Environmental Information in the Isotopic Record in Trees [and Discussion]

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Environmental information in the isotopic record in trees

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Twenty-three trees from widely different geographic locations and different environments were analysed for the δD and $\delta^{13}C$ records. The δD values suggested that the temperature of the Earth's surface rose over the past 100 years and probably for the past 1000 years. The rate of warming appears to be latitude dependent, greatest in the cooler areas. The $\delta^{13}C$ record, obtained for seven of the 23 trees, contain the $\delta^{13}C$ decrease due to the anthropogenic effect, the addition of CO_2 from coal and petroleum burning. This effect appears to be twice as high in the Northern Hemisphere as in the Southern Hemisphere.

Introduction

The direct relation between climatic temperatures and the D:H and $^{18}O:^{16}O$ ratios of precipitation is well documented. Generally, these ratios correspond quite faithfully to the worldwide climatic distribution (Daansgaard 1964; Siegenthaler & Oeschager 1980), and as shown in numerous examples of isotopic records in snow and rain, also respond to seasonal variations (Epstein *et al.* 1959). There is a linear relation between the D:H and $^{18}O:^{16}O$ ratios of precipitation and the mean annual temperature of the locations of the samples. The vigorous activity on the isotopic analysis of ice cores from the polar ice caps is a good example of using isotopic analyses of precipitation to obtain climatic information (Arnason 1981).

More recently, efforts have been made to extract climatic information from the isotopic composition of hydrogen and oxygen in plants and more specifically in tree rings. It has been shown that the hydrogen and oxygen isotopic composition in plants is determined by the isotopic composition of the water used by the plants (Epstein *et al.* 1976; DeNiro & Epstein 1979; Ramesh *et al.* 1986; Gray & Song 1984). Thus in principle the isotopic compositions of plants should permit the measurement of the climatic temperatures of their locations.

There are some complications associated with measuring the isotopic composition of hydrogen, oxygen and carbon in plants, due to the isotopic heterogeneity of the various chemical components. For example it has been shown that the δD* and $\delta^{13}C$* of the lipids in the plants can be 100‰ and 10‰ respectively lower than the δ values of the total plants (Smith & Epstein 1970). Thus the variation of the lipid fraction in a plant may introduce large isotopic composition changes independent of those resulting from the water it used. Consequently, it is necessary to use a single chemical component in plants to have the best chance of determining uniquely the isotopic composition of the water it used during its growth.

It has now been established that whereas cellulose should be used for the $\delta^{13}C$ and $\delta^{18}O$ analyses, it cannot be used for the δD analyses. The cellulose monomer contains 10 hydrogens, three of which are in the OH group and hence exchangeable. The exchangeable hydrogen will acquire the δD value of its immediate environmental water and will modify the original δD of the cellulose. This problem can be overcome by nitration to replace the OH hydrogen with NO_2 to form nitrocellulose, which then can be used for the δD analysis.

$$\delta D^* = (R_{\text{sample}}/R_{\text{standard}} - 1) \times 1000,\ R = {}^{13}C/{}^{12}C, \quad D/H, \quad {}^{18}O/{}^{16}O.$$

Standard is mean ocean water for O_2 and H_2 and Pee Dee belemnite for C.

A relation between the δD of the nitrocellulose from plants and the environmental water was determined (Epstein *et al.* 1976) using 25 different species of plants including marine turtle grass, fresh water lakes or pond plants, and terrestrial plants. For the non-aquatic plants the δD of the environmental waters were estimated from the analysis of lakes or rivers in close proximity to the plants. This relation, with a standard error of ± 10‰, was found to be of the form δD(plants) = δD(water) − 20, the water media concentrating deuterium. Considering the large variety of plants used and the possible biochemical and biophysical differences that may exist among them, this relation is good. It is reasonable to expect that isotopic data from a series of tree rings from a single tree will reflect more faithfully the variation of the isotopic composition of the water it uses. Probably the most serious modifying effect would be the evaporative transpiration of the leaf water that would enrich the deuterium in the tree relative to the environmental water source. Thus it is possible that warm, dry climate would show a higher δD value and a higher temperature than actually exists. However, we really do not understand this effect and its magnitude. In many cases, the fixation of CO_2 is inhibited when the tree is subjected to unusually warm dry weather. In addition, Sternberg & DeNiro (1983) have shown that at least some of the oxygen in the wood may be in part determined by the water in the tree trunk rather than the leaf water.

It was necessary to demonstrate that the δD of the nitrocellulose from the trees can be correlated with the environmental climatic temperatures. Hydrogen isotope analyses were made on wood from trees from 25 different localities in the North American continent (Yapp 1980; Yapp & Epstein 1982*a*) that covered a wide climatic range. These locations included Alaska, Texas, southwestern and eastern United States. In addition the δD values of eight time-equivalent five-year periods of seven trees in North America that grew in areas for which the climatic temperatures were well documented were compared with the mean annual temperature of their locations. The spatial temperature distribution versus the δD values gave a linear relation expressed by the equation (T is in degrees Centigrade)

$$\delta D(\text{cellulose nitrate}) = 7.7 \times T - 150.$$

This large coefficient of 8‰/°C can be useful because δD can be measured to within 1‰ and very precise temperature data should be attainable from the isotopic data.

