Diurnal Precipitation Variations in South-Central New Mexico

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ABSTRACT

Orographic forcing of diurnal precipitation variations in south-central New Mexico is examined. Harmonic analysis reveals a strong diurnal cycle in precipitation frequency at all stations studied. In addition, relatively high amplitudes in the second, third, and fourth harmonics were present at several stations in the region. Cumulant methods confirm the importance of the higher harmonics and can also divide the stations into precipitation regimes.

At each of the stations one of the maxima in the precipitation frequencies appears to be due to surface convergence caused by a mountain–valley circulation system. Surface wind data support this explanation. All stations have a maximum near midnight local time, which seems to have its source in larger-scale forcing. A possible cause is diurnal variations in the plateau circulation system of the western United States. Upper-air wind data indicate that such variations could result in the formation of a low-level jet that would destabilize the atmosphere near midnight local time.

1. Introduction

The existence of a clear diurnal cycle in precipitation in many parts of the United States has been established for some time (Wallace 1975). This periodicity is especially strong for convective precipitation (Easterling and Robinson 1985) and therefore is stronger during the summer than during the winter. This cycle is also especially pronounced in regions subject to topographic influences such as land–sea contrasts (Schwartz and Bosart 1979) and elevated terrain (Landin and Bosart 1989; Riley et al. 1987). Reiter and Tang (1984) showed that some of the diurnal forcing in the western United States, pointed out by Wallace, could be the result of diurnal variations in a plateau monsoon circulation.

Most areas with complex terrain do not have enough precipitation data to resolve the influence of individual mountain ranges, but studies have been done in a few regions. Detailed surface observations did allow Mass (1982) to spot likely topographic causes of diurnal precipitation variations in western Washington. Toth and Johnson (1985) were able to relate radar echo patterns in eastern Colorado to orographically influenced winds. Kousky (1980) has shown some evidence for the influence of mountain–valley winds on diurnal precipitation patterns in Brazil. Diurnal precipitation variations in these three studies were, to a large degree, explainable by local forcing.

The larger-scale studies (Wallace 1975; Schwartz and Bosart 1979; Riley et al. 1987; Landin and Bosart 1989) have used harmonic analysis to compare precipitation patterns at a moderately large number of stations. Using this method, investigators can determine the amplitudes and phases of the diurnal and semidiurnal cycles. Thus, this technique can give an indication of whether the physical processes that force these types of cycles should be considered to explain the precipitation patterns at a particular location. Because of the scale size at which these studies were carried out, local forcing mechanisms were considered as possible explanations for the inferred precipitation patterns but were not investigated extensively.

This paper will examine diurnal precipitation patterns during the summer in south-central New Mexico. No detailed study of diurnal precipitation variations has concentrated on this area, although Balling and Brazel (1987) did look at summer patterns in Arizona. Larger-scale studies (Wallace 1975; Easterling and Robinson 1985) have included only data from El Paso, Texas. The New Mexico region has a number of hourly precipitation observing stations in different locations with respect to two mountain ranges. In addition, White Sands Missile Range has a surface mesonet, takes frequent sounding data, and has an operational wind profiler. The diurnal variation of precipitation at these stations can be partially explained by local mountain effects, but this study presents evidence that larger-scale forcing contributes to it as well.

Section 2 presents the dataset and its geographic setting. Section 3 delineates the precipitation patterns shown by an analysis of the data. Harmonic analysis

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yields the basic structure of the diurnal cycle and provides a basis for comparison with other studies. Harmonic analysis, however, does not indicate whether the precipitation patterns are significantly different in a statistical sense from a diurnally uniform one, nor does it provide an objective way of separating stations into different precipitation regimes. If one station has a stronger amplitude or a different phase from another, it may be difficult to determine whether the differences are caused by separate physical mechanisms. Investigators (e.g., Riley et al. 1977; Landin and Bosart 1989) who attempted to divide regions into different precipitation regimes have admitted that it was a subjective process. Therefore, cumulant methods (Mielke and Berry 1987) are used in this study for the analysis of the diurnal precipitation patterns, especially for separating stations into regimes.

Section 4 focuses on the mountain–valley wind system revealed by surface data and how it could influence the diurnal precipitation patterns. Section 5 deals with larger-scale effects and what upper-air data indicate about them. A summary and overall conclusions complete the paper in section 6.

2. The region and its data

a. Geography and climatology

The study area is a small one in south-central New Mexico. It is bounded by 32.3°N to the south and 34.0°N to the north. The eastern and western borders are 105.7° and 106.8°W, respectively. Thus, the area is roughly 200 km (north–south) by 150 km (east–west).

The higher and wider Sacramento Mountains are in the eastern part of the region (see Fig. 1), with the Organ and San Andreas mountains on the western part of the domain. The Tularosa Basin between these mountain ranges has an average elevation of about 1300 m. Rainfall is usually between 8 and 9 in. (200–225 mm), but as in most areas with sparse precipitation, it varies greatly from year to year. Precipitation has been above normal, however, for 14 of the 20 years studied. For both the lowlands and mountains, well over 50% of the annual precipitation falls during the period June–September when southerly flow brings moisture into the region. Convective storms cause the overwhelming majority of rainfalls during this period. These storms are primarily of the airmass variety described by Byers and Braham (1949).

The mountainous regions are cooler and wetter, and climate is heavily dependent on elevation. Precipitation amounts are commonly two or three times those of the lowlands, depending on the exact location.

b. Precipitation data

This study will examine hourly precipitation data in the region described in subsection 2a over the summer season. Summer is defined to extend from 1 June to 15 September of each year. The data for most of the stations listed in Table 1 are for a 20-yr period from 1970 to 1989. The dataset for the station designated C station was taken by the U.S. Army Atmospheric Sciences Laboratory at White Sands Missile Range and spans only the 9 years from 1983 to 1991; it has no periods of missing data. The data at the other stations were taken by cooperative observers and have 20 years of data except for the missing hours shown in Table 1. Only about 10% of the data are missing in the worst case.

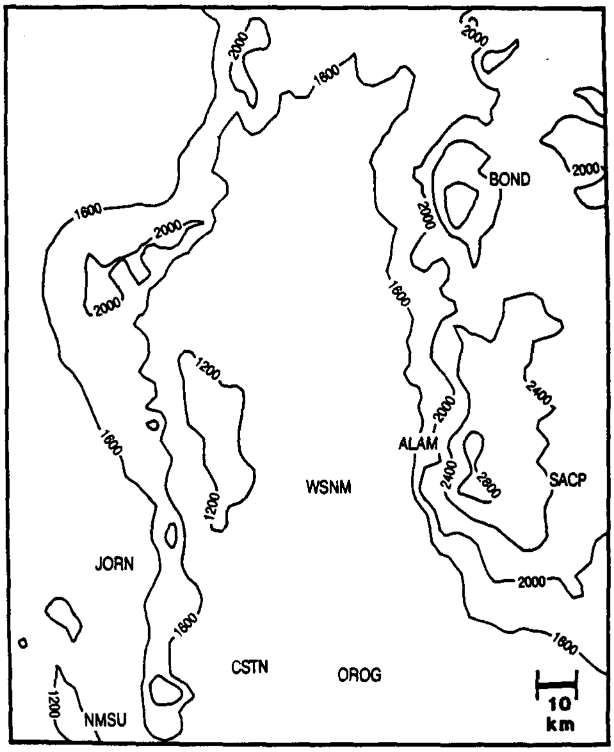

FIG. 1. Topographic contour line and locations of precipitation stations. Contours are drawn every 400 m, and precipitation stations have four-letter identifiers. The domain is 180 km × 148 km.

