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THE INFLUENCE OF OPEN PINE FOREST ON DAYTIME TEMPERATURE IN THE SIERRA NEVADA

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MANY skiers and other visitors to the mountains of the western United States in winter and spring have remarked on the warmth of the climate. Easterners, even when they are not warmed by strenuous exercise, commonly find themselves overdressed and immediately start shedding their outer clothing. The warmth is not alone a result of strong sunshine; the air itself is warm. Although it lies over deep snow, its daytime temperature in spring often reaches 60° F.

The high temperatures are not in agreement with the general belief that snow cover produces a cold climate. This anomaly and others in the local climate of the Sierra Nevada, such as the intense solar radiation, the long sequences of warm days, the mild nights, and the high rates of snow melting, present a problem in physical geography. The writer has examined this problem with the aid of a grant from the National Science Foundation[1] and here gives a summary explanation of the daytime warmth, as an illustration of the importance of a region's landscape in a physically based explanation of its climate.

Landscape is so often thought of as being primarily a result of a climatic regime that the active part it may itself play in creating a distinctive climate is easily overlooked. In a wide sense, of course, climate is the causative factor, as Köppen indicated when he named some of the broad climatic zones after plant associations. But on a smaller scale the surface of the earth is as important as the atmosphere in determining the climate of a region. The surface influence manifests itself particularly on days of "local" or "independent" climate, when inflow of air that bears the mark of other regions is small. Economic geographers are frequently concerned with the dependence or independence of a region in food supply, sources of raw materials, or manufactured products; physical geographers may be equally concerned with its dependence or independence in heat and moisture. Days of local climate, when a near independence is achieved within a region, are commoner than may be realized. In the Sierra they occur almost half of the time. On

[1] D. H. Miller: Snow Cover and Climate in the Sierra Nevada, California, *Univ. of California Publs. in Geogr.*, Vol. 11, 1955.

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these days climate is a derived property of the regional landscape and thus should be of special interest to geographers. The physical reactions in the landscape on these days fit into a hypothesis that may account for the high daytime temperatures.

The general scale of the Sierra Nevada climate is, as has been indicated, regional. The warmth is not a minor feature of the microclimate inside a

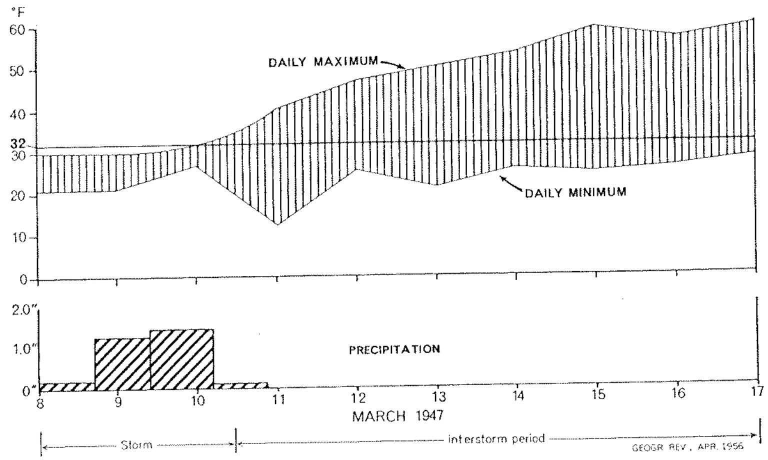

Fig. 1—Local climate following storm.

forest stand, in special confined topographic sites, or in the lowest foot of the atmosphere. Instead, it is representative of a broad region at the crest of the Sierra—a region of deep snow and sparse forest. Although vertically the regional climate occupies only a thin layer of air—what Leighly has called the "climatologic air"—this layer is thick in relation to most of man's activities and to biologic and hydrologic processes. Air temperature may not be the ideal index to thermal conditions in this layer, but it does show the general level of energy.

A few figures summarizing observations made in a thermometer shelter at the standard height above the surface illustrate the warmth of the local climate. After a storm in spring, temperature rises rapidly about 20°, then levels off (Fig. 1). Daytime temperatures are in the 50's or low 60's (Table I) and occasionally reach the 70's. Days are much warmer here than in the Alps, even when adjustments are made for the difference in latitude.

