Relationships between Spring Snow Mass and Summer Precipitation in the Southwestern United States Associated with the North American Monsoon System

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ABSTRACT

This paper provides a detailed description of the relationship between spring snow mass in the mountain areas of the western United States and summertime precipitation in the southwestern United States associated with the North American monsoon system and examines the hypothesis that antecedent spring snow mass can modulate monsoon rains through effects on land surface energy balance. Analysis of spring snow water equivalent (SWE) and July–August (JA) precipitation for the period of 1948–97 confirms the inverse snow–monsoon relationship noted in previous studies. Examination of regional difference in SWE–JA precipitation associations shows that although JA precipitation in New Mexico is significantly correlated with SWE over much larger areas than in Arizona, the overall strength of the correlations are just as strong in Arizona as in New Mexico. Results from this study also illustrate that the snow–monsoon relationship is unstable over time. In New Mexico, the relationship is strongest during 1965–92 and is weaker outside that period. By contrast, Arizona shows strongest snow–monsoon associations before 1970. The temporal coincidence between stronger snow–monsoon associations over Arizona and weaker snow–monsoon associations over New Mexico (and vice versa) suggests a common forcing mechanism and that the variations in the strength of snow–monsoon associations are more than just climate noise. There is a need to understand how other factors modulate monsoonal rainfall before realistic predictions of summertime precipitation in the Southwest can be made.

1. Introduction

Predicting interannual variations in summertime precipitation over the southwestern United States is important because local economies are dependent on adequate summer precipitation. Between 30% and 50% of the annual precipitation in the desert Southwest typically occurs during July and August, when the region is dominated by the monsoon climate regime. The most promising method to predict monsoonal precipitation is through antecedent seasonal precipitation. Several investigators have demonstrated an inverse relationship between winter and subsequent summer precipitation (Carleton and Carpenter 1990; Gutzler and Preston 1997; Higgins and Shi 2000; Gutzler 2000). Winters with high precipitation tend to be followed by drier summers and vice versa. These statistical associations are thought to occur because of land surface memory: an extensive and deeper-than-normal winter snowpack over the Southwest acts as an energy sink. In high snow years, more energy is required to melt the snowpack and to evaporate the subsequently higher levels of soil moisture. The higher spring albedo of the surface plays a complementary reinforcing role. These factors can lead to delayed and decreased warming of the North American landmass and a reduction of the large-scale land–ocean heating contrasts that are necessary for strong monsoonal circulations.

Although connections between the winter snowpack and summer monsoon have received considerable attention in both North America and Asia (see also Hahn and Shukla 1976; Barnett et al. 1989; Sanker-Rao et al. 1996; Bamzai and Shukla 1999), much is still unknown about the dominant factors responsible for the observed linkages. In North America, Gutzler (2000) examined spring snowpack and summer rainfall anomalies using empirical orthogonal function (EOF) analysis and demonstrated that the snow–monsoon associations are stronger in New Mexico than in Arizona. He also showed that the relationship between the spring snowpack and the summer monsoon is strong during the period of 1961–90 but tends to break down in the years before and after this period. He suggests that other forcing factors such as different combinations of tropical and extratropical sea surface temperatures related to the Pacific Decadal Oscillation (PDO) and the existence of long-term drought (such as what occurred in the 1950s) may be important in modulating the snow–monsoon linkages.

The intent of this paper is to provide a detailed description of the relationship between spring snow mass

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in the mountain areas in the western United States and summer (July and August) monsoonal precipitation in the southwestern United States. Details about the data sources are in section 2. Section 3 describes the use of one-point correlation maps to examine spatial variations in the snow–monsoon relationships. In section 4, we examine the temporal stability of the snow–monsoon associations for various subregions in the Southwest. Results are summarized in section 5.