During the period studied, most of the stations switched from the tipping-bucket raingage to the Fisher–Porter raingages. The Fisher–Porter raingages measure rainfall only to the nearest one-tenth of an inch, whereas the tipping bucket is accurate to one-hundredth of an inch. The date of the changeover for each of these station is given in Table 1. The data at C station are all from a tipping-bucket raingage. The results of harmonic analysis and cumulant methods analysis are not substantially affected by this changeover; therefore, data from both types of raingages are considered together. The most likely reasons for this uniformity is that the vast majority of the rainfall during the summer is convective and precipitation frequently falls in amounts exceeding one-tenth of an inch at a time.

TABLE 1. Names, abbreviations, and relevant information of stations in the study.

Name	Abbreviation	Hours of missing data	Date of changeover
Alamogordo	ALAM	3053	September 1984
Bonito Dam	BOND	5524	September 1976
Jornada experiment station	JORN	2099	July 1977
Orogrande	OROG	3701	June 1985
Sacramento 2	SACP	1562	September 1979
New Mexico State University	NMSU	314	June 1978
White Sands National Monument	WSNM	1522	June 1985
C station	CSTN	0	N/A

The locations of these stations with respect to the mountain ranges described above can be seen in Fig. 1. Note that C station (CSTN) and White Sands National Monument (WSNM) are near the center of the basin, Sacramento (SACP) and Bonito Dam (BOND) are in the mountains, and the other stations are in the foothills.

3. Analysis of the precipitation data

a. General characteristics

To get a broad overview of the features of the diurnal precipitation variations in this region, let us look at the precipitation frequency as a function of the time of day (Fig. 2) for each of the stations. All stations have a primary or a secondary frequency maximum within two hours of midnight. For C-Station, White Sands National Monument, Alamogordo (ALAM), and New Mexico State University (NMSU) it is a primary maximum. All stations except for C station have another maximum either near noon or in the early evening. Overall, the stations can be divided into three categories.

The first category includes Sacramento (Fig. 2a) and Bonito Dam (Fig. 2b); both are in the mountains. They have a maximum at 1300 LST, as might be expected in a mountainous area with strong solar heating. They also have a noticeable maximum at 0200 LST, possibly indicating a semidiurnal cycle. Since the maxima are almost 12 h apart, harmonic analysis should be able to represent them well if both are truly important.

The stations in the second category (Figs. 2c–g) also have two maxima per day but they are not as symmetrically distributed. These stations are close to the mountains, but not actually in them. Harmonic analysis may not be as useful a tool for such distributions. Since these stations and those in the first category both have two maxima with one of them near midnight, it is not clear whether the differences between the two stations are significant. In other words, should they be in the same precipitation regime or not?

On the other hand, C station (Fig. 2h) has only one maximum per day, again near midnight. Its pattern is unique among the stations studied and puts it into a third category. This diurnal pattern also lends itself well to harmonic analysis.

Several characteristics emerge that seem reasonable given the geography of the region. Since C station is near the center of the basin, it would make sense that downslope convergence could force a midnight maximum here. Likewise, a late afternoon or early evening maximum does not seem unexpected for the stations in the second category, since surface convergence would occur here as downslope flow initiates. What is more puzzling are the apparent semidiurnal patterns at the stations in and near the mountains. Is this periodicity important, and if so, why does C station lack a dual maxima in its precipitation curve when the other stations have one? The consistency of the maximum near midnight would argue for a larger-scale forcing than the mountain–valley circulation. Looking at the precipitation frequencies themselves is a subjective judgment. It will be worthwhile to see if these patterns are confirmed by more objective measures.

b. Harmonic analysis

Harmonic analysis has been employed for describing diurnal precipitation patterns by a large number of investigators (e.g., Wallace 1975; Schwartz and Bosart 1979; Riley et al. 1987; Landin and Bosart 1989; Balling and Brazel 1987), and the method is well known. A complete description, given in Conrad (1944), indicates that the amplitudes and phases of the sine and cosine curves for each frequency are commonly found using the method of least squares. The disadvantages of using a technique such as this one, which is based on squared differences, have been pointed out by Mielke (1985, 1986).

The analysis presented here is for precipitation frequency so that it may be compared with the results from the cumulant methods to follow. Results from an analysis of precipitation amounts are not substantially different. As is customary, the amplitudes will be normalized by dividing by the mean over the 24 h of precipitation data.

The amplitude and percentage of variance accounted for by the first harmonic (the diurnal curve) for the