Experimental procedures

The experimental techniques involved in the extraction of H_2 and CO_2 for isotope analyses is described in detail elsewhere (Epstein *et al.* 1976; Yapp & Epstein 1982*b*; DeNiro 1981). Basically a cross-sectional strip of the tree is subdivided into five- or three-year intervals. The wood is ground into sawdust, oxidized with sodium chlorite to produce clean cellulose and the cellulose is nitrated with fuming nitric acid to produce nitrocellulose. The nitrocellulose is isolated by taking advantage of its solubility in acetone. The nitrocellulose is combusted and the water produced is passed over uranium to produce H_2. The $\delta^{13}C$ is measured in the CO_2, combustion product of cellulose.

With the knowledge that the trees can record δD values that can be interpreted as environmental temperatures our object was to analyse a series of temporal δD records in trees from many different environments to determine if we can get a consistent record of the Earth's past climatic temperature.

Sections from 23 trees, spanning at least 30 years, randomly selected, including the 12 dealt with by Yapp (1980), were analysed for their δD records. In several cases, δ^{13}C analyses were also made on the same tree rings. There were no special criteria set for selecting the tree sites except that we preferred that they should have grown on relatively flat land and as much as one can determine to have had a normal growth and represent a wide range of climatic conditions. The δD of 12 of the 23 trees are reported on by Yapp (1980) and Yapp & Epstein (1982*a*). Yapp (1980) has provided the most thorough description of the location of the 12 trees he dealt with as well as the information to compare the δD and the local climatic data. The 23 trees allowed us to determine if a random sampling of locations would still permit the extraction of meaningful environmental information from the isotopic record in the trees *per se*, because it is not always possible to obtain wood samples whose conditions of growth are available.

Results and discussion

The location of the trees and the isotopic data are shown in table 1 and figure 2, respectively. Figure 1 shows 25-year running averages of the δD data of the bristlecone pines located in Shulman Grove in White Mountain, California. The running averaging of the data provides a better opportunity to determine the trends in the data by eliminating the short-time

Table 1. The identification and approximate location of the tree samples used in this study

sample no.	sample label	sample identity and location
1	Red-2	redwood (sequoia sempervirens); Miller Creek, California
2	AW-BO-1	bur oak (Quercus macrocarpa); Albion, Wisconsin
3	MO-O-2	oak from Owensville, Missouri
4	IE-10	juniperous phoenicea; Gebel Halal, N. Sinai
5	MNY-GA-2	green ash (Fraxinus pennsylvania); Montezuma National Wild Life refuge, New York
6	OPW-DF-1	sitka spruce (picea sitchensis); Olympic peninsula, Washington
7	UCI-1	cedar (Lubocedrus decarrens); Great Grove Sequoia National Forest
8	TAS	huon pine (Lagarostrobos franklini); Maydena S.W. Tasmania
9	ORE-1	douglas fir; Illinois valley, Oregon
10	SNO	red gum (Eucalyptus camaldulensis); Snowy Mountains, New South Wales, Australia
11	NEZ	rimu (Dracrydium cupressinum); Westland National Park, New Zealand
12	RE-CO-2	chestnut oak (quercus prinus); Reston, Virginia
13	MNY-BO-7	bur oak (quercus macrocarpa); Montezuma National Wildlife refuge, New York
14	COL-DF-1	douglas fir (Pseudotsuga menziesii) Mt. Vernon canyon; Colorado
15	MNY-RM-5	red maple (acer rubrum); Montezuma National Wildlife refuge, New York
16	SNF-LP-1	lodgepole pine (pinus contorta); Sierra National forest, California
17	Brpn	bristlecone pine; White Mts; California
18	BCT-12	pine near Seeley Lake; British Columbia
19	NMK-1	juniperous procera; Mau Narok, Kenya
20	FCA-WS-1	white spruce (picea glauca); Alberta, Canada
21	KSA-AS-1	aspen; Anchorage, Alaska
22	FAAS1	aspen; Fairbanks, Alaska
23	SAS-JP-1	jackpine (pinus banksiana); Near Porter Lake, North West Territories, Canada

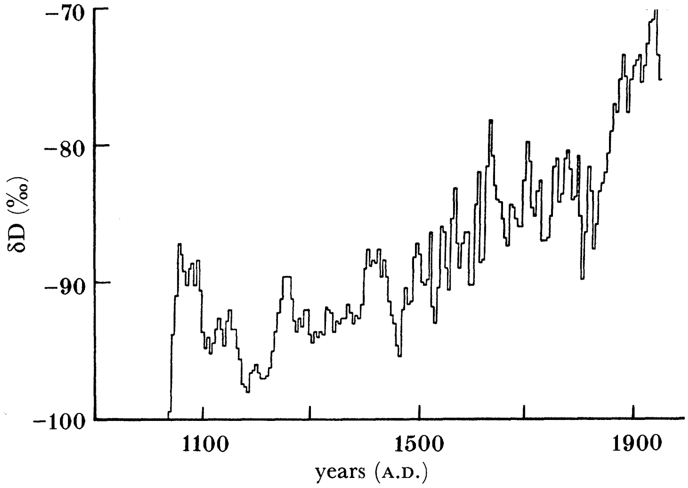

FIGURE 1. δD (25-year running average) against time of the bristlecone pine from White Mountain California.

oscillations. There are several interesting features regarding this isotopic record, the most obvious of which is the overall increase in the δD record with time indicating that the temperature of the White Mountain area and possibly of the Earth as a whole has been rising for the last 1000 years. We cannot discount a possible decrease in relative humidity associated with this temperature rise. Both of these factors can cause increase in the δD values (Epstein *et al.* 1977; Yapp & Epstein 1982*b*). A temperature rise independent of the anticipated rise due to the greenhouse effect would have some serious consequences as far as our civilization is concerned. This interesting result focused our attention on the necessity to examine whether similar increasing trends in the δD records are present in the other trees that came from many parts of the world.