2. Data

For snowmass data, we use measurements of snow water equivalent (SWE) from permanent snow-course sites in the western United States maintained by the U.S. Department of Agriculture (USDA) cooperative snow survey program. SWE is measured by pushing a hollow aluminum tube down through the snowpack to the ground surface and extracting a core, weighing the tube with its snow core, and subtracting the weight of the empty tube. SWE is generally measured on or about the beginning of each month between January and June. The frequency and timing of the measurements varies considerably with the locality, difficulty of access, cost, avalanche hazard, and the nature of the snowpack such as extremely high or low SWE (Natural Resources Conservation Service 1988). Possible problems with the snow-course measurements include changes in vegetation and patterns of snow accumulation along the snow course, the inability to measure at every snow course on the first day of every month, and errors in data entry. In this study, attention is restricted to SWE measurements on 1 April because it provides an estimate of the total cold-season snow accumulation. We use snow-course sites with at least a 45-yr record during the period of 1948–97. The 370 snow-course stations are plotted in Fig. 1a.

Assessments of precipitation are derived from data from the network of National Weather Service (NWS) cooperative climate observing stations in the United States. Data for the contiguous 48 states were extracted from the National Climatic Data Center (NCDC) Summary of the Day (TD3200) dataset by J. Eischeid, National Oceanic and Atmospheric Administration Climate Diagnostics Center, Boulder, Colorado (Eischeid et al. 2000). Reek et al. (1992) outlined quality-control procedures on the dataset. We limit analyses to the 6822 stations west of the Mississippi River (Fig. 1b). Records at most stations start in 1948 and continue through 1998.

To examine relationships between monsoonal precipitation in July–August and the antecedent winter snowpack, we focus our attention on spatial variations in summertime precipitation in regions where the North American Monsoon System (NAMS) has the greatest effect. Using Mock's (1996) description, the monsoon region is defined as the area of the country for which the difference between monthly mean June and July precipitation is greater than 5% of the average annual total: [(July − June)/annual] > 5%. This definition includes Arizona, New Mexico, southern Colorado, and southern Utah, which is generally known as the Southwest. Spatial variations within the monsoon region are examined by simply regridding the NWS cooperative station data to a 2.5° × 2.5° grid as outlined in Fig. 1b.

3. Spatial variation

The relationship between 1 April snow mass and summer precipitation associated with NAMS is assessed using one-point correlation maps. The July–August (JA) precipitation anomalies in each 2.5° × 2.5° grid box within the monsoon area were correlated with the 1 April SWE anomalies at each snow-course station. Figure 2 is composed of 12 spatial correlation maps. Each map shows the correlation coefficient between the JA precipitation at a different 2.5° × 2.5° subregion and 1 April SWE at all snow-course stations. Negative correlations are plotted in cool colors, positive correlations in warm colors. Snow-course stations with correlations greater than the 90% confidence level are plotted with large asterisks. The center of each 2.5° × 2.5° grid box is marked by a diamond. For example, the four bottom-left plots (Figs. 2e,f,i,j) illustrate snow–monsoon associations over different parts of Arizona, and the four bottom-right plots (Figs. 2g,h,k,l) illustrate associations over different parts of New Mexico.

The primary conclusion drawn from Fig. 2 is an overall negative correlation between SWE and JA precipitation anomalies throughout the monsoon region. This inverse relationship is consistent with the hypothesis presented earlier: anomalously high (low) spring snow leads to less (more) intense warming of the North American continent and a weakening (strengthening) of the monsoon circulations and associated anomalously low (high) JA precipitation. Note in Fig. 2 that the summer rains are associated with SWE anomalies in a few crucial areas: the Colorado Rocky Mountains, Four Corners area, and Utah's Unita Mountains.

Within the large-scale pattern of inverse snow–monsoon relationships, there also exists considerable subregional variability. In southern Colorado and northern New Mexico, the associations between SWE and summertime precipitation are spatially extensive (Figs. 2d,g,h). This is indicated by the large number of snow-course stations with significant correlations. Snow–monsoon associations in Arizona are more localized than in New Mexico. However, even though the spatial extent of the relationship is varied, the amplitude of the relationship is similar throughout the Southwest. Table 1 summarizes correlations between JA precipitation and a multistation SWE index, defined as the average SWE of the 20 most negatively correlated snow-course stations associated with each subregion. Note that correlations between the SWE index and JA precipitation in Arizona are of similar magnitude (and in some cases slightly higher, although not significantly so) than those

