AN *ALARMS* CLIMATOLOGY OF GULF OF CALIFORNIA MOISTURE SURGES AND THE ASSOCIATED PRECIPITATION, 1993–2004

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Abstract: This study applies the ALARMS (Assessing Low-level AtmospheRic Moisture using Soundings) method to 12 years of data from Phoenix, Arizona; Tucson, Arizona; Yuma, Arizona; and Empalme, Mexico, in order to establish a climatology of low-level moisture surges from the Gulf of California and their effects on precipitation. There are 64 events detected using the available data, and data inventories are used to estimate the actual number of events that occurred at each station for every year. Surge totals are consistent with previous research. Interseasonal variability cannot be significantly related to ENSO, but intraseasonal variability appears to be related to certain phases of the MJO. Composite soundings illustrate the atmospheric profile of typical surges, and it is clear that surface moisture values at Yuma, Arizona, are not consistent with moisture content in the low levels above the surface. Precipitation analyses show that increased low-level moisture significantly increases the amount of rainfall at each gauge as well as the number of stations receiving measurable precipitation. Also, rainfall is more likely on days with higher dewpoints, and gulf surges appear to significantly increase precipitation across the study area. [Key words: monsoon, moisture surge, Gulf of California, Arizona.]

INTRODUCTION

During the annual North American Monsoon, periodic surges of moisture travel northward along the Gulf of California and into the low-lying deserts of Arizona, southeast California, and southern Nevada. These gulf surges were first identified in the literature by Hales (1972), and they were described as displaying increased moisture, cooler temperatures, increased pressure, southerly winds, increased wind speeds, and decreased visibilities, all typically occurring below 700 hPa (Brenner, 1974; Adams and Comrie, 1997).

Originally, it was thought that the surges were the result of cool, moist, low-level air being channeled up the Gulf of California from an area of extensive cloudiness over the central or southern gulf (Hales, 1972; Brenner, 1974). The increased clouds were thought to be usually the result of mesoscale convective systems (MCS) over the gulf. Later research suggested that surges are the result of tropical storms or tropical easterly waves passing across or near the southern end of the gulf (Stensrud et al., 1997; Anderson, Roads, and Chen, 2000; Fuller and Stensrud, 2000; Higgins et al., 2004). Furthermore, some evidence suggests that strong surges typically occur when a mid-latitude trough passes to the north of the region several days prior to the passage of an easterly trough across the southern part of the region (Stensrud et al., 1997), although Higgins et al. (2004) could not support this claim.

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Douglas (1995) identified a mean southerly low-level jet (LLJ) along the Gulf of California that is likely related to gulf surges, and Douglas et al. (1998) argued that gulf surges could simply be the result of an increased LLJ. The idea of an LLJ was supported by Kanamitsu and Mo (2003) as well as Saleeby and Cotton (2004). However, a recent dynamic analysis (Zehnder, 2004) showed that gravity currents and ageostrophic winds are not strong enough to support surge-like flows along the entire length of the Gulf of California. According to Zehnder, Rossby edge waves appear to behave like observed surges, but the lack of observational data and the loss of detail in composite analyses make it difficult to diagnose accurately the actual dynamic mechanisms responsible for the initiation and propagation of gulf surges.

BACKGROUND

Since there is incomplete understanding about how surges form, most studies have focused on case studies of major events or on the simulation of surge-like flows through the use of numerical models (McCollum et al., 1995; Stensrud et al., 1997; Mullen et al., 1998; Anderson, Roads, Chen, et al., 2000; Berberry and Fox-Rabinovitz, 2003; Saleeby and Cotton, 2004). There have been few attempts to develop detailed climatological analyses of surge frequency, intensity, structure, and spatial extent. This is most likely due to the lack of a widely-accepted standard for identifying gulf surges, and observational data from the region are often sparse.

Many researchers have made the assumption that gulf surges increase precipitation across southern Arizona because of the increase in low-level moisture (Hales, 1972; Brenner, 1974; Adang and Gall, 1989; Dunn and Horel, 1994; Maddox et al., 1995; McCollum et al., 1995; Stensrud et al., 1997). However, no published studies have successfully correlated increased low-level moisture or gulf surges with increased precipitation across the deserts of Arizona (Adams and Comrie, 1997; Douglas et al., 1998; Fuller and Stensrud, 2000; Douglas and Leal, 2003). Douglas and Leal showed an apparent relationship between the arrival of gulf surges at Empalme, Mexico, and precipitation in the Mexican states of Sonora and Sinaloa, but results were not conclusive because of composition of large geographic areas and inclusion of mountainous terrain that tends to initiate convective precipitation by orographic processes (Douglas and Leal, 2003). Their study showed only modest enhancement of precipitation by gulf surges, and precipitation in the state of Sinaloa (situated along the east coast of the southern Gulf of California) was more likely caused by the passage of the tropical cyclones or easterly waves that initiated the surges rather than the surges themselves.

According to Mullen et al. (1998), intraseasonal variability of precipitation over the southwest United States shows little relation to the daily to synoptic-scale variability in low-level moisture transport over the Gulf of California as depicted in the T106 European Center for Numerical Weather Forecasting reanalysis product. Conversely, the precipitation anomalies over Arizona are associated with increases in mid-level southerly fluxes of moisture over the Sierra Madre Occidental and the Gulf of California (Mullen et al., 1998). Therefore, Mullen et al. suggest that low-level moisture is less important for convection than is precipitable water and subtle

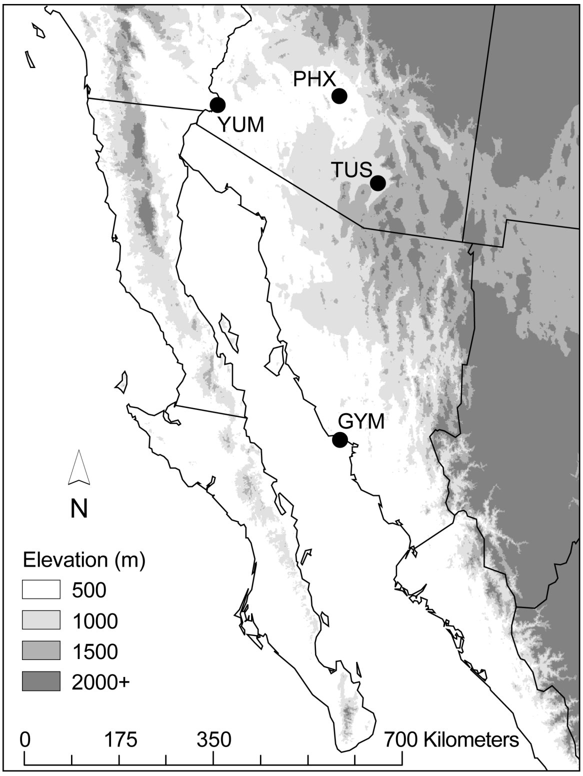

Fig. 1. Locations of the four sounding sites GYM (Empalme, Mexico), YUM (Yuma, Arizona), TUS (Tucson, Arizona), and PHX (Phoenix, Arizona) used in this study.

changes in vertical motion. Similarly, Higgins et al. (2004) show that rapid increases in surface dewpoints are not necessarily associated with increased precipitation across eastern Arizona and western New Mexico.

