Reports

Oxygen Isotope Ratios in Trees Reflect Mean Annual Temperature and Humidity

Abstract. *Values of the oxygen isotope ratios ($\delta^{18}O$) in tree-ring cellulose closely reflect the $\delta^{18}O$ values in atmospheric precipitation and hence mean annual temperature. The change in $\delta^{18}O$ in cellulose is 0.41 per mil per degree Celsius for selected near-coastal stations. The values of $\delta^{18}O$ in precipitation and cellulose also change with altitude, as demonstrated for Mount Rainier, Washington. A temperature lapse rate of 5.2° ± 0.5°C per 1000 meters calculated from cellulose $\delta^{18}O$ values agrees with the accepted mean annual lapse rate of 5°C per 1000 meters for this region. Cellulose $\delta^{18}O$ values and $\delta^{18}O$ values of carbon dioxide equilibrated with leaf water differ by a fixed 16 per mil.*

Oxygen isotope ratios ($\delta^{18}O$) (*1*) based on measurements of water and carbonate derived from glacial ice, foraminifera, mollusks, and sedimentary carbonates have been used extensively as indicators of past climate (*2*). Important climatic information can be derived because the variation in the ratio of ^{18}O to ^{16}O in chemical compounds is dependent on equilibrium and kinetic effects that are related to temperature. Recently the ^{18}O content of tree-ring cellulose and wood has been used as an indicator of past climate (*3*).

It has been demonstrated that the ^{18}O composition of plant cellulose is related to environmental water and may also be related to humidity (*4*). It is also known that the $\delta^{18}O$ values of precipitation become more negative with increases in altitude and latitude. The $\delta^{18}O$ values for precipitation from coastal stations closely follow mean annual temperatures (*5*). To investigate the possibility that the temperature dependence for $\delta^{18}O$ in precipitation is also reflected in the $\delta^{18}O$ values of tree rings, we measured the $\delta^{18}O$ composition of cellulose (*6*) from trees collected at various latitudes along the West Coast of the United States and from various altitudes on Mount Rainier, Washington.

International Atomic Energy Agency (IAEA) yearly weighted average data on the $\delta^{18}O$ composition of precipitation (*7*) and cellulose $\delta^{18}O$ values in Fig. 1A show a parallel change with respect to latitude (r^2 = .98). In view of this agreement and the relationship between $\delta^{18}O$ in precipitation and mean annual temperature shown in Fig. 1B, it is clear that there is a direct correlation between $\delta^{18}O$ values in cellulose and mean annual temperature (Fig. 1C). Soil water collected during the growing season reflects in part earlier precipitation events, and hence a comparison is made with mean annual temperature rather than with mean growing-season temperature. Coastal trees were emphasized in this study because there are linear relationships between $\delta^{18}O$ in precipitation and temperature for coastal regions (*5*), because humidity is relatively constant (67 ± 6 percent), and because greater variation in the $\delta^{18}O$ values of cellulose has been demonstrated for trees grown in more continental regions (*8*).

Figure 1C demonstrates the value of this method for paleoclimatic work. The maximum error in the mean of the cellulose $\delta^{18}O$ data is ± 0.2 per mil, and thus it should be possible to detect long-term climatic changes in north Pacific coastal areas of approximately 0.5°C. Because individual sites may be subject to local conditions which may affect the $\delta^{18}O$ ratios, samples from a range of latitudes are preferred for paleoclimatic work. Comparisons with meteorological data and $\delta^{18}O$ data for precipitation or soil water are essential to demonstrate that this method can be used for a given area.

Figure 2A demonstrates an altitude effect for the $\delta^{18}O$ composition of precipitation at Mount Rainier. Precipitation samples were collected approximately every 2 weeks during the 1976–1978 growing seasons (May through September). A similar effect for $\delta^{18}O$ values in cellulose averaged from 1976–1978 tree rings is shown in Fig. 2B (*9*).

