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A climatic record from ^{14}C-dated wood fragments from southwestern Colorado

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Abstract. Deuterium concentrations in trees are related to the climatic temperature at which the trees grew. Deuterium analyses were made on all available (39) ^{14}C-dated (all ^{14}C dates cited are uncorrected) wood fragments collected from Lake Emma sediments. The ^{14}C dates range from 9600 to 5400 "B.P.". Tree line was above Lake Emma at 9600 "B.P.", was at Lake Emma at about 5000 "B.P.", and is 80 m below Lake Emma at the present time. The isotopic records at the various intervals of time coincide very well with this history. The range of δD values is maximum at 9600 "B.P." and is minimum at about 5400 "B.P.". These data allow us to estimate the temperature range for the area between tree line and Lake Emma between these times. These results confirm previously observed cooling trends from several sources in the Western Hemisphere.

There are several continental isotope climatic records in the Holocene. The continental glacier on Devon Island in Arctic Canada, whose source of precipitation is primarily the Atlantic Ocean, shows a decrease in $\delta^{18}O$ from about 6000 to about 1000 "B.P.", representing a cooling trend [*Paterson et al.*, 1977]. This trend is also observed between about 7000 and 2000 "B.P." in the δD record of bristlecone pine from the White Mountains, California [*Feng and Epstein*, 1994], which obtains most of its moisture from the Pacific Ocean. More recently, *Thompson et al.* [1995] reported a similar trend from 6500 to 1000 "B.P." in a $\delta^{18}O$ record of a tropical glacier from Huascarán, Peru, which obtains most of its moisture from the Atlantic Ocean. The range and the magnitude of these trends are not identical which reflect their locations and the nature of the records. For example, the isotopic records in wood should not correspond in detail to the isotopic records in ice caps. Trees record the hydrogen in rain and snow which is indicated by the measurements of modern trees in cold areas [*Feng and Epstein*, 1995], whereas records in the ice caps are strictly from snow.

The similarity of the three records is sufficiently strong to suggest that a continental scale cooling trend may have existed in the Western Hemisphere during the early to middle Holocene. However, it would take more than a few records of this kind to understand the climatic situations that existed on the continents during this period of time. Toward this aim it is important to increase the contribution of the isotopic records in trees. There are also special circumstances whereby the accepted relationship between temperature and the hydrogen (and oxygen) isotopic composition of precipitation may not hold in some areas. For example, a warming or cooling of ocean surface waters in themselves could affect the deuterium and ^{18}O concentrations in rain or snow, particularly in the colder continental areas. Thus the δD and $\delta^{18}O$ in the precipitation of these areas may not correspond to their climatic temperatures [*Yapp and Epstein*, 1982; *Epstein*, 1995]. The approach of using the stable isotope data of ^{14}C-dated wood fragments collected in restricted continental areas can provide independent climatic information which can confirm the Holocene cooling trend by the change in the tree line for that area. In this paper we report the isotopic analyses of 39 ^{14}C-dated wood fragments from Lake Emma, San Juan Mountains, Colorado, United States to illustrate the usefulness of using the combined ^{14}C and the δD data of these wood fragments.

The San Juan Mountains are situated along the continental divide in southwestern Colorado. During the Pleistocene the San Juan Mountains were extensively glaciated. The last major glaciation in Colorado is estimated to have reached its height about 22,000 "B.P." [*Madole*, 1986]. However, the glaciation disappeared prior to 10,000 "B.P.", at which time vegetation began to reappear in the area [*Carrara, et al.*, 1991]. At present in the San Juan Mountains, timberline, the upper altitudinal limit of large upright trees, is generally between 3535 and 3600 m. Tree line, the upper altitudinal limit of small, scattered and windswept trees (krummholz), is at about 3660 m. Both timberline and tree line are known to be determined by growing season temperature. The $10^{\circ}C$ July isotherm is known to agree well with upper timberlines in the Northern Hemisphere [*Tranquillini*, 1979]. The subalpine forest in these mountains ranges from about 2900 m to

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timberline and is dominated by Engelmann spruce (Picea engelmannii) and subalpine fir (Abies lasiocarpa). Above timberline, krummholz, dominated by Engelman spruce with minor amounts of subalpine fir, extends to tree line [*Carrara et al.*, 1984, 1991].

