

4.9 SENSITIVITY OF WET AND DRY NORTH AMERICAN MONSOON SEASONS TO VARIABILITY IN SEA SURFACE TEMPERATURE AND SOIL MOISTURE

Stephen M. Saleeby*
Colorado State University, Ft. Collins, Colorado
William R. Cotton
Colorado State University, Ft. Collins, Colorado

1. INTRODUCTION

The summer months over western Mexico and the western U.S. are annually influenced by a substantial increase in rainfall associated with the North American Monsoon System (NAMS). Many locations in the Desert Southwest and northwest Mexico can receive 40-60% of their annual rainfall in the months from June-September (Bryson and Hare 1974; Douglas et al. 1993). The Gulf of Mexico (GoM) (Carleton 1986), the Gulf of California (GoC) (Douglas et al. 1993; Saleeby and Cotton 2004), and the waters off the Pacific coast of the U.S. (Cavazos et al. 2002; Saleeby and Cotton 2004) all act as contributing moisture sources for monsoonal rainfall in the southwest U.S.

In addressing extreme warm seasons such as those in 1988 (wet monsoon) and 1993 (dry monsoon), Carleton (1990) attributes a wet (dry) monsoon season with increased (decreased) rainfall over the Desert Southwest in association with a northward (southward) displaced monsoon anti-cyclone. Likewise, Higgins et al. (1999) present a relationship whereby wet (dry) monsoon seasons correlate with an early (late) onset date into the U.S. relative to the average, which in turn, correlates with dry (wet) pre-monsoon conditions over the U.S. during the preceding winter and spring.

Inter-annual variability in the intensity, timing, and duration of NAMS is partly attributed to variability in the sea surface temperature (SST) over the tropical eastern Pacific and the tele-connections associated with the SST field (Higgins et al. 1998; Castro et al. 2001). While long distance tele-connections exert some control over the monsoon, Farrara and Yu (2003) have shown that SST anomalies tend not to be a *dominant* factor in explaining inter-seasonal precipitation variances associated with the monsoon. Their study revealed that variances in predicted summertime precipitation were inconsequential among simulations using climatological versus inter-annually varying SSTs. Carleton et al. (1990) noted that during wet monsoons, typically characterized by multiple, intense GoC surges, there exists a strong longitudinal gradient in SSTs between the GoC and west coast of Baja partially due to a negative SST anomaly over the eastern Pacific. In contrast, Cavazos et al. (2002) found that a positive SST anomaly over the eastern Pacific off the west coast of Baja, along with an enhanced latitudinal thermal gradient, favored a strong moisture flux over the Desert Southwest and a resulting wet monsoon.

Variability in soil moisture also contributes to inter-seasonal variations in warm season precipitation via convective and large-scale rainfall. Higgins et al. (1999) suggest that antecedent precipitation and soil moisture content provide a possible contributing factor to the timing of monsoon onset and intensity. Differential heating along soil moisture gradients can contribute to formation of convection (Chang and Wetzel 1991). Enhanced soil moisture tends to influence the relative surface sensible and latent heat fluxes (Small 2001) and alters the degree of convective inhibition (Colby 1984). Oglesby and Erickson (1989) found that drier soil results in reduced precipitation due to weaker evapotranspiration and subsidence aloft caused by higher temperatures, low pressure at the surface, and a strengthened monsoon ridge.

Our current modeling study involves an inter-seasonal modeling comparison of the 1988, 1993, and 1997 monsoon seasons, using the Regional Atmospheric Modeling System at Colorado State University (RAMS@CSU). We have chosen to simulate the 1988 and 1993 seasons due to their notoriety in exhibiting pre-monsoon-onset episodes of extreme drought (1988) and flooding (1993) followed by a post-onset reversal toward classification as anomalously wet (1988) and dry (1993) monsoons. The 1997 season is also presented as an extreme event due to a very strong El Niño present at that time. Andrade and Sellers (1988) note, though, that anomalously strong El Niños tend not to have a significant impact on precipitation over the southwest U.S. during the summer months due to the dominant monsoon signal and excess moisture flux that occurs regardless of the presence of El Niño.