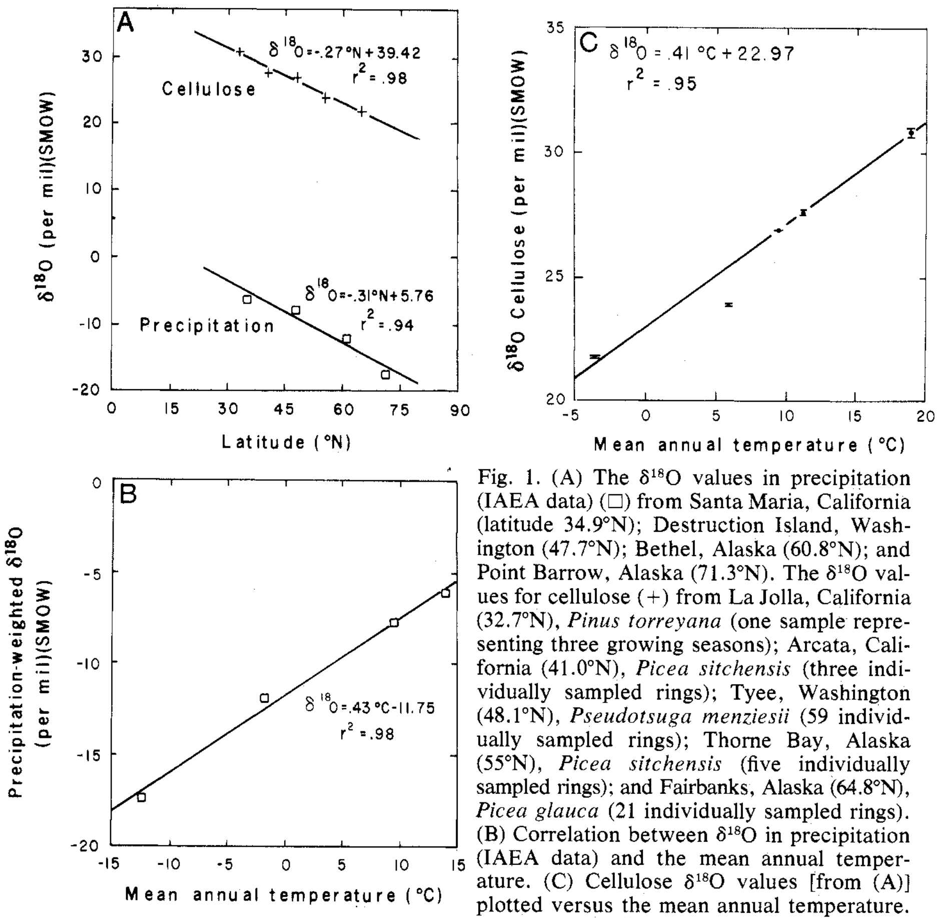

Fig. 1. (A) The $\delta^{18}O$ values in precipitation (IAEA data) (□) from Santa Maria, California (latitude 34.9°N); Destruction Island, Washington (47.7°N); Bethel, Alaska (60.8°N); and Point Barrow, Alaska (71.3°N). The $\delta^{18}O$ values for cellulose (+) from La Jolla, California (32.7°N), *Pinus torreyana* (one sample representing three growing seasons); Arcata, California (41.0°N), *Picea sitchensis* (three individually sampled rings); Tyee, Washington (48.1°N), *Pseudotsuga menziesii* (59 individually sampled rings); Thorne Bay, Alaska (55°N), *Picea sitchensis* (five individually sampled rings); and Fairbanks, Alaska (64.8°N), *Picea glauca* (21 individually sampled rings). (B) Correlation between $\delta^{18}O$ in precipitation (IAEA data) and the mean annual temperature. (C) Cellulose $\delta^{18}O$ values [from (A)] plotted versus the mean annual temperature. The point with the greatest deviation from the least-squares line is also the point with the greatest distance to a weather station (45 km for temperature data).

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Table 1. Model test data.

Location	Latitude (°N)	Growing-season daytime humidity (%)	Average growing-season temperature (°C)	Source water δ_1 (per mil)	Measured cellulose $\delta^{18}O$ (per mil)	Model-calculated $\delta^{18}O$ (per mil)	Model calculated humidity (%)	Model calculated $\delta^{18}O$ (per mil) (100% humidity)	α*
Fairbanks	64.8	59.3 ± 11.7	14.6	−16.6	21.8	20.6	55.0	9.6	1.027
Thorne Bay	55.2	72.3 ± 6.3	13.8	−11.3	23.9	22.8	68.4	15.3	1.027
Tyee	48.1	70.5 ± 4.9	13.4	− 7.7	26.9	27.2	71.5	19.1	1.027
Manashtash	46.9	35.3 ± 5.8	18.1	−16.3	27.3	26.5	32.4	9.2	1.026
Arcata	41.0	(70)	13.1	− 6.9	27.6	28.2	72.3	20.0	1.027
La Jolla	32.7	66.8 ± 4.4	20.0	− 4.4	30.8	30.0	64.0	21.2	1.026