Lake Emma, the source of the old wood fragments we analyzed, was at an altitude of 3740 m, well above present tree line. The nearest krummholz trees are about 0.9 km down valley from Lake Emma at an altitude of about 3660 m, although a few individuals attain an altitude of 3700 m. Timberline is about 1.5 km down valley from Lake Emma at an altitude of 3600 m [*Carrara et al.*, 1991]. Lake Emma, located in a south facing cirque, once occupied an area of about 0.05 km^2 and had a maximum depth of about 10 m. On June 4, 1978, the lake was drained by the collapse of underground mine workings. After Lake Emma was drained, inspection of the former lake basin revealed numerous coniferous wood fragments in the lake sediments. These fragments were from trees growing on the surrounding slopes above Lake Emma and deposited by snow avalanches or other mass wasting processes. Most of these fragments are probably from krummholz in that they are small, contain contorted ring patterns, and commonly contain reaction wood. The majority of the wood fragments were identified as *Picea* (probably Engelmann spruce); the rest were identified as *Abies* (probably subalpine fir). Thirty-nine radiocarbon dated wood fragments from Lake Emma were available to us. The radiocarbon ages form an almost continuous suite of ages ranging from 9600 to 5400 "B.P.". Only one wood fragment has an age less than 5400 "B.P.".

There is now sufficient data relating temperature and δD of unexchangeable hydrogen in cellulose extracted from modern wood samples to have confidence in the ability to extract climatic temperature information from ancient wood fragments [*White et al.*, 1994; *Yapp and Epstein*, 1982; *Gary and Song*, 1984]. Any loss of cellulose due to degradation does not affect the isotope composition of the remaining cellulose in the wood [*Yapp and Epstein*, 1977]. In Figure 1 we present δD data of all the 39 wood fragments from Lake Emma which grew when tree line was above the lake. There are several observations that can be made. The range of the δD values of about 35‰ is greatest at 9000 "B.P.". For any specific time period the highest δD values, specified by squares in Figure 1, we interpret to represent the maximum climatic temperatures of the trees which grew at the Lake Emma site. The minimum δD values for any specific age, designated by circles in Figure 1, represent the highest elevation and the lowest temperature condition at which trees grew at this time, namely, the tree line. The δD range, as well as the maximum δD values, decrease as the ages of the samples decrease. Since we considered the maximum δD values represent trees which grew at the elevation of ancient Lake Emma, the temperatures at Lake Emma decreased with decreasing age. Assuming the coefficient relating the temperatures and δD values is 8 ‰/°C [*Yapp and Epstein*, 1982], the maximum average climatic temperature change from about 9000 to 5000 "B.P." was roughly 4°C at Lake Emma. The minimum δD values for any one period of time, which we interpret to be a record of the temperature history of the tree line, change to a much smaller degree with age. Even the change we show for the tree line is due primarily to a single point at 5500 "B.P.". At about 5000 "B.P.", the minimum temperature at which the trees could grow, namely, the tree line, appears to have been at Lake Emma. Wood fragments no longer existed after 5000 "B.P."

