Frequency Modes of Monsoon Precipitation in Arizona and New Mexico

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ABSTRACT

The interannual and intraseasonal variability of the North American monsoon is of great interest because a large proportion of the annual precipitation for Arizona and New Mexico arrives during the summer monsoon. Forty-one years of daily monsoon season precipitation data for Arizona and New Mexico were studied using wavelet analysis. This time-localized spectral analysis method reveals that periodicities of less than 8 days are positively correlated with mean daily precipitation during the 1 July–15 September monsoon period. Roughly 17% of the years indicate no significant periodicity during the monsoon period for either region and are associated with low monsoon precipitation. High- and low-frequency modes explain an equivalent percentage of the variance in monsoon precipitation in both Arizona and New Mexico, and in many years concurrent multiple periodicities occur. Wavelet analysis was effective in identifying the contribution of high-frequency modes that had not been discerned in previous studies. These results suggest that precipitation processes during the monsoon season are modulated by phenomena operating at synoptic (2–8 days) and longer (>8 days) time scales and point to the need for further studies to better understand the associated atmospheric processes.

1. Introduction

The North American monsoon is an important feature of the atmospheric circulation over the North American continent, and its effects are distinguishable over a large area of the western United States and northwestern Mexico. The North American (NA) monsoon regime experiences climate variations on time scales ranging from intraseasonal to decadal (Carleton 1986; Carleton et al. 1990; Higgins et al. 1998, 1999; Higgins and Shi 2000; Stensrud et al. 1997; Mullen et al. 1998; Yu and Wallace 2000) and also demonstrates considerable spatial variability (Adams and Comrie 1997). Although centered over northwestern Mexico, the NA monsoon contributes a significant proportion of the annual precipitation for the southwestern United States. The North American summer monsoon regime produces 35%–45% of the annual rainfall across the desert Southwest during July–September (Higgins et al. 1999). However, throughout the warm season of the southwest United States, the atmosphere typically undergoes several oscillations between hot, dry conditions with little rainfall and more humid weather with frequent afternoon thunderstorms. Changes between dry and wet regimes can be gradual, spanning several days, or very abrupt, taking place within a 24-h period.

The accurate assessment and understanding of intraseasonal, annual, and decadal variations that this system displays are crucial for forecasting the potential availability for current and future management of water resources for the western United States (Higgins and Shi 2001). The improved understanding of these dynamics can lead to more accurate seasonal–intraseasonal forecasting of precipitation and may provide a basis for improving the management of scarce water resources.

