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Tropospheric moisture and monsoonal rainfall over the southwestern United States

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[1] This study investigates the role of increased atmospheric humidity in occurrences of wet days in the southwestern United States during the monsoon seasons of 1996–2002, using spatiotemporal analyses of ground-measured precipitation, spatial analyses of surface and 700-hPa humidity, and air-parcel trajectory analyses. A precipitation regionalization indicates that the Gila River basin in southern Arizona/southwest New Mexico should be divided into a western region and an eastern region. A rainfall peak occurred in late August/early September for the western region; however, similar to that of the core monsoon zone in northwestern Mexico, the eastern region of the basin had a rainfall peak in late July/early August. Wet days in the western (eastern) region were associated with a large (moderate) peak in dew point temperature in the southwestern (south central) portion of the basin. The middle troposphere was more humid than normal on both sets of days, with the anomalies for western region wet days being larger and located more over the Gila River basin than anomalies for the eastern region wet days. The Sierra Madre Occidental was the most likely source of middle troposphere moisture for both regions; however, the Gulf of Mexico may have been a significant contributor to rainfall in parts of the eastern region. The Gulf of California probably was the dominant source of low-level moisture for western region wet days, with gulf surges likely causing the late August/early September peak.

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1. Introduction

[2] The Mexican monsoon (also known as the North American monsoon) is centered over the Sierra Madre Occidental in northwestern Mexico and mostly through convective thunderstorms can deliver over 400 mm of precipitation to the region from June through September [*Higgins et al.*, 1999]. Monsoonal precipitation can also extend into the southwestern United States; this precipitation is most intense in south central Arizona [*Diem*, 2005]. For most of the southwestern United States, July and August are the peak precipitation months, with parts of southeastern Arizona and southwestern New Mexico receiving up to 50% of their annual precipitation during the monsoon season [*Higgins et al.*, 1997; *Barlow et al.*, 1998]. As a result, monsoonal precipitation is a vital component of the region's annual hydrologic cycle, and in particular is a significant factor in aquifer and reservoir recharge. Heavy rainfall events are not uncommon in the Southwest during the monsoon season; for example, a storm in September 1970 produced 29 mm of precipitation in central Arizona in 1 hour [*Hales*, 1972]. These events can trigger flash flooding in urbanized areas as well as rural washes and streambeds, creating transportation and safety hazards as well as environmental concerns such as severe erosion in areas of marked topographic relief.

[3] Monsoon-thunderstorm activity in the Southwest has been linked to increased atmospheric humidity. On the basis of frequencies of lightning strikes across Arizona, *Watson et al.* [1994] examined twelve monsoon bursts from 1985–1990 and found a tongue of increased moisture in the lower and middle troposphere extending primarily into Arizona from northern Mexico during the bursts. *Mullen et al.* [1998] identified 172 "wet days" and 171 "dry days" in southeastern Arizona during July and August of 1985–1992, with the "wet days" having higher surface specific humidities (i.e., up to 3 g kg^{-1}) over eastern Arizona and western New Mexico, and 500-hPa increases in specific humidity (i.e., >1 g kg^{-1}) located over southeastern and central Arizona. For the Phoenix, Arizona, area, *Maddox et al.* [1995] identified 31 severe thunderstorm events during monsoon seasons from 1978–1990. Severe thunderstorm events in the Phoenix area were associated with large positive anomalies in dew point temperature over northwestern Mexico and the entire southwestern United States, especially the western portion, at 850 hPa and 500 hPa, respectively; in addition, the mean mixing ratio during severe thunderstorm events for the lowest 100 hPa was

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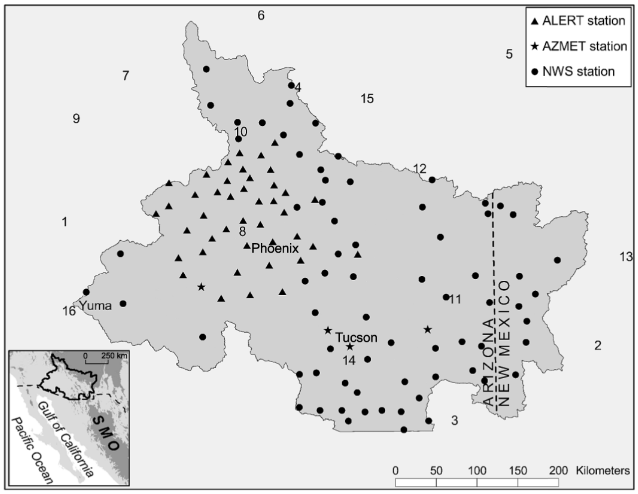

Figure 1. Locations of the 115 precipitation stations and 16 dew point temperature stations in the Gila River basin. The numbers denote the dew point temperature stations (1, Blythe; 2, Deming; 3, Douglas; 4, Flagstaff; 5, Gallup; 6, Grand Canyon NP; 7, Kingman; 8, Luke AFB; 9, Needles; 10, Prescott; 11, Safford; 12, Show Low; 13, Truth or Consequences; 14, Tucson; 15, Winslow; 16, Yuma). Also shown is the basin's location in the southwestern United States and its proximity to the Sierra Madre Occidental (SMO) and the Gulf of California. Darker areas in the lower map are greater than or equal to 1500 m above sea level.

$\sim$13 g kg^{-1}, which was $\sim$50% higher than the typical monsoon-season value [*Maddox et al.*, 1995].

[4] The Gulf of California is the most logical major direct source for low-level moisture transport into the Southwest, particularly via northward flows of tropical-maritime air known as gulf surges [*Hales*, 1972]. Surges can extend several kilometers above sea level and cause increased lower troposphere humidity levels extending from the mouth of the Gulf of California into northwestern Mexico [*Anderson et al.*, 2000], before spreading up the Colorado River valley as well as northward and northeastward to the mountainous terrain of Arizona [*Hales*, 1972]. Surges tend to occur approximately three times per month and increase surface dew point temperatures by 5°C at Yuma, AZ [*Higgins et al.*, 2004], which is less than 100 km from the Gulf of California. Surges also have caused intense rainfall as far north as Las Vegas, NV [*Berg et al.*, 2002], which is $\sim$400 km north of Yuma.

[5] With large values of vertically integrated moisture-flux convergence over the Sierra Madre Occidental, much middle troposphere moisture over North America can be traced back to the mountain range [*Anderson and Roads*, 2001; *Berbery*, 2001]. The Sierra Madre Occidental is therefore presumed to be a major direct "source" of middle troposphere moisture to the Southwest during the monsoon season. The afternoon sea breeze from the Gulf of California transports moisture toward the western slopes of the Sierra Madre Occidental; thus winds converge at the crest of the range [*Berbery*, 2001; *Fawcett et al.*, 2002]. As a result, the Sierra Madre Occidental facilitates the flow of moisture from Mexico into Arizona and New Mexico in the middle troposphere [*Douglas and Li*, 1996; *Anderson and Roads*, 2001].

[6] Another possible direct source of monsoonal moisture in the Southwest is the Gulf of Mexico. For a typical summer season, the vertically integrated (i.e., surface to 200 hPa) moisture transport from the Gulf of Mexico into western Texas is much stronger than the transport of moisture into western Arizona from the northern Gulf of California [*Schmitz and Mullen*, 1996]. The influence of the Gulf of Mexico on monsoon-precipitation events in the Southwest may be primarily focused in New Mexico, rather than Arizona [*Mo and Berbery*, 2004].

