R50-23

1 copy only

[Reprinted from BULLETIN OF THE AMERICAN METEOROLOGICAL SOCIETY, Vol. 31, No. 8, October, 1950, pp. 295-299]
Printed in U. S. A.

Insolation and Snow Melt in the Sierra Nevada *

DAVID H. MILLER

Cooperative Snow Investigations, So. Pacific Div., Corps of Engineers, Oakland, Calif.

ABSTRACT

The role of solar radiation in processes causing melting of a deep snow pack in the Sierra Nevada in 1946 was found important, both in direct absorption and as source of heat relayed to the snow by forest canopy and other elements in the environment of the snow.

INTRODUCTION

INSOLATION, weather, snow pack, and stream flow in a mountain valley during the water year 1945–46 were studied by the Cooperative Snow Investigations, under joint auspices of the Corps of Engineers and the Weather Bureau. Observations were made at the Central Sierra Snow Laboratory, reduced and studied in the Processing and Analysis Unit, and reported as *Technical Report No. 5.*

The snow laboratory is a small mountain basin near Donner Pass, California, consisting of a rolling glaciated granite and lava surface between 6,900 and 9,100 feet altitude with a scattered cover of sub-alpine forest [5]. Most of the observations were made at headquarters, at the basin outlet, where standard temperature, wind, and precipitation data were obtained, supplemented by Eppley pyrheliometer measurements of solar radiation, both incoming and reflected from the snow surface, observations of temperature and wind within and above the forest, and measurement of flow of liquid water out of the 4 square mile basin. Snow pack over the basin was surveyed by 16 field stations (see map, FIG. 1).

SUMMARY OF SEASON

Weather during 1945–46 did not differ significantly from the long-term average of Sierra crest climate except insofar as the snow pack was established earlier, suffered less attrition, and melted more rapidly under the cloudless skies of late spring with little complication from late storms. Early winter was stormy, daily values of the zonal index to the westerly circulation being below normal 60% of the time; two-thirds of the year's precipitation of approximately 60 inches fell before the end of December. In January and February the index was above normal 76% of the time and the weather was cold and dry, preserving the deep pack, which was again increased by March precipitation to an average over the basin of 50 inches water equivalent. On 10 April came a sharp increase in insolation, hence also in air temperature; the zonal index was above normal 60% of the time; a succession of clear warm days continued on into the dry summer with but few breaks. This weather was ideal for studying melt caused by high insolation and resulting high daytime temperatures, with little complicating effect of the advection of warm, humid, cloudy air over the snow fields. At this time a northerly position of the east end of the Pacific anticyclone was closely associated with rises in the runoff hydrograph from accelerated snow melt.

HEAT

Prior to the melting season insolation was reduced by cyclonic cloudiness averaging 5 tenths sky cover, and had an average daily intensity of 350 calories per square centimeter. During the melt season, on the other hand, cloud cover averaged only 2.6 tenths; insolation abruptly increased to 650–700 calories/sq cm per day, a level which it retained with minor interruptions through the melting season and on past the summer solstice.

Insolation was found well correlated with daily range in air temperature, the coefficient being 0.75. Albedo of the snow surface was determined, from continuous records of incident and reflected short-wave radiation, to be generally lower than generally reported formerly [1]. Before the melt season it averaged 0.62 and during it 0.45, suggesting that the snow surface may have been continuously moist during daylight hours. Pitting and contamination of the snow surface late in the melt season are also causes of low albedos. Efficient utilization of the abundant solar energy is indicated.

High daytime air temperatures occurred frequently during winter, and most of the time dur-

* Abstracted from a paper presented to meetings of the American Geophysical Union at Berkeley, California, 14 February 1948, which was based upon Technical Report No. 5 of the Corps of Engineers—Weather Bureau Cooperative Snow Investigations, "Hydrometeorological Log of the Central Sierra Snow Laboratory, 1945–1946." Published by permission of the Office, Chief of Engineers, Dept. of the Army, and U. S. Weather Bureau.