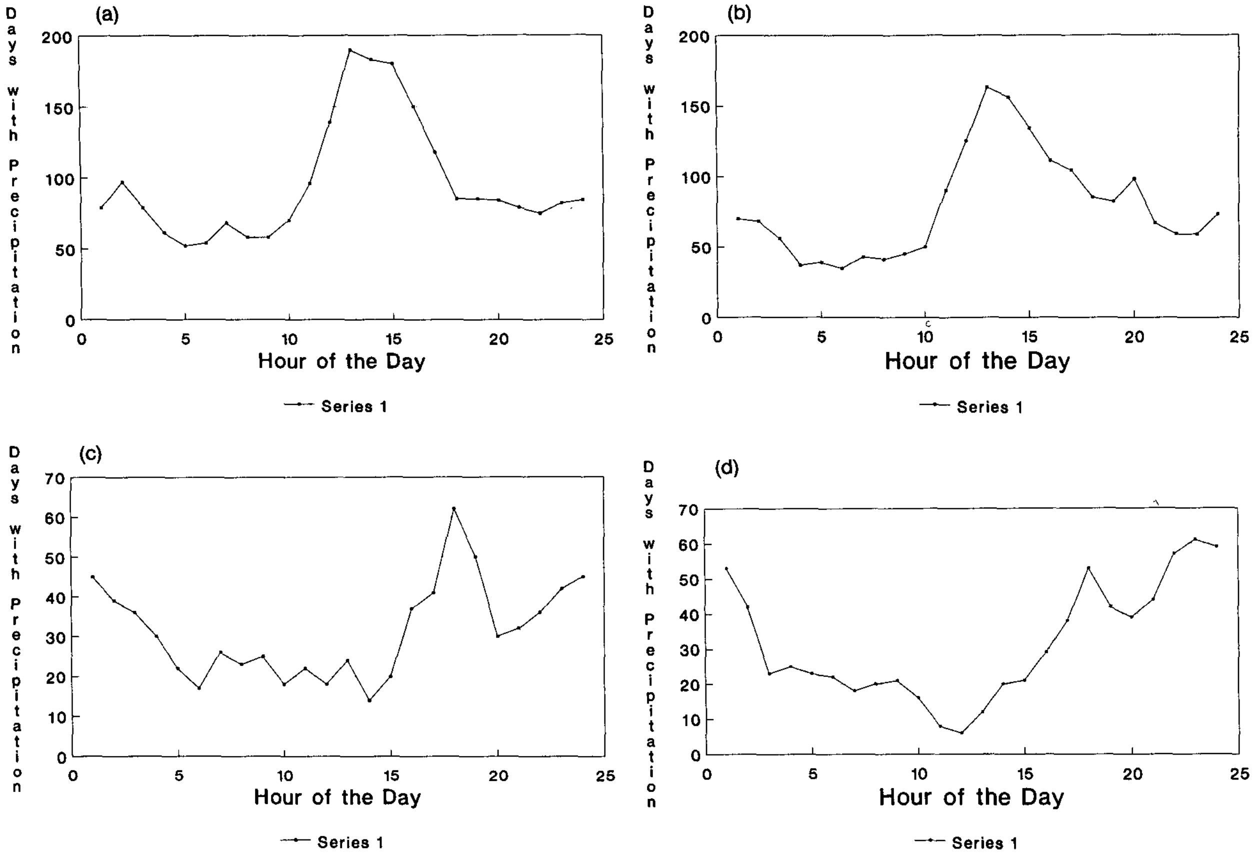

FIG. 2. Diurnal variation of precipitation frequency for (a) Sacramento 2, (b) Bonito Dam, (c) Jornada Experiment Station, (d) New Mexico State University, (e) Orogrande, (f) White Sands National Monument, (g) Alamogordo, and (h) C station.

dataset described in section 2 are found in Table 2. The amplitudes are fairly high, considering all precipitation events (except trace events) are included here. Thus, a strong diurnal cycle is indicated. Values are similar for the mountain stations as for the stations in the basin. From this analysis, it is not clear if there are important differences between these stations. The percentage of variance accounted for by this cycle is always greater than 45%, and in two cases is 80% or greater. The first harmonic for Orogrande has the smallest amplitude but it accounts for over half of the variance, indicating that the diurnal cycle there is not as strong as for the other stations; C station in particular has a high percentage of the variance represented by this cycle. This outcome is not surprising since the graph in the previous section (Fig. 2h) shows C station having a single maximum in its diurnal curve.

Since the other stations have more than one maximum value in their diurnal curves, the higher harmonics are also worth examining for these stations. Amplitudes of the second harmonic are high for SACP (0.36), BOND (0.23), and ALAM (0.24). These stations have substantial symmetry in their diurnal curves. These amplitudes are quite large, larger than those for stations studied by other investigators reporting results for a semidiurnal curve (Wallace 1975; Schwartz and Bosart 1979). Therefore, the diurnal precipitation patterns in this region differ from those of some other regions that have been given detailed study.

But Jornada (JORN) has 11% of its variance in the third harmonic, and New Mexico State University and White Sands National Monument have 11% of their variance in the fourth harmonic. This outcome represents the asymmetrical nature of the distributions of

TABLE 2. Normalized amplitudes and percentage of variance accounted for by first harmonic.

Station	Normalized amplitude	Percent of variance
ALAM	0.32	48
BOND	0.53	61
CSTN	0.56	89
JORN	0.40	54
OROG	0.29	62
NMSU	0.68	80
SACP	0.44	51
WSNM	0.33	48

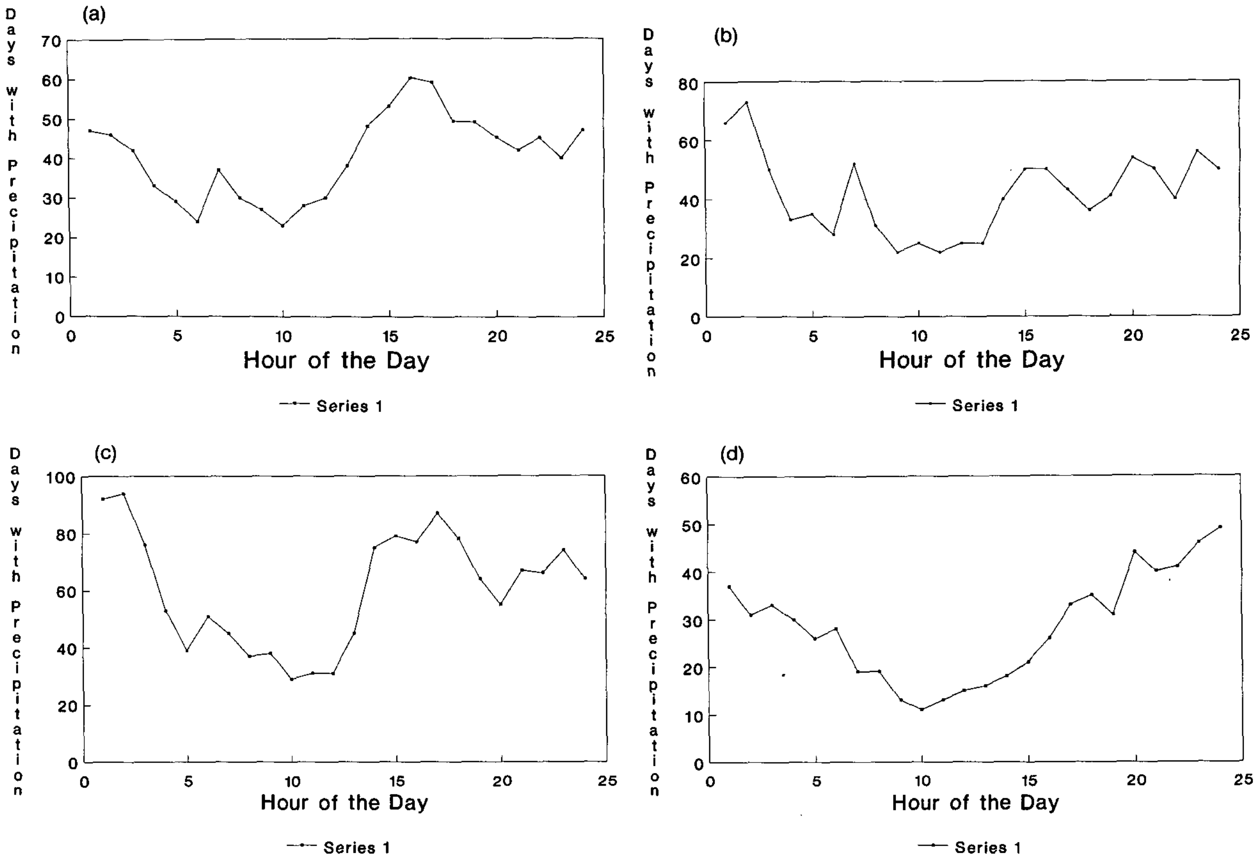

FIG. 2. (*Continued*)

their maxima, which are not represented well by harmonic analysis. Jornada, for example (Fig. 2c), has only two maxima but they are close enough together to be represented by a thrice-daily curve rather than the semidiurnal one. The amplitude of the third harmonic at Jornada is fairly large (0.26), especially considering the curve does not actually have three maxima.