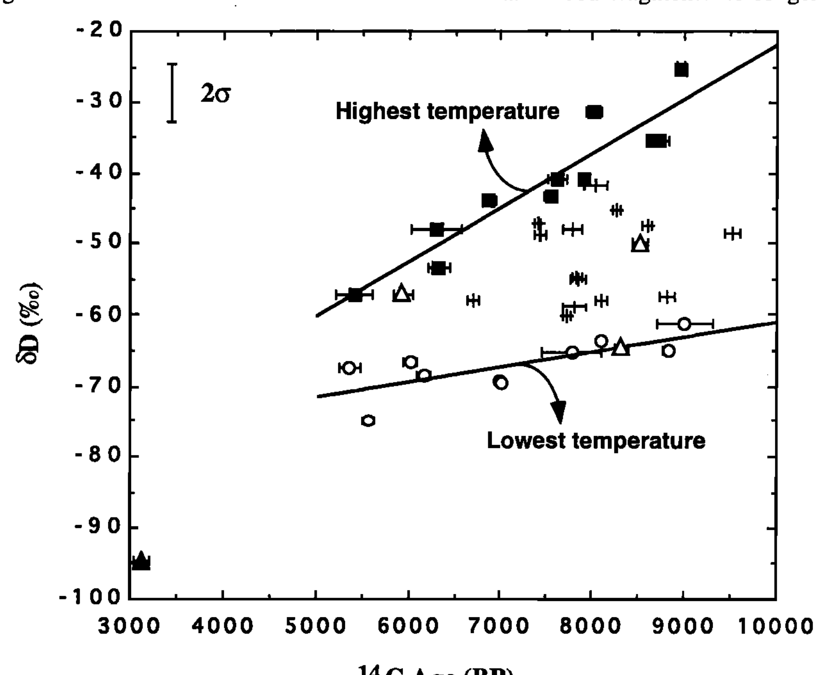

Figure 1. Plot of δD values of wood fragments from Lake Emma against their ^{14}C ages. The highest δD values for each age (squares) represent the climatic record at Lake Emma. The circles represent the samples from above Lake Emma at the various tree lines. The lines are the least squares fit of the two groups. The crosses represent the samples which grew between the tree lines and the Lake Emma site. All but the three open triangles are *Picea* trees, and the other three are *Abies* trees. The solid triangle is for the anomalous sample which was dated at 3120 "B.P.".

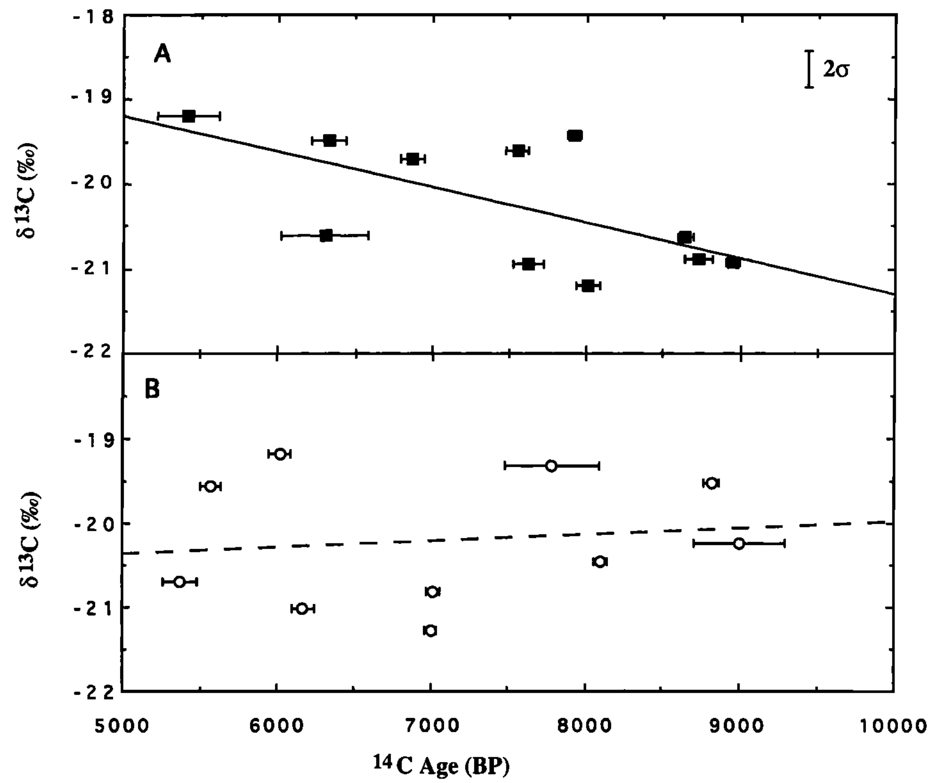

Figure 2. (a) Plot of $\delta^{13}C$ with age for the samples which grew at the Lake Emma site. (b) Similar plot for the samples which grew close to the tree lines at various ages. The lines are the least squares fit of the two groups.

except for one sample of age 3100 "B.P.". The temperature at Lake Emma continued to drop as indicated by the fact that the present tree line is 80 m lower than Lake Emma. This value of 80 m includes the possibility that there may have been warming in the past 100 years. Consequently, the continental drop in tree line (and in temperature) in the past 5000 years could have been greater. The variation in temperature as recorded by δD in the trees at Lake Emma is qualitatively similar to that observed in the Devon Island and Huascarán ice caps [*Paterson et al.*, 1977; *Thompson et al.*, 1995] and in the bristlecone pine record from California [*Feng and Epstein*, 1994]. It would therefore appear that the climatic record presented by these wood fragments could qualify to be part of the general climatic record in the Western Hemisphere rather than characteristic only of the Lake Emma area. There has been detailed discussion in the literature about the various sources of moisture to the Lake Emma area [*Carrara et al.*, 1984, 1991]. The relative contribution of these various sources of moisture should determine the integrated δD value of the moisture available to the trees. Our δD data suggest that whatever the sources of moisture in the Lake Emma area they responded to the general climatic regime of North America which was recorded as a cooling period during the early to middle Holocene.