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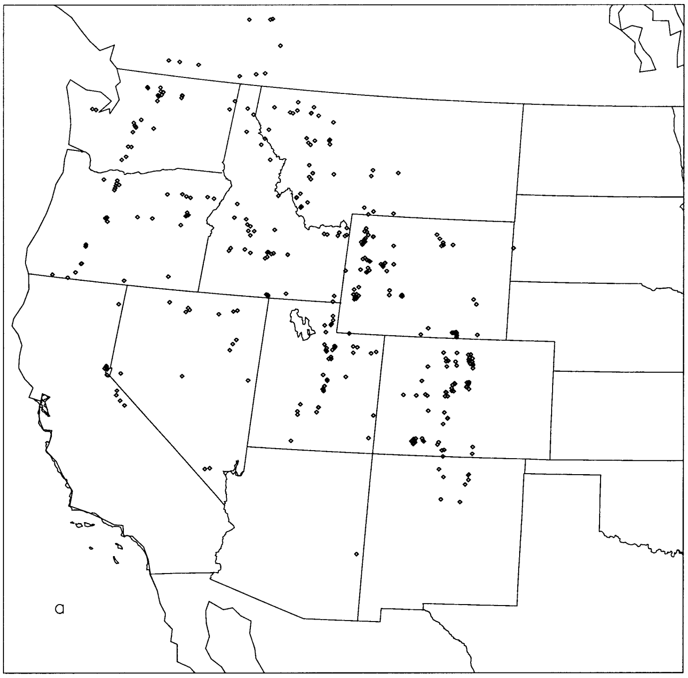

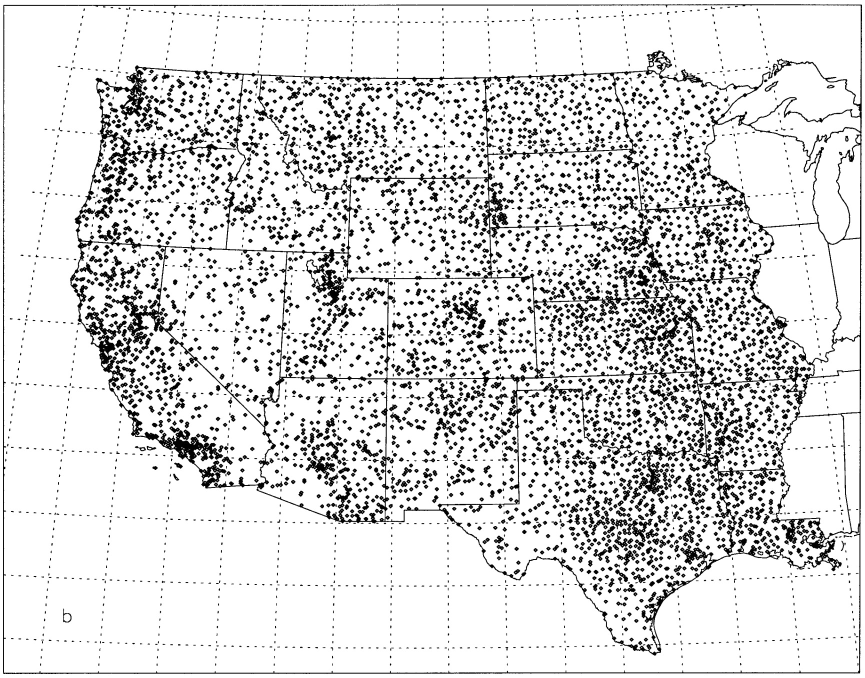

FIG. 1. Location of (a) USDA snow-course 1 Apr snow water equivalent stations and (b) NWS precipitation stations and the 2.5° × 2.5° grid.