This study employs the method for Assessing Low-level AtmospheRic Moisture using Soundings (ALARMS), which identifies significant increases in low-level (~1 km above the surface) moisture that tend to occur with gulf surges (Dixon, 2005). The ALARMS method is applied to 12 years of sounding data (48 years of data from Tucson are used) in order to develop a detailed climatology of surges in northwestern Mexico and southern Arizona and to relate these events to precipitation across the region. The purposes of this study include: to validate further use of the ALARMS method, to identify temporal and spatial patterns of surge occurrence, and to test relationships between increased low-level moisture and precipitation.

DATA

The ALARMS method uses daily sounding observations from four sites (Empalme, Mexico; Yuma, Arizona; Tucson, Arizona; Phoenix, Arizona) to identify increases in low-level moisture associated with gulf surges (Fig. 1). In order to be

Table 1. Inventory of Available (0000 and 1200 UTC) Sounding Observations During the Study Period 1993–2004[a]

Year	GYM	YUM	TUS	PHX	Total
1993	25.0	21.8	100.0	28.2	43.8
1994	11.3	11.3	98.4	84.7	51.4
1995	70.2	2.4	99.2	79.8	62.9
1996	41.9	0.0	100.0	86.3	57.1
1997	79.0	8.9	99.2	88.7	69.0
1998	0.0	27.4	94.4	25.0	36.7
1999	21.0	29.0	100.0	31.5	45.6
2000	38.7	43.5	98.4	76.6	64.3
2001	34.7	41.1	100.0	54.0	57.5
2002	35.5	36.3	98.4	98.4	67.1
2003	46.8	29.0	98.4	94.4	67.1
2004	94.4	44.4	99.2	97.6	83.9
Total	41.5	24.6	98.9	70.4	47.1

[a] Values are expressed as percentage of possible days during the months of July and August (62).

identified by ALARMS, four consecutive days are required. Days 3 and 4 must experience a dewpoint at approximately 1 km above the surface (925 hPa at Empalme and Yuma; 850 hPa at Tucson and Phoenix) that is at least 4°C greater than days 1 and 2 (Dixon, 2005). Therefore, this method identifies significant increases in moisture rather than just extended periods of high dewpoints. The ALARMS method has been shown to be successful at identifying gulf surges using low-level moisture, especially when compared to other methods that use soundings or those that rely heavily upon surface data (Dixon, 2005).

Some common shortcomings of sounding-based methods used to detect gulf surges include decreased frequency (most sounding sites launch balloons twice daily), lower spatial resolution, and occasionally poor data availability. Nevertheless, a sounding-based method is preferred over surface-based methods because the profile of observations gives a better representation of events. Surface data in the region are easily influenced by thunderstorm outflow and intense diurnal winds, so "false alarms" are common when using surface data to identify surges (Douglas and Leal, 2003).

Radiosonde data were collected for the months of July and August during the years 1993–2004, but some years of the study experienced relatively sparse data availability. Prior to 1993, soundings were not regularly launched in Phoenix, Arizona (PHX). Since that time, Salt River Project (SRP), an Arizona utility company, has launched radiosondes during the monsoon season. Data from Yuma, Arizona (YUM), are sparse prior to 1992, and Empalme, Mexico (GYM), soundings, although reliable throughout most of the 1980s, were unreliable from 1990 through 1992. Tucson, Arizona (TUS), is the only station with a long and consistent record of reliable sounding data. Therefore, 1993 is the first year with at least three stations consistently reporting sounding observations, and data availability generally increases with time at all stations (Table 1). However, TUS sounding data for the years 1957–2004 are used to validate some of the findings of this project. As described by Dixon (2005), 0000 UTC and 1200 UTC sounding data are kept separate because of the extreme diurnal cycles experienced in this region. Therefore, surges must be detected using consecutive days of data from soundings launched at the same time, which makes it nearly impossible to determine the time of day that each surge initially passes the stations.

Phoenix sounding data are provided by SRP in Phoenix, Arizona. Data from the other three sounding sites were obtained from the Forecast Systems Laboratory in Boulder, Colorado (Forecast Systems Laboratory, 2004).

Precipitation values used in this study are based on rain-gauge observations from 81 surface weather stations located across the study area. Most of the data are from automated surface observing system (ASOS) stations or cooperative stations and are archived by the National Climatic Data Center (NCDC) in Asheville, North Carolina. This study utilizes data from 57 NCDC stations within Arizona and another 8 within Nevada. Some of these stations record hourly observations while most take only one reading per day. Therefore, only daily data are used in this study.

Data from another 16 stations are provided by the Arizona Meteorological (AZMET) network. The stations are operated and maintained primarily by the University of Arizona in order to provide climate and meteorological data for agricultural purposes. Precipitation data are totaled and archived each hour, but daily totals are calculated for this study. The archived AZMET data were obtained from the AZMET website (http://ag.arizona.edu/azmet).

CLIMATOLOGY

During the 12 years of this study, there were 64 events (32 in July; 32 in August) identified by the ALARMS method. This number is consistent with previous studies that have attempted to tabulate the number of gulf surges that occur each season (Fuller and Stensrud, 2000; Douglas and Leal, 2003; Higgins et al., 2004). Unfortunately, previous studies do not list specific surge events, so it is difficult to determine if the events identified in this study are the same events identified by previous studies. Significant interannual variability is seen during this study period, and some years experienced many more surges than other years. Tables 2–5 list the dates of each event recorded at the respective sounding sites.

