

PLEISTOCENE CLIMATE IN NEW MEXICO

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ABSTRACT. Recently published meridional profiles of the mean temperature of the free atmosphere provide an opportunity to apply meteorologic upper air data to the problem of snowlines. The modern snowline of the Rocky Mountains is shown to be nearly identical to the mean level of the 0°C. isotherm for the summer months, corroborating the well-known postulate that snowlines are controlled by summer temperatures. This postulate is applied in speculating on the annual march of temperature in glacial time in New Mexico. The mean annual temperature so derived is applied to the hydrologic balance of a late Pleistocene lake in the closed basin of Estancia, New Mexico, in an attempt to check the computation for that lake made by Antevs.

THE line that separates areas of snow accumulation from those lower areas where snow disappears in summer is the regional snowline (Flint, 1947). The Pleistocene snowline discussed here is the approximation furnished by the level of cirque excavation.

The altitude of the snowline of Wisconsin time was approximately 12,000 feet in the southern Rocky Mountains and decreased in height northward. Data on the elevations of Wisconsin and the present snowlines have been published by Klute (1928) and Louis (1926). Depending on how much snow blows over the mountain crest, the snowline on an individual mountain range is not at the same elevation on opposite sides. This was true in Wisconsin time as well as at present and contributes to the difficulties of establishing the exact position of the Wisconsin snowline.

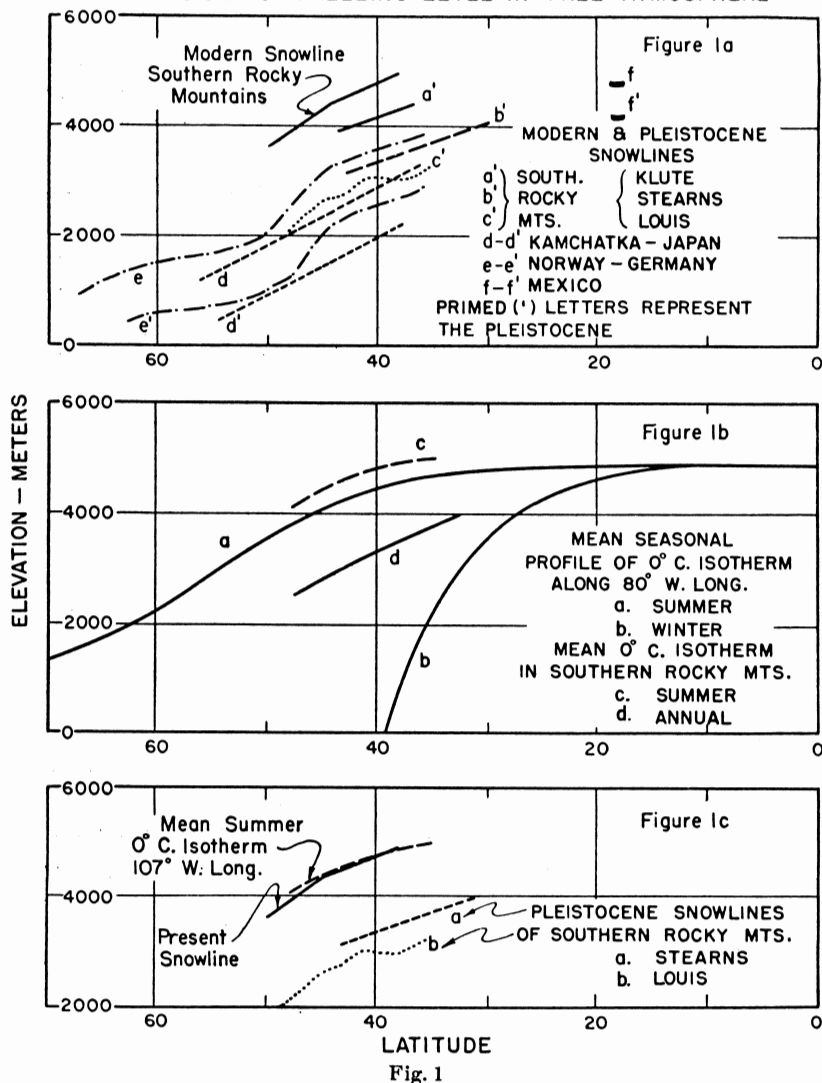
Certain of Klute's (1928) snowline profiles have been re-plotted in figure 1. His meridional profiles for the modern and Pleistocene snowlines are included in figure 1a for Japan, central Europe, Mexico, and the southern Rocky Mountains. A profile for the southern Rocky Mountains along the 110° W. Long. has also been plotted from the map of Louis (1926).