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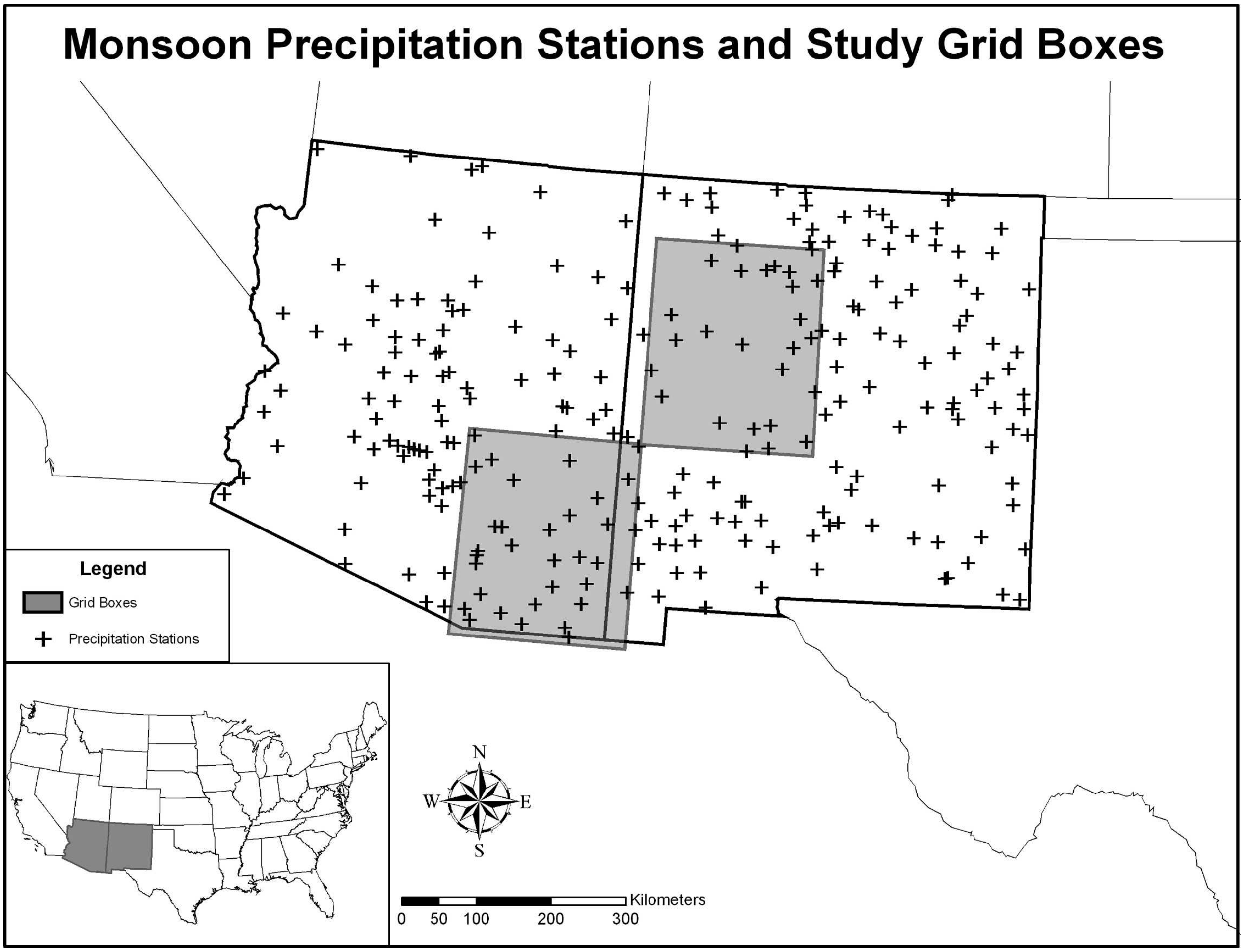

FIG. 1. Cooperative observing station network of the NWS (as of January 1999). Station locations are indicated with black plus signs. Shaded boxes show the 2.5° × 2.5° subregions within which the precipitation data were spatially averaged.

The intent of this research note is to describe the intraseasonal variability and frequency modes of monsoon precipitation for Arizona and New Mexico. The data and methodology used are described in section 2. Section 3 describes the results from the frequency analysis in terms of particular periodicities and correlations between high-frequency modes and low-frequency modes. Conclusions are briefly summarized in section 4.

2. Data and methodology

a. Precipitation data

The precipitation data used in this investigation are derived 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 (TD-3200) dataset (Eischeid et al. 2000). Reek et al. (1992) have outlined quality-control procedures on the dataset.

For this study, we used daily averaged precipitation measurements from a network of 104 National Oceanic and Atmospheric Administration (NOAA) cooperative observing stations in two regions, each 2.5° latitude × 2.5° longitude. The southeast Arizona region contained 104 stations and the west-central New Mexico region contained 64 observing stations. The 41-yr dataset covers the period from 1958 to 1998. Precipitation data from reporting stations within each grid box (see Fig. 1) were spatially averaged.

The regions were carefully selected for this analysis because Arizona generally exhibits a rapid onset of monsoon rains, while New Mexico has a more gradual increase due to mixed influences. Western New Mexico has a rapid onset signal, but eastern New Mexico is influenced by the Great Plains low-level jet (Higgins et al. 1997).

