Reports

Deuterium Content of Snow as an Index to Winter Climate in the Sierra Nevada Area

Abstract. *The winter of 1968–69 produced two to three times the amount of precipitation in the Sierra Nevada area, California and Nevada, as the winter of 1969–70. The deuterium content in snow cores collected at the end of each winter at the same sites, which represents the total snowfall of each interval, shows a depletion in 1968–69 of approximately 20 per mil. The higher snowfall in 1968–69 and the depletion of deuterium can be explained by an uncommonly strong westward flow of cold air over and down the western slopes of the Sierras, which interacted with an eastward flow of moist Pacific air that overrode and mixed with the cold air; this resulted in precipitation that occurred in greater than normal amounts and at a lower than normal temperature. Pluvial periods of the Pleistocene may have had the same shift in air-mass trajectory as the wet 1968–69 year. Snow cores collected in the normal 1970–71 winter have deuterium concentrations that resemble those of the normal 1969–70 winter. Small and nonsystematic differences in samples from these two normal winters are due to variations in climatic character as well as to factors inherent in the sampling sites.*

We have presented data on the deuterium content of snow cores which represented the 1968–69 winter's precipitation in the Sierra Nevada area, California and Nevada (*1*). Snowfall that winter was exceptionally heavy; the total snowfall in the Sierra Nevada ranged from about 190 to 240 percent of the norm, and from 1 October to 31 March the total precipitation locally exceeded 360 percent of the norm (*2*). The 1969–70 snow year, however, was more nearly normal; it averaged 75 to 80 percent of normal snow precipitation in the area (*3*). The 1970–71 snow year was slightly higher, averaging 90 to 135 percent of normal (*4*). We have made a study of snow cores representative of these years similar to the study for 1968–69.

The deuterium content of snow cores from all 3 years, expressed as D : H ratios in per mil relative to SMOW (Standard Mean Ocean Water), are given in Table 1. All collection and laboratory procedures were as described earlier (*1*).

The data in Table 1 show the shift in the deuterium content of snow cores from identical stations. The 1968–69 year, characterized by a very deep snowpack, is best compared with the second year (1969–70), which had the least snowpack of the 3 years sampled. The 1969 cores are consistently depleted in deuterium relative to the 1970 cores. This difference is shown graphically in Fig. 1 by tielines that connect the 18 stations sampled in both years. The average of the numerical differences between the D : H values for these stations is 19 per mil. The differences in deuterium content in cores collected at identical sites for both years ranged from 6 to 42 per mil, but, for every station, snow representative of 1969–70 was enriched in deuterium compared to snow representative of 1968–69.

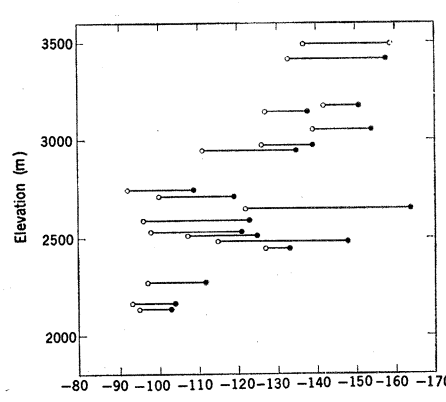


Fig. 1. Relation between elevation and deuterium content, expressed as D : H. (Solid circles) Snow cores collected on or near 1 April 1969. (Open circles) Snow cores collected on or near 1 April 1970. The radius of each circle is the experimental uncertainty (± 1 per mil).

At the 12 stations sampled for both years that are part of the California Cooperative Snow Survey network, for which long-term averages are available (Table 1), the water content of snow collected during the 1969 snow year was 214 percent of normal relative to the 1930–60 average (*5*). The water content in the 1970 samples from these stations was 68 percent of the 1930–60 average. These data, and data based on a much larger number of cores [cited in (*2*, *3*, and *6*)], show that, in terms of water equivalent at the time of the 1 April surveys, there was about three times as much snow in 1969 as in 1970 at the stations from which we collected samples and also in the Sierra Nevada area as a whole. We believe, therefore, that the stations we studied for each snow year gave a representative sampling of the total precipitation of snow in the Sierra Nevada and that the differences in deuterium content are meaningful.