It can be shown by an analysis of upper-air charts that the anomalous

warmth is not a characteristic of the higher layers of the atmosphere into which the Sierra projects. Neither is it, except to a minor degree, a product of heat generated in the upper air by subsidence in the North Pacific anticyclone, though this sinking motion does play an important part in the total climatic picture. Nor is the heat imported at lower levels by air flowing up the Sierra block from the hot plains of the Central Valley, to the west; this air would be cooled by expansion to a temperature 20° lower than the temperatures observed.

The heat is clearly generated within the local environment, but this conclusion is not consistent with the textbook theory as formulated by

Table I—Maximum Temperatures on Days between Storms
(*In °F.*)

REGION	APRIL	MAY	REGION	APRIL	MAY
*Sierra Crest**			*Alps* (Davos)**		
Mean daily maximum	54	60	Mean daily maximum (obs.)	40	46
Mean monthly maximum	63	71	Mean daily maximum		
Absolute highest (5 yrs.)	67	74	(adjusted to 39° N. lat.)	48	54

*Altitude about 7000 feet. Observations by Cooperative Snow Investigations (*Hydrometeorological Log of the Central Sierra Snow Laboratory, Water Years 1945–1946, 1946–1947, 1947–1948, 1948–1949, 1949–1950, and 1950–1951*, U. S. Dept. of the Army, Corps of Engineers, and U. S. Dept. of Commerce, Weather Bureau, Cooperative Snow Investigations, San Francisco, various years) and by Weather Bureau cooperative stations (*Climatological Data for the United States by Sections: California*, U. S. Weather Bureau, various years).

**Altitude about 5000 feet. Observations by Swiss Institute for Snow and Avalanche Research (*Winterberichte*, 1946–1947, 1947–1948, and 1948–1949, Eidgenössisches Institut für Schnee-und Lawinenforschung, Davos, 1949 and 1950).

Alexander Voeikov,[2] who stated that over a snow cover the air temperature, except during strong south winds, cannot rise above 0° C. From his store of climatic and geographic knowledge Voeikov demonstrated his thesis so well that most later climatologists accepted it without further examination, and it has come to be applied without qualification to all snow-covered areas. But in this aspect of physical climatology, the whole trans-Rockies region is, like California, "the great exception."

The release of this large amount of heat within the local environment must be effected through the action not of the snow but of other components of the landscape (shown in summer on Figure 4). The problem is to identify these components and to evaluate the flow of heat through them. In tracing the flow of heat from the sun through the landscape, special attention should be given to the stands of evergreens (Figs. 2 and 3). Although sparse and open,

[2] Der Einfluss einer Schneedecke auf Boden, Klima und Wetter, *Geogr. Abhandl.*, Vol. 3, No. 3, 1889.