There were 16 surges identified in GYM, 13 in YUM, 37 in TUS, and 26 in PHX. However, TUS was the only station without large periods of missing data. During 1993–2004, 0000 UTC observations were available from GYM only 26.3% of the time while 1200 UTC data were available 56.7% of the time. There are no 0000 UTC sounding data from YUM during the study, and 1200 UTC observations were available only 49.2% of the time. PHX sounding data from 0000 UTC and 1200 UTC were available 58.3% and 82.5% of the time, respectively. If these data shortcomings are accounted for, then it is probable that YUM experienced the most

Table 2. Significant Increases in Low-Level Moisture in Empalme, Mexico (Gym), as Identified by the Alarms Method for the Years 1993–2004[a]

Year	Month	Day
1993	7	29
1996	8	8
1996	8	14
1997	7	16
1999	7	6[b]
2000	8	22
2001	7	3
2002	8	18[b]
2003	8	18[b]
2004	7	3
2004	7	5[b]
2004	7	19[b]
2004	7	21
2004	8	17[b]
2004	8	23
2004	8	28[b]

[a] The day of surge onset is the first of at least two consecutive days with sufficiently increased dewpoints.

[b] Detected only at this station.

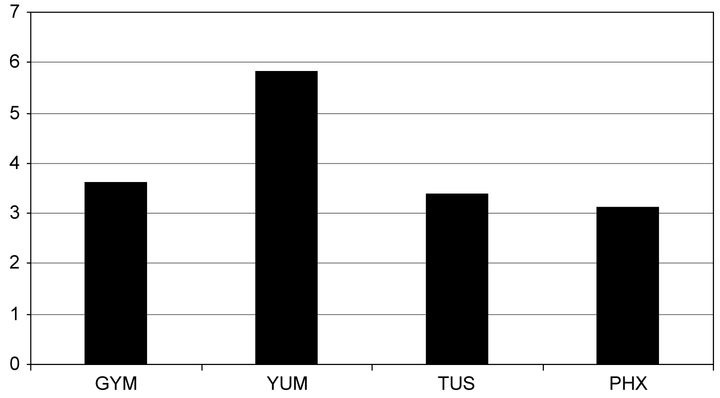

Fig. 2. Estimated average annual number of surge events at four sounding sites used in this study. Estimates are based on actual number of detected events and the percentage of available data.

events, followed by GYM, TUS, and PHX, respectively (Fig. 2). However, it should be noted that these estimates are based on percentages of available data (e.g., two detected surges in a year with only 50% of the data available will yield an estimated season total of four surges), so years with no available data will yield estimates of

Table 3. Significant Increases in Low-Level Moisture in Yuma, Arizona (YUM), as Identified by the Alarms Method for the Years 1993–2004[a]

Year	Month	Day
1998	8	5[b]
2000	7	15
2000	8	23
2001	7	18
2001	8	29
2002	7	10
2002	7	31
2002	8	4[b]
2003	8	8[b]
2003	8	13
2004	7	10
2004	7	24[b]
2004	8	6

[a] The day of surge onset is the first of at least two consecutive days with sufficiently increased dewpoints.

[b] Detected only at this station

zero. Therefore, years with no data are ignored when calculating average annual totals.

These results are consistent with past research that identifies YUM as the best location to identify surge events (Hales, 1972; Brenner, 1974; Stensrud et al., 1997; Fuller and Stensrud, 2000; Higgins et al., 2004). Nevertheless, inconsistent data are likely responsible for missing many surges, and the apparent intraseasonal and interannual variability makes it difficult to estimate accurately the number of surges missed. Thus, these estimates cannot be used to determine if multiple locations experience the same surge, so an all-station total cannot be estimated using the data percentages. For example, if it is estimated that GYM experiences four surges in a single season while six events occur at YUM, it is unknown whether there were only six total surges that year (with YUM detecting all six while GYM did not experience two events), or if there were as many as ten surges that affected only one station each.

Composite Soundings

Two different types of composite soundings (i.e., pre-surge, surge) were developed for each sounding site in this study in order to identify potential patterns for the purpose of forecasting surges and determining whether surges tend to be deeper at sites that are closer to the Gulf of California. The composites were calculated by dividing each sounding into 20-hPa layers and averaging all available observations

Table 4. Significant Increases in Low-Level Moisture in Tucson, Arizona (TUS), as Identified by the Alarms Method for the Years 1993–2004[a]

Year	Month	Day
1993	7	29
1995	7	6[b]
1995	7	14[b]
1995	8	2[b]
1995	8	11[b]
1996	8	2[b]
1996	8	9
1996	8	15
1997	7	4
1997	7	16
1997	8	16[b]
1998	7	3[b]
1998	8	25[b]
1999	8	10[b]
1999	8	14[b]
1999	8	26[b]
2000	7	7[b]
2000	7	14
2000	7	22
2000	7	28[b]
2001	7	4
2001	7	17
2001	8	9[b]
2001	8	29
2002	7	9
2002	8	1
2002	8	28
2003	7	6
2003	7	11
2003	7	18
2004	7	4
2004	7	9
2004	7	14[b]
2004	7	22
2004	8	2[b]
2004	8	13[b]
2004	8	24

[a] The day of surge onset is the first of at least two consecutive days with sufficiently increased dewpoints.

[b] Detected only at this station.

Table 5. Significant Increases in Low-Level Moisture in Phoenix, Arizona (PHX), as Identified by the Alarms Method for the Years 1993–2004[a]

Year	Month	Day
1993	8	24[b]
1994	7	10[b]
1994	8	5[b]
1994	8	8[b]
1995	7	27[b]
1995	8	7[b]
1996	8	9
1997	7	5
1997	7	27[b]
1997	8	4[b]
2000	7	20
2001	7	25[b]
2001	7	29[b]
2001	8	28
2002	7	9
2002	7	14[b]
2002	7	31
2002	8	12[b]
2002	8	29
2003	7	6
2003	7	11[b]
2003	7	19
2003	8	13
2004	7	7[b]

[a] The day of surge onset is the first of at least two consecutive days with sufficiently increased dewpoints.

[b] Detected only at this station.

for each layer. Every layer yielded an average pressure, temperature, and dewpoint that were then used to draw the composite. The "pre-surge" composite is made up of all soundings taken within two days prior to a surge onset, and the "surge" composite is composed of all observations taken during surge events. Both types of composites were developed for 0000 UTC and 1200 UTC at each site (no 0000 UTC observations are available from YUM during the study period).