In this current paper, we focus on examining extreme monsoon seasons to determine relationships among SST, soil moisture, and inter-seasonal variability and their influence on monsoon rainfall.

2. MODEL DESCRIPTION

Monsoon seasonal simulations were performed for the 1988, 1993, and 1997 warm seasons with use of the non-hydrostatic, compressible version of the RAMS@CSU model version 4.3 on an Arakawa-C grid and sigma-z terrain following coordinate system (Cotton et al. 2003). The model is configured with a two-grid, nested domain whose outermost grid spacing is 120km (115 x 90 x 36 grid points in the x, y, and z directions) and encompasses much of the north and western hemisphere. The center of the domain falls over the southwest U.S. as does the 40km nested grid (104 x 100 x 36) which covers the western two-thirds of the U.S. and nearly all of Mexico. Further information on

Corresponding author address: Stephen M. Saleeby, Colorado State Univ., Atmos. Sci. Dept., Fort Collins, CO 80523; e-mail: smsaleeb@atmos.colostate.edu

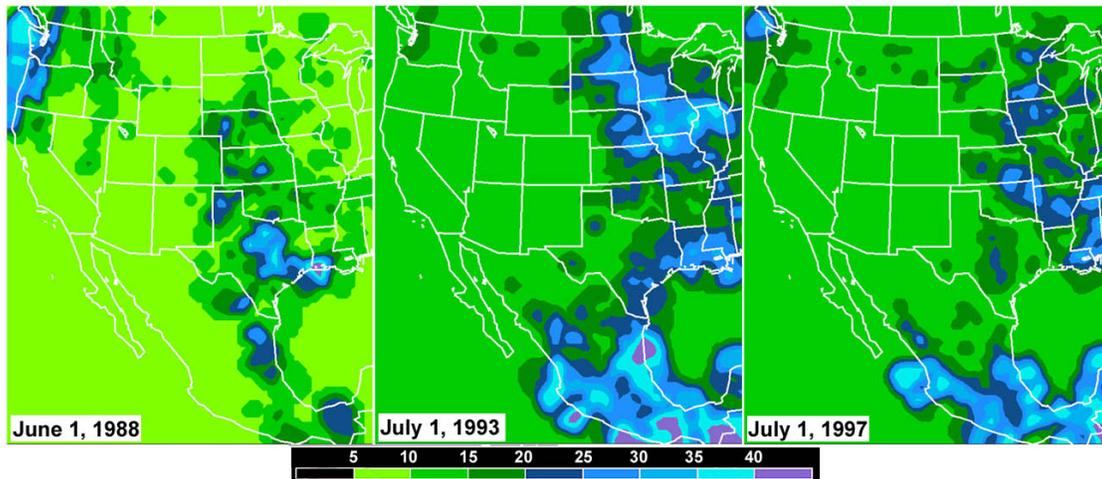


Figure 1. Volumetric soil moisture fraction ($\times 100$) for the above dates coinciding with model initial start times. Values obtained using the API technique. A maximum value of 42 indicates completely saturated soil; this maximum coincides with the porosity of the soil.

the RAMS model and the current setup are given in Saleeby and Cotton (2004). Soil moisture is initialized using API estimation (Blanchard et al. 1981), and initial SSTs are represented by the Reynolds weekly averaged data sets (Reynolds and Smith 1994). Initial conditions in soil moisture and SSTs vary considerably among these three simulation seasons due to differences in pre-season conditions and the various model start dates. Soil moisture initial fields are displayed in Figure 1 for each warm season.