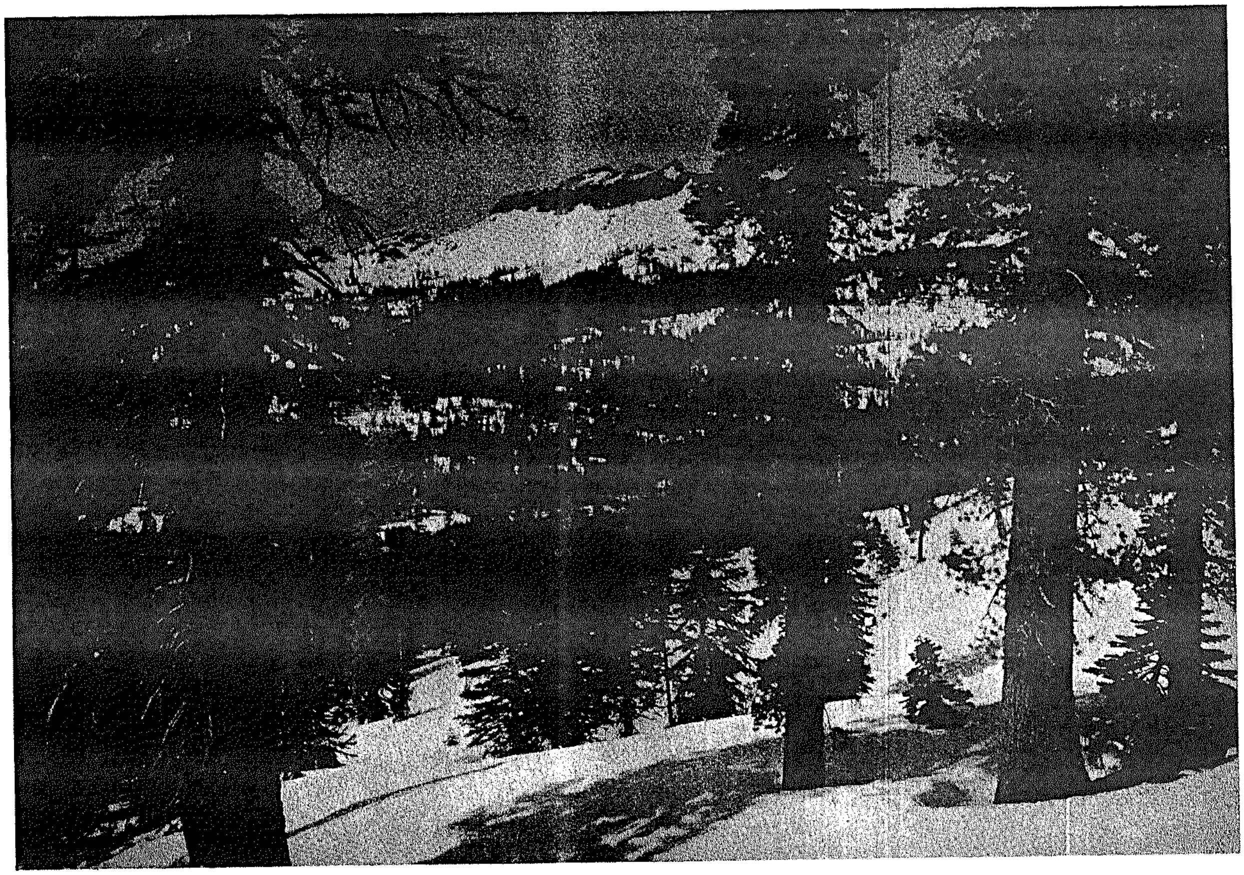

FIG. 2—Snow and trees near end of season of accumulation (early April). Even from this low angle, the open nature of the forest is plain. Shadows on the snow in the foreground indicate interception of radiation by the scattered trees. (Photograph from Cooperative Snow Investigations [see footnote to Table 1].)