For the most part, the composite soundings from all of the sites appear similar to each other. Surprisingly, the 1200 UTC YUM surge composite displayed the driest low-levels when compared to the 1200 UTC surge composites from the other sites. GYM surge composites for both 0000 and 1200 UTC were the most humid, and the 0000 UTC surge composite from PHX showed the overall driest atmosphere. As

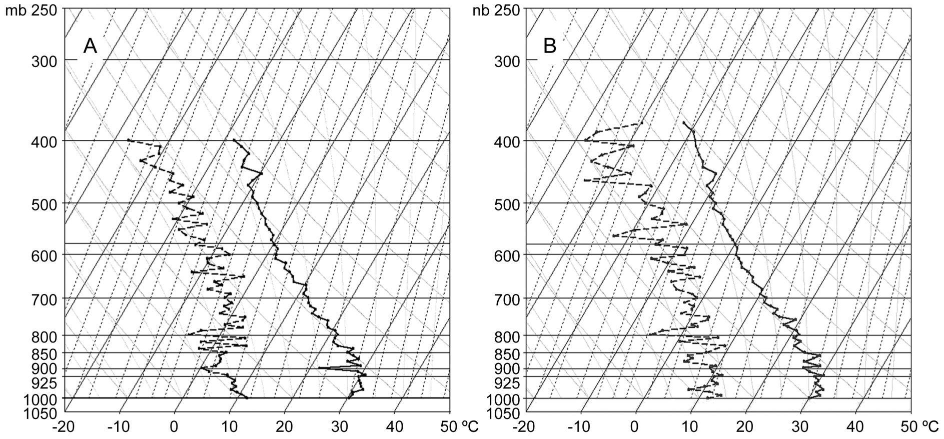

Fig. 3. (A) Composite pre-surge 1200 UTC sounding for YUM; (B) Composite surge 1200 UTC sounding for YUM.

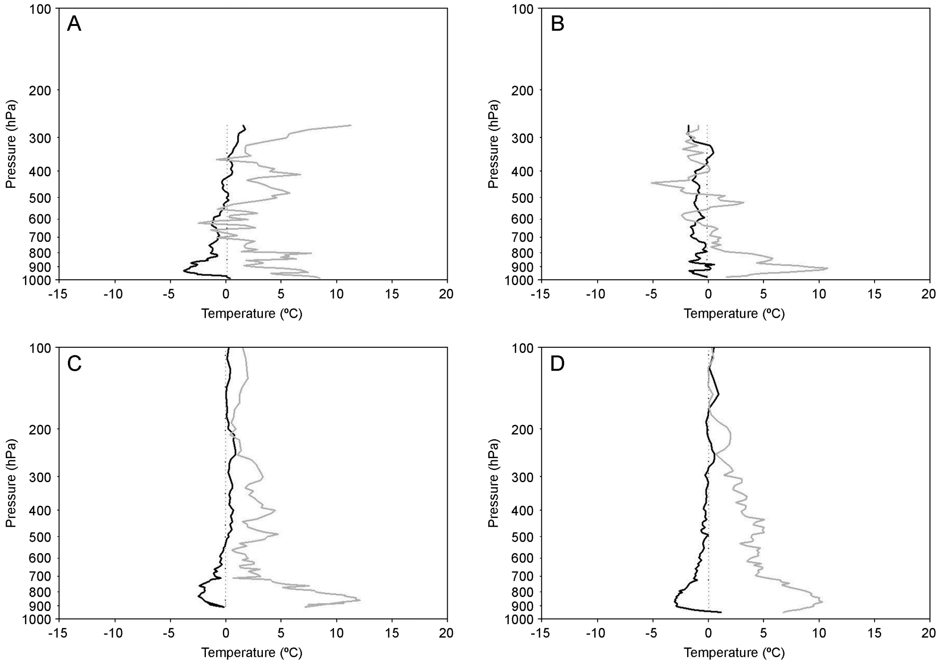

Fig. 4. Differences between the composite 1200 UTC surge sounding and the composite 1200 UTC pre-surge sounding for (A) GYM, (B) YUM, (C) TUS, and (D) PHX. Positive numbers indicate that the surge composite has greater values than the pre-surge composite. A moving average was applied to the values. Datk line = T; gray line = Td.

expected, pre-surge composites were distinctly drier than the corresponding surge composites. Another interesting finding is that both YUM composites (pre-surge and surge) display approximately the same surface temperatures (~30°C) and dewpoints (~12°C; Fig. 3). This is important because previous gulf surge climatologies

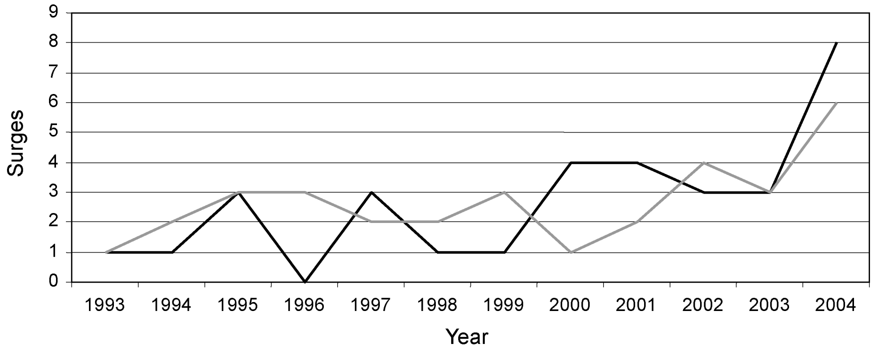

Fig. 5. Number of surges recorded at all sites by month for each year of the study period. The solid line represents July total; the dotted line represents August total.

are based on surface dewpoints in YUM (Stensrud et al., 1997; Fuller and Stensrud, 2000; Higgins et al., 2004). However, low-level humidity (above the surface) is significantly higher during surge events. This is illustrated more clearly by subtracting the composite pre-surge values from the composite surge values (Fig. 4). All of these images look different, yet they all display considerably higher dewpoints between the surface and 700 hPa. YUM, TUS, and PHX clearly show that surge moisture is much less prevalent at the surface than at slightly higher levels.

Intraseasonal Variability

The number of surge events detected during the months of July and August for each year of the study period demonstrates a notable variability within some seasons as one month experiences more events than the other (Fig. 5). However, there does not appear to be a preferential time of the season for surges as both July and August have 32 total events. Nevertheless, it appears that July and August only rarely experience an equal number of events in any given year (Fig. 3). Therefore, because of its 30- to 60-day period, the Madden-Julian Oscillation (MJO) is tested as a possible causal factor in gulf surge occurrence. The MJO involves variations in wind, sea surface temperature, cloudiness, and rainfall within the tropics. However, the MJO is most noticeable owing to changes in outgoing longwave radiation (OLR) across the tropical Pacific Ocean (Madden and Julian, 1994).

