Seasonal and Interannual Trends of Sierra Nevada Clouds and Precipitation

THOMAS F. LEE

Electronic Techniques, Inc., Auburn, CA 95603

(Manuscript received 1 November 1986, in final form 27 March 1987)

ABSTRACT

Seasonal and interannual variations in Sierra Nevada winter storms are discussed with reference to precipitation augmentation. Seasonal variations occur with respect to freezing level, storm type, vertical cloud distribution, mesoscale precipitation systems, snowmelt and runoff. Statistical results from a previous operational program by Mooney and Lunn suggest that "cold westerly" storms yield increased precipitation from cloud seeding. Case studies from the Sierra Cooperative Pilot Project have shown that postfrontal conditions, which closely correspond to cold westerly storms, are characterized by high supercooled liquid water contents. Eight years of data from the American River Basin have been analyzed here which show that cold westerly storms 1) are more frequent in late winter and spring than earlier in the precipitation season; 2) contribute greater precipitation in seasons of normal and below-normal precipitation than in above-normal seasons. Hydrological factors make these storms attractive targets for precipitation augmentation.

1. Introduction

Sierra Nevada winter storms, which are often seeded with the intent to increase precipitation, show substantial seasonal and interannual variations. Such variations occur with respect to freezing level, storm type, vertical cloud distribution, mesoscale precipitation systems, snowmelt and runoff. The Sierra Cooperative Pilot Project (SCPP) has built a large database of storm observations. Climatological summaries offer the opportunity to assess long-term effects of seasonal and interannual variations on precipitation augmentation.

Along the West Coast of North America, the mean position of the polar jet stream shifts gradually equatorward from fall through late winter. The seasonal poleward shift of the jet in spring is not as gradual: often one jet appears to wane in the south in late winter, while another branch develops near the Arctic Circle (Trewartha, 1961). Also, beginning around late February there is a tendency toward a lower zonal index as cold air, which has been stored in the higher latitudes during the winter, moves equatorward and warm air moves into the higher latitudes (Namias, 1950). Williams and Peck (1962) tabulated monthly 500-mb cyclone frequency between the Continental Divide and the Sierra Nevada/Cascades and 35° and 45°N latitude. A distinct maximum in the frequency of these systems, referred to as "cold" or "closed" lows, occurred in late winter and spring.

From examination of satellite images, Pyke (1972) found that Pacific cyclones often had extensive warm frontal shields in late fall and early winter. By early spring they had less cloudiness over winter, but over land often developed a well-marked cold frontal band and extensive postfrontal convection. Pyke suggested that clouds at a significant distance ahead of a spring cold front are usually confined below approximately 800 mb, producing, mainly, drizzle. He also discussed a general tendency for late winter and spring to be snowier than fall and early winter in California, because of a northwest-to-southeast cyclone track and a greater proportion of cold frontal and post-cold frontal precipitation. Pyke's finding of increased post-cold frontal precipitation in spring is significant because post-cold frontal conditions in the Sierra Nevada have larger amounts of supercooled liquid water (SLW) than other stages of storms (Heggli and Reynolds, 1985; Kuciauskas, 1986).

Storms in a randomized cloud seeding experiment in the Lake Almanor region of the northern Sierra Nevada were divided into four classifications: cold westerly, warm westerly, cold southerly and warm southerly (Mooney and Lunn, 1969). Wind directions during 12-h experimental periods were averaged from 1525 to 3050 m (5000 to 10,000 ft). Twelve-h experimental periods were then termed southerly if the wind direction mean was between southeast and southwest, and westerly if between southwest and northwest. Experimental units were classified as warm if the −5° isotherm was above 2290 m (7,500 ft) and cold if below this height. During seeded events (1962–67) a 37% increase in precipitation was recorded for the cold westerly category, significant at the 0.05 confidence level, using either regression analysis or covariance analysis. Seeding only the cold westerly storms, which accounted for about 15% of annual precipitation, was estimated to increase annual runoff by about 5%. No other category showed a significant increase. The increases noted in cold westerly storms may have resulted from better targeting by ground-based generators, in addition to the possibility that these storms contained more SLW.