Figure 2B is plotted from the data given in Table 1, and contours representing equal D : H ratios have been drawn. The divide of the Sierra Nevada is also plotted. When this D : H contour map is compared with the similar map for 1968–69 in our earlier report (*1*), it is evident that the contour lines are systematically displaced to the west. However, the pattern of contours—notably their northeastward bulge at the headwaters of the San Joaquin River—is similar in both maps.

The increased amount of snow in the first year cannot be attributed to a greater frequency or duration (or both) of storms of the normal character because the isotopic composition of the snow that accumulated during the two normal years is different. The storms that characterized the first year, therefore, must have had a fundamentally different character.

One way in which the fundamental character of the 1968–69 snow storms could have differed from the norm is that some storms might have resulted from moist air that moved from the North Pacific, entered the continent in British Columbia, and proceeded south (*7*). This trajectory, however, is unusual and should give a north–south gradient in deuterium, rather than the strong west–east gradient found. For this reason we think that this mechanism is not a likely one.

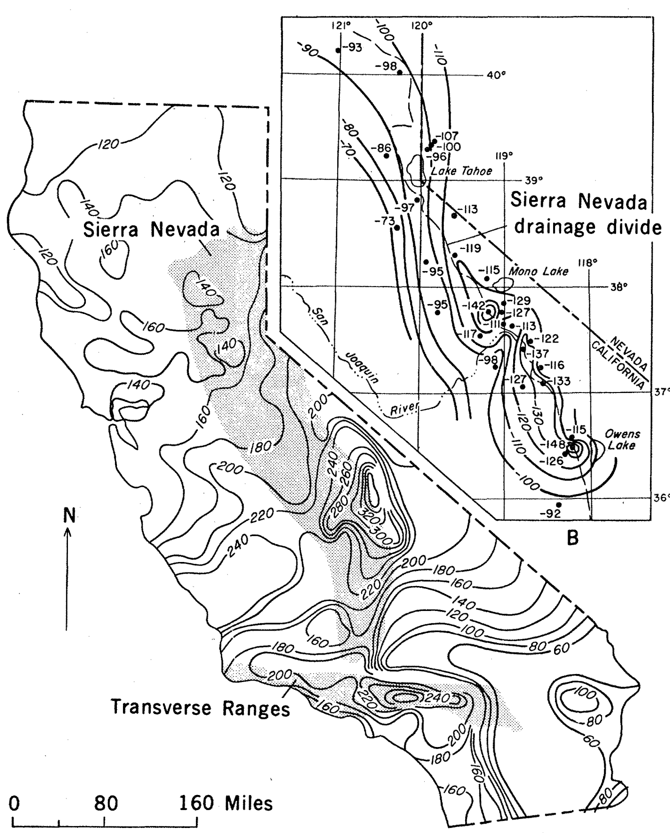
We believe that the best explanation for the anomalous storms is shown by the upper diagram in Fig. 3—a simultaneous flow of moist warm air from the Pacific and dry cold air from the northeast, with the denser cold air forming a lower layer that flowed southwest over the crest of the Sierras and down toward the coastal regions and the lighter warm air forming an upper layer that flowed northeast. This storm pattern was probably a result of increased cyclonic circulation. The northeastward flow of the air that contained the moisture is indicated by the northeastward decrease in deuterium. The southwestward flow of cold drier air is suggested to account for two aspects. The first is that it would create an increased horizontal temperature gradient in the moist Pacific air mass between the coast and the Sierra crest (Fig. 3); this is required to account for the greater deuterium fractionation that characterized the entire snowpack. The second is that such a flow could account for the extremely abnormal precipitation that occurred on the eastern side of the Sierras and in the Transverse Ranges during the abnormal first year (Fig. 2A) but not during the more normal second and third years.

