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CLIMATIC TRENDS OF SIERRA NEVADA CLOUD SEEDING POTENTIAL

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ABSTRACT

Seasonal and interannual variations in Sierra Nevada winter storms are discussed with reference to cloud seeding potential. Seasonal variations occur with respect to snow level, storm type, vertical cloud distribution and mesoscale precipitation systems. Snowmelt and runoff may compound the importance of these seasonal variations. Interannual fluctuations, based on eight years of data from the American River Basin, suggest that seedable conditions are more frequent in years of normal and below-normal precipitation than in above-normal years.

1. Introduction

Seasonal and interannual variations in Sierra Nevada winter storms may have large effects on seeding potential. Such variations occur with respect to snow level, storm type, vertical cloud distribution and mesoscale precipitation systems. Seasonal and interannual fluctuations can also promote or retard snowmelt or runoff. As will be shown, variations in these hydrological parameters may compound the importance of concurrent variations in seeding potential.

1.1 Literature Review

Examining 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 water, but over land often developed a well-marked cold frontal band and extensive post-frontal convection. Pyke suggested that precipitating clouds at a significant distance ahead of a spring cold front are usually confined below approximately 800 millibars, 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 concerning the increased prevalence of cold frontal precipitation in spring may imply better seeding potential at that time of year. Recent scientific evidence from the Sierra Cooperative Pilot Project (SCPP) suggest that post-cold frontal conditions offer the best opportunities for seeding. Heggli and Reynolds (1985) documented from a passive microwave radiometer the seedability of a split front (a type of cold front sometimes called a "katafront") over the Sierra crest. Their study analyzed a shallow moist zone containing high amounts of supercooled liquid water (SLW) following the passage of an upper cold front but before the surface front. Comparison of in-situ radiometer and radar data revealed large increases in SLW after cold frontal bands passed Kingvale, a station near the Sierra Crest (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 twelve-hour experimental periods were averaged from 1525 meters to 3050 meters (5000 to 10,000 feet). Then twelve-hour experimental periods were termed southerly if the 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 meters (7,500 feet) and cold if below. During seeded events (1962-1967) a 37% increase in precipitation was recorded for the cold westerly category, significant at the .05 confidence level. Seeding only the cold westerly storms, which accounted for about 15% of annual precipitation, would increase runoff by about 5%; no other category showed a significant increase.

The cold westerly category of Mooney and Lunn should contain a high percentage of the apparently seedable post-cold frontal conditions studied by Heggli and Reynolds, and Kuciauskas. The cold temperature requirement and the westerly wind requirement filter out most prefrontal events with a relatively warm lower atmosphere, a southerly wind component, or both. The same two requirements tend to include post-cold frontal conditions. Behind Sierra cold fronts, wind direction tends to veer from southerly to westerly at the wind direction classfication levels. Thus, the large seeded increases in the cold westerly category found by Mooney and Lunn may have resulted from elevated levels of SLW which often accompany post-cold frontal conditions.

Data from the SCPP are used here to investigate the effects on seeding potential of seasonal and interannual variations in atmospheric structure. For the SCPP, conducted in the American River Basin in California (Fig. 1), rawinsonde and radar measurements were taken at Sheridan (elevation 60 meters); NWS personnel took conventional observations at Blue Canyon (elevation 1,610 meters).