Data from the SCPP are used here to investigate seasonal and interannual variations of clouds and precipitation; of particular interest are storms that have been experimentally shown to contain large amounts of SLW, and also, the cold westerly storms of Mooney and Lunn (1969). To guide precipitation augmentation projects in the region, a primary goal of this paper is to determine when these types of storms are most likely to occur.

2. Measurements and study area

For the SCPP, conducted in the American River Basin in California (Fig. 1), rawinsonde and radar measurements were taken at Sheridan (elevation 60 m). Conventional surface observations were taken at Blue Canyon (elevation 1,610 m) by the National Weather Service.

3. Seasonal variations

a. Precipitation, snowfall and temperature

January is the coldest month of the year at Blue Canyon and receives the greatest precipitation (Fig. 2). February and March are drier than January but only slightly warmer.

To compute the relative proportions of rain versus snow, Blue Canyon observations from January 1976 through April 1986 were tabulated. Data for April 1976, 1977 and 1979 were missing, as were data for March 1979. The dataset included observations three times a day (07, 10, and 13 PST), 5 days a week. The data were sorted into three categories: liquid types (e.g., rain, rain shower, drizzle, thundershower, etc.), solid types (e.g., snow, snow pellets, freezing drizzle, etc.) and mixed liquid and solid particles (Fig. 3). Liquid precipitation appeared over half the time in November, then decreased during the winter and early spring. By March and April, liquid precipitation appeared in only about one-quarter of all the observations. Solid precipitation showed the opposite trend: barely one-third of the observations showed solid precipitation in November; in March and April this percentage increased to more than two-thirds. Mixed precipitation showed no consistent trend.

From January through March, rawinsondes at Sheridan were released every 3 h during storm periods from 1978–86, except 1981. Except for infrequent days off, coverage included all storms: 422 soundings in January, 495 in February and 540 in March. Table 1 gives Sheridan mean temperature profiles for January, February and March, showing the 0°C, −5°C and −10°C levels. The change in the 0°C level from February to March was pronounced, dropping from 2020 m in February to 1750 m in March. The lower 0°C isotherm in March helps explain the higher prevalence of March snow at Blue Canyon compared to January and February (Fig. 3). These results are consistent with the findings of Pyke (1972), Namias (1950), Trewartha (1961) and Williams