Seasonal simulations chosen here are run for the following periods: June 1 - July 31, 1988, July 1 - August 31, 1993, and July 1 - August 31, 1997. These simulation periods encompass at least four weeks prior to the relative onset date through at least three weeks following onset. Specific monsoon onset dates in the U.S. are derived from guidance of the Precipitation Index method from Higgins et al. (1998) and from the surface characteristics of dewpoint, temperature, and meridional wind (v -wind) at Yuma, AZ from Stensrud et al. (1997). The onset dates are: June 24 in 1988, August 3 in 1993, and July 22 in 1997. Several sensitivity tests to soil moisture and SST variability were run for each season. The control (CTRL) is compared to simulations with: (1) a domain-wide reduction in SST by 4°C (SSTS1), (2) a cold SST anomaly over the northern GoC whose coldest point is 3°C cooler than observed (SSTS2), (3) a domain-wide reduction in soil moisture by 30% (SOIL1), and (4) a saturated soil moisture anomaly over northwest Mexico (SOIL2). Analysis of the experiment SSTS2 has been omitted from this paper since the relative influences of the SST anomaly were very small.

3. SENSITIVITY TO SOIL MOISTURE AND SST

a. Surface latent heat fluxes

Variations in SST and soil moisture directly influence the surface energy balance through variation in the surface latent and sensible heat fluxes. Altering the relative magnitudes of these surface fluxes influences the surface temperature as well as horizontal

and vertical moisture fluxes. These, in turn, can alter the larger scale circulation and result in precipitation differences (Small 2001).

The July averaged differences for 1800 UTC in surface latent heat fluxes due to the imposed SST and soil moisture anomalies are shown in Figure 2. These differences constitute the response of the fluxes compared to the control experiment, such that the sensitivity test values were subtracted from the control case (ie. CTRL-SOIL1). Positive (negative) values indicate a decrease (increase) due to the anomalies.

The reduced domain-wide soil moisture in experiment SOIL1 produces the most dramatic large-scale change in surface fluxes among the sensitivity tests. The maximum change in the average 1800 UTC latent heat flux is up to 250 W m^{-2} . For each season, the greatest change in latent heat flux occurs for regions with the greatest initial soil moisture. The 30% decrease in soil moisture produces the greatest magnitude change for saturated areas; so it is generally expected that reduced soil moisture = reduced latent heat flux. However, in 1993, portions of southern Iowa, northern Missouri, northern Illinois, and southern coastal Mexico experience a slight increase in the surface latent heat flux despite being in regions of maximum initial soil moisture. Despite a 30% reduction in soil moisture, these local zones of maximized soil moisture did not receive enough of a reduction to decrease latent heat flux. The soil moisture remained saturated enough such that evaporation and transpiration were still quite strong in the sensitivity test. There is a cut-off point in the surface model volumetric soil moisture at which transpiration will be significantly reduced so as to retain moisture in the vegetation root zone. This effect accounts for the very small change in fluxes in this region bounded by the large flux changes.

The local saturated soil moisture anomaly in experiment SOIL2 results in very small flux differences outside of the anomaly, with respect to the magnitude of the changes over the anomaly. Over the soil moisture anomaly, the increase in latent heat flux reaches a maximum change of nearly 250 W m^{-2} . Outside of the anomaly, flux changes are less than 25 W m^{-2} ; the sole

