MONTHLY VARIATIONS OF THE PRECIPITATION-ALTITUDE RELATION IN THE CENTRAL SIERRA NEVADA OF CALIFORNIA.

By B. M. VARNEY.

[University of California, Oct. 19, 1920.]

SYNOPSIS.

Study of the precipitation data for a series of stations across the central Sierra Nevada of California indicates that the rate of increase of precipitation with altitude varies throughout the year in a well-defined progression from smallest rate in summer to greatest in winter. Similarly, the rates of decrease in the zone above the level of maximum precipitation, and in the zone from the summit down the leeward slope are smallest in midsummer and greatest in midwinter.

It is suggested that the observed seasonal variations are probably the result of seasonal differences in the relative humidity of the air currents involved, and that, if this be true, well marked seasonal variations in the precipitation-altitude relation may be a general characteristic of regions having pronounced wet and dry seasons.

The precipitation-altitude relation for the Sierra Nevada of California has been discussed in various connections during recent years. Lee,[1] in work for the feet of added elevation up to the zone of maximum at some 5,000 to 6,000 feet, above which there is a decrease toward the crest of the mountains and down on the leeward side. This zone of maximum becomes higher from north to south along the Sierra.

In the course of preparing data for monthly precipitation maps of California, the writer's attention was drawn to the fact that the precipitation-altitude relation is here by no means constant throughout the year. The mean annual rate of increase divided by 12 can not be used in the drawing of monthly charts. It became necessary, therefore, to determine how the rate varies from month to month. This has been done for the central Sierra, using the often-referred-to string of stations along the line of the Southern Pacific Railroad from Sacramento,

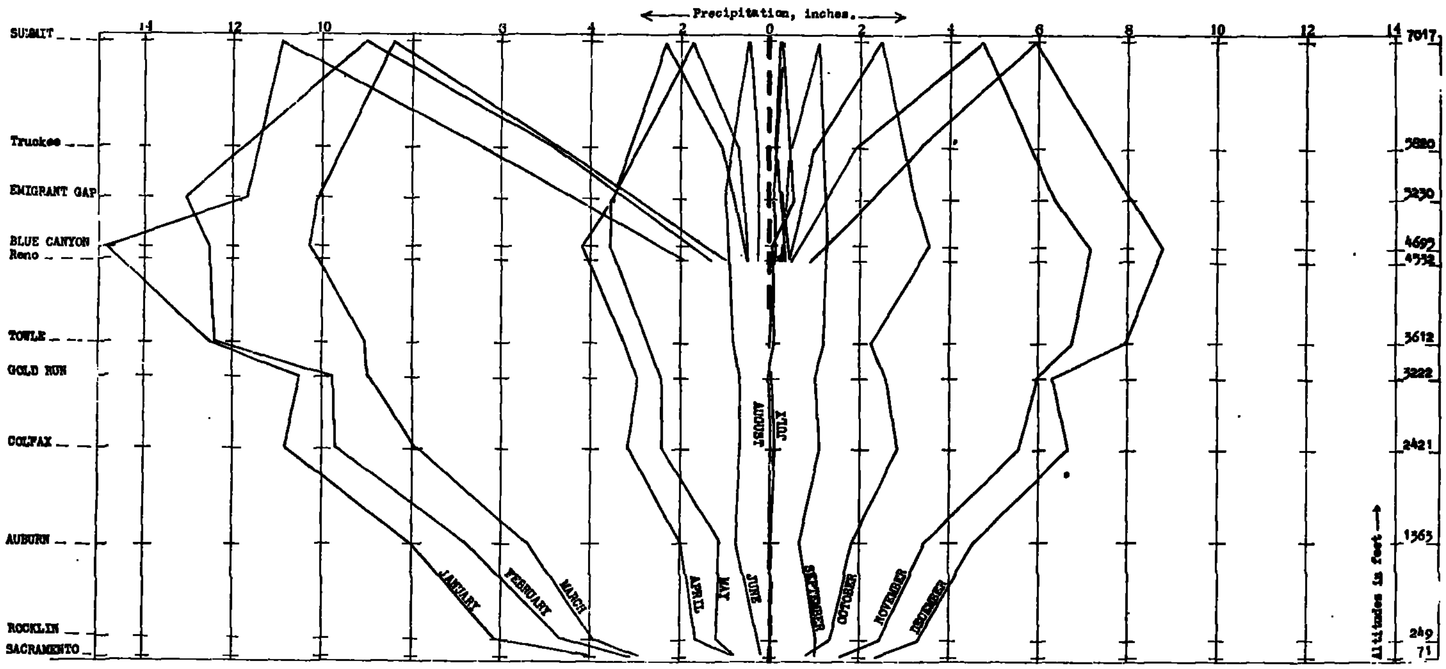

FIG. 1.—The monthly amounts of precipitation for 11 stations in the central Sierra Nevada of California. Stations arranged according to their altitudes. Precipitation scale reads from 0" in the middle toward both right and left. Stations on windward slope in capital letters, on leeward slope in small letters.