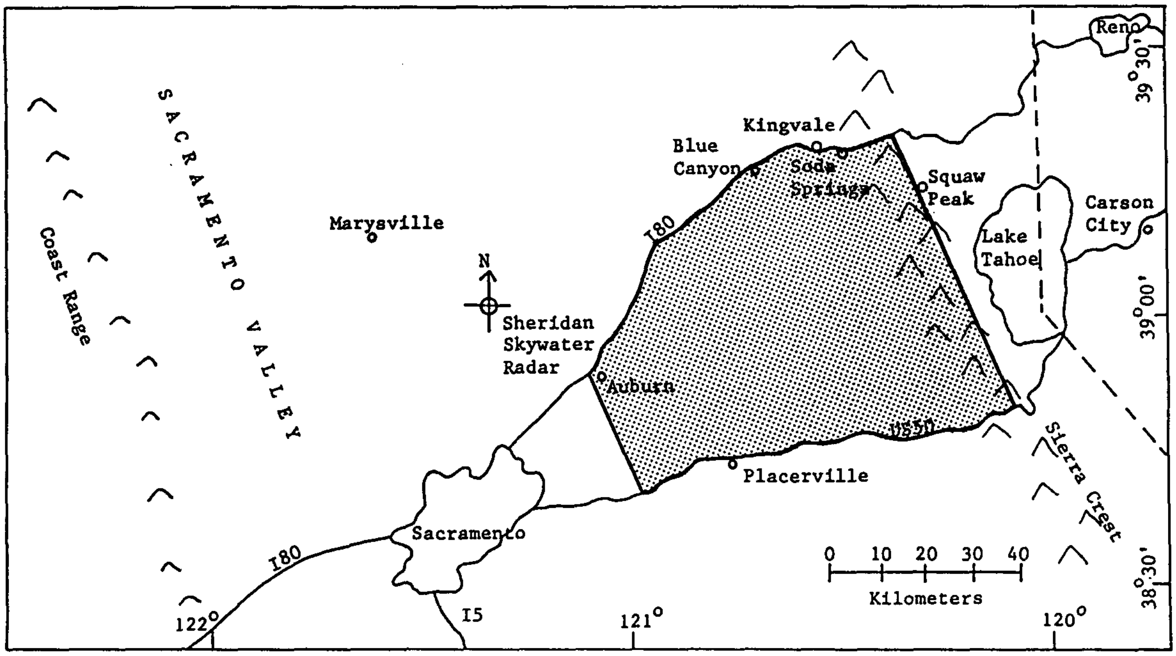

FIG. 1. Study area (shaded) of the Sierra Cooperative Pilot Project (SCPP).

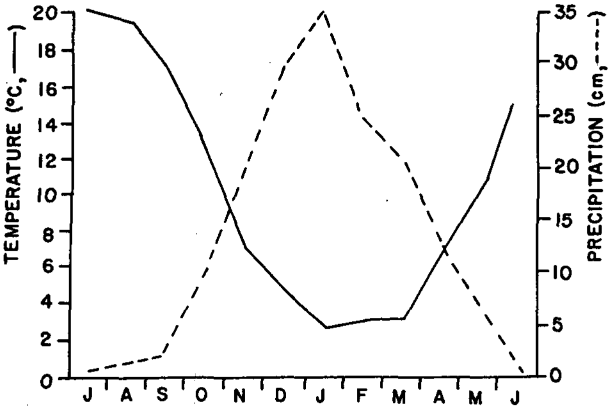

FIG. 2. Normals of precipitation (1940–85) and temperature (1941–85) at Blue Canyon by month.

and Peck (1962), who show that regional circulation patterns bring colder air masses to the region in late winter and spring.

b. Cloud structure

The vertical distribution of cloud inferred from rawinsonde measurements also shows seasonal differences. For each Sheridan sounding temperature, dewpoint and frostpoint were interpolated at 200-m levels and were used to determine the presence of cloud. Clouds were assumed to be ice-saturated if the frostpoint depression was 0.2°C or less; water saturation was assumed if a dewpoint depression was 0.2°C or less. Known deficiencies in this method include nondetection of thin or broken cloud layers. However, these criteria were considered adequate for the purpose of this analysis. The presence of cloud was inferred at an interpolated level for each sounding by applying the previous criteria. For each level the frequency of cloud was computed as a fractional percent of the entire sample (Table 2).

In January and especially February, the frequency of ice saturation above approximately 4500 m was greater than in March, indicating a higher frequency