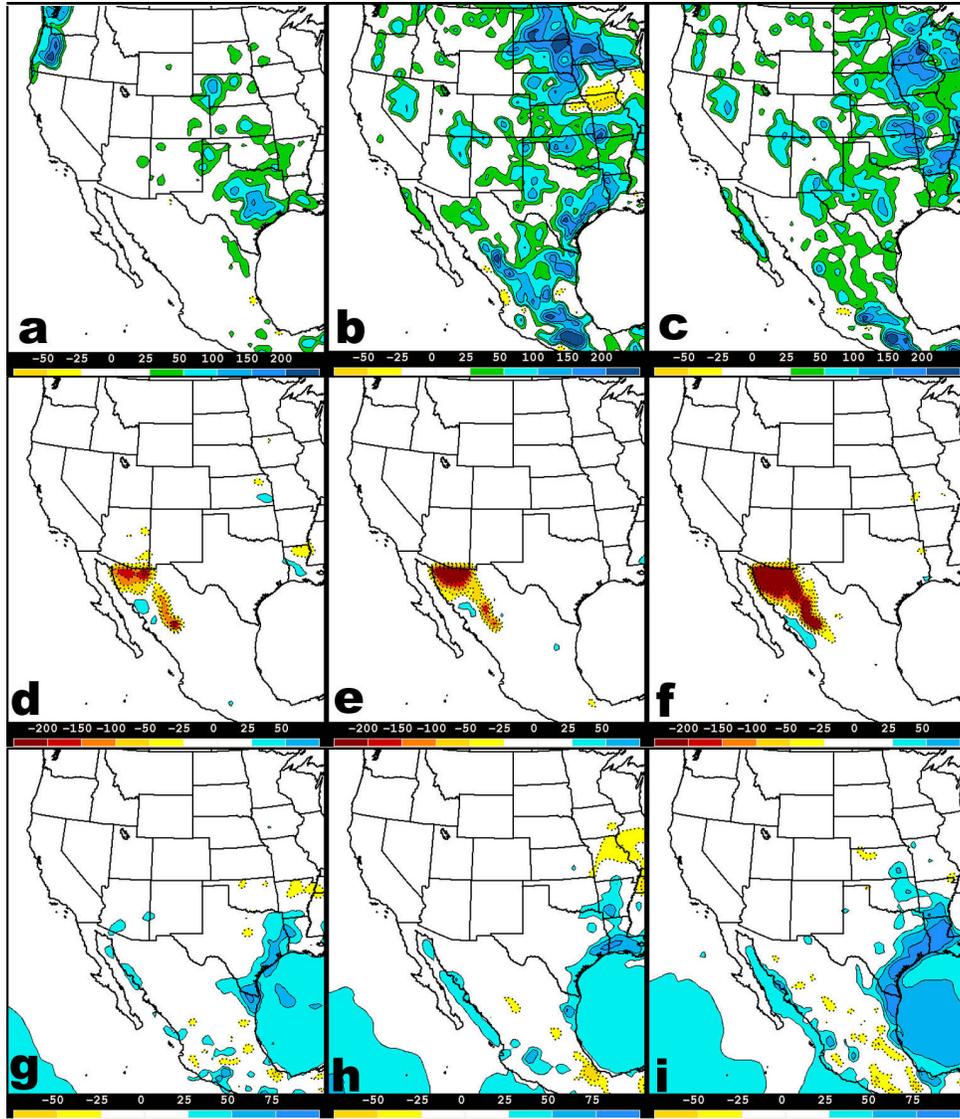


Figure 2. Average July maximum latent heat flux (1800UTC) difference (W/m^2) calculated as the control run minus: a) 88SOIL1, b) 93SOIL1, c) 97SOIL1, d) 88SOIL2, e) 93SOIL2, f) 97SOIL2, g) 88SSTS1, h) 93SSTS1, i) 97SSTS1.

exception is a small decrease along the Mexican coast in association with the southern portion of the anomaly. The small area of decreased latent heat flux over the southwest portion of the anomaly is partially due to the smaller magnitude changes in soil moisture; this region of the anomaly was initialized in the control run with moisture values above the background value seen over extreme northwest Mexico. This region of the anomaly is also adjacent to the flux change maxima over the SMO and is influenced by elevated convection during the course of the monsoon seasonal simulation.

In experiment SSTS1, the entire GoM and the coastal zones of the GoM and GoC experience a decrease in latent heat flux of up to $100 W m^{-2}$. The decreased latent heat flux is maximized right along the shore zone where onshore moisture flux and sea-breeze convection are maximized during the summer months. The flux differences were greatest for 1997. This season tended to exhibit the greatest near-surface horizontal

and vertical temperature differential along the GoM coast, which influenced the strength of the sea breeze circulation and regional precipitation.

b. Geopotential height

The imposed change in soil moisture and SSTs induced changes in the surface fluxes, which further induced perturbations in the geopotential height field due to altered vertical temperature and moisture profiles. The 500mb height field differences are shown in Figure 3. A reduction in the domain-wide soil moisture field generally resulted in increased heights and increased stability over the affected areas. In contrast, the local saturated soil moisture anomaly over northwest Mexico, which resulted in increased latent heat flux, reduced the height field and stability over the anomaly region; it also influenced areas into interior Mexico and the southwest U.S. where monsoon