It should be possible to test the temporal temperature record in tree rings by comparing the δD values in many trees with the temperature records of the area. This was attempted by Yapp (1980) on 12 trees. He showed that wherever such a comparison is possible the δD records sometimes relate to the mean annual temperature, sometimes to the mean summer temperatures and sometimes to the amount of summer precipitation. In two cases (samples 18 and 20), the sources of moisture for the trees were so variable that it was not possible to get a good temporal relation between the recorded temperatures and the δD values in the tree rings.

The time relations between the δD and the recorded temperatures are sensitive to the variations in the δD of the soil water and to any uncertainty in assigning a recorded temperature of an area. For example in some high-latitude areas the relation between the δD of the soil water and the temperature can become complicated if during the growing season two reservoirs of water are available for the soil. One source could be water from melting snow having a low δD value and the other source could be rain water with a higher δD value. A warm dry spring season could introduce low δD melt-water into the soil whereas a cool rainy spring can introduce more high δD rain into the soil. The δD of the tree rings that grew under the warmer conditions would be lower than that recorded in cooler conditions. The relation between the recorded temperature and the δD of the tree rings would be contrary to the expected trend. An exaggerated increase of δD in tree rings with temperature can also be accomplished if mild weather before the growing season removes the snow cover and rain water

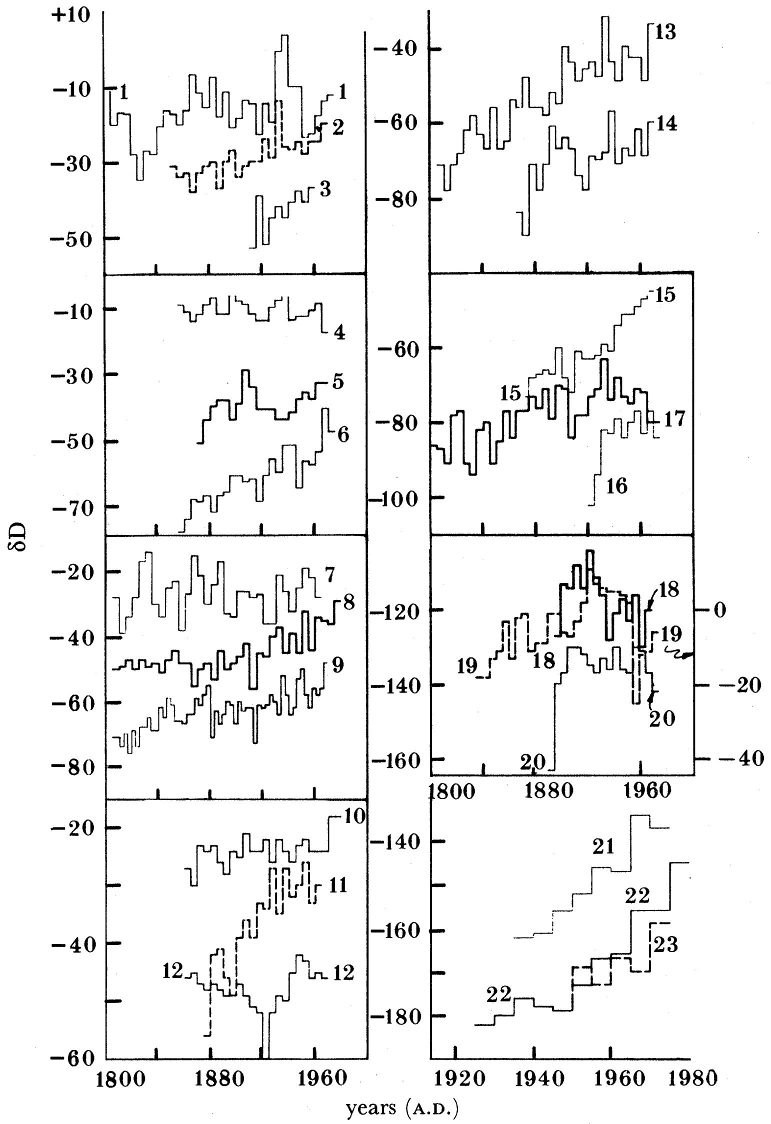

Figure 2. δD against time plots of trees from 23 different locations.

with high δD values then dominates the source of water in the soils when the tree grows. These erratic trends appear in short-time records in the tree samples from the high latitude. Over a long range of time such fluctuations in δD tree records would probably average out and result in an overall trend that reflects the average δD of the water and a correct temporal climatic trend of the area.

In spite of these possible difficulties the verification of the presence or absence of a good climate record in the δD of tree rings could be obtained by re-examining the isotopic record of the 12 trees from Yapp & Epstein (1982*a*) and the isotopic record of an additional 11 trees from other areas, a total of 23 trees. All totalled, the 23 trees come from three different continents and cover a climatic range from the equatorial and arid areas of Africa to the cold environments, such as found in Tasmania and the Canadian Yukon Territories. All but one of the trees has a δD record greater than 50 years. In the majority of cases the records cover more than 100 years, and two (bristlecone pine and juniper from the Sinai) cover 1000 and 400 years, respectively. Figure 2 shows these records.