In the southwestern United States, the monsoon season extends from early July thrpugh mid-September (Ellis et al. 2004) and here is defined as 1 July–15 September. Both the monsoon season precipitation and annual precipitation for grid points in Arizona/New Mexico are analyzed.

b. Wavelet transform analysis

The wavelet transform technique (Torrence and Compo 1998) is used to identify characteristic frequency modes within the precipitation time series. Wavelet analysis enables the detection of intermittent or transient frequency components. Wavelet analysis of intraseasonal frequency modes is preferred over the more traditional Fourier analysis because intraseasonal analysis requires that the frequency modes be associated with a particular time of year. The wavelet transform can be used to analyze time series that contain nonstationary power at many different frequencies (Daubechies 1990). By decomposing a time series into time-frequency space, one can explore both the dominant modes of variability and how those modes vary in time (Torrence and Compo 1998). While a windowed Fourier transform can also provide time-localized frequency information, it does so using a sinusoid as the basis function within a finite window. Because the windowed Fourier transform has a fixed time resolution, it is not as accurate in tracking frequencies that can change quickly. Furthermore, the sinusoidal kernel used with the windowed Fourier transform is not an ideal choice for characterizing sharp precipitation peaks that occur during the monsoon season. With the appropriate choice of wavelet basis, wavelet analysis can identify the modulation of a signal's amplitude or its frequency as well as abrupt changes in a time series or its frequency characteristics (Barry and Carleton 2001).

A continuous wavelet transform is performed using the Paul wavelet basis (Barry and Carleton 2001, p. 77). The Paul wavelet basis offers better time localization than the more commonly used Morlet wavelet basis and so is a good choice for time series data that may have sharp peaks. Significance testing is performed on the wavelet transform results using the 95% confidence level and a red noise (lag 1) background spectrum.

We analyze both the full 41-yr dataset and each individual year. Analysis of the full dataset allows one to discriminate between possible ubiquitous patterns of precipitation that persist throughout the year and those that occur only during the monsoon season. However, the primary focus of this study is to identify intraseasonal temporal patterns of precipitation for the monsoon period of each year. Such intraseasonal patterns are best resolved by producing annual subsets and performing wavelet analysis on each individual year. Analyzing a full year of data rather than just the monsoon period eliminates the influence of the edge of the time series and zero padding.

TABLE 1. Linear Pearson's correlation coefficient for the number of days within a particular frequency mode vs mean daily precipitation for monsoon and non-monsoon periods of the 41-yr dataset. Values in boldface font are significant at the two-tailed probability value of 0.05.

	Arizona		New Mexico	
Frequency mode (days)	Monsoon	Non-monsoon	Monsoon	Non-monsoon
2–4	**0.57**	−0.09	**0.64**	0.22
4–8	**0.53**	0.002	**0.54**	0.04
8–16	0.38	−0.17	0.40	−0.31
16–32	0.33	−0.02	0.48	−0.28
32–64	0.14	0.23	0.25	0.006

3. Results and discussion

a. Analysis of frequency modes of monsoon precipitation

Results of the wavelet transform analysis using the full 41-yr daily precipitation dataset show that the monsoon and non-monsoon time periods have distinctly different frequency modes and that these are also related to the mean daily precipitation received during the respective periods. Table 1 shows correlations between the number of days having frequency modes of 2–4, 4–8, and 8–16 days and mean daily precipitation for both monsoon and non-monsoon time periods. For both Arizona and New Mexico, 2–4-day periodicities are well correlated with monsoon mean daily precipitation ($r_{\mathrm{AZ}} = 0.57$, $r_{\mathrm{NM}} = 0.64$). The 4–8-day periodicities are also well correlated ($r_{\mathrm{AZ}} = 0.53$, $r_{\mathrm{NM}} = 0.54$) with monsoon mean daily precipitation. Correlations between 8- and 16-day periodicities and monsoon mean daily precipitation are not statistically significant at the 0.05 level ($r_{\mathrm{AZ}} = 0.40$). Conversely, for the non-monsoon time period, there were no statistically significant correlations between frequency modes and mean daily precipitation. As expected, these results suggest that the mechanisms controlling the characteristic frequency modes of precipitation are different for the monsoon and non-monsoon time periods.