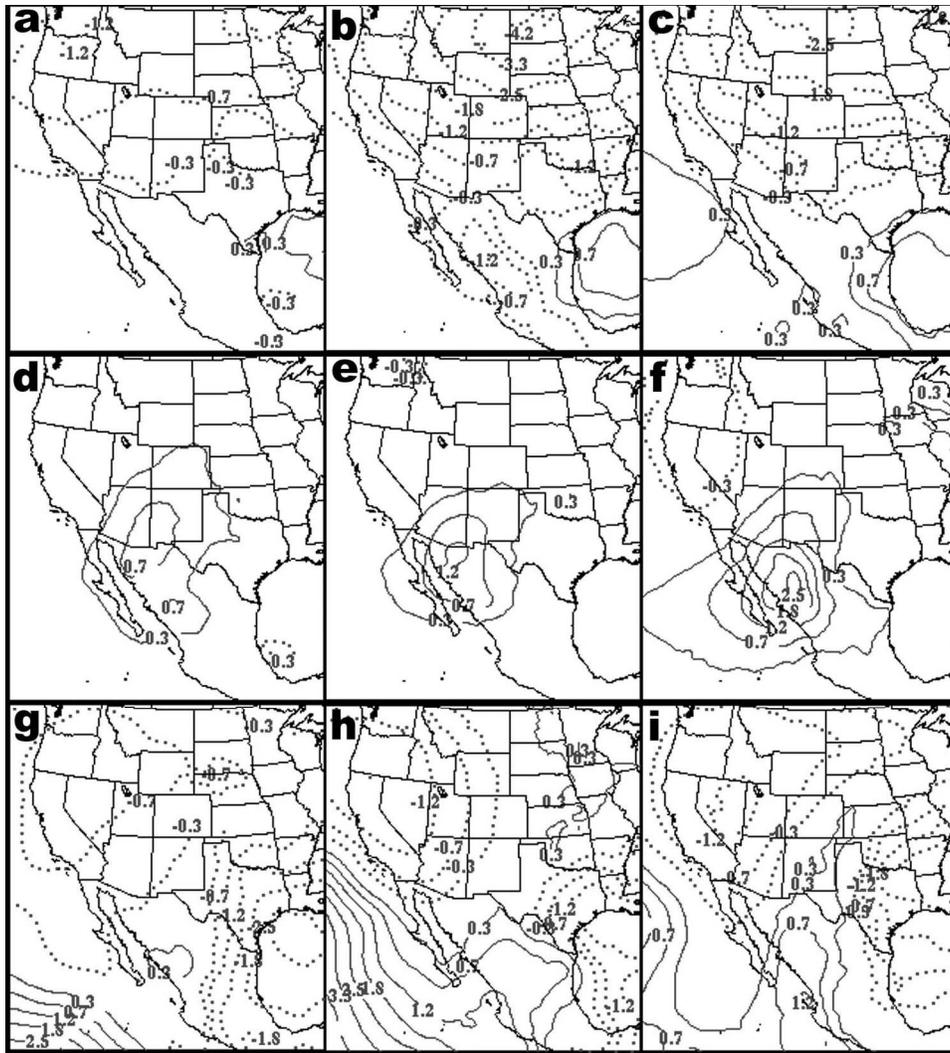


Figure 3. Average difference in the 500mb geopotential height field (m) for July calculated as the control run minus: a) 88SOIL1, b) 93SOIL1, c) 97SOIL1, d) 88SOIL2, e) 93SOIL2, f) 97SOIL2, g) 88SST1, h) 93SST1, and i) 97SST1.

convection has a pronounced affect. For both soil moisture tests, the trend follows that the greater the average change in latent heat flux, the greater the change in geopotential height over the affected area. Surrounding areas tend to be influenced as well, but to a lesser degree. Furthermore, the change in the height fields decreases with vertical distance from the surface.