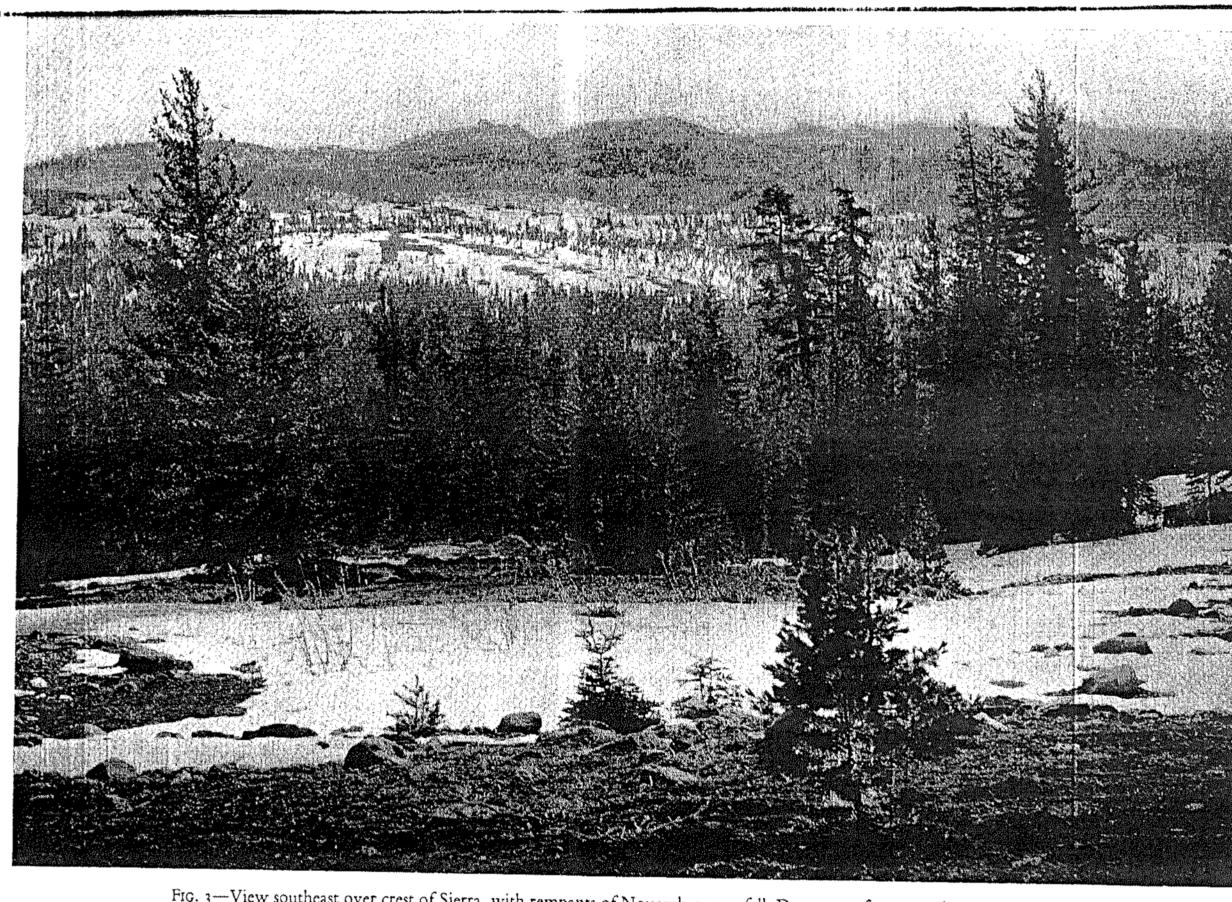

FIG. 3—View southeast over crest of Sierra, with remnants of November snowfall. Denseness of trees nearby contrasts with openness in distance. Area under forest canopy is about 10 per cent. No climatic timberline is evident, though ridges average 8000 feet, peaks 9000. (Photograph from Cooperative Snow Investigations.)