Although harmonic analysis yields the percentage of variance explained by each cycle, it does not tell whether the diurnal variations themselves are statistically significant. Therefore, it is difficult to judge the importance of the higher harmonics by this technique. In addition, it is not easy to tell whether patterns at one station are different from those of another. To tackle these problems, another method will be needed.

c. *Cumulant methods*

Mielke and Berry (1987) developed cumulant methods for the analysis of r-way contingency tables and for determining the goodness of fit of frequency data. Therefore, Mielke and Berry's methods are similar to the chi-square test but they do not use squared differences. Further details on cumulant methods are given in the Appendix. For precipitation we have a two-way table—it either rained or did not rain during a certain hour. There are 24 h of data corresponding to the number of hours in a day. One station can be compared to see whether its diurnal precipitation distribution is statistically significant—that is, whether some hours are preferred for precipitation over others. The probability that the distribution is due to chance is denoted by the P value. In addition, two or more stations can be compared by adding another dimension to the table. Thus, we can see if the variation between the two or more stations is statistically significant. If they are, then the stations most likely belong to different precipitation regimes.

1) PATTERNS AT INDIVIDUAL STATIONS

In this application, cumulant methods are sensitive to the number of times per day in which data are taken. Maximum usefulness can be obtained by examining the data as if they were taken 12 times per day (every 2 h) instead of 24. Therefore, 2-h-long groupings of the data were made. The P values for these groups are displayed in Table 3. For the 2-h groupings, five stations have a significant diurnal precipitation distribution at the 5% level. Jornada and C station are significant if

3-h groupings are used instead of the 2-h groupings. The only station that does not show significant diurnal variations for any time grouping is Orogrande (OROG). The amplitude of the diurnal curve shown by the harmonic analysis for this station is also low. Possibly, local influences in the vicinity of this station keep the diurnal variation there from being as regular as that for the other stations.

It should be possible to tell whether harmonics of higher order than the first one cause the precipitation distribution to be significantly different from a uniform one. A distribution is created for each station that has higher harmonics in which the value of the first harmonic at each hour is subtracted from the actual precipitation frequency for that hour. The resulting pattern, therefore, contains only the higher harmonics. The *P* values of these distributions can be calculated for the 2-h groupings (Table 4). All of the stations that were previously significant at the 5% level for the 2-h groupings with the original data remain so. Thus, the higher harmonics are important elements that cause these distributions to deviate from a uniform one, and the maxima and minima they include may have their root in real physical causes.

2) RELATIONSHIPS BETWEEN STATIONS

Some stations in the dataset have certain patterns in common. The mountain stations have maxima near 0100 and 1300 LST. The stations near the base of the mountains also have the maximum near 1300 LST, but then the additional one is in the late afternoon or early evening. Thus, some stations may have differences between them and some may not. This type of separation can be handled by harmonic analysis only in a qualitative sense. It is a key factor, however, in dividing stations into regimes that may have similar forcing mechanisms.

The results of this analysis can be seen in Table 5. A level of significance at 1% will be taken. All comparisons with *P* values below 5% are also below 1%. With two exceptions, the two mountain stations, SACP and BOND, are significantly different from all other stations and, interestingly, from each other. The two exceptions involve SACP with CSTN and OROG. CSTN has the shortest record of all the stations and that may contribute to the difficulty of getting a statistically significant result for it. OROG is in close proximity to SACP and that condition may account for the similarity of their precipitation records. The differences between all other combinations of stations are not statistically significant. Thus, the analysis can show a distinct difference between the precipitation regimes of the valley and the mountain. The differences between the valley stations cannot be brought out by this analysis.

TABLE 3. The *P* values for precipitation data at each station grouped as if taken every 2 h (12 times per day).

Station	*P* value
ALAM	1.18×10^{-2}
BOND	9.74×10^{-10}
CSTN	7.70×10^{-1}
JORN	3.10×10^{-1}
NMSU	1.11×10^{-3}
OROG	6.80×10^{-1}
SACP	6.86×10^{-5}
WSNM	1.07×10^{-2}

TABLE 4. The *P* values for 2-h precipitation frequencies from which the diurnal cycle has been subtracted.

Station	*P* value
ALAM	1.21×10^{-3}
BOND	8.20×10^{-12}
JORN	2.30×10^{-1}
NMSU	2.03×10^{-2}
OROG	9.10×10^{-1}
SACP	2.98×10^{-5}
WSNM	1.74×10^{-3}

Cumulant methods provide a more statistical measure of the strength of diurnal precipitation patterns than harmonic analysis. They also give a quantitative way to separate stations into different precipitation regimes. They show a difference in a statistical sense, however, and do not tell what sort of pattern may be causing the difference. Harmonic analysis is better at determining the overall diurnal pattern of the precipitation. Together they indicate not only the clear importance of the diurnal cycle but also a semidiurnal pattern that cannot be ignored. Explanations must be sought for both these features.

4. Surface winds

One of the causes for the precipitation patterns examined in section 3 could be a mountain–valley wind system. Defant (1951) found two components of this system: the slope winds and the along-valley flow. This circulation is best developed during the summer when solar heating of the earth's surface is strong. Since these wind variations can cause surface convergence (which could encourage convection) in distinct regions during different times of the day, it seems reasonable to look for evidence that such a wind system may exist in this region. Fortunately, the U.S. Army has set up an extensive system of remote observing stations in this area. The group of instruments is known as a Surface Automated Meteorological Station (SAMS) and is described by Tucker and Bonner (1990). Their locations in southern New Mexico can be seen in Fig. 3. Observations on the hour (5-min averages) for these stations over three summers (1989, 1990, 1991) were averaged,

TABLE 5. The *P* values for precipitation frequencies of pairs of stations.