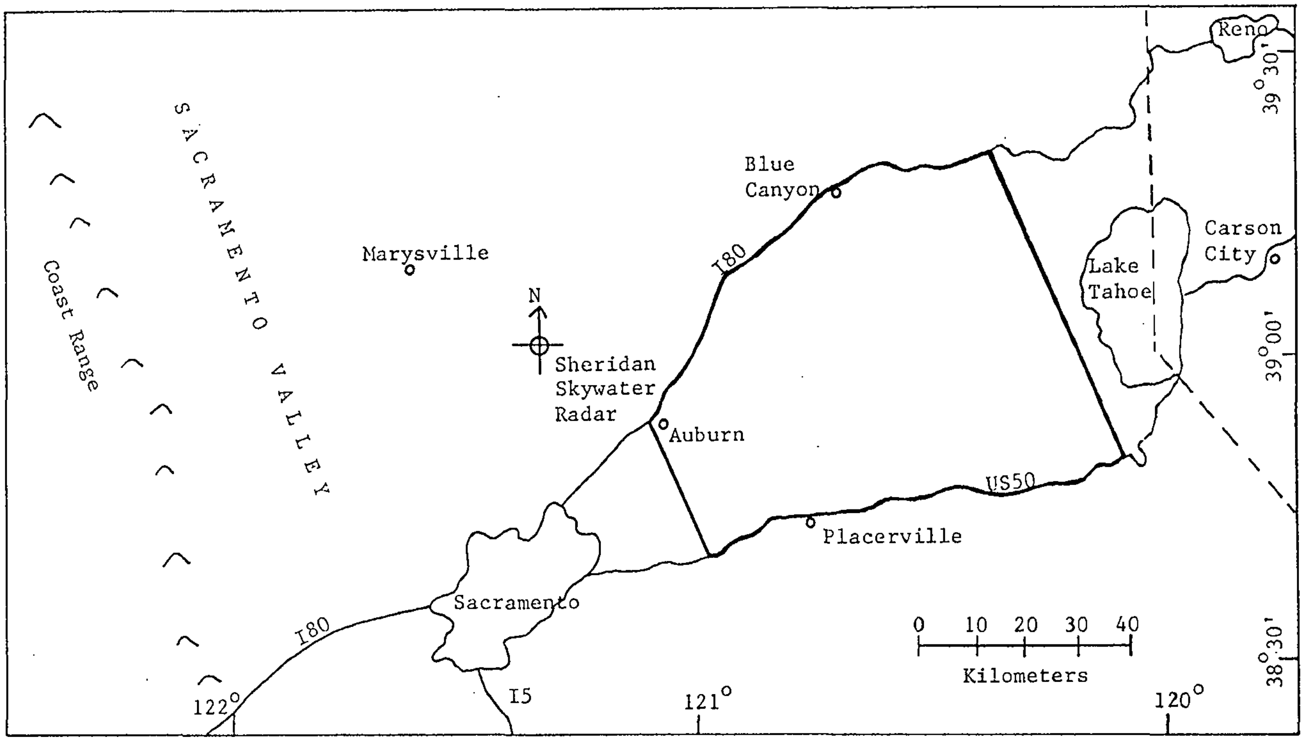

Fig. 1. Study Area of the Sierra Cooperative Pilot Project (SCPP).

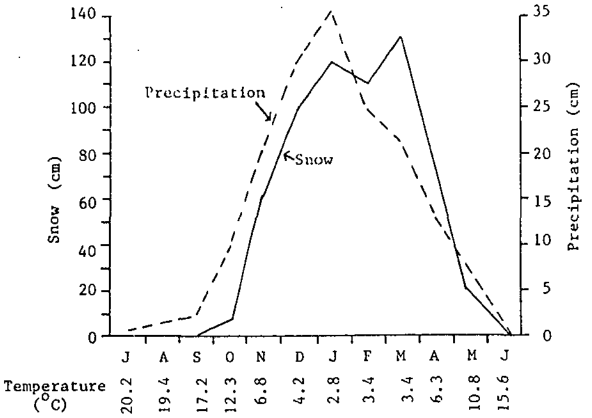

Fig. 2. Normals of Precipitation (1940-1985), Snow (1941-1985) and Temperature (1941-1985) at Blue Canyon by month.

2. Seasonal Variations

2.1 Precipitation, snowfall and temperature

At Blue Canyon snow is much more likely in the latter portion of the precipitation season (Fig. 2). January is the coldest month of the year and receives the most precipitation, but March, which is slightly warmer and averages 13.08 less precipitation, receives more snow. (Precipitation is defined here as liquid equivalent--rain plus melted snow.) The same trend is illustrated by the relative proportions of rain versus snow from visual observations of precipitation, from January 1976 through April 1986. Data for April 1976, 1977 and 1979 were missing, also March 1979. The data set included observations at three times of day (07, 10 and 13 PST) on five days a week.