in New Mexico. This finding is inconsistent with a conclusion of Gutzler (2000) in which he finds that the effects of SWE on summertime precipitation are significantly stronger in New Mexico than in Arizona. Gutzler based his analysis on the time series associated with the dominant EOF of SWE variability in the four states of Colorado, Utah, Arizona, and New Mexico. Using only 48 snow-course sites, Gutzler's EOF mainly describes SWE variability in Arizona and New Mexico. Despite the large spatial coherence in SWE in the western U.S. mountains (Cayan 1996; Clark et al. 2001), it is probable that the snow-course stations most strongly

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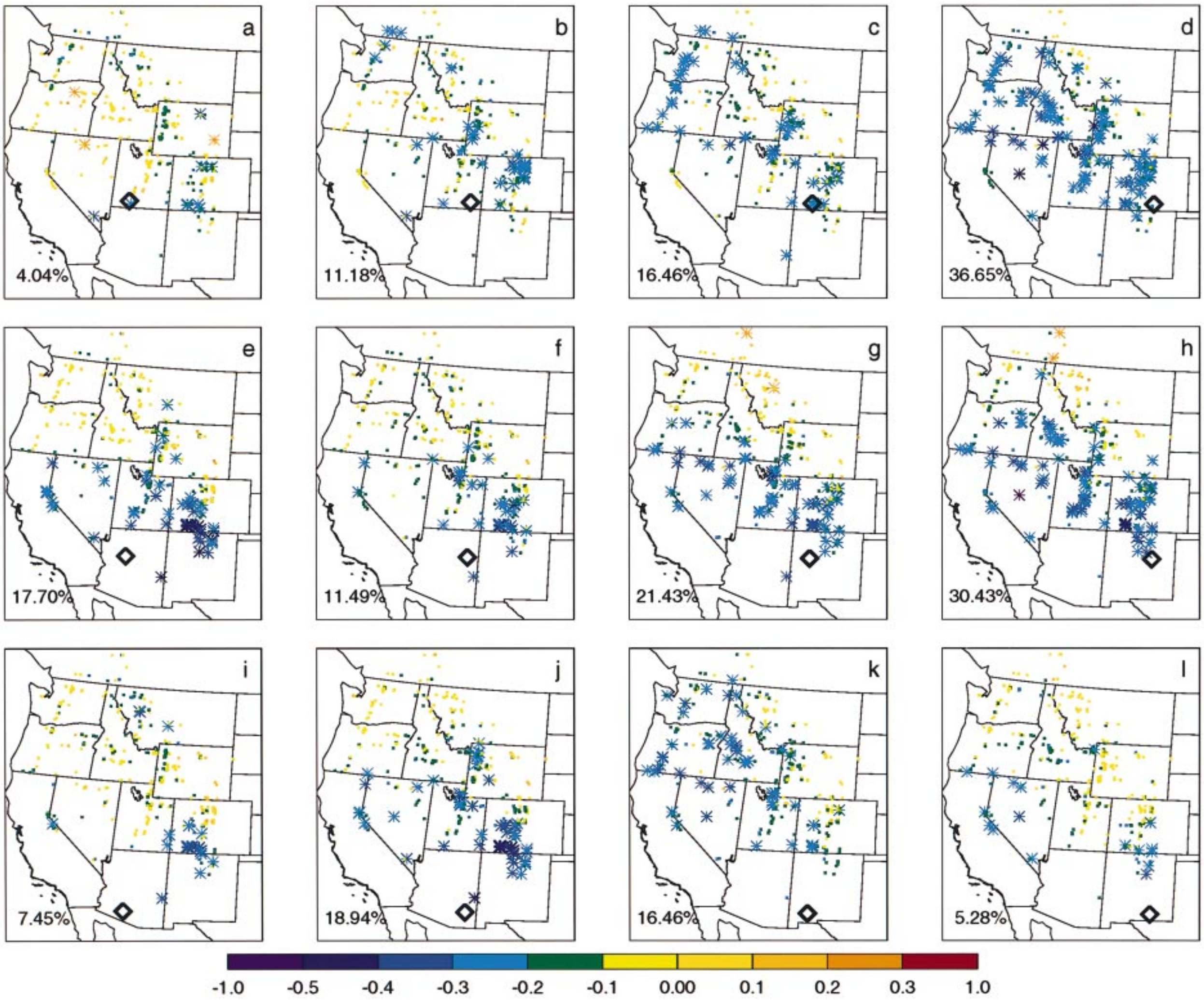