On the basis of the distribution of fossil marmots, Stearns (1942) suggests that the snowline of north central New Mexico might have been depressed 4500 feet during Wisconsin III time. He thinks that although the 2000 feet of depression suggested by Klute probably was meant to apply to the larger Wisconsin II ice advance, it is too small even for the smaller

W_3 advance. It will be noted from figure 1a that Stearns' suggestion agrees better with Louis' profile than does the smaller snowline depression proposed by Klute for the area.

All these profiles show a comparable magnitude of snowline depression for different parts of the world at this latitude, a resemblance which has been discussed in detail by Klute (1928).

RELATIONS BETWEEN MODERN AND PLEISTOCENE SNOWLINES
AND HEIGHT OF FREEZING LEVEL IN FREE ATMOSPHERE



MERIDIONAL TEMPERATURE PROFILES IN THE FREE
ATMOSPHERE

The modern network of upper air meteorological stations (radiosonde) provides data of direct interest to the problem of snowlines. A profile representing average upper air conditions for summer and winter from the arctic to the equator has recently been published by Hess (1948). His profile extends along the line of 80° W. Long. through Florida and Michigan. From Hess' data the profile of the freezing isotherm for summer and winter is reproduced in figure 1b. It is necessary to consider the possible difference between his data at 80° W. and the area of interest to this paper lying near the 107° W. meridian. For this reason profiles of the freezing isotherm were constructed for the period 1946-48 using radiosonde data from Albuquerque, New Mexico, Grand Junction, Colorado, Lander, Wyoming, and Great Falls, Montana. The average profiles for summer and for the complete year are plotted in figure 1b for comparison with the Hess data.

It is apparent from the figure that the summer profile for the 107° meridian is parallel to and slightly higher than that for the 80° W. line. The slight difference in elevation might be due in part to the different period of record used for the two curves. Also the high mean elevation of the land surface along the 107° meridian implies a high elevation heating surface and a consequently warm air column between the surface and the level of the freezing isotherm.

The mean winter profile for the 0°C. isotherm could not accurately be constructed along the 107° W. meridian because the stations considered, which are located at moderate elevations, have mean surface temperatures in winter near or below freezing. To clarify the relations between the free air temperature profiles and the snowline curves, selected profiles from figures 1a and 1b have been replotted in figure 1c.

Before discussing the comparison of the profiles of the freezing isotherm with that of the modern snowline, the importance of the precipitation factor should be emphasized. A snowline would be lower where precipitation is heavy than where it is light, and in the absence of adequate precipitation, no snowline would occur, regardless of temperature.

However, as a broad generalization it can be said that at a given elevation, any general increase in precipitation with in-

creased latitude in the Rocky Mountain area is small enough to be nearly obscured by large local variation resulting from different exposure, topography, and other local features.

It seems valid, therefore, to assume that the close correspondence of the profiles of freezing temperature in the free atmosphere in summer and the modern snowline, indicated by figure 1c, results from a causal relation between the two factors.

If the modern snowline were controlled by winter temperature alone, its elevation would not decrease with latitude northward from about latitude 30°, and south of that latitude it would bend sharply upward to be parallel to the winter freezing isotherm. It seems evident, then, that the modern snowline is controlled, with respect to temperatures, by summer conditions. This has been asserted by Klute (1928), Antevs (1928), and others. Their viewpoint on this matter was based primarily on studies of glaciers in which it has been shown that the magnitude of an ice sheet is predominantly controlled by summer temperature.

ESTIMATES OF POSSIBLE TEMPERATURES IN PLEISTOCENE TIME IN NEW MEXICO

It is clear that any speculation concerning meteorologic conditions in another geologic time is subject to grave error. On the other hand, certain ideas of value can be gained by setting up a set of hypotheses and then analyzing the relations which would ensue. In the present analysis these hypotheses will, in part, be stated quantitatively. Assignment of specific values to factors such as temperature should be construed as a quantitative statement of an assumption and not as an assertion of reality.

