# Relationships Between Gulf of California Moisture Surges and Precipitation in the Southwestern United States

by

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February 2004

(Journal of Climate – in Press)

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## Abstract

Relationships between Gulf of California moisture surges and precipitation in the southwestern United States are examined. Standard surface observations are used to identify gulf surge events at Yuma, Arizona for a multi-year (July-August 1977-2001) period, and CPC precipitation analyses and NCEP/NCAR Reanalysis data are used to relate the gulf surge events to the precipitation and atmospheric circulation patterns, respectively. Emphasis is placed on the relative differences in the precipitation and atmospheric circulation patterns for several categories of surge events, including those that are relatively strong (weak) and those that are accompanied by relatively wet (dry) conditions in Arizona and New Mexico after onset. It is shown that rapid surface dewpoint temperature increases are not necessarily a good indicator of increased rainfall in the region.

The extent to which the precipitation and atmospheric circulation patterns are influenced by a phasing of tropical easterly and midlatitude westerly waves is also considered. Results indicate that a significant fraction of the events in all categories are related to the passage of westward propagating tropical easterly waves across western Mexico. However, the occurrence of wet versus dry surges in the southwestern United States is not discriminated by the presence of tropical easterly waves, but rather by the relative location of the upper-level anticyclone in midlatitudes at the time of the gulf surge.

## 1.0 Introduction

During the North American summer monsoon season there are northward surges of relatively cool, moist maritime air from the eastern tropical Pacific into the southwestern United States via the Gulf of California (e.g. Hales 1972; Brenner 1974; Stensrud et al. 1997; Fuller and Stensrud 2000). These events, referred to as "gulf surges" or "moisture surges" in the literature, are related to the amount of convective activity in northwestern Mexico and portions of the southwestern United States, including Arizona and New Mexico. Typical characteristics of gulf surges have been discussed in all of the studies referenced above, so it will be assumed that the reader is familiar with these. It is well known that low-level moisture is an important ingredient for thunderstorm activity in the southwestern United States during the monsoon season (e.g. McCollum et al. 1995), yet there are periods with relatively little precipitation even when sufficient moisture is present. A thorough understanding of the synoptic reasoning for this remains elusive.

Previous diagnostic and modeling studies of gulf surges have emphasized their basic characteristics and their relationships to tropical easterly and midlatitude westerly waves. To date, however, the spatial and temporal relationships between gulf surges and precipitation have not been thoroughly examined. Hales (1972) and Brenner (1974) used surface, radiosonde and satellite observations, with some radar data, to identify unique features of the surges (e.g. surface weather changes, depth of the moist plumes, sources of moisture, evolution of the cloud mass, changes in thunderstorm activity) and possible factors in their development, including easterly waves. In their landmark study, Stensrud et al. (1997) showed that the detailed characteristics of surges could be reproduced by a mesoscale numerical model. In particular, they found that strong surges occurred in the model when the passage of a midlatitude westerly wave trough across the western United States preceded the passage of a tropical easterly wave trough across western Mexico by several days. Fuller and Stensrud (2000) extended these results by establishing how often gulf surges were related to tropical and midlatitude wave passages over a 14-yr period. While their results were suggestive, further evidence is needed to establish how the tropical and midlatitude wave passages are related to surges and the precipitation patterns that accompany them. Clearly, improved understanding of relationships between gulf surges and precipitation is a potentially important prerequisite for improved warm season precipitation simulations and predictions in southwestern North America.

Consequently, the primary objective of this study is to examine relationships between Gulf of California moisture surges and precipitation in the southwestern United States and northwestern Mexico. While the emphasis is on precipitation patterns in the core monsoon region, we also examine relationships between these events and the large-scale precipitation pattern. An important related objective is to determine the extent to which these relationships are influenced by a phasing of tropical easterly waves and midlatitude westerly waves as proposed by Stensrud et al. (1997).

For the study we use a combination of standard surface observations, observed precipitation and atmospheric circulation data. As in previous studies (e.g. Fuller and Stensrud 2000), the surge events are identified using hourly surface observations of dewpoint temperature, wind direction and wind speed at Yuma, AZ and Tucson, AZ, for a multi-year (July-August 1977-2001) period. Relationships to the observed precipitation pattern are examined using a daily precipitation reanalysis (1948-present) for the U.S.

and Mexico. Tropical easterly waves and midlatitude westerly waves are identified using daily meridional wind data from the NCEP/NCAR Reanalysis over the 24-year period. Large-scale circulation patterns are examined using both zonal and meridional wind data from the Reanalysis.

It is shown that the relationships between surge strength and precipitation in Arizona and New Mexico are not simple or linear. In fact, while many surges are accompanied by relatively wet conditions in the core monsoon region, many others are not. The surge events are partitioned into several categories based on their strength and on the amount of precipitation that accompanies them in order to isolate critical atmospheric circulation features that might explain these differences.

A discussion of the datasets and the method used to identify surge events is found in section 2. Relationships between the surge events and precipitation for several categories of surge events are discussed in section 3. Critical large-scale circulation features that help explain differences in the precipitation patterns are discussed in section 4. Section 5 includes a brief summary and discussion of future plans.

## 2.0 Data and Methodology

As in previous studies (e.g. Fuller and Stensrud 2000) we employ hourly surface observations of dewpoint temperature, wind speed and wind direction at Yuma, Arizona and Tucson, Arizona to identify gulf surge events. These events are identified during both July and August for a 25-year (1977-2001) period. The daily precipitation analysis is obtained from CPC's Unified Precipitation Database (Higgins et al. 2000) together with additional daily data from the Mexican Weather Service. Daily data are gridded to a horizontal resolution of (lat,lon)=(1° x 1°) and are available for a multi-year (1950-2002) period.  Zonal and meridional winds and streamfunction at 700-hPa and 200-hPa are from the NCEP/NCAR Reanalysis (Kalnay et al. 1996).  For all fields anomalies are defined as departures from base period (1971-2000) mean values.  Time series for July-August 1977-2001 were constructed for each field prior to the analysis.  Surface observations for Yuma, AZ were missing during July-August 1992.

Statistical significance tests were performed on each anomaly pattern in Figures 6-12 below.  Shaded anomalies on the figures were found to be significant at the 95% confidence level for the most part, except in a few cases when the anomalies were weak (usually several days before or after the onset date of the Yuma surges).  Since the discussion focuses on the strongest anomalies, the results of the significance tests are not shown in order to avoid unnecessary clutter on the figures.

## 2.1 Identification of Surges

Surges were identified using the method outlined in Fuller and Stensrud (2000). In particular hourly observations of surface dewpoint temperature, wind direction and wind speed from Yuma, AZ, and Tucson, AZ were used to diagnose the occurrence of gulf surges during the period July-August 1977-2001.  July and August were chosen because these are the two months when the summer monsoon season is most active (e.g. Douglas et al. 1993).

Previous gulf surge studies have used rapid increases in surface dewpoint temperature at particular sites as one of the primary characteristics to identify the onset of gulf surge events (e.g. Hales 1972; Brenner 1974; Fuller and Stensrud 2000), but the diurnal cycle of dewpoint temperature in the Desert Southwest is large and can be misleading.  For this reason, we apply a 25-hr running mean to the hourly dewpoint, wind direction and wind speed data, prior to the identification of surge events at Yuma and Tucson. While this provides a slight smoothing to the data, it has almost no impact on the identification of individual surge events.

Fuller and Stensrud (2000) identified days of surge onset as those with rapid increases in surface dewpoint temperature, after which the maximum daily dewpoint temperature remains at or above 15.7°C at Yuma, AZ for at least several days. In addition, they also required the surface wind speeds on the day of the rapid dewpoint temperature rise to be greater than 4 $ms^{-1}$ for at least one reporting time and for the surface wind direction to be southerly (or thereabouts). Here we apply their criteria to the 25-hr running mean dewpoint temperature timeseries, but with a few minor modifications. First, we require a rapid increase in dewpoint temperature, after which it remains at or above the climatological mean (July-August 1977-2001 base period) for several days. As in Fuller and Stensrud (2000), we did not impose a specific change in dewpoint temperature over a specified period to define "rapid" increase, though such occurrences are quite self evident from visual inspection of the time series. In addition, we also require the surface wind direction on the day of the rapid dewpoint temperature increase to be southerly (or thereabouts) and the wind speed to exceed the climatological mean wind speed (July-August 1977-2001 base period).

Also, as in Fuller and Stensrud (2000), we identify strong and weak surges by examining the change in dewpoint temperature over the 3 days after surge onset. If the 25-hr running mean dewpoint temperature decreases during this 3-day period, then the surge is categorized as weak. In contrast, if the dewpoint temperature increases during this 3-day period, then the surge is categorized as being strong. As noted in Fuller and

Stensrud (2000), this taxonomy is more closely associated with the duration of a surge than with any initial change in moisture associated with the surge leading edge.

A comparison of the 25-hr running mean dewpoint temperature, wind speed and wind direction time series at Yuma for July-August 1986 (Fig. 1) to the hourly timeseries for July 1986 used in Fuller and Stensrud (2000) (their Fig. 2) indicates that we obtain the same set of events identified in their study using the modified time series as described above (we note that the dashed vertical lines on Fig. 1 denote the onset day of each surge event). The climatological mean values of dewpoint temperature and wind speed (15.7°C /60.2°F and 3.3 m $s^{-1}$ at Yuma for July-August 1977-2001) are very close to the values used by Fuller and Stensrud (2000) (15.6°C / 60.1°F and 4 m $s^{-1}$, respectively). We recognize that applying a running mean to wind direction can have an adverse effect when winds are predominantly northerly and light, but again this has little or no impact on case selection because persistent, relatively strong southerly winds are required.

During the 24-year period analyzed, a total of 142 surges were identified at Yuma for an average of roughly 3 surges per month. Of these, 81 (57%) were strong and 61 (43%) were weak (Table 1). By comparison, 111 surges were identified at Tucson for an average of roughly 2.5 surges per month. Of these, 65 (59%) were strong and 46 (41%) were weak (Table 1). When the objective criteria are strictly enforced, we find that 65% of Yuma surges are also identified at Tucson. However, 82% of Yuma surges are accompanied by a simultaneous upward trend in dewpoint temperature at Tucson, though in some cases the objective criteria are not strictly satisfied.