Station	ALAM	BOND	CSTN	JORN	NMSU	OROG	SACP	WSNM
ALAM	—	2.3×10^{-4}	9.4×10^{-1}	4.5×10^{-1}	1.0×10^{-1}	9.7×10^{-1}	1.5×10^{-3}	1.1×10^{-1}
BOND	2.3×10^{-4}	—	9.3×10^{-3}	5.5×10^{-4}	6.1×10^{-5}	6.1×10^{-3}	1.4×10^{-6}	1.4×10^{-4}
CSTN	9.4×10^{-1}	9.3×10^{-3}	—	9.8×10^{-1}	8.9×10^{-1}	9.9×10^{-1}	1.3×10^{-1}	9.5×10^{-1}
JORN	4.5×10^{-1}	5.5×10^{-4}	9.8×10^{-1}	—	2.7×10^{-1}	9.8×10^{-1}	4.6×10^{-3}	2.2×10^{-1}
NMSU	1.0×10^{-1}	6.1×10^{-5}	8.9×10^{-1}	2.7×10^{-1}	—	9.0×10^{-1}	8.5×10^{-3}	6.0×10^{-2}
OROG	9.7×10^{-1}	6.1×10^{-3}	9.9×10^{-1}	9.8×10^{-1}	9.0×10^{-1}	—	1.0×10^{-1}	9.5×10^{-1}
SACP	1.5×10^{-3}	1.4×10^{-6}	1.3×10^{-1}	4.6×10^{-3}	8.5×10^{-3}	1.0×10^{-1}	—	5.3×10^{-4}
WSNM	1.1×10^{-1}	1.4×10^{-4}	9.5×10^{-1}	2.2×10^{-1}	6.0×10^{-2}	9.5×10^{-1}	5.3×10^{-4}	—

and the resultant winds for several hours are presented in Fig. 4. Generally, the winds are highly variable from day to day since the resultant average winds are weaker than the average wind speed. Toth and Johnson (1985) also found this characteristic in their study, which in their case was a reflection of variations in the timing of the diurnal variations from day to day. Unlike Toth and Johnson's study, though, the ridge-top resultant winds here are not strong. This situation would indicate that the upper-level winds in this area are also somewhat erratic. The proximity of this region to the tropics may contribute to this variability.

At midnight local time the stations near the mountains clearly show downslope flow as would be expected as the mountain–valley circulation develops. The downslope flow has not reached the center of the valley at this time. Thus, the favored time for precipitation in the center of the valley appears to be when the downslope flow just reaches the center of the valley and the convergence starts. Only one station at this time indicates down-valley (northerly) flow.

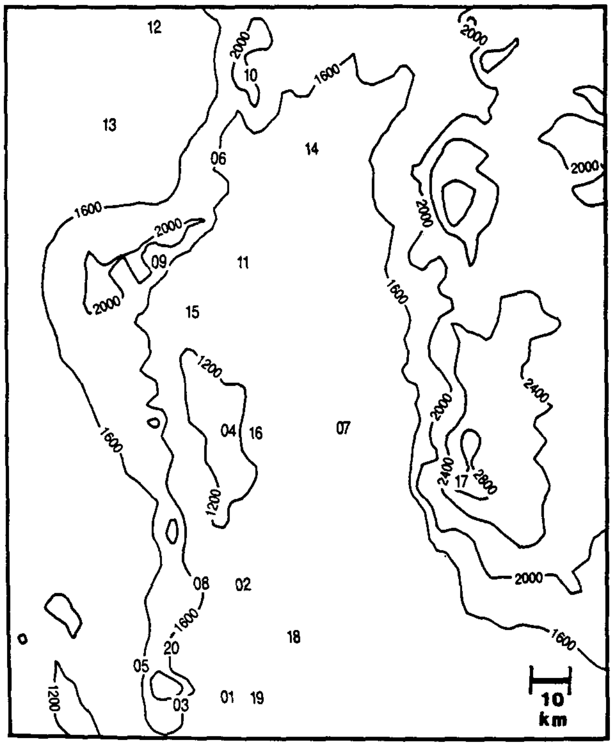

FIG. 3. Locations of the surface mesonet stations given by the numbers. Contours of topography are as in Fig. 1.

At 0600 LST, both the downslope and down-valley flows are well established. At this time, maximum surface convergence should occur in the center of the valley, but the stations in this region generally show a precipitation minimum at this time. Presumably, any instability has been released at the time the surface convergence initiated in the valley. In addition, due to radiational cooling, the vertical thermal structure of the atmosphere is not suitable for convection at this time.

By noon local time there is strong upslope and up-valley flow throughout the basin. At 1800 LST some downslope flow is evident near the peaks. This situation would result in convergence near the base of the mountains. Indeed, at this time a couple of the stations near the base of the mountains (JORN, OROG) have their maximum precipitation frequency near this time.

The major oddity about the surface winds that needs further examination is the relatively weak resultant winds of stations located on mountain peaks (numbers 9, 10, and 17). One would expect that these stations would be exposed to some free atmosphere winds. This question can be investigated by examining the persistence of the winds at three representative stations (Fig. 5). Persistence is defined by Panofsky and Brier (1968) to be the speed of the resultant wind divided by the mean wind speed. Station 1 is collocated with C station and has a persistence maximum in the midafternoon. Station 3 at the base of the mountains has a maximum just before sunrise. Persistence values at station 9 on Salinas Peak are lower than both of the other stations except at midmorning. Thus, its low values for the resultant wind are not because of low wind speeds but because of high wind variability. If this station is a good example, it indicates low values of persistence in the winds just above the boundary layer.

These results contrast with those of Toth and Johnson (1985) for the Front Range of Colorado. They found high values of persistence during the night, es-

