NOAA Technical Memorandum NWS WR-156

THE EFFECTS OF TERRAIN DISTRIBUTION ON SUMMER THUNDERSTORM ACTIVITY AT RENO, NEVADA

Salt Lake City, Utah
July 1980

U.S. DEPARTMENT OF COMMERCE / National Oceanic and Atmospheric Administration / National Weather Service

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Christopher Dean Hill

National Weather Service Forecast Office
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This Technical Memorandum has been reviewed and is approved for publication by Scientific Services Division, Western Region.

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ABSTRACT. Synoptic and climatological evidence is presented which suggests that the frequent moderate summer afternoon winds east of the central Sierra Nevada are largely terrain induced, and that these winds inhibit convective activity over the Sierra. Discriminant analysis indicates these anomalous surface winds, plus terrain interaction with middle tropospheric winds, affect the distribution of thunderstorms around Reno, Nevada. This results in an area of much higher summer rainfall, and likely a greater frequency of flash flooding than for the region in general.

I. INTRODUCTION

Climatology suggests thunderstorms are not rare over western Nevada, but the frequency of occurrence is low enough to consider their impact minimal. Sakamoto (1972) found the mean number of annual thunderstorm days at Reno to be 13.50 with a standard deviation of 6.1. His study was based on the forty-year period 1931 to 1970.

A number of causes are attributed to this apparent low incidence of thunderstorms. Trewartha (1966) characterizes the area from the crests of the Sierra Nevada and Cascade Mountains eastward to the Rocky Mountains as a transition zone between the strong winter precipitation maximum on the Pacific coast and the marked summer maximum of the plains to the east. He further suggests western Nevada lies in a secondary north-south transition zone which results in a primary winter precipitation maximum and a secondary spring maxima. The bi-modal distribution is attributed to the movement of the East Pacific High from its central location near 34 degrees north latitude in May and June to about 40 degrees north in July. While the anticyclone is in its southern location, Pacific disturbances are able to reach western Nevada. When the high pressure cell shifts abruptly northward in July, Nevada comes under increasing anticyclonic control. The associated subsidence results in summer being the driest season.

Houghton et al (1975) found a similar distribution with mean annual precipitation curves showing bimodal winter-spring maxima at most Nevada sites. Houghton also suggests that along with the Eastern Pacific High, the cold California Current acts to preclude the Pacific as a moisture source for summer convective showers. As a result, Nevada depends on moisture from the Gulf of Mexico, the Gulf of California and the tropical Pacific for summer rains.

The above considerations appear to explain adequately the general processes governing summer convection over Nevada. This study attempts to show that smaller scale orographic features also play a major role in the resultant thunderstorm climatology of the area. Evidence will be presented which suggests the frequent gusty summer afternoon surface winds just east of the Sierra Nevada are often terrain-induced. Using a ten-year data base, statistical tests will be used to find relationships between convective days and various synoptic flow patterns plus the occurrence or non-occurrence of these terrain-induced surface winds. The results of the statistical tests will be used to classify each day based on possible mechanisms which either produce or inhibit convection. A discriminant function is developed for air-mass type days. This function will be applied to other types of days to show that certain synoptic flow patterns produce forced convection in specific locations around Reno. Evidence will be presented which suggests that one such preferred area appears to have a higher frequency of summer flash flood events than western Nevada in general.

II. POSSIBLE SIGNIFICANT TERRAIN FEATURES

On a synoptic scale, Nevada is a plateau characterized by high valleys and numerous north-south oriented mountain ranges. Major valley floors in the western portion of the state are near 1200-m above sea level (ASL) while valley floors in the eastern portion of Nevada are closer to 1800-m ASL. Along the western border of the plateau the Sierra Nevada rise abruptly to a crest which averages near 3000-m ASL. The western slopes of the Sierra Nevada fall off more gradually to near sea level in the Great Central Valley of California. Farther to the west, the Pacific coastline interacts with the southward flowing California Current to produce cold upwelling. This effectively places a stable cap on a potential moisture source.

East of the Sierra Front Range a number of smaller scale terrain features appear significant. To the north of Reno there are no major valleys or mountain ranges. However, general elevated terrain does extend westward across northern California to the coast. As shown in Figure 1, the area to the east northeast of Reno is characterized by the Carson Sink, a large alkali flat which lies between Fallon and Lovelock. To the south of Reno, the fairly large Carson Valley lies just east of the very steep east slope of the Sierra Nevada. To the east and southeast of Reno, Figure 1 shows the Pinenut Range, a fairly broad area of elevated terrain. These mountains may be large enough to interact with middle tropospheric winds and also possibly act as a local elevated heat source.

That this area southeast of Reno may play a significant role in the climatology of summer convective activity over western Nevada is suggested by the results of a study of the Sacramento California weather radar climatology by Pappas and Veliquette (1970). The study showed that in June, the maximum precipitation echo frequency is to the west of the crest of the Sierra Nevada. This is likely caused by upslope precipitation events due to Pacific disturbances. In July, however, the maximum echo frequency abruptly shifts east of the Sierra crest. The maximum hourly precipitation echo frequency remains over the general area southeast of Reno through August and September as well. This shift has even greater significance if detection capabilities of the radar are considered. Pappas (1967) shows that, due to terrain blocking, convection must reach significant heights east of the Sierra crest before being detected by the Sacramento radar. It appears from the radar climatology that the frequency of summer thunderstorms is much greater over the Pinenut Mountains than the nearby higher Sierra Nevada.

III. SUMMER AFTERNOON SURFACE WINDS

Windy afternoons are perhaps the most interesting climatological feature of the valleys just east of the steep central Sierra Nevada. The first documentation of this phenomenom may have come from Samuel Clemmens, who under the pen name Mark Twain (1871), typified a mid nineteenth century August day in Carson City:

> This was all we saw that day, for it was two o'clock now, and according to custom the daily "Washoe Zephyr" set in; a soaring dust drift about the size of the United States set up edgewise came with it, and the capitol of Nevada Territory disappeared from view . . . The "Washoe

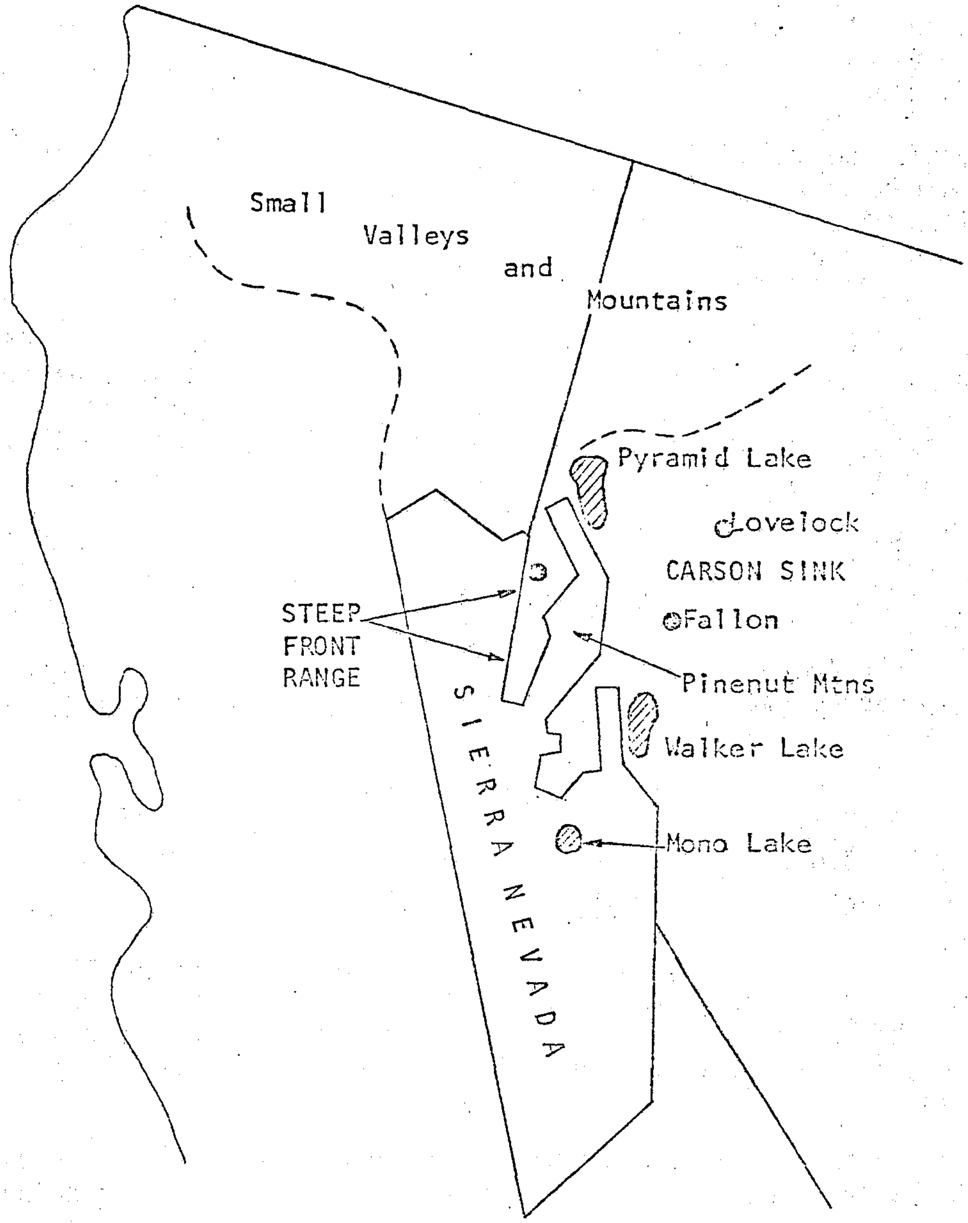

Figure 1 Significant orographic features around Reno.

> Zephyr" (Washoe is a pet nickname for Nevada) is a peculiarly Scriptural wind, in that no man knoweth "whence it cometh". That is to say, where it originates. It comes right over the mountains from the West, but when one crosses the ridge he does not find any of it on the other side! It probably is manufactured on the mountaintop for the occasion, and starts from there. It is a pretty regular wind, in the summer-time. Its office hours are from two in the afternoon, til two the next morning . . .

Little wind information is available for this area, but the existing climatological data suggests the "Washoe Zephyr" does occur from the Sierra crest eastward, and that it is not produced by synoptic scale forces.

The decennial census of the United States Climate, for Reno, shows that moderate surface winds dominate summer afternoons. The data indicates that the majority of the time winds are very light during the night, usually increase to the 2 to 5 m/s range around noon, local time. On about fifty percent of summer afternoons winds greater than 5 m/s develop.

Figure 2, a surface wind frequency diagram for July at Reno, was prepared from the same data source. This figure indicates that the moderate afternoon winds are predominately westerly. Table 1 based on 00 GMT (1600 LST) observations for the ten years (1969-1978) of data used in this study, helps to illustrate further the afternoon wind regime at Reno during the summer months.

Table 1. 00 GMT average Reno surface wind speed, resultant winds, and persistence of the wind for summer months based on ten years of data.

Month	Average Speed (m/s)	Resultant Direction	Resultant Speed (m/s)	Persistence
June	6.1	280	3.9	0.64
July	6.1	280	4.6	0.75
August	5.5	280	3.2	0.58
September	5.1	300	2.3	0.45

Table 1 shows that the average late afternoon wind is greater than 5 m/s for all summer months and the resultant direction is westerly. Note also the relatively high persistence of the wind, especially during June and July. The persistence is defined as the resultant wind speed divided by the average speed of the wind.

From mean sea-level pressure charts these frequent late afternoon west winds appear to be anomalous. The charts indicate a gradual strengthening and westward displacement from the Sierra Nevada of the sea-level thermal trough during the summer. The general increase in the pressure gradient between the California interior and western Nevada through the summer is apparently reflected in Table 1. Afternoon west winds at Reno are weaker and occur with somewhat less frequency as the sea-level thermal trough strengthens to the west.