An examination of the composite evolution of hourly dewpoint keyed to the onset of all 142 surge events at Yuma (Fig. 2a) shows a large change in dewpoint temperatures after surge onset.  Interestingly, however, the composite evolution shows diurnal maximum values of dewpoint temperature both before and after surge onset near 1600Z and diurnal minimum values near 0000Z throughout the evolution.  This compares very well with the climatology of the diurnal cycle of dewpoint temperature at Yuma, AZ for July-August 1977-2001 (not shown), which indicates maximum dewpoint temperatures around 1600Z and minimum values around 0000Z and an average diurnal range of around 5.4°F (3.0°C).  A consideration of Fig. 2a suggests that the diurnal range in dewpoint temperatures is enhanced for a couple of days after surge onset, but then returns to climatological values.

A comparison of the evolution of strong (Fig. 2b) and weak (Fig. 2c) surges shows that the strong events have higher dewpoint temperature values for a much longer period after onset than the weak surges.  For both strong and weak surges the dewpoint temperatures remain elevated above values observed prior to onset throughout the period examined.  Similar results are obtained for surges at Tucson (not shown) though average values of dewpoint temperature are lower, consistent with the lower climatological mean at Tucson.

Composites of wind speed and wind direction (not shown) are consistent with dewpoint temperature, but the signals are weaker, and there is considerable diurnal modulation in the composites.  Wind speeds increase following surge onset and remain elevated for a week or more in the strong surge composite.  Wind direction shows a weak signal in the composites, with the direction turning from southwesterly to southeasterly (on average) as the surge begins.  There is a tendency for the amplitude of the daily inertial oscillation to decrease after surge onset as winds tend to remain more southerly and precipitation continues.

### 2.2 Identifying Tropical Easterly and Midlatitude Westerly Waves

Procedures from Fuller and Stensrud (2000) are used to identify tropical easterly and midlatitude westerly waves in section 4. The tropical easterly (midlatitude westerly) waves are identified using 700-hPa (200-hPa) meridional wind data from the NCEP/NCAR Reanalysis for the period July-August 1977-2001. The data are available in 24-h increments at a horizontal resolution of 2.5°. Previous authors (e.g. Reed et al. 1977; Stensrud et al. 1997; Fuller and Stensrud 2000) have indicated that the 700-hPa level is well suited for identifying tropical easterly waves since this level minimizes problems associated with interactions of the waves and topography over Mexico, yet it is sufficiently low in the troposphere to capture these features.

## 3.0 Precipitation Patterns

### 3.1 Statistics

Though a rapid increase in surface dewpoint temperature is one of the primary characteristics used to identify the onset of a surge event, it does not always accompany or precede a period of enhanced precipitation in the region. An examination of 25-hr running mean values of dewpoint temperature at Yuma together with area mean (112.°5-107.5°W, 32°-36°N) daily precipitation anomalies for eastern Arizona and western New Mexico (hereafter AZNM) during July-August 1986 clearly shows that some surges are accompanied by wetter-than-normal conditions in the region while others are accompanied by drier-than-normal conditions (Fig. 3). We note that the AZNM region is chosen to encompass the eastern half of Arizona and western quarter of New Mexico, where monsoon-related precipitation in the southwestern United States tends to be concentrated.

If we define wet (dry) surge events as those with positive (negative) precipitation anomalies in AZNM for the 5 day period (day 0 to day +4) after onset, then 54% (46%) of all surges at Yuma during the period July-August 1977-2001 are anomalously wet (dry) (Table 1). Similarly, at Tucson we find that 63% (37%) of all surges are wet (dry). Further subdivisions of the surge categories into those that are strong and wet, strong and dry, weak and wet, or weak and dry are shown in Table 2.

Surge duration information (defined as the period during which dewpoint temperature exceeds the climatological mean after onset) was used to compute the fraction (in percent) of total AZNM precipitation per July-August during surge events keyed to Yuma, AZ (Table 3, top) and Tucson, AZ (Table 3, bottom); results are based on July-August 1977-2001. The fractions for all, strong, weak, wet and dry surges were computed. The average number of surge days per July-August is also shown (the maximum number possible is 62 per July-August). The average AZNM precipitation per July-August (based on July-August 1977-2001) is 115 mm. Interannual standard deviations in the percentage of total AZNM precipitation per July-August during surges and in the number of surge days per July-August are also given in parentheses.

Gulf surges at Yuma are accompanied by 66% of the rainfall in AZNM while those at Tucson are accompanied by roughly 38%. The average number of surge days is lower at Tucson than at Yuma, which helps to explain the significant differences in the percentage of AZNM rainfall. Also, there is a tendency for the dewpoint temperature at Yuma to persist above the climatological (July-August) mean for many days after surge onset (e.g. Fig. 2) contributing to relatively long surge duration compared to Tucson. It is not clear whether this is a systematic bias in the Yuma data or a manifestation of the summer climatology of the region. Nevertheless, the range between Yuma and Tucson seems to be a reasonable bound on the fraction of AZNM precipitation that accompanies gulf surges. As anticipated Table 3 also shows that the largest fraction of AZNM precipitation per surge day occurs during wet surges at both locations.

Gulf surge duration information was also used to determine the fraction (in percent) of surge days and non-surge days per July-August at Yuma, AZ (Table 4, top) and Tucson, AZ (Table 4, bottom) with AZNM precipitation exceeding various thresholds (in mm); results are based on July-August 1977-2001. The average number of surge (non-surge) days per July-August is 32 (30) at Yuma, and 18 (44) at Tucson. Interannual standard deviations in the fraction of surge (non-surge) days per July-August for each threshold are also given. The relatively large number of surge days at Yuma relative to Tucson reflects the longer duration and greater frequency of surge events at Yuma. Despite these differences, the fractions of surge days associated with AZNM precipitation exceeding each threshold are surprisingly similar for both stations (compare Table 4).

### 3.2 Composite Evolution

The composite evolution of AZNM daily precipitation anomalies for all surges keyed to Yuma (Fig. 4a) and Tucson (Fig. 4b) is characterized by positive precipitation anomalies in AZNM after onset at both locations (solid lines on Fig 4). On average the strong surges are accompanied by wetter-than-normal conditions for more than a week after onset, though positive precipitation anomalies decrease after about day +4. Weak surges at Tucson are dominated by negative precipitation anomalies after day +3. Differences for strong and weak surges keyed to Yuma are smaller than those for strong and weak surges keyed to Tucson. This is likely due to the fact that Yuma lies to the west of the main axis of monsoon precipitation.

Though the composite evolution of AZNM precipitation anomalies for strong and weak surges is quite different, especially at Tucson (Fig. 4b), the composite evolution of dewpoint temperature for wet and dry surges is quite similar at both locations (Fig. 5), especially during the onset period of the surge events. This implies that a rapid increase in dewpoint temperature associated with the onset of a gulf surge at these stations is not a good indicator of AZNM precipitation following onset. Thus, other factors related to the large-scale circulation must determine whether a given surge will be accompanied by relatively wet (dry) conditions in the region (see section 4).

Geographic maps of the composite evolution of precipitation anomalies over Mexico and the conterminous United States for all surges keyed to Yuma, and for strong and weak surges keyed to Yuma are shown in Fig. 6. When all surges are considered, the composites show a southeast to northwest progression of positive precipitation anomalies along the west coast of Mexico towards Arizona (Fig. 6a). Just prior to onset the conditions are drier-than-normal in the northern half of Mexico and wetter-than-normal in the southern half. During onset positive anomalies span the west coast of Mexico. After onset positive anomalies are found in Northwest Mexico and Arizona. The evolution just described is enhanced for strong surges (Fig. 6b) and suppressed for the weak ones (Fig. 6c). The composite evolution for wet surges (Fig. 7a) is similar to that for strong surges, except that the positive precipitation anomalies are larger and even more widespread. The composite evolution for dry surges is dominated by negative anomalies over most of Mexico and the Southwest U.S. (Fig. 7b).

The composites in Figs. 6 and 7 show strong evidence of westward propagation over Mexico and the Southwest U.S., suggesting a relationship between the gulf surges and westward propagating tropical disturbances, which might include tropical easterly waves, tropical storms, middle to upper level inverted troughs and cyclones, and westward shifts in the monsoon moisture boundary separating east Pacific or continental air to the west from the deep/moist subtropical air mass to the east.

The westward propagation of the precipitation anomaly pattern discussed in Figs. 6 and 7 is consistent with previous studies (e.g. Stensrud et al. 1997; Fuller and Stensrud 2000) that have discussed relationships between surge onset at Yuma and the passage of tropical easterly wave troughs from east to west across Mexico during the period just prior to surge onset. To date however, there has been relatively little analysis of relationships between surge onset, the precipitation pattern in the region and the passage of tropical easterly wave troughs across Mexico (see section 4).

The results in Figs. 6 and 7 clearly demonstrate that Gulf of California moisture surges are associated with significant changes in the precipitation pattern over Mexico and the conterminous United States during their evolution. However, it is unclear whether the surges are accompanied by a net increase or decrease in the amount of precipitation. Clearly this depends on the area under consideration. Area mean precipitation anomalies from the composites in Figs. 6 and 7 for the period during and after onset at Yuma (Day 0 to day +4) are given in Table 5. As one might expect, strong surges and wet surges in AZNM, Mexico, and US_Mexico are accompanied by wetter-than-normal conditions, while the opposite is true for weak surges and dry surges.

Previous studies have linked the onset of summer rains over northern Mexico and the Southwest United States to a decrease in rainfall in the Great Plains of the United States (e.g. Higgins et al. 1997; Mock 1996; Tang and Reiter 1994; Douglas et al. 1993; Douglas and Englehart 1996) and to an increase of rainfall along the East Coast (e.g. Tang and Reiter 1984). Higgins et al. (1998) showed that this pattern is a continental-scale pattern of interannual variability. That is, anomalously wet (dry) summers in the Southwest U.S. tend to be accompanied by anomalously dry (wet) summers in the Great Plains of the United States. The interannual variability was strongly tied to the strength of the upper-tropospheric monsoon anticylone over the southwestern United States and the associated downstream trough in the eastern United States, with the wet monsoons exhibiting stronger features than the dry monsoons.

Interestingly, the onset of surges at Yuma is linked to a similar continental-scale precipitation pattern (Fig. 8). On average the surges at Yuma are accompanied by an increase in rainfall in the Southwest United States, a decrease in rainfall in the northern Great Plains and northern tier-of-states, and an increase in rainfall along portions of the East Coast (especially the Northeast). This pattern is particularly evident for strong (Fig. 8b) and wet (Fig. 8c) gulf surges. Thus, it appears that these phase relationships apply at synoptic time scales and that this variability is tied to the strength of the upper-tropospheric monsoon anticyclone (see section 4).