[7] Previous monsoon-moisture studies have not considered explicitly the potential for substantial variations across the peripheral monsoon zone (i.e., southern Arizona and southwestern New Mexico) in moisture characteristics of rainfall events. Therefore the purpose of this study is to investigate the role of increased atmospheric humidity in occurrences of wet days within the southwestern United States during the monsoon season. The Gila River basin, which encompasses most of the southern half of Arizona and part of western New Mexico (Figure 1), is the chosen study domain. As noted by *Diem* [2005], the basin is an excellent study region, because (1) daily precipitation totals have been measured at hundreds of weather stations in the basin during the past decade, and (2) it contains a diverse array of stakeholders (e.g., natural resource managers, ranchers, farmers, municipalities, etc.) with respect to water issues. An improved understanding of the climatological characteristics of monsoon-precipitation days, while contributing to a broader understanding of intraseasonal and interseasonal monsoonal circulation variability and impacts, may also help inform decision-making in the region by city managers, emergency response personnel, and others regarding flood control and mitigation strategies.

2. Data

[8] Ground-measured precipitation, surface dew point temperature, and middle troposphere specific-humidity data were acquired for the period of 16 June to 15 September from 1996 to 2002. Thus the study period included seven seasons consisting of 92 days each. The thermal-low system, which is a main feature of the monsoonal circulation, is typically located over the desert region from mid-June to mid-September [*Rowson and Colucci*, 1992].

[9] The precipitation data consisted of precipitation totals measured at Automated Local Evaluation in Real Time (ALERT), Arizona Meteorological Network (AZMET), and National Weather Service (NWS) stations. Hourly precipitation totals were obtained for the ALERT and AZMET stations from the Flood Control District of Maricopa County and The University of Arizona Cooperative Extension, respectively. Daily precipitation totals were obtained for the NWS stations from the National Oceanic and Atmospheric Administration (NOAA). Complete details regarding precipitation data collection and calibration are provided by *Diem* [2005]. The final weather-station network was comprised of 115 stations, with over 60% of the stations being NWS stations. Only 2% of the daily precipitation totals needed to be estimated, and only one station was originally missing more than 20% of its daily

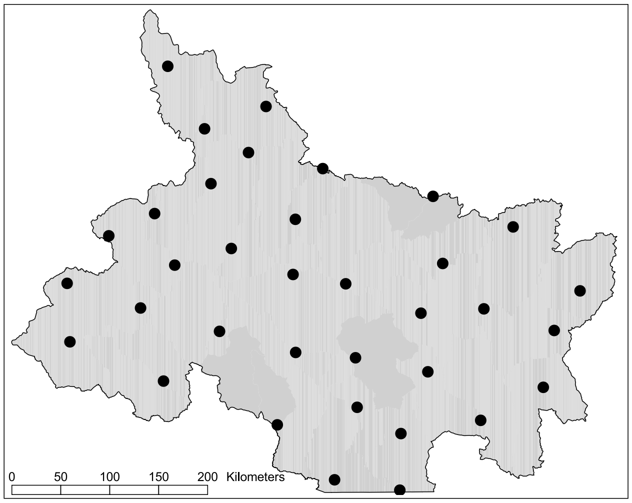

Figure 2. The 35 stations used in the precipitation regionalization.

values. Missing values at all stations were estimated using an inverse-distance-weighting scheme involving data from at least three nearby stations, and any station having data for the selected missing-data day was a potential predictor station.

[10] Mean daily dew point temperatures from 16 World Meteorological Organization stations within and proximate to the Gila River basin were acquired from NOAA's Global Summary of the Day data set. Missing values from 1 July to 15 September 1997 at the Safford station were replaced with adjusted dew point temperatures from a nearby AZMET station. For the entire surface network, fewer than 2% of the daily values were missing, and none of the stations were missing more than 6% of the values. None of the missing values were replaced with estimated values.

[11] Specific-humidity data at 700 hPa were extracted from the NCEP/NCAR Reanalysis data set [*Kalnay et al.*, 1996] of the Climate Diagnostics Center of the National Oceanic and Atmospheric Administration and the Cooperative Institute for Research in Environmental Sciences (NOAA-CIRES CDC). All data had a spatial resolution of 2.5°. The geographic extent of the extracted data ranged from 25°N to 45°N latitude and from 100°W to 130°W longitude.

3. Methods

3.1. Precipitation

[12] A precipitation regionalization was needed initially to determine locales within the Gila River basin that would be further analyzed with respect to the characteristics of wet days. The complete network of 115 precipitation stations was clustered in some portions of the Gila River basin; thus the initial spatial distribution of stations was not optimal for a regionalization analysis based on principal components analysis (PCA). A minimum spacing of ∼60 km between stations was needed to produce a dispersed point pattern, which is an ideal distribution for regionalization [see *Richman and Lamb*, 1985]. This spacing produced a dispersed network of 35 stations (Figure 2).

[13] The precipitation data could not be retained as daily totals, because that temporal resolution resulted in an overwhelming amount of zero values. As a result, the distribution of daily precipitation totals in the southwestern United States was highly positively skewed, which is a far from ideal distribution for PCA. In order to reduce the positive skewness of the distributions, 18-day precipitation totals were calculated for a 90-day period (i.e., 17 June to 14 September), and the resulting values were adjusted subsequently with a square-root transformation. The 18-day totals yielded 35 time periods (i.e., five periods for seven seasons), which was the minimum number of cases needed to perform the PCA-based regionalization.

[14] Standardized PCA was used to determine the precipitation regions. The input S-mode matrix consisted of 35 rows (i.e., cases) and 35 columns (i.e., stations). The subsequent use of a correlation matrix, rather than a covariance matrix, ensured that relatively dry stations at lower elevations could be directly compared with relatively wet stations at higher elevations [e.g., *Comrie and Glenn*, 1998]. A scree plot of log-transformed eigenvalues was used to determine the number of components to retain; the components represented the precipitation regions. In order to enable a proper examination of the loadings, the loadings matrix was orthogonally rotated using the VARIMAX technique [e.g., *Richman and Lamb*, 1985]. Each station was assigned to the component (i.e., region) on which it had the highest loading (i.e. the maximum-loading rule).

[15] Specific stations within the PCA-defined regions were selected for additional analyses. Since the Gila River basin is topographically complex, with station elevations ranging from 99 to 2454 m above sea level (asl), the influence of elevation on intraseasonal precipitation characteristics needed to be minimized. Therefore, within the resulting regions, spatial clusters of stations with similar elevations and precipitation totals were selected. In addition, station clusters within south central Arizona, which has been described as an intense monsoon zone (IMZ) within the Gila River basin [*Diem*, 2005], were selected.

[16] Wet days were determined for each cluster of stations. Daily precipitation totals for a cluster were the mean of the daily precipitation totals for all stations in the cluster. For each cluster, a wet day was defined as a day with a precipitation total within the top 10% of the 644 daily precipitation totals; therefore each cluster had 64 wet days. Selecting only the top 64 precipitation days, as opposed to all days with nonzero precipitation totals, was done for the following reasons: (1) the minimum nonzero precipitation total varied among the ALERT, AZMET, and NWS stations, and thus station type influenced the number of precipitation days; and (2) using exactly 64 observations from each cluster facilitated clear comparisons among the clusters.