The first assumption made here is that the Pleistocene snowline in New Mexico was controlled by summer temperature. For the moment variations in precipitation will be omitted from consideration. It is proposed to investigate the possible variations in snowline by assuming variations in temperatures alone.

The mean lapse rate of temperature (rate of decrease with elevation) measured by soundings varies only slightly from year to year at a particular point and only slightly between points in a given geographic region. Conrad (1942) has shown

that lapse rates are remarkably similar over large portions of the globe. For the approximation desired here, it will be assumed, therefore, that the lower troposphere above New Mexico had the same lapse rate in Pleistocene time as at present. This assumption would not apply near the edge of a large glacier but appears to be reasonable for an area some distance from the edge of the major ice sheets, as was New Mexico.

At levels near the freezing isotherm, the Albuquerque radiosonde data in July 1947 and 1948 showed a decrease of temperature with height amounting to about 8 Centigrade degrees per 1000 meters. This rate is somewhat higher than the average for winter at the same station, and being based on a short period of record, may be too high to represent an average summer condition. To be in accord with the data for a large number of areas studied by Conrad, a value of 6 C.° (10.8F.) per 1000 meters will be used in the analysis.

The second assumption is, then, that if the snowline were lowered 1000 meters, the July mean temperature at a given place would be decreased 6 C.° (10.8F.).

It is probable that glacial times were more different from the present in summer than in winter. A blanket of snow over Canada and northern United States provides cooling by radiation just as intense as if there were a great thickness of ice under the snow. Though the thickness of the ice has certain meteorologic effects, particularly owing to the considerable mass of air which it displaces, the main difference in winter probably lies in the permanence of the snow cover during glacial times compared with the alternation of snow cover and lack of snow which characterizes the modern winter in the latitude band from 40° to 50° N. Greater duration of cooling would make winter considerably colder over a large glacial mass and at its margin than at some distance south of the ice sheet. As far south as New Mexico, it is probable that the coldest month was little if any colder than the present. Thus it is postulated for purposes of discussion that the lowering of summer temperature was much greater than the lowering of winter temperature.

To put this postulate in quantitative terms, it will be assumed initially that in glacial times, Santa Fe, elevation 7000 feet, had the same average January temperature as at present. Later, various amounts of lowering of winter temperature will be discussed. Consideration of summer lapse rates leads to the

hypothesis that a lowering of the snowline would be accompanied by a decrease of July temperature by 10.8°F. per 1000 meters depression. It will be assumed, further, that the mean

POSTULATED RELATIONS BETWEEN PRESENT
AND PLEISTOCENE TEMPERATURES AND THE SNOWLINE

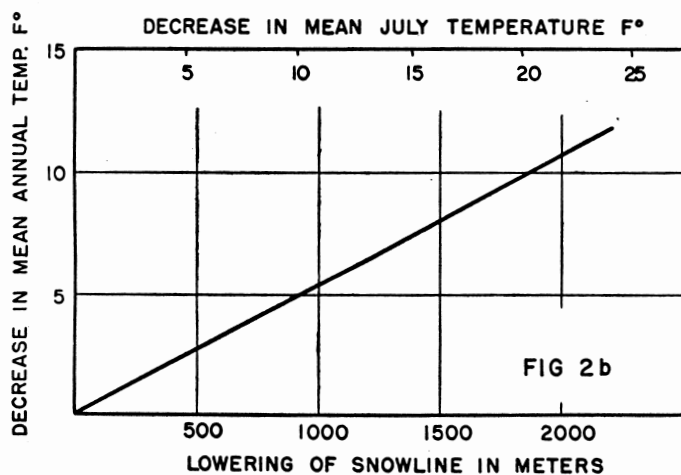
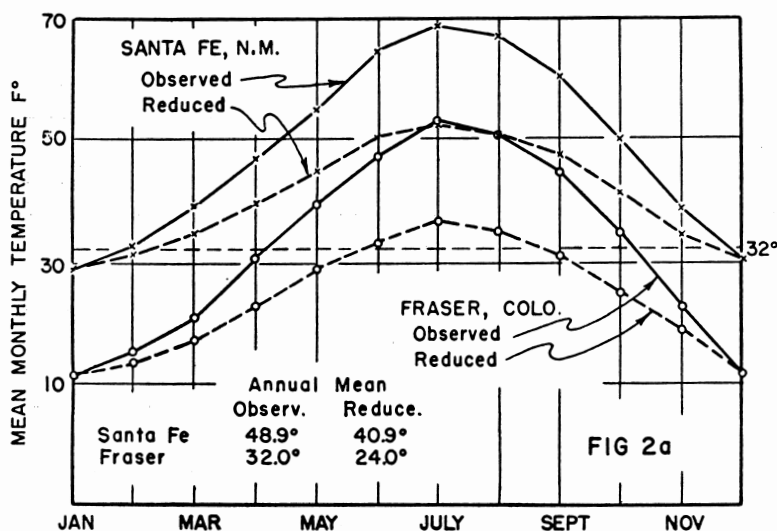