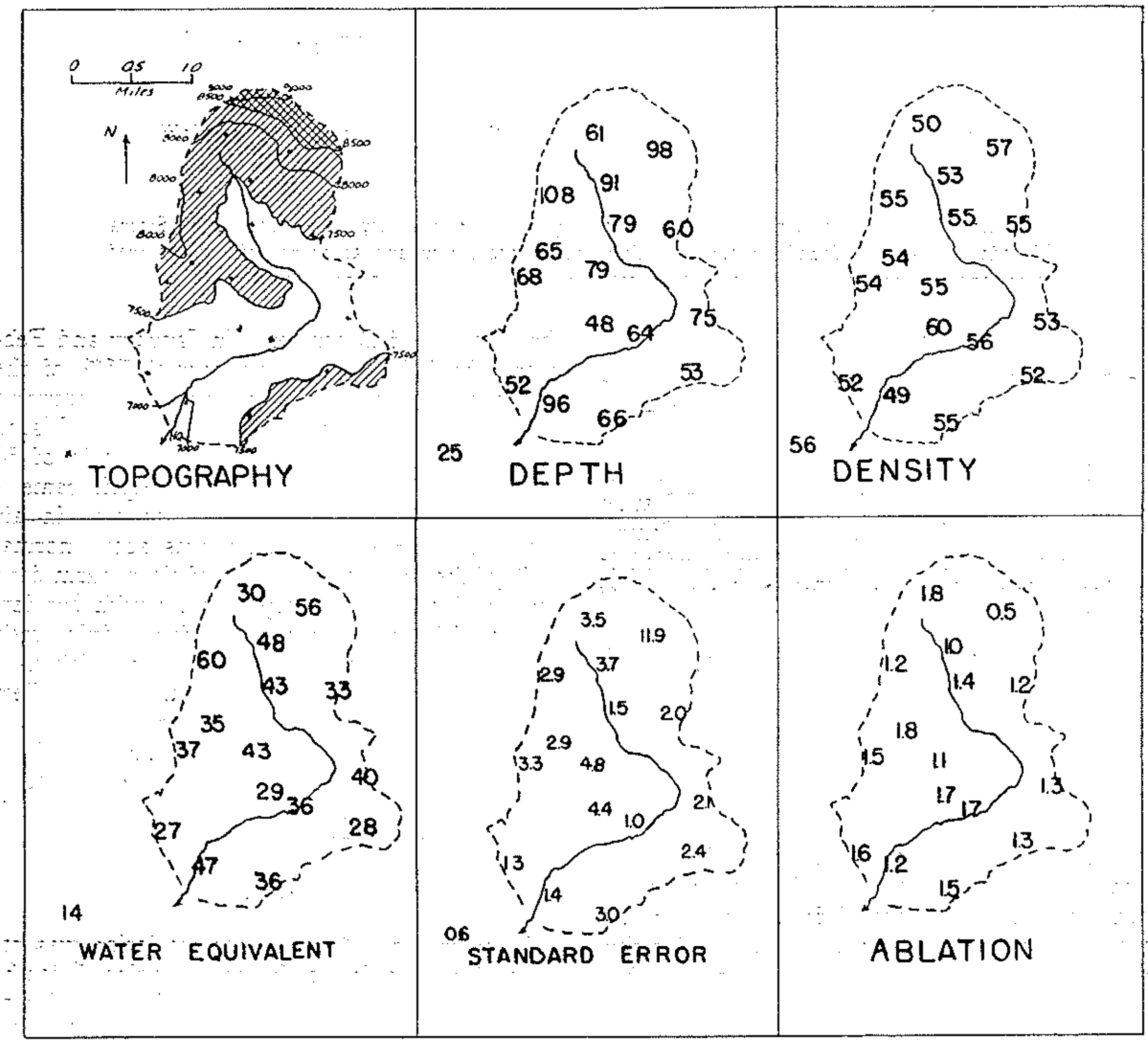

FIG. 1. Snowpack characteristics in the central Sierra snow laboratory basin on 1 May 1946. Areal distributions of several characteristics of the snow pack over the basin about three weeks after the onset of rapid melting. *a*) Topography map shows Castle Creek traversing the two major valleys of the basin, which separate three remnant volcanic ridges. Snow measurements were made at stations shown by X, including the snow course at Soda Springs, about a mile west of the basin outlet (data by California Cooperative Snow Surveys). Laboratory headquarters is at basin outlet. Shaded areas above 7,500 and 8,500 ft elevation. *b*) Depth of snow pack, inches, at the 16 observation stations and Soda Springs. *c*) Density of snow pack, in percent. *d*) Mass of snow pack, in inches water equivalent. The average of all samples at each station is shown. *e*) Small-scale variance of water equivalent, expressed as standard error of the five to fifteen samples taken at each station. In inches and tenths. *f*) Ablation of the snow pack, or loss of mass in the period 1 to 13 May, approximately, reduced to average inches per day; includes both evaporation and meltwater runoff.