This altitude effect on Mount Rainier can be used to evaluate the general reliability of the change in $\delta^{18}O$ values per degree Celsius developed from data collected on trees from different latitudes (Fig. 1A). Using the calculated change in the $\delta^{18}O$ composition of cellulose of 0.41 ± 0.06 per mil per degree Celsius from Fig. 1C, the temperature lapse rate on Mount Rainier is 5.2° ± 0.5°C per 1000 m. This value compares favorably with the value of 5°C per 1000 m from meteorological data (*10*).

The temperature relationships for the latitude and altitude data are only first approximations. More extensive work is needed for refinement. However, the initial results indicate the possibility that this method may be used as a temperature indicator.

It is clear from Fig. 1A that, by adding 35.1 per mil to the $\delta^{18}O$ precipitation values, one can calculate the cellulose $\delta^{18}O$ values. This systematic increase in $\delta^{18}O$ could be attributed to a biological fractionation factor. Such a simple model, however, does not explain $\delta^{18}O$ data obtained from trees grown east of the Cascade Mountain range. A tree grown at Manashtash Ridge near Ellensburg, Washington, derived its water from a year-round spring with an average $\delta^{18}O$ value of −16.3 ± 0.6 per mil (N = 17, intermittent samples over 3 years). According to the above model, the $\delta^{18}O$ values for cellulose should equal approximately 18.8 per mil. Actual values average 27.3 per mil, suggesting that other important factors must be taken into account. Current knowledge regarding the oxygen isotope uptake into cellulose suggests that humidity (*11*) and equilibrium between CO_2 and water must also be considered (*4*).

It is well established that the oxygen in cellulose comes principally from CO_2 (*12*). DeNiro and Epstein (*13*) demonstrated that CO_2 completely equilibrates with plant water prior to the synthesis of cellulose. If we assume that CO_2 isotopically equilibrates with average leaf water, then $\delta^{18}O$ values for cellulose can be calculated from equations used for calculating leaf water $\delta^{18}O$ combined with the standard equation for equilibrating CO_2 and water. For steady-state equilibrium conditions, the leaf water equation (*14*) may be written as follows:

$$\delta_{LW} = \delta_1(1 - h) + h\delta_{AV} + \epsilon^* + \epsilon_K(1 - h) \quad (1)$$

where δ_{LW} is the $\delta^{18}O$ composition of leaf water, δ_1 is the $\delta^{18}O$ composition of water supplied to the leaf by the stem, δ_{AV} is the $\delta^{18}O$ composition of atmospheric water vapor, ϵ^* is the equilibrium fractionation factor, ϵ_K is the kinetic fractionation factor, and h is the relative humidity (*15*). Equation 1 has also been used to model experimental results on the ^{18}O composition of bean plants; however, it was derived without assuming the complete equilibration of CO_2 with plant water (*16*).

When CO_2 is equilibrated with leaf water, the CO_2 gas will obtain a $\delta^{18}O$ value according to

$$\delta_{CO_2} = \delta_{LW} + 10^3(\alpha - 1) + (\alpha - 1)\delta_{LW} \quad (2)$$

where α is the CO_2-water fractionation factor (*17*).

The final equation for calculating $\delta^{18}O$ values in cellulose then becomes

$$\delta^{18}O_{\text{cellulose}} = \alpha[10^3 + \delta_1(1 - h) + \epsilon^* + \epsilon_K + (\delta_{AV} - \epsilon_K)h] - 10^3 + K \quad (3)$$

A major unknown in Eq. 3 is the value of ϵ_K; this factor is known to vary with wind speed (*18*) and has been calculated from kinetic theory to be equal to 16, 21, and 32 per mil for turbulent, laminar, and static boundary-layer conditions (*19*). Detailed work in controlled environment chambers is needed to define ϵ_K for the trees under discussion. We have assumed a value of +16 per mil, representing turbulent leaf boundary-layer conditions, for the calculations shown in Table 1. If this value for ϵ_K is incorrect, a change will need to be made in the value of the constant K. If, for example, ϵ_K = 21 per mil, then K would equal approximately −18 per mil to achieve the same cellulose $\delta^{18}O$ values as obtained with an ϵ_K of 16 per mil.