Fig. 2

temperature of each other month would be decreased by a constant percentage of the difference between the temperature of that month and January temperature. In other words, there would be a graduated reduction of the temperature of each month, with the maximum reduction in July and no reduction in January.

Such a reduction provides a new annual march of temperature and, therefore, a new annual mean temperature. Assuming a snowline depression of 1500 meters or a reduction of July average temperature of 16.2 F.[°], the new temperature curves for Santa Fe, New Mexico, and Fraser, Colorado, have been computed and are presented in figure 2a.

Santa Fe lies near the foothills of the Sangre de Cristo Mountains and at the head of a broad sloping pediment surface. It can be considered a slope station. Fraser is in a valley nearly surrounded by mountains. Neither of these locations is climatologically similar to exposed mountain flank locations where glaciers would form, but temperature records from the latter locations are not available in the area.

At Fraser, the elevation of which is 8670 feet, the present mean annual temperature is 32.0°F. The annual mean computed under the assumptions stated above is 24°. A uniform decrease of 8° in each month would have resulted in four months with mean temperatures well above freezing as can be seen by inspection of figure 2a. In modern times the same four months have above freezing mean temperatures. The graduated reduction here postulated provides three months with mean temperatures less than 37° but above freezing, and the other nine months with subfreezing averages. The efficacy of such a reduction in bringing on glacial conditions seems clear.

At the latitude of Fraser, the Pleistocene snowline lay about at the elevation of this station at the maximum depression. Had the temperature reduction amounted to 8 F.[°] in each month, it is nearly certain that a glacial condition due to temperature would not have been attained, while the graduated reduction postulated probably meets the requirement.

Under the set of assumptions used here there would be a definite relation between the lowering of the snowline and the corresponding reduction of summer and annual temperatures. From the graph of figure 2b it can be seen that if the snowline were lowered 925 meters as postulated by Antevs (1935) there

would be a reduction of July temperature by about 10°F. and of mean annual temperature by 5 F.°. Antevs estimated the lowering of mean annual temperature to be 8 F.° on the basis of the latitudinal gradient of elevation of the modern snowline.

It can be concluded, then, that the application of the method used here gives results of the same order of magnitude as those of Antevs and extends the reasoning to define the annual distribution of temperature.

It is clear, however, that the determination of the temperature of a glacial period depends directly on the value used for the mean depression of the snowline. Application of the present method to the various estimates of the snowline depression mentioned previously gives the following results:

TABLE 1
Use of Various Estimates of Pleistocene
Snowline Depression to Estimate the Reduction
of Temperature

Author	Average Depression of Snowline		Estimated Reduction of Mean Temperature (F.°)		Glacial Stage
	(meters)	(feet)	Annual	Summer	
Klute	650	2000	3.5	7.0	W ₂ ?
Louis	1800	5500	9.8	19.6	?
Antevs	925	2800	5.0	10.0	?
Stearns	1500	4500	8.2	16.4	W ₃

LAKE ESTANCIA

In north-central New Mexico, bordered by the Sandia-Manzano Mountains on the west and Mesa Jumanos on the south, is a broad closed basin at an elevation of about 6000 feet. This flat grassy valley is at present partly covered with small farms where the raising of frijoles (pinto beans) and small herds of cattle supports a scattered population. It was early recognized by Meinzer (1911) that this basin was once the bed of a lake, which at its maximum extent was 150 feet deep and had a surface area of 450 square miles. Bryan and McCann (unpublished) have discussed in detail the origin of the basin and present evidence which indicates that there were actually two lake stages, of which the second was smaller and contained within the one outlined by Meinzer.