Wavelet spectra from 82 individual years (41 yr for each region) were analyzed for periodicity patterns and other characteristic observations. Of the 41 yr in the precipitation dataset, 7 yr (17%) in each of the two regions showed no significant periodicities. The years

TABLE 2. Monsoon years with no significant periodicities.

Arizona	New Mexico
1960	1960
1965	1962
1978	1969
1983	1978
1985	1983
1993	1985
1997	1986

without periodicities for each region are listed in Table 2. Four of the years identified were the same for both regions (1960, 1978, 1983, and 1985), but these could not be explained on the basis of ENSO phase. However, in Arizona, 6 of 7 (and 5 of 7 in New Mexico) of these years had below average monsoon precipitation. The mean daily monsoon precipitation averaged over 41 yr is 2.3 and 1.7 mm for Arizona and New Mexico, respectively.

Figures 2–4 show examples of monsoon periods with predominantly high, low, and concurrent high- and low-frequency modes, respectively. One can interpret these figures by first examining the wavelet power in the contour plot. Here we used periods of 2–4, 4–8, 8–16, 16–32, and 32–64 days. The wavelet power (the square of the absolute value of the power) is the explained variance at a particular frequency at a certain time in the monsoon period. To put these examples in context, for Arizona, 27 of 41 yr contain high frequencies but only 6 of 41 yr contain only high frequencies. Conversely, 21 of 41 yr in the Arizona dataset contain low frequencies but only 5 of 41 yr contain only low frequencies. Nine of 41 yr contain all five of the frequencies examined. New Mexico, however, shows a different behavior with regard to the co-occurrence of frequency modes. There are no years that show only high or low frequencies and 30 of 41 yr show all frequencies. The year 1984 had very high monsoon precipitation and the only statistically significant variability was at a scale of 16–32 days. For Fig. 3, this was the only example of a monsoon season with a prominent low-frequency mode but no shorter frequencies. This was a monsoon season with much higher-than-average mean daily precipitation and, when the monsoon began, it rained every day without a break until September. For Fig. 4, with both high and low frequencies, one cannot determine if the occurrences of high frequencies are embedded within an overall low-frequency pattern or if the low-frequency pattern derives from the high-frequency pattern.