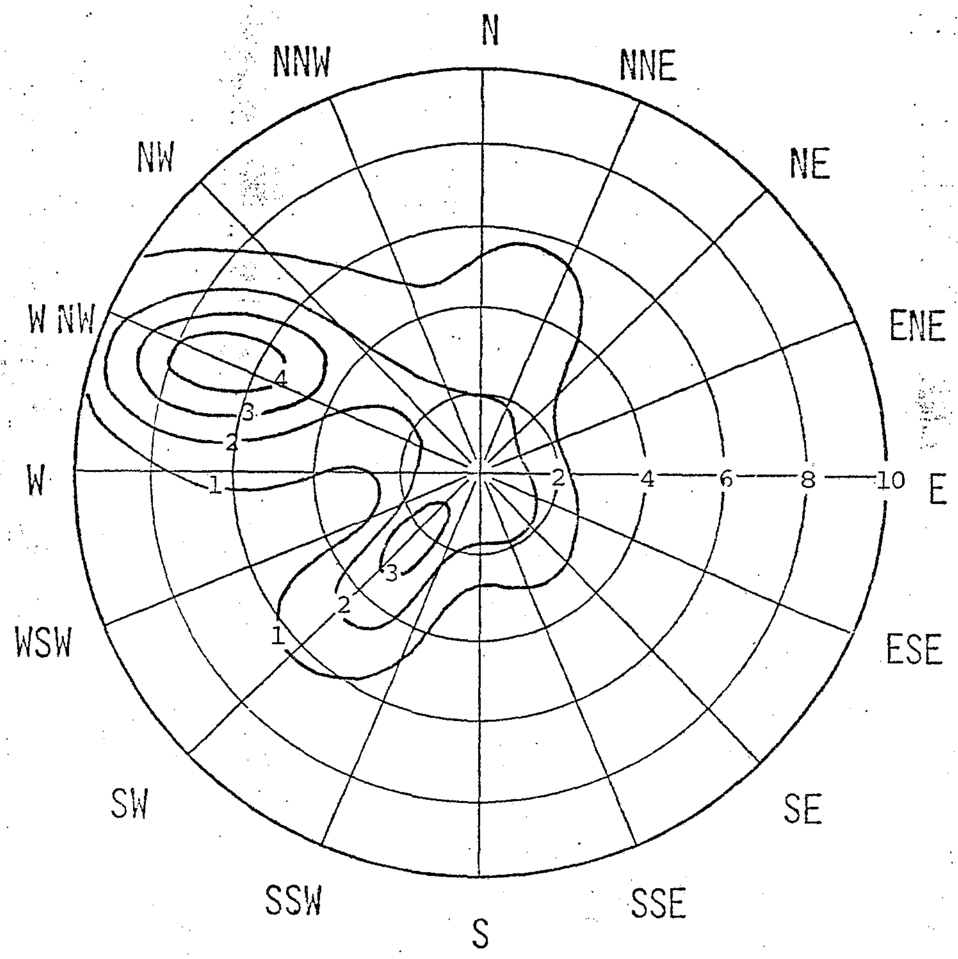

Figure 2 Wind frequency diagram for July at Reno, based on 3720 observations and 16 compass points. Speeds are in meters per second. Isopleths are percent of total observations.

However, this apparent general relationship between the character of the afternoon winds at Reno and sea-level pressure patterns may have no real physical basis. Serious shortcomings in the ability of sea-level pressure charts to delineate pressure patterns adequately over the plateau region of the western United States have long been recognized. (Little and Vernon, 1934).

Bullock (1978), gives a comprehensive discussion of the problems involved with sea-level pressure charts over the plateau. He also presents evidence which indicates that detailed charts for the 850-mb pressure level produced by reduction of hourly surface observations on the plateau may provide a much better estimate of pressure patterns near the mean surface elevation of the plateau.

From statistics supplies by Crutcher (1959), a theoretical mean 850-mb wind distribution for the summer season at Reno was computed. The distribution, based on five years of data is shown in Figure 3. The choice on an elliptical rather than circular distribution was accepted at the five percent level of significance based on Mauchley's test (1950). Comparison of Figure 2 with Figure 3 shows that the surface wind distribution at Reno during the summer months bears a strong resemblance to a theoretical 850-mb wind distribution.

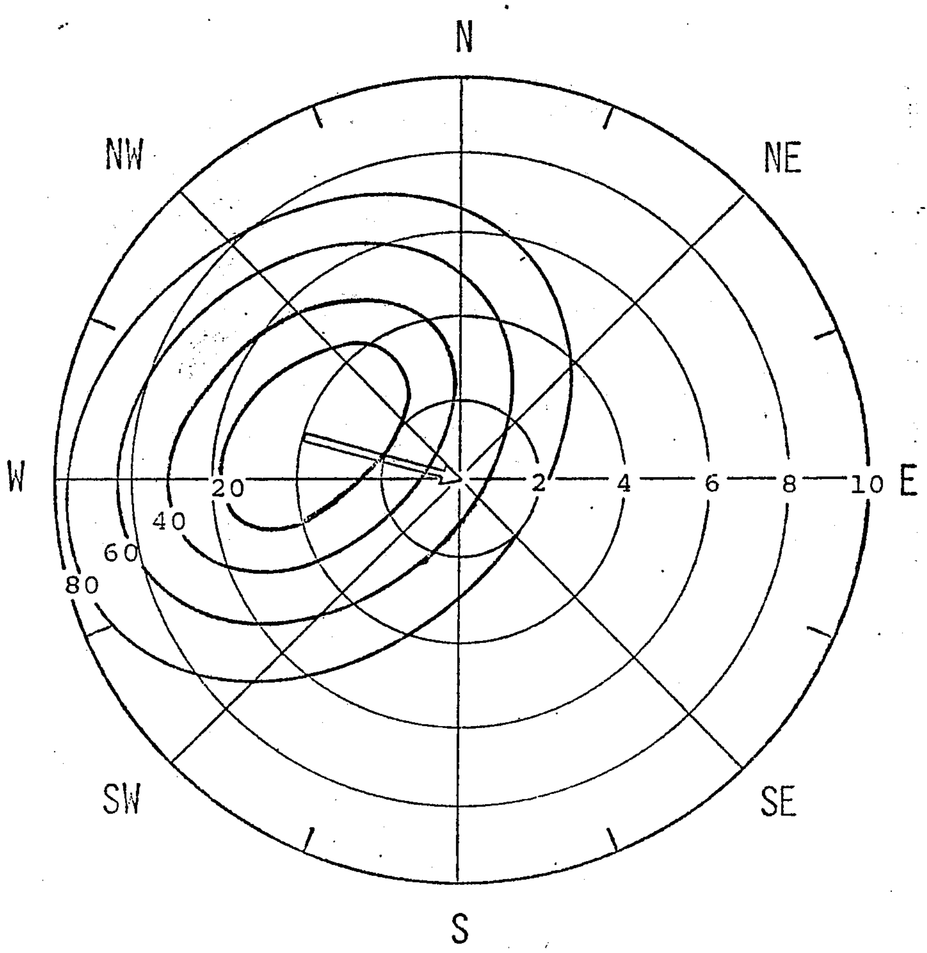

Figure 3 Theoretical distribution of 850-mb winds at Reno during the summer season (in meters per second). Arrow denotes the resultant wind. Ellipses are labeled with the percent of wind vectors which are expected to originate within each enclosed area.

Mean 850-mb height charts for 1200 GMT and 00 GMT based on ten years of data (Korte, 1971), reveal additional information. The charts show that for the summer months, a low pressure cell is generally found at 850 mb over the plateau during the afternoon (00GMT). The analyses indicate the mean 850-mb geostrophic wind at Reno on summer afternoons is northerly at about 6 m/s. Since the 850-mb surface is generally within 200 m of the valley floor at Reno during the summer, the actual wind at 850 mb (and the surface) will differ markedly from the geostrophic due to the effects of friction. If an ageostrophic magnitude of ½ to 2/3 the geostrophic magnitude (Young, 1973) is assumed, the mean charts suggest mean 850-mb wind speed of about 3 to 4 m/s. The effects of friction will also produce a mean wind with a more westerly direction.

The charts also indicate significantly different diurnal changes in the height of the 850-mb level over California compared to the Nevada plateau. Between 1200 GMT to 00 GMT during June there are mean daily height rises of about 10 m over northern Nevada, and height rises near 15 m over northern California. During July and August there are mean diurnal height falls on the order of 5 to 10 m over the plateau, and rises of 5 to 10 m over California. In September, there are again 5-to 10-m diurnal falls in the height of the 850-mb surface over Nevada, but also height falls of about 5 m over the interior of California. Thus, the height-change analyses indicate summer afternoon mean isallobaric (or more precisely isallohypse) gradients between the plateau and the 850-mb level over California on the order of 5 m/12 hours during June and September and 10 to 20 m/12 hours during July and August, over a distance of around 200 km or less. These patterns are largely a result of strong daytime heating of the plateau.

The mean 850-mb charts were computed by interpolation of radiosonde data to grid points using a Cressman (1959) analysis. As a result, the depiction of a low center over north central Nevada near the radiosonde station of Winnemucca may be somewhat misleading. Figure 4, showing July hourly mean station-pressures at Reno and Winnemucca, indicates a very weak mean surface-pressure gradient over the northern plateau area at 00 GMT (1600 LST). Further, it is likely that since the plateau, serving as an elevated heat source, is a major cause of the diurnal pressure fall, the isallobaric gradient is concentrated (and oriented east-west) on the western edge of the plateau.

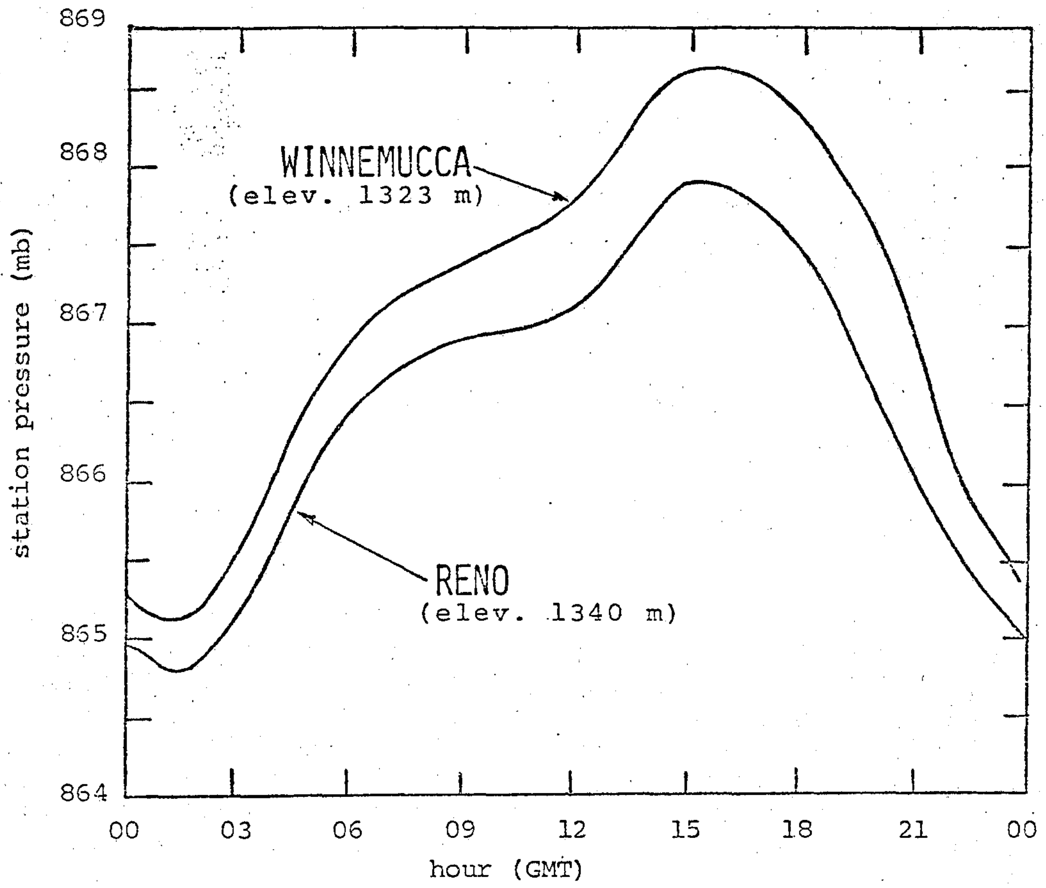

Figure 4 Mean July hourly station pressures at Reno and Winnemucca, in millibars.