The data were sorted into three categories: liquid types (e.g., rain, rain shower, drizzle, thundershower, etc.), frozen types (e.g., snow, snow pellets, freezing drizzle, etc.), and mixed liquid and frozen particles (Fig. 3). Liquid precipitation appears over half the time in November, then decreases during the winter and early spring. By March and April, liquid precipitation appears in only about a quarter of all the observations. Frozen precipitation shows the opposite trend: barely one third of the observations show frozen precipitation in November; in March and April this percentage increases to more than two thirds. Mixed precipitation shows no consistent trend.

From January through March, rawinsondes at Sheridan were flown every three hours during storm periods from 1978 through through 1986, 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. All three isotherms are lowest in March and highest in February. The change in the 0°C level from February to March is especially dramatic, dropping from 2020 m in February to 1750 m in March. The results help explain the higher prevalence of March snow at Blue Canyon compared to January and February (Fig. 3).

2.2 Cloud structure

The vertical distribution of cloud from rawinsonde measurements also shows seasonal differences. Interpolated at 200 m, temperature, dewpoint and frostpoint were used to determine the presence of cloud at each level. Clouds were assumed to be ice saturated if the frostpoint depression was .2°C or less; water

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Table 1

Mean Sheridan Temperature Profiles (C)
During Storm Periods

Jan-Mar 1977-1986 except 1981

Height	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	
3700	-10.1	-9.8	-11.6	
3600	-9.5	-9.2	-11.0	
3500	-8.9	-8.6	-10.3	
3400	-8.3	-8.0	-9.7	-10°C
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	
2800	-4.7	-4.5	-6.3	
2700	-4.2	-3.9	-5.7	
2600	-3.6	-3.3	-5.2	
2500	-3.0	-2.8	-4.6	-5°C
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	
2000	-0.2	0.1	-1.6	
1900	0.4	0.7	-1.0	
1800	1.0	1.2	-0.3	
1700	1.5	1.8	0.3	0°C
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	