The only previous isotopic results on Lake Emma samples were published by *Friedman et al.* [1988]. The 16 δD values they published were actually not comparable to other published work on unexchangeable cellulose hydrogen. Their δD values are unrealistically high. Although their δD trend follows a cooling trend with time, the trend with age that they observed with their limited number of samples may have been fortuitous. It is obvious from our data that it is possible to analyze a limited number of samples from Lake Emma covering the total ^{14}C range and yet observe a much smaller change of δD over the time period reported by *Friedman et al.* [1988]. *Friedman et al.* [1988] interpreted their data to indicate that an increased contribution of moisture from the Gulf of Mexico to the precipitation in the Lake Emma area was responsible for the increase of δD in the Lake Emma samples prior to 5000 year "B.P.". We do not consider this to be a valid explanation. Surely, all of the sources of water available to Lake Emma, including the Gulf of Alaska and the northern Pacific and the Gulf of Mexico [1988], must have been affected by the same widespread climate change. Hence moisture derived from any of these sources during the early to middle Holocene would have a higher δD value. Therefore, in the case of Lake Emma, higher δD values cannot be used to identify the source of moisture. Also, the model of *Friedman et al.* [1988] certainly cannot be responsible for the records obtained from the glaciers in Huascarán, Peru, and Devon Island in Arctic Canada and in bristlecone pines from the White Mountains, California. The other proposed interpretation by *Friedman et al.* [1988] was that the trees received more summer rains than winter snows during the early Holocene. It may very well be that the sources of water determined the δD values of cellulose, but the sources of water are temperature related. That is, if more water originates from summer rains than from winter snows, the annual temperature (and δD value) is usually higher. Therefore this scenario is equivalent to our cooling scenario. Also, varying degrees of summer or winter precipitation cannot explain our observed pattern that the minimum δD values decreased very little with age. Our interpretation is based on a set of data markedly different from that of *Friedman et al.* [1988]. The additional data that we obtained might very well have affected their interpretations.

The one wood fragment that yielded a radiocarbon age of

3100 "B.P." is hard to interpret because this is the only fragment of the 39 specimens found in Lake Emma that is so young [*Carrara et al.*, 1991]. It is not clear if it represents some short-lived climatic suitability for growth or if this fragment was from a unique krummholz individual that grew above the general tree line limit at that time. Its $\delta^{13}C$ value is also 0.5‰ lower than any other Lake Emma samples suggesting a different condition of the soil in which it grew.

In summary, the δD data of the Lake Emma samples indicate that there is good correlation between the hydrogen isotopic composition of the ^{14}C-dated trees in that area and the temperature of that area that is also compatible with a change of the tree line with time. The range of δD values of the wood cellulose for any one particular time reflected the climatic temperature range of the area in which the trees grew. The more positive the δD value is for maximum values, the greater the range of the δD value of the wood samples at that time is. Both the δD value and the range record synchronously the change of climatic temperature.

The $\delta^{13}C$ records of the tree samples we analyzed are shown in Figure 2. The total range in the $\delta^{13}C$ values is only 2.5‰. However, even in this relatively small range, there are certain trends which may provide information about the conditions of growth for the trees. We have considered the $\delta^{13}C$ values for the trees in two different environments. Group A includes trees which had the maximum δD values at any specific time and therefore grew very near in elevation to Lake Emma. The other group (B) includes trees that had the minimum δD values for any period of time and therefore grew at a range of elevations which were probably at the tree line above Lake Emma. The plot of $\delta^{13}C$ versus age for the samples at the elevation of Lake Emma (group A) shows a rough trend of increasing $\delta^{13}C$ with decreasing age. The trend of $\delta^{13}C$ with time is roughly related to the climatic temperature trend as indicated by the δD values at the Lake Emma site. The colder the climate is, the less negative the $\delta^{13}C$ values are. The $\delta^{13}C$ data for the trees, which we have interpreted to have grown above Lake Emma at the tree line temperatures (group B), show no significant trend with time or temperature and behave basically in a random manner within the 2.5‰ range observed for all the trees. Also, the δD values of these samples change little with time. Consequently, the variations in $\delta^{13}C$ values must be due to other factors, such as the nonuniformity of the soil conditions for the tree lines in which these trees grew. The significant variation of $\delta^{13}C$ with time for the elevation at Lake Emma's surface appears to relate to temperature, but we do not know the condition of the soils in which the trees grew nor the amount of water available for the trees during their growth [*Park and Epstein*, 1960; *Farquhar et al.*, 1982]. Additional data such as tree ring width would be useful in evaluating the variation of $\delta^{13}C$ for these samples. However, we wish to stress that there is no indication of major profound differences in conditions of growth in any of these samples that would significantly affect the isotopic composition of hydrogen in the wood fragments.