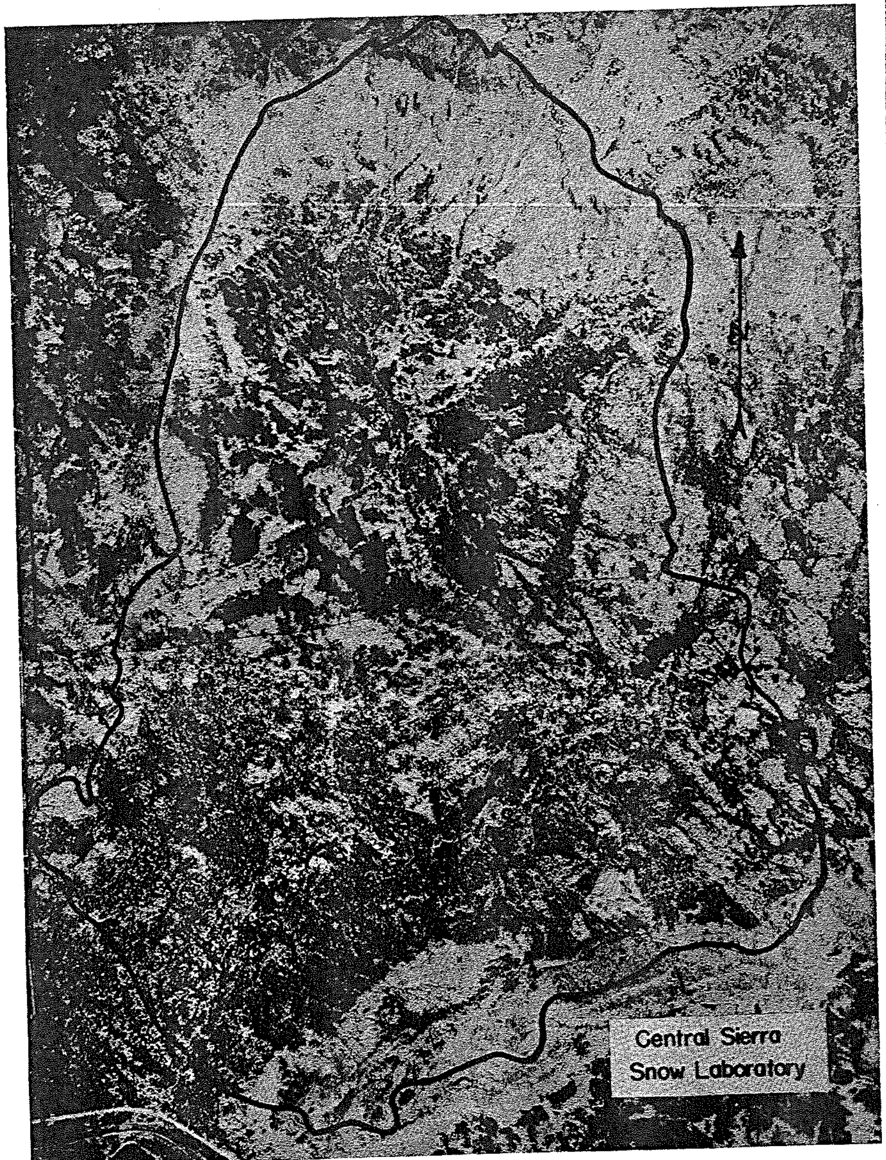

FIG. 4—Aerial mosaic of basin of Castle Creek, near Donner Pass. Forest stands cover about 40 per cent of region. Basalt, rimrock, and volcanic talus at north end and basalt ridge at southeast are bare; granodiorite near center of east side bears a few trees; rest of area has mingled thin forest and small openings (meadows, dry pockets, granite knobs), a surface highly absorbent of solar radiation. (Mosaic from U.S. Forest Service prints, for Cooperative Snow Investigations.)

these stands, principally of lodgepole pine, are in the spring the major dark elements in the landscape; accordingly, the reaction of the trees to radiation —how much gets through their canopies, how much is reflected back to the sky, and how much is retained in their foliage by absorption—needs to be examined.

From measurements made by foresters and botanists[3] for their own purposes, the writer estimates that about 40 per cent of the incoming solar

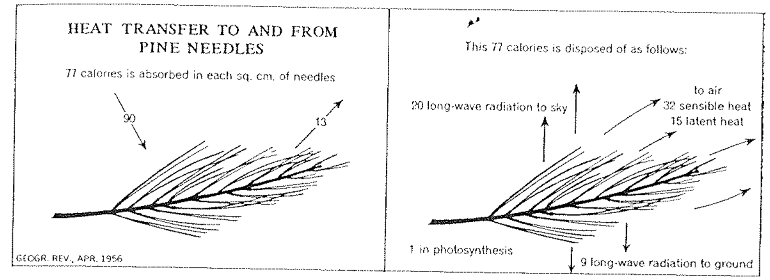

FIG. 5

radiation is transmitted through openings in and between tree crowns. Reflection by individual needles is small; reflection by groups of needles pointing toward the sky, and by branches and crowns, which entrap radiation in their interstices, is even smaller. Slightly more than half the radiation is absorbed by the foliage, even in stands with many openings. Absorption is fostered by the honeycomb structure of the forest, in which the edge effect is important. This structure effectively traps sunshine and also cuts down loss by long-wave radiation.

Incoming solar radiation on a horizontal surface is 90 calories per square centimeter. The needles absorb 77 calories (Fig. 5), and as they become warmed, they give off the same amount of heat, part by radiation, the rest by transfer to the air as latent and sensible heat. The heat absorbed by the pine

[3] See, for example, W. R. Adams: Studies in Tolerance of New England Forest Trees, Part 8, *Vermont Agric. Exper. Sta. Bull. 282*, 1928, and Part 12, *ibid.*, *390*, 1935; G. M. Byram: Sun and Wind and Fuel Moisture, *Journ. of Forestry*, Vol. 38, 1940, pp. 639–640; P. R. Gast: A Thermoelectric Radiometer for Silvical Research, *Harvard Forest Bull. 14*, 1950; G. Mitscherlich: Das Forstamt Dietzhausen, *Zeitschr. für Forst- und Jagdwesen*, Vol. 72, 1940, pp. 149–188; F. Obaton: Le pouvoir reflecteur des conifers pour la rayonnement infrarouge, *Comptes Rendus Acad. des Sci. [de] Paris*, Vol. 228, 1949, pp. 939–941; F. Sauberer: Über die Strahlungseigenschaften der Pflanzen im Infrarot, *Wetter und Leben*, Vol. 1, 1948–1949, pp. 231–234; H. L. Shirley: Reproduction of Upland Conifers in the Lake States as Affected by Root Competition and Light, *Amer. Midland Naturalist*, Vol. 33, 1945, pp. 537–612; J. W. B. Sisam: The Use of Aerial Survey in Forestry and Agriculture, *Imperial Agric. Bureaux Joint Publ. No. 9*, 1947; C. A. Wellner: Estimating Light Intensity in Residual Stands in Advance of Cutting, *U. S. Forest Service, Northern Rocky Mountain Forest and Range Exper. Sta. Research Note 47*, 1946.