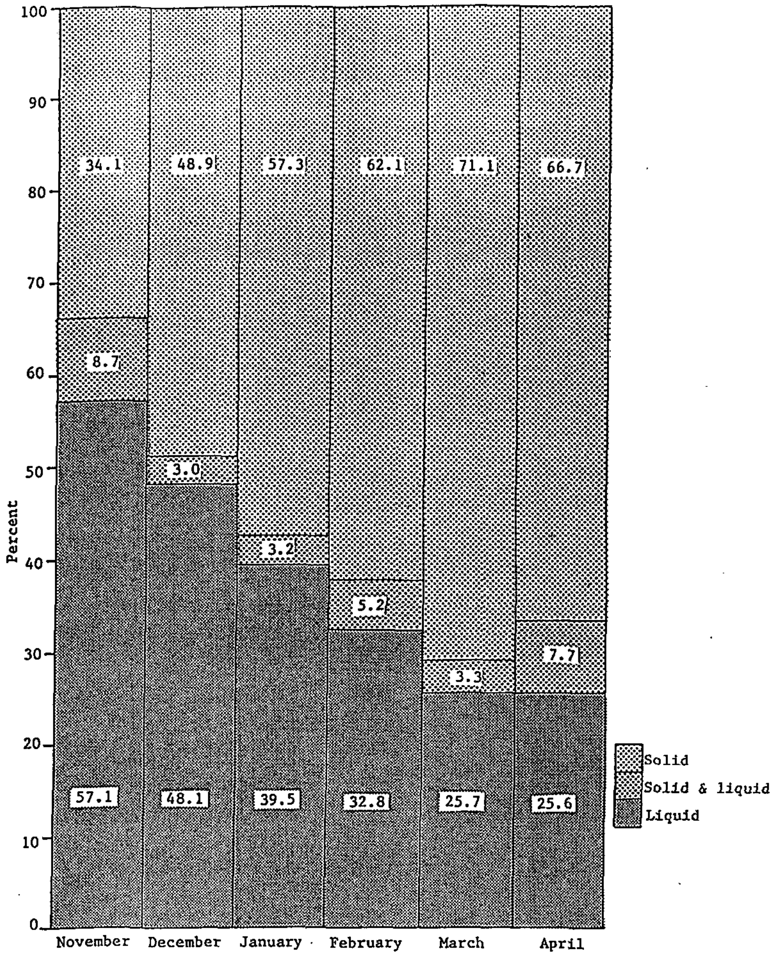

FIG. 3. Percent of Blue Canyon visual reports of precipitation as 1) liquid, 2) solid and liquid and 3) solid, January 1976–April 1986.

TABLE 1. Mean Sheridan temperature profiles. Seasons indicated are 1978–86, excluding 1981.

Height (m)	January	February	March
4500	−15.0	−14.7	−16.8
4400	−14.4	−14.0	−16.2
4300	−13.8	−13.4	−15.5
4200	−13.1	−12.8	−14.8
4100	−12.5	−12.2	−14.2
4000	−11.9	−11.6	−13.5
3900	−11.3	−11.0	−12.9
3800	−10.7	−10.4	−12.2
		−10.0°C	
3700	−10.1	−9.8	−11.6
	−10.0°C		
3600	−9.5	−9.2	−11.0
3500	−8.9	−8.6	−10.3
			−10.0°C
3400	−8.3	−8.0	−9.7
3300	−7.7	−7.4	−9.2
3200	−7.1	−6.8	−8.6
3100	−6.5	−6.2	−8.0
3000	−5.9	−5.7	−7.4
2900	−5.3	−5.1	−6.8
	−5.0°C	*−5.0*°C	
2800	−4.7	−4.5	−6.3
2700	−4.2	−3.9	−5.7
2600	−3.6	−3.3	−5.2
			−5.0°C
2500	−3.0	−2.8	−4.6
2400	−2.4	−2.2	−4.0
2300	−1.9	−1.6	−3.4
2200	−1.3	−1.0	−2.8
2100	−0.7	−0.4	−2.2
		−0.0°C	
2000	−0.2	0.1	−1.6
	−0.0°C		
1900	0.4	0.7	−1.0
1800	1.0	1.2	−0.3
			−0.0°C
1700	1.5	1.8	0.3
1600	2.1	2.5	0.9
1500	2.7	3.1	1.6
1400	3.3	3.7	2.2
1300	3.9	4.3	2.9
1200	4.5	4.9	3.5
1100	5.1	5.6	4.2
1000	5.7	6.2	4.9
900	6.3	6.8	5.6
800	6.9	7.5	6.3
700	7.5	8.1	7.0
600	8.0	8.7	7.7
500	8.6	9.2	8.4
400	9.1	9.8	9.1
300	9.6	10.4	9.8
200	9.9	10.8	10.4
100	10.0	11.0	10.8
60	9.1	11.0	10.5

of deep precipitation systems in the earlier two months. At the cirrus level of 7600 m, for example, saturated conditions were more than three times as common in January and February as in March. Near the surface, however, the trend was reversed. The frequency of ice saturation was greater in March than during the earlier two months, particularly between 1400 and 2400 m. This tendency is reflected by the downward shift of the most frequent cloud occurrence layer (flagged by asterisks): 3200 m in January; 2800 m in February; 2400 m in March.