FIG. 2. Correlation between JA precipitation anomalies (at the diamond) and 1 Apr snow water equivalent at each snow-course site. Colors correspond to correlation coefficients shown in the color bar. Large asterisks indicate stations with correlation coefficients statistically significant at the 90% level. Numbers in lower left of plots are the percentage of significant stations.

associated with summertime precipitation variability in Arizona are not accounted for in the dominant EOF of SWE used by Gutzler. Differences between snow–monsoon associations in Arizona and New Mexico are discussed further in the next section.

We repeated the correlation calculations using winter precipitation anomalies for January–February–March (JFM) in place of 1 April SWE. The maps in Fig. 3 show JA precipitation at the same 12 subregions correlated with JFM precipitation at stations with 90% or greater significance. The NCDC precipitation stations are at low elevations, in contrast with the snow-course SWE stations that are located at higher altitudes. JFM precipitation anomalies provided a better spatial sampling, particularly in the southern section of the monsoon region that was absent in the SWE–JA precipitation correlation map calculation because of lack of SWE data. Figure 3 shows that local correlations between JFM and JA precipitation are often much weaker than nonlocal correlations (note in particular Figs. 3f,g,i,k, l). This supports some recent modeling results by Small (2001). Small used the Fifth-Generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model to compute the sensitivity of precipitation in the NAMS region to positive July soil moisture anomalies in different areas of the western United States. Results showed that while wet soil in the southern Rocky Mountains in July inhibits precipitation in the NAMS region (lending credence to the inverse correlations in Figs. 2 and 3), wet soil within the NAMS region actually enhances July precipitation within that area because of positive soil moisture–rainfall feedbacks. We find no evidence of a positive soil moisture–rainfall feedback, but our results indicate that local associations between JFM and summer precipitation in the southernmost regions are generally weaker than in

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TABLE 1. Correlation between the SWE indices and JA precipitation anomalies for 2.5° × 2.5° subregions in the Southwest.

	247.5°E		250.0°E		252.5°E		255.0°E	
37.5°N	SW UT	−0.338	SE UT	−0.382	SW CO	−0.390	SE CO	−0.453
35.0°N	NW AZ	−0.493	NE AZ	−0.422	NW NM	−0.424	NE NM	−0.450
32.5°N	SW AZ	−0.413	SE AZ	−0.485	SW NW	−0.402	SE NM	−0.360

regions farther north. Note that the Small (2001) study examines the impacts of soil moisture anomalies in July, not in midwinter, and the timescales of soil moisture effects are much shorter than those examined in our study. Nevertheless, our hypothesis theorizes snow–monsoon associations occur because of the linkage between spring snow anomalies and late spring and early summer soil moisture anomalies. Therefore, we must consider the possibility that JFM precipitation gives rise to the soil moisture anomalies and that a positive local feedback and a negative nonlocal feedback may combine to produce relatively weak land surface memory effects in the southern part of the monsoon region.

4. Temporal variation

If the snow–monsoon relationship is stable in time, the summer rains in the NAMS region can potentially be predicted. Gutzler (2000) observed that spring snow cover in the Rocky Mountains has a significant inverse correlation with New Mexico summer rains between 1961 and 1990. Outside that period, the correlation breaks down and is insignificant. He suggests that other forcing factors, such as different combinations of tropical and extratropical sea surface temperatures related to the PDO and the existence of long-term drought, may be important in modulating or masking the snow–monsoon linkages.

We examined the temporal stability of the relationship between 1 April SWE anomalies and JA rainfall anomalies over the 50-yr period of 1948–97. For each of the 12 subregions in the Southwest, we used the 20-station SWE index to predict JA precipitation. Tests showed that the SWE index is not sensitive to the number of stations used to calculate the index. Results were similar if we used 10, 20, 30, or all stations statistically significant to 90%. To examine temporal changes in the relationship between the SWE indices and JA precipitation, a 15-yr moving window was centered on each year in the historical record, and the correlation was computed between the SWE index and JA rainfall. A 15-yr window provides enough cases for meaningful correlation calculations but is also short enough to examine variations within the 50-yr record. Results are relatively insensitive to window sizes ranging from 9 to 21 yr. We began with a window centered at 1955, then moved the window year by year throughout the record to get a continuous time series ending in 1990. Changes in correlations calculated for the 12 subregions are plotted in Fig. 4.