The differences in the deuterium content of snow cores from successive years, however, are not large compared to the changes observed between individual storms (*8*). For example, the deuterium content of snow samples collected at a station on Mount Barcroft in the White Mountains of eastern California during the winter of 1968–69 ranged from −85 to −214 per mil. For snow samples collected from Bodie, California, during that winter it ranged from −111 to −213 per mil, and for those from Mono Lake it ranged from −116 to −207 per mil. These data illustrate that the differences between the snow cores representing the two winters could be produced by a small shift in the number of storms containing high or low deuterium.

The lower amount of deuterium in the wetter year is of interest because other studies we are making suggest that there were low amounts of deuterium in the snowpacks that formed in the Sierras during the relatively wet periods of the Pleistocene. Some support for the relation between winters characterized by snow with low D : H ratios and the Pleistocene climate is offered by a comparison of the average temperatures of the inland areas of California during the winters being compared. The average temperatures for 1 October to 31 March for the climatological districts known as the Northeast Interior Basins and Southeast Desert Basins (*9*) were about 1.1° and 0.6°C below normal during the wet 1968–69 season and about 0.6° and 0.1°C above normal during the subsequent dryer season. The correspondence between lower average temperatures, higher winter precipitation, and the depletion of deuterium in the snow for the wet 1968–69 winter relative to the more normal 1969–70 winter tends to confirm our hypothesis about the isotopic nature of the storms that characterized Pleistocene climates.

In all of the above discussion we are using snow cores collected on 1 April to represent the seasonal snowfall. Such cores, however, may not be completely representative. Early snows may be melted or drained off by thaws or rainfall; later rains and thaws do not generally remove water from the snowpack because the pack acts much like a sponge, but midseason or premature spring thaws may remove all the snow from sample sites at low elevations and allow late storms to supply all the snow obtained in a snow core on April 1. Ablation of the surface snow by evaporation or sublimation may remove part of the winter's record. Sites that are subject to depletion or accumulation of snow because of wind will be more or less representative depending on the windiness of the year. Large differences in core density and water content, relative to those at other nearby stations (Table 1), allow some nonrepresentative sites to be identified.

A measure of the importance of these factors is provided by a comparison of the second and third years of our snow core collections. These 2 years are



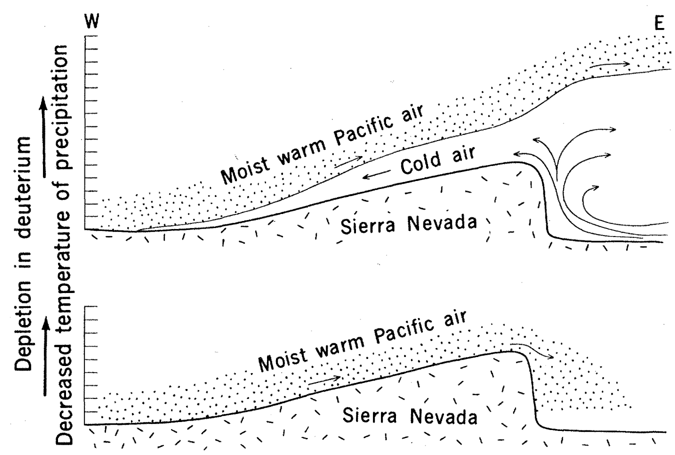


Fig. 2 (left). (A) Map of California showing precipitation from 1 October 1968 through 31 March 1969. The contours show precipitation in percent of normal (normals are averages of 1930–60 precipitation for the same period). [Figure after (*2*)] (B) Map with contours representing equal D : H values in the study area for the 1969–70 snow year. Fig. 3 (right). Diagram showing the movement of air masses and the directions of increasing temperature and D : H ratio. The lower part represents a normal storm pattern, while the upper part shows the effect of a strong cold air mass east of the Sierra Nevada crest. The upper diagram illustrates the abnormal storm patterns postulated in this report.

Table 1. Sample localities, collection data, and D : H ratios of snow samples collected on or near 1 April 1969–71 (arranged in order of decreasing elevation). Core densities and water content (percent of average, based on 1930 through 1960 average) are from (*10*).