TABLE II—THERMAL BALANCE OF PINE NEEDLES AND CROWNS*
(*In calories per sq. cm.*)

COMPONENT	NEEDLES		TREE CROWNS	
Solar radiation				
Reflected to sky	13		7	
Transmitted to ground	0		15	
Absorbed		77		154
Long-wave radiation				
Net loss upward	20		18	
Net loss downward	9		11	
Photosynthesis	1		3	
Stored in wood	0		2	
Transferred to air				
By convection	32		80	
By transpiration	15	77	40	154

*Midday hour of a spring day between storms.

TABLE III—CONVECTION OF HEAT TO THE AIR*
(*In calories per sq. cm.*)

	FROM NEEDLES	FROM CROWNS	FROM FOREST STANDS	AVERAGE OVER CREST REGION
As sensible heat	32	80	24	10
As latent heat (transpiration)	15	40	13	4

*Midday hour of a spring day between storms.

needles heats them, in calm weather, to about 20° F. above air temperature.[4] As wind picks up, the excess warming decreases, and the manner of decrease was found analogous to the transfer of heat from staggered banks of cylinders having a fixed heat input, according to formulas developed by heating engi- neers.[5] The amount of heat given off from the needles to the air can thus be considered independent of wind speed. During a midday hour in spring it is about 32 calories per square centimeter of leaf surface (Table II).

Figure 6 and the second column in Table II show heat transfer from tree crowns. It will be noted that the first three figures add up to more than the 90

[4] Leaf temperatures have been measured principally by entomologists and botanists. See, for example, J. H. Ehlers: The Temperature of Leaves of *Pinus* in Winter, *Amer. Journ. of Botany*, Vol. 2, 1915, pp. 32–70; P. Filzer: Das Mikroklima von Bestandsrändern und Baumkronen und seine physiologischen Ruckwirkungen, *Jahrbuch für wiss. Botanik*, Vol. 86, 1938, pp. 228–314; R. Geiger: Das Standortsklima in Altholznähe, *Mitt. Göring Akad. deutsch. Forstwirtschaft*, Vol. 1, 1941, pp. 148–172; W. R. Henson and R. F. Shepherd: The Effects of Radiation on the Habitat Temperatures of the Lodgepole Needle Miner, *Recurvaria milleri* Busck (Gelechiidae: Lepidoptera), *Canadian Journ. of Zool.*, Vol. 30, 1952, pp. 144–153; G. and P. Michaelis: Ökologische Studien an der alpinen Baumgrenze, III: Über die winterlichen Temperaturen der pflanzlichen Organe, insbesondere der Fichte, *Beihefte zur Botanisches Zentralblatt*, Vol. 52, 1934, pp. 333–377; W. G. Wellington: Effects of Radiation on the Temperature of Insectan Habitats, *Scientific Agriculture*, Vol. 30, 1950, pp. 209–234.

[5] *Heating, Ventilating and Air Conditioning Guide*, Vol. 27, American Society of Heating and Ventilating Engineers, New York, 1949.