The equation of motion for hydrostatic frictionless flow may be written in the form:

$$\frac{\partial \vec{V}}{\partial t} + (\vec{V}\cdot\nabla)\vec{V} + \omega\frac{\partial \vec{V}}{\partial p} + f\vec{k}\times\vec{V} = -\nabla\Phi . \qquad (1)$$

where f is the Coriolis parameter, and $\nabla\Phi$ the total gradient of geopotential, gz.

If vertical advections are ignored, the quasi-geostrophic form of (1) may be expressed (Young, 1977) as:

$$\underset{(A)}{\frac{\partial \vec{V}_g}{\partial t}} + \underset{(B)}{(\vec{V}_g\cdot\nabla)\vec{V}_g} + \underset{(C)}{f\vec{k}\times\vec{V}} = -\nabla\Phi = \underset{(D)}{f\vec{k}\times\vec{V}_g} . \qquad (2)$$

From (2), the total wind, $\vec{V}$, may be thought of as arising from D, the geostrophic wind; B. the ageostrophic inertial correction; and A, the ageostrophic isallobaric wind. Note that in (2) $\nabla\Phi$ is now the horizontal gradient of geopotential. Using the beta approximation $f = f(y) - f_o + \beta(y-y_o)$ where f_o is the local Coriolis parameter, and neglecting products of small terms, (2) may be approximated by:

$$\frac{\partial \vec{V}_g}{\partial t} + (\vec{V}_g\cdot\nabla)\vec{V}_g + \beta(y-y_o)\vec{k}\times\vec{V}_g = -f_o\vec{k}\times\vec{V}_{ag} . \qquad (3)$$

Neglecting the inertial term for the moment, it can be seen that the quasi-geostrophic isallobaric wind is:

$$\vec{V}_{ag} = -\frac{1}{f_o}\frac{\partial \vec{V}_g}{\partial t}\times\vec{k} . \qquad (4)$$

Since $\vec{V}_g = \frac{1}{f_o}\vec{k}\times\nabla\Phi$, (4) may be expressed as:

$$\vec{V}_{ag} = \vec{V}_{is} = -\frac{1}{f_o^2}\nabla\frac{\partial\Phi}{\partial t} . \qquad (5)$$

Using a very conservative estimate of a 10 m/12-hour isallobaric gradient over 100 km gives an ageostrophic west wind component of about 3 m/s. Note, however, Figure 4 shows that the actual pressure fall over the plateau does not normally begin until about 1600 GMT (0800 LST) and also that in the mean, pressures are still falling at 00 GMT. Thus, more realistic values of 10 m/8 hours over 50 km produce an ageostrophic west-wind component on the order of 8 m/s. When frictional effects are again considered, this terrain-induced ageostrophic west-wind component is about as strong as the mean frictionally adjusted geostrophic wind component.

Averaged surface observation data at Reno for July give a resultant 00 GMT wind of 280 degrees at 5 m/s, very close to the total wind (frictionally adjusted geostrophic and ageostrophic isallobaric components) suggested by the above analysis. If the surface-pressure gradient on the Nevada plateau is relatively weak during the late afternoon as suggested by Figure 4, and if the isallobaric gradient is concentrated near the western edge of the plateau, then the ageostrophic component would be strongest just east of the Sierra Nevada. This may explain why strong afternoon west winds are not observed over the interior of Nevada nearly as frequently as in the valleys just east of the Sierra Nevada.

Upper wind statistics from Crutcher and Halligan (1967), and other similar investigations, indicate the 700-mb resultant wind over the Reno area during the summer season to be about 240 degrees at 3 m/s. Thus, while it appears that neither mean sea-level pressure gradients, nor downward mixing of momentum for the middle troposphere adequately explain the high frequency of moderate afternoon winds just east of the Sierra Nevada, mean total 850-mb winds do provide a plausible explanation. In addition, terrain features on a meso-scale may also be a major factor in shaping the observed diurnal character of surface winds in the valleys just to the east of the Sierra Nevada. This terrain influence appears to be a more complex phenomenon than the simple mountain-valley wind regime of Defant (1949).

Since the early work on terrain induced winds by Wagner (1938), other investigators have suggested additional factors may produce wind patterns which differ from the simple upslope day-time and downslope nighttime winds of the mountain-valley model. Gleeson (1951) found that differential heating of mountain slopes through the day produces a cross-valley wind component. In his solution which included friction, inertia, and the Coriolis force, he noted that both the orientation of the valley and slope inclinations were significant. In particular, Gleeson's results suggested the more north-south the orientation of the valley, the more westerly would be the cross-valley wind component, and the earlier it would develop. He also found that the steeper the slopes, the stronger the cross-valley wind; however, the strongest winds would occur when the slopes of the mountains on the east side of the valley are less than on the west side. From these considerations, it appears the valleys just east of the Sierra crest are orographically favorable to maximize cross-valley winds produced by daily differential solar heating.

Figure 2, the wind frequency diagram for July at Reno, indicates agreement with many of the theoretical characteristics suggested by Gleeson. Figure 16, from Gleeson, shows that light southeast winds are expected during the morning hours, with winds veering to stronger northwesterly during the late afternoon. The hodograph in Figure 5 suggests that east winds would be the least frequent and west winds the second least frequent in terms of duration per day. Southwest winds would occur more frequently than west winds but northwest winds should exhibit both the strongest speeds and the greatest duration each day in a north-south oriented valley. These basic characteristics are found in Figure 2.

Schroeder (1961) found a phenomenon apparently similar to the Washoe Zephyr on the east side of the California Coast Range and also in the southern Sierra Nevada. In a detailed study, which included meso-scale temperature and wind observations, but unfortunately no detailed meso-scale pressure data, Schroeder suggested that:

1. The mountain range acts as an elevated heat source during the day.
2. The warm belt of higher potential temperature that forms over the range during the forenoon moves progressively eastward during the

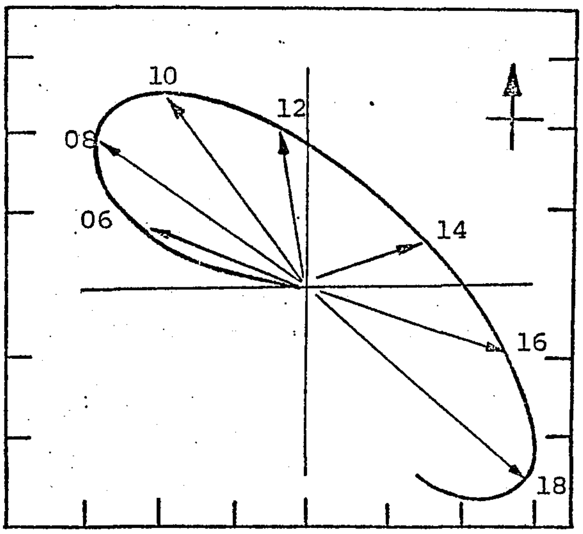

Figure 5 Time (LST) hodograph of theoretical cross-valley surface winds in a north-south oriented valley during midsummer.

afternoon, apparently in response to the sea breeze or some other more dominant circulation such as that caused by the pressure difference between the East Pacific High and the thermal trough in the interior.

3. Alternately the west wind may be caused by the heat source of mountains farther to the east (as suggested by Edinger, 1959).

Thus, Schroeder's study also suggests that the distribution of terrain around Reno would tend to maximize the production of west winds at the surface due to the effects of differential heating.

Data is not available to sufficiently determine the complete cause of the "Washoe Zephyr" phenomenon but it appears that a number of factors ranging from synoptic scale terrain-induced circulations to meso-scale differential heating enters into the production of these winds. On some days, the west winds can be produced by surface-pressure gradients or downward mixing of momentum from aloft, but even on these occasions the distribution of terrain features likely modifies the synoptic scale winds.

Additional factors which may be of significance to this study are apparent from the sparse data that is available. Unpublished observations of Fallon Naval Air Station east of Reno suggest a preference for a westerly component of summer afternoon surface winds. However, the winds are generally much weaker than those which occur in the valleys just east of the Sierra Nevada. The weaker winds are consistent with the concept of generally weak surface-pressure gradients over the plateau on summer afternoons, and the isallobaric gradient concentrated near the western edge of the plateau. Climatological data for Auburn, California located on the west slope of the Sierra Nevada at an elevation of 400 m shows that on an annual basis, winds exceed 5 m/s only ten percent of the time. The date indicates that east winds are most common. This is likely due to the mean location of the summer sea-level thermal trough in the Sacramento Valley just to the west. The light wind speeds may result from the counteracting influence of the upslope component of the wind produced by solar heating.

Thus, available climatological data suggests the "Washoe Zephyr" quite likely is "manufactured on the mountaintop for the occasion."

IV. RELATIONSHIP BETWEEN WINDS AND CUMULONIMBUS OCCURRENCE

Ten years (1969-1978) of data for the summer months June through September were used to test if synoptic scale data could reveal any relationships between winds at Reno and cumulonimbus days in the area. Information was interpolated from National Meteorological Center analyses (Cressman, 1959) to Reno. Full information for some days was unavailable, resulting in a data base of 1132 days. Original surface observations at Reno which contain such information as the quadrant of development of cumulonimbus clouds were also utilized.

On an annual basis, the ten-year period chosen showed a total of 135 thunderstorm days at Reno, suggesting this short period was similar to the longer and possibly statistically stable forty-year sample used by Sakamoto (1972). A summary of convective days at Reno for the summer months during the ten-year period is given in Table 2. The data indicates Reno averages about 10.5 thunderstorms a summer, and an additional 30 days when cumulonimbus clouds are observed in the area. Climatological data indicates that extensive cloud cover which might possibly make cumulonimbus clouds indiscernable occurs only about 20 percent of the time on summer afternoons. Thus, cumulonimbus occurrence is almost always observable and Table 2 is likely quite representative of the actual frequency of occurrence.

Table 2 Thunderstorm and cumulonimbus-day frequencies observed at Reno, Nevada. Computed yearly summer season standard deviation of total occurrences for each category are listed in the last row.

	Thunderstorm Days					Cumulonimbus Days					Total Convective Days				
	Jun	Jul	Aug	Sep	Total	Jun	Jul	Aug	Sep	Total	Jun	Jul	Aug	Sep	Total
1969	11	2	1	0	14	6	16	1	1	24	17	18	2	1	38
1970	5	3	1	0	9	12	12	6	1	31	17	15	7	1	40
1971	0	8	3	0	11	4	8	16	0	28	4	16	19	0	39
1972	2	2	6	4	14	18	10	6	4	38	20	12	12	8	52
1973	2	5	3	0	10	5	10	6	0	21	7	15	9	0	31
1974	1	2	2	0	5	10	14	9	4	37	11	16	11	4	42
1975	2	0	5	3	10	10	14	6	8	38	12	14	11	11	48
1976	0	5	3	3	11	5	10	4	10	29	5	15	7	13	40
1977	9	3	3	0	15	11	4	6	3	24	20	7	9	3	39
1978	1	2	4	0	7	6	11	7	4	28	7	13	11	4	35
Total	33	32	31	10	106	87	109	67	35	298	120	141	98	45	404
Std Dev.					3.0					5.8					5.7

The definite diurnal pattern often exhibited by the surface winds at Reno does not appear conducive to using resultant winds as a factor in delineating Zephyr from non-Zephyr days. Thus, it was arbitrarily decided that if surface observations at Reno indicated winds with a westerly component in excess of 5 m/s developed and persisted through the late afternoon, the day would be considered a Zephyr day. Since the time of onset of the Zephyr is quite variable, and sometimes does not commence until after 00 GMT, the above screening technique was found to work much better than simply choosing a specific hour as the criteria for labeling a day as a Zephyr or non-Zephyr day.

Table 3 is a contingency table from the ten-year sample showing the relationship between cumulonimbus and west wind occurrences. Tested against a no-relation table (the values in parentheses), the data gives a chi-square value of 8.92.

Table 3 Observed joint frequency distribution between cumulonimbus and Zephyr days based on ten years of summer data. Computed no-relation expected values are shown in parentheses.