Station name (California snow course number)	Elevation		Latitude (W)	Longitude (N)	1969			1970			1971		
	Feet	Meters			Core density (g/cm^3)	Water (% of normal)	D : H (per mil SMOW)	Core density (g/cm^3)	Water (% of normal)	D : H (per mil SMOW)	Core density (g/cm^3)	Water (% of normal)	D : H (per mil SMOW)
Mono Pass (182)	11,450	3490	37°26.3′	118°46.4′	0.42	201	−159	0.38	86	−137	0.41	85	−139
Bishop Pass (222)	11,200	3415	37°06.0′	118°33.4′	0.44	263	−158	0.41	97	−133	0.41	94	−138
Cottonwood Lakes No. 2 (220)	11,100	3385	36°29.0′	118°13.0′		331		0.33	98	−148		18	
Charlotte Ridge (299)	10,700	3260	36°46.2′	118°24.9′					93		0.36	65	−124
Gem Pass (281)	10,400	3170	37°46.8′	119°10.2′	0.42	198	−151	0.40	90	−142	0.41	84	−118
Blackcap Basin (223)	10,300	3140	37°40′	118°46.2′	0.43	204	−138	0.36	74	−127	0.37	80	−126
Rock Creek No. 3 (209)	10,000	3050	37°27.0′	118°44.5′	0.40	277	−154	0.35	85	−139		75	
Big Whitney Meadow (257)	9,750	2970	36°26.4′	118°15.3′	0.44	268	−139	0.37	68	−126	0.36	61	−138
Mammoth Mid Station	9,670	2945	37°38.5′	119°01.7′			−135	0.49		−111	0.50		−117
Center Mountain (151)	9,400	2865	38°09.0′	119°28.0′		214			98		0.40	101	−121
Onion Valley	9,180	2800	36°46.3′	118°20.3′							0.42		−134
Round Meadow (258)	9,000	2745	35°57.9′	118°21.6′	0.46	277	−109	0.43	70	−92	0.39	83	−88
Mount Rose C–1	8,885	2710	39°18.1′	119°53.9′	0.43		−119	0.45		−100	0.45		−114
Highland Meadow (323)	8,800	2680	38°29.4′	119°48.1′		178			91		0.48	120	−109
Sonora Pass (152)	8,800	2680	38°18.8′	119°36.4′		213		0.38	81	−119	0.37	102	−126
Rock Creek No. 1 (211)	8,700	2650	37°29.5′	118°43.0′	0.40	362	−164	0.37	61	−122		11	
Mount Rose A–2	8,500	2590	39°17.9′	119°55.1′	0.45		−123	0.45		−96	0.38		−109
Whitney Portal	8,367	2550	36°35.2′	118°14.4′				0.35		−115	0.29		−130
Bishop Park	8,300	2530	37°14.6′	118°35.8′				0.29		−116	0.35		−135
Badger Flat (346)	8,300	2530	37°15.9′	119°06.5′	0.43	222	−121	0.39	76	−98	0.43	84	−97
Mono Craters, South	8,300	2530	37°50.2′	119°00′				0.31		−129	0.35		−125
Mount Rose G	8,140	2480	39°19.6′	119°53.1′	0.48		−125	0.47		−107	0.43		−115
Mammoth Lakes	8,150	2485	37°39.2′	118°59.4′				0.42		−113		36	−108
Leviathan Peak	8,150	2485	38°40.4′	119°36.4′				0.52		−113	0.40		−118
Conway Summit*	8,140	2480	38°05.3′	119°11.0′	0.41		−148	0.36		−115	0.45		−133
Deadman Summit	8,020	2445	37°46.5′	119°00.9′	0.44		−133	0.41		−127	0.42		−108
Big Meadows (236)	7,600	2315	36°42.9′	118°50.5′	0.54	296		0.62	67		0.49	75	−88
Echo Summit (108)	7,450	2270	38°49.7′	120°02.2′	0.43	176	−112	0.44	79	−97	0.42	107	−101
Herring Creek (142)	7,300	2225	38°14.5′	119°56.5′	0.44	217		0.46	80	−95	0.44	102	−93
Fred Meadow (239)	7,200	2195	37°02.3′	119°04.8′	0.47	273	−98				0.50	79	−77
Boreal Ridge	7,140	2175	39°20.1′	120°21.1′							0.50		−99
Mount Dyer No. 1 (48)	7,100	2165	40°14.6′	121°02.1′	0.43	180	−104	0.44	97	−93	0.41	129	−104
Clover Meadow (200)	7,000	2135	37°31.7′	119°16.5′	0.45	271		0.41	68	−117	0.47	73	−89
Gin Flat (179)	7,000	2135	37°45.9′	119°46.4′	0.43	197	−103	0.46	60	−95	0.47	91	−80
Sonora Junction	6,880	2095	38°21.3′	119°28.1′	0.51		−140				0.29		−108
Rowland Creek (280)	6.700	2040	40°00.8′	120°17.6′	0.40	188		0.40	105	−98	0.38	137	−113
Lumberyard (135)	6,500	1980	38°32.7′	120°18.3′	0.52	185		0.47	62	−73	0.45	112	
Kingvale	6,050	1845	39°19.0′	120°17.0′				0.43		−86	0.40		−91
Blue Canyon	5,290	1610	39°17.2′	120°41.1′	0.46		−84				0.46		−71