[17] The seasonal evolution of precipitation was determined for the regions and the station clusters within the regions. For each of the 35 stations and the station clusters, the typical percentage of seasonal precipitation occurring on each of the 92 days was calculated. Using percentages rather than raw precipitation totals ensured that the time series for the regions did not mostly reflect precipitation characteristics at the high-elevation stations.

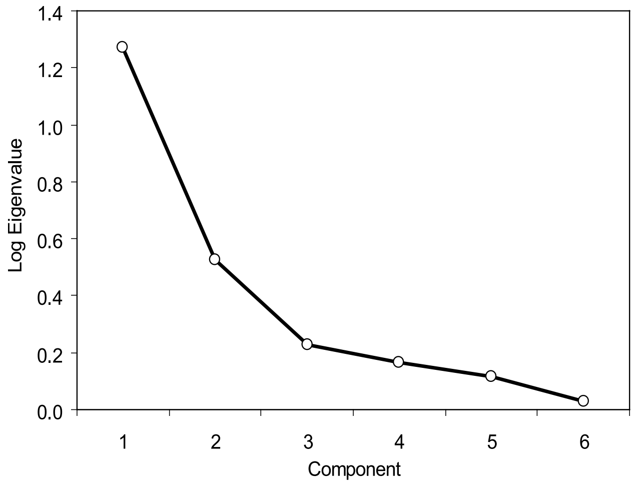

Figure 3. Scree plot of log-transformed eigenvalues. Only components with eigenvalues greater than or equal to 1 are shown.

3.2. Atmospheric Humidity

[18] Spatial variations in surface and middle troposphere humidity levels were determined for wet days. Surfaces were created for surface dew point temperature, dew point temperature anomalies, and 700 hPa specific-humidity anomalies. Anomalies were defined as wet-day values minus mean daily values for the entire season. The 16 dew point temperature stations ranged in elevation from 60 to 2130 m asl; therefore dew point temperatures were adjusted to sea level values using the dew point temperature lapse rate (i.e., 1.8°C per 1000 m).

3.3. Air-Parcel Trajectories

[19] Two-day air-parcel back trajectories were computed for wet days for the station clusters. While back trajectories are generally most effective when applied to areas of free convection, they provide a useful supporting tool for this study regarding the possible sources of increased humidity related to wet days. The HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) model by R. R. Draxler and G. D. Rolph (available at http://www.arl.noaa.gov/ready/hysplit4.html) was run in modeled-vertical-velocity mode with NCEP/NCAR Reanalysis data [*Kalnay et al.*, 1996]. This data set was used because, unlike alternative back-trajectory data sets, it contained no missing data. End heights of 3180 m asl and 5890 m asl were utilized to capture the respective mean heights of the 700 hPa and 500 hPa levels over the study region during the 16 June to 15 September period.

4. Results

4.1. Precipitation Regionalization

[20] Results of the precipitation regionalization indicated that the Gila River basin should be divided into two regions: a western region and an eastern region. The first six components had eigenvalues greater than one, and a scree plot indicated that only the first two components explaining 63% of the total variance should be retained (Figure 3). Using the maximum-loading rule, 21 stations were assigned to the western region and 14 stations were assigned to the eastern region (Figure 4). The median loadings on the first component for the western and eastern regions were 0.73 and 0.34, respectively, while the median loadings on the second component were 0.34 and 0.74, respectively.

[21] Two high-elevation stations located within each of the regions had nearly opposite loadings: Towers Mountain (i.e., ALERT station 5340) in the western region had loadings of 0.73 and 0.42, while Luna Ranger Station (i.e., NWS station 295273) in the eastern region had loadings of 0.20 and 0.77. Each of those stations had two nearby stations that had similar elevations and precipitation totals. Therefore both the western and eastern regions could be represented by a cluster of three stations. The western region stations were in the Bradshaw Mountains and the eastern region stations were in the White Mountains (Figure 4). The elevations of the stations ranged from 2043 m asl to 2454 m asl, and the mean elevation of the western region stations (i.e., 2218 m asl) was identical to the mean elevation of the eastern region stations. The two locales also had nearly identical seasonal precipitation totals (∼270 mm) and approximately the same latitudinal position (∼34°N). The minimum daily precipitation totals for wet days in the Bradshaw Mountains and the White Mountains were 11.5 mm and 8.2 mm, respectively.

[22] In addition to geographically defining the Gila River basin, the regionalization also split the IMZ into an eastern area and a western area, with clusters of stations within each area (Figure 4). The mean loadings for regionalization stations in the western IMZ and eastern IMZ were 0.61 and 0.53, and 0.28 and 0.67, respectively. Three stations within the western IMZ with similar elevations and precipitation totals were Tucson 17 NW (NWS station 28795), Tucson (AZMET stations 22), and Vail 7 N (NWS station

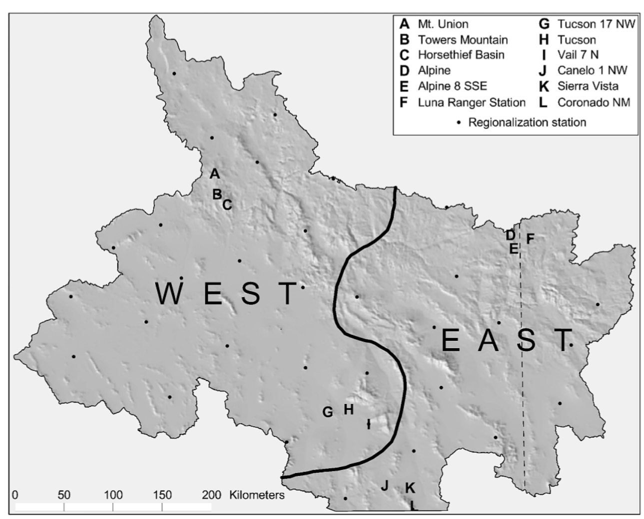

Figure 4. Division of the Gila River basin into a western region and an eastern region. The dashed line is the Arizona/New Mexico border. Grey-scale shading shows the topography of the basin. Stations "A," "B," and "C" are in the Bradshaw Mountains; stations "D," "E," and "F" are in the White Mountains; stations "G," "H," and "I" are in the western portion of the IMZ; and stations "J," "K," and "L" are in the eastern portion of the IMZ.