Figure 4 shows the correlations to be mostly inverse for all subregions, supporting the general snow–monsoon relationships identified earlier. However, correlations in most regions are variable through time. For instance, in northeastern New Mexico and south-central Colorado (Figs. 4d,h) there are strong correlations for the period of 1972–85 (accounting for the 15-yr window, this corresponds to 1965–92) and weaker correlations outside that period. Similar results are evident for other subregions in New Mexico. This supports Gutzler's (2000) results: the strongest correlations between New Mexico summer rains and Rocky Mountain SWE are between 1961 and 1990. Contrasting patterns are particularly evident in southwest Arizona (Fig. 4i). Here, correlations are most strongly negative in the earlier part of the record, with the weakest correlations for the 15-yr window centered on 1979. The temporal coincidence between stronger snow–monsoon associations over Arizona and weaker snow–monsoon associations over New Mexico (and vice versa) suggests a common forcing mechanism and that the variations in the strength of snow–monsoon associations are not simply climate noise. Building on research that points to PDO as modulating the strength of ENSO-based predictions of surface climate (e.g., McCabe and Dettinger 1999), Gutzler (2000) argues that the PDO may be responsible for decadal variations in the strength of snow–monsoon associations. Also, results from Higgins and Shi (2000) have suggested that North Pacific SSTs (the basis of the PDO index) may be an important factor in determining summertime precipitation amounts in the Southwest. The temporal changes in the correlation amplitude shown in Fig. 4 do resemble decadal shifts in the PDO, but it is not clear that the PDO is the culprit. Factors such as topography, localized surface fluxes, and regional differences in moisture sources may also play key roles in influencing subregional variations in snow–monsoon associations. Identifying the factors that modulate snow–monsoon relationships will increase the prospects for SWE-based long-lead predictions of summertime precipitation.

5. Summary

This paper describes the relationship between spring snow mass in the mountain areas in the western United States and summer (July–August) monsoonal precipitation across the southwestern United States. One-point correlation maps were created between July–August precipitation anomalies in subregions of the monsoon areas and 1 April snow water equivalent at snow-course stations. Correlation maps were also made of JA pre-