## 4.0 Large-scale Circulation Features

In the previous section we found that some gulf surges are wetter-than-normal while others are drier-than-normal, and that this is not simply related to the strength of the surge. Thus it is important to determine if there are particular large-scale circulation features that influence surge-precipitation relationships, independent of the strength of the surge.

Following the results of Stensrud et al. (1997) and Fuller and Stensrud (2000) (see section 1 for a brief review), we examine whether tropical easterly and midlatitude westerly disturbances might help to explain differences in the precipitation patterns for each category of surge event discussed in sections 2 and 3. The methods of Fuller and Stensrud (2000) are employed to identify the tropical easterly and midlatitude westerly wave troughs (see section 2.2).

The tropical easterly wave troughs are identified as they cross 110°W using time-longitude diagrams of 700-hPa meridional wind anomalies (departures from base period 1971-2000 mean daily values) for the latitude band 20°N-25°N. As the easterly waves shift westward across 110°W, the wave troughs are generally accompanied by a coherent transition from northerly to southerly winds as time increases. If a gulf surge begins at Yuma within 3 days after the passage of an easterly wave trough across 110°W, then the two events are defined as being related. Otherwise the events are considered to be unrelated. Fractions of the total number of surge events at Yuma associated with easterly waves by surge category are shown in Table 6.

Temporal relationships between the easterly waves and gulf surges at Yuma are illustrated using longitude-time sections of composite mean 700-hPa wind anomalies keyed to Yuma surges (Fig. 9). Since composites are used here, we do not attempt to distinguish the influences of westward propagating easterly waves from other types of westward propagating disturbances (i.e. tropical storms, upper-level inverted troughs, etc.), though clearly a synoptic analysis of each case in the composite would be useful. The composites show that, on average, wet and dry surges are both associated with easterly wave troughs that move across 110°W. On average, the easterly wave troughs arrive at 110°W roughly 3 days prior to the onset of the surges at Yuma, in agreement with Fuller and Stensrud (2000). Similar results are found for both strong and weak surges (not shown). Note, however, that the southerly regime that follows trough passage tends to be much stronger for the wet surges (Fig. 9b) than the dry ones (Fig. 9c). The southerly regime following trough passage is even more pronounced in a composite that includes cases that are both strong and wet (not shown). Similarly, the northerly regime preceding trough passage is more pronounced in a composite that includes cases that are both strong and dry (not shown). Composites that include weak and wet (weak and dry) cases are very similar to those shown in Fig. 9b (Fig. 9c), suggesting that the wet (dry) cases dominate these composites.

Consistent with Fuller and Stensrud (2000), midlatitude westerly waves are identified as they cross 110°W using longitude-time diagrams of 200-hPa meridional wind anomalies for the latitude band 37.5°N-42.5°N. As the westerly waves shift eastward across 110° W, they are accompanied by a coherent transition from southerly to northerly winds as time increases (not shown). In some cases, the westerly wave trough axis does appear to cross 110°W a few days prior to an easterly wave trough axis, but this is not always the case.

Longitude-time sections of composite mean 200-hPa meridional wind anomalies near 40°N for all, wet, and dry Yuma surges (Fig. 10) do not show a very strong relationship to eastward propagating midlatitude westerly waves, at least on average; the same is true for both strong and weak surges (not shown). However, the composites do indicate a strong relationship to quasi-stationary features that reflect the strength and location of the upper tropospheric monsoon anticyclone. Note in particular that the wet composite (Fig. 10b) is dominated by southerly flow (ridge axis to the east) and the dry composite (Fig. 10c) by northerly flow (ridge axis to the west) throughout the evolution. We note that there may be some sensitivity of the results in Fig. 10 to the choice of latitude band since midlatitude disturbances are often confined poleward of 40°N during NH summer.

Composites of the 200-hPa streamfunction and vector wind anomalies indicate that wet surges are dominated by anomalously strong easterly (and diffluent) flow into AZNM in association with an anomalous anticyclonic circulation over the central U.S. (ridge axis east of AZNM) throughout the evolution (Fig. 11a). Composites of the same fields at 700-hPa reveal that the anticyclonic circulation is a barotropic feature (especially during the onset period) capable of advecting considerable moisture into the region (Fig. 12a). During wet surges the lower tropospheric southerly flow around the west side of the monsoon anticyclone phases with the flow around the tropical wave allowing a deep layer of tropical moisture to be advected into AZNM from the south and east (Fig. 12a).

Dry surges are dominated by upper-tropospheric (200-hPa) northerly flow into AZNM in association with an anomalous anticyclonic circulation near the west coast of the U.S. (ridge axis west of AZNM) during and after onset (Fig. 11b). Composites at

700-hPa reveal that this also is a barotropic feature (Fig. 12b). During dry surges the northerly flow around the east side of the monsoon anticyclone "caps" the atmosphere inhibiting convective development, even when a shallow, moist southerly flow is present below 700-hPa. We note that when the surge categories of Table 2 are used (i.e. strong and wet, strong and dry, weak and wet, and weak and dry), the resulting composites at both 200-hPa and 700-hPa are consistent with the results in Figs. 11 and 12 (not shown).

Given the persistent orographic forcing for vertical motion always present in the core monsoon region, it is likely that an important driver for precipitation is how surges affect the intensity and areal extent of boundary layer Convective Available Potential Energy (CAPE) (Bob Maddox, personal communication). If low-level moisture increases are accompanied by strong middle level warming, there can be zero or negative changes in CAPE even though the moisture has increased. Thus we speculate that the dry surges are most likely shallow and thus do not substantially increase boundary layer CAPE while the wet surges are deeper and accompanied by increases in CAPE. This is consistent with differences in the relative positions of upper-level anticyclones in midlatitudes for wet and dry surges.

Thus, it appears that two critical factors that relate gulf surges to wetter-than-normal conditions in AZNM are (i) the presence of moist low-level southerly or southeasterly flow, often associated with the passage of easterly wave troughs across western Mexico and (ii) the presence of a strong anticyclonic circulation at upper levels over the central United States (ridge axis to the east of AZNM). Tropical easterly waves are often present for the dry surges as well, but the anticyclonic circulation in midlatitudes is often located near the west coast (ridge axis to the west of AZNM), which inhibits deep convection in AZNM. A schematic depicting the 700-hPa circulation features (heights and winds) that typically accompany wet (dry) surges keyed to Yuma, AZ is shown in Fig. 13.

For the wet surges, it is interesting to note that the anomalous anticyclonic circulation precedes the surges (Fig. 11a) providing an environment that is favorable for the development of deep convection associated with the surge. After the surge arrives, the associated deep convection can help to sustain the anticyclone at upper levels (i.e. contribute to enhanced upper-level divergence) contributing to the persistence of the pattern. The Hovmoeller diagram (Fig. 10) also indicates that the anticyclone is not forced by the increasing monsoon rains, but precedes it. The analysis appears to provide a new explanation for the attending dry Great Plains conditions often seen during active periods of the monsoon. Both are consequences of the dynamical / thermodynamical influences exerted by this circulation.

Finally, we emphasize that the results shown in Figs. 9-12 are based on composites. These relationships are likely to vary for individual cases. In future work we plan to examine the composites on a case-by-case basis to determine the particular tropical and midlatitude circulation features involved.

## 5.0 Summary and Future Plans

Relationships between Gulf of California moisture surges and precipitation were examined. Whereas previous studies emphasized basic characteristics of gulf surges and their relationships to tropical easterly and midlatitude westerly waves (e.g. Stensrud et al. 1997; Fuller and Stensrud 2000), this study emphasized the relative differences in the precipitation and atmospheric circulation patterns for several different categories of gulf surges. Significantly, it was found that the relative location of the upper-level anticyclone in midlatitudes at the time of the gulf surge affects the response to the surge in the southwestern United States. The results are consistent with previous studies that have discussed the importance of the Arizona monsoon moisture boundary that separates east Pacific or continental air to the west from the deep/moist subtropical air mass to the east (e.g. Adang and Gall 1989; Moore et al. 1989). The boundary is very important for delineating environments in which deep convection can develop. Given the persistent orographic forcing for vertical motion always present in the core monsoon region, it is likely that an important driver for precipitation is how surges affect the intensity and areal extent of boundary layer CAPE, though this was not investigated. When deep easterly flow is present, the moister thermodynamic profile can lead to a greater likelihood of squall lines over Arizona (Smith and Gall 1989), consistent with our results.

It was shown that a significant fraction of the events in all categories were related to the passage of tropical easterly waves across western Mexico, but the explicit role of other types of tropical disturbances (e.g. tropical storms, upper-level inverted troughs and cyclones) remains to be considered.

The occurrence of wet surges versus dry surges in the southwestern United States is not discriminated by the presence of tropical easterly waves, but rather by the relative location of the upper-level anticyclone in midlatitudes at the time of the gulf surge. During wet surges lower tropospheric southerly flow around the west side of the monsoon anticyclone phases with the flow around the tropical wave allowing a deep layer of tropical moisture to be advected into AZNM from the south and east. During dry surges the northerly flow around the east side of the monsoon anticyclone “caps” the atmosphere inhibiting convective development, even when a shallow, moist southerly flow is present near the surface.

Several mechanisms have been proposed to explain the dynamics of Gulf surges. In a recent study, Zehnder (2004) reviews several mechanisms, which include gravity currents, ageostrophic flows, Kelvin waves, and Rossby edge waves. Through scale analyses and idealized numerical simulations he concludes that gravity currents and ageostrophic flows may contribute only to weak surges and that idealized simulations of Kelvin waves are not in qualitative agreement with observations. From the idealized experiments he finds that Rossby edge waves would propagate along the Gulf of California in better agreement with observations.

As noted by Zehnder (2004), the major difficulty in identifying the correct dynamic mechanism for gulf surges is the lack of observational data in the region. Since composites were used in our study and the emphasis was on relationships between gulf surges and the precipitation patterns (not the dynamic mechanism for gulf surges per se), additional studies are required to determine which of the proposed mechanisms agrees best with observations.

Several improvements to the current analysis are envisioned. First, we will examine the individual cases that make up the composites to elucidate relationships between the surges and various types of tropical disturbances (tropical cyclones, upper-level inverted troughs and cyclones, etc.). Also, the analysis will be extended down the Gulf of California using hourly station data along the Gulf (currently in house at CPC) in order to refine our understanding of the spatial and temporal relationships between tropical disturbances, gulf surges and precipitation. Hourly precipitation data to be gathered during NAME in Northwest Mexico will be used to develop an integrated gauge-only precipitation database that will resolve the diurnal component of these relationships in this region. The NAME project should help to verify many of the conjectures in the literature about low-level circulation features over Mexico and the Gulf of California (including the Gulf of California low-level jet and land / sea breezes). The enhanced observations to be gathered during NAME 2004 (Higgins et al. 2003) will be used in conjunction with high resolution atmospheric analyses that incorporate the NAME data in an attempt to elucidate the relevant dynamical mechanisms controlling gulf surges and to improve our understanding of gulf surge-precipitation relationships.