TABLE 2. Percent of Sheridan soundings at ice saturation. Period: 1978–86, excluding 1981. Asterisk indicates maximum value.

	Jan	Feb	Mar
Level (m)	percent		
		5.0	
7800	5.7	5.4	1.7
7600	6.1	5.7	1.7
7400	7.8	7.2	3.0
7200	8.7	8.7	3.4
	10.0	*10.0*	
7000	11.3	11.7	4.1
6800	12.6	13.6	4.6
			5.0
6600	13.6	15.4	6.2
6400	15.1	17.6	6.7
6200	15.9	17.6	9.1
			10.0
6000	16.1	19.9	10.1
		20.0	
5800	19.0	21.6	11.5
5600	19.9	22.3	14.3
	20.0		
5400	20.7	24.2	14.9
5200	20.5	26.5	16.3
5000	22.6	27.5	15.4
4800	21.3	29.2	19.6
		30.0	*20.0*
4600	21.9	31.4	21.9
4400	23.0	30.2	23.1
4200	23.0	31.5	25.0
4000	23.0	31.5	26.2
3800	25.1	32.6	27.5
3600	24.0	32.5	27.6
3400	24.8	32.8	28.2
			30.0
3200	26.3*	31.7	31.6
3000	26.1	32.6	30.4
2800	23.6	33.3*	29.6
		30.0	
2600	21.7	28.3	30.6
	20.0		
2400	19.2	26.1	32.8*
2200	14.8	21.2	32.4
		20.0	*30.0*
2000	11.3	14.1	24.0
	10.0	*10.0*	*20.0*
1800	9.0	9.7	17.4
1600	6.7	5.2	12.9
	5.0	*5.0*	*10.0*
1400	4.8	1.9	6.6
	5.0		*5.0*
1200	3.1	0.2	2.7
1000	1.9	0.0	1.1
800	0.6	0.0	0.4
600	0.0	0.0	0.1
400	0.0	0.0	0.0
200	0.0	0.0	0.0
60	0.0	0.0	0.3

c. Radar patterns

Half-hour precipitation echo-type (PET) classifications were determined for the American River Basin from a visual analysis of radar echo patterns recorded by the Bureau of Reclamation 5-cm Skywater Radar (Heggli et al., 1983). Figure 4 shows that PETs indicative of deep stable cloud systems (AREA WIDE and EMBEDDED BANDS) are more frequent in the earlier months. The sum of these two PETs makes up 28.7% of the total in January and only 17.4% in March. The PETs induced primarily by orographic lift (OROGRAPHIC, SCATTERED CONVECTION and BROKEN CONVECTION) show the opposite trend, making up 54.0% of the total in January, but 63.8% in March. These PETs often result as shallow post-frontal moisture is forced over the barrier.

d. Storm classification

To investigate the seasonal trends of storm types, SCPP Sheridan soundings were sorted into the four temperature and wind classifications of Mooney and Lunn (1969). Precipitation associated with each of the four classifications was estimated from Blue Canyon daily precipitation and snowfall records. Blue Canyon data were chosen because snowfall was reported. SCPP gauges in the vicinity reported only liquid equivalent. Precipitation and snow during the 3-h period covered by a sounding was estimated by multiplying the daily amounts by 3/24 (0.125). The accuracy of the precipitation estimation procedure was tested over a subset of hourly precipitation data. The results of the estimation procedure approximated actual three-hour totals. The estimates were summed, and the relative contributions of precipitation and snowfall were computed for the four classifications. During the eight years, cold westerly storms accounted for only 6.8% of the precipitation in the American River Basin, compared to the 15% for the Lake Almanor region (1962–67) reported by Mooney and Lunn (1969). Cold westerly storms contributed a substantially larger percentage, 15.1%, of snowfall at Blue Canyon (Table 3).