Wheeler and Hendon (2004) developed an MJO index that tracks variations in 850-hPa zonal wind, 200-hPa zonal wind, and satellite-observed OLR data. This index assigns a phase value of 1–8 for any given day, and each phase corresponds to a part of the globe where the MJO might be most noticeable. During the Northern Hemispheric summer, Phases 1 and 8 are associated with decreased OLR in the eastern Pacific Ocean, while Phases 3–5 are associated with increased OLR in the eastern Pacific Ocean. OLR is inversely related to cloudiness, so increased thunderstorms should be expected over the equatorial eastern Pacific Ocean during Phases 1 and 8 with decreased thunderstorms during Phases 3–5. MJO index data were obtained from Wheeler (2004).

Table 6. Total Number of Days Experiencing Each Phase During the Study Period, Total Number of Observed Surges at All Stations During Each Phase, and the Average Number of Days Between Surges for Each Phase of the Madden-Julian Oscillation (MJO)

Phase	Days	Surges	Days per surge
1	132	18	7.3
2	113	10	11.3
3	69	3	23.0
4	85	5	17.0
5	76	4	19.0
6	104	8	13.0
7	85	7	12.1
8	80	9	8.9

Table 7. Total Number of Days Experiencing Each Phase During the Period 1974–1990, Total Number of Observed Surges at TUS During Each Phase, and the Average Number of Days Between Surges for Each Phase of the Madden-Julian Oscillation (MJO)

Phase	Days	Surges	Days per surge
1	180	31	5.8
2	127	12	10.6
3	134	10	13.4
4	112	19	5.9
5	128	11	11.6
6	126	4	31.5
7	103	11	9.4
8	82	4	20.5

Clearly, Phase 1 experienced many more gulf surge events while Phases 3–5 experienced the fewest (Table 6). However, it should be noted that many more days experienced Phase 1 than any other phase during the study period. Nevertheless, surge events occurred, on average, every 7.3 days when the MJO was in Phase 1, which is the least amount of time among all of the phases (Table 6). Phase 3 illustrated the largest period between surge events with 23.0 days. The lack of surges that occur during Phases 3–5 is perhaps more important than the number of surges that occur during Phase 1. With that in mind, a discriminant analysis is conducted to determine whether there is a significant difference in the annual number of surges that occurs during Phases 3–5 as opposed to all other phases. As expected, approximately one third of the surges can be successfully predicted based solely on the variance in MJO phase (Wilks's $\lambda = .662$; $\rho = .003$). For further explanation of discriminant analysis statistics, see Wilks (1995).

The decrease in thunderstorms over the eastern Pacific Ocean during Phases 3–5 is consistent with the original ideas that surges are the result of thunderstorm

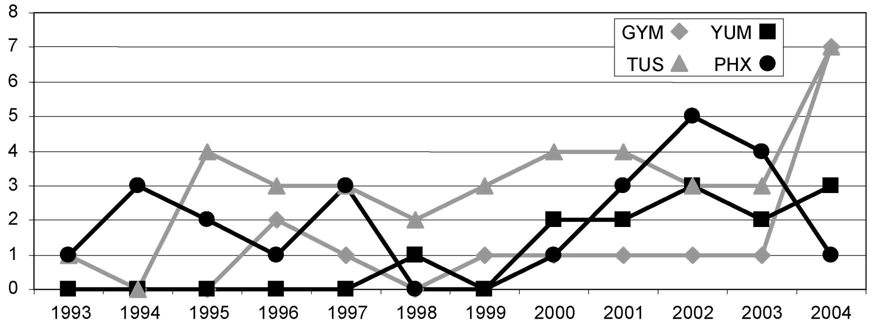

Fig. 6. Number of recorded surge events each year for all four sounding sites used in this study. GYM is represented by the diamond, YUM by the square, TUS by the triangle, and PHX by the circle.

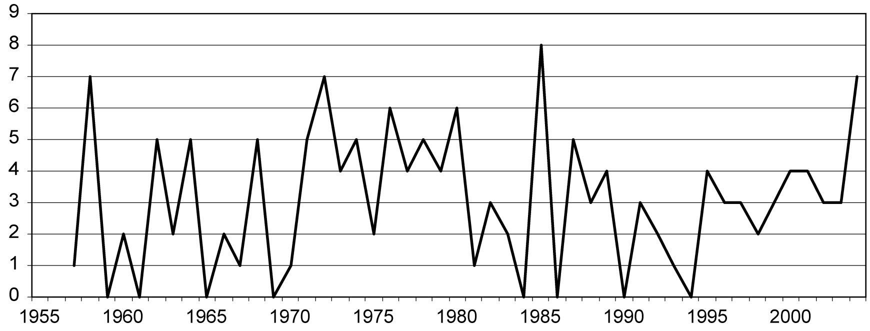

Fig. 7. Annual number of surges at TUS during the period 1957–2004.

activity over the southern end of the Gulf of California (Hales, 1972; Brenner, 1974). Therefore, it appears that the MJO certainly affects the frequency of gulf surge events. However, a 15-year analysis (using TUS soundings and MJO index values from 1974–1990 excluding 1978) shows Phase 4 with the second most number of surge events and the second fewest days between surge events (Table 7). In addition, Phase 8 experiences fewer events than expected. So while Phase 1 still appears to be most favorable for surge events, there are certainly some questions about how variance in MJO phase affects gulf surges.

Interannual Variability

Based on this study period, there is notable interannual variability at all four sounding sites (Fig. 6). Furthermore, there appears to be an increasing trend over time. However, an extended analysis of TUS surges (1957–2004) shows that the recent trend is just part of a longer cycle (Fig. 7). Higgins and Shi (2001), using principal component analyses, show that interannual variability of North American Monsoon precipitation is most associated with variability of the El Niño–Southern Oscillation (ENSO). Redmond and Koch (1991) found that ENSO's effects on Arizona precipitation were most noticeable when the ENSO index preceded the

Table 8. Correlation of Monthly SOI Values and Seasonal Surge Totals at Each Sounding Site for Lag Periods of 3 Months and 4 Months[a]

Site	r^2 (3-month)	ρ	r^2 (4-month)	ρ
GYM	**.319**	**.070**	.070	.492
YUM	.008	.819	.003	.890
TUS	.202	.143	.238	.183
PHX	**.266**	**.086**	.283	.140

[a] Relationships that are significant at $\alpha = .10$ are shown in bold.

precipitation period by three to four months. This study tests the relationship between ENSO and gulf surge events using lag times of three and four months.