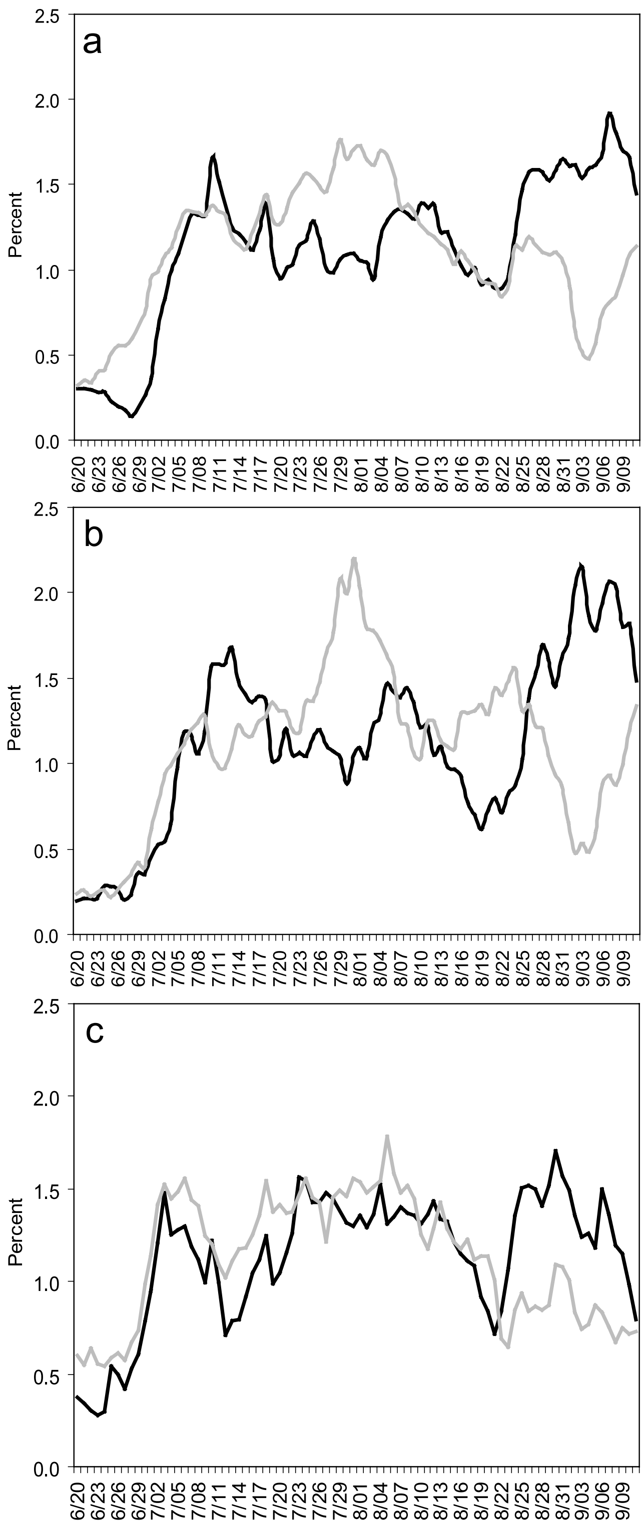

Figure 5. Smoothed time series of typical percentage of seasonal precipitation for (a) the western region (black line) and the eastern region (grey line), (b) the Bradshaw Mountains (black line) and the White Mountains (grey line), and (c) the western IMZ (black line) and the eastern IMZ (grey line). A 9-day moving-mean filter was applied to all time series.

28998); the mean elevation and mean seasonal precipitation total for these stations were 801 m asl and 171 mm, respectively. Three stations within the eastern IMZ with similar elevations and precipitation totals were Canelo 1 NW (NWS station 21231), Sierra Vista (NWS station 27880), and Coronado NM (NWS station 22140); the mean elevation and mean seasonal precipitation total for these stations were 1509 m asl and 230 mm, respectively. The minimum daily precipitation totals for wet days in the western IMZ and the eastern IMZ were 6.2 mm and 8.6 mm, respectively.

4.2. Seasonal Evolution of Precipitation

[23] The two regions of the Gila River basin had considerably different seasonal evolutions of precipitation. There was a peak in precipitation in late August/early September for the western region; however, the eastern region had a precipitation peak in late July/early August (Figure 5a). It needs to be noted that none of the daily precipitation totals from 16 June to 15 September were directly enhanced by tropical systems.

[24] The Bradshaw Mountains and White Mountains had seasonal evolutions of precipitation similar to those of the respective parent regions. The major differences in precipitation totals between the Bradshaw Mountains and the White Mountains occurred in late July/early August and in early September (Figure 5b). In fact, during approximately the first week of September the Bradshaw Mountains received over four times as much rainfall as did the White Mountains.

[25] The western IMZ and eastern IMZ also had seasonal evolutions of precipitation similar to that of their parent regions. Both areas had similar variations in precipitation prior to late August; thus there was not a large difference in late July/early August precipitation (Figure 5c). The western IMZ did have a late August/early September peak in precipitation, similar to that of the Bradshaw Mountains and the entire western region.

4.3. Surface Humidity

[26] Western region wet days were associated with a peak in dew point temperatures in the southwestern portion of the basin (Figures 6a and 6c). Dew point temperatures tended to decrease with increasing distance from the Gulf of California. Yuma, which was the station closest to the Gulf of California, had the largest mean dew point temperature; the elevation-adjusted dew point temperature at Yuma was approximately equal to or exceeded 19°C.

[27] Eastern region wet days were associated with a peak in dew point temperatures in the south central portion of the basin (Figures 6b and 6d). Dew point temperatures tended to decrease from south to north; unlike the situation for wet days in the western region, there was not a peak in dew point temperature at Yuma. Moreover, the largest mean dew point temperature barely exceeded 17°C.

[28] The entire Gila River basin was considerably more humid than normal on western region wet days (Figures 6a and 6c). There was a decreasing trend in dew point temperature anomalies from west to east across the basin. Wet days in the Bradshaw Mountains were associated with a strong spatial gradient in dew point temperature anomalies. On wet days in both the Bradshaw Mountains and the