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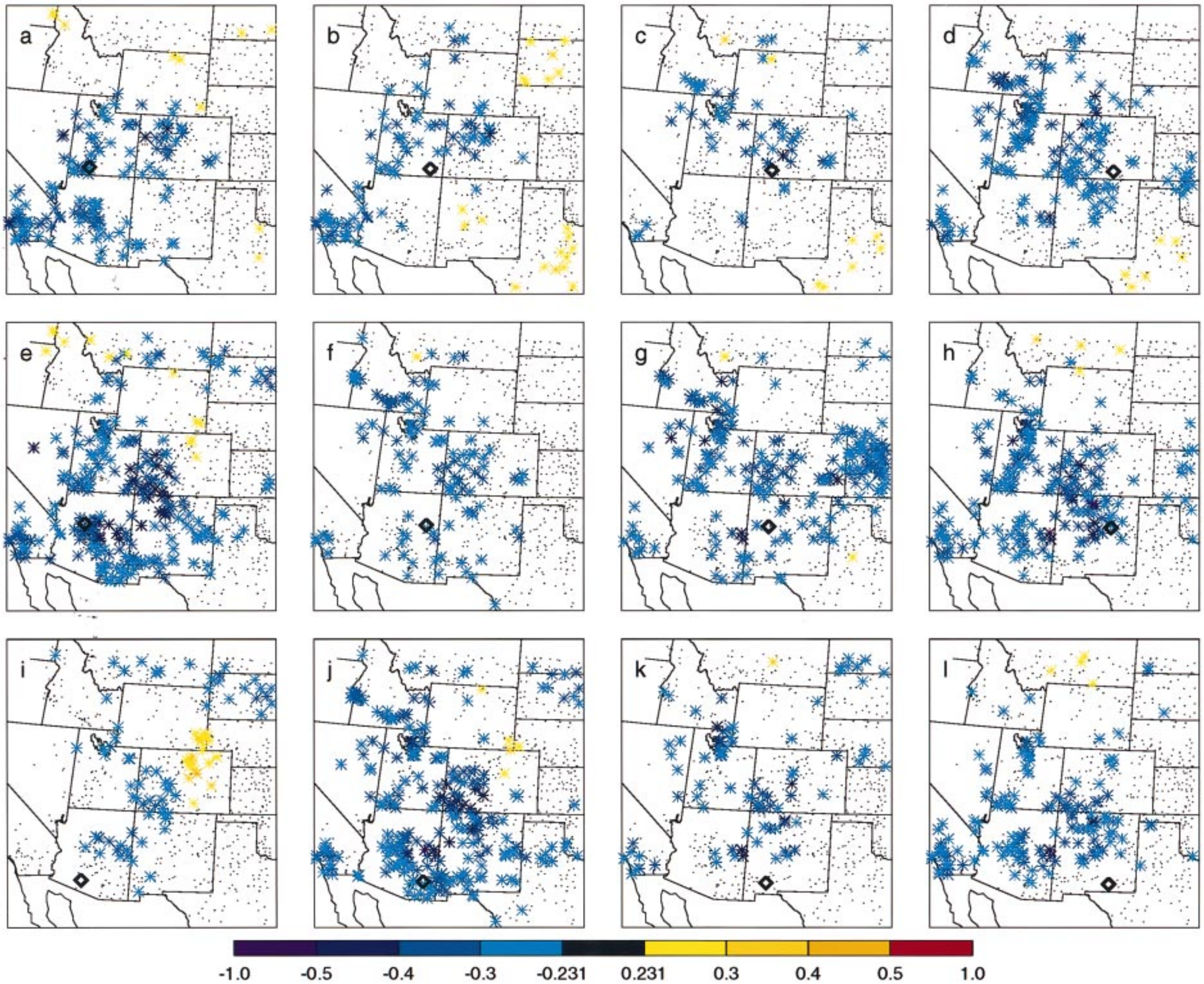

FIG. 3. Correlation between JA precipitation anomalies (at the diamond) and JFM precipitation at each NWS station. Colors correspond to correlation coefficients shown in the color bar. Asterisks indicate stations with correlation coefficients statistically significant at the 90% level.

cipitation anomalies and JFM precipitation anomalies at the NWS cooperative stations. We observed a general inverse relationship between monsoonal rain and antecedent spring snow in the Southwest. The areas of high-elevation spring snow mass most strongly associated with the summer monsoon rains are the Colorado Rocky Mountains, Four Corners area, and Utah's Unita Mountains. There also exists subregional variability. The spatial extent of snow–monsoon associations is much greater in New Mexico than in Arizona. However, when using a set of multistation SWE indices to predict summer monsoonal precipitation, we found the overall strength of the correlations between SWE and JA precipitation is just as strong in Arizona as in New Mexico. The potential for using local land surface conditions to predict Arizona precipitation thus deserves further attention.

Correlations between JA precipitation anomalies and 1 April SWE anomalies using 15-yr windows through the 50 yr of data for each subregion show the snow–monsoon relationship to be unstable though time. Correlations in New Mexico are stronger in the time period of 1965–92 and weaker outside that period. These results support the work of Gutzler (2000), in which he found that the relationship between spring snowfall and New Mexico's summer rainfall are only strong during 1961–90. By contrast, correlations in southern Arizona are strongest (weakest) in the earlier (later) part of the record. The shift from strong snow–monsoon associations in Arizona to strong associations in New Mexico may be indicative of a common forcing mechanism, which, if identified, could result in improved predictions of Southwest summertime precipitation.