Since the sounding data and, therefore, the surge totals, are incomplete, an estimate of surge totals per year is used again for these analyses. Following the methods described earlier, these estimates are based on the observed number of surges and the percentage of available sounding data. There are several indices that are commonly used to illustrate the existence and/or strength of ENSO. The Southern Oscillation Index (SOI) is calculated using the sea level pressure departure from average at Tahiti minus the standardized monthly sea level pressure departure at Darwin, Australia (Redmond and Koch, 1991). Therefore, negative SOI values correspond to cold events (Bradley et al., 1987). Also, sea surface temperature anomalies averaged over the region of the eastern equatorial Pacific Ocean from 5°N to 5°S and from 150° to 90°W (Nino3) are commonly used as a measure of ENSO strength. Monthly SOI and Nino3 values were obtained from the Climate Prediction Center (2004) and daily SOI values were obtained from the Climate Impacts and Natural Resource Systems group within the Queensland Department of Natural Resources located in Queensland, Australia (State of Queensland, 2004).

Monthly SOI values and monthly Nino3 values for April and May (3-month lag), as well as March and April (4-month lag), are regressed against surge totals for July and August for each station. The amount of variance (r^2) shared between the SOI and surge totals at each station during the study period is shown in Table 8, but only two relationships are significant at the 0.10% confidence level. The two significant relationships are the 3-month lags at GYM and PHX. These results imply that GYM and PHX experience fewer surges during El Niño years. However, no more than 2% of the variance in the number of surges at any site can be explained by variations in Nino3.

Independent-samples *t* tests were used to determine whether daily SOI values associated with surge days are significantly different from SOI values associated with non-surge days. Values for a 3-month lag, 4-month lag, and no lag were all tested, and the only statistically significant relationships ($\alpha = .10$) are for the 3-month lag at YUM and the 4-month lag at TUS (Table 9). Missing data at all of the sites certainly contribute to these inconsistent results, but it is seen that all of the sites illustrate at least a weak relationship between SOI (either monthly or daily values) and surge events, while Nino3 does not illustrate any notable correlations

Table 9. Independent-Samples *t* Test Statistics for SOI Values Associated with Surge Events at Each Station for a 3-Month Lag, 4-Month Lag, and No Lag[a]

Site	*t* (3-month)	p	*t* (4-month)	p	*t* (no lag)	p
GYM	-0.206	.837	-1.108	.298	-0.123	.905
YUM	**-3.612**	**.004**	0.223	.826	0.643	.529
TUS	0.236	.814	**-1.896**	**.058**	0.233	.817
PHX	0.849	.404	-0.192	.849	1.048	.305

[a] Relationships that are significant at $\alpha = .10$ are shown in bold.

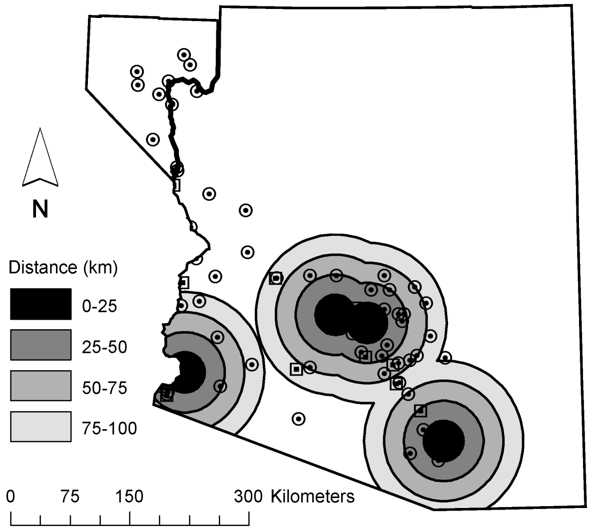

Fig. 8. Surface weather stations identified along with 100-km "local areas" (25-km intervals) surrounding each upper-air sounding site within Arizona. Circles represent stations provided by NCDC; Squares represent AZMET stations.

with surges at any of the sites. However, this study period is heavily influenced by the abnormally strong ENSO event during 1997–1998. Extended analyses of TUS surges (1957–2004) show no statistically significant relationships between the variance of SOI or Nino3 with respect to surge events. Therefore, any effects of ENSO on gulf surge occurrence is likely very weak and often masked by more important variables.

PRECIPITATION ANALYSES

In order to determine if local precipitation is affected by low-level moisture (as detected by soundings), all stations within a 100-km radius of each sounding site are considered to be within that sounding site's "local area" (Fig. 8). Owing to a lack of data in Mexico, this part of the study is restricted to low-lying parts of Arizona and southern Nevada. The term "low-lying" refers to areas at or below 915 m above sea level, according to the definition of the Sonoran Desert used by Shreve and Wiggins (1964). Each station's daily precipitation is compared to surge events and low-level moisture (925 hPa at YUM; 850 hPa at TUS and PHX) within the respective local area as well as the entire study area. Forty stations are within the PHX local area, 10 are within the TUS local area, and 12 are within the YUM local area. Another 19 stations, including those in southern Nevada, are not located within 100 km of any sounding sites, but they are still included in some of the analyses.

In order for a surge to be detected by the ALARMS method, there must be four consecutive days of sounding data. The first two days are the "pre-surge" period when low-level dewpoints are relatively low. The following two days are the actual surge, and dewpoints are at least 4°C greater than during both of the pre-surge days. Therefore, an independent-samples *t* test is used to determine whether the mean daily precipitation total at each local station during pre-surge days is significantly different from the mean daily precipitation total during surge days. This same test was also applied to all local stations as a whole (i.e., Do the local stations around a sounding site experience a significantly different amount of precipitation on surge days as compared to pre-surge days?). Unfortunately, precipitation data rarely display a normal distribution due to a large percentage of the observations being the same (i.e., 0.00 mm). Therefore, in order to avoid problems with statistical analyses that require normally distributed data, discriminant analyses (Glahn, 1968) are used to determine whether the amount of precipitation at each local station, as well as the total precipitation from all local stations, can be used to consistently distinguish between surge days and pre-surge days.

Beyond the simple dichotomy between surge and pre-surge, low-level dewpoint values are used to determine whether local changes in moisture affect precipitation at nearby stations. Therefore, independent-samples Student's *t* tests are used to test whether the mean 1200 UTC low-level dewpoint at the local sounding site is significantly different on days with measurable precipitation than on days with no precipitation at each local surface station. Likewise, discriminant analyses are used to establish whether low-level dewpoints at the local sounding site can be employed to differentiate between days with precipitation and those without at each local surface station.