Event	Zephyr day	Non-Zephyr day	Total
Cumulonimbus day	166 (190)	235 (211)	401
Non-cumulonimbus day	371 (347)	360 (384)	731
Total	537	595	1132

Using one degree of freedom and an apriori choosing the 0.1 percent limit, Thompson (1941) indicates the null hypothesis, that no relation exists, cannot be rejected. The limit chosen may appear excessively stringent. However, the computed tetrachoric correlation coefficient of -0.15 also suggests that no significant relationship exists.

Figure 6 is a cumulative frequency diagram of the time of the first report of cumulonimbus clouds, based on Reno surface observations. The figure illustrates the marked diurnal nature of convection in the area. Cumulonimbus development begins about 90 percent of the time between the hours of 1800 GMT and 0600 GMT. To test if synoptic scale upper-air flow patterns exhibit any relationship to convective development, geostrophic winds from 00 GMT (1600 LST) National Meteorological Center 700-mb analyses were computed at Reno. There is no suggestion here that these were the actual winds over the area. The derived winds serve only as a synoptic signature of the upper flow pattern near the time of onset of cumulonimbus activity.

For the test, a meridional or zonal component of the geostrophic wind greater than 2.5 m/s was chosen to separate days with a significant upper flow pattern from days when the synoptic pattern was characterized by light and variable winds aloft.

A joint frequency distribution of the relationships between meridional wind components and the occurrence of cumulonimbus days reveals that significant convection occurs on about 40 percent of the days with a synoptic signature of southerly flow. This is only slightly more frequent than the average rate of occurrence of 35 percent for all summer days indicated in Table 3. When tested

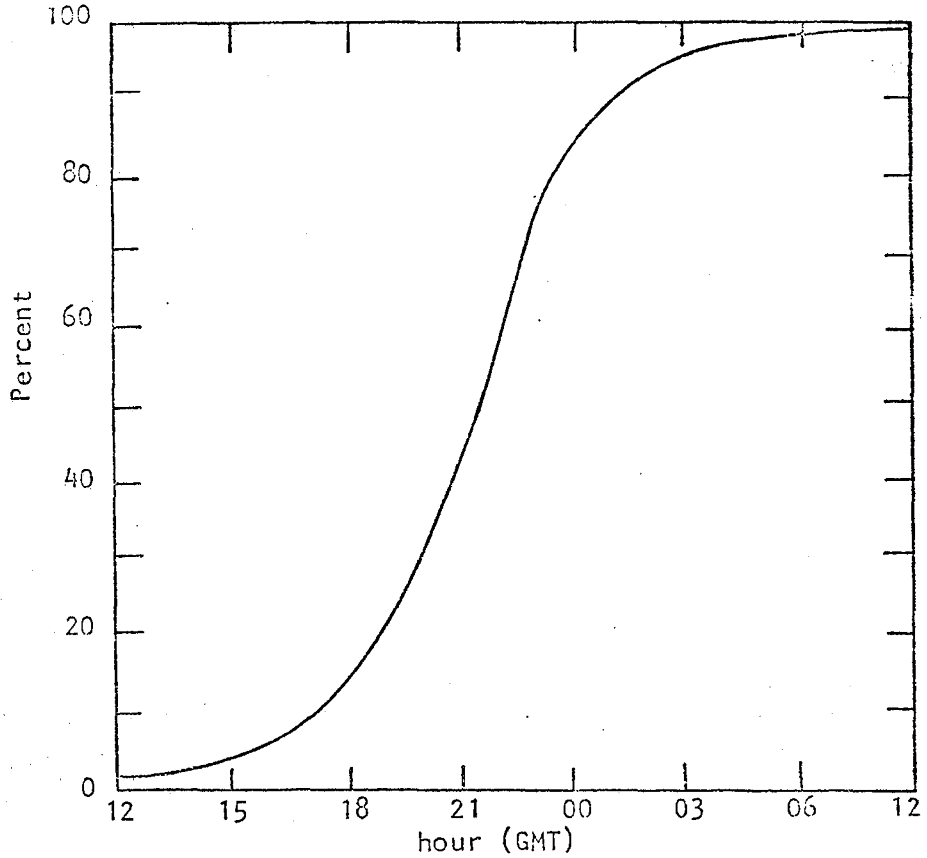

Figure 6 Cumulative frequency distribution of time of first report of cumulonimbus clouds at Reno.

against computed no-relation values, and if the 0.1 percent significance level is again chosen the computed chi-square value of 10.7 with two degrees of freedom suggests that the null hypothesis of no relation cannot be rejected.

A joint frequency distribution between cumulonimbus occurrence and zonal wind components suggests a significant west wind at 700 mb may be a strong inhibitor of thunderstorm development. This is consistent with previously cited concepts regarding the influence of the East Pacific High. The data also suggest that east winds, while infrequent, are very favorable for cumulonimbus development in the area around Reno. When compared to computed no-relation values, the computed chi-square value from the data is 162.2. With two degrees of freedom, the null hypothesis of no relation can be rejected. There is a clear relationship between zonal flow and the occurrence of thunderstorms in the area around Reno. A further breakdown of the data for zonal cases based on the occurrence or non-occurrence of Zephyr days is probably not advisable due to the strong likelihood of an auto-correlation between west winds aloft and west surface winds. However, it may be possible to gain additional information by dividing meridional signatures into Zephyr and non-Zephyr categories.

When meridional flow on non-Zephyr days only is compared to a non-relation table, a chi-square value of 14.5 is obtained. Based on two degrees of freedom and the 0.1 percent limit, the null hypothesis of no relationship between the meridional 700-mb wind component and the occurrence of significant convection on non-Zephyr days can be rejected.

The rejection of the null hypothesis of no relation is not to say however, that south winds aloft are correlated with cumulonimbus occurrence on non-Zephyr days. In fact, it appears from the data that the lack of cumulonimbus occurrence with a possibly significant north wind component at 700 mb may be the largest contributor to the rejection of the null hypothesis.

A test based on meridional flow versus cumulonimbus occurrence only on west surface-wind days yields a chi-square value of 5.0 when compared to a no relation table. This is not even significant at the five percent level. Thus, it appears there may be no relationship between meridional flow and the occcurrence or non-occurrence of significant convection around Reno on Zephyr days.

Summarizing to this point, a statistical analysis suggests:

1. There appears to be no relationship between the occurrence or non -occurrence of cumulonimbus clouds and the occurrence of Zephyr days.
2. For a signature of a geostrophic wind at 700 mb with a zonal component greater than 2.5 m/s there exist relationships in which west winds aloft are negatively correlated and east winds aloft are strongly positively correlated with cumulonimbus occurrence.
3. For meridional flow there does not appear to be a relationship between synoptic signatures and the occurrence of significant convection that can be accepted at better than the one percent level for all cases and the five percent level on Zephyr days.
4. There may, however, be a relationship that can be accepted at better than the one percent level for non-Zephyr days and meridional flow.

V. QUADRANT OF CUMULONIMBUS DEVELOPMENT VERSUS SYNOPTIC SIGNATURES

The tests in the previous section indicate west winds aloft are negatively correlated with cumulonimbus occurrence in the Reno area while east winds are positively correlated. For meridional flow, results of the tests were inconclusive. In an attempt to find possible relationships with meridional flow, the quadrant from Reno in which cumulonimbus clouds first developed was compared to flow pattern signatures as defined by the 700 mb geostrophic wind. The quadrant of initial development was used since once cumulonimbus activity begins, a mesoscale environment is generally created which may produce phenomena not representative of synoptic scale patterns. The area where the first cumulonimbus cloud forms is much more likely to be related to a synoptic signature.

Table 4 depicts the joint probability distribution of quadrant (from Reno) of the first reported cumulonimbus cloud versus meridional wind components. It should be noted that on some occasions the first report fell on or across the class limits chosen. Thus, the totals in Table 4 add to more than those presented in Table 3. Versus a no-relation table, a chi-square value of 51.46 comes from

Table 4. With six degrees of freedom, Table 5 indicates this is significant at better than the 0.1 percent level and the null hypothesis of no relationship between meridional flow and the quadrant of onset of cumulonimbus activity can be rejected.

Table 4 Quadrant from Reno in which the first cumulonimbus was reported versus the coincident 700 mb geostrophic meridional wind component. No-relation values are shown in parentheses.

Quadrant	(south wind)		(light wind)		(north wind)		Total
north thru east	25	(31)	19	(25)	21	(9)	65
east thru south	120	(91)	59	(75)	13	(26)	192
south thru west	50	(70)	79	(58)	19	(20)	148
west thru north	22	(25)	23	(22)	9	(7)	54
Total	217		180		62		459

Table 5, based only on non-Zephyr days with meridional flow provides additional information. The apparent preferred quadrant of east through south in Table 4 shifts to south through west on non-Zephyr days.

Table 5 Quadrant from Reno in which the first cumulonimbus was reported versus the coincident 700 mb geostrophic wind class on non-Zephyr days only. Computed no-relation values are given in parentheses.

Quadrant	(south wind)		(light wind)		(north wind)		Total
north thru east	8	(9)	9	(13)	9	(4)	26
east thru south	29	(26)	39	(38)	6	(10)	74
south thru west	44	(48)	75	(69)	17	(19)	136
west thru north	18	(15)	19	(22)	6	(6)	43
Total	99		142		38		279

Possibly even more significant than this shift in preferred quadrant is the chi-square value of 9.24 (with Yate's correction) which comes from Table 5. With six degrees of freedom, this indicates that the null hypothesis of no relation cannot be rejected even at the ten percent level. Thus, there appears to be no relationship between the quadrant of onset of convection and meridional flow on non-Zephyr days.

Table 6, based only on Zephyr days, suggests the overall preference for cumulonimbus development in the east through south quadrant revealed in Table 4 is caused by a marked preference for this quadrant on days with significant west surface winds and south winds at 700 mb.

Table 6 Quadrant from Reno in which the first cumulonimbus was reported versus the coincident 700 mb geostrophic wind class on Zephyr days only. Computed no-relation values are given in parentheses.

Quadrant	(south wind)		(light wind)		(north wind)		Total
north thru east	17	(26)	10	(8)	12	(5)	39
east thru south	91	(77)	20	(25)	7	(16)	118
south thru west	6	(7)	4	(3)	2	(2)	12
west thru north	4	(7)	4	(2)	3	(1)	11
Total	118		38		24		180

As can be seen, Table 6 has a large number of classes where both the observed and expected numbers of occurrences are less than five. This precludes the use of a chi-square test. If a test is based on the east through south quadrant versus all other quadrants and the occurrence or non-occurrence of Zephyr days as shown in Table 7, a chi-square of 69.48 results. Using two degrees of freedom, the null hypothesis of no relation is rejected. This is further supported by a tetrachoric correlation coefficient based on Table 7 of 0.58. These results suggest with a high probability that there is a relationship between surface winds, meridional flow aloft, and the quadrant of onset of cumulonimbus clouds in the Reno area.

Table 7 Joint frequency distribution between the occurrence of the first reported cumulonimbus in the east through south quadrant from Reno versus all other quadrants and Zephyr versus non-Zephyr days. No-relation values are given in parentheses.

Quadrant	(Zephyr day)		(non-Zephyr day)		Total
east thru south	118	(75)	74	(117)	192
all other quadrants	62	(105)	205	(162)	267
Total	180		279		459

VI. POSSIBLE TERRAIN INDUCED MECHANISMS

The distribution of terrain features around Reno plus the results of the previous statistical tests suggest summer days may be classified according the possible physical mechanisms which contribute to the development or suppression of convective clouds.

A number of investigators have suggested that in addition to mountains acting as elevated heat sources, which produce deformations in the surrounding isentrophic field, other mechanisms may play a role in mountains acting as roots for convection. Braham and Dragnis (1960), Vul'fson (1965), and others have suggested mountain-valley breezes due to slope heating may cause updrafts and transport moisture upward. It appears from their studies that above the mountain, the core of the updraft may at times be too large for complete horizontal spreading at an equilibrium level. This results in a convergence of moisture flux and forced convection.

Such upslope-wind generated forced convection could be greatly enhanced by a significant cross-valley wind. This would be especially true if no compensating downslope wind developed on the east facing slopes of the mountains on the east side of the valley as appears to be the case in some areas of western Nevada.