ing spring—94% of spring days had maxima above 50°F and 49% had maxima above 60°. Occurrence of such temperatures in the presence of an extensive, long-enduring snow pack, without significant advection of surface air from snow-free areas, raises a question about the process by which local heating can reach so high a level. A possible answer involves the intermediary action of the forest foliage as the "outer active surface" of the earth, to use Geiger's [3] term, absorbing short-wave insolation which has passed through the nearly transparent atmosphere and converting it into sensible heat on a large scale. General subsidence in the east end of the Pacific anticyclone may also be a factor [4].

This hypothesis is also suggested by the persistence during daytime of temperature inversions. Most of the time the 50-ft station, being nearer the canopy level most strongly irradiated, was warmer than the 4-ft station, the exception being a short period in the early afternoon when the sun was at an angle high enough to penetrate to foliage near the lower level, which then averaged as much as 2F° warmer than the upper and of course much warmer than the snow.

Wind speeds were low, averaging only 4 miles per hour above the tree crowns, and there was a regular alternation of mountain and valley winds. Heat supply by condensation was generally small.

Moisture

After opening of the melt season storms were few and insignificant, and had more the effect of depressing stream flow than of causing rises. Low freezing levels in these storms caused snow to fall instead of rain, and melting was stopped by the cold air and the cloudiness.

The snow pack was established at the end of October. At the beginning of melt it extended over 95% of the basin. This cover decreased to about two-thirds of its original extent by early May and to less than one-third by early June.

Station data on the map, Figure 1, show at top center the snow depth on 1 May, after three weeks of melting had reduced the 16-station average to 73 inches, approximately 60% of that at beginning of the melt season. No overall elevation effect is evident from the map: large depths occur both in the lower valley and a thousand feet higher on the slopes of Castle Peak. Local exposure of the stations, particularly to solar radiation, seemed to be of predominant importance in influencing depth at this stage of melting.

Melt during the three weeks preceding the time of the map increased the average snowpack density from 41% to 54%. Density values appear in the upper right corner of the figure.

Water equivalent of the snow pack, or mass of water present both as liquid and solid, averaged about 50 inches at the onset of melting and decreased to an average of 39 inches at the time of the map. Station data show water equivalent at lower left, for 16 stations. Greatest values were 55 to 60 inches on slopes of the upper basin, and smallest were 25 to 30 inches on south exposures in both upper and lower basins. The proximity of stations with widely different values of mass, for example, 27, 47, and 36 inches in a mile-long line across the south end of the basin, evidences the importance of slope and orientation in each station's exposure. As melt proceeded, the relative size of the dispersion from the 16-station mean grew larger, the coefficient of variation increasing from approximately 25% (standard deviation 9.8 inches) at the time of the map to over 100% at the end of May.

Small-scale variation of snowpack mass, as distinguished from the large-scale variation just discussed, is indicated by the standard error of the samples taken at each station, shown in lower center of the figure. Often an element's variation within a small area can be neglected, as done in meteorology generally (unless micrometeorological conditions specifically are being studied), because exposure conditions have long been standardized; but standardizing exposure of snowpack measurements would defeat the objective of determining the total mass of water in storage in the forests, valleys, and hillsides of the basin. Hence standard error is used to aid evaluation of data from these various exposures.

Melt

Snow melt, not directly observable, was estimated in two ways: first, by measuring ablation at snow courses, including evaporation as well as melt; second, by measuring runoff from the contributing area. During the period 1 to 13 May ablation was found to range from 0.5 to 1.8 inches per day at various locations (see upper right corner of station models). Over all 16 stations it averaged 1.36 inches per day, or the equivalent of 0.13 inch per degree-day. Measured runoff during this same period, assuming that all the snow-covered area contributed, averaged 1.41 inches per day.

Peak runoff occurred on 6 May, in the middle of the two-week period mentioned above, and again on 18 May, hourly maximum flows being approximately 200 cubic feet per second on both days. There were five periods of fairly uniform runoff-temperature behavior, clearly separated from each other. In the first period, temperature had little effect, this being before the melt season; in the second, the ratio was low and fluctuating; in the third, which lasted a month, and included the two peak flows, the ratio was very uniform and the two variables had a highly significant correlation. In the fourth period, the ratio was erratic, apparently disrupted by the storms of late May; in the fifth, stream flow receded independently of air temperature. In early periods the ratio depended on condition of the snow, in late ones on its area.