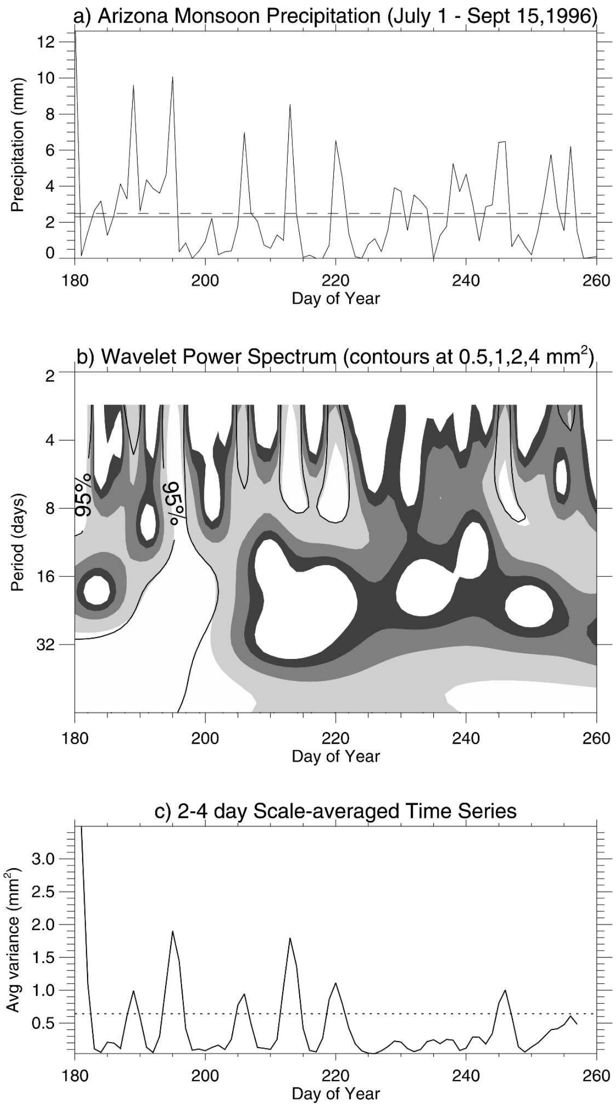

FIG. 2. Example of a monsoon period dominated by high-frequency periodicities: Arizona, 1996. (a) Daily rainfall with mean daily precipitation for that monsoon year (dashed horizontal line) and the mean daily monsoon precipitation averaged over all years (solid horizontal line) shown. (b) The time-localized wavelet power spectrum. Shaded contour bands represent wavelet power in intervals of 0.5, 1, 2, and 4 mm^2 of rainfall. The black contour is the 5% significance level. (c) A "slice" of the wavelet power spectrum. Here, we look at just one range of frequencies (2–4 days) and scale average over that range. Points above the dotted line are significant at the 5% significance level.

It should be noted that wavelet studies often include a plot of the global wavelet spectrum, which is the time-averaged spectrum and is similar to a smoothed Fourier spectrum. We omit the global wavelet spectrum here because the significant spectral features that are important for characterizing intraseasonal variability are overshadowed by annual and seasonal cycles of precipitation. The global wavelet spectrum shows that the annual and wet/dry seasonal cycles are the dominant modes. However, this is a biased estimator of the true

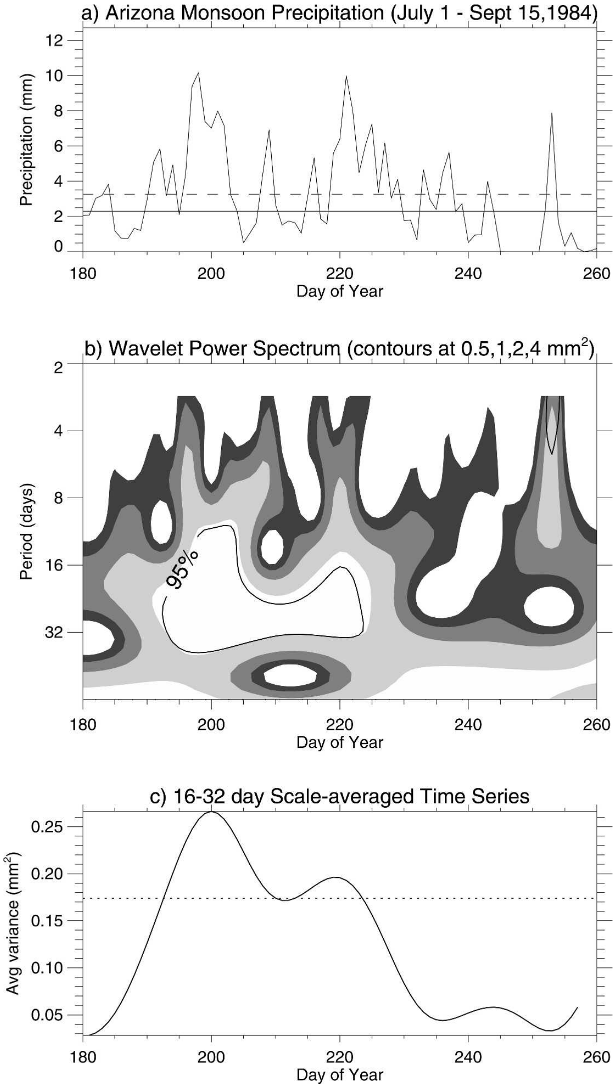

FIG. 3. As in Fig. 2 but for a monsoon period with a strong low-frequency mode: Arizona, 1984.