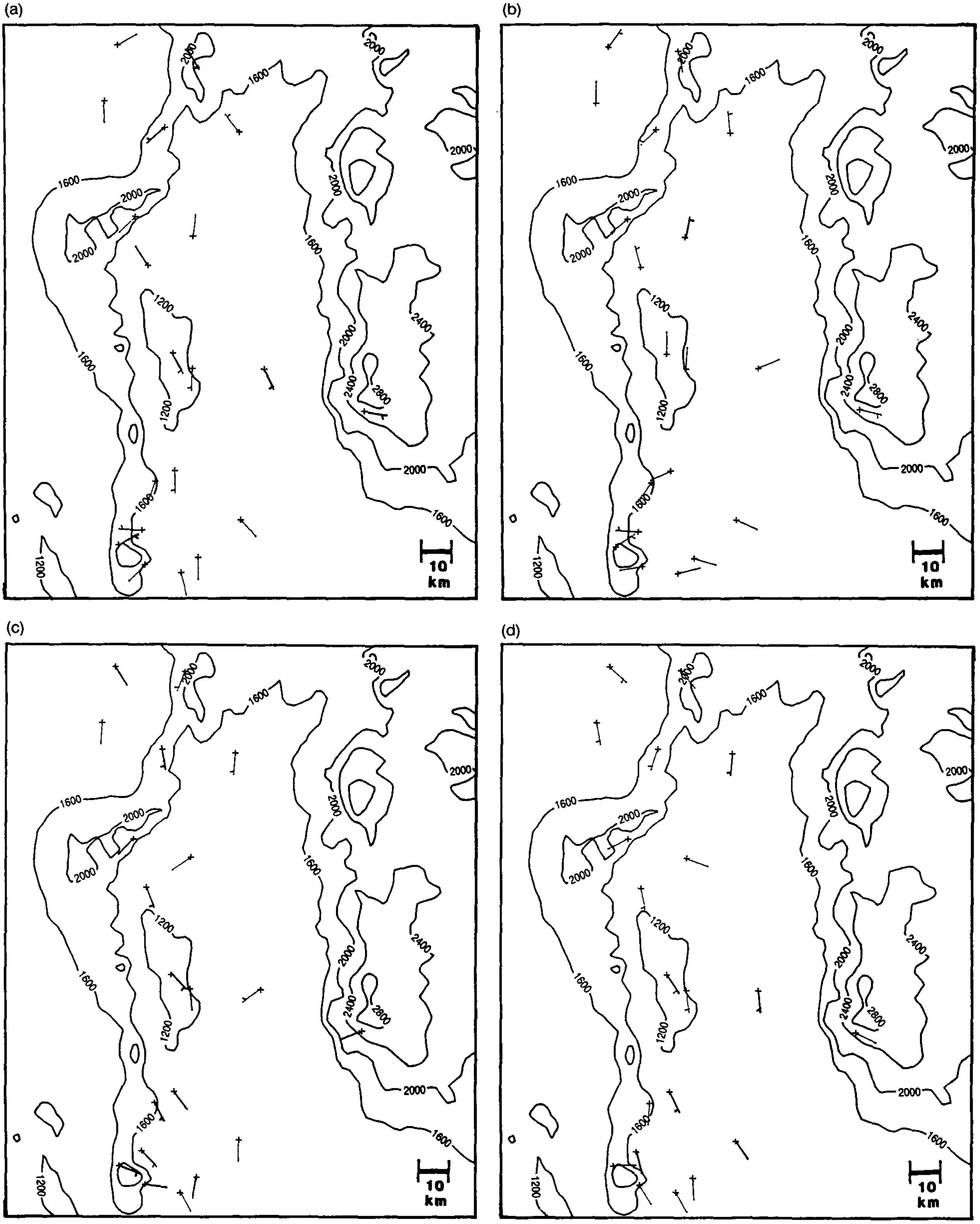

FIG. 4. Mean resultant winds for three summers of surface data at the stations shown in Fig. 3 for (a) 0000 LST, (b) 0600 LST, (c) 1200 LST, and (d) 1800 LST. The short barbs represent speeds of 3–7 kt (1.5–3.5 m s^{-1}). Lines without barbs represent speeds less than 3 kt (1.5 m s^{-1}).

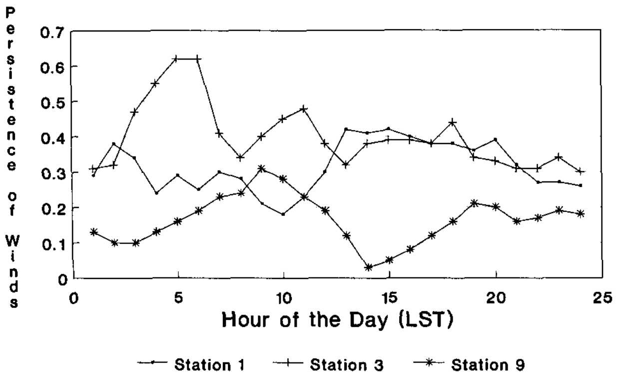

FIG. 5. Persistence of the surface winds as a function of time of day at three stations. Values for station 1 are given by dots, for station 3 by crosshairs, and for station 9 by asterisks.

pecially for the mountain stations. In the southern New Mexico region the convective activity near midnight is a likely cause of the lower nighttime persistence. Maximum persistence values in this region occur when convective activity is least likely. The high values of persistence at stations 1 and 3 at sunrise and sunset point to less variability in the time of transition for the mountain–valley regime than was noted by Toth and Johnson. Like the Colorado region, however, the lowland stations in New Mexico have relatively high values of persistence in the afternoon.

Therefore, the surface wind patterns show a classic mountain–valley circulation in this region. This regime could produce surface convergence patterns that would account for some of the precipitation maxima that occur. Except at C station, however, this circulation system would not account for the precipitation maxima seen near midnight at all the stations. A larger-scale forcing mechanism to account for this pattern may be seen in the upper-air data.

5. Larger-scale forcing

a. Background

The element of the precipitation patterns that remains unexplained by the mountain–valley circulation is the maximum or secondary maximum at or shortly after midnight. With the mountain–valley wind patterns, such a situation would seem likely for CSTN and WSNM near the center of the basin. It does not seem as reasonable for the stations located in the mountains. Since all the stations have this feature, however, it appears as though a larger-scale forcing mechanism could be involved.

Reiter and Tang (1984) showed that precipitation in the Great Basin region had its diurnal maximum at different times of day according to where the study site was relative to the center of the basin (Fig. 6). They argued that the diurnal variation of the plateau pressure systems was responsible for this pattern. In a companion paper, Tang and Reiter (1984) maintained that the development of the low-level jet over the southern plains of the United States would be encouraged by the pressure systems they investigated. If their argument is correct, however, one would expect low-level jets to be found around the entire periphery of the plateau. The direction of these winds would change depending on the location of their region with respect to the plateau.

The data of Reiter and Tang (1984) were taken from Wallace (1975), who used National Weather Service data. Thus, the only station considered near the south-central New Mexico area was El Paso, Texas, which according to harmonic analysis has a maximum at 2100 LST (Wallace 1975). Considering the distance of this region from the center of the Great Basin, one would expect a later maximum. Precipitation in El Paso may be affected by local mountain–valley influences in the same manner as the stations used in this study. If it has more than one maximum in its diurnal precipitation frequency, then the time of the primary maximum given by harmonic analysis would not be representative.

b. Sounding data

If there were some large-scale influence causing convergence and/or destabilization in this region near midnight, one might expect to see some evidence of it in the upper-air data. Soundings are not normally taken near midnight or in the afternoon in most parts of the United States, but White Sands Missile Range and Holloman Air Force Base take them occasionally and irregularly. Available data for these times of the day during the summer of 1988 were averaged and resultant winds were calculated. The night soundings (17 of them) were taken within 1 h of 0100 LST, and the day

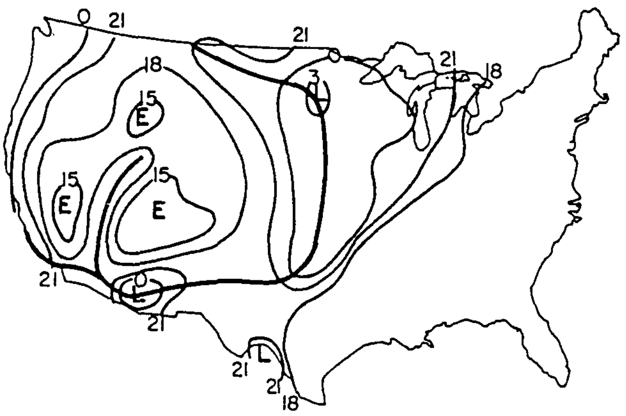

FIG. 6. Local time of day of the maximum occurrence of thunderstorm frequency: E—early; L—late (from Reiter and Tang 1984).