In summary, we have shown that the combination of hydrogen isotopic compositions and ^{14}C dates, determined for the same wood samples, could allow the simultaneous estimation of temperature change recorded in the δD values and in the elevation of the tree line for trees dating back thousands of years. We believe that the isotopic records in ^{14}C-dated wood remains in other locations should give relevant information about climatic change. The $\delta^{13}C$ data for wood fragments in this area indicate that its variation may be due primarily to the conditions of soils covering the large areas of growth rather than climatic temperature.

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References

Carrara, P. E., W. N. Mode, M. Rubin, and S. W. Robinson, Deglaciation and postglacial timberline in the San Juan Mountains, Colorado, *Quat. Res.*, *21*, 42-55, 1984.

Carrara, P. E., D. A. Trimble, and M. Rubin, Holocene tree line fluctuations in the northern San Juan Mountains, Colorado, U.S.A., as indicated by radiocarbon-dated conifer wood, *Arct. Alp. Res.*, *23*, 233-246, 1991.

Epstein, S., The isotopic climatic records in the Alleröd-Bølling-Younger Dryas and post-Younger Dryas events, *Global Biogeochem. Cycles*, *9*, 557-563, 1995.

Farquhar, G. D., M. H. Leary, and J. A. Berry, On the relationship between carbon isotope discrimination and the intercellular carbon dioxide concentration of leaves, *Aust. J. Plant. Physiol.*, *9*, 121-137, 1982.

Feng, X., and S. Epstein, Climatic implications of an 8000-year hydrogen isotope time series from bristlecone pine trees, *Science*, *265*, 1079-1081, 1994.

Feng, X., and S. Epstein, Climatic temperature records in δD data from tree rings, *Geochim. Cosmochim. Acta*, *59*, 3029-3037, 1995.

Friedman, I., P. E. Carrara, and J. Gleason, Isotopic evidence of Holocene climatic change in the San Juan Mountains, Colorado, *Quat. Res.*, *30*, 350-353, 1988.

Gary, J., and S. J. Song, Climatic implications of the natural variations of D/H ratios in tree ring cellulose, *Earth Planet. Sci. Lett.* *70*, 129-138, 1984.

Madole, R. F., Lake Devlin and Pinedale glacial history, Front Range, Colorado, *Quat. Res.*, *25*, 43-54, 1986.

Park, R., and S. Epstein, Carbon isotope fractionation during photosynthesis, *Geochim. Cosmochim. Acta*, *21*, 110-126, 1960.

Paterson, W. S. B., R. M. Koerner, D. Fisher, S. J. Johnsen, H. B. Clausen, W. Dansgaard, P. Bucher, and H. Oeschger, An oxygen-isotope climatic record from the Devon Island ice cap, Arctic Canada, *Nature*, *266*, 508-511, 1977.

Thompson, L. G., E. Mosley-Thompson, M. E. Davis, P.-N. Lin, K. A. Henderson, J. Cole-Dai, J. F. Bolzan, K.-B. Liu, Late glacial stage and Holocene tropical ice core records from Huascarán, Peru, *Science*, *269*, 46-50, 1995.

Tranquillini, W., *Physiological Ecology of the Alpine Timberline; Tree Existence at High Altitudes With Special Reference to the European Alps*, 137 pp, Springer-Verlag, New York, 1979.

White, J. W. C., J. R. Lawrence, and W. S. Broecker, Modeling and interpreting D/H ratios in tree rings: A test case of white pine in the northeastern United States, *Geochim. Cosmochim. Acta*, *58*, 851-862, 1994.

Yapp, C. J., and S. Epstein, Climatic implications of D/H ratios of meteoric water over North America (9500-22,000 B.P.) as inferred from ancient wood cellulose C-H hydrogen, *Earth Planet. Sci. Lett.*, *34*, 333-350, 1977.

Yapp, C. J., and S. Epstein, Climatic significance of the hydrogen isotope ratios in tree cellulose, *Nature*, *297*, 636-639, 1982.

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