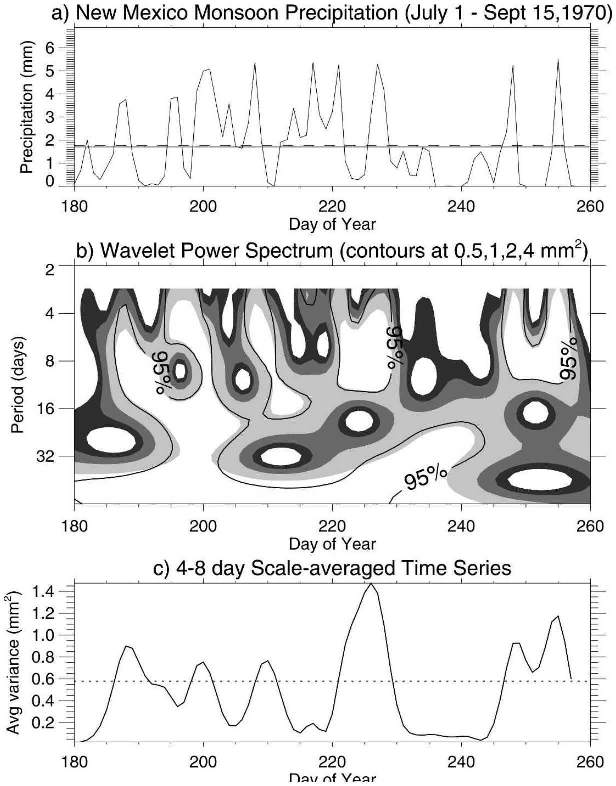

FIG. 4. As in Fig. 2 but for a monsoon period with multiple, concurrent frequency modes: New Mexico, 1970.

power spectrum in that the wavelet spectrum will tend to smooth out high-frequency peaks, leaving only the broader yet less-relevant peaks (C. Torrence 2006, personal communication).

b. Proportions of variance explained by different frequency modes

1) ARIZONA

We examine the explained variance by looking at composites of frequencies as well as relationships between different frequencies. For Arizona, the high-frequency periodicities (8 days and shorter) were able to explain an average of 34% of the total variance of monsoon precipitation while the low frequencies (longer than 8 days) explained an average of 29% of the total variance. Although the proportion of variance explained by high-frequency modes is not much larger than that explained by low-frequency modes, there are some interesting temporal differences between the two. Figure 5 shows the proportion of variance explained by high versus low frequencies for the 41-yr record and clearly, there are periods when high- and low-frequency modes are in phase (e.g., 1980–90) and periods when they are antiphase (1991–97). There is no correlation between the phasing of the high/low-frequency modes and major climate indices such as ENSO, the North Atlantic Oscillation (NAO), and the Pacific decadal oscillation (PDO). Overall, there is an inverse but insignificant relationship between the explained variance of the two frequency modes ($r = -0.24$). Looking at relationships between individual frequency modes (Table 3), we see that the correlation between the explained variance for 2–4-day and 4–8-day periodicities is high ($r = 0.64$), but low for correlations between 4–8-day and 8–16-day periodicities ($r = 0.14$) and negative for correlations between 2–4-day and 32–64-day periodicities ($r = -0.52$). These results indicate, respectively, that in some monsoon years, both low- and high-