Los Angeles aqueduct, McAdie [2] in his paper on the Rainfall of California, Henry [3] in a recent survey of the precipitation-altitude relation throughout the world, and others,[4] have contributed to our appreciation of the importance of orographic control of precipitation. For California, this control is a vital thing in the life of the State. Without it, reclamation of vast areas of the Great Valley by irrigation would have been impossible. Hydroelectric power for lighting, pumping, railway operation, manufacturing, is abundantly available (though not yet adequately developed to meet California's needs in long periods of deficient precipitation), because of the fact that precipitation increases rapidly from the west base of the Sierra up to a zone maximum amount. The annual value of this increase is about 0.9 inch per 100

[1] Lee, C. H., MONTHLY WEATHER REVIEW, July, 1911, 39; 1039.
[2] McAdie, A., The Rainfall of California (Univ. Calif. Pub. Geog., 1914, vol. 1, pp. 127-240).
[3] Henry, A. J., Increase of Precipitation with Altitude (MONTHLY WEATHER REVIEW, 1919, vol. 47, No. 1, pp. 33-41).
[4] See paper by A. J. Henry (loc. cit.) for numerous additional references.

Calif., to Reno, Nev. The facts indicated by the graphs herewith are somewhat more striking than the preliminary inspection of the data seemed to show.

Figure 1 is a plat of the mean monthly precipitation for the 11 stations used, arranged according to their altitudes in the vertical scale. The precipitation scale runs from 0 inch in the middle of the diagram to 15 inches toward both right and left. This arrangement allows the months to appear in order across the figure and so far as possible avoids the confusion that would result from the use of a one-way scale. All stations from base to summit on the windward side of the Sierra are in capital letters, stations on the leeward side in small letters. The period on which the means are based is 20 years ending 1919. Several stations, hitherto used in discussions of the mean annual precipitation-altitude relation, have been omitted in the present study. Of these, Iowa Hill at 2,825 feet elevation on the windward side of the mountains was discontinued in 1910.

Cisco (5,939 feet, windward), Boca (5,531 feet, leeward), and Fernley (4,150 feet, leeward) were closed at various times during 1916 on account of faulty record. The precipitation at two stations with short periods, but very necessary in a series where the number of stations is small at best, was reduced to the 20-year period by the usual method: Rocklin, 17 years, reduced by Sacramento, and Emigrant Gap, 14 years, reduced by Blue Canyon.

TABLE 1a.—*Average monthly rates of increase of precipitation with altitude, from windward base station to level of maximum precipitation.*

Month.	Altitude difference.		Rate.	
	Feet.	Meters.	Inches per 100 feet.	Millimeters per 100 meters.
January	4,624	1,409	0.232	19.3
February	4,624	1,409	0.201	16.7
March	4,624	1,409	0.161	13.4
April	4,624	1,409	0.074	6.1
May	5,159	1,572	0.055	4.6
June	5,159	1,572	0.014	1.2
July	6,946	2,117	0.004	0.3
August	5,159	1,572	0.010	0.9
September	4,624	1,409	0.005	0.4
October	4,624	1,409	0.058	4.8
November	4,624	1,409	0.120	10.0
December	4,624	1,409	0.134	11.4

TABLE 1b.—*Average monthly rate of decrease of precipitation, from level of maximum precipitation to Summit, windward.*

Month.	Altitude difference.		Rate.	
	Feet.	Meters.	Inches per 100 feet.	Millimeters per 100 meters.
January	2,322	708	0.168	14.0
February	2,322	708	0.153	12.7
March	2,322	708	0.079	6.5
April	2,322	708	0.075	6.2
May	2,322	708	0.079	6.5
June	1,718	545	0.023	5.4
July	0	0	0	0
August	1,787	545	0.019	1.6
September	2,322	708	0.008	0.7
October	2,322	708	0.048	3.9
November	2,322	708	0.104	8.6
December	2,322	708	0.122	13.7

TABLE 1c.—*Average monthly rate of decrease of precipitation, from Summit to base station, leeward.*

Month.	Altitude difference.		Rate.	
	Feet.	Meters.	Inches per 100 feet.	Millimeters per 100 meters.
January	2,485	757	0.363	30.3
February	2,485	757	0.312	25.8
March	2,485	757	0.302	25.1
April	2,485	757	0.075	6.2
May	2,485	757	0.050	4.2
June	2,485	757	0.010	0.8
July	2,485	757	[1] 0.006	0.5
August	2,485	757	[1] 0.006	0.5
September	2,485	757	0.031	2.6
October	2,485	757	0.082	7.0
November	2,485	757	0.170	14.1
December	2,485	757	0.196	16.4

[1] Increase.