The constant K is added to Eq. 3 because investigations of deuterium and ^{13}C in cellulose have suggested biological fractionation factors for these isotopes (*20*). If biochemical reactions associated with cellulose production also fractionate oxygen, a constant K must be added to the basic equation. We found that K equals −16 per mil when fitting actual cellulose values measured over a range of latitudes to Eq. 3.

Correlations with temperature given

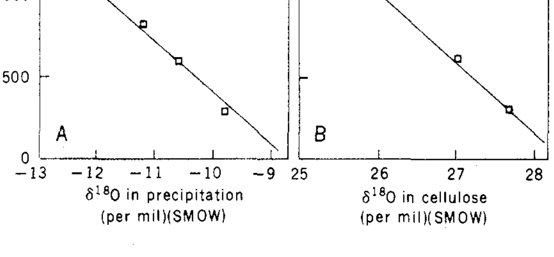

Fig. 2 (A) Values of $\delta^{18}O$ in precipitation during the 1976–1978 growing seasons (May through September, collected every 2 weeks) at different elevations on Mount Rainier, Washington (46.8°N). The independent variable was plotted on the ordinate to emphasize the effect of altitude. (B) Cellulose $\delta^{18}O$ values from *Pseudotsuga menziesii* (three individually sampled rings, 1976–1978) at five different elevations on Mount Rainier.

earlier are relationships which depend on the influence of temperature on the isotopic composition of precipitation rather than any direct temperature effect. Our model relates only to those changes in oxygen isotope composition that occur in and immediately around the tree leaf.

The $\delta^{18}O$ values calculated from Eq. 3 agree rather closely with measured values (Table 1; $r^2 = .96$). The model-calculated $\delta^{18}O$ value for the tree from Manashtash Ridge is much closer to the measured value than the value from the simple model mentioned above. This difference is thought to be related to the large (~30 percent) difference in humidity between coastal sites and Manashtash Ridge.

If, instead of substituting temperature and humidity, we substitute temperature and the measured cellulose $\delta^{18}O$ values, Eq. 3 can then be used to calculate relative humidity (*21*). The calculated values (Table 1) are all within 1 standard deviation of the average measured daytime relative humidity values for the growing season (*22*).

Valuable information on past changes in humidity can be obtained from measured cellulose $\delta^{18}O$ values and our model, if D/H or other isotope ratios can provide source water $\delta^{18}O$ values (δ_I). A 1 per mil change in δ_I represents approximately a 1 per mil shift in cellulose $\delta^{18}O$ values.

We have used Eq. 3 to calculate humidity values and could make a similar calculation for temperature since α and ϵ^* in the model are a function of temperature. The change with respect to temperature, however, is approximately 0.2 per mil per degree Celsius, which is a small effect compared to changes in relative humidity (1 percent change in relative humidity $\simeq$0.3 per mil change in cellulose $\delta^{18}O$).

Epstein *et al.* (*4*) have shown that α^* (*23*) between aquatic plants and their surrounding water is 1.027. The calculated α^* for the samples in Table 1, with 100 percent relative humidity to approximate the conditions under which aquatic plants grow, is either 1.027 or 1.026. This result suggests that the model can be used for aquatic plants as well as terrestrial plants. However, for aquatic plants ϵ^* no longer maintains its physical significance and must be treated as a constant.

We have shown that the oxygen isotope content of cellulose from trees can be used as a temperature indicator in specific West Coast areas where humidity values are fairly constant. An empirical model is derived which incorporates the currently known factors which determine $\delta^{18}O$ values in cellulose. Model results suggest that source water $\delta^{18}O$, humidity, leaf boundary-layer dynamics, and the $\delta^{18}O$ composition of atmospheric water vapor are factors that must be considered when evaluating oxygen isotope data in tree rings.