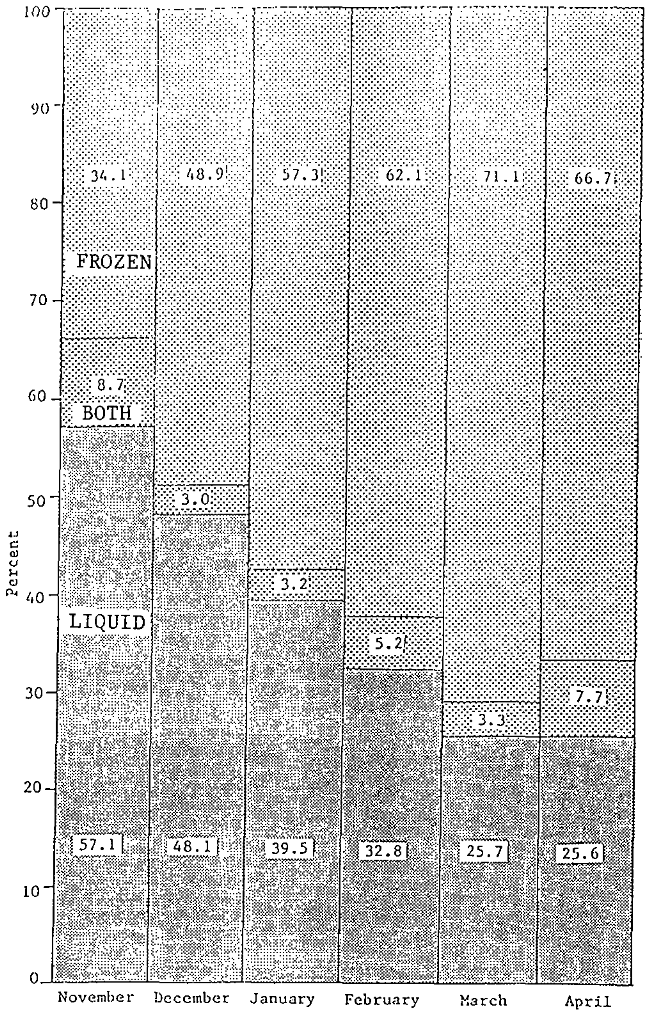

Fig. 3. Percent of Blue Canyon visual reports of precipitation as (1) liquid, (2) frozen and liquid and (3) frozen, January 1976 through April 1986.

Table 3

Percent Contribution to January-March Blue Canyon Precipitation and Snowfall, 1978-1986, except 1981, by Storm Class and by Month

	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

	January	February	March	Total
Liquid Equivalent	28.2	40.4	31.4	100.0
Snowfall	21.7	37.6	40.7	100.0

Table 2

Percent of Sheridan Soundings at Ice Saturation During Storm Periods

1978-86 except 1981
*indicates maximum value

Level Meters	January	February	March
	Percent		
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
7000	11.3	11.7	4.1
6800	12.6	13.6	4.6
6600	13.6	15.4	6.2
6400	15.1	17.6	6.7
6200	15.9	17.6	9.1
6000	16.1	19.9	10.1
5800	19.0	21.6	11.5
5600	19.9	22.3	14.3
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
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
3200	26.3*	31.7	31.6
3000	26.1	32.6	30.4
2800	23.6	33.3*	29.6
2600	21.7	28.3	30.6
2400	19.2	26.1	32.8*
2200	14.8	21.2	32.4
2000	11.3	14.1	24.0
1800	9.0	9.7	17.4
1600	6.7	5.2	12.9
1400	4.8	1.9	6.6
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

saturation was assumed with a dewpoint depression of .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 high frequency of deep precipitation systems in January and February is indicated by the high frequency of ice saturation above 4500 m (Table 2). By March, such systems occur less often and the frequency of clouds at these altitudes diminishes. At the cirrus level of 7600 m, for example, saturated conditions are more than three times as common in January and Feburary as in March. Near the surface, however, the trend is reversed. The frequency of ice saturation is 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