**6.0 Acknowledgments**

We gratefully acknowledge Will Spangler and Charles Jones for assistance in accessing the hourly surface observations used in this study. We also thank Miguel Cortez for providing us with daily precipitation data for Mexico. Thanks are extended to Vernon Kousky, David Stensrud, Song Yang, Evgeney Yarosh and 2 anonymous reviewers for providing many insightful comments on a preliminary draft of this manuscript.

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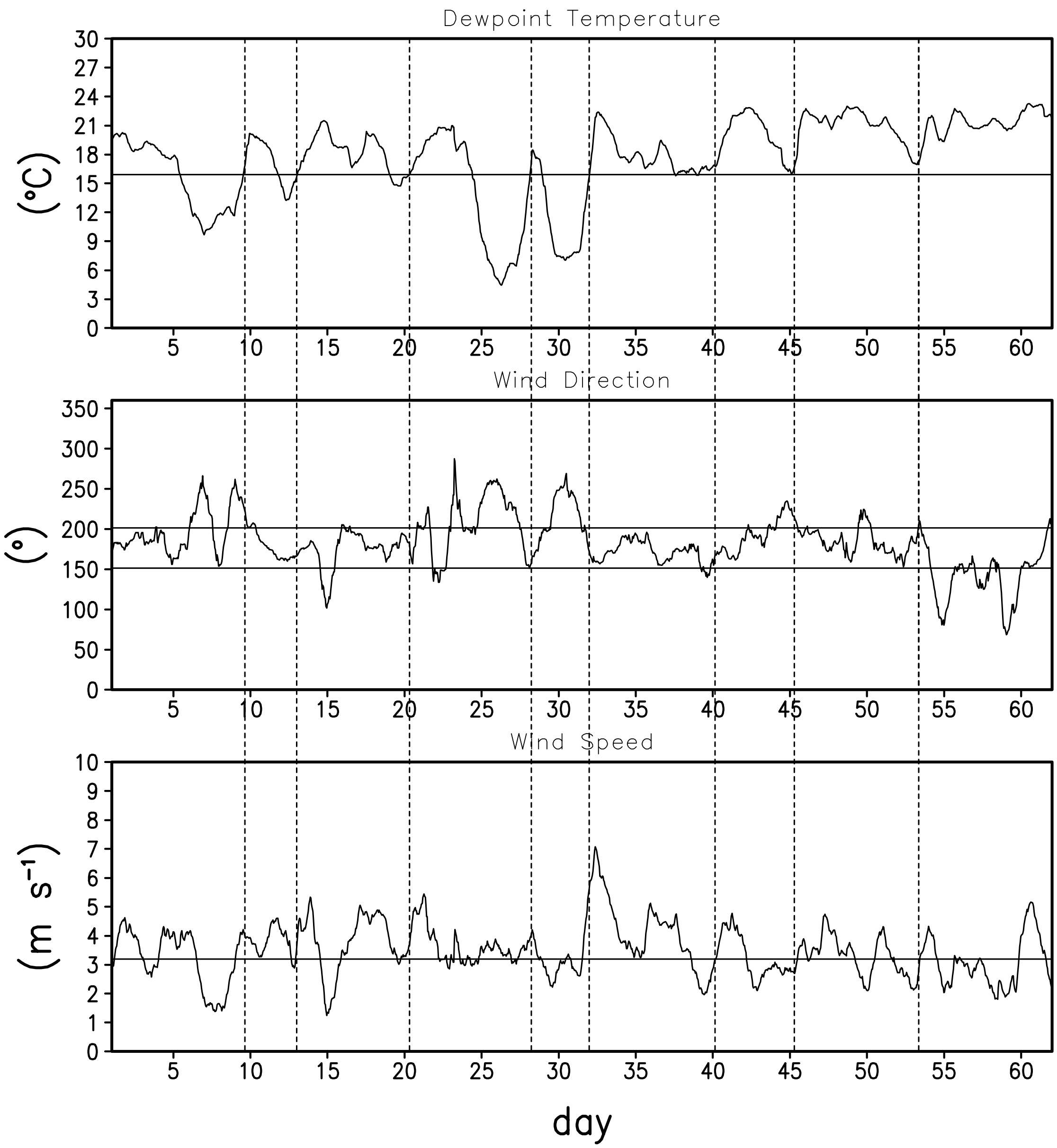


**Figure 1**. 25-hr running mean values of dewpoint temperature (°C), wind direction (°) and wind speed (m $s^{-1}$) at Yuma for July-August 1986. The mean values of dewpoint temperature and wind speed for July-August 1977-2001 are indicated by horizontal lines. Dashed vertical lines denote the onset day of each surge event.

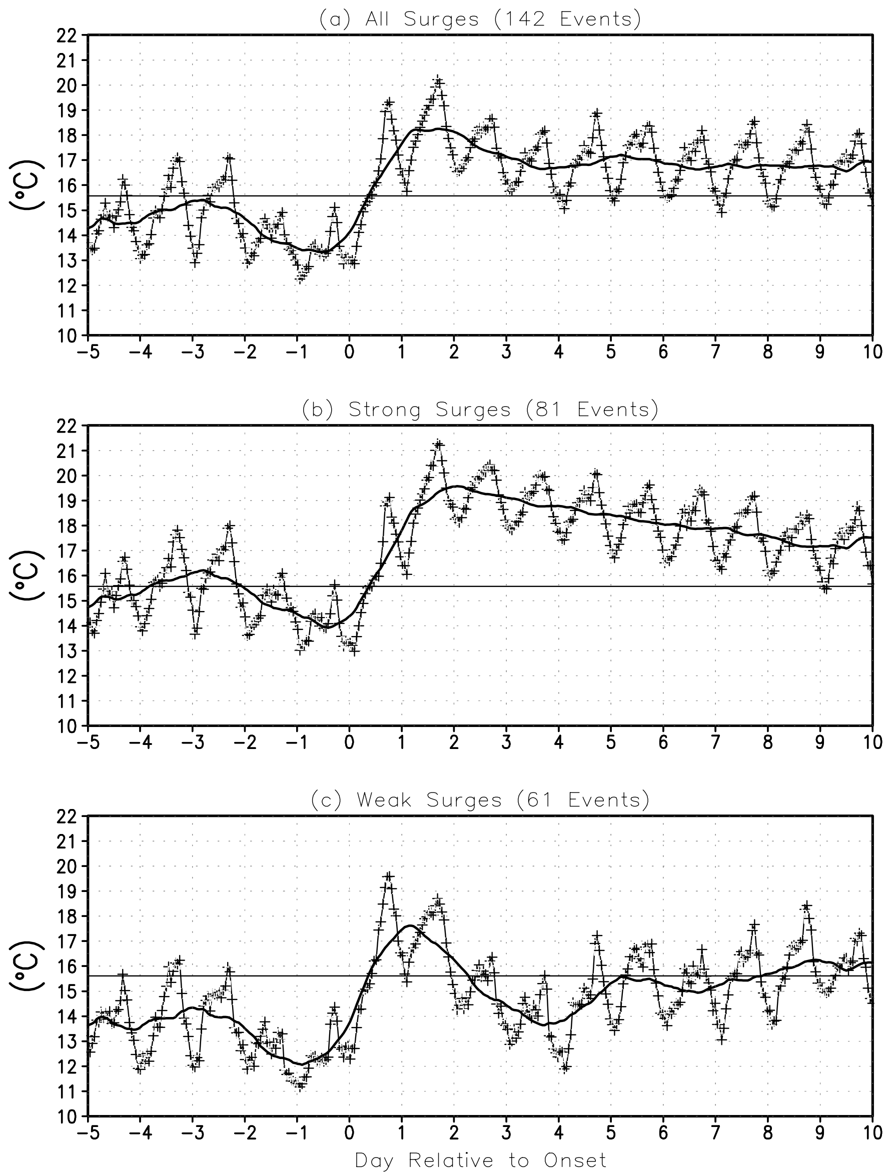


**Figure 2.** Composite evolution of hourly (curves with crosses) and 25-hr running mean (solid curves) dewpoint temperature (°C) at Yuma keyed to the onset of moisture surges at Yuma for (a) all, (b) strong and (c) weak surge events. The onset day is indicated as day 0 along the abscissa, with the composite evolution shown from 5 days before onset until 10 days after onset in each panel. The climatological mean value of dewpoint temperature(15.7° C) for July-August 1977-2001 is indicated by a horizontal line on each panel.

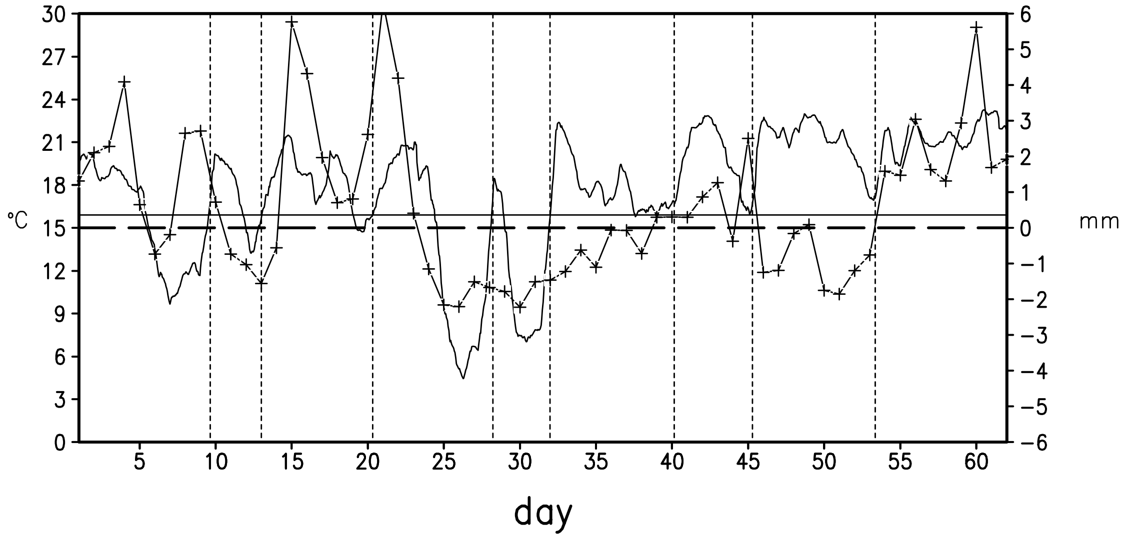


**Figure 3.** 25-hr running mean values of dewpoint temperature (°C) at Yuma (solid curve) together with area mean (112.°5-107.5°W, 32°-36°N) daily precipitation anomalies (mm) for AZNM (curve with crosses) during July-August 1986. The base period (July-August 1977-2001) mean value of dewpoint temperature is indicated by a horizontal solid line. Dashed vertical lines denote the onset day of each surge event. Precipitation anomalies are departures from base period (July-August 1977-2001) mean values; for reference the horizontal dashed line indicates precipitation anomalies of zero mm.

