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Tree-Ring δD as an Indicator of Asian Monsoon Intensity

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Oxygen and hydrogen isotopic compositions of meteoric water are known to correlate with surface air temperature, except in tropical areas. This relationship has been described using a number of terms corresponding to specific observations, such as latitude, altitude and seasonal effects. However, these temperature effects do not seem to apply to precipitation in monsoonal areas of Asia. Questions have been raised as to whether the isotopic composition of meteoric water can be used to reconstruct paleomonsoon intensity. Tree rings of two modern spruce trees (*Picea meyeri*) and a 10,000-yr-old timber (*Picea jezoensis*) were analyzed for hydrogen isotopic composition. On average, the older tree is depleted in deuterium by 45‰ compared to the modern trees. We attribute this isotopic depletion to the strength of summer monsoons, which were more intense in the early Holocene than at present. Although this study is not definitive, it suggests that paleomonsoon intensity can be reconstructed by direct or proxy methods that yield the oxygen or hydrogen isotopic composition of meteoric water. © 1999 University of Washington.

Key Words: **Asian Monsoons; δD of tree rings; Holocene climate.**

INTRODUCTION

Many environmental factors have been known to affect the isotopic composition of meteoric water, but remarkably good positive correlations between surface temperature and the oxygen and hydrogen isotopic ratios of precipitation have been established globally (Dansgaard, 1964). However, this rule does not seem to apply to areas that are significantly affected by Asian monsoons (Rozanski *et al.*, 1993; Wei and Lin, 1994; Hoffmann and Heimann, 1997). Little correlation has been found between the isotopic composition of meteoric water and temperature, and in many areas, enrichment of deuterium and ^{18}O is greater in winter precipitation than in summer precipitation. These abnormal isotopic distributions may cause difficulties in using observed or inferred isotopic values of meteoric water to reconstruct paleoclimate.

Some researchers suggest that changes in the isotopic composition of precipitation in monsoon-affected areas may indicate the changing intensity of summer monsoons, which bring the majority of moisture to the Asian continent. Independent paleoclimate studies indicate that both southeast and southwest summer monsoons were stronger in the early Holocene (10,000–7000 yr B.P.) than today, resulting in a wetter climate over the Asian continent. These reconstructions were based on a wide variety of techniques, including pollen and diatom analyses (Prell and Kutzbach, 1987; Van Campo and Gasse, 1993; Jarvis, 1993; Van Campo *et al.*, 1996), oxygen isotopes of marine sediments (Sirocko *et al.*, 1993), magnetic susceptibility (Maher *et al.*, 1994), alluvial and terracing cycling (Porter *et al.*, 1992), lake levels (Pachur and Wünnemann, 1995), vegetation dynamics (Miehe, 1996), and Arabian Sea upwelling intensities (Prell and Van Campo, 1986; Overpeck *et al.*, 1996). The observed monsoonal variations in the Holocene have been attributed to greater insolation during the early Holocene, which caused greater land–sea temperature and pressure gradients (Overpeck *et al.*, 1996). Analysis of oxygen isotopes in a Holocene core from the Lake Bangong basin, western Tibet, indicates isotopically depleted carbonates be-

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tween 9600 and 6000 yr B.P. (Fontes *et al.,* 1996). Although the mechanism is not clear, these authors proposed that a greater intensity of early Holocene Asian monsoons, as compared to the present, was a possible cause for the isotopic variations. Tan *et al.* (1992) studied oxygen isotopes of carbonates in paleosols interlayered between eolian loess in Luochuan, China. The authors linked the oxygen isotopic composition of carbonates to paleomonsoonal strength, assuming that an intense monsoon climate should cause less isotopic enrichment in soil water due to reduced evaporation. However, variations of the original isotopic composition of precipitation prior to evaporation was ignored. In this study, we explore further the possibility of using meteoric water as an indicator of paleo-Asian summer monsoon strength. We do this by comparing the hydrogen isotopic composition of tree rings in modern conifer trees with that of a 10,000-yr-old timber. Assuming that these trees record the isotopic composition of soil water and that this water largely represents meteoric water (e.g., Epstein and Yapp, 1977; White *et al.,* 1994), we have found that the meteoric water that the trees used was more depleted in deuterium (D) 10,000 yr ago than it is now. We will argue that, at least for this location, an increase in monsoonal intensity would cause an isotopic depletion in precipitation. We suggest that such a relationship may result from changes in the ratios of summer/winter precipitation and/or southwest/southeast monsoons.