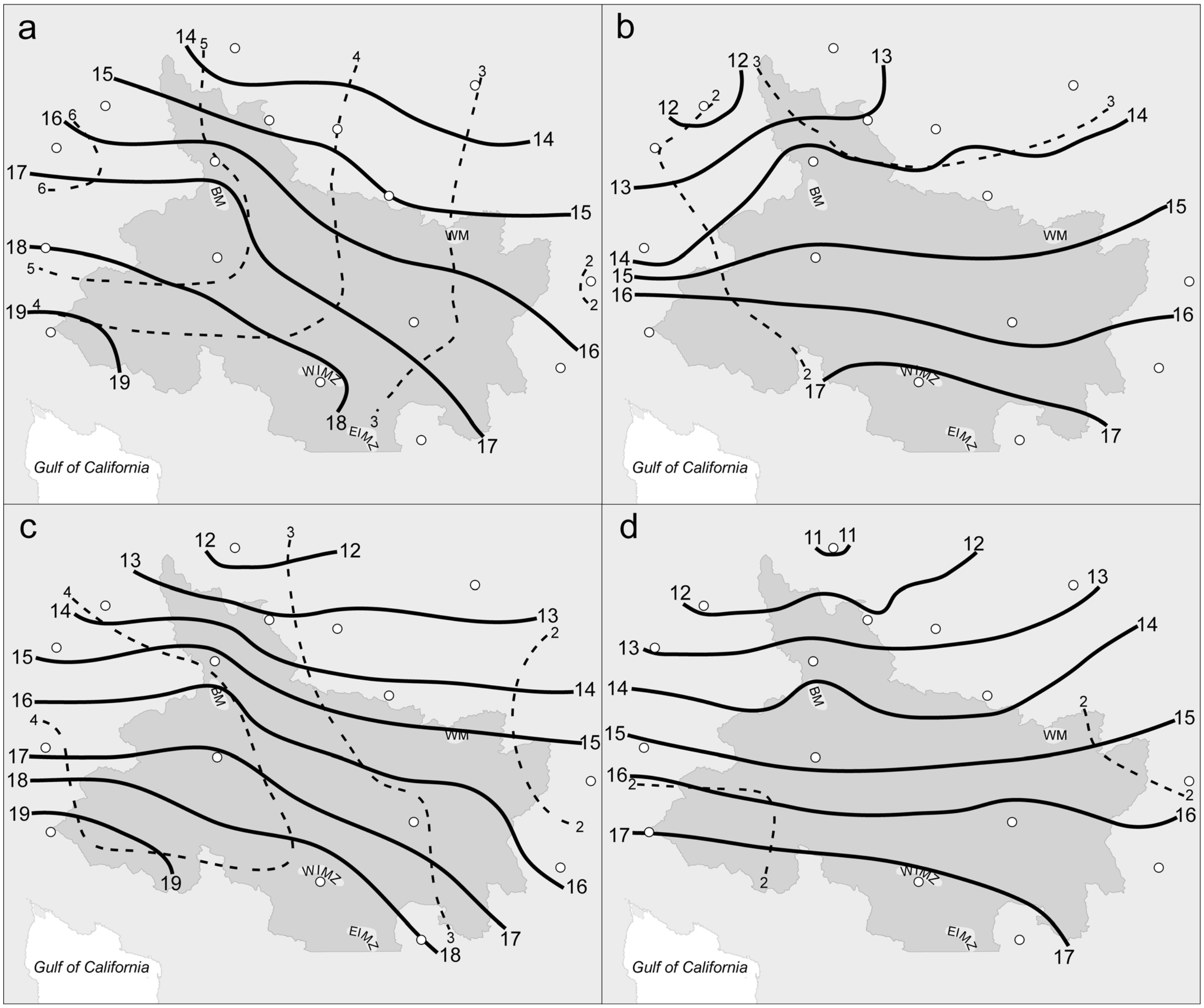

Figure 6. Mean dew point temperatures (solid lines) and anomalies (dashed lines) on wet days in the (a) Bradshaw Mountains, (b) White Mountains, (c) western IMZ, and (d) eastern IMZ. Anomalies are deviations from the seasonal mean. Isolines are drawn at 1°C intervals. Dew point temperature stations are shown as open circles.

western IMZ, much of the western region had dew point temperature anomalies exceeding 4°C.

[29] Dew point temperatures were only slightly higher than normal across the Gila River basin during eastern region wet days (Figures 6b and 6d). There were no strong spatial trends in dew point temperature anomalies across the basin; only for the wet days in the White Mountains did anomalies tend to increase from southwest to northeast. The largest dew point temperature anomalies tended to occur in the far northern portion of the basin; however, these anomalies barely exceeded 3°C.

4.4. Middle Troposphere Humidity

[30] Specific-humidity anomalies at 700 hPa for western region wet days were larger and centered more over the Gila River basin than were specific-humidity anomalies for eastern region wet days. For wet days in both the Bradshaw Mountains and the western IMZ, there were larger than normal 700-hPa specific-humidity values over the basin. The largest anomaly occurred directly over the basin for wet days in the Bradshaw Mountains, and this anomaly exceeded 1.2. g kg^{-1} (Figures 7a and 7c). In contrast to the western region, the largest specific-humidity anomalies for wet days in the White Mountains and the eastern IMZ occurred primarily over New Mexico, and the anomalies over the Gila River basin did not reach 1.2 g kg^{-1} (Figures 7b and 7d). The specific-humidity positive-anomaly center for wet days in the White Mountains was located over northeastern New Mexico and was the most distant anomaly center from the basin (Figure 7b). The IMZ areas exhibited the most similar specific-humidity patterns; the eastern IMZ had only a slightly weaker anomaly than did the western IMZ.

4.5. Middle Troposphere Moisture Transport

[31] Backward air-parcel trajectories with ending altitudes of 3180 m asl for wet days differed substantially between the western and eastern regions. The Bradshaw Mountains

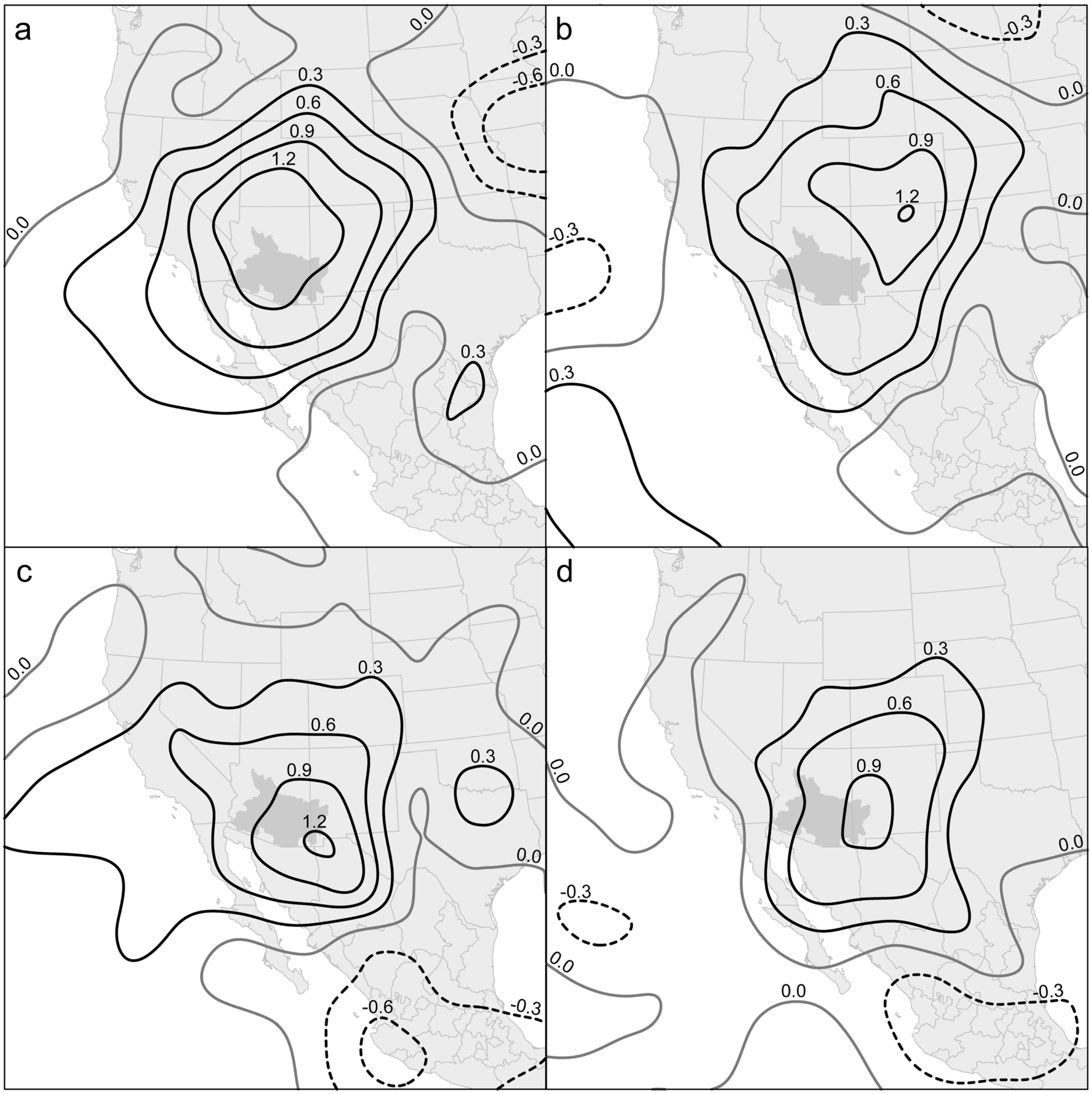

Figure 7. Specific-humidity anomalies at 700-hPa for wet days in the (a) Bradshaw Mountains, (b) White Mountains, (c) western IMZ, and (d) eastern IMZ. Anomalies are deviations from the seasonal mean. Solid lines are positive anomalies, and dashed lines are negative anomalies. Contour interval is 0.3 g kg^{-1}. The shaded region is the Gila River basin.

wet days had a cluster of trajectories extending to the south/southwest (Figure 8a). For wet days in the White Mountains, the trajectories extended mostly toward the Gulf of California/Pacific Ocean or the Gulf of Mexico; thus few trajectories intersected the Sierra Madre Occidental (Figure 8b). The trajectories for the two areas of the IMZ were nearly identical, and, compared to the trajectories for the Bradshaw Mountains and the White Mountains, respectively, the IMZ areas had fewer trajectories extending toward the Gulf of California and more trajectories extending toward the Sierra Madre Occidental (Figures 8c and 8d).