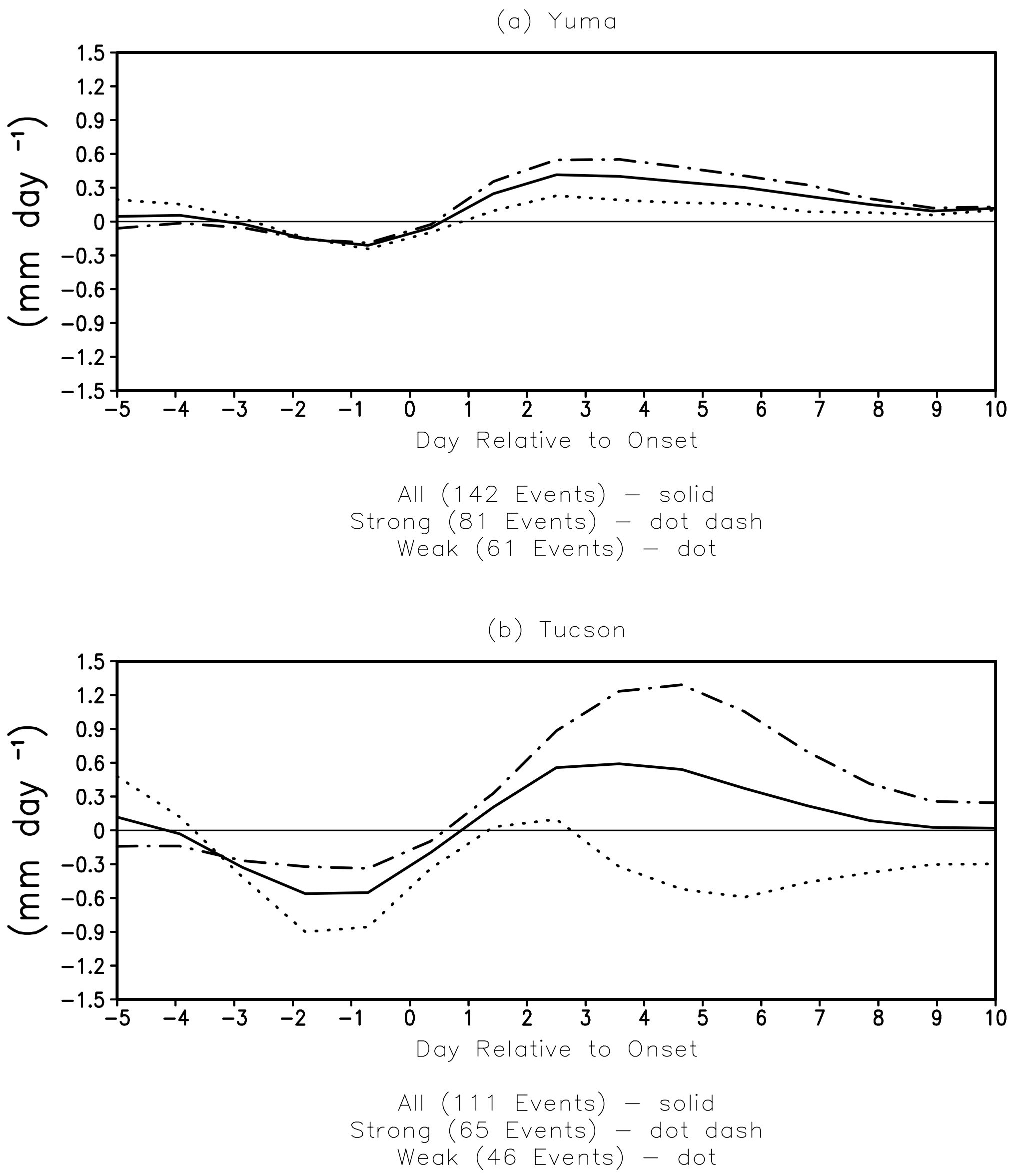


**Figure 4.** Composite evolution of area mean (112.°5-107.5°W, 32°-36°N) daily precipitation anomalies (mm) in AZNM keyed to the onset of moisture surges at (a) Yuma and (b) Tucson. Composites are shown for all (solid line), strong (dash dotted line) and weak (dotted line) surges. A 3-day running mean has been applied to the precipitation composites in each case. Horizontal lines indicating an anomaly of zero are added for clarity.

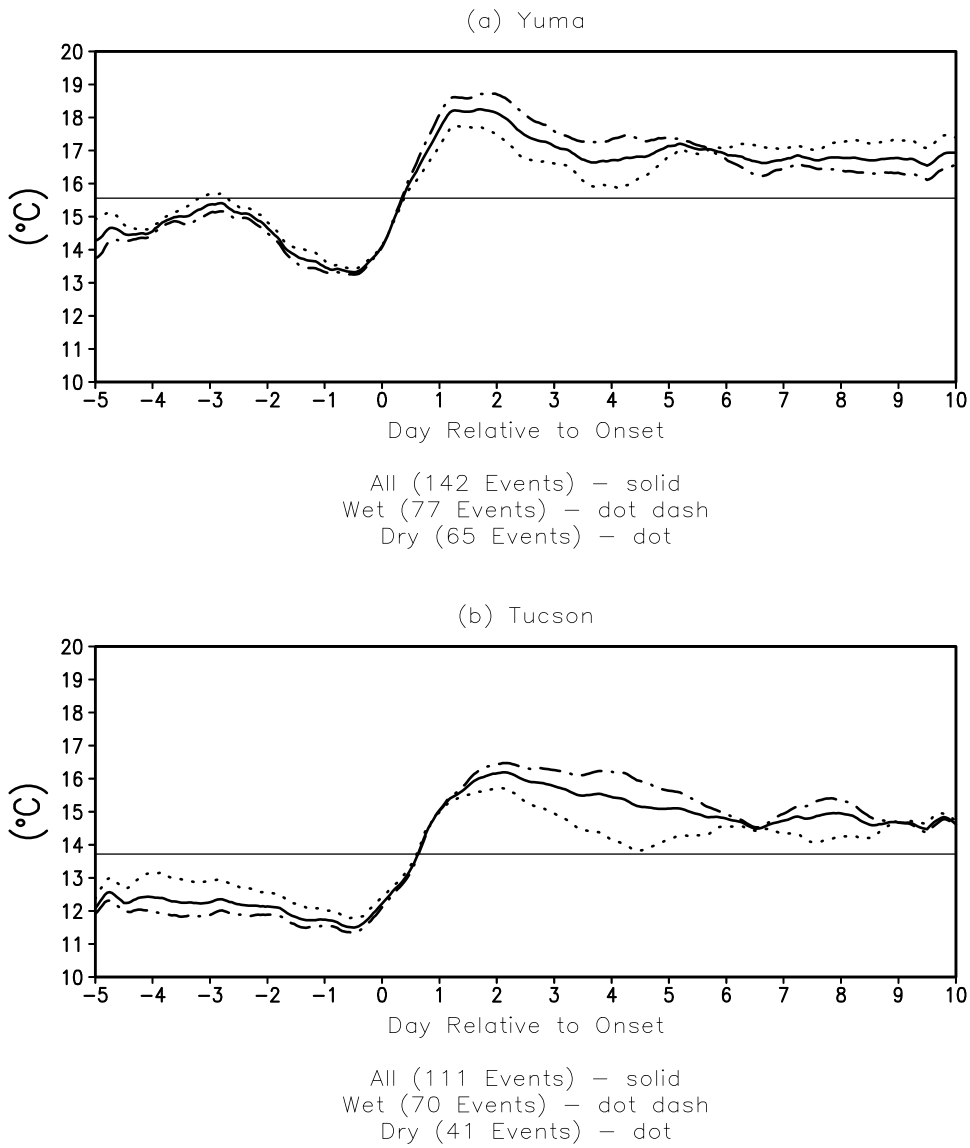


**Figure 5.** Composite evolution of 25-hr running mean values of dewpoint temperature (°C) keyed to the onset of moisture surges at (a) Yuma and (b) Tucson. Composites are shown for all (solid line), wet (dash dotted line) and dry (dotted line) surges. Wet (dry) surges are defined as those with positive (negative) precipitation anomalies in AZNM during the period from day 0 to day +4. The climatological mean value of dewpoint at Yuma (15.7°C) and Tucson (13.8°C) for July-August 1977-2001 is indicated by a horizontal line on each panel.