It is obvious that 21 of the 23 trees show an increase in δD with time indicating a warming trend of various magnitudes in their respective locations. The two exceptions are in the high-latitude areas we discussed previously. The warming trends are not always smooth and are disrupted by introduction of anomalous surges in the δD records. A good example of an anomaly that modified the trend in the δD record without markedly changing its overall δD characteristic values is illustrated in the 150-year δD record of the juniper tree in Maunarok in Kenya, East Africa (Krishnamurthy & Epstein 1985). The δD in this tree rises from −20 to +20‰ from 1830 to 1960, at which time there was a strong decrease of δD of about 40‰ that lasted for about five years, after which the rise in δD resumed to the present time. The data suggested that the temperature in Kenya rose until 1960 and dropped quickly. It is obvious that such a drop in δD could not be due to world-wide cooling, but to a local perturbation caused by unusual rainfall for several seasons. The compelling evidence that this was the case lies in the measurements made of the level of Lake Victoria, which is in the catchment area of the forest, and which rose by 2 m in 1960, a circumstance that has not been observed in the 50-year record of the measurements of the level of Lake Victoria. This local effect will modify the slope of the line particularly if only the last 50 years of the record are used. Because local effects can modify the δD records in trees, the fact that such a high percentage of trees randomly sampled over a wide geographic area have such a consistent δD record must add credence to the global climatic significance of this record. This must be especially true for the bristlecone pine δD record, because of its length and its continuous trend over and above any possible local perturbations.

Although the majority of the 23 δD records shown in figure 2 show a warming over the period of growth, it is obvious that the degree of warming is not the same for the different trees. The unbiased value for the degree of warming could be estimated by carrying out a linear regression of the δD records in the trees with time. The slope expresses the specific warming as the change of δD per year. The δD value of the youngest tree ring gives the most recent climatic temperature of the area. A plot of the slope against this δD value reveals that there is an approximate linear relationship between the two quantities (figure 3). If all the data points are included, a linear regression gives a correlation coefficient of 0.60 (significant at 0.01 level). If two of the least fitting points (samples 18 and 20) are removed this coefficient rises to 0.83 (significant at 0.01 level).

Yapp (1980) noted that the δD temporal record in samples 18 and 20 was not correlated with the climate record of the area because of the interplay of the different air masses in their areas that produced rain patterns that was not characteristic of the mean annual or average summer temperature but rather of very restricted temperature ranges. The location of the data point for the bristlecone pine (no. 17) in figure 3 appears to be somewhat removed from the trend observed for the 20 other trees. Actually, the trend becomes similar to those of the other trees if we discount the last 30 years of its growth and use the period 1800–1940 in the linear regression. After 1940 the data shows a cooling trend.

The plot in figure 3 alerts us to several complications when we discuss climatic records. It is obvious that in low-latitude areas, where trees have δD values that are on the average of 0 to −30‰, a global warming will not be as pronounced as those occurring in the higher-latitude areas. If the appropriate trees of great age can be found in these areas, the effect of

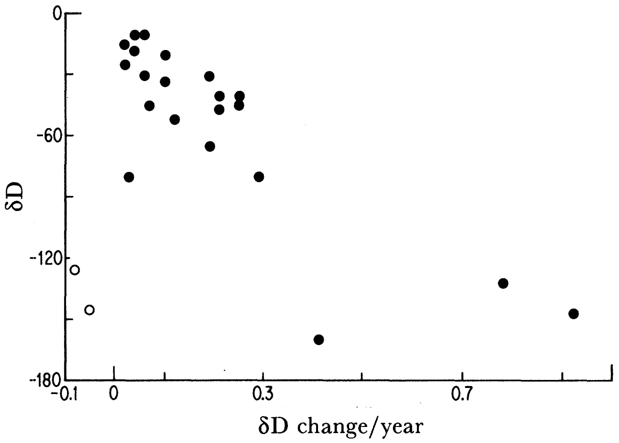

FIGURE 3. Plot showing δD values that are the actual temperatures of the past 10–20 years of growth against the change in δD per year (i.e. rate of warming) of the 23 samples. The correlation coefficient is 0.6. This coefficient improves to 0.83 if the open circled data (samples 18 and 20) are omitted.

global warming on the δD rise should be enhanced. It is reasonable to suppose that the warming trends of the Earth would effect the climatic temperature of the higher latitude to a greater degree than the equatorial latitude, creating smaller latitudinal gradients of temperature. For example, during the Cretaceous period the temperatures of the Earth were much warmer than they are now, and a more uniform temperature existed (Douglas & Woodruff 1981). The historical data that is presented to indicate the presence or absence of global warming or cooling should take this into account (Jones *et al.* 1986).

Our results suggest that isotope analyses of the bristlecone pine or of the trees growing in even cooler climates in Alaska or in the northern latitudes of Europe and Asia would represent a reasonable approach to measure the prehistoric climatic record. In the meantime the δD record in the bristlecone pine may be a good indicator of the relative magnitude of the change in global climate in the past 1000 years.

There are climatic changes reported in the literature (Lamb 1982) that can also be found in the bristlecone pine. There was a cold Arctic period associated with a loss of colonies in southern Greenland about 1100 A.D. There was a parallel drop in the δ value of about 10‰ between 1090 and 1100 A.D. There was a cooling period around 1780 in Europe, and the δD drops around that time.