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References and Notes

1. Oxygen isotope ratios are calculated from

$$\delta^{18}O = \left(\frac{R_{\text{sample}}}{R_{\text{standard}}} - 1\right) \times 1000 \text{ (per mil)},$$

where $R = {}^{18}O/{}^{16}O$ (atom ratio). The standard is standard mean ocean water (SMOW).
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5. W. Dansgaard, *Medd. Grønland* **165**, 1 (1961); *Tellus* **16**, 436 (1964).
6. We measured cellulose $\delta^{18}O$ values on tree-ring wood to a precision of ±0.26 per mil, using a method modified from D. Rittenburg and L. Pontecorvo [*J. Appl. Radiat. Isotopes* **1**, 208 (1956)].
7. *Technical Report Series Nos. 96, 117, 129, 147, and 165* (International Atomic Energy Agency, Vienna, 1969, 1970, 1971, 1973, and 1975). Precipitation $\delta^{18}O$ values are weighted for precipitation amount according to

$$\bar{\delta}_w = \frac{\sum_{i=1}^{n} P_i\delta_i}{\sum_{i=1}^{n} P_i}$$

where P_i and δ_i represent, respectively, the monthly precipitation and its δ value.
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14. The original equation is from H. Craig and L. Gordon, paper presented at the Stable Isotopes in Oceanographic Studies and Paleotemperatures Conference, Spoleto, 26–30 July 1965. It was first applied to leaf water in a dissertation by W. Schiegl and reported in W. Schiegl [*Nature (London)* **251**, 582 (1974)].
15. It is assumed that δ_{AV} is in equilibrium with the average $\delta^{18}O$ of precipitation: $\epsilon^* = 2.644 - 3.206(10^3/T) + 1.534\ (10^6/T^2)$ where T is in degrees Kelvin [Y. Bottinga and H. Craig, *Earth Planet. Sci. Lett.* **5**, 285 (1969)]. Only daytime humidity values are used. Temperatures used are daily averages since daytime-only values were not usually available.
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17. This factor is given by

$$\alpha = \frac{(5.112 - 0.214t + 0.00041t^2 + 1000)1.04075}{1000}$$

where t is in degrees Celsius [Y. Bottinga and H. Craig, *Earth Planet. Sci. Lett.* **5**, 285 (1969)].
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21. Relative humidity is given by

$$h = \frac{\delta^{18}O_{\text{cellulose}} + 1016 + \alpha(-10^3 - \delta_1 - \epsilon^* - \epsilon_K)}{\alpha(\delta_{AV} - \epsilon_K - \delta_1)}$$

and

$$K = -16 \text{ (see text)}$$

22. The growing season used for Fairbanks was June, July, and August; for Ketchikan, May through August; and for the sites in Washington and California, May through September. Water $\delta^{18}O$ values (δ_I) used in the model are from an interpolation of IAEA values (see Fig. 1C) or from our direct measurements on lakewater (Fairbanks) or precipitation (Tyee).
23. $$\alpha^* = \frac{1 + \delta^{18}O_{\text{cellulose}}/1000}{1 + \delta^{18}O_{\text{precipitation}}/1000}$$
24. This research was supported by Department of Energy contract DE-AT06-79 EV10206 and NSF grant EAR-7904523, Geochemistry Program. We appreciate the assistance of P. Grootes, J. McCracken, P. Quay, P. Reimer, J. White, P. Wilkenson, and A. Yang.

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Volcanic Origin of the Eruptive Plumes on Io

Abstract. *A quadruple long exposure of Io in eclipse exhibits faint auroral emission from the eruptive plumes. No luminous spots in the vents, predicted by Gold, were observed. Heat from the interior of Io appears to be the predominant source of energy in the plumes.*

Gold (*1*) has recently expanded upon the idea that the large potential across Io generated by its interaction with the Jovian magnetosphere must drive electric currents (*2*). He proposed that these currents concentrate through the observed volcanic vents (*3–5*) and then pass through Io's interior. He calculated that these currents can be strong enough to account for the observed volcanic activity and that they are responsible for the eruptive plumes. He also predicted that luminous spots might be seen at night at the vents, a phenomenon not to be expected in the volcanic model based on sulfur dioxide as the driving gas and molten sulfur as the hot contact surface from which it proceeds (*5, 6*). This continues to be true for the models corresponding to observed temperatures (*7*) higher than those originally believed plausible. In these models (*8*) both sulfur vapor and SO_2 are present, the former predominating as driver.

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