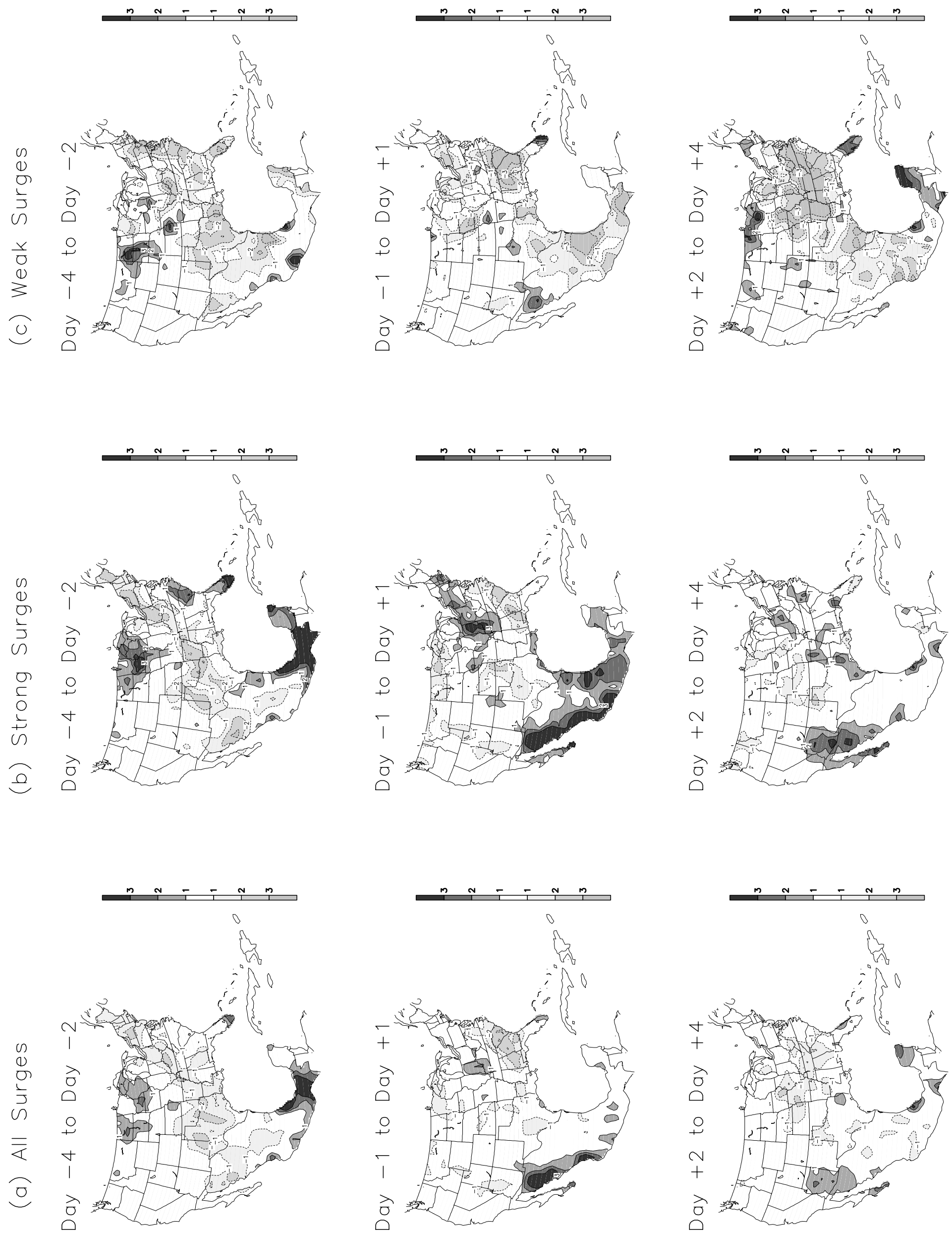


**Figure 6.** Composite evolution of precipitation anomalies (mm) for (a) all, (b) strong and (c) weak surges keyed to Yuma, AZ. Day 0 is the onset date of the surges at Yuma. The averaging period relative to onset is indicated on each panel. The contour interval is 1 mm day$^{-1}$, the zero contour is omitted for clarity and values greater than 1 mm day$^{-1}$ (less than -1 mm day$^{-1}$) are shaded dark (light).

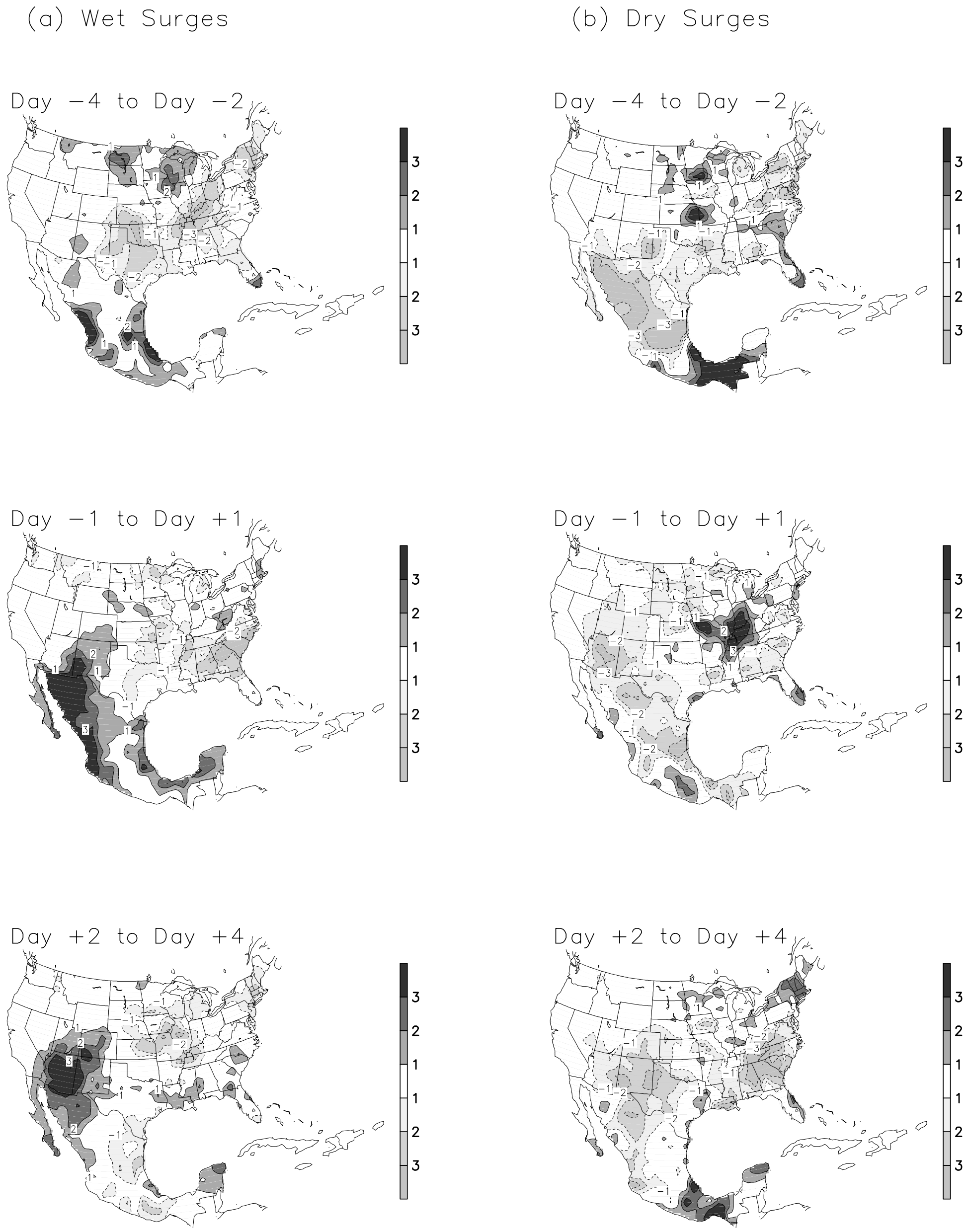


**Figure 7.** Composite evolution of precipitation anomalies (mm) for (a) wet and (b) dry surges keyed to Yuma, AZ. Day 0 is the onset date of the initial rapid dewpoint temperature rise at Yuma. The averaging period relative to onset is indicated on each panel. The contour interval is 1 mm day$^{-1}$, the zero contour is omitted for clarity and values greater than 1 mm day$^{-1}$ (less than -1 mm day$^{-1}$) are shaded dark (light).

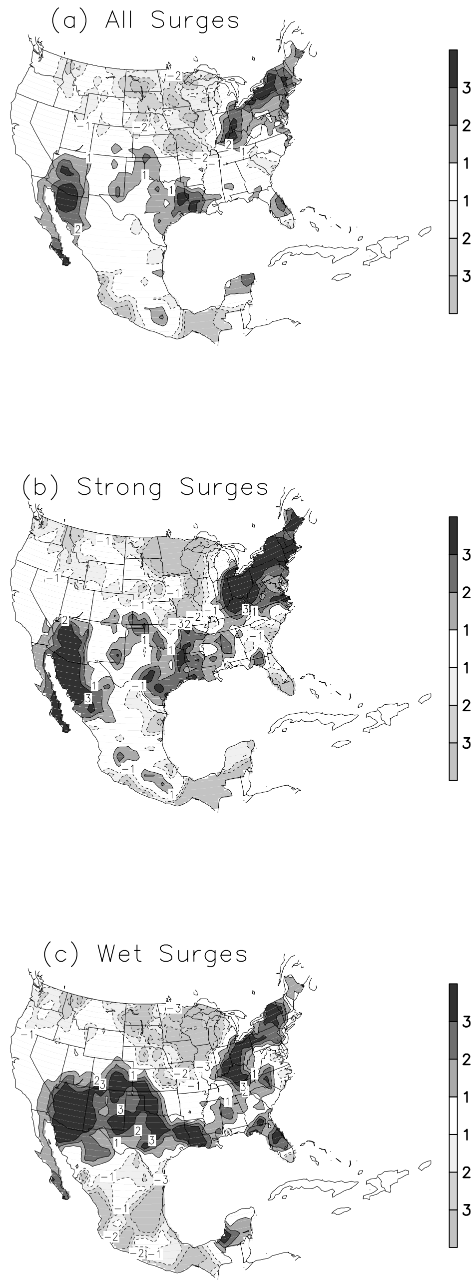


**Figure 8.** Observed precipitation represented as the composite mean difference between the 5 day period after onset (day 0 to day +4) and the 5 day period before onset (day -5 to day -1) for (a) all, (b) strong and (c) wet surges keyed to Yuma, AZ. The contour interval is 1 mm day$^{-1}$, the zero contour is omitted for clarity and values greater than 1 mm day$^{-1}$ (less than -1 mm day$^{-1}$) are shaded dark (light).