The relation between the δD in trees and temperature has been estimated to be about 7–8‰ $°C^{-1}$ (Yapp & Epstein 1982*a*). This would suggest that a temperature rise between 1800 and 1940 is about 2 °C. This value may be too high for a global average but, as pointed out above, the response to world warming or cooling would be magnified in the higher latitudes and altitudes.

The rising trend in global temperature over the past 150 years is present in the 21 samples we analysed. In addition, the bristlecone pine record shows that this trend may have been in effect for the past 1000 years, and thus even if we find a way to stop the greenhouse warming due to anthropogenic activity, there is still an additional warming we might have to deal with if the Earth warming represents a danger to mankind. Considerable thought must be given to that problem as well.

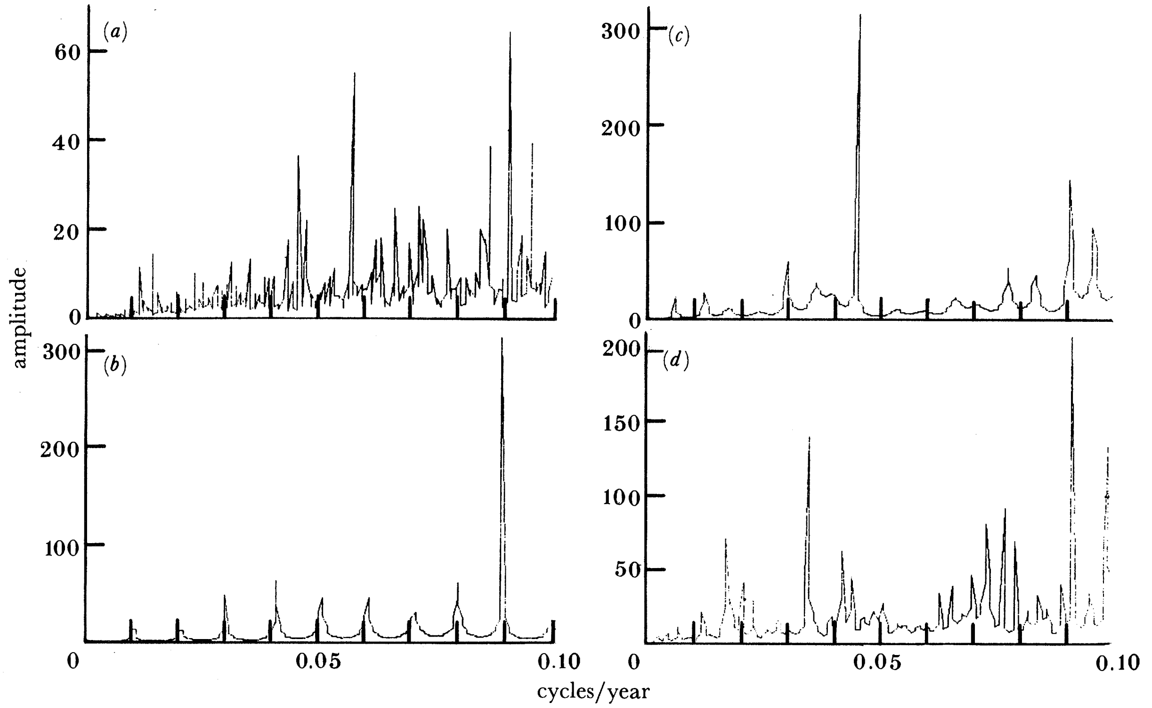

FIGURE 4. Fast Fourier spectra of the tree δD values that show either a 11- or 22-year cycle. The trees that show such cycles are those with a relatively smaller climatic trend; (*a*) and (*b*) sample 17, (*c*) sample 7, (*d*) sample 4. The time-periods covered in the Fourier analysis are (*a*) 970–1975 A.D.; (*b*) 1650–1750 A.D.; (*c*) 1805–1970 A.D.; (*d*) 1540–1970 A.D.

It has been previously shown that the δD and δ^{18}O in trees are affected by the relative humidity of the environment (Epstein *et al.* 1977). The δ^{18}O disproportionately increases with lowering of humidity, thus simultaneous δ^{18}O analyses of the cellulose should allow the estimation of the relative humidity on the δD values, and thus provide an appropriate correction on the δD to eliminate the effect of the humidity.

Periodicities in the δD *record in the trees*

It was of interest to subject the hydrogen isotopic record of the trees to a Fourier analysis to determine if significant cycles such as the solar 11-year or 22-year cycles were present in the data. Presumably, such cycles would indicate the influence of the sunspot activity on the Earth's climate. Because it has been shown that a number of factors, such as humidity, anomalous rain patterns, soil drainage (Yapp 1980), and other unknown factors affect the detailed δD record in trees, it is unlikely that Fourier analysis of the data will show striking cycles. It is possible that there are localities where the temperature variations are affected by solar radiation. An effort to find these special trees will be needed. Of the 23 trees that we have analysed, there are three trees that contain in them either 22- or 11-year cycles (figure 4). It is perhaps noteworthy that the cycles are present in trees that suggest a modest warming trend. The δD values of many of the other trees show such a strong trend with time that it probably interferes with the extraction of cycles from their isotopic data. The establishment of the connection of solar cycles with climatic cycles is an important problem. The use of isotopic records in trees to search for these cycles appears to be a viable possibility.