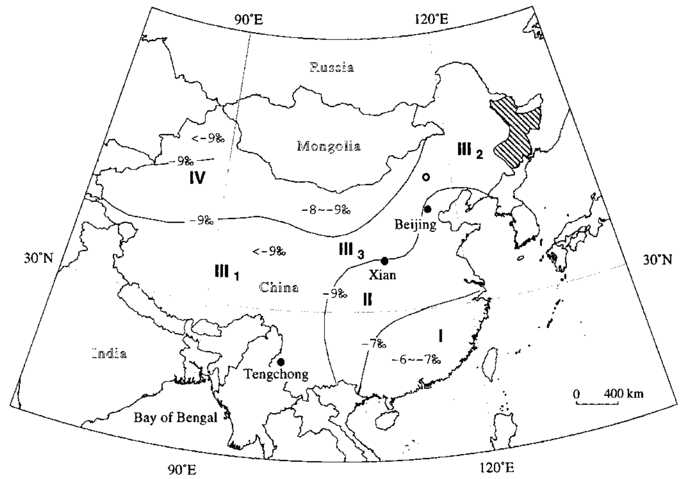

FIG. 1. Map of China showing the location of both the modern and the ca. 10,000-yr-old *Picea* trees (open circle). The 10,000-yr-old tree is *Picea jezoensis,* a species that does not exist at the study site but prevails in areas about 800 km to the northeast, shown as the shaded area on the map (Cui *et al.,* 1997). The contour lines illustrate the oxygen isotopic distribution of meteoric water in China, as adopted from Wei (1997). The isotopic zones labeled with Roman numerals are divided according to the strength and relative importance of the SE and/or SW summer monsoons in each zone. See text for more detail.

SAMPLING SITE AND METHODS

The sampling location (42°37.14′N, 116°49.04′E, 1409 m altitude) lies within Inner Mongolia, China, ca. 350 km north of Beijing (Fig. 1). Two nearby meteorological stations are in Duolun County, 54 km southwest of the site, and at a timber farm ca. 60 km southeast of the site. The mean annual temperature is 1.6°C. The annual precipitation is 386 mm at Duolun County and 474 mm at the timber farm. The majority of the moisture is brought by summer monsoons: June to August precipitation averages 66% of the annual total and May to October 94%. The vegetation is meadow-steppe dominated by *Stipa baicalensis* and *Leymus chinensis.* Trees are restricted to shady hill slopes with *Betula platyphylla* and *Quercus mongolica* being the most common species (Cui *et al.,* 1997).

We evaluated one piece of old wood and two modern trees for hydrogen isotopic composition. The old wood was taken from a *Picea* (spruce) timber that was discovered by a local farmer who unearthed it from sandy eolian and lacustrian sediments 2.4 m below the surface. The timber, measuring 6 m long and 25 cm in diameter at breast height, was dated to 10,040 ± 100 yr B.P. (Cui *et al.,* 1997).

The conifer trees closest to the buried timber are located 10–20 km away. This patch of conifers contains fewer than 100 individuals of *Picea meyeri* and is considered to be a remnant of a *Picea meyeri* forest (Cui *et al.,* 1997). Almost all trees are less than 60 yr old and grow in eolian sandy soil. Tree cores were taken from breast height. To avoid age effect (Lipp *et al.,* 1993) and to use mature rings that formed using relatively deep soil moisture, we analyzed rings of the outer 30 yr from two relatively old trees (about 60-yr-old) from the site.

Isotopic analyses were conducted for 5-yr segments of all trees. The ground wood was extracted for α-cellulose and nitrated into cellulose nitrate using standard techniques (Epstein *et al.,* 1976; DeNiro, 1981). The cellulose nitrate, which contains only nonexchangeable hydrogen, was combusted with CuO at 850°C. The combustion product, H_2O, was reduced to H_2 by reacting with Zn metal at 500°C (Vennemann and O'Neil, 1993). The H_2 gas was analyzed for the δD value using a mass spectrometer. We express the result with the standard δ-notation defined as

$$\delta D = \left(\frac{(D/H)_{\text{sample}}}{(D/H)_{\text{standard}}} - 1 \right) \times 1000,$$

where the standard is standard mean ocean water (SMOW). The analytical uncertainty is 2‰ (1σ).