The toll of water taken by evapo-transpiration, mostly during summer, was about 12 inches.

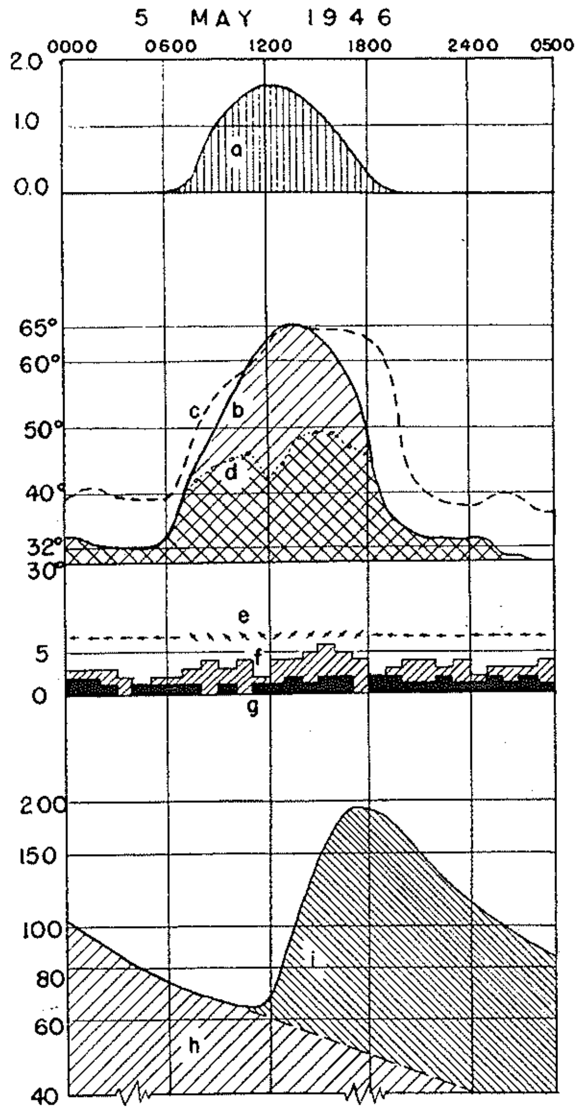

FIG. 2. Weather and stream flow on 5 May 1946. Hourly values of meteorologic and hydrologic elements at headquarters station, Central Sierra Snow Laboratory. *a*) Incident shortwave radiation from sun and sky, in gram-calories per square centimeter and minute (measured on a horizontal surface). Total for the day 718 cal cm^{-2}. *b*) Air temperature at 4 ft, in °F. Site is a small clearing in open lodgepole-pine forest and the snow had just disappeared.* *c*) Air temperature at 51 ft, in °F, above the tree canopy. *d*) Dewpoint at 4 ft, in °F. *e*) Wind direction at 59 ft, with mountain-valley alternation. *f*) Wind speed at 57 ft, in miles per hour. *g*) Wind speed at 8 ft, in miles per hour. *h*) Stream flow from melt on preceding days, in cubic feet per second. Note scale is logarithmic. *i*) Stream flow generated by melt on 5 May, in cubic feet per second. Note lag behind peak insolation and temperature.

* Snow still covered ground around the station, as well as most of the basin (about 65%).

THERMAL BALANCE ON AN ILLUSTRATIVE DAY

The individual hydrometeorological elements can be brought together by considering their variation during one day of high melting, representing the clear, warm weather of the spring, and by computing an approximate balance of the heat-transfer processes on this day. FIGURE 2 presents hourly values of various elements on 5 May. Besides illustrating the lag of runoff after heat supply (four to five hours), it also makes plain the intermittent nature of the processes. Insolation is interrupted completely once a day; wind shifts regularly in direction and speed; temperature and dew point fall so low at night that the snow-surface temperature drops below freezing and melt ceases.

TABLE 1 presents an approximate thermal budget for this day, for snow-covered ground open to the sky, to indicate the relative importance of various modes of heat transfer to the snow pack.