TABLE 3. Percent contribution to January–March Blue Canyon precipitation and snowfall, 1978–86, except 1981, by storm class.

	Warm westerly	Warm southerly	Cold westerly	Cold southerly	Total
Liquid equivalent	42.8	42.8	6.8	7.7	100.0
Snowfall	30.4	38.0	15.1	16.4	100.0

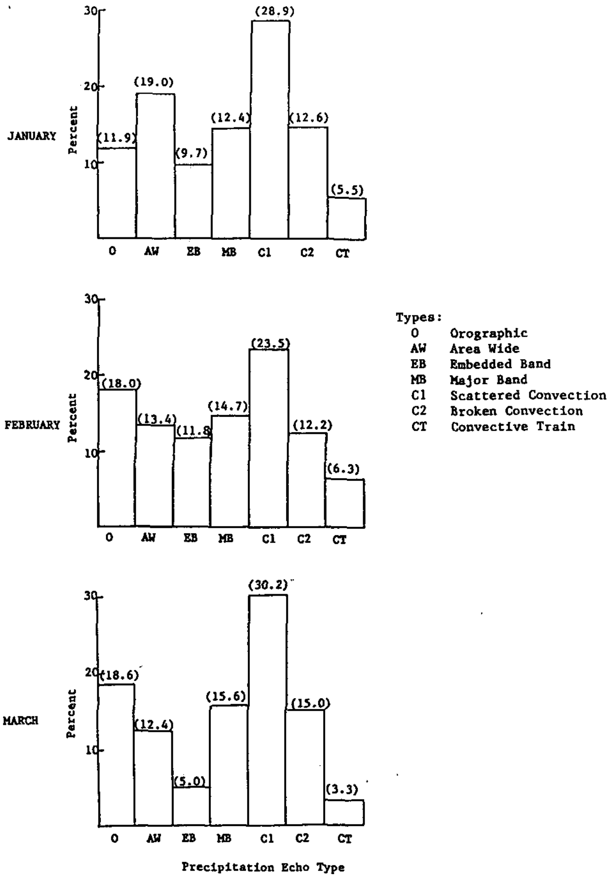

FIG. 4. Percent occurrence of PETs by month, 1977–85, except 1981.

During the 8-yr period, January received 28.2% of January–March precipitation, February, 40.4%, and March, 31.4%. Figure 5 summarizes each classification by month. For the cold westerly category, March contributed nearly one-half of the 3-month total of precipitation. For the cold southerly category, March contributed nearly two-thirds, suggesting a high prevalence of coastal cutoff lows, which tend to be classified as cold southerly as they combine cold cores with southerly winds. On the other hand, January and February contributed relatively little to the precipitation associated with the cold categories; warmer precipitation events were common. The February 1986 flood-producing rains on the American River were an extreme example.

4. Interannual variations

During the eight seasons considered (1978–86, except 1981), precipitation totals varied significantly: the wettest four seasons contributed 65.3% of the 8-yr total; the driest four contributed only 34.7% (Fig. 6). Cold westerly precipitation was disproportionately greater during the drier seasons (Fig. 7). Although the four driest seasons yielded barely one-third of overall precipitation, they yielded 84% of the precipitation from the cold westerly events. In fact, with the exception of 1983, the four wettest seasons yielded negligible precipitation from the cold westerly storms.