As noted earlier, the area north of Reno is characterized by small valleys and mountains which extend westward across northern California to the Pacific coast. The terrain is not conducive to the establishment of forced convection due to upslope winds enhanced by cross-valley winds. The area is also not likely to experience significant isallobaric west winds caused by differential heating. To the east of Reno there may be compensating downslope winds on the east-facing slopes of the Pinenut Mountains into the low lying Carson Sink at times. Farther southeast of Reno, the terrain of small valleys and mountains east of the Pinenuts precludes the development of significant compensating downslope winds on east-facing slopes.

Table 5 indicates that on non-Zephyr days there is a marked preference for thunderstorms to develop over the Sierra Nevada. This is a reflection of the ability of these massive mountains to act as an effective elevated heat source. However, Table 6 illustrates on Zephyr days a remarkable lack of cumulonimbus occurrence over the Sierra Nevada. The strong downslope winds are apparently not compensated by upslope winds on the west facting slopes of the Sierra. The result is divergence at the mountaintop level and subsiding motion over the mountains. Thus, the Washoe Zephyr inhibits the ability of the Sierra Nevada to act as an elevated heat source.

The marked preference for cumulonimbus development in the southeast quadrant in Table 6 (meridional flow and Zephyr days), may result for two reasons. First, on days when the air mass over the area is sufficiently moist and unstable to produce cumulonimbus clouds due to surface heating, west winds at the surface may inhibit development in the west quadrant due to subsidence over the mountains there. This leaves convection to develop in the eastern quadrants. However, this would not explain the east through south quadrant over the north through east quadrant. It is possible that the meridional flow aloft may contribute additional convergence to the westerly upslope winds over the elevated terrain southeast of Reno. This would further feed the forced convection mechanism.

Available data suggests that significant convection occurs nearly 60 percent of the time with easterly flow at 700 mb. This easterly flow, under certain conditions, likely acts to enhance the elevated heat source mechanism of the Sierra Nevada by adding a convergence component and initiating forced convection.

VII. CLASSIFICATION OF SUMMER DAYS

The concept of terrain-induced mechanisms which may produce, inhibit, or redistribute significant convection provides a basis for classifying each summer day based on terrain interaction with synoptic scale signatures. An important percentage of summer days are controlled by strong over-riding synoptic scale dynamics. McNulty (1978), Uccellini and Johnson (1979), and others have shown that the secondary circulations associated with propagating wind maxima can play a major role in thunderstorm development and suppression. Short-wave troughs in the mass field aloft with their associated positive and negative vorticity advection patterns can also produce or inhibit convective storms. The boundaries of surface bubble-highs produced by nearby thunderstorm clusters have been shown by Maddox et al (1977), and others to be related to convective development in a manner somewhat similar to classic synoptic scale frontal thunderstorms. Middle tropospheric areas of divergence determined from 700-mb streamline analyses have also been found to be related to convective development over Nevada.

Such dynamics are controlled by large scale atmospheric flow patterns. Thus, the effects may be quite variable from summer to summer, but should not, barring climatic change, significantly alter the climatology of an area. There are likely important terrain influences on these days, but the dynamics themselves are so complex and in some instances not fully understood, that any attempt to filter out the orographic effects utilizing only synoptic scale data is not likely to be successful. This study will concentrate on days when conditions in a three-to six-hour time frame are nearly steady state with regard to the forcing functions which appear to produce thunderstorms. Thus, all National Meteorological Center standard level analyses from the surface to 300 mb were examined and all days were removed from the data base where one or more of the above synoptic scale dynamic signatures were detectable. In the original data base of 1132 days, 396 were considered dynamic. Of these, 124 were found to be cumulonimbus days.

The remaining days were divided into three categories based on possible terrain induced mechanisms. The first category, labeled "Sierra days", had to meet five requirements:

1. No synoptic scale dynamic signatures were detected.
2. It was a no-Zephyr day.
3. The 00 GMT 700-mb geostrophic wind had an easterly component greater than 2.5 m/s.
4. If the zonal component of the 700-mb wind was easterly, but less than 2.5 m/s, the afternoon surface wind at Reno had to have a persistent easterly component greater than 5 m/s.
5. Observations had to indicate that cumulonimbus clouds initially developed over the Sierra Nevada.

The second classification, labeled "Pinenut days," had to meet the following criteria:

1. No synoptic scale dynamic signatures could be found.
2. Afternoon surface winds at Reno did not exceed 5 m/s from any direction, unless from the surface observations it was determined that stronger winds were produced by thunderstorms.
3. The zonal component of the 00 GMT 700-mb geostrophic wind was constrained to be less than 2.5 m/s based on previous statistical suggestions.
4. The meridional component of the 700-mb geostrophic wind was arbitrarily constrained to be less than 5 m/s.

Finally, there exists a group of days which met the above airmass criteria and additionally, the meridional 700-mb wind was less than 2.5 m/s. Afternoon Zephyr winds developed with only weak 850-mb gradients over the plateau and the sea-level thermal trough over the California interior. No cumulonimbus clouds occurred on these days and they are considered "Airmass days" when terrain-induced surface winds may have inhibited convection.

The general synoptic pattern associated with airmass days was found to be a broad ridge of high pressure over the western United States, no 850-mb low over Nevada and a fairly strong sea-level thermal trough over the California interior. Such patterns produce light winds aloft and often inhibit the development of the Washoe Zephyr.

Pinenut-type days are usually associated with a sharper ridge aloft, often with a large scale trough over the eastern Pacific. The sea-level thermal through is again over the interior of California, but weaker, and an 850-mb low is analyzed over Nevada, allowing afternoon terrain-induced west winds to develop east of the Sierra Nevada. The screening process used to type each summer day specified for Pinenut cases that the meridional component of the 700-mb geostrophic wind had to be greater than 2.5 m/s. No criteria was placed on the zonal component. When the 700-mb wind components were compared to the occurrence of thunderstorms on Pinenut days as depicted in Figure 7, it was found that cumulonimbus clouds failed to develop on all days with a zonal component greater than 4 m/s. From this analysis, the additional criteria focuses the signature of the meridional component on more southerly flow, and eliminates dry, strong southwesterly flow patterns. It also insures that afternoon surface winds at Reno are terrain-induced and not produced by the downward mixing of momentum through thermal convection.

For the days typed as "Sierra" by the screening process, the sea level thermal trough was usually strong over California and no deepening 850-mb low was over the Nevada plateau. Only about 25 percent of the cumulonimbus days were associated with east to southeast winds at 700 mb produced by an area of low pressure near southern California. About 25 percent of the Sierra convective days were associated with a northeast to east flow caused by low pressure aloft east of western Nevada. In these cases, if an 850-mb low was present over Nevada, it was associated with a transient trough in the westerlies and was moving eastward. Thus, pressures were rising on the plateau and no significant isallobaric wind component developed at Reno. Somewhat surprisingly, nearly 50 percent of the Sierra cumulonimbus days were associated with east winds at 700 mb produced by a synoptic pattern characterized by high pressure aloft building into Oregon from the East Pacific. Thus, it appears that about 75 percent of all Sierra thunderstorm days were not associated with moisture transport into the area from the usual climatological sources to the south of Nevada.

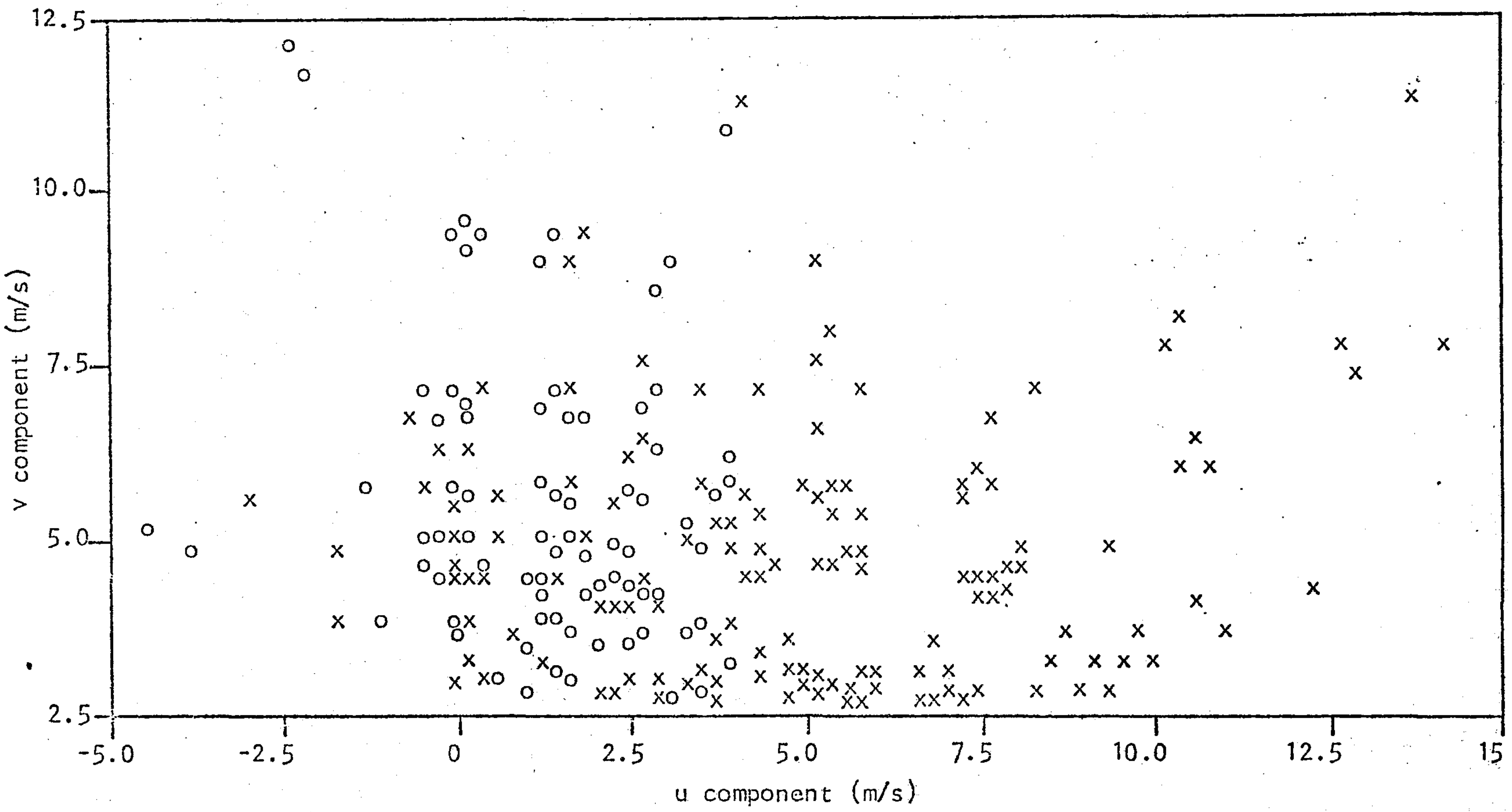

Figure 7 Zonal (u) and meridional (v) components of the 00 GMT 700-mb geostrophic wind over Reno on days classified as Pinenut-type. A day when cumulonimbus clouds were observed is denoted by a "o." A day when no cumulonimbus clouds were observed in indicated by an "x."

The screening process used to categorize summer days based on possible terrain-induced surface winds and synoptic signatures divided the data base into mutually exclusive types of which 383 were Airmass, 238 Pinenut and 115 Sierra days. As mentioned earlier, 396 days were labeled as Dynamic. Table 8 shows how this system of classification distributed the types of cumulonimbus days by month. It is interesting to note that the system labeled over 40 percent of June convective days as dynamic while less than 25 percent were airmass-type. This is consistent with the concept of the center of the East Pacific High in its southerly location during June still allowing disturbances to reach Nevada from the west. It is also consistent with radar climatology. Airmass cumulonimbus activity peaks in July and August in the area around Reno, consistent with concepts of the summer "monsoon" in the southwestern United States. At the same time, the classification process indicates dynamic activity decreases sharply in July and August, coincident with the northward shift of the East Pacific High cell.

Table 8 Average percentage of monthly total cumulonimbus days in the Reno area represented by each day-type as determined by the classification process applied to ten years of summer season data.