It will be noted that during the melting hours most of the heat supplied to the snow came directly from solar radiation, which exceeded by a large

TABLE 1. THERMAL BUDGET OVER THE SNOW PACK 5 MAY 1946

Heat transfer in calories per square centimeter

	Day (10 hrs.)	Night (14 hrs.)	Total
1. Short-wave radiation	+430	0	+430
2. Long-wave radiation	−140	−180	−320
3. Convection and condensation	+110	+ 80	+190
4. Carry-over from day to night	−100	+100	0
5. Melt	−300	0	−300

Assumptions and Computations

Line 1. Albedo was taken as 0.40 from data of the preceding three weeks; incident radiation was measured as 718 calories per square centimeter.

Line 2. Long-wave radiation was calculated by the formulas of Ångström and Brunt [2], assuming snow-surface temperature as 32°F during the 10 hours of direct sunlight on the snow, and as an average of 14°F during the 14 hours of twilight and darkness.

Line 3. Convection and condensation were residuals and were not computed from turbulence considerations. The values agree generally with computations made by Sverdrup's formulas.

Line 4. Carry-over of heat in the snow pack from day to night, chiefly as re-frozen meltwater, was estimated from crust thicknesses observed to be about four inches containing about half an inch of re-frozen water. This represents a loss of heat during the day, and a source of heat at night (from freezing of previously melted water) to help supply the long-wave drain.

Line 5. Net melt was estimated from measured outflow of 210 acre-feet attributable to melting on 5 May. Assuming no net change in liquid water storage in the snow or soil, and contributing area as 65% of the basin, a value of melt of 1.5 inches was obtained.

margin the net gain, by convection and condensation, from the overlying air itself. Some of this heat is derived from adjacent bare ground, where as much as 300 calories/sq cm per day, from insolation, goes to heat the air, and from sunlit foliage as discussed in the fourth section above. The major part of the heat absorbed by the snow is used for melting, but some is lost as long-wave radiation (line 2). Under the forest, long-wave radiation probably represents a net gain of heat during the day instead of a loss; again it derives largely from sun-heated foliage. At night the drain of heat to the cloudless sky is made up from re-freezing of some of the previous day's meltwater and from heat in the air over the snow. The importance of insolation, either directly or indirectly, on the snow or on its environment, was very large in every positive item in Table 1.*

Conclusion

The role of solar radiation in the various processes involved in liquefaction of a mountain snow pack in spring has been discussed from observations in the Sierra Nevada. Further study of these processes is anticipated.

* Recent studies of snow melt by a hydrologic approach, in reconstructing hourly flows in Castle Creek, tend to confirm the relative values of various heat-flow processes reached by the meteorologic approach described above [6].

Acknowledgments

The author wishes to acknowledge the work of Dr. Robert W. Gerdel and other personnel of the Central Sierra Snow Laboratory, where the basic observations were made, and of personnel of the Processing and Analysis Unit in processing the data.

References

[1] Ångström, A.: The Albedo of Various Surfaces of Ground, *Geografiska Annaler*, 7: 323–342, 1925. Wallen, C. C.: Glacial-Meteorological Investigations on the Karsa Glacier in Swedish Lappland 1942–48, *Geogr. Ann.*, 1948–49. Olsson, H.: Radiation Measurements on Isachsen's Plateau. Part VIII *in:* Sci. res. of Nor.-Sw. Spitsbergen Exped. in 1934. *Geogr. Ann.*, 18: 225. Kalitin, N.: The Measurements of the Albedo of a Snow Cover. *Mon. Wea. Rev.*, 58: 59–61, 1930.

[2] Brunt, David.: *Physical and dynamical meteorology.* Cambridge University Press, 1939. Ångström, A.: A Study of the Radiation of the Atmosphere, *Smithsonian Misc. Coll.*, 65: 1. 1915. Å Angström, A.: Uber die Gegenstrahlung der Atmosphäre, *Met. Zeit.*, 33: 12, 1916.

[3] Geiger, R. *Das Klima der bodennähen Luftschicht.* Die Wissenschaft, Bd. 78, Braunschweig, 1927.

[4] Blake, D.: The Subsidence Inversion and Forecasting Maximum Temperature in San Diego Area, *Bull. Amer. Met. Soc.*, June 1948, pp. 288–293.

[5] U. S. Corps of Engineers and U. S. Weather Bureau, Cooperative Snow Investigations: *Terrain of the Central Sierra Snow Laboratory Basin.* Technical Rept. No. 4A, 1950.

[6] Hullinghorst, D. W. and D. H. Miller: *Interim Report on a Current Study.* Corps of Eng. Civil Works Invest., Project CW-171, Techn. Bull. No. 8, 1950 (mimeogr.).