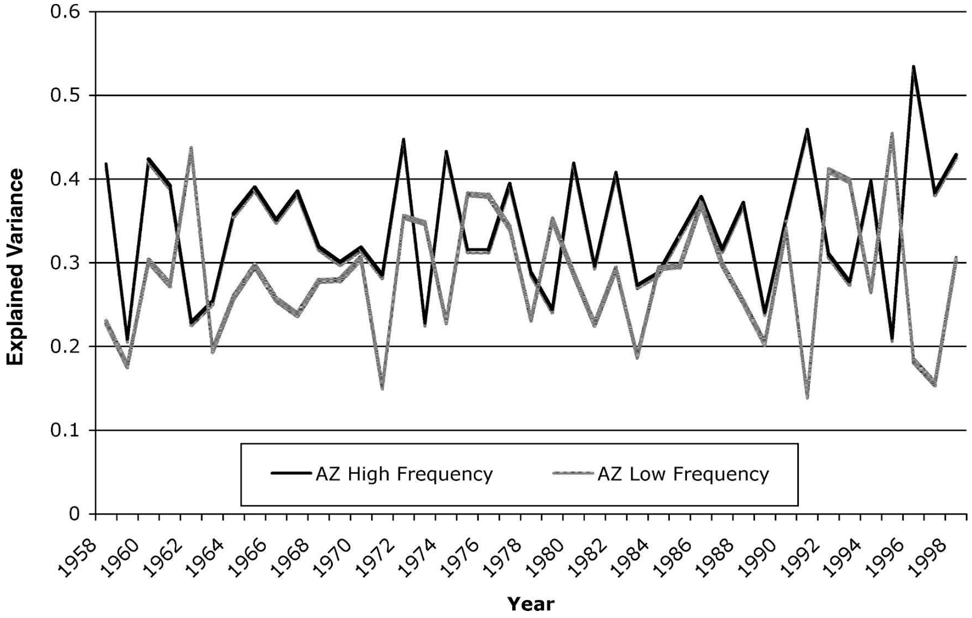

FIG. 5. The fraction of the variance explained by high- and low-frequency modes for Arizona.

frequency modes are equally dominant, while in other years either one or the other is dominant.

2) NEW MEXICO

In this region, the high- and low-frequency modes explained nearly equal amounts of the variance (35% and 34%, respectively). Figure 6 shows the temporal variability of the explained variance for high and low frequencies. As with southeastern Arizona, there is a weak negative correlation between the two (r = −0.18), but there are some interesting consistencies from year to year. There are some periods when the explained variances of the frequency modes are in phase (1958–63, 1983–91) and other periods when they are antiphase (1964–77). As with southeastern Arizona, we find no correlation between the phasing of the high/low-frequency modes and such major climate indices as ENSO, the NAO, and the PDO. Table 4 shows the relationships between individual frequency modes. Here, we see that the correlation between the explained variance for 2–4-day and 4–8-day periodicities is high (r = 0.62), but low for correlations between 4–8-day and 8–16-day periodicities (r = 0.28) and negative for correlations between 2–4-day and 32–64-day periodicities (r = −0.62). This would indicate that the mechanisms responsible for the high-frequency modes are distinctly different than those involved in the low-frequency modes.

TABLE 3. Correlations between the scale-averaged explained variance of different frequency modes for Arizona monsoon precipitation. Values in boldface font are significant at the two-tailed probability value of 0.05.

Frequency mode (days)	2–4	4–8	8–16	16–32	32–64
2–4	1	**0.64**	−0.17	−0.31	**− 0.56**
4–8		1	0.14	−0.34	−0.52
8–16			1	0.42	−0.44
16–32				1	−0.01
32–64					1

Our results contrast with a prior study by Mullen et al. (1998), who found that time scales longer than 7 days explained 75% of the variance and noted a dominant frequency mode of 12–18 days. This contrast can be explained primarily in the difference in methodology between the two investigations. In Mullen et al., the authors used precipitation data from only eight monsoon seasons (1985–92) over southeastern Arizona, whereas our study uses a much longer dataset and examines both southeastern Arizona and New Mexico. However, even if we subset our dataset to the years and region used by Mullen et al., our results still show a roughly equal influence of high- and low-frequency modes. This is because Mullen et al. used a single spectrum analysis, a variation of a Fourier method that relies on a sinusoidal basis function, which is not able to resolve high-frequency precipitation spikes as efficiently as does the Paul wavelet. Higgins and Shi (2001) also found that two-thirds of the total variance in mon-