In addition to studying the effects of low-level moisture on precipitation totals, various statistical methods are used to understand the effects of low-level moisture and surge events on the spatial extent of precipitation across the study area. A linear regression of low-level dewpoints and the number of stations receiving precipitation on the respective day is performed along with an independent-samples Student's *t* test for difference of means between the number of stations receiving precipitation on surge days and on pre-surge days. However, owing to potential normality problems with precipitation data, discriminant analyses are also performed to determine whether the variance in the number of stations receiving precipitation can consistently predict surge and pre-surge days. Each of these statistical methods is applied individually to each sounding site and its respective group of local surface stations. The difference of means test and discriminant analysis are then applied to all three

Table 10. The Differences in the Mean Number of Stations Recording Precipitation for Surge Days and Pre-Surge Days, and Results of Discriminant Analyses Testing Whether Surge Days and Pre-Surge Days Can Be Predicted Consistently by Variance in the Total Number of Stations Recording Precipitation[a]

Site	Surge	Pre	ρ	Wilks's λ	ρ
PHX	5.54	1.17	.001	.891	.001
TUS	2.61	1.09	<.001	.903	<.001
YUM	0.19	0.00	.090	.944	.090
Total	9.79	3.34	<.001	.876	<.001
PHX	9.73	2.28	<.001	.854	<.001
TUS	8.35	3.24	<.001	.900	<.001
YUM	9.50	2.58	.001	.802	.001

[a] "Total" values depict the relationship between surge events at each (or all) sounding site(s) and storm totals from throughout the study area.

sounding sites collectively, and low-level dewpoints at each sounding site are then compared to precipitation data through linear regression.

Effects of Gulf Surges on Precipitation

All but 3 of the 81 stations used in this study experienced, on average, more precipitation on surge days than on pre-surge days (Fig. 9). Independent-samples Student's *t* tests show that 42 (51.9%) of the stations display a significant difference ($\rho = .100$) in mean daily precipitation between surge and pre-surge days. When precipitation from all stations is used, rather than from each station individually, a statistically significant relationship ($\rho < .001$) is shown with a mean daily precipitation total of 17.2 mm (0.2 mm per station) on pre-surge days and 67.2 mm (0.9 mm per station) on surge days.

Discriminant analyses show no station with any more than approximately 6% (Wilks's $\lambda = .943$; $\rho < .001$) of the variance between surge and pre-surge days being explained by the variance in average daily precipitation at that station. However, a statistically significant relationship between surge occurrence at TUS and total precipitation at all the local TUS stations is also displayed (Wilks's $\lambda = .865$; $\rho = .025$), with 14% of the variance in surge events explained by precipitation, and approximately 40% (Wilks's $\lambda = .600$; $\rho = .173$) of the variance between surge and pre-surge days at PHX is explained by precipitation from across the study area. A much weaker correlation at YUM (Wilks's $\lambda = .939$; $\rho = .382$) is likely owed to the fact that 8 of the 12 YUM surface stations did not experience any measurable precipitation on surge or pre-surge days during the study period.

In addition to precipitation occurrence at any given station, it appears that gulf surge events also affect the spatial extent of precipitation (i.e., the number of surface stations reporting precipitation). Independent-samples Student's *t* tests show statistically significant ($\alpha = .100$) differences between the number of local surface stations reporting precipitation on surge days as opposed to pre-surge days at PHX,

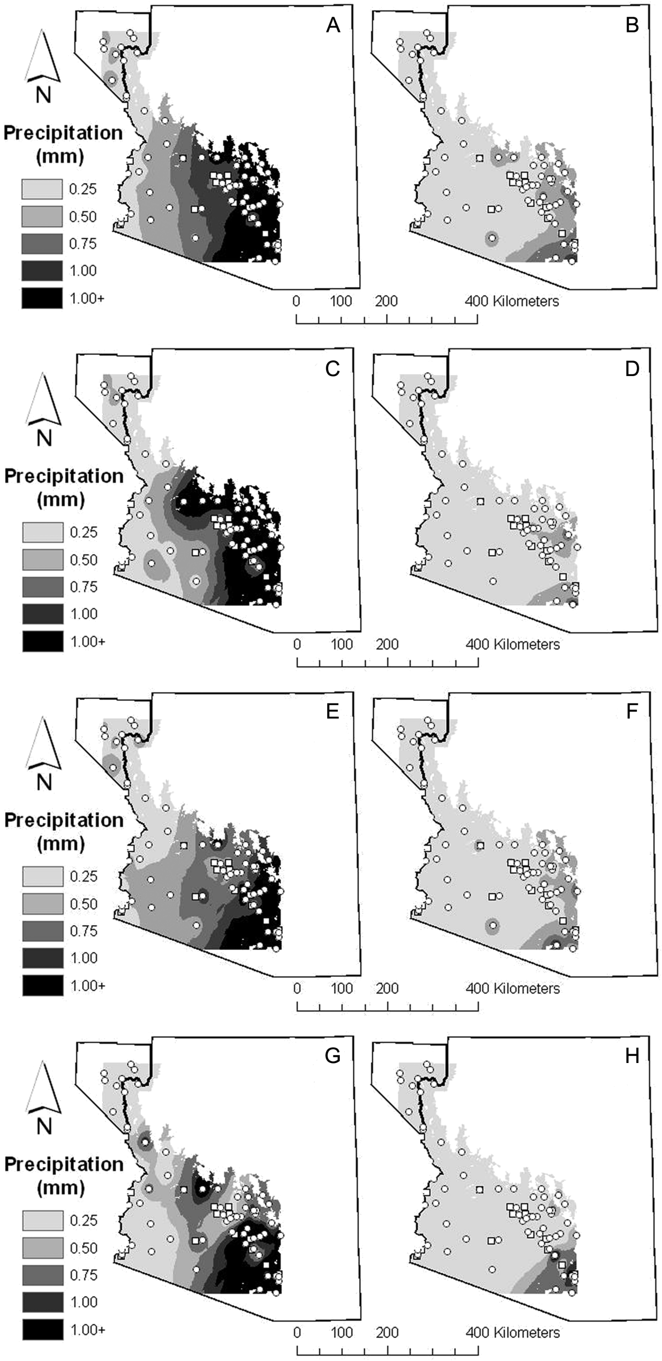

Fig. 9. Mean daily precipitation totals during surge days at (A) all stations, (C) PHX, (E) TUS, (G) YUM and during pre-surge days at (B) all stations, (D) PHX, (F) TUS, and (H) YUM.