Small glaciers existed in Wisconsin time in the highest parts of the Sangre de Cristo range 100 miles north of the Estancia Valley. The peaks of these mountains exceed 12,000 feet in elevation, but because of their relatively low latitude, the largest glacier located above the present site of Santa Fe, was only 7 miles long. Melt waters from these glaciers fed either the Rio Grande to the west or the Pecos River system to the east, but did not contribute water to the closed basin of Lake Estancia.

The time relations between Lake Estancia and the glacial chronology have been studied by Antevs (1935, 1949) in an attempt to date the artifacts and bones found on the Llano Estacado. It is one purpose of the present discussion to review the Antevs analysis.

Hydrologic Balance of Lake Estancia.—Having made estimates of the relation between changes in temperature and the corresponding amounts of depression of the snowline in Pleistocene time, it is possible to examine the relation of these temperature changes to the water supply of Lake Estancia. The plan will be as follows. Given the depression of the snowline as determined from geologic evidence, the corresponding temperature changes will be used to estimate the change in annual evaporation. The resulting value of evaporation will be applied to Lake Estancia at its maximum stage to determine whether the lake could have existed under conditions having the same precipitation as that now experienced in the locality. If the lake could not be maintained under the assumed conditions of reduced evaporation, then it must be postulated that a greater rainfall existed at that time than at present, and some estimate of the magnitude of this increase might be made.

Values of evaporation from open lakes in the western United States are meagre. Although there are a reasonable number of evaporation data for Class A pans, a coefficient must be chosen to convert even roughly the pan data into evaporation from the free water surfaces of lakes.

Though there is no direct relation between air temperature and evaporation, a plot of mean monthly temperature against the mean evaporation in respective months is a graph widely used in hydrologic practice. The graph shows a hysteresis loop proceeding through the seasons. Figure 3a shows these loops for a number of lakes in the Great Basin determined by measurement of inflow and outflow (Harding, 1945). As might

be expected, evaporation generally increases with mean air temperature.

It is necessary to estimate such a hysteresis loop for central New Mexico. No evaporation record is available for Estancia. The nearest record is a Class A evaporation pan at Santa Fe which has been plotted as the full line in figure 3b. The rainfall and temperature conditions at Santa Fe are nearly identical to those of the Estancia Valley. Though the topography is somewhat different, Estancia being more exposed and for this reason possibly more windy, the Santa Fe curve will be applied after adjustment. Using a coefficient of .70 to reduce the pan observations to conditions of a free water surface, the evaporation measured for each month at Santa Fe was reduced

RELATION OF MEAN MONTHLY TEMPERATURE AND MONTHLY EVAPORATION

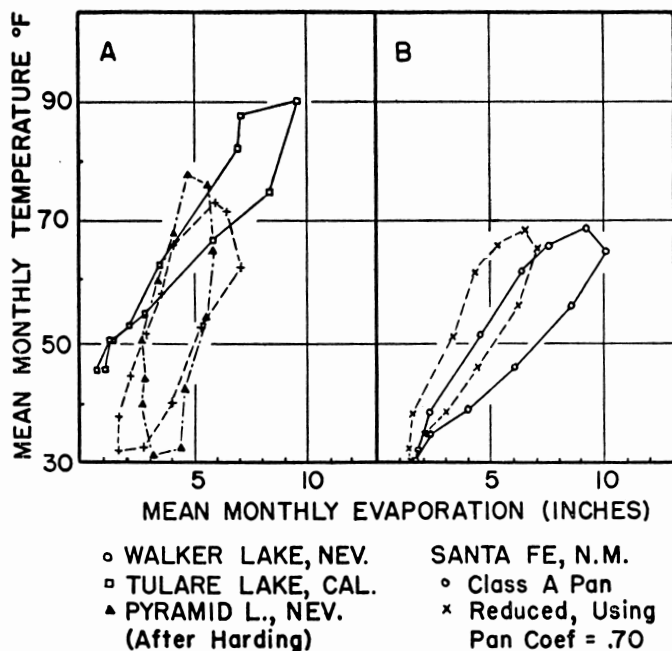


Fig. 3

to provide the hysteresis loop plotted as the dashed line in figure 3b.