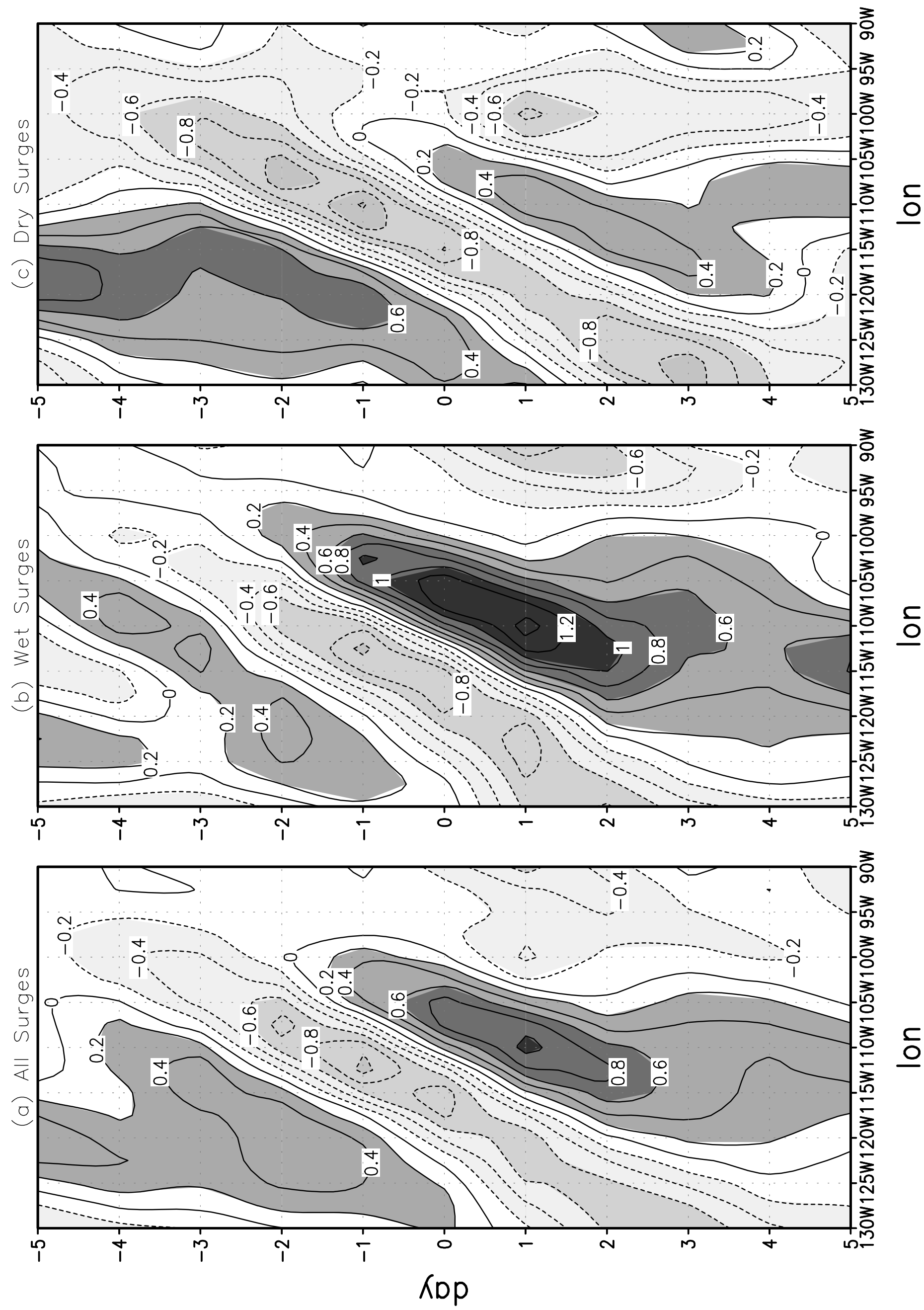


**Figure 9.** Longitude-time sections of the composite mean 700-hPa meridional wind anomalies (m $s^{-1}$) along 20°N-25°N for (a) all, (b) wet and (c) dry surges keyed to the onset of moisture surges at Yuma. Contour interval is 0.2 m $s^{-1}$. The onset day for surges at Yuma is day 0. The vertical lines in each case are 110°W.

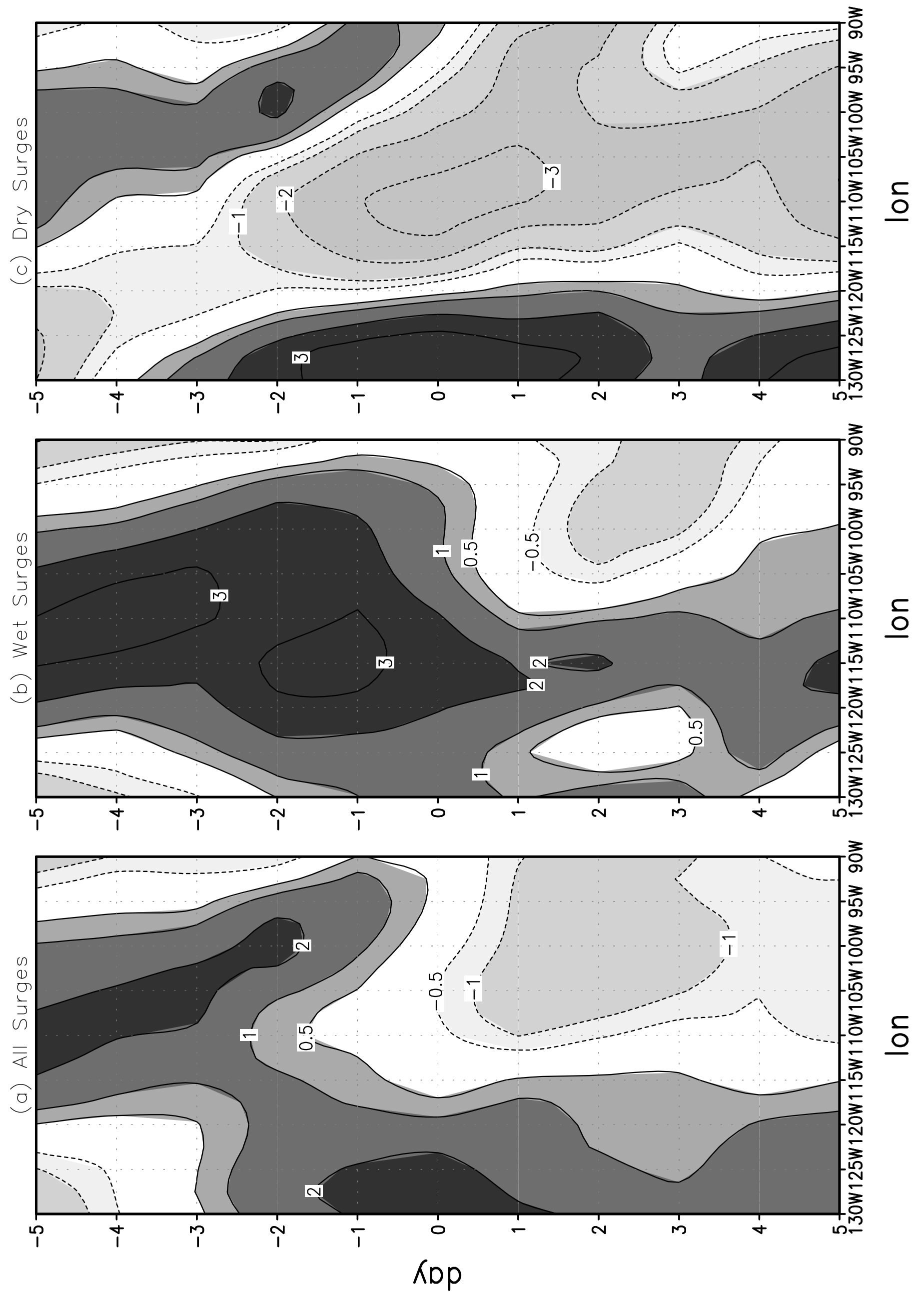


**Figure 10.** Longitude-time sections of the composite mean 200-hPa meridional wind anomalies (m $s^{-1}$) along 37.5°N-42.5°N for (a) all, (b) wet and (c) dry surges keyed to the onset of moisture surges at Yuma. Contour interval is 1 m $s^{-1}$ (to which the 0.5 contour has been added). The onset day for surges at Yuma is day 0. The vertical lines in each case are 110°W.

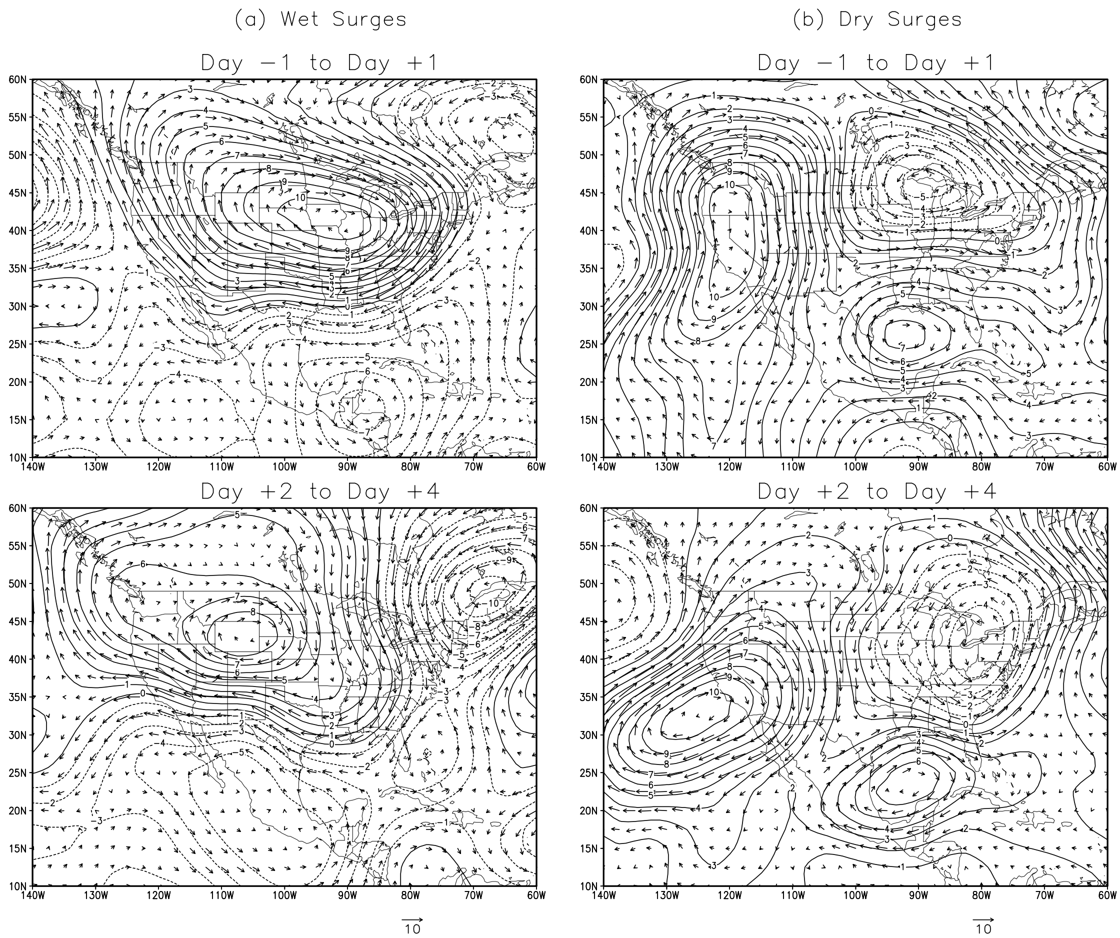


**Figure 11.** Composite evolution of 200-hPa streamfunction anomalies ($m^2 s^{-1} x10^6$) and vector wind anomalies ($m s^{-1}$) for (a) wet and (b) dry surges keyed to the onset of moisture surges at Yuma. The contour interval is 1 $m^2 s^{-1} x10^6$. The onset day for surges at Yuma is day 0.