The δ^{13}C *record in trees*

One of the important questions that has attracted our attention in recent years is the role that CO_2 concentration in the atmosphere plays in affecting our environment. Here we briefly discuss the δ^{13}C record of the seven trees analysed. The isotopic compositions of carbon in the cellulose of different trees vary. The δ^{13}C values that we have observed range from about -17.5 to -24‰. This large variation reflects the environmental condition of growth rather than the differences in the isotopic composition of carbon in the global atmospheric CO_2. However, for a single tree, the variations are much smaller and vary from ring to ring by significant amounts and reflect the isotopic composition of its immediate atmospheric CO_2 or in some cases the δ^{13}C of the global CO_2.

The 1000-year comprison of the δ^{13}C and the δD records of the bristlecone pine is shown in figure 5. There are obvious similarities in their variations with time up to 1850. At this time the δ^{13}C values drop continuously whereas the δD record continues to climb to its maximum 1940 value. The drop in the δ^{13}C value is obviously as a result of the introduction of anthropogenic CO_2 of much lower δ^{13}C into the atmosphere. This signal is present in all of the seven trees we have analysed (figure 6), although in different degrees (Francey 1982; Freyer 1986). These trees are from the Australian mainland, New Zealand, Kenya, Tasmania, the Sinai, and California. Perhaps the most interesting result that we have obtained is shown in figure 7 where the δ^{13}C value of the bristlecone pine is superimposed on the δ^{13}C record of the juniper located in the Sinai. These *ca.* 400-year records of δ^{13}C variations are identical within experimental error. It is of interest to note that the δD records of the two trees do not match as well as the δ^{13}C record. Therefore, the synchronous nature of the δD–δ^{13}C record in the

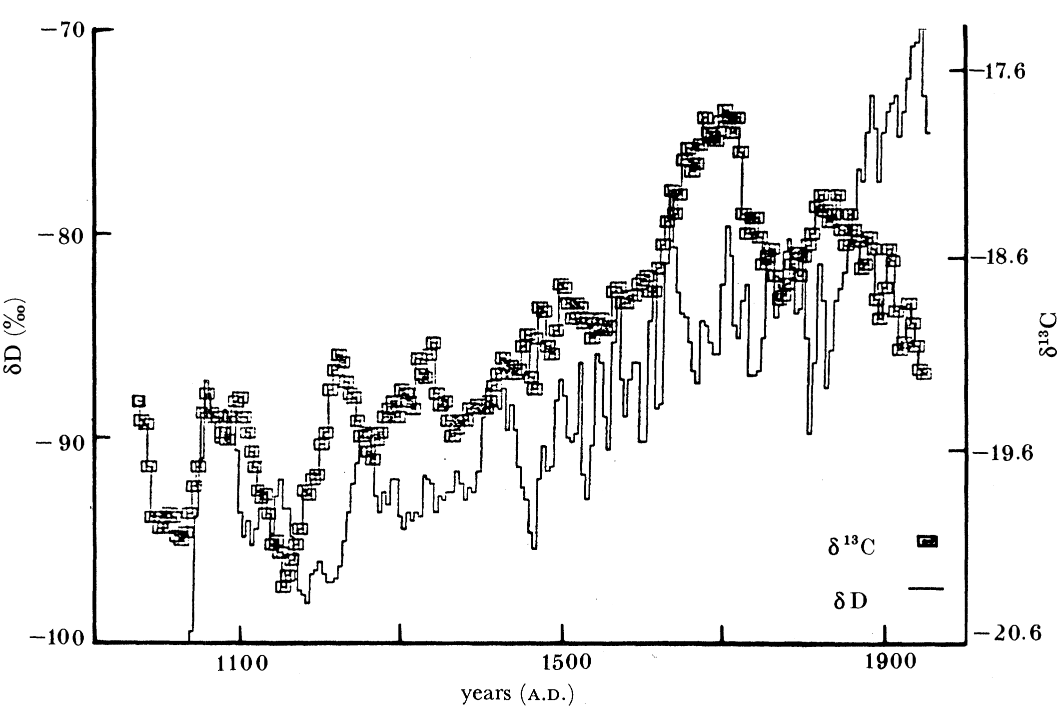

FIGURE 5. A comparison of the δD and δ^{13}C records of the bristlecone pine covering the past 1000 years.