Using the method outlined, the annual evaporation from a lake surface at Santa Fe is estimated to be 44 inches. Interpolating from the map of Furness (1947) a value of 48 inches would be obtained. His map of reservoir evaporation was derived from pan records similarly adjusted by a coefficient of .70. The map also indicates that Estancia at present would experience an annual evaporation about 3 inches greater than Santa Fe. Since this is much smaller than other possible errors in the present analysis, the Santa Fe record will be assumed applicable to Estancia.

A quantitative method has been specified for computing a new mean temperature for each month of the year for any given amount of snowline depression. Curves of annual march of temperature computed in this manner were presented in figure 2. In the next step, a given snowline depression was assumed and a new mean temperature was computed for each month. These values were applied to the dashed curve of figure 3b to obtain a new set of monthly evaporation values. By adding the twelve monthly values, a new annual evaporation was obtained. This process was performed for a number of values of snowline depression and a graph relating annual evaporation to the depression of the snowline was constructed.

Figure 4 is a nomogram or composite graph of which quadrant A is reproduced from figure 2b. It shows the relation of the lowering of the snowline (abscissa) to the lowering of mean annual temperature (ordinate). The same ordinate can now be applied to quadrant B where the evaporation values just discussed are plotted.

Present conditions are indicated by the origin of the graph in quadrant A; that is, zero snowline depression and zero temperature reduction. In quadrant B, y equals 0 when x , the evaporation, is 44 inches. This value is the present annual evaporation of an open body of water at Santa Fe and was computed by adding the values around the hysteresis loop of the dashed line of figure 3b.

For a value of 1500 meters of snowline depression, one can follow the arrows up to the sloping line of quadrant A, and left to the value of 8° representing the corresponding lowering of mean annual temperature. Proceeding horizontally from

$y = 8^\circ$ to the evaporation line and thence downward, one can read the value of 29 inches for the annual evaporation corresponding to a snowline depression of 1500 meters.

Let us return for a moment to the assumption that in Pleistocene time the mean January temperature remained equal to that of the present time while the summer temperature was considerably lower. Though winter might have been somewhat colder than the present, for the reasons already stated it is probable that the reduction in winter was small compared with that of summer. To test the effect of a reduced winter temperature, assume that the mean January temperature was $5F^\circ$ lower than at present and that the July temperature was reduced $16.2F^\circ$ in accordance with a snowline depression of 1500 meters. Under this set of assumptions the mean annual temperature would be lowered $11.8F^\circ$. It can be seen that the new