[32] Backward air-parcel trajectories with ending altitudes of 5890 m asl for wet days were similar among the four areas analyzed. A relatively large percentage of the trajectories extending from the four locales intersected the Sierra Madre Occidental (Figure 9), with the western IMZ probably having the highest percentage. In addition, the IMZ areas had a relatively low number of trajectories extending westward (Figures 9c and 9d).

5. Discussion

[33] The precipitation regionalization of the Gila River basin resulted in a western region and an eastern region, with the precipitation regime for the eastern region similar to that of the core monsoon zone in northwestern Mexico.

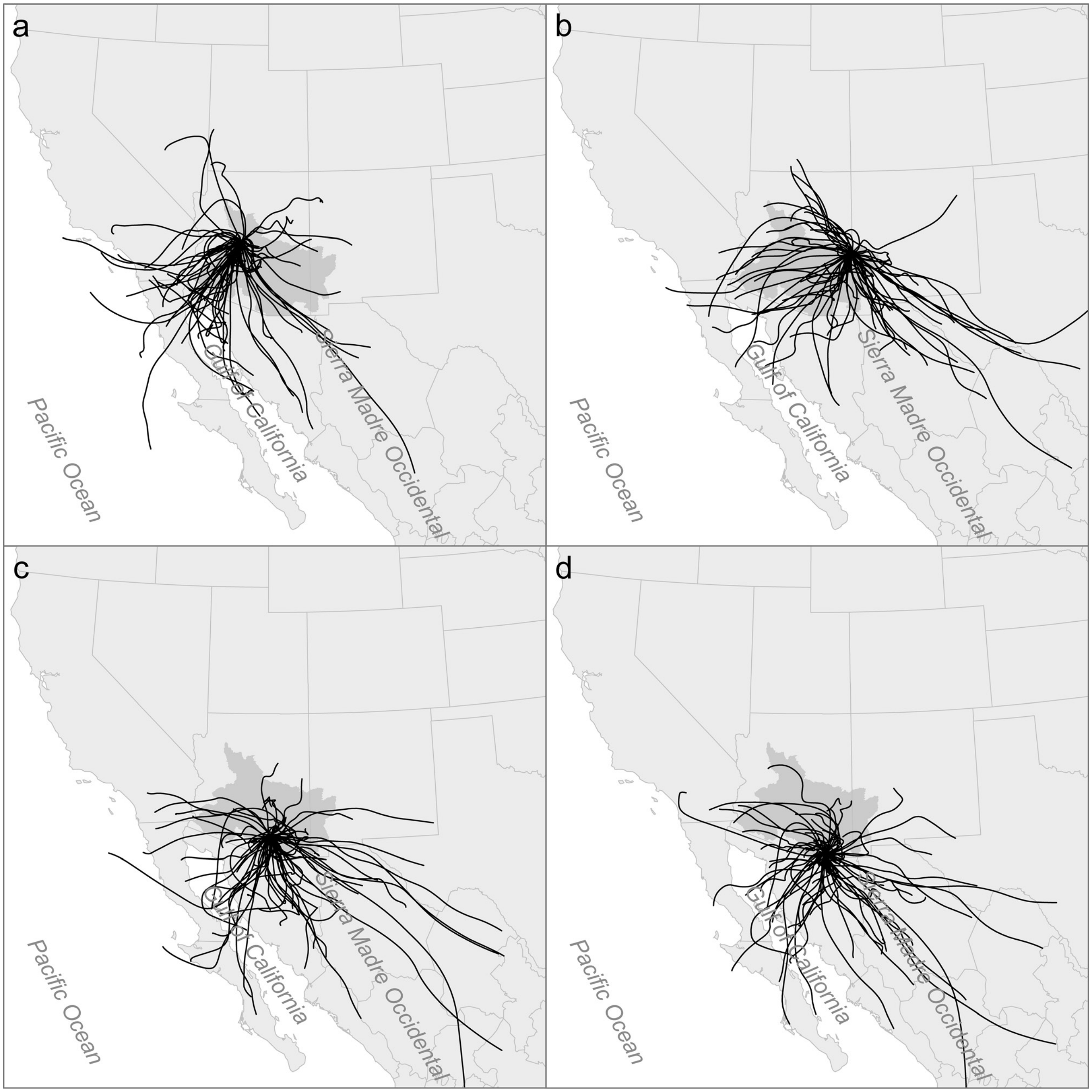

Figure 8. The 64 two-day back trajectories for wet days in the (a) Bradshaw Mountains, (b) White Mountains, (c) western IMZ, and (d) eastern IMZ. The elevation of the end points of the trajectories is 3180 m asl.

The eastern region of the Gila River basin had a single rainfall peak in late July/early August, which corresponds to the mature phase of the Mexican monsoon [*Higgins et al.*, 1999]. Therefore this rainfall peak coincides with a widespread maximum in tropospheric moisture across the monsoon region. For the entire monsoon season, the eastern region was more humid than the western region, especially in the middle troposphere (Figure 10). On eastern region wet days, specific humidity at 700-hPa over the eastern region was $\sim$20% higher than that over the western region. Increased middle troposphere moisture was therefore associated with wet days in the eastern region. On the basis of results from the trajectory analyses, the Sierra Madre Occidental was the most likely source of the middle troposphere moisture. Since the southern portion of the eastern region is closest to the Sierra Madre Occidental, it is reasonable to assume that this section of the Gila River basin was most impacted by moisture transport from the Sierra Madre Occidental. Air-parcel trajectories also suggest that the Gulf of Mexico may have been a significant moisture source for the far eastern portions of the Gila River basin. The findings for the eastern region are congruent with findings by *Mo and Berbery* [2004] for large precipitation events over New Mexico, where there was