For each season, the domain-wide reduction in SST reduced the height field to the greatest degree over the east Pacific and western Mexico over the core monsoon region. One would expect that reduced latent heat flux from cooler oceans would allow the 500mb heights to increase, but since the Pacific Ocean off of the Baja coast is quite cool, the temperature drop has a greater impact than the surface flux change. The cooler ocean reduced the air temperature near the surface and the overall 1000mb-500mb thickness. In contrast, the 500mb heights over the GoM and interior areas of the U.S. responded with a geopotential height increase, whose maximum for each season is centered over the GoM. Again, this is the region with the maximum

average reduction in surface latent heat flux. Generally, regions exhibiting less than a 0.70 m height difference experienced very little change in the surface latent heat flux and accumulated precipitation.

c. Accumulated Precipitation

In examining the entire U.S. and Mexico, it becomes apparent that the greatest magnitude changes in the accumulated July precipitation occur for the two tests in which the domain-wide perturbations were introduced. The local anomalies impacted the domain to a lesser degree. The impact was greatest within close proximity to the anomalies. Figure 4 reveals the precipitation differences. Imposing a domain-wide reduction in soil moisture produces a reduction of precipitation over most of Mexico and the western and central U.S., with the greatest differences of more than 30 mm for the month of July in 1993 and 1997 ($\sim 1 \text{ mm d}^{-1}$) over portions of Mexico. Though reduced precipitation is the primary response, the GoM