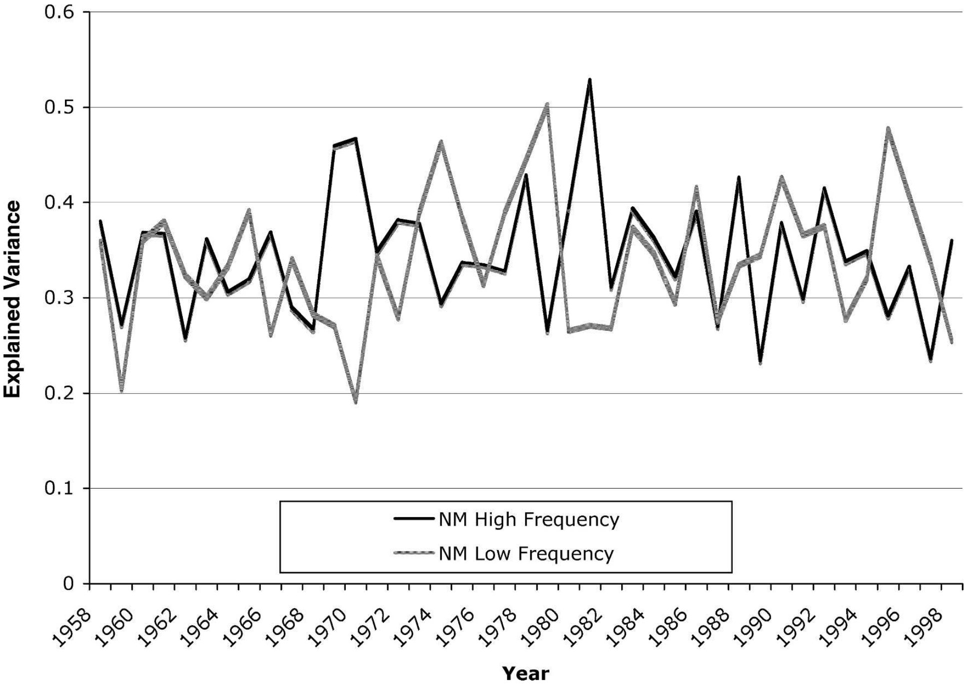

FIG. 6. As in Fig. 5 but for New Mexico.

soon precipitation anomalies for Arizona and New Mexico is explained by the 30–60-day window of a power spectrum analysis. However, they had smoothed their dataset and had used a windowed Fourier technique, thereby reducing the effects of high frequencies in the dataset. Our investigation shows that both high- and low-frequency modes are important and that they explain roughly equal amounts of the variance. This time-localized spectral analysis technique shows that while longer periodicities are important in some portions of the 41-yr record, their significance varies over time, sometimes in phase and antiphase with high-frequency modes.

4. Summary and conclusions

Wavelet analysis of 41 yr of daily precipitation for regions of Arizona and New Mexico indicates that precipitation during the monsoon period has significant frequency modes that are correlated with mean daily precipitation. This is in contrast to the non-monsoon period, which does not exhibit such correlations. For both Arizona and New Mexico, there was a significant positive relationship between mean daily monsoon precipitation and the number of days within high-frequency modes (2–4 and 4–8 days). Roughly 17% of the years indicate no significant periodicity during the monsoon period. These years of nonperiodicity of precipitation are equally evident in Arizona and New Mexico, although the years were not the same for both. This is only a small number of years but nearly all of them had below average monsoon precipitation.

High- and low-frequency modes explain an equivalent percentage of the variance in monsoon precipitation in both Arizona and New Mexico, and concurrent high- and low-frequency modes occur in many years. Using wavelet analysis with daily precipitation data, we were effective in identifying the contribution of high-frequency modes that had not been discerned in previous studies. These results suggest that precipitation processes during the monsoon season are modulated by phenomena operating at synoptic (2–8 days) and longer (>8 days) time scales. Interestingly, the fraction of variance explained by high- and low-frequency modes is at times in phase and at other times antiphase. This preliminary statistical analysis suggests a number of tracks

TABLE 4. As in Table 3 but for New Mexico.

Frequency mode (days)	2–4	4–8	8–16	16–32	32–64
2–4	1	**0.62**	−0.13	−0.40	−0.48
4–8		1	0.28	−0.35	**−0.62**
8–16			1	0.44	−0.48
16–32				1	0.19
32–64					1

for further investigation. In a forthcoming paper, we will relate these frequency modes to atmospheric circulation processes such as the Madden–Julian oscillation, tropical cyclones, and surge processes in the Gulf of California. We believe that future studies of atmospheric circulation and moisture flux patterns associated with the specific frequency modes will provide useful information with the aim of improving operational forecasting capabilities.

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