Table 11. The Mean Low-Level (925 hPa at YUM; 850 hPa at TUS and PHX) Dewpoint at Each Sounding Site on Wet Days (Measurable Precipitation at a Surface Station) and Dry Days (No Measurable Precipitation at a Surface Station) During the Months of July and August 1993–2004

Site	Wet days (°C)	Dry days (°C)	Difference (°C)	ρ
PHX	11.5	6.9	4.6	<.001
TUS	11.9	9.1	2.8	<.001
YUM	13.6	7.1	6.5	<.001

Table 12. Normal Monthly Precipitation Totals (mm) for the Months of July and August and Elevation above Sea Level (m) at the Sounding Sites Used in This Study[a]

Site	July (mm)	August (mm)	Elevation (m)
PHX	21.1	24.4	384
TUS	60.2	55.6	788
YUM	6.6	16.2	98

[a] Data provided by the Western Regional Climate Center (2004) in Reno, Nevada.

TUS, and YUM (Table 10). However, discriminant analyses testing whether surge and pre-surge days can be predicted consistently by the number of local surface stations reporting precipitation do not support a strong relationship. Less than 11% (Wilks's $\lambda = .891$; $\rho = .001$) of the variance between surge and pre-surge days can be explained by the spatial extent of precipitation at each sounding site (Table 10).

Nevertheless, discriminant analyses of the relationship between each sounding site and the total number of stations reporting precipitation across the entire study area show as much as approximately 20% of the variance in surge days can be explained by the spatial extent of precipitation (Table 10). Difference of means tests for the total number of stations receiving precipitation across the entire study area for surge and pre-surge days show more impressive values than those for the local areas only (Table 10).

Effects of Low-Level Dewpoint on Precipitation

All stations used in this study show that low-level sounding dewpoints are significantly higher on days with precipitation than on days with no measurable precipitation (Table 11). YUM shows the greatest difference in dewpoint between wet and dry days (6.5°C), PHX displays a mean difference of 4.6°C, and the average difference at TUS is 2.8°C. The variance between stations can likely be explained by differences in elevation and/or total precipitation during the months of July and August (Table 12).

Again, to account for data that are not normally distributed, discriminant analyses are employed in addition to the difference of means test. Consequently, no more

Table 13. Results of Discriminant Analyses Testing Whether Wet Days and Dry Days, Based on All Available Surface Stations, Can Be Predicted Consistently by Low-Level Dewpoint Values at Each Sounding Site

Site	Wilks's λ	ρ
PHX	.022	<.001
TUS	.018	<.001
YUM	.060	<.001

Table 14. Linear Regression of Low-Level Dewpoints at Each Sounding Site and the Spatial Extent of Precipitation Based on the Local Surface Stations and on All Available Surface Stations

	Local surface stations		All available surface stations	
Site	r^2	ρ	r^2	ρ
PHX	.172	<.001	.229	<.001
TUS	.142	<.001	.157	<.001
YUM	.119	<.001	.270	<.001

than approximately 10% (Wilks's λ = .899; ρ < .001) of the variance between wet and dry days at any individual surface station is explained by the low-level dewpoint at the local sounding site. However, when all surface data are analyzed as one value, as much as 98.2% (Wilks's λ = .018; ρ < .001) of the variance between wet and dry days is explained by the low-level dewpoint (Table 13).

Linear regression analyses show that statistically significant relationships exist between the variance in the spatial extent of precipitation and the variance in low-level (925 hPa at YUM; 850 hPa at TUS and PHX) dewpoint (Table 14). This relationship is strongest at PHX with 17.2% of the variance in the number of surface stations reporting precipitation shared by the dewpoint at approximately one kilometer above the surface. It should also be noted that these relationships become even stronger when each sounding site is compared to all available surface stations used in this study (Table 14).

CONCLUSION

Several years of inconsistent data and the absence of a widely accepted method for identifying gulf surges both contribute to the lack of detailed gulf surge climatologies in the research literature. The introduction of the ALARMS method enables detection of surge events at multiple locations for the purposes of comparison and pattern identification. Based on this method, 64 surges were detected during the 12-year study period. However, missing data certainly keep the recorded total lower than the actual number. Data inventories can be used to estimate the number of surges that might have been detected at each site with complete data records, but these estimates cannot provide details required for many analytical methods.

Based on recorded events and the individual site estimates, an average monsoon season should experience approximately six to eight surge events. Of course, there is significant interannual variability that will raise or lower these numbers each year. However, it seems unlikely that much of this variability is caused by variations in ENSO. The intraseasonal variations of surges seem to be related to the propagation of the MJO across the Pacific Ocean, but the reasons why more surges occur during certain phases of the MJO are still unclear.

Through the use of composite soundings for each study site, the typical depth and structure of surge events become clearer. These profiles support previous research (Hales, 1972; Brenner, 1974) claiming that surge moisture remains mostly below 700 hPa, but they also illustrate the problem with using surface moisture at YUM to detect surges. Both composite YUM soundings (pre-surge and surge) possess approximately equal dewpoints at the surface even though their moisture content between the surface and 700 hPa vary significantly. This is evidence of the usefulness of sounding-based surge identification methods such as ALARMS.

The precipitation analyses provide support for assumptions by many previous studies on low-level moisture in the desert Southwest (Hales, 1972; Brenner, 1974; Adang and Gall, 1989; Dunn and Horel, 1994; Maddox et al., 1995; McCollum et al., 1995; Stensrud et al., 1997). Not surprisingly, precipitation appears to be strongly influenced by changes in low-level humidity across the lower elevations of Arizona and southern Nevada. As much as 27% of the variance in the spatial extent of precipitation is consistent with the variance in low-level dewpoints at YUM, and surge days can be accurately distinguished from pre-surge days as often as 98.2% of the time based on low-level dewpoints. More importantly, it is shown that surge days (based on the ALARMS method) tend to result in greater amounts (~450%) of precipitation at each station as well as more stations (~3 times as many) receiving measurable precipitation than on pre-surge days. Therefore, these results contradict the few previous studies that found little or no correlation between low-level moisture and precipitation across the region (Mullen et al., 1998; Higgins et al., 2004). However, conclusions from those studies likely still apply to higher elevations across the region.

As more events and better data become available, it is hoped that continued climatic study of surge events will improve the understanding of spatial and temporal patterns displayed by gulf surges.

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