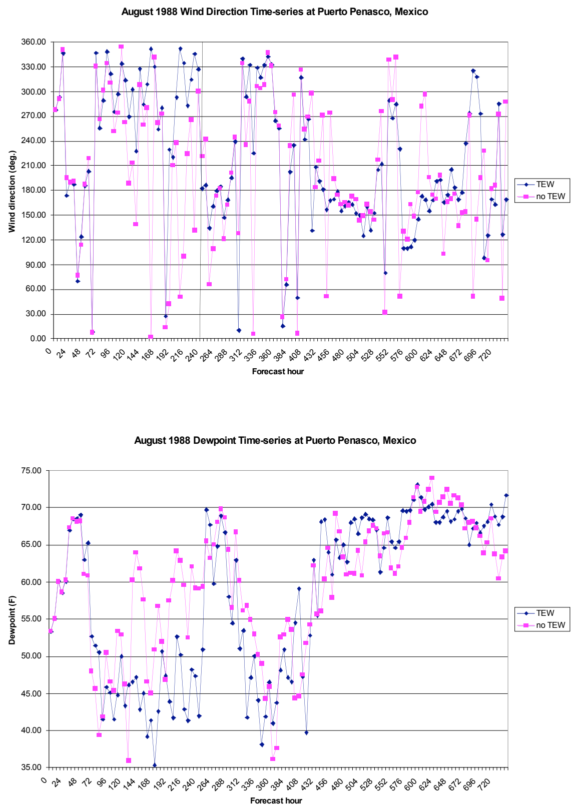

Figure 3. August 1988 time-series of wind direction and dewpoint at Puerto Penasco, Mexico. Time-series are done at the 0.945 sigma level.

presence of TEWs has noticeable impacts on the environment of the NAM region. In order to get an initial idea of simulated surge occurrences, time-series of various meteorological parameters are generated. The fields that are examined include temperature, dewpoint, wind direction, wind speed, meridional moisture flux, and sea level pressure. Surges are identified when the time-series indicate a southerly wind shift as well as an increase in dewpoint (Figures 3a-b). Decreases in temperature, increases in wind speed, and rises in sea level pressure are also typically associated with surge events although these parameters are not shown here. During the three surges in August 1988, the winds shift to a southerly direction in both the control run and the simulation without TEWs (no-TEW). However, the winds are generally not as consistently southerly nor are they as strong in the no-TEW run. Also, the dewpoints appear to remain elevated for a longer period of time after most surges.

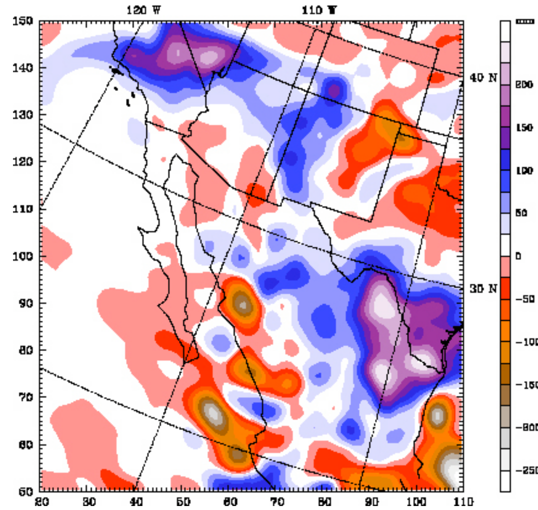

Figure 4. Total monthly rainfall differences over the NAM region (control –no TEW run). Rainfall is shown in millimeters.

This shows that TEWs may be important to surge strength and longevity.

After the approximate times of surge events are determined, TEW passages are examined to find whether the surges can be associated with them. Each of the three surges that occurred during August 1988 appear to be related to the passage of a TEW over the Gulf of California. On average, a surge is found to occur within 6-12 hours of wave passage in the model simulation. Through examination of 700 hPa wind patterns and 650 hPa relative vorticity, TEWs that were apparent in the control run are largely missing from the run where the waves have been removed. It is important to note that not all TEW passages during August 1988 induced a gulf surge.

Rainfall amounts over the monsoon region are also affected by the absence of TEWs. A significant portion of the area impacted by the NAM has great simulated monthly rainfall totals when TEWs are present (Figure 4). During August 1988, TEWs appear to have the biggest influence on rainfall totals over the southwestern United States. In particular, rainfall is enhanced in the control run in an area that stretches from northwestern Mexico, across northern Arizona, and into southern California. This suggests a much farther northward extension of the NAM during

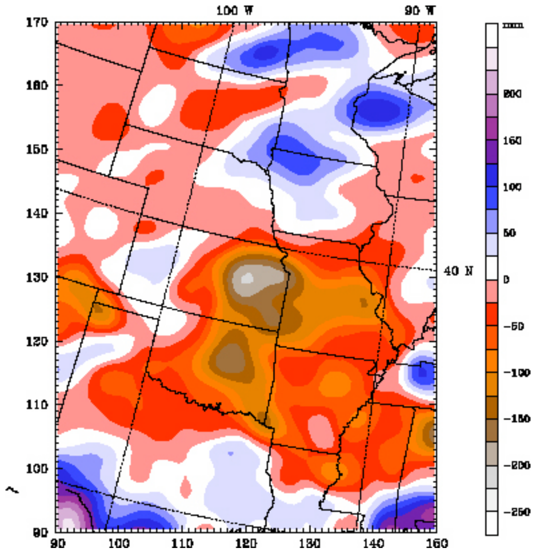

Figure 5. Total monthly rainfall differences over the Central Plains region (control –no TEW run). Rainfall is shown in millimeters.

1988 when TEWs are present in comparison to the run in which TEWs are removed. Thus, the moisture flux produced by the influences of TEWs may affect the northward extent of the NAM rainfall.

The effects of TEWs are not confined to northwestern Mexico and the southwestern United States. The U.S. Central Plains appears to experience a decrease in rainfall when TEWs are present (Figure 5) suggesting TEWs are important to rainfall in the central United States as well. While the precipitation differences are larger in the model simulations, Higgins et al. (1997) notice a similar change in the central U.S. precipitation distribution in association with monsoon onset. Results suggest that TEWs may also influence the amount of rainfall in the central United States during the summertime, in addition to their role in modifying the precipitation over the NAM region.

4. CONCLUSIONS

While only the results from August 1988 are shown here, simulations are also being done for August 1986, July 1990, and July 1992. Each month is unique in TEW activity and monsoon strength, yet results suggest that the removal of TEWs from the model boundary conditions produces substantial environmental changes in the NAM region. Reduction of TEW passages over the Gulf of California has an effect on the number of gulf surges, thereby decreasing rainfall amounts and northward moisture flux when TEWs are not present. While not all impacts of TEW removal on the NAM are shown here, the MM5 successfully captures many other mesoscale features associated with TEWs and the NAM. Future work includes determining any possible diurnal impacts of TEWs as well as the cumulative effects of TEWs and gulf surges.

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