* The 1970–71 sample site is ½ mile west (38°05.2′N, 119°11.6′W) of the 1969–70 site.

nearly normal in terms of snow water content but have slight differences in character. The second year (1969–70) snowpack averaged 75 to 80 percent of normal water content. Snow accumulated at a relatively even rate, and maximum water contents were reached in March (*5*). The third year (1970–71) snowpack averaged 90 to 135 percent of normal. Snow accumulated rapidly early in the year, and near-maximum water contents were reached in January; it thawed from mid-January through February, and more accumulated in March (*5*). Exceptional winds near the Sierra crest resulted in notable drifting during the third year [(*4*), including figure 1].

A comparison of D : H values for identical stations in the second and third years shows that 16 of the 26 stations have D : H values for the third year that are lower than those for the second year, and 10 have values that are higher. The average of the differences between the D : H values for identical stations is only 2 per mil. The inconsistency in the isotopic character at identical stations may be due to the factors inherent in snow core samples that were described above. However, the pattern of the D : H distribution is very similar in both years, which indicates that there were no fundamental differences in the magnitudes of storms or directions of storm tracks during these 2 years.

The important fact that emerges is that snow cores collected in 1969—a very abnormal year—are depleted in deuterium relative to cores collected in both of the more normal years that followed. We have suggested (*1*) that differences in the deuterium content of snow cores collected in different years at the same place can be used to characterize the weather patterns of the respective winters. The comparisons made in this report show that winters with very different weather patterns can be distinguished easily in this way, but that similar or nearly normal winters cannot. Also, the winter of 1968–69 may have resembled the Pleistocene in both isotopic character and increased precipitation. Our preferred explanation for the weather pattern of that winter provides a reasonable model for the climate of the Pleistocene compared with present climates in this area.

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References and Notes

1. I. Friedman and G. I. Smith, *Science* **169**, 467 (1970).
2. *Calif. Dep. Water Resour. Bull.* **120-69** (Rep. 3), 3, 6, 7, 10, and figure 1 (1969).
3. *Ibid.*, **120-70** (Rep. 3), 6, 7, 14, and figure 1 (1970).
4. *Ibid.*, **120-71** (Rep. 3), 6, 7, 14 (1971).
5. The data for California Cooperative Snow Survey stations are from the basic data supplements of *Calif. Dep. Water Resour. Bull.* [**120-69–120-71** (Rep. 3, 1969–71)].
6. *California Cooperative Snow Surveys, Index and Measurement Schedule* (California Department of Water Resources, Sacramento, 1967–68).
7. A somewhat similar trajectory was described by J. Rosinski, G. Langer, and R. Bleck [*J. Atmos. Sci.* **26**, 294 (1969)].
8. H. E. Kleiforth, I. Friedman, G. I. Smith, in preparation.
9. Data from monthly California summaries for these months are presented in *Climatological Data* (U.S. Department of Commerce, Environmental Science Service Administration, Washington, D.C., 1968–70), vols. 72–74.
10. H. S. Gale, *U.S. Geol. Surv. Bull.* **580-L**, 251 (1914); G. I. Smith, in *Means of Correlation of Quaternary Successions*, R. B. Morrison and H. Wright, Jr., Eds. (Univ. of Utah Press, Salt Lake City, 1968), pp. 292–310.
11. We thank K. Hardcastle and J. Gleason for their aid in carrying out the deuterium analyses. Snow core samples were collected by cooperators of the California Snow Survey, listed in (*6*), and by H. E. Klieforth, R. G. Smith, and G. I. Smith. Publication authorized by the director, U.S. Geological Survey.