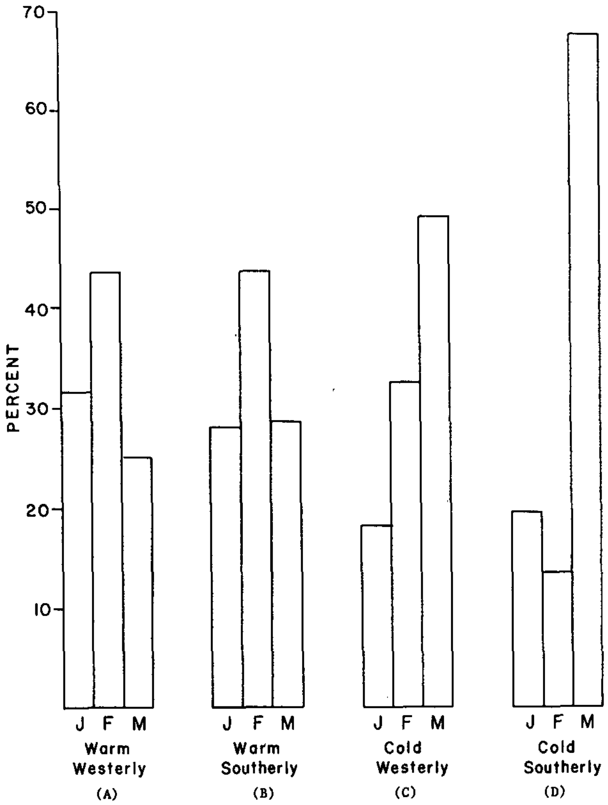

FIG. 5. Distribution by month of precipitation within the four classifications of Mooney and Lunn (1969). The sum over each classification is 100%. Data are based on Blue Canyon precipitation, January–March 1978–86 except 1981, and Sheridan rawinsondes, same period.

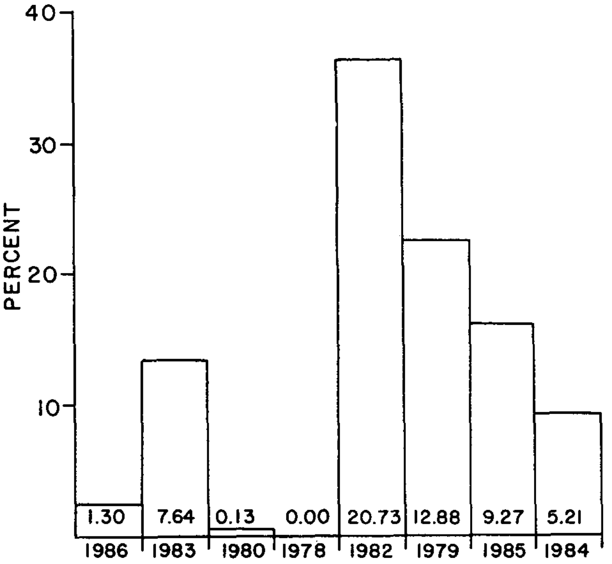

FIG. 7. Blue Canyon January–March precipitation from cold westerly storms as a percent of the January–March eight-year total from such storms, 1978–86 except 1981. Numbers represent estimated precipitation (millimeters).

5. Summary and conclusions

As well as being colder than storms of midwinter, storms in late winter and spring exhibit changes in cloud structure. For example, summarized PETs reflect a greater frequency of deep, stable cloud systems in January and a greater frequency of orographically enhanced, shallow cloud systems by March (Fig. 4). These changes in PET prevalence agree with Pyke's (1972) satellite observations that warm frontal cloud shields are common in early winter, giving way to shallow, postfrontal cloud systems by late winter and spring. The increasing frequency of orographically enhanced PETs from January to March also agrees with the trend of rawinsonde saturation from Table 2, reflecting shallower cloud systems later in the season. The increasing frequency of orographically enhanced PETs in March is significant because these PETs usually represent postfrontal conditions that SCPP has investigated because of higher supercooled liquid water content within the clouds.

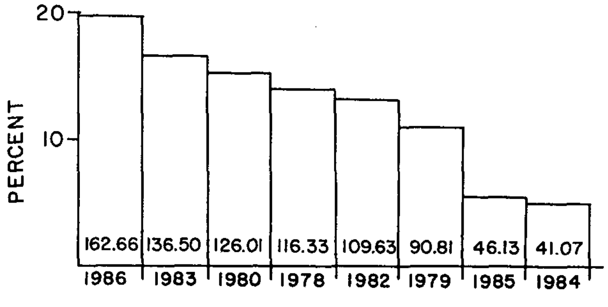

FIG. 6. Blue Canyon January–March precipitation in each year as a percent of the January–March eight-year total precipitation, 1978–86 except 1981. Numbers represent measured precipitation (millimeters).