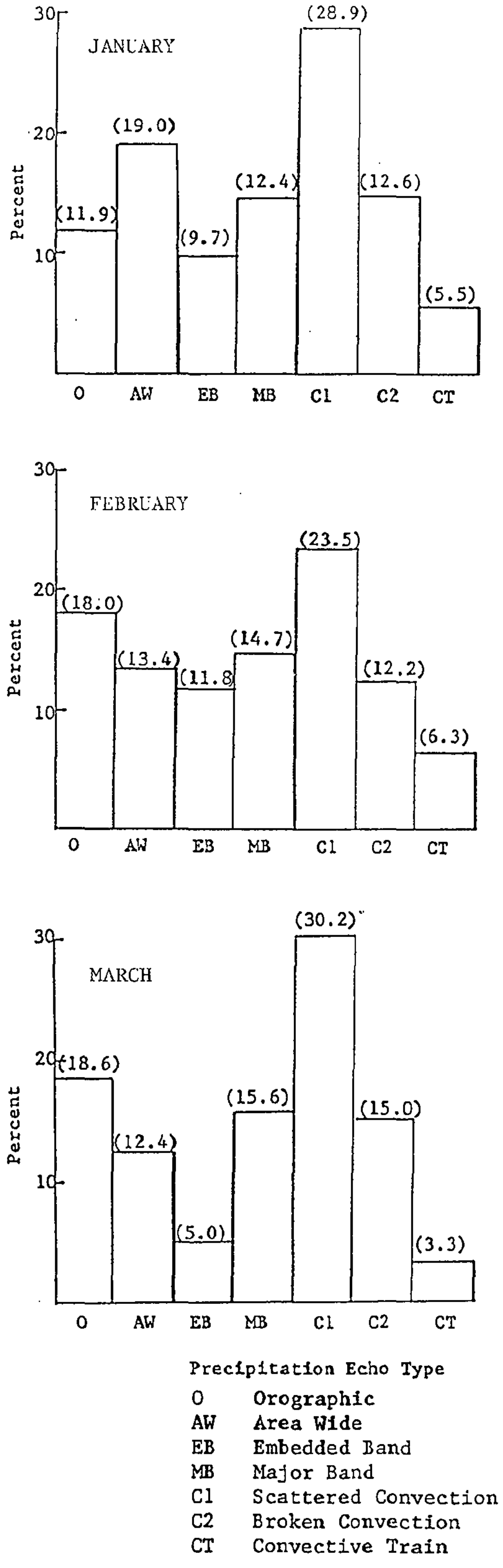

Fig. 4. Percent occurrence of PETS by month, 1977-1985, except 1981.

asterisks): 3200 m in January; 2800 m in February; 2400 m in March. The results support Pyke's observation that cloudiness from late winter and spring storms tends to occur closer to the surface than in earlier months.

2.3 Radar patterns

Seasonal trends discussed by Pyke are also reflected in precipitation echo type (PET) prevalence. Half-hour 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). PETS indicative of deep stable lifting--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 (Fig. 4). 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.

2.4 Storm classification

To investigate the effects of seasonal trends on seeding potential, SCPP Sheridan soundings were sorted into the four 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 is reported; SCPP gauges in the vicinity report only liquid equivalent. Precipitation and snow during the three-hour period covered by a sounding was estimated by multiplying the daily amounts by 3/24 (0.125). These estimates were summed for each classification, 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 (1962-1967), reported by Mooney and Lunn (1969). Lake Almanor, well north of the American River Basin, may be subjected to a larger proportion of cold storms. Cold westerly storms contributed a substantially larger percentage, 15.1%, of snowfall at Blue Canyon (Table 3). February yielded the largest share of the liquid precipitation during the period while March yielded the largest share of the snow.

Fig. 5 summarizes each classification by month. For the cold westerly category March contributed nearly half of the three-month total. For the cold southerly category the month contributed nearly two-thirds, suggesting a high prevalence of coastal cutoff lows, which tend to classify as cold southerly, combining 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.

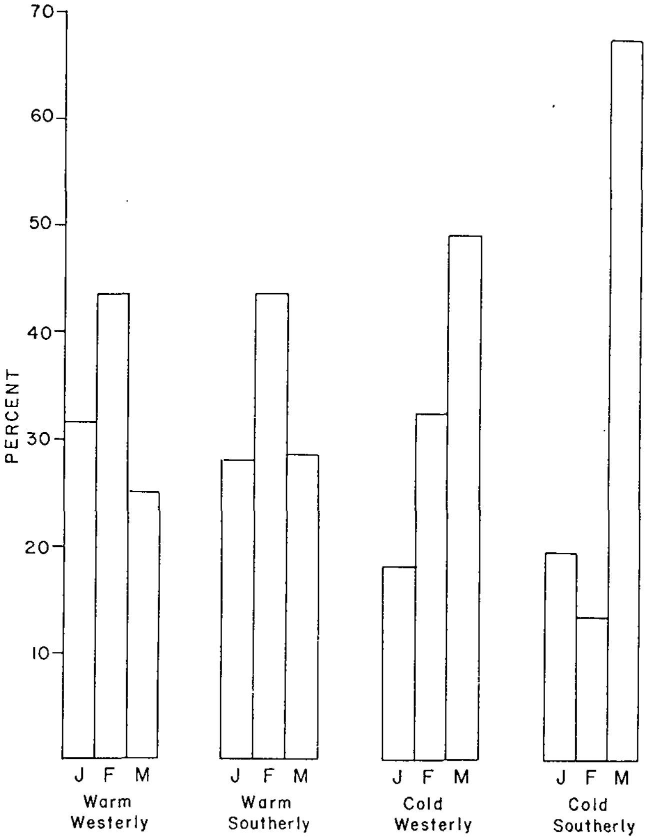

Fig. 5. Distribution by month of precipitation within the four categories of Mooney and Lunn (1969). The sum over each classification is 100%. Based on Blue Canyon precipitation, January-March 1978-86 except 1981, and Sheridan rawinsondes, same period.