COMPOSITE GRAPH OF POSTULATED
RELATIONS BETWEEN HYDROLOGIC FACTORS
AFFECTING PLEISTOCENE LAKE ESTANCIA

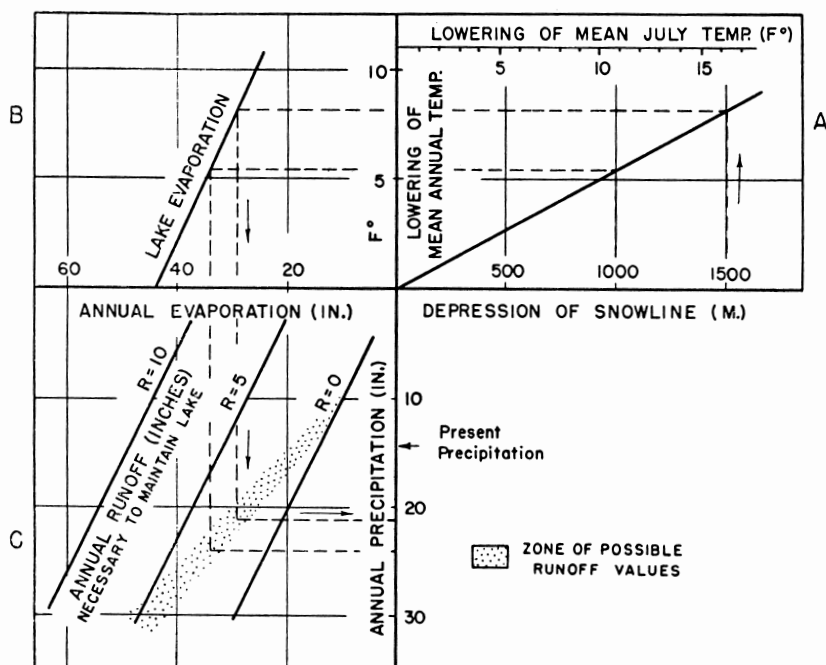


Fig. 4

assumption of a specific lowering of January temperature would increase the slope of the curve shown in quadrant A of figure 4.

Using the new annual march curve of temperature a new value of annual evaporation can be obtained. The assumptions and results are summarized below:

Assume:

- 1) Depression of snowline of 1500 meters
Therefore: July temperature lowered 16.2F.°
- 2) January temperature lowered 5F.° and intervening months proportionately

Compute from above assumptions:

- 1) Annual mean temperature reduction of 11.8° F.
- 2) Annual evaporation from lake, 26 inches

As would be expected, the additional assumption of a lower winter temperature would reduce the mean annual temperature. The consequent reduction of evaporation would be relatively small because the evaporation occurs primarily in summer. In summary, an assumed reduction of winter temperature provides a steeper slope to the line in quadrant A but the relations in quadrant B remain essentially unchanged, and for purposes at hand, the original assumptions provide a satisfactory approximation.

As Lake Estancia lay in an enclosed basin, the rainfall on the lake plus runoff into the lake was balanced by the evaporation from the lake surface.

Let e equal annual evaporation in inches

r equal annual runoff in inches

p equal annual precipitation

The contributing drainage area was 1550 square miles, and the area of the lake at maximum stage was 450 square miles. Following the reasoning used by Antevs (1935), the total volume of water can be equated:

$$p(450) + r(1550) = e(450)$$

or

$$e - p \left(\frac{450}{1550} \right) = r$$

This is a linear equation the solution of which may be represented as a family of straight lines on a graph. It is shown in quadrant C of figure 4. Given values of evaporation (abscissa) and precipitation (ordinate), the runoff r necessary to main-

tain the lake can be read off the graph by interpolation between the sloping lines.

It is obvious that for any given value of annual precipitation only a certain range of annual runoff values can occur in nature. A map of annual runoff for the United States has been published by Langbein (1949). It shows values of .25 inches near Estancia, .50 inches near Santa Fe, and an increase of values with elevation in central New Mexico. The relation of rainfall to runoff existing under present vegetative types and the geologic formations occurring in New Mexico determines the possible range of values, and this range is indicated by the stippled area in quadrant C of figure 4.

It is now possible to determine the rainfall necessary to maintain Lake Estancia under various assumed conditions of evaporation which in turn are determined by temperature. Referring back to the example cited above, a depression of the snowline of 1500 meters, one can follow the arrows along the dashed line into quadrant C and observe that according to the assumptions made, a precipitation of 21 inches would be necessary to maintain the lake at its high stage. The reasoning so far has considered no change of precipitation but only changes of temperature. It can be reasoned, then, that the snowline depression of 1500 meters indicated by geologic data and caused by temperature alone would not be associated with a low enough evaporation to maintain Lake Estancia under the present precipitation of 14 inches. If the precipitation were 21 inches at that time, the increased precipitation would also apply in the mountains and would in itself lower the snowline.

Therefore, the case of no temperature reduction will be considered. If the temperature were the same as that of the present, the lake evaporation would be 44 inches ($y = 0$, $x = 44$, in quadrant B). To maintain Lake Estancia under that condition, the precipitation would have to be about 30 inches. Such a rainfall would have brought the upper part of the pine forest, bordering the spruce zone, down to the margins of Lake Estancia. Such an occurrence would surely be indicated by well-developed soil profiles, which are not to be found anywhere in the Estancia area. Actually, some streams tributary to Lake Estancia have not discharged enough water since the lake receded to breach the lake shore deposits damming them (Bryan and McCann, manuscript). It is impossible to believe, then, that

increased precipitation without lowered temperature could account for the lake.