	June	July	August	September
Airmass	23	29	29	23
Sierra	18	14	23	32
Pinenut	15	29	26	9
Dynamic	44	28	22	36

In Table 8, Sierra days show a general increase through the summer and represent nearly one-third of all September cumulonimbus days. This is consistent with mean 850-mb charts which indicate the 00 GMT 850-mb thermal low to be weakest over the Nevada plateau in September compared to the other summer months. In addition, September has the weakest mean afternoon isallobaric gradient. In July, when the ageostrophic isallobaric winds due to heating of the plateau are strongest, and there are more Zephyr days, Table 8 confirms that Pinenut days peak.

VIII. DISCRIMINANT ANALYSIS OF AIRMASS-TYPE DAYS

Prediction schemes and many analysis studies of significant convective events have utilized numerous atmospheric parameters to characterize airmass stability. Most schemes such as the K index (George, 1960) make use of: a) some type of change of temperatures with height, and b) moisture parameters. Hambidge (1967) has shown that the K index performs reasonably well as a predictor of thunderstorms over Nevada in a probalistic sense. In this study, however, multiple discriminant analysis was applied to determine if a set of observed atmospheric characteristics could successfully distinguish between observed cumulonimbus and non-cumulonimbus days. For the test, only the sub-set of days chosen as airmass-type by the screening process were used. A number of parameters were offered and tested for significance using the screening techniques suggested by Miller (1962). These parameters were:

1. The daily surface maximum dry bulb temperature at Reno.
2. The 00 GMT 700-mb dewpoint temperature depression over Reno.
3. The 00 GMT 700-mb dry bulb temperature minus the 00 GMT 500-mb dry bulb temperature over Reno.
4. The 00 GMT 500-mb dry bulb temperature.
5. The 00 GMT surface dewpoint temperature at Reno.
6. The 00 GMT 850-mb dry bulb temperature minus the 500-mb dry bulb temperature over Reno.

Only the last two parameters were chosen by the screening test, with the other four apparently adding no significant information. Figure 8 illustrates how excellent the 850-mb to 500-mb temperature difference and the surface dewpoint at Reno alone were able to discriminate between airmass cumulonimbus and non-cumulonimbus days. Holzworth (1972) indicates the mean afternoon mixing height over western Nevada in the summer to be near the 700-mb level. Thus, it appears the afternoon surface dewpoint is a reasonably good measure of the atmospheric moisture content between the ground and 700 mb, and while addition of the 700-mb dewpoint depression would produce a modified K index, no additional information would be gained.

The varied terrain over western Nevada obviously exerts influence on convective activity even on days classified airmass-type, purely airmass convection that would occur over flat terrain is modified. The exact nature of such modifications appears indeterminate from synoptic scale data. However, the effects may be regarded as relatively constant, and not to a large degree a result of interaction with synoptic scale flow patterns. If such a view is accepted, the remarkably good discriminant function may be used as a baseline, possibly providing insight into terrain effects on days with synoptic scale winds of significant strength.

IX. POSSIBLE EFFECTS OF A TERRAIN DISTRIBUTION AND SYNOPTIC WINDS

Data indicated a synoptic signature of significant east winds aloft over the Reno area during the summer is very conducive to convective development. The work of previously cited authors suggests that such flow could act to enhance the elevated heat source mechanism associated with the Sierra Nevada by producing forced convection. Figure 9 shows the distribution of cumulonimbus and non-cumulonimbus Sierra-type days compared to the computed airmass discriminant function. In the figure, no non-cumulonimbus days fall in the airmass defined cumulonimbus category. However, about 40 percent of the Sierra convective days occur on days which are apparently too stable to support airmass convection. The dispersion of the data suggests a simple linear relationship does not exist for these forced convection cases. It is likely that synoptic scale data alone, as used in this study would be unsuccessful in determining the actual function which is able to differentiate convective from non-convective days in the central portion of Figure 9. What is possibly significant is that synoptic scale data suggest terrain interaction with a flow pattern appears to increase the frequency of cumulonimbus days over the Sierra Nevada.

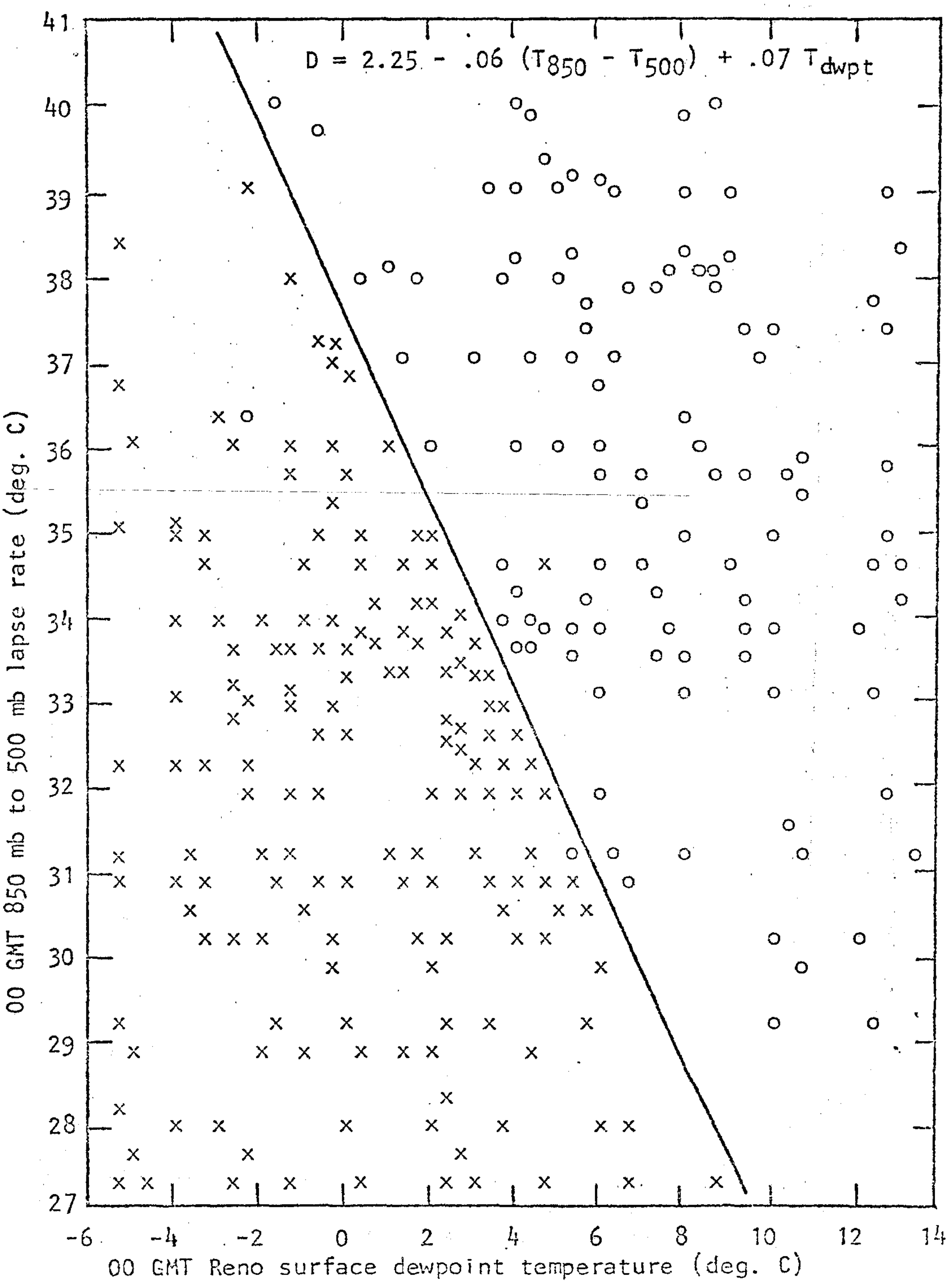

Figure 8 Distribution of observed airmass cumulonimbus days (o) and airmass days with no convection (x) as functions of Reno surface dewpoint and 850-mb to 500-mb temperature lapse rate.

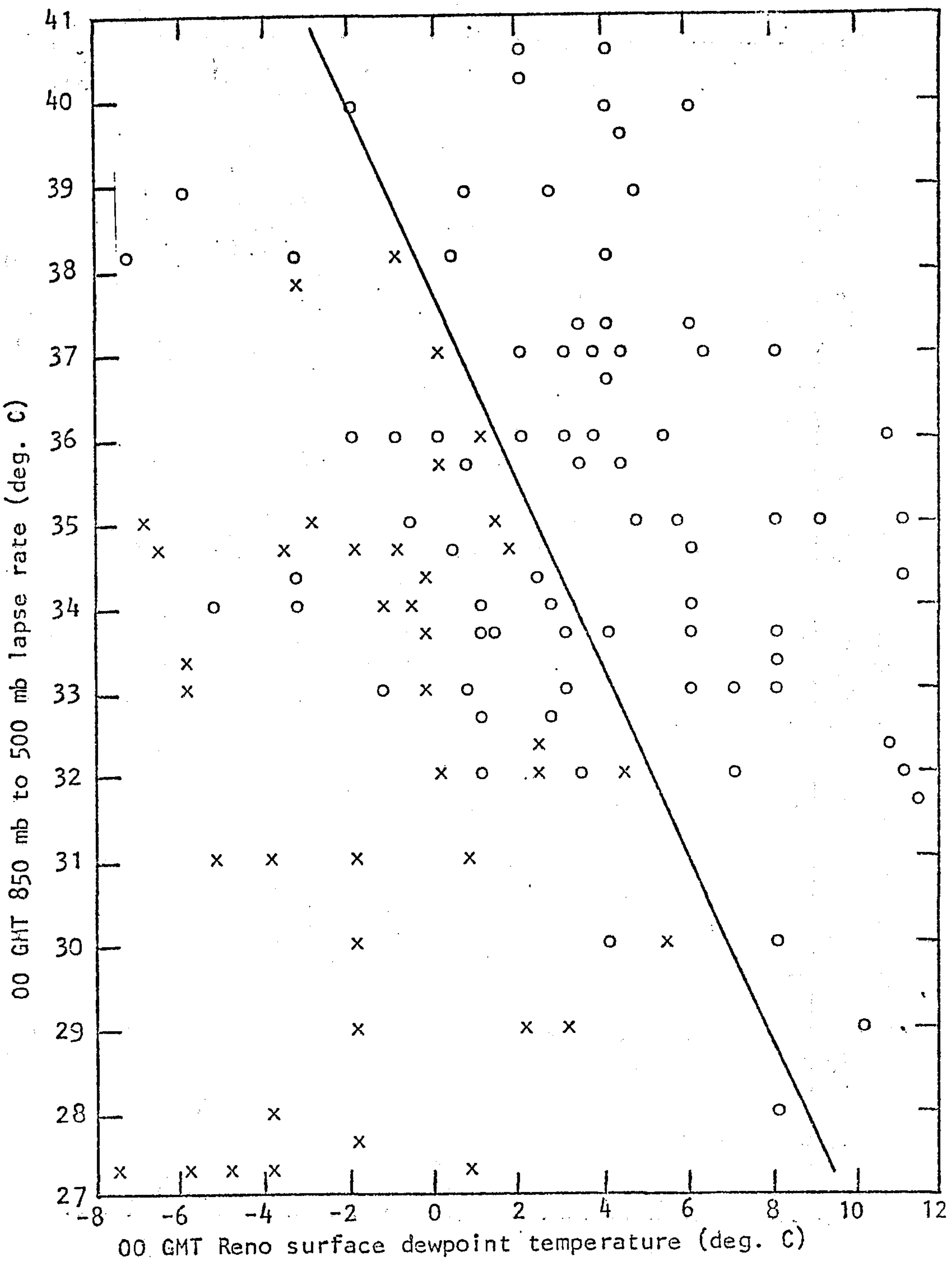

Figure 9 Distribution of observed Sierra cumulonimbus days (o) and Sierra days with no convection (x) as functions of Reno surface dewpoint and 850-mb to 500-mb lapse rate.