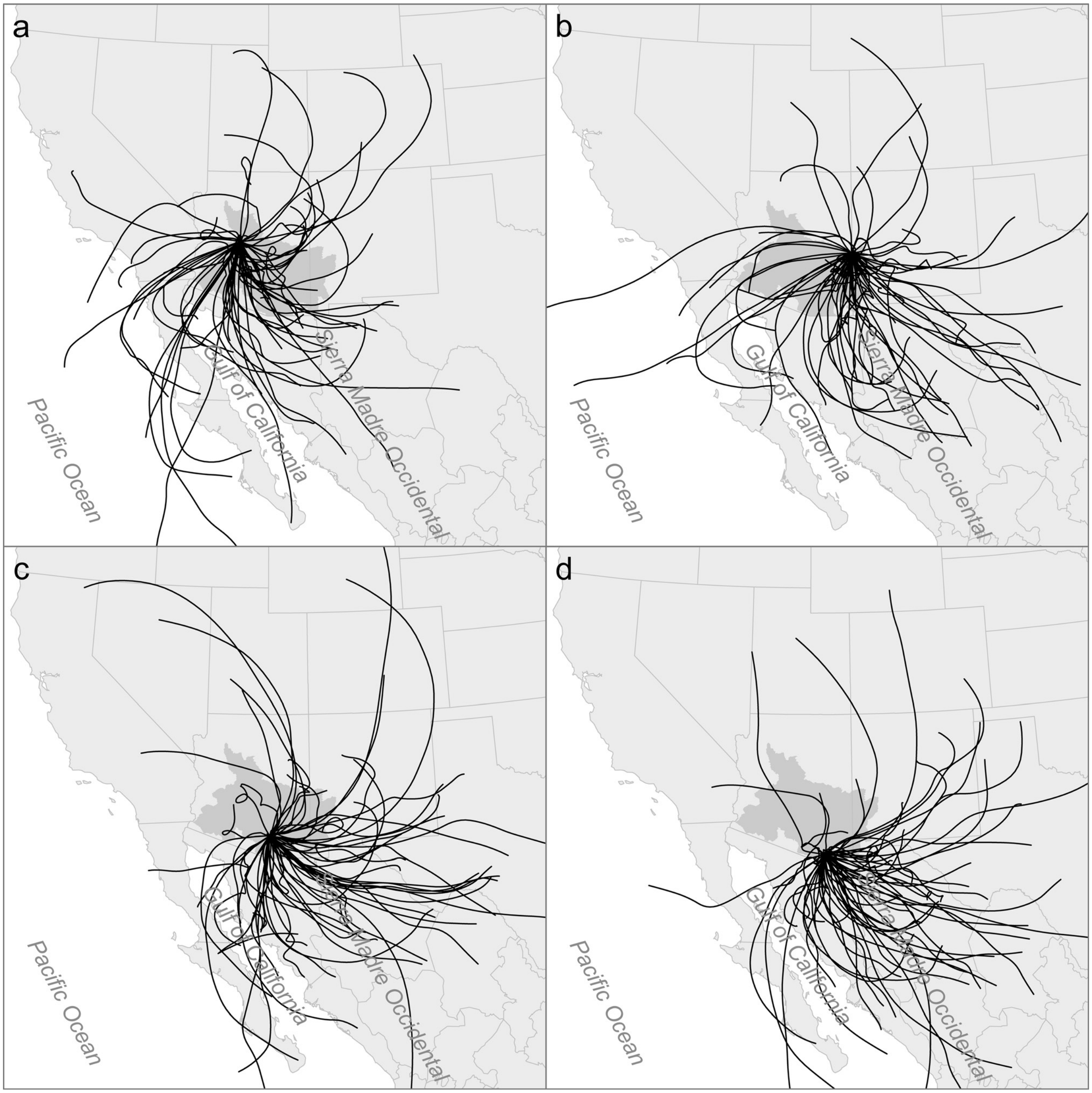

Figure 9. The 64 two-day back trajectories for wet days in the (a) Bradshaw Mountains, (b) White Mountains, (c) western IMZ, and (d) eastern IMZ. The elevation of the end points of the trajectories is 5890 m asl.

an increase in moisture fluxes from the border of Texas and the Gulf of Mexico to New Mexico and northern Mexico.

[34] Gulf surges probably were the major control of wet days in the western region. A high level of atmospheric humidity from the surface to at least 700 hPa was associated with wet days. Trajectory analyses indicate that the Gulf of California and the Sierra Madre Occidental were the most likely sources of the moisture in the western region. These results are supported both by *Mo and Berbery* [2004], who found an increased northward moisture flux from the Gulf of California during large precipitation events over Arizona, and by *Higgins et al.* [2004], who linked strong gulf surges to precipitation anomalies over Arizona of at least 1 mm day^{-1}. In addition, most of the eastern region apparently was not impacted strongly by gulf surges. For instance, the eastern IMZ was noticeably less impacted by low-level moisture than was the western IMZ, even though the longitudinal difference between the regions is relatively small. Therefore the boundary between the eastern and western IMZ areas may represent the eastward extent of strong impacts on wet days from gulf surges.

[35] The precipitation characteristics of the western region of the Gila River basin differed from those of the core monsoon zone in that a late August/early September precipitation peak was evident. This temporal precipitation anomaly has not been associated with the Mexican mon-

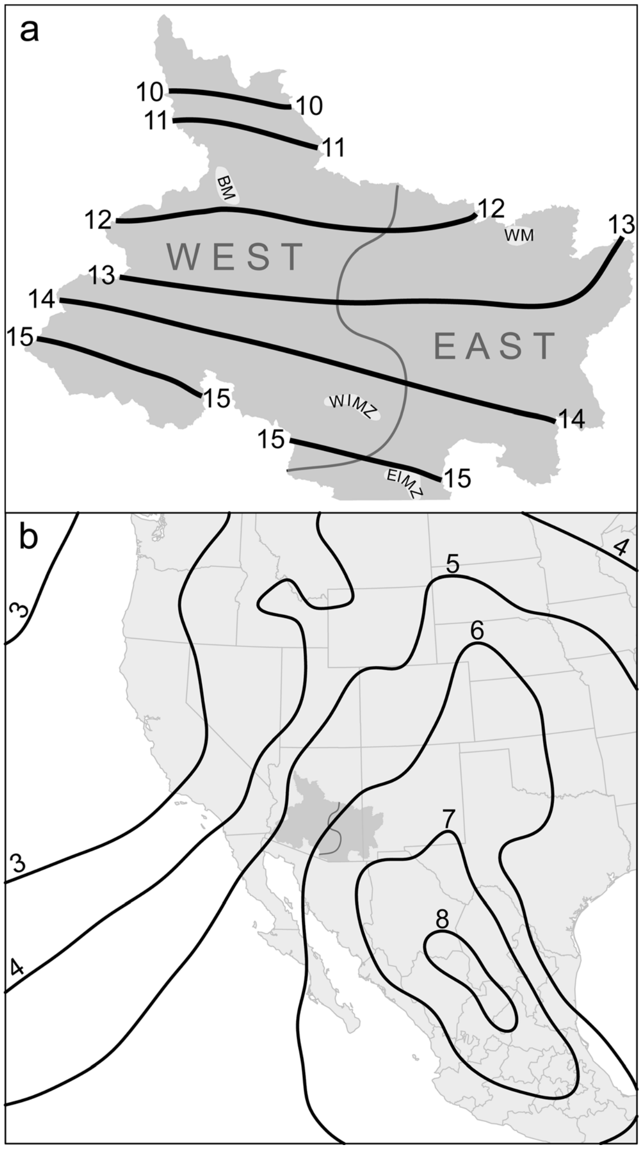

Figure 10. Mean monsoon-season values of (a) dew point temperature and (b) 700-hPa specific humidity. Units for dew point temperature and specific humidity are °C and g kg^{-1}, respectively. The shaded region is the Gila River basin.