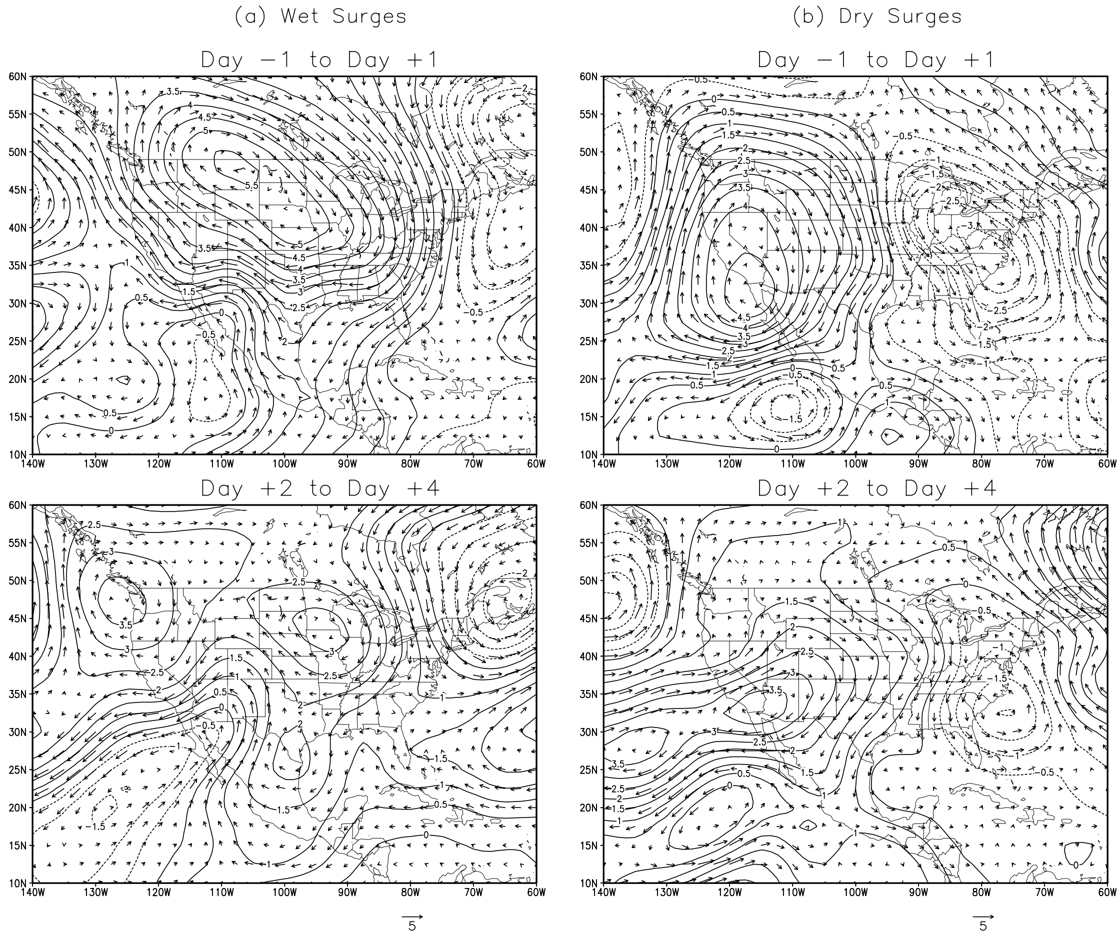


**Figure 12.** Composite evolution of 700-hPa streamfunction anomalies ($m^2\ s^{-1}\ x10^6$) and vector wind anomalies ($m\ s^{-1}$) for (a) wet and (b) dry surges keyed to the onset of moisture surges at Yuma. The contour interval is 0.5 $m^2\ s^{-1}\ x10^6$. The onset day for surges at Yuma is day 0.

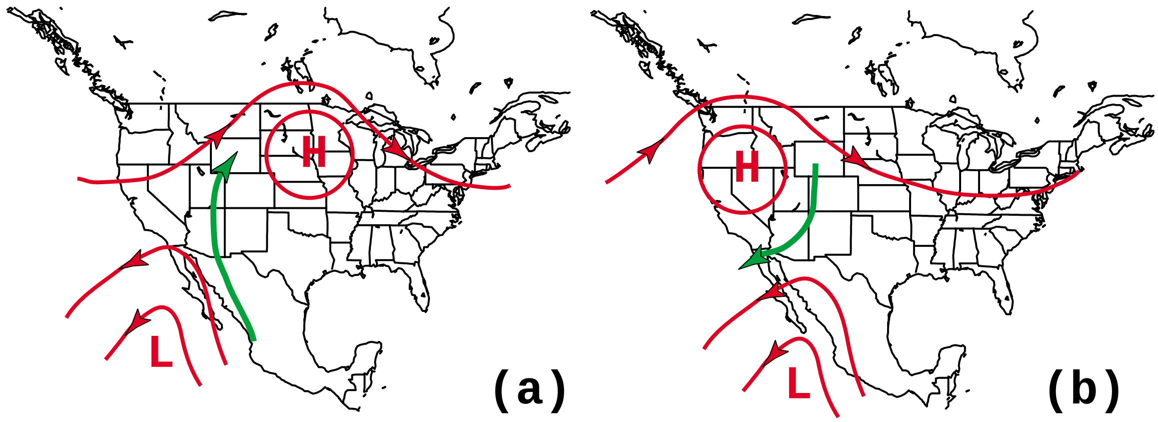


**Figure 13.** Schematic of the typical 700-hPa circulation features (heights and winds) that accompany (a) wet and (b) dry surges keyed to Yuma, AZ.

**Table 1**. Number (fraction in percent) of total surge events at Yuma and Tucson during the period July-August 1977-2001 that were strong or weak, and wet or dry (see text for definitions of the categories).

| **Surge Category** | **Yuma** | **Tucson** |
|---|---|---|
| **Strong** | 81<br>(57%) | 65<br>(59%) |
| **Weak** | 61<br>(43%) | 46<br>(41%) |
| **Wet** | 77<br>(54%) | 69<br>(63%) |
| **Dry** | 65<br>(46%) | 42<br>(37%) |

**Table 2.** Number (fraction in percent) of total surge events at Yuma and Tucson during the period July-August 1977-2001 that were strong and wet, strong and dry, weak and wet, or weak and dry (see text for definitions of the categories).

| Surge Category | Yuma | Tucson |
|---|---|---|
| **Strong and Wet** | 50 (35%) | 50 (45%) |
| **Strong and Dry** | 31 (22%) | 15 (14%) |
| **Weak and Wet** | 27 (19%) | 20 (18%) |
| **Weak and Dry** | 34 (24%) | 26 (23%) |

**Table 3.** Fraction (in percent) of total AZNM precipitation per July-August during surge events keyed to Yuma, AZ (top) and Tucson, AZ (bottom). Results are based on July-August 1977-2001. The average number of surge days per July-August is also shown in each case (the maximum possible number is 62). Interannual standard deviations in the percentage of total AZNM precipitation and in the number of surge days are shown in parentheses.

**Yuma, Arizona**

| | **All** | **Strong** | **Weak** | **Wet** | **Dry** |
|---|---|---|---|---|---|
| **% of total AZNM Precipitation** | 66% (28%) | 57% (28%) | 9% (5%) | 49% (30%) | 17% (17%) |
| **Avg. # of Surge Days** | 32 (10) | 27 (11) | 5 (3) | 19 (11) | 13 (11) |

**Tucson, Arizona**

| | **All** | **Strong** | **Weak** | **Wet** | **Dry** |
|---|---|---|---|---|---|
| **% of total AZNM Precipitation** | 38% (17%) | 31% (17%) | 7% (7%) | 31% (15%) | 7% (7%) |
| **Avg. # of Surge Days** | 18 (6) | 14 (7) | 4 (4) | 13 (6) | 5 (5) |

**Table 4.** Fraction (in percent) of surge days and non-surge days per July-August at Yuma, AZ (top) and Tucson, AZ (bottom) with AZNM precipitation exceeding various thresholds; results are based on July-August 1977-2001. The average number of surge (non-surge) days per July-August at Yuma is 32 (30). The average number of surge (non-surge) days per July-August at Tucson is 18 (44). Interannual standard deviations in the percentage of surge days (non-surge days) per July-August for each threshold is shown in parentheses.

**Yuma, Arizona**

| | **0.1 mm** | **0.5 mm** | **1 mm** | **2 mm** | **5 mm** |
|---|---|---|---|---|---|
| **surge days** | 97% (31%) | 87% (29%) | 72% (27%) | 48% (24%) | 9% (6%) |
| **non-surge days** | 80% (29%) | 57% (28%) | 47% (22%) | 27% (15%) | 3% (3%) |

**Tucson, Arizona**

| | **0.1 mm** | **0.5 mm** | **1 mm** | **2 mm** | **5 mm** |
|---|---|---|---|---|---|
| **surge days** | 98% (31%) | 90% (29%) | 77% (29%) | 47% (24%) | 9% (9%) |
| **non-surge days** | 84% (16%) | 66% (19%) | 52% (16%) | 32% (14%) | 5% (3%) |

**Table 5**. Area mean accumulated precipitation anomalies (mm) for the 5 day period (day 0 to day +4) following the onset of moisture surges keyed to Yuma. Results are based on the composites shown in Figs. 6 and 7 for all, strong, weak, wet, and dry surges as defined in the text.

| **Region** | **All** | **Strong** | **Weak** | **Wet** | **Dry** |
|---|---|---|---|---|---|
| **AZNM** | 1.4 | 2.0 | 0.6 | 5.8 | -3.9 |
| **Mexico** | 0.1 | 1.1 | -1.5 | 1.0 | -1.1 |
| **US and Mexico** | -0.4 | 0.1 | -1.2 | 0.0 | -1.0 |

Table 6. Fraction (in percent) of surge events at Yuma related to easterly waves crossing 110°W by surge category. Results are based on July-August 1977-2001.

| | **All** | **Strong** | **Weak** | **Wet** | **Dry** |
|---|---|---|---|---|---|
| **% of surges** | 63% | 76% | 42% | 68% | 55% |