A significant number of Zephyr days occurred with a zonal component of the 700-mb geostrophic wind less than 4 m/s and a meridional component less than 2.5 m/s. Thus, except for the surface winds, these could be considered airmass-type days. In all cases, the sea-level thermal low was analyzed over the interior of California, and since both the 850-mb height and afternoon isallobaric gradients over the Nevada plateau were weak, the winds were considered terrain-induced. Of these 94 cases, about 40 percent were sufficiently unstable, as defined by the airmass discriminant function, to support significant convection. Thus, if the surface winds at Reno are viewed as terrain-induced, there is a loss of cumulonimbus days as a result of the Washoe Zephyr phenomenon.

Figure 10 depicts the distribution of convective and non-convective days for those dates classified as Pinenut days. As with the Sierra cases, the linear discriminant function developed on airmass days cannot make the distinction in the Pinenut cases. Like the Sierra days, about 40 percent of the Pinenut cases occurred on days apparently too stable for airmass convection. Figure 10 also indicates that on a significant number of days, airmass thunderstorms likely would have occurred, but failed to develop. Thus, there again appears to be a loss of cumulonimbus days in the Reno area as a result of the Zephyr phenomenon. It also appears that this type of convection is even more complex than the Sierra-type. That Pinenut-type cumulonimbus clouds failed to develop on all Zephyr days without a significant 700-mb southerly geostrophic wind component indicated that the upper wind is a necessary factor. However, Figure 10 suggests these upper winds on Zephyr days are not sufficient to insure thunderstorm development. There are cases where the required balance cannot be established, and sustained forced convection does not develop.

Sea-level and 850-mb analyses for all cases which met Pinenut wind criteria, and airmass instability criteria but failed to develop convection were carefully checked. It may be that on those days general west surface winds existed over western Nevada, including the east slopes of the Pinenut Mountains. Such a condition would greatly reduce the possibility of convergence of mass and moisture flux. However, the available synoptic scale data did not show this, and the cases are considered Zephyr-type.

The analysis of Pinenut days based on Figure 10 does give some insight into a sometimes observed phenomenon at Reno which might be termed a convective slosh. In some instances the following sequence of events has been observed:

1. Convection begins over the Sierra Nevada to the west of Reno shortly after noon. Clouds may grow to towering cumulus or even reach the small cumulonimbus stage.
2. West surface winds in excess of 5 m/s commence in the valleys just east of the Sierra about mid-afternnon and convective clouds over the Sierra dissipate rapidly.
3. Shortly thereafter convection develops over the Pinenut Mountains to the southeast of Reno. Clouds reach mature cumulonimbus stage by late afternoon.
4. On some occasions the thunderstorms drift northward and become vigorous enough east of Reno for outflow winds to overcome the downslope Zephyr winds from the west. When this happens, convective clouds develop over the Sierra Nevada again during the evening hours.

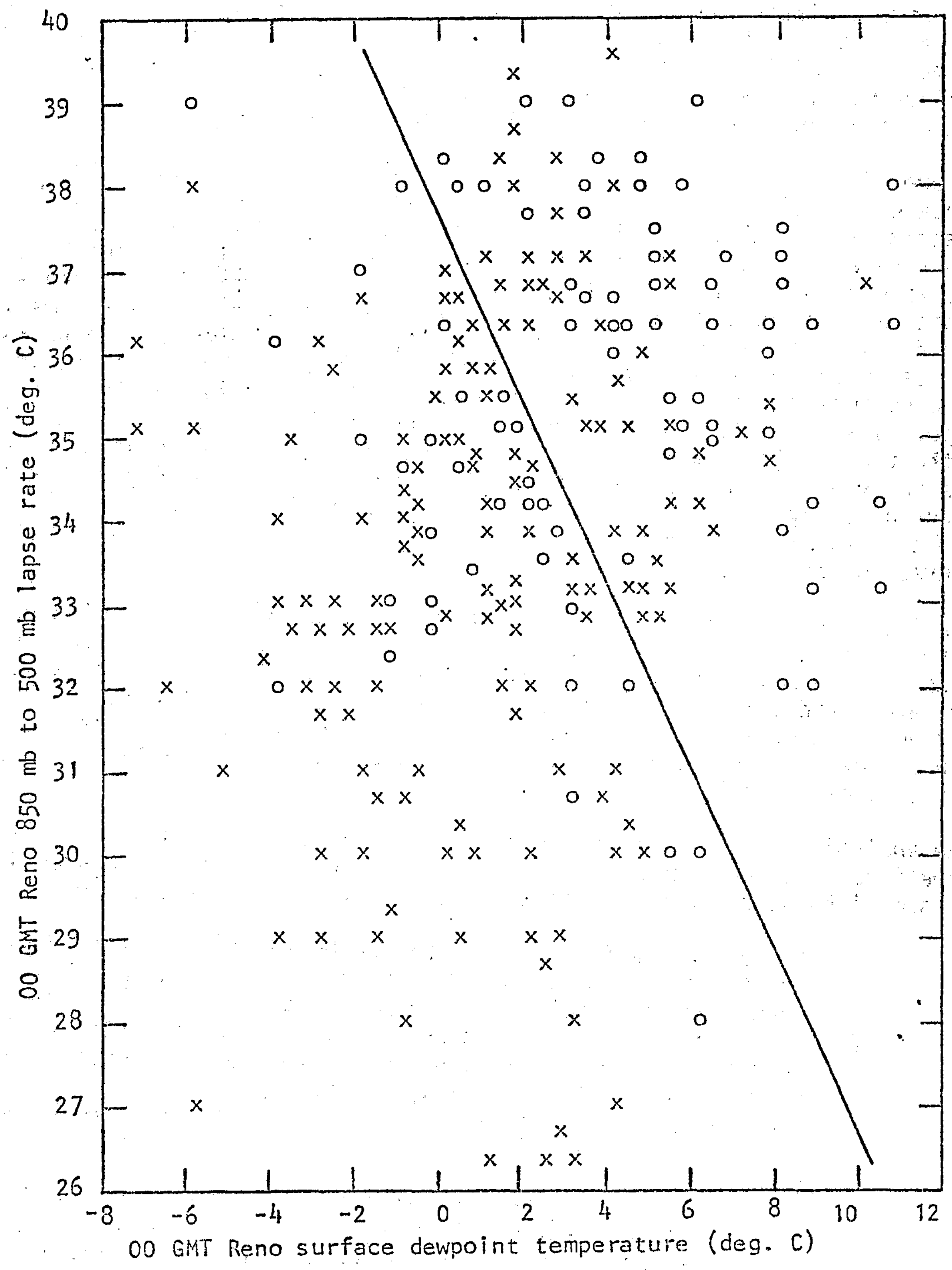

Figure 10 Distribution of observed Pinenut cumulonimbus days (o) and Pinenut days with no convection (x) as functions of Reno surface dewpoint and 850-mb to 500-mb lapse rate.

5. On most occasions, however, the Washoe Zephyr prevails and thunderstorms are constrained to remain east of Reno, with the Sierra Nevada cloud-free.

These convective slosh days likely occur when airmass-type thunderstorms would develop, but the activity is redistributed due to the Zephyr winds. On other days, even when afternoon west winds are late to develop, the Sierra remain cloud-free. Shortly after the onset of the Zephyr, however, cumulonimbus clouds are observed to develop rapidly southeast of Reno over the Pinenut Mountains. By evening, radar and satellite imagery show Nevada and the Sierra Nevada to be virtually cloud-free except for a line of thunderstorms stretching north-south over the Pinenuts. Those are likely days when the forced convection mechanism causes convergence of available moisture and produces thunderstorms in an environment too dry and stable to support airmass convection.

In the context of terrain generated surface winds plus terrain interaction with upper winds, it appears summer cumulonimbus activity is redistributed in the area around Reno, Nevada. There may also be an effect on the actual number of thunderstorms reported at Reno since there are significant differences in the percentage of different types of cumulonimbus days which results in thunderstorm reports. The ten years of data used in this study indicate that about one-fourth of the dynamically induced cumulonimbus days result in reported thunderstorms at Reno. Nearly 40 percent of the airmass-type days produce reported thunderstorms, and about one-third of the Sierra-type days. Significantly, only six percent of the cumulonimbus activity on Pinenut-type days result in thunderstorm reports at Reno.

Table 9, based on terrain concepts, the airmass discriminant function, and probability of thunderstorms being reported at Reno for each day-type indicates:

1. While cumulonimbus activity appears to be redistributed, there is no appreciable net gain or loss to the total number of convective days.
2. It appears this redistribution results in a significant decrease in the number of thunderstorms which affect Reno. The synoptic scale data suggest that, on the average, about three thunderstorms per summer are lost at Reno as a result of this redistribution. This is equivalent to a full standard deviation of the average number of thunderstorms at Reno.

X. AN AREA OF INCREASED FLASH FLOOD FREQUENCY

Of greater importance than the effect on the thunderstorm climatology at Reno appears to be the establishment of a preferred area for summer convective showers over the Pinenut Mountains. Thus, the terrain-induced redistribution may result in an area of increased flash flood events. Flash flooding is, of course, dependent on more than simply frequency and intensity of rainfall. Slope aspects, vegetation, soil type, antecedent soil moisture conditions, and even the direction and speed of movement of a storm in relation to the drainage area all play major roles in flash flood events. Thus, any inferences regarding the frequency of flooding, especially in data and population sparse areas such as Nevada, are

Table 9 Net gain of cumulonimbus (CB) and thunderstorm (TSTM) days at Reno, Nevada, as a result of terrain effect.

	10-year total	Reno TSTMS	TSTMS as percent of type	Net CB gain	Net TSTM gain
AIRMASS-TYPE (AMS)					
A. CB days	113	43	38		
B. Non-CB days	176				
C. AMS day plau ZEPHYR	94				
1. Possible AMS CB day	37			-37	-14
SIERRA-TYPE					
A. CB days	74	25	34		
1. Below AMS CB criteria	28			+28	+9
B. Non-CB days	41				
1. Meeting AMS CB criteria	0				
PINENUT-TYPE					
A. CB days	85	5	6		
1. Meetings AMS CB criteria	51			0	-16
2. Below AMS CB criteria	34			+34	+2
B. Non-CB days	153				
1. Meeting AMS CB criteria	30			-30	-11
DYNAMIC-TYPE					
A. CB days	124	31	26		
B. Non-CB days	272				
TOTALS		104		-5	-30

tentative at best. There is, however, some information which strongly suggests the area southeast of Reno has a high frequency of summer flash flooding relative to the surrounding region of western Nevada.

Figure 11 was developed with data obtained from a stream gaging network operated by the United State Geological Survey (Moosburner, 1978). The available information from this program, which began in 1961, unfortunately only consists of annual maximum flood dates at each gaging site. Thus, while Figure 11 indicates the percent of summers of record for which flash flood events occurred, it is only indirectly suggestive of summer flash flood frequency. This is because more than one event may have occurred at a gage during a summer, or the maximum flood may have occurred during a non-summer month with lesser flooding during the summer. The analysis does suggest that on a seasonal basis the frequency of flash flooding for the area southeast of Reno is higher than for the much steeper front range of the Sierra Nevada.