soundings (13 of them) within 1 h of 1400 LST. As would be expected, the daytime temperature sounding (not shown) is a little more unstable, but both of the nighttime and daytime temperature profiles are near dry adiabatic. Any destabilization of the column occurring near midnight cannot be detected by a radiosonde. A closer examination of the mean resultant winds (Fig. 7) reveals a maximum in the wind speed between 800 and 700 mb for the soundings taken near 0100 LST. This feature could be a low-level jet causing destabilization of the lower layers of the atmosphere. Although the maximum is not as strong as the low-level jet of the southern Great Plains, this features does warrant further investigation.

c. Profiler data

It can be argued that a rawinsonde is not the best tool for investigating the wind field in this region. Since the lapse rates are nearly dry adiabatic in the lower levels, the atmosphere would be quite turbulent and the relatively instantaneous measurements of a rawinsonde might not be representative of what was actually occurring. An alternative is to use hourly mean profiler data that would not favor individual turbulent eddies. The profiler would thus give a better picture of the mean flow. A profiler having the same specifications as those for the National Profiler Program (Weber et al. 1990) has been installed at White Sands Missile Range and has yielded reliable data for most of the summer of 1992.

The hodographs of the mean resultant winds at 0100 and 1300 LST for the summer of 1992 are presented in Fig. 8. A slight maximum shows up at 0100 LST, 2250 m above the earth's surface (AES). It is fairly high, but the height of the boundary layer in this region would approach 3000 m AES at times. The winds are from the southwest, which would be consistent with the presence of a low over the Great Basin. The major difference between the two time periods is in the winds at 3000 and 3750 m AES. At 1300 LST these winds are considerably stronger than they are at 0100 LST. These results would indicate that the source of the jet is not a speeding up of the winds at 2000 m AES but a slowing down of the winds just above it. Examination of data for individual days indicates considerable variability of this feature—it is there on some days and not on others.

To further examine this variability, persistence values can be calculated for the profiler observed winds (Fig. 9). For winds above the earth's surface these values are fairly low, with nighttime having a lower persistence than daytime. Again, these characteristics could be due to the area's subtropical location and its

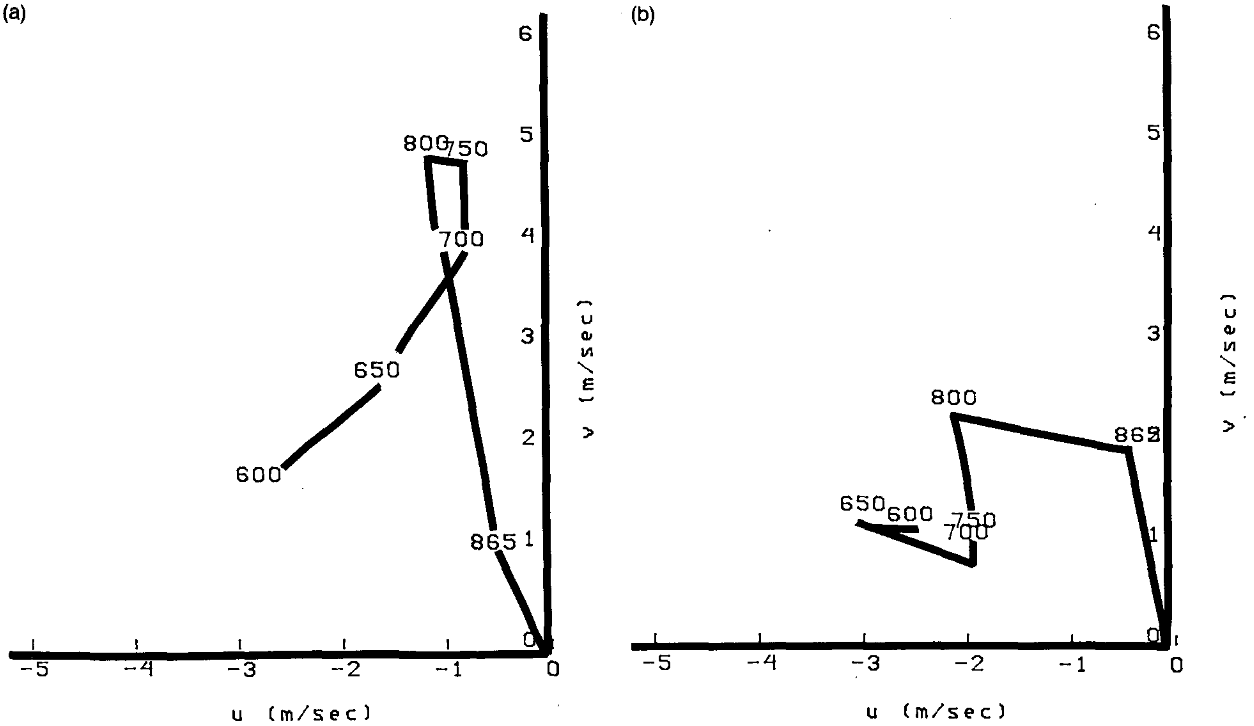

FIG. 7. Hodographs by pressure (mb) of mean resultant winds for soundings taken during the summer of 1988. The two times are approximately (a) 0100 LST and (b) 1400 LST.

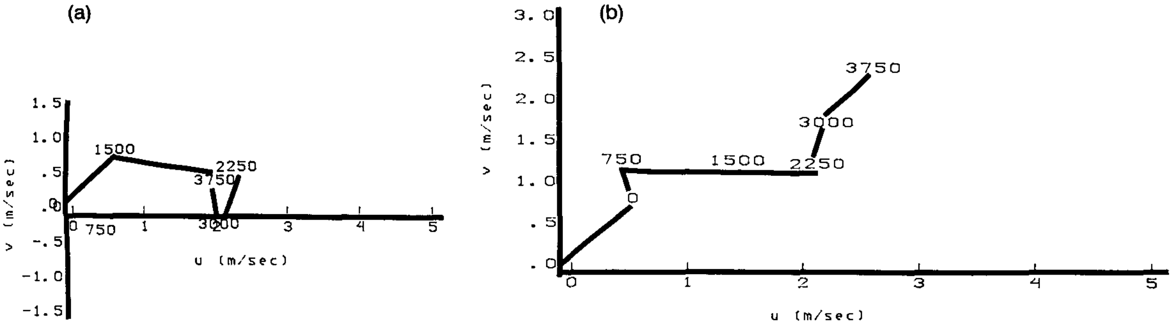

FIG. 8. Hodographs by height above the earth's surface (m) of mean resultant winds for wind profiler data taken during the summer of 1992. The two times are (a) 0100 LST and (b) 1300 LST.

near-midnight precipitation frequency, respectively. At night there is a persistence maximum at the 2250 m AES with lower values of persistence above it. Thus, the variable nature of the low-level jet feature comes as much or more so from the variable nature of the winds above it.