Great variations in rainfall would change the vegetative associations sufficiently to affect the runoff coefficient. Also the change in the period of snow cover might have an important effect on runoff. However, as long as the postulated changes require only moderate changes in precipitation and do not require major changes in the vegetation in the Estancia Valley, the use of modern rainfall-runoff relation in the present analysis seems justified.

The analysis leads to the conclusion, therefore, that Lake Estancia must have existed at a time when temperature was lower and precipitation higher than the present. How much did each of these factors contribute to the lowering of the snowline? A postulation of the relation of temperature, explored in some detail in the present study, has been made possible owing to two basic facts: first, the modern snowline seems controlled to a considerable degree by summer temperature, and second, the average lapse rate of temperature is so nearly uniform around the earth in the middle latitudes that an assumption of similar lapse rate in Pleistocene time seems very reasonable.

The relation of snowline to precipitation is much more difficult to postulate because it has not been investigated in detail in the Rocky Mountains even for modern conditions. Although a reasonable guess might be made, it would be founded on an even less logical set of assumptions than the temperature relation already discussed.

Consider the graphs of figure 4 for an assumed depression of the snowline of 1000 meters. Following the dashed line around the graph from that value, it is seen that a precipitation of 24 inches is necessary for maintaining the lake. That the difference between 24 inches and present 14 inches would account for the extra 500 meters of snowline depression necessary to make the 1500 meters inferred from geologic evidence, is a speculation which cannot be supported or tested.

It seems desirable to mention one other feature of the present analysis. Antevs (1935) used very similar reasoning to that presented here and concluded that Lake Estancia could not have existed at the same time that glaciers occurred in the mountains. He postulated (Antevs, 1949) that the lake postdated the maximum glaciation and existed 10,000 to 12,000

years ago at a time when both temperature and precipitation were higher than the present. He chose values of 20 inches for precipitation and 35 inches for evaporation as likely during the existence of the lake. These values require a runoff of about 4.5 inches from a precipitation of 20 inches, a high runoff coefficient for the western country. Assuming, however, that this might still be possible, his postulation of a temperature higher than that of the present would necessitate an increase in evaporation. The evaporation data from Santa Fe used in the present study indicate that 35 inches of evaporation would require a lower, not a higher temperature. Antevs used the evaporation of Lake Tahoe, California, as a criterion. The question is whether the Lake Tahoe evaporation provides a better measure of evaporation in New Mexico than an adjusted Santa Fe record.

The present analysis supports the conclusion of Antevs that Lake Estancia must have existed in a period more humid than the present. Antevs interpreted the necessity for increased precipitation as an indication of a post-glacial date, while the present study leads to the conclusion that a decreased temperature should also be necessary, indicating contemporaneity of the lake with glaciers in the mountains. These opposing viewpoints point to the hazard of using a date assigned to the lake as a measure of the age of associated artifacts.

The writer gratefully acknowledges the help of Prof. Kirk Bryan, Prof. Chas. F. Brooks, and Dr. V. Conrad, of Harvard University, and Mr. G. E. Harbeck of the U. S. Geological Survey, who read the manuscript and made many valuable suggestions.

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ERRATUM

In a recent paper on Pleistocene climate in New Mexico (AM. JOUR. SCI., vol. 249, pp. 152-168), the writer mistakenly stated (p. 167) that Dr. Ernst Antevs believes that Lake Estancia existed at a time when temperature was greater than at present. To correct my statement, Antevs' views on this matter are presented in the following excerpt from his appendix to Wormington, H. M., *Ancient Man in North America*, Denver Museum of Natural History, Popular Series No. 4, 1949, p. 189: "The lake (pluvial Lake Estancia) therefore may have attained its largest expanse first when the Azores high pressure area, which was displaced southward during the glacial age, again moved sufficiently far north in summer to send masses of moist tropical air in over New Mexico and Texas, as it is doing at present. Since the lake would have been greatly favored if the evaporation had been smaller, the ideal conditions may have prevailed when the summer temperature was somewhat lower than at present."

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