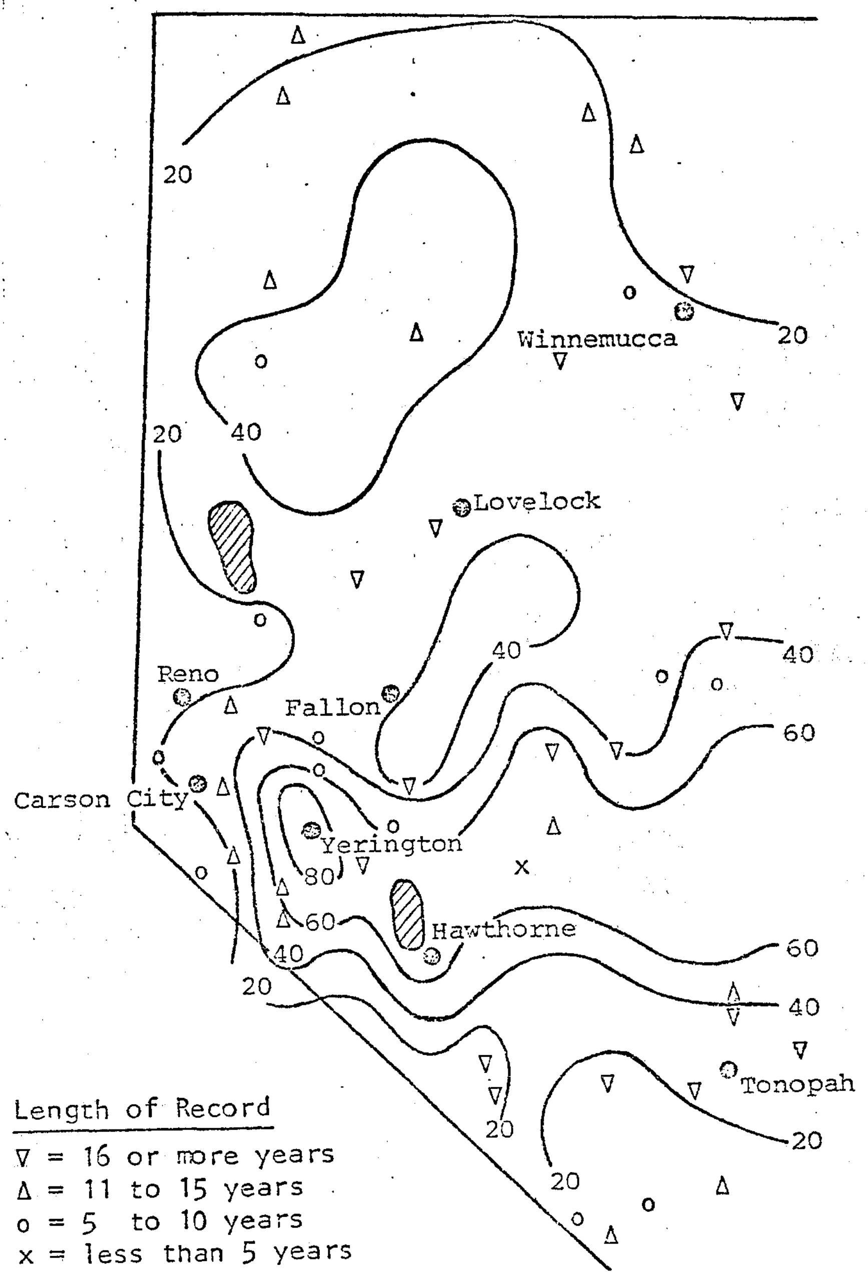

Figure 11 Annual frequency of summer flash flood events over western Nevada based on stream gaging network. Isopleths are percent of summers of record with one or more flood events.

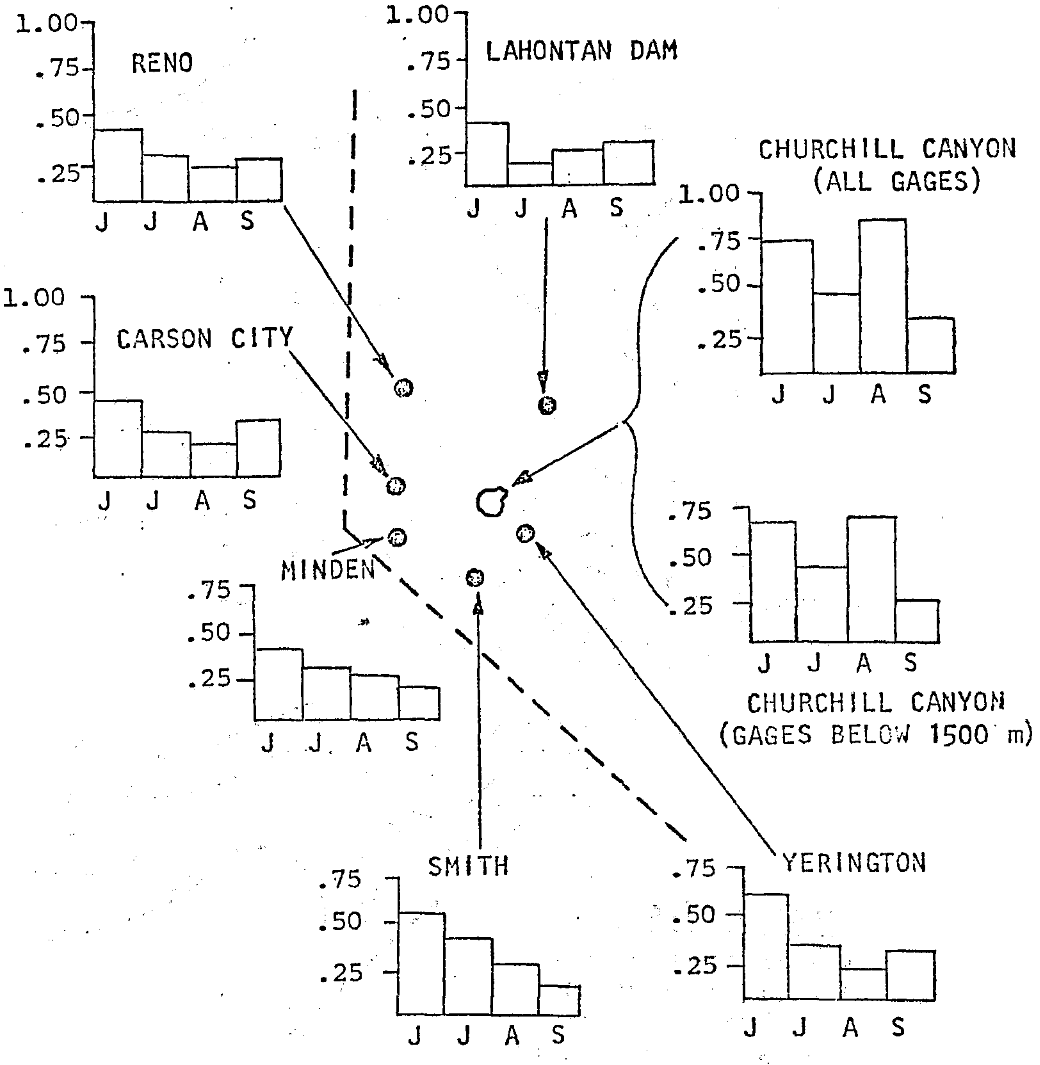

Figure 12 Average monthly precipitation totals (in inches) during the summer. Data based on 30-year normals except Churchill Canyon which is based on a 16 gage network for the period 1963 through 1977.

The Bureau of Land Management has used the Churchill Canyon area in the Pinenut Mountains east of Carson City for watershed studies the past sixteen years. Unpublished data indicates that this area receives substantially more summer rainfall on the average than Reno or surrounding valley climatological sites. Figure 12 shows summer month precipitation normals for the period 1941 to 1970 for climatological stations in west central Nevada. The displayed data for the Churchill Canyon area is based on a sixteen gage network for the period 1963 to 1977.

Even when only the four gages with elevations below about 1500-m ASL are considered, the data indicates the Churchill Canyon area receives, on average, almost twice the summer precipitation of nearby valley sites. All the gages also indicate an interesting August precipitation maxima.

Thus, available information does suggest that the mountainous area to the southeast of Reno receives substantially more summer rain and quite possibly has a greater frequency of flash flood events than the rest of western Nevada.

XI. SUMMARY AND CONCLUSIONS

The valleys just east of the steep slopes of the central Sierra Nevada experience moderate gusty west winds on nearly fifty percent of summer afternoons. From synoptic scale data, these surface winds often appear anomalous. The winds are the result of terrain influences, on many scales, and apparently do not occur on the west side of the Sierra Nevada as well. The result is a strong divergence near the crest of the Sierra and subsidence over the mountains. It appears then that the terrain-induced winds significantly decrease the number of thunderstorm days over these large and extensive mountains. However, statistical tests indicate that there is no relation between the occurrence or non-occurrence of cumulonimbus clouds in the area as a whole, and the occurrence or non-occurrence of these anomalous surface winds.

Further statistical tests show that for cases with a synoptic signature of significant meridional flow aloft there is a strongly preferred area for cumulonimbus development on west-wind days. This preferred area, which is over the Pinenut Mountains southeast of Reno, appears to result from forced convection. Another statistical test indicates there is a strong relationship between synoptic signatures associated with a significant zonal wind component and the occurrence of cumulonimbus clouds in the area; non-dynamic thunderstorms rarely occur with west winds aloft while east winds aloft produce a very high frequency of convective days. In this latter case, the easterly flow produces forced convection over the Sierra Nevada.

The statistical analysis leads to a classification of summer days in the Reno area according to the mechanisms which produce or inhibit cumulonimbus activity. A screening process developed on the concepts of terrain-induced surface winds and terrain interaction with synoptic scale flow patterns provides the basis for the classification system. Multiple discriminant analysis applies to those days for which there are no significant terrain influences chose parameters which work remarkably well in differentiating between airmass-type cumulonimbus and non-cumulonimbus days. Using the discriminant function as a baseline, it appears that east winds aloft do produce a form of forced convection. In addition, the discriminant function applied to cases of cumulonimbus development southeast of Reno suggests that at times, forced convection occurs over the area while on other occasions the convective development is simply due to the redistribution of airmass cumulonimbus activity by the terrain-induced west surface winds.

The combination of terrain effects on synoptic flows, and the redistribution by surface winds generated by differential heating results in no significant change in the total number of cumulonimbus days in the area around Reno, Nevada. However, this alteration does cause a significant decrease in the number of thunderstorms reported at Reno. Available evidence also suggest the mountainous area southeast of Reno receives, on the average, substantially more summer rainfall than surrounding valley climatological stations. An August precipitation maxima in the Churchill Canyon area of the Pinenut Mountains southeast of Reno is a climatological precipitation anomaly. Analysis of limited stream gage data indicates this area may also have a higher frequency of summer flash floods than the remainder of western Nevada.

This study, through the use of simple statistical methods and only synoptic scale data tries to provide a reasonable explanation of the relatively high incidence of summer convection southeast of Reno compared to the more elevated Sierra Nevada. It also suggests that in mountainous areas such as western Nevada, a thunderstorm prediction scheme, to be successful, cannot be based solely on airmass stability and moisture parameters. Such parameters will work only when applied under appropriate conditions. On other days it is not the amount of moisture and instability available, but rather the manner in which these parameters are focused and released. This study suggests that rather than considering all convective days in an attempt to develop a forecast model, the days should be separated into categories, based on mechanisms which appear important. A prediction scheme can then be developed for each type of day. Such an approach greatly reduces the changes of over-fitting the data by attempting to choose a set of predictors which maximize the amount of explained variance for all days, but actually decreases the accuracy of the forecast scheme for each day-type.

Thus the study not only provides some understanding of the effects of terrain on summer thunderstorms around Reno but also provides a basis for attacking the forecast problem. Preliminary indications suggest that a parameter such as the K index will perform well as a predictor when applied to days which can be determined to be airmass-type for an area. However, in the mountainous western United States, indiscriminate application of such a parameter as the sole predictor often will not yield acceptable results. This is because terrain interaction with atmospheric flow patterns can produce forced convection.

XII. ACKNOWLEDGMENTS

This memorandum is a portion of the author's thesis accepted by the University of Wisconsin-Madison. Special thanks are extended to Dr. Werner Schwerdtfeger and Dr. Lyle Horn who provided guidance and critical reviews of the larger work, of which this is a part.

A very special thanks is extended to Dr. Harold Kleiforth of the Desert Research Institute, University of Nevada Reno who provided the data base which made this study possible.

Also a very special thanks to Mr. Leonard Snellman, Chief Scientific Services Division, National Weather Service Western Region for his help in extracting portions of the larger work that will hopefully be of interest to Western Region forecasters.

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CONTRACT AND GRANT REPORTS — Reports prepared by contractors or grantees under NOAA sponsorship.

ATLAS — Presentation of analyzed data generally in the form of maps showing distribution of rainfall, chemical and physical conditions of oceans and atmosphere, distribution of fishes and marine mammals, ionospheric conditions, etc.

TECHNICAL SERVICE PUBLICATIONS — Reports containing data, observations, instructions, etc. A partial listing includes data serials; prediction and outlook periodicals; technical manuals, training papers, planning reports, and information serials; and miscellaneous technical publications.

TECHNICAL REPORTS — Journal quality with extensive details, mathematical developments, or data listings.

TECHNICAL MEMORANDUMS — Reports of preliminary, partial, or negative research or technology results, interim instructions, and the like.

Information on availability of NOAA publications can be obtained from:

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