The decrease in speed of winds near 3000 m AES at night could be due to a decrease in the intensity of the boundary-layer cyclonic circulation at night over the plateau region. Southwesterly winds at the top of the boundary layer in the New Mexico area would decrease, perhaps becoming northeasterly at times. Winds below this level would not decrease as much, resulting in a wind maximum just above 2000 m AES.

The low-level jet in this region is not as intense or persistent as the one over the southern Great Plains (Bonner and Paegle 1968). The southern Great Plains jet is the result of multiple forcing mechanisms. In southern New Mexico only the forcing of the plateau circulation exists. The jet in this region is not strong enough to encourage the production of the severe thunderstorms for which the southern Great Plains is noted. It can, however, produce a maximum in precipitation frequency near midnight in this region.

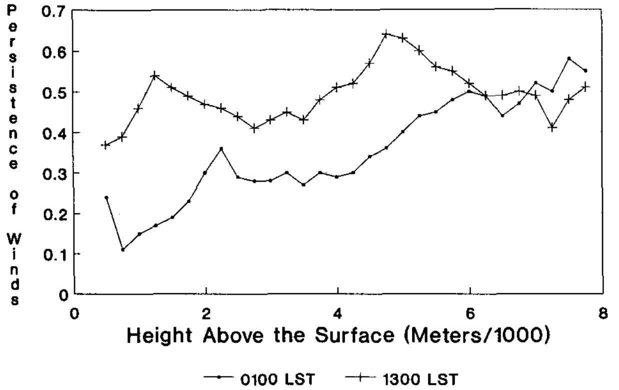

FIG. 9. Persistence of the wind profiler winds as a function of height above the earth's surface (m). The two times are 0100 LST, given by the dots, and 1300 LST, given by the crosshairs.

6. Conclusions

The diurnal precipitation distributions at stations in south-central New Mexico have been described with harmonic analysis and cumulant methods. Harmonic analysis reveals not only a strong diurnal cycle but also noticeably high amplitudes in the higher frequencies. The graphs of diurnal precipitation frequencies for stations with strong higher harmonics have only two maxima per day. Significant amplitudes for frequencies with higher harmonics result from asymmetric distribution of the two maxima.

Harmonic analysis, however, yields only relative amplitudes. How large the amplitude must be for the cycle to be considered important is a somewhat arbitrary decision. In addition, differences between stations can be determined only subjectively from this relative information.

As a statistical technique, cumulant methods provide a way to test the significance of a precipitation distribution compared to a uniform one. The entire precipitation distribution was significant for most stations. By subtracting harmonics from the dataset, these methods also can determine which harmonics are producing the statistically significant result. The higher harmonics were shown to be significant in several cases. A valuable use of cumulant methods is to tell whether there are significant differences between stations. Researchers can use this information to objectively divide regions into precipitation regimes. In the stations studied, cumulant methods identified a mountain regime and a valley regime but could not make further distinctions.

Cumulant methods and harmonic analysis are complementary techniques that are best used together. Data from south-central New Mexico are employed to show how both methods together can yield more information than either can alone. The cumulant methods confirm that a physical cause should be sought for the higher frequencies brought out by the harmonic analysis.

The importance of the diurnal cycle in this region is clear, and this conclusion is in line with that of earlier investigators (Wallace 1975; Easterling and Robinson 1985). Specific features of this area are the dramatic changes in precipitation distributions that take place over a small geographic area. From west to east there is first a station with two maxima—one in early evening, then a station with a single maximum, then a station with two maxima—one in late afternoon, and finally a station with two maxima almost 12 h apart. Stations differ as to when their maxima occur but all stations have one maximum near midnight.

The 1300 LST maximum in the mountains, the single 0100 LST maximum in the center of the valley, and the late afternoon and early evening maxima in the foothills suggest a mountain–valley forcing mechanism. Surface wind data confirm that convergence patterns due to mountain–valley circulation could encourage precipitation at these times. The fact that all stations have at least a secondary maximum near midnight suggests a large-scale forcing mechanism. Such a combination of forcing mechanisms would explain why a station in the center of the valley (CSTN) is the only one without important harmonics beyond the first one. Therefore, the semidiurnal precipitation patterns seen here are the result of forcing mechanisms on two different scales: one local and one regional.

Upper-air wind data give some indication that a low-level jet similar to but weaker than that observed over the southern Great Plains is present at times. The jet is not present at all times, and further work is needed to show whether it is directly related to precipitation. This jet could be generated by the plateau circulation system described by Reiter and Tang (1984). If so, one would expect such jets around the entire periphery of the Great Basin Plateau. Landin and Bosart (1989) found precipitation characteristics in California that they felt could be related to the presence of a low-level jet. It would be worthwhile to look for this jet in other areas around the plateau. A midnight maximum of precipitation in Phoenix described by Balling and Brazel (1987) is still unexplained but this region borders on the plateau as well.

This paper has focused on general characteristics of the precipitation patterns in south-central New Mexico and techniques for investigating them. It is hoped that in the future investigators may learn more about what is happening here and what it can tell them about what may be happening in other regions with complex terrain.

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APPENDIX

Cumulant Methods

Mielke and Berry (1987) developed cumulant methods for the analysis of r-way contingency tables and for determining the goodness-of-fit of frequency data. Therefore, they are similar to the chi-square test but they do not use squared differences. The observed frequencies in each of the $j_1 \ldots j_r$ cells of the r-way contingency table is denoted by $O_{j1} \ldots O_{jr}$. Each j_i may have values from 1 to n_i where $i = 1 \cdots r$. There are n_i marginal frequency totals, one for each of the r dimensions. The quantity $\langle i \rangle_j$ represents the jth of these n_i marginal frequency totals. Then

$$\sum_{j=1}^{n_i} \langle i \rangle_j = N,$$

where N is the total number of observations in the table. The statistic for cumulant methods is given by

$$S = \sum_{j_1=1}^{n_1} \cdots \sum_{j_r=1}^{n_r} \frac{O^{(2)}{}_{j_1,\ldots j_r}}{\prod_{i=1}^{r} \langle i \rangle_j},$$

where the superscript notation can be represented by

$$c^{(m)} = \prod_{i=1}^{m} (c + 1 - i).$$

Cumulant methods yield a probability that the frequency distribution given in the table could be due to chance. If this probability is low, a process other than chance is most likely causing the observed distribution. As a statistical technique, cumulant methods do not indicate what that cause might be.

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