3. Interannual Variations

During the eight seasons considered (1978-1986, except 1981), precipitation totals varied significantly. The wettest four seasons contributed 65.3% of the eight-year 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.

4. Summary and Conclusions

An effective seeding program of only the cold westerly storms, as suggested by Mooney and Lund (1969), would tend to bring larger precipitation increases in late winter and spring than during midwinter. This trend is supported by the distribution of precipitation during eight three-month seasons of the SCPP. About half of the precipitation associated with the cold westerly events fell during March, although the month provided only 31% of the overall precipitation.

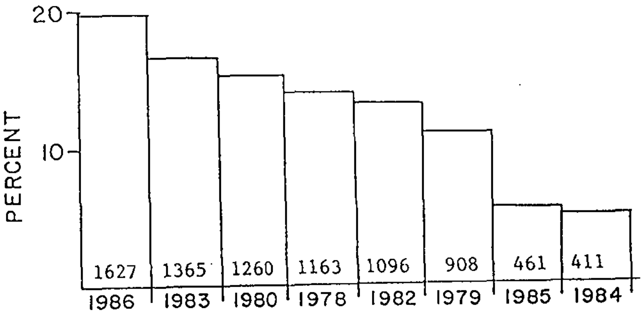

Fig. 6. Blue Canyon January-March precipitation in each year as a percent of the January-March eight-year total precipitation, 1978-86 except 1981. Numbers represent measured precipitation (mm).

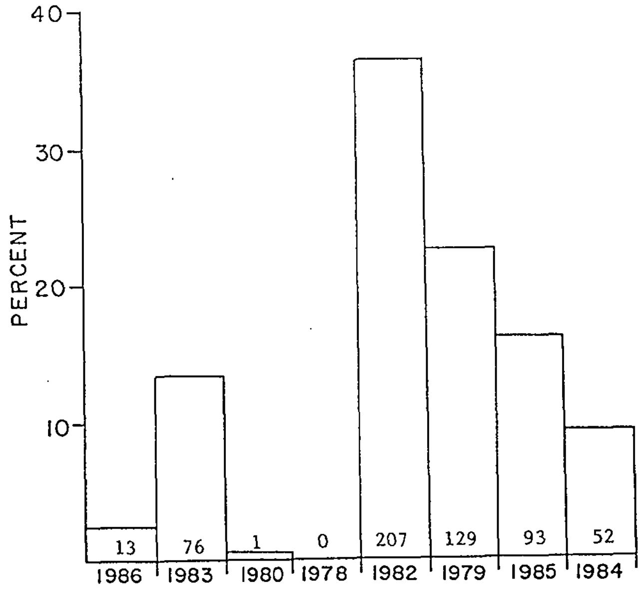

Fig. 7. Blue Canyon January-March precipitation from cold westerly storms as a percent of the January-March eight-year total from such storms, 1978-86 except 1981. Numbers represent estimated precipitation (mm).

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

Seeded increases in the early or mid-season snowpack, 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 fact, Pyke (1972) documents that excessive winter rains in California caused by warm, southwesterly storms have often been preceded by colder, snowier storms from more northerly latitudes. In two extreme cases the sequence worsened flooding, as warm rains melted heavy snowpack. All five examples of this storm type transition discussed by Pyke occurred from December through February, none in March or April. Thus, 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, effective seeding of the cold westerly storms only should lead to greater increases in precipitation in normal and below-normal seasons than in above-normal seasons. In fact, despite large precipitation totals overall, the above-normal years had relatively little potential for increases from cold westerly storms. This interannual variation, with greater prevalence of cold westerly storms in drier years, favors optimal water management from effective seeding of the cold westerly events. 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.

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