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Terrestrial Atmospheric Composition from Stellar Occultations

Abstract. *Stellar ultraviolet light transmitted through the earth's upper atmosphere is strongly absorbed by ozone and molecular oxygen. The stellar ultraviolet photometers aboard the Orbiting Astronomical Observatory (OAO-2) satellite have measured the intensity changes of several stars during occultation of the star by the earth's atmosphere. From the occultation data the nighttime vertical number density profiles of molecular oxygen at altitudes from 120 to 200 kilometers and of ozone at altitudes from 60 to 100 kilometers have been obtained.*

In the earth's upper atmosphere, stellar ultraviolet light is strongly absorbed in the Schumann-Runge continuum of O_2 and the Hartley continuum of O_3. By monitoring the intensity of ultraviolet starlight in these continuum regions from a satellite as the star is occulted by the earth's atmosphere, we are able to obtain information on the number density profile of O_2 in the lower thermosphere and O_3 in the upper mesophere (*1*, *2*). In this report we describe the technique used to obtain the number density profiles from stellar occultation measurements. The data were obtained by the University of Wisconsin stellar photometers aboard the Orbiting Astronomical Observatory (OAO-2) satellite. We discuss here the inversion process and also show the O_2 and O_3 distributions determined from a typical occultation scan.

In the occultation technique classical absorption spectroscopy is used to determine the number density profile of the absorbing species in the upper atmosphere. The star is the source of ultraviolet light, the OAO stellar photometers are the detectors, and the atmosphere between them is the absorption cell. During the occultation process, the ultraviolet light is selectively absorbed in spectral regions for which O_2 and O_3 have large absorption cross sections. The intensity of the transmitted ultraviolet light is related to the number density along a tangential column of the absorbing species (N_i) by Beer's law

$$I(\lambda,r_0) = I_\infty(\lambda)\exp\left[-\sum_i \sigma_i(\lambda)\cdot N_i(r_0)\right] \quad (1)$$

where $I_\infty(\lambda)$ is the unattenuated intensity above the atmosphere of the star at wavelength λ, $\sigma_i(\lambda)$ is the absorption cross section of the ith absorbing species, and $N_i(r_0)$ is the tangential column number density of the ith absorbing species at a tangent ray height r_0. The star's spectrum is measured above the atmosphere by the OAO ultraviolet spectrometer. By also knowing the absorption cross section, one can relate $N_i(r_0)$ to the intensity of the transmitted ultraviolet light. In practice, Eq. 1 must be integrated with respect to wavelength because of the finite passband of the ultraviolet filter. The best

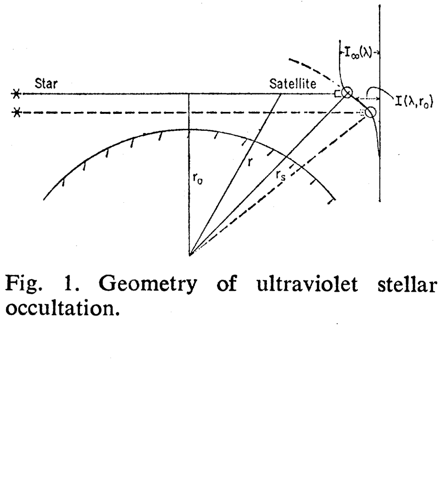

Fig. 1. Geometry of ultraviolet stellar occultation.