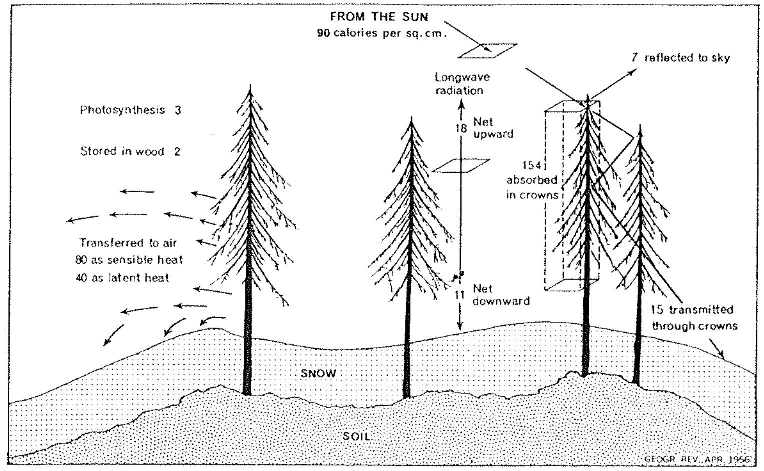

FIG. 6—Flow of heat through open pine forest, Sierra Crest region. The trees shade the snow behind them, so that a prism through the crown space receives radiation on sides as well as on top. A square centimeter of canopy absorbs much more heat than the 90 calories per square centimeter measured on a horizontal surface.

calories received on a square centimeter of horizontal surface, because the trees, by reason of their vertical projection above the snow, intercept more than their share of sun before it reaches the ground behind them. A small amount of radiation is also reflected from snow in front of the trees. Therefore a column of unit area and of height equal to crown depth has available to it nearly twice as many calories as a unit-area horizontal surface. Table III shows the transfer of heat to the surrounding air from needles, crowns, forest stands, and the entire forest-and-snow landscape of the region. In the Sierra Nevada, forest stands cover about 40 per cent of the land surface, and crowns themselves cover about 12 per cent.

On a typical spring day about 120 calories of heat per square centimeter are supplied to the air of the region, most of it from the needles of the pine forest. Eventually the heat reaches the snow. However, according to a study of the daily regime of runoff, most of the melting in the morning is caused by the sun, and flow of heat from air to snow is not large until afternoon and evening.

The amount of air that is heated is not large. A detailed terrain analysis[6] has shown that two-thirds of the surface of the Sierra crest is classified as

[6] D. H. Miller: A Terrain Sample of the Sierra Crest Region, *Yearbook Assn. of Pacific Coast Geogrs.*, Vol. 10, 1948, pp. 46–47. (Abstract.)

concave rather than convex. Below the level of the crest line (8000 feet) the concave surface holds a local layer of air that averages about 500 feet in thickness and has a mass of about 15 grams. In the typical morning rise of temperature this layer stores from 25 to 40 calories of heat per square centimeter. Heat added beyond this amount up to 120 calories either is transmitted by turbulent eddies down to the snow surface or leaks out aloft into the free air, principally as latent heat.

Thus the heat given off from the trees to the air is sufficient to heat the surface layer, supply direct heat to the snow, and provide for a small loss aloft. The trees, therefore, as one component of the landscape, produce several characteristic phenomena of the climate.

The combination of a heat sink at the ground surface and a heat source in the trees above it produces a marked stratification in the environment.[7] Inversion of the "normal" decrease of temperature with height is usual almost everywhere on calm nights, but here the inversion strengthens from 6° at night to 30° during the morning, instead of disappearing. As the sun heats the trees, the level of highest temperature migrates from 50 feet downward to 30 feet and lower. For several hours this middle level is warmer than the air either above or below it, and heat flows both upward and downward from it.[8] This heat source, evident in temperature profiles in the forest and also in profiles over open meadows, covered by air streaming out from the surrounding forest, cannot be explained except as a result of absorption of sunshine by the foliage of the trees; thus it lends additional support to the hypothesis.

Heat absorbed by the trees is given off into the local air, which is trapped between the concave ground surface below and a subsidence inversion in the free air above. While this heat is in temporary storage in the local air it produces the high daytime temperatures that make the climate enjoyable to skiers and that are at such variance with textbook statements on the climate of a snow-covered region.

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[7] This effect has also been noted by J. E. Church (Studies on Snow Melt, *Yearbook Amer. Philos. Soc.*, 1949, pp. 139–141), who began his pioneering surveys of snow cover 50 years ago in this part of the Sierra.

[8] D. H. Miller: Micro-meteorological Conditions over Snow Pack in Open Forest, Corps of Engineers, Civil Works Investigation Project CW-171, *Tech. Bull. 11*, 1950.