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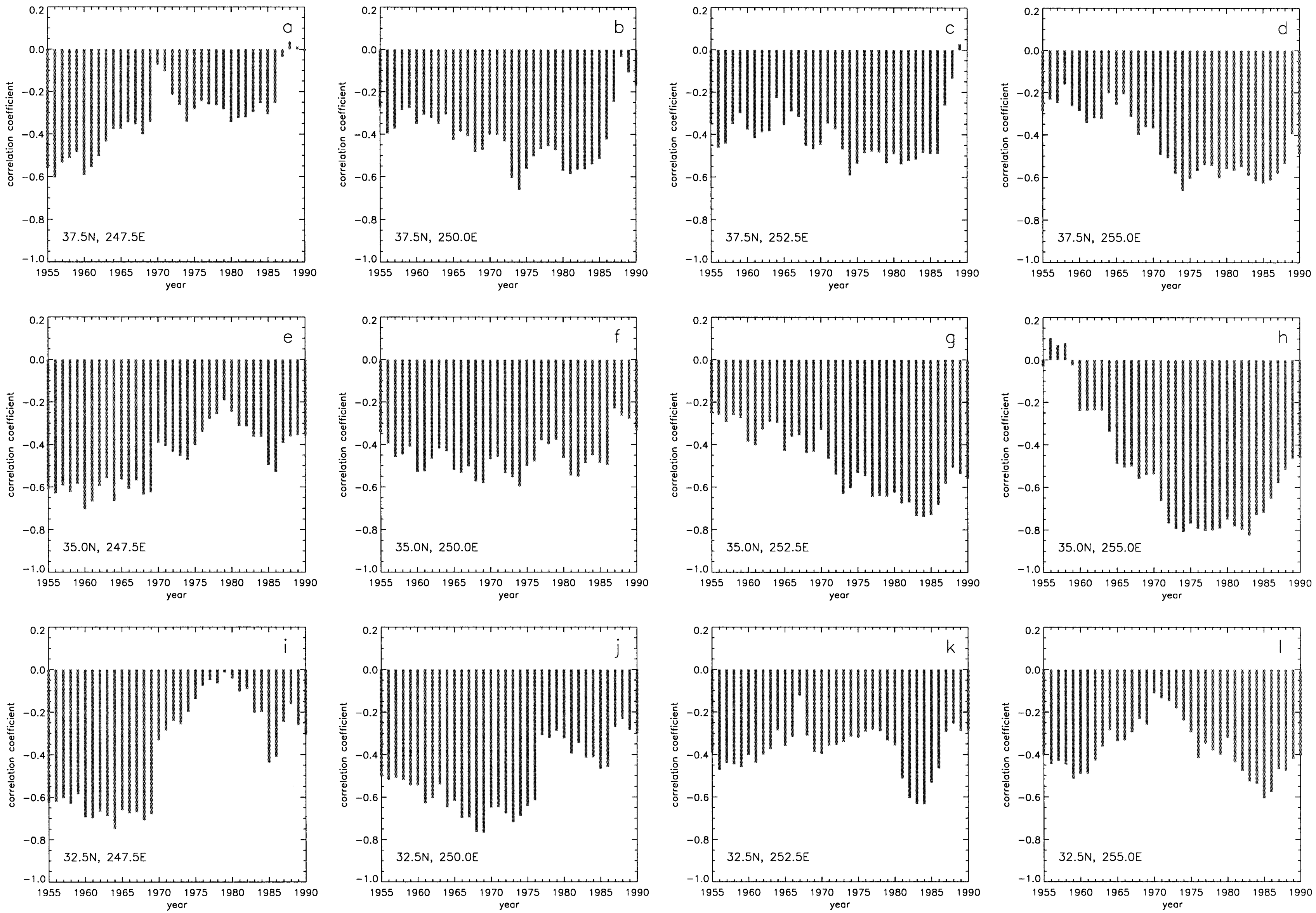

FIG. 4. Correlation coefficients for the SWE index with JA precipitation centered for a 15-yr window at the location indicated in the lower-left-hand corner of plot.

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