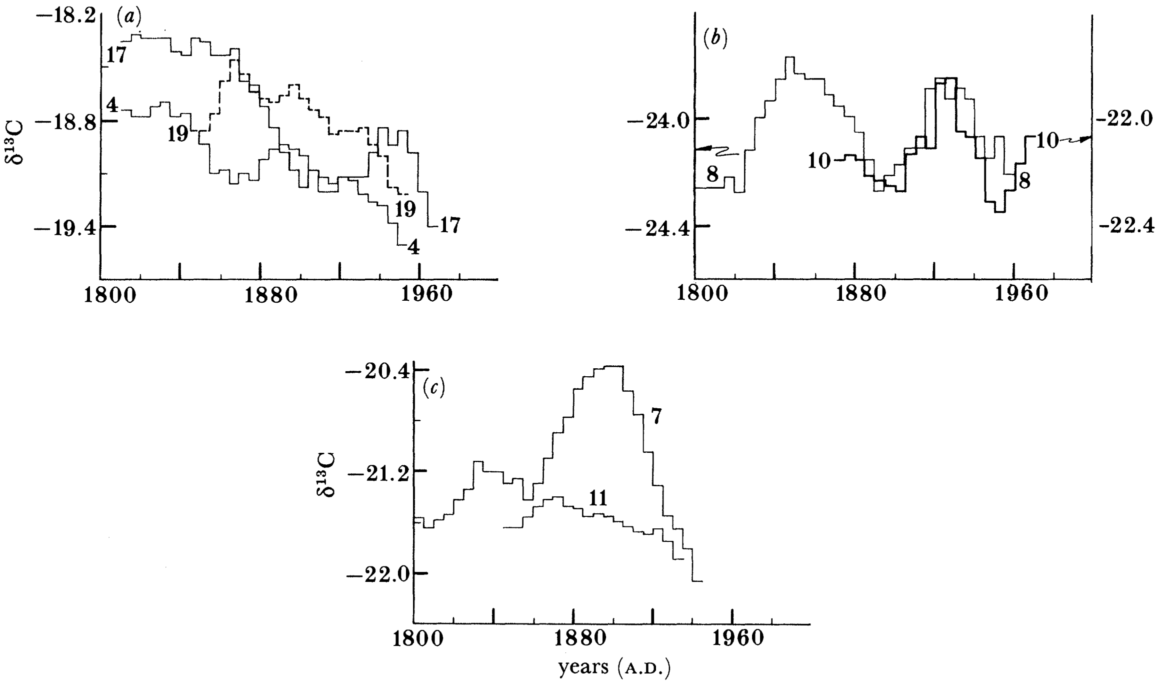

FIGURE 6. $\delta^{13}C$ (25-year running average) against time, of the seven samples analysed.

bristlecone and its absence in the juniper enhance the likelihood that those two trees have in their carbon isotope composition a record of the $\delta^{13}C$ variation in the global CO_2. Otherwise the difference in temperature might very well have affected the $\delta^{13}C$ of the juniper.

We can compare the degree of the anthropogenic $\delta^{13}C$ effect in the different trees we have analysed. Such a comparison based on a simple linear regression model is shown in table 2. It is interesting to note that the $\delta^{13}C$ anthropogenic effects in the Northern Hemisphere trees is about twice that obtained for the trees from the Southern Hemisphere (Tasmania, New Zealand and Australia). Such a difference is reasonable because the major source of industrial CO_2 is the Northern Hemisphere and this CO_2 probably loses much of its $\delta^{13}C$ signature by partial equilibration with the ocean surface before being fixed by plants in the Southern Hemisphere. The possible difference between the anthropogenic ^{13}C effect between the Southern and Northern Hemispheres suggests that there might be an interhemispheric difference in the $\delta^{13}C$ values of the two atmospheres.

In as much as the $\delta^{13}C$ record in the bristlecone pine and the juniper is taken to represent a Northern Hemisphere 'global' trend, it is tempting to ascertain if the $\delta^{13}C$ effects due to deforestation, which would lower the $\delta^{13}C$ value, unusual volcanic activity that would increase the $\delta^{13}C$ value, as well as effects arising out of human activities in the past 1000 years, are present in the bristlecone pine record. The overall increasing trend in the $\delta^{13}C$ in the bristlecone pine must be because of some major world-wide effect, probably the continuous warming of the world's oceans. This would release ^{13}C-enriched CO_2 into the atmosphere and could contribute to the gradual rise in its $\delta^{13}C$. It would be very useful to compare long records from additional trees whose environments are similar to the Sinai and White Mountain area. Sparsely wooded areas at high elevations as well as those away from industrial CO_2 contributions or perhaps even high-wind-prone areas that help in the rapid dissipation of industrial CO_2 might provide good sampling locations.

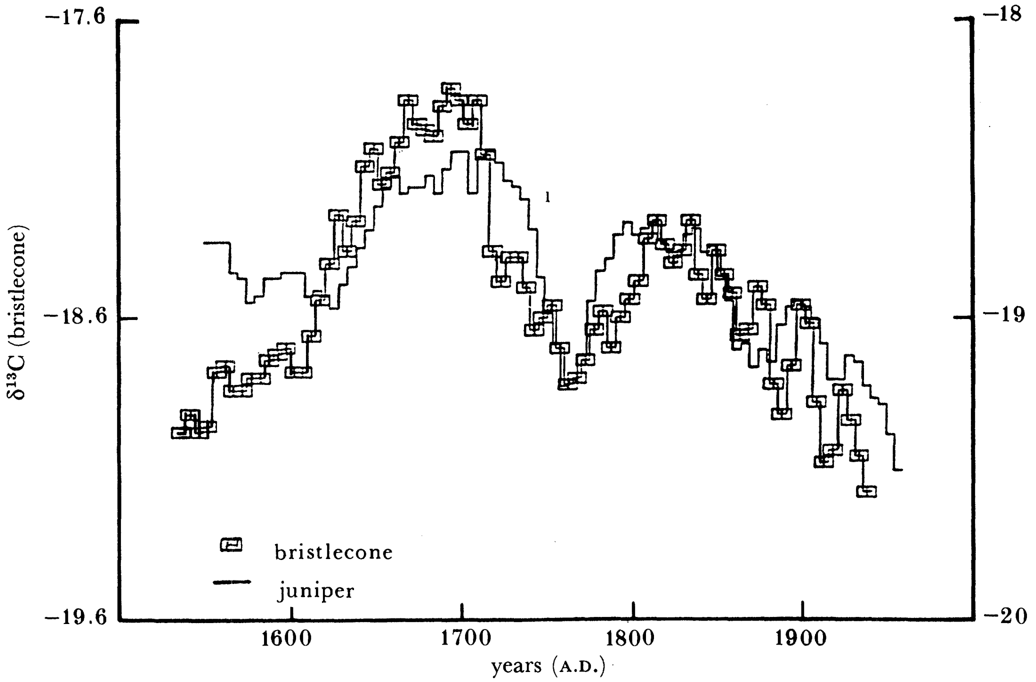

Figure 7. Comparison of the $\delta^{13}C$ records of the bristlecone pine and the juniper from the Sinai peninsula.