A study of the figures and the table emphasizes several facts, which may be stated with reference to the three zones of precipitation indicated: First, the zone from the base station up to the approximate average level of maximum precipitation on the windward slope, Blue Canyon, at 4,620 feet, being the station nearest to the actual level of the maximum for most months; second, the zone between the level of the maximum and the highest station of the series (Summit, at the crest along the line of the railroad); third, the zone from Summit down the leeward slope of the Sierra to Reno.

For the first zone it is evident that a mean of all the monthly values of the precipitation-altitude relation is not even approximately that of a given month. In place of monthly values oscillating but slightly on either side of a mean, there is a gradual though somewhat irregular progression from the maximum rate of increase in the midwinter to the minimum rate in midsummer, followed by an increase toward the succeeding midwinter. Or, in terms of the seasonal subtropical régime of precipitation, which largely influences most of the important activities of California, the rate is least in the dry season and greatest in the middle of the rainy, with all gradations between.

For the second zone, the windward zone of decreasing precipitation, the same sort of relation holds. The rate of decrease, at its maximum in January, declines slowly

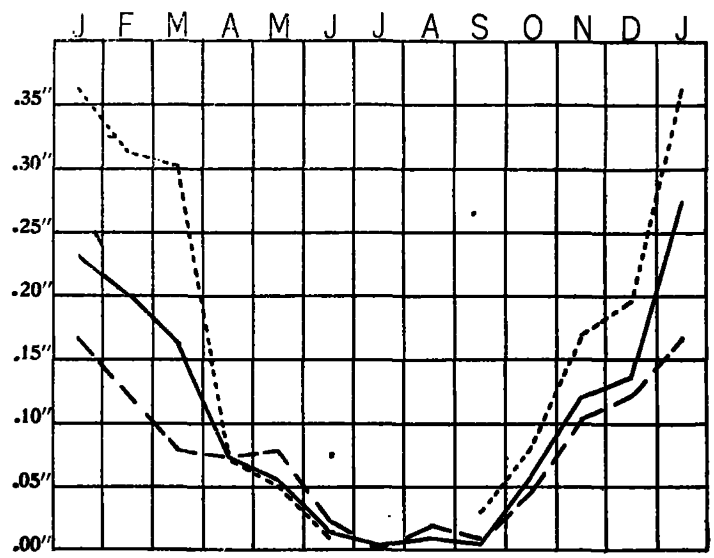

FIG. 2.—The monthly variations of the precipitation-altitude relation, central Sierra Nevada of California, in hundredths of an inch change per 100 feet difference of elevation. Data from table 1.
Solid line=average rate of increase between base stations and zone of maximum precipitation, windward slope.
Broken line=average rate of decrease between zone of maximum precipitation and summit, windward slope.
Dotted line=average rate of decrease, summit to base station, leeward slope.

through February and March, and then very rapidly. The almost negligible rate of decrease of the midsummer months is succeeded by the progressively more rapid decrease of the autumn and early winter.

For the third zone, that of decreasing precipitation on the leeward side of the Sierra, the general fact is evident that in addition to the similarity as to rates of change through the year as compared to the other zones, the rate for most months is much greater than in the zone of decrease on the windward side.

Reference to figure 2, in which are shown the average monthly rates of change for the three zones, in hundredths of an inch of precipitation per 100 feet of change in elevation, as set out in the table, will make the above facts clearer. Only April to June, inclusive, and September-October, show essentially the same rate of change for all three zones. The zone of increase (solid line) shows a rate of change that is, broadly speaking, midway between the rates in the windward and leeward zones of decrease.

Further details of the relations between the rates in the different zones are obvious from the figure.

A number of other points in connection with figure 2 may be mentioned. The break in the dotted line for the leeward decrease zone is made necessary by the fact that for July and August the decrease with lessening altitude is replaced by an increase, when the whole zone from Summit to Reno is considered. Decrease holds at least as far down the leeward slope as Truckee (1,179 feet below the summit), but at Truckee or beyond, an increase begins, in spite of the fact that Reno has, like all the other stations in this series, a pronounced midwinter maximum of precipitation. Reno has also, however, a slight midsummer secondary maximum, the rainfall of which, though small in amount, is not as scanty as the summer rains of higher altitudes.