soon in previous published studies. The Bradshaw Mountains received as much total monsoonal precipitation as did the White Mountains, which are considered to be well within the peripheral monsoon zone. Twenty-two of the 64 wet days in the Bradshaw Mountains occurred between 27 August and 11 September, and most of those 22 days probably were linked to gulf surge events as indicated by the atmospheric-humidity and trajectory analyses (Figure 11). Surface humidity in the western region was exceedingly high on those wet days: the far western portion of the region had dew point temperatures 50% higher than normal, and the mean dew point temperature for the western region was nearly 2°C higher than the mean value for the eastern region. In addition, 700-hPa specific humidity anomalies exceeded 1.2 g kg^{-1} for the entire basin. It is therefore very

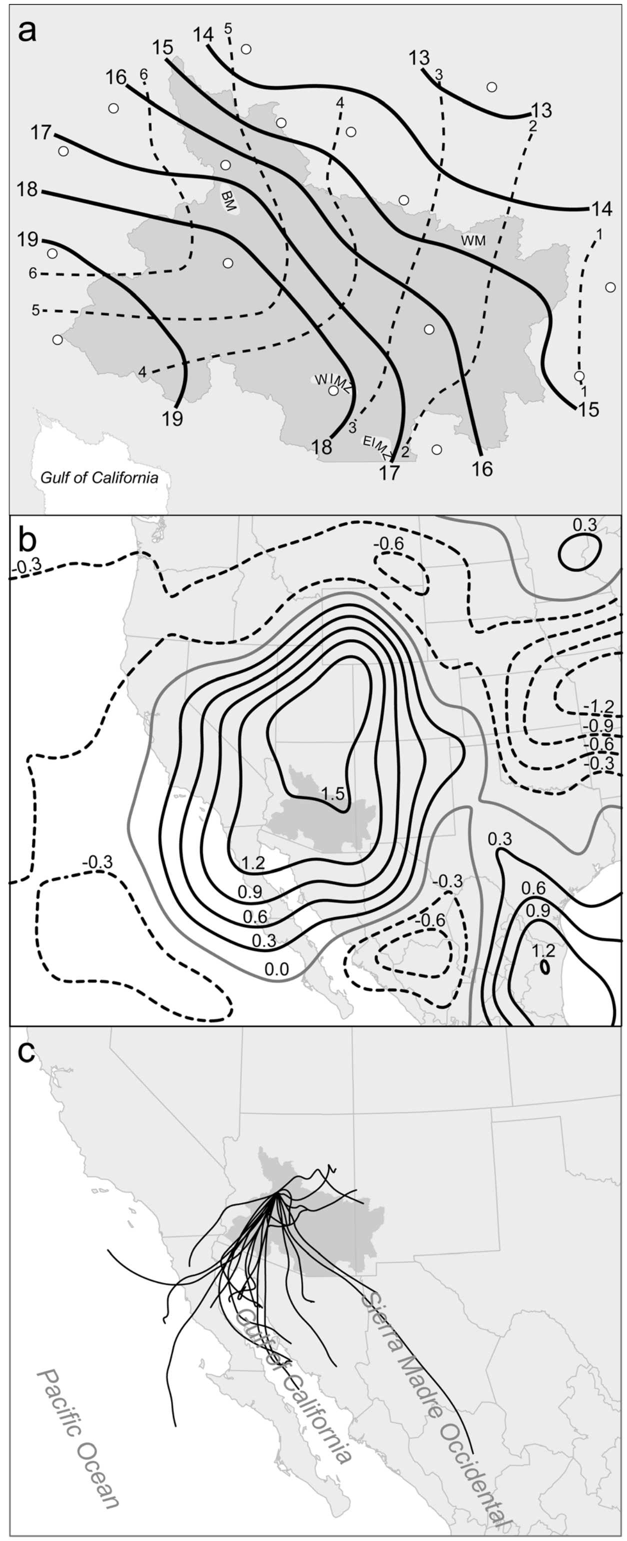

Figure 11. (a) Dew point temperatures (solid lines) and anomalies (dashed lines), (b) specific-humidity anomalies, and (c) two-day back trajectories ending at 3180 m asl for late August/early September wet days in the Bradshaw Mountains. Units for dew point temperature and specific humidity are °C and g kg^{-1}, respectively.

likely that surges of moisture from the Gulf of California were the cause of the late August/early September peak in precipitation over the western portion of the Gila River basin.

6. Conclusions

[36] Using daily precipitation totals from 115 stations, surface dew point temperature from 16 stations, gridded 700-hPa specific-humidity data, and an air-parcel trajectory model, the role of increased atmospheric humidity in occurrences of wet days during the monsoon season was examined for the Gila River basin in the southwestern United States. The time period was 16 June to 15 September from 1996 to 2002. The main methods employed were spatiotemporal analyses of ground-measured precipitation, spatial analyses of surface and 700-hPa humidity, and air-parcel trajectory analyses. The spatiotemporal analyses of precipitation were guided by a precipitation regionalization, which indicated that the study domain could be divided into an eastern region and a western region. Large differences in precipitation and atmospheric humidity existed between the regions.

[37] Precipitation in the eastern region exhibited similar characteristics as the core monsoon zone centered over the Sierra Madre Occidental in northwestern Mexico. The eastern region had a rainfall peak in late July/early August, coinciding with the mature phase of the monsoon. Wet days in the eastern region were associated with a slight increase in surface dew point temperatures across the entire Gila River basin; the highest dew point temperatures were in the south central portion of the basin. The middle troposphere was more humid than normal on wet days; however, the maximum positive anomalies were located mostly over New Mexico rather than any portion of the Gila River basin. The Sierra Madre Occidental and the Gulf of Mexico were the most likely sources of moisture on wet days. There was no indication that moisture surges from the Gulf of California played a significant role in contributing to eastern region wet days.

[38] The western region was impacted strongly by moisture from the Gulf of California. Wet days in the western region were associated with an extremely large increase in surface dew point temperatures in the far western portion of the Gila River basin; the highest dew point temperatures occurred at Yuma, which is less than 100 km from the Gulf of California. The middle troposphere over the western region was substantially more humid than normal on wet days, with the maximum positive anomalies located directly over the Gila River basin. The Gulf of California probably was the major source of low-level moisture on wet days in this region, while the Sierra Madre Occidental probably was the major source of middle troposphere moisture. A precipitation peak occurred in late August/early September, and the Gulf of California was the dominant source of low-level moisture, and possibly middle troposphere moisture, during that period.

[39] The findings presented in this study are significant because they demonstrate the spatial complexity of atmospheric moisture associated with Mexican-monsoon precipitation within a single river basin in the southwestern United States. Consequently, monsoon studies should not treat the southern half of Arizona as a homogeneous region with respect to spatiotemporal variations in monsoon-season rainfall and moisture advection. The implications of this spatial complexity could be used to inform and improve the decision-making processes of stakeholder groups in different parts of the Gila River basin regarding management of impacts of monsoonal storms. In addition to using ground-based precipitation measurements, which have a sparse spatial coverage of the southwestern United States and northwestern Mexico, future studies should employ spatially continuous information such as lightning-flash data to better understand the spatiotemporal complexity of monsoonal rainfall. The implications of this spatial complexity could also be used to inform and improve the decision-making processes of stakeholder groups, such as ranchers, farmers, water managers, and other partners of NOAA's State Climatologist and Regional Integrated Sciences and Assessments programs, regarding management of impacts of monsoonal storms in different parts of the Gila River basin.

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