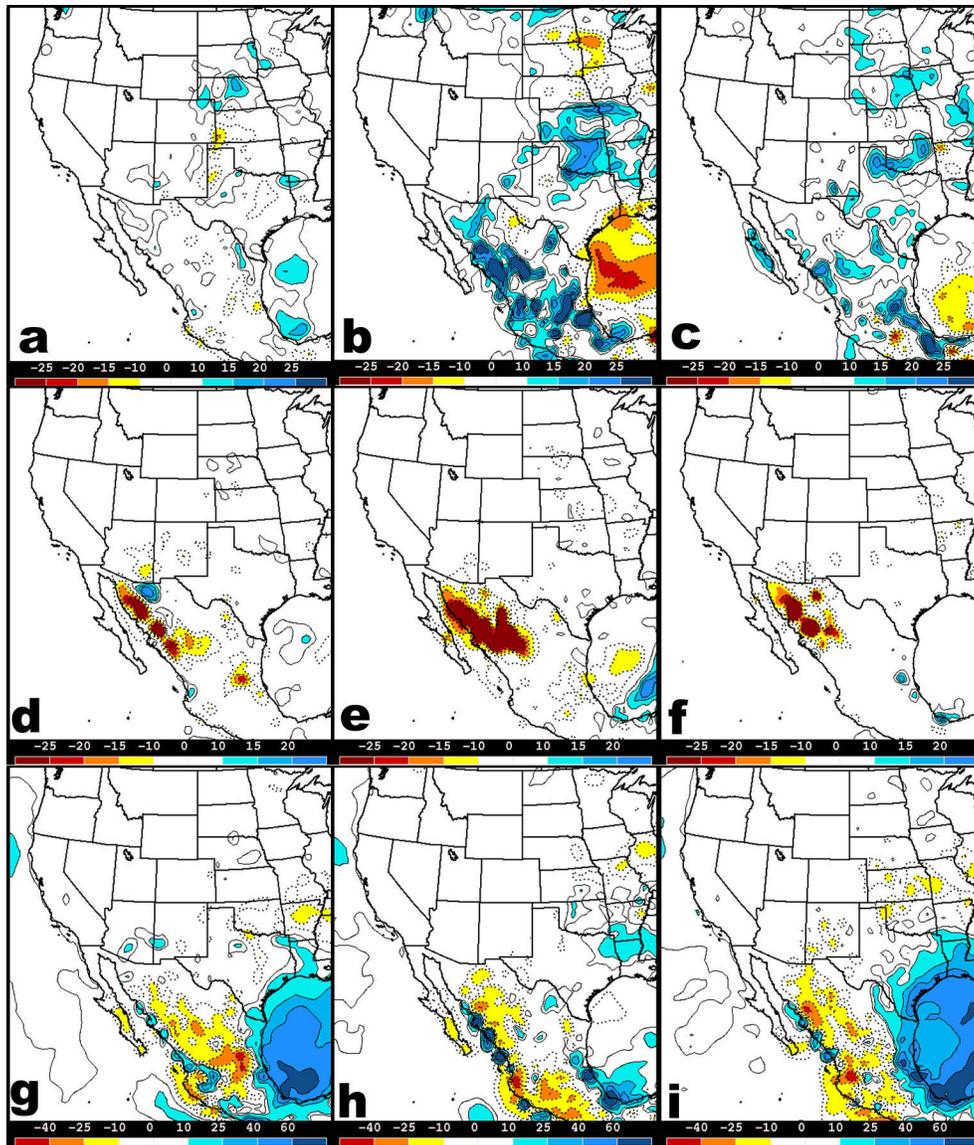


Figure 4. July precipitation difference (mm) calculated as the control run minus: a) 88SOIL1, b) 93SOIL1, c) 97SOIL1, d) 88SOIL2, e) 93SOIL2, f) 97SOIL2, g) 88SSTS1, h) 93SSTS1, i) 97SSTS1.

experiences an increase of up to 25 mm in 1993. This increase corresponds to the decrease in the height field over the GoM, which exists despite no change in the local surface fluxes. It is possible that the soil moisture reduction along the gulf coastal region played an indirect role in altering the height field upstream over the GoM. Finally, in comparing the altered precipitation among simulated seasons, it is apparent that a greater change in soil moisture induces a greater change in precipitation; this explains the weak change in 1988 given that the soil was initially very dry.

On a more local scale, the saturated soil moisture anomaly over northwest Mexico primarily imposed intense local changes to the precipitation accumulation in each simulated season. Over the moist anomaly, rainfall increases are greater than 30 mm during July for all three years. Of the three simulated seasons, 1993 experiences the greatest and most

widespread precipitation increase over northwest Mexico, despite exhibiting only the second largest latent heat flux change and height field perturbation among the three simulated seasons. So, we cannot assume that the greatest average surface flux change will produce the greatest precipitation change. Many other short term and mesoscale processes can influence the final precipitation outcome.

Imposing a strong cooling to the entire ocean surface temperature produces rather interesting results, such that, the greatest impact occurs primarily along coastal regions and the warmest ocean areas. The U.S. interior is only weakly affected, while the interior of Mexico largely experiences a broad increase in precipitation of ~15 mm with local maxima greater than 40 mm. Regions of significantly reduced precipitation, greater than 40 mm, appear along the east and west coasts of Mexico and over the GoM. These extremes

along the western coast extend slightly inland and between peaks in the orography of the Sierra Madres. Cooler ocean temperatures result in a decrease in latent heat flux, an increase in the height field, and less onshore moisture flux. In contrast, the greater land-sea temperature gradient tends to enhance the sea-breeze circulation. This helps explain the reduced precipitation along the coastline and enhanced precipitation over inland Mexico along the inland convergence zone and Mexican mountain ranges.

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4. CONCLUSIONS

The influence of variability in soil moisture and SST varies significantly with the type of monsoon season (wet, dry, or average) and with the magnitude and extent of the surface anomalies. A large-scale change in surface conditions produces the largest scale difference in precipitation. Generally, a decrease in soil moisture or SST reduces the surface latent heat flux, which increases the geopotential height and environmental stability and reduces the amount of rainfall. Mesoscale anomalies exert their greatest influence directly over the anomaly, though their range of influence does extend outward to an unspecified degree. The magnitude of downstream influence depends strongly on the magnitude of the anomaly and synoptic forcing. For example, for each season, the saturated soil moisture anomaly over northwest Mexico was imposed, yet the changes in surface fluxes and geopotential height were quite different among seasons. Further investigation is needed to fully understand why these differences arise given the same type anomaly for different monsoon seasons. On a final note, the resulting change in rainfall due to surface differences remains relatively small compared to the variability in rainfall that occurs depending upon the strength and location of the seasonal monsoon ridge. The average synoptic conditions are still the driving force behind the southwest monsoon.

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