A seeding program of only the cold westerly storms, as suggested by Mooney and Lunn (1969), would tend to target late winter and spring storms more often than midwinter ones. This trend is supported by the distribution of precipitation during eight 3-month seasons of the SCPP. For example, about half of the precipitation associated with the cold westerly events fell during March, although the month provided only 31% of the overall precipitation.

An anticipated increase in late winter and spring snowpack, compared to late fall through midwinter, should have favorable hydrological results. The increase would occur near the end of the precipitation season, and much of the water would run off after the precipitation season had ended. Since warm over-running storms and associated heavy rains are not common at this time of year, snowmelt is not likely to coincide with heavy, rain-induced runoff.

Increases in the early or midseason snowpack due to cloud seeding, on the other hand, might increase runoff into streams already high from winter rains and snowmelt. Winter temperatures in the Sierra Nevada are seldom cold enough to prevent snowmelt (Fig. 2), and frequent midwinter rain (Fig. 3) sometimes accelerates this process. In midwinter there is a chance that seeding of cold westerly storms might increase runoff problems, should warm rains follow. The risk is smaller in March and April, when storms of subtropical origin diminish in frequency and the extent of the winter snowpack is known.

Based on eight SCPP seasons, a strategy to seed only the cold westerly storms should result in more opportunities during seasons of normal and below-normal precipitation than in above-normal seasons. In fact, despite large precipitation totals overall, the above-normal years had very few cold westerly storms. This interannual variation, with greater prevalence of cold westerly storms in drier years, favors optimal water management. In above-normal years, when additional runoff was least needed, such storms were less common. They were more common in years when seeding was most needed, in normal and below-normal years.

Acknowledgments. The author wishes to acknowledge all of the participants from the Sierra Cooperative Pilot Project in Auburn, California, especially those from Electronic Techniques, Inc. and the Bureau of Reclamation. Special thanks go to Dr. Robert Rauber, Mr. Arlen Huggins and Ms. Carol Wilcox who assisted in the drafting of the figures and the preparation of the manuscript. This research was funded by the Bureau of Reclamation, Department of the Interior, under Contract No. 4-CR-81-03860.

REFERENCES

Heggli, M., and D. W. Reynolds, 1985: Radiometric observations of supercooled liquid water within a split front over the Sierra Nevada. *J. Climate Appl. Meteor.*, **24**, 1258–1261.

——, L. Vardiman, R. E. Stewart and A. Huggins, 1983: Supercooled liquid water and ice crystal distributions within Sierra Nevada winter storms. *J. Climate Appl. Meteor.*, **22**, 1875–1886.

Kuciauskas, A. P., 1986: Use of radar in forecasting seedable conditions for the SCPP. *Preprints, 10th AMS Conf. on Weather Modification*, Arlington, Amer. Meteor. Soc., 50–60.

Mooney, M. L., and G. W. Lunn, 1969: The area of maximum effect from the Lake Almanor randomized cloud seeding experiment. *J. Appl. Meteor.*, **8**, 68–74.

Namias, J., 1950: The index cycle and its role in the general circulation. *J. Meteor.*, **7**, 130–139.

Pyke, C. B., 1972: Some meteorological aspects of the seasonal distribution of precipitation in the western United States and Baja California. Ph.D. thesis, University of California at Los Angeles, 204 pp.

Trewartha, G. T., 1961: *The Earth's Problem Climates*, Chaps. 17–19. The University of Wisconsin Press, 251–292.

Williams, P., Jr., and E. L. Peck, 1962: Terrain influence on precipitation in the Intermountain West as related to synoptic situations. *J. Appl. Meteor.*, **1**, 343–347.