A second point of interest concerns the high altitude rains just mentioned. They are thunderstorm rains, and they cause a slight increase in the rates of change of precipitation with altitude in August, in the midst of a season otherwise characterized by rates of change so small as to practically negligible. Cyclonic control of precipitation is at a minimum in this season, so that even the small amount of water vapor condensed in the convectional updrafts over the mountains (small by reason of the very low initial relative humidity of these ascending currents) is sufficient to cause the observed effect. The rate of increase is not adequate to cause a secondary summer maximum of precipitation in the mountains, nor would it occur at all were not the Great Valley and foothills almost absolutely rainless. This very slight increase is a good index to the character of the "dry" Sierra thunderstorms. What these storms lack in moisture they compensate for by the destructiveness of their lightning, whereof the most important consequence is the starting of many forest fires, which would never achieve their devastating power were the thunderstorm rainfall commensurate with the convectional activity displayed.

A third item of interest is the rapid rate of increase of precipitation between the base station and the first station in the Sierra foothills, only 178 feet higher than the base station. This increase is more rapid than in any other part of the cross section, for every month, and it takes place in the flattest part of the section—in other words, in that part where local topography would be expected to have the least influence. This suggests that it is probably due to the growth westward, of the thickened cyclonic cloud mass over the mountains and foothills, thus extending the influence of the Sierra as a rain maker some little distance out over the Great Valley. This thickening and westward growth is probably due to the action of the air currents under either one or both of the following conditions: It is conceivable that even in the very obtuse angle formed by the almost dead-level surface of the valley and the sloping surface of the Sierra a retarding and banking up of air may occur (similar to that observable in an air current on the windward side of a high fence), probably aided by friction over the increasingly rough country of the foothills. Or, a similar banking up may be induced by the obstruction offered to the general flow of air by increased convection resulting from the more rapid condensation at higher altitudes over the mountains. In either case the upward slope of the overpassing air currents would not begin over the foothills but to the west of them, with consequent increased precipitation in the valley as observed.

The cause of the great seasonal fluctuation in the rates of change is an important item. It can not lie in monthly variations in the numbers of cyclones crossing the area, because in a given month that is the same for both mountains and valley. It probably lies in the higher initial relative humidity of the moisture-bearing cyclonic winds (S., SE., SW.) from the Great Valley in the winter as compared to the summer. This seasonal difference in relative humidity is very great. Sacramento at 5 p. m. (local time) in January has a mean relative humidity of 75 per cent, in July of 36 per cent. For Fresno, further south, and not under the influence of the damp winds flowing through the break in the coast ranges at San Francisco Bay, the percentages are 70 and 14, respectively. Another factor that may have some influence in producing more condensation in winter is the snow cover in the mountains. It might seem that this should be a very important factor, but temperature differences between the valley and the zone of maximum in January and July suggest that it is not. The difference between the mean temperatures at Sacramento and Blue Canyon in January is 8 degrees F., and in July is 8.4 degrees F.

The question arises as to whether the strong seasonal swing of the precipitation-altitude relation here described may not be a characteristic of many regions having marked seasonal types of rainfall. If relative humidity is the controlling factor, it would seem that this character should hold for any region where, in addition to the systematic advance and retreat of a belt of rains, the intervening dry seasons bring on sharp contrasts in the relative moisture content of the air.

Finally, the changes in the elevation at which the maximum precipitation occurs is of interest. The generally accepted view that this level is higher in summer and lower in winter, with gradations between, seems, for the central Sierra at least, to be true only in part. Blue Canyon at 4,695 feet is the station nearest the level of maximum from September to April with the exception of February. Pronounced upward tendency begins in May, when Emigrant Gap at 5,230 feet and Blue Canyon have the same rainfall. The level rises to its greatest height (Summit, 7,017 feet) in July, after which it declines again to Blue Canyon by September. For the major part of the precipitation season, there is, so far as our sparse data show, no change except a contrary one in February, up instead of down. Nevertheless, judging from the trend of relative humidity values in the valley (pronounced midwinter maximum, summer minimum) the level should decline consistently toward the middle of the season and rise thereafter. It could descend some 540 feet below Blue Canyon before appearing as a maximum in the data for the next station below, at 3,612 feet. At the best, then, any lowering of the level there may be during the months whose precipitation counts most, is small compared to the rise in the summer months. The scarcity of stations makes it impossible to determine with any approach to accuracy what the real behavior of the level is during the greater part of the rainfall season.