Table 2. The $\delta^{13}C$ change ($\Delta^{13}C$) due to anthropogenic effect between 1850 and the present

(The $\Delta^{13}C$ values were estimated by using a linear regression of the $\delta^{13}C$ record of the individual seven trees.)

sample no.	sample label	$\Delta^{13}C$ (‰)
8	TAS	−0.26
10	SNO	−0.08
11	NEZ	−0.5
19	NMK-1	−0.78
17	Brpn	−0.84
4	IE-10	−0.75
7	UCI-1	−1.08

A well-confirmed 'global' record of the $\delta^{13}C$ in trees would provide the opportunity to determine the effect of local conditions on the $\delta^{13}C$ record of individual trees. For example, a forest fire contributes a great deal of CO_2 of low $\delta^{13}C$ in the atmosphere. The carbon isotope composition of the tree growth for several years subsequent to the fire might provide a pattern characteristic of the event and its magnitude so that such prehistoric events could be identified and its magnitude estimated. Similar environmental ^{13}C perturbations due to volcanic activity and deforestations could also be located and their magnitude estimated.

Summary

Tree rings from 23 trees from various locations have been analysed for the δD and $\delta^{13}C$ values. Twenty-one of these trees give a consistent spatial and temporal pattern suggesting a world-wide warming trend for the past 100 and possibly for the past 1000 years. The degree of warming is latitude dependent.

The $\delta^{13}C$ record in the trees shows the $\delta^{13}C$ decrease in the past 100 years resulting from the anthropogenic contribution of low-^{13}C CO_2 to the atmosphere. The identical $\delta^{13}C$ temporal record of the juniper tree from the Sinai Peninsula and the bristlecone pine in the White Mountains of California suggests that both of these trees probably record the $\delta^{13}C$ of Northern Hemisphere CO_2. The Northern Hemisphere $\delta^{13}C$ effect is twice that for the Southern Hemisphere, and consequently there may be a small steady-state difference of about 0.3‰ in their atmospheric CO_2.

A strong argument has been made for the use of δD values of non-exchangeable hydrogen in cellulose extracted from trees to determine the past history of the Earth's climate and how the temperature was distributed on the surface of the Earth. We perceive this argument as a basis for expanding this effort to search for trees that are especially suited for this purpose. It is obvious that the bristlecone pine trees whose dendrochronology span thousands of years with the possibility of going back to the transition between the glacial–interglacial period are particularly attractive for study. A similar investigation of the $\delta^{13}C$ in trees can go back thousands and millions of years. A sample of glacial–interglacial transition in the $\delta^{13}C$ for ^{14}C-dated tree samples has already been attempted (Krishnamurthy & Epstein 1990).

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Discussion

H. Oeschger (*Physics Institute*, *Bern*, *Switzerland*). How much do changes in plant physiology affect the isotopic signature in tree rings? For example, the increase in CO_2 (25% in the past 200 years) might have lead to a decrease of evaporation (less stomata opening) that could simulate a δD shift independent of the δD in the environmental water.

S. Epstein. If the evaporation of water from the leaves would decrease as a result of the constriction of the stomata opening, then the δD values in the tree rings would decrease. Because the δD has risen over the past 1000 years in the bristlecone pine, a rise substantiated in the other trees for the past several hundred years, it would appear that the stomata effect would not be important. I would guess that the effect of temperature and possibly the relative humidity would be more profound on the δD hydrogen in the bristlecone pine.

J. A. Eddy (*UCAR*, *Boulder*, *Colorado*, *U.S.A.*). How does Professor Epstein's δD record of the past 900 years obtained from measurements of δD in bristlecone pine from the White Mountains of California compare with the temperature reconstruction derived for the same area and the same period by Valmore C. LaMarche? LaMarche derived a temperature history for simple ring *widths*, having found that trees at this altitude are temperature sensitive in their pattern of growth.

S. Epstein. The tree ring width record in the bristlecone pine determined by LaMarche is reasonably compatible with the δD of the bristlecone pine over the past 500 years. Before that time (between 1000 and 1500 years), there is a considerable difference in the records of the δD and ring width. I see no reason why the bristlecone pine would not record the δD of precipitation before 1500 years ago. The best answer for your question would be the analysis of additional tree records in other locations for both the δD and ring width for this time period. It might prove interesting to check ring width records in younger trees in other locations and see if they match the δD records.

J.-C. Pecker (*Collège de France*, *Paris*). Is it conceivable to introduce a 'global' (planetary) 'tree-ring index', in the way people have introduced 'planetary' geomagnetic indices, which give many useful ways to study the solar–terrestrial relations? Is it conceivable to use the 'petrified forests' trees (such as in Arizona) to derive tree-ring indices?

S. Epstein. It is conceivable that a global isotope tree-ring index may eventually be developed. This will involve a world-wide cooperative effort. As we have already indicated (figure 4) solar–terrestrial relations may be present in the isotopic record in trees. I cannot comment on the potential of silicified wood. We have not tried to extract cellulose from such materials.