RESULTS AND DISCUSSION

The hydrogen isotopic composition (Table 1; Fig. 2) of modern trees varies from −59 to −83‰ with an average value of −73‰ and a standard deviation of 8.7‰. The δD values of the old tree range from −98 to −141‰, and the average and standard deviation are −119‰ and 10‰, respectively. The two mean values of the two sets of data are different by 46‰, which is statistically significant ($p < 10^{-6}$).

TABLE 1
Hydrogen Isotopic Compositions of Tree Rings[a]

Old tree[a,b]	Modern tree 1[b]	Modern tree 2[b]	Time (yr A.D.)
−124	−63	−59	1992–1996
−114	−81	−68	1987–1991
−119	−78	−62	1982–1986
−141	−83	−78	1977–1981
−131	−67	−79	1972–1976
−133	−81	−80	1967–1971
−127			
−124			
−123			
−102			
−98			
−114			
−118			
−115			
−113			
−115			
−115			

[a] The values of the old tree are arranged from outer (top) to inner (bottom) rings.
[b] 1σ error = 2‰.

Using scanning electron microscopy, the 10,000-yr-old timber was identified as *Picea jezoensis*, a tree species known to prevail in cold and humid environments (Cui *et al.*, 1997). The modern distribution of this species is 800 km northeast of the study site (Fig. 1). Although the mean annual temperatures of these two locations are similar, annual precipitation for the modern *P. jezoensis* forest (500–600 mm) is ca. 200 mm higher than at the study site (300–400 mm). Cui *et al.* (1997) concluded that the 800-km displacement of this species was not caused by a change in temperature but by a change in moisture availability. Fossil pollen and mammal remains also support this conclusion. Thus, we do not consider temperature to be responsible for the observed isotopic shift from ca. 10,000 yr B.P. to the present.

Assuming that the δD of tree cellulose recorded the isotopic composition of meteoric water, the precipitation would have been isotopically more depleted at 10,000 yr B.P. than at present. We attribute this to greater monsoonal intensities in the early Holocene. We further suggest that this isotopic depletion in precipitation with increasing monsoonal intensity results from two mechanisms: (1) changes in the ratios of summer/winter precipitation and/or (2) changes in the ratios of southwest/southeast monsoons.

Wei and Lin (1994) showed that the $\delta^{18}O$ of precipitation is lower by 0.7 to 9‰ in summer than in winter for 15 Asian cities in monsoon-influenced areas. They argued that long-range transport of moisture from the open ocean carried by summer monsoons causes progressive isotopic fractionation by raining out a significant portion of water over the ocean and oceanic islands, making air masses depleted in ^{18}O upon arrival over the Asian continent. This interpretation is consistent with GCM simulations (Hoffmann and Heimann, 1997). In winter, winds are offshore and marine moisture is pushed away from the land. Occasionally, maritime air near the coast invades the land and meets with cold continental air, producing precipitation. In this scenario, the martime air has not traveled far from the sea, and it is relatively enriched in ^{18}O and deuterium.

The summer monsoon brings most of the annual precipitation to China (Domrös and Peng, 1988) with the highest intensity in June to August. At the timber farm weather station, the precipitation from these three months consists of 45 to 81% of the total precipitation (1959–1994). The annual total precipitation is highly correlated with June–August precipitation ($r = 0.93$, $n = 35$) with a slope close to one (1.05) and an intercept of 147 mm. This relationship indicates that the amount of precipitation for the remaining 9 months is rather constant and that the total precipitation depends on the amount of rain carried by the summer monsoons. Because precipitation is more isotopically depleted in summer than in winter in the monsoon-affected areas, an increase in summer precipitation at this site with a decrease in δD in the annually weighted meteoric water would be expected.

China is influenced by both the southeast (SE) monsoon that brings moisture from the Pacific Ocean and the southwest (SW) monsoon that brings moisture from the Indian Ocean through the Bay of Bengal. Chinese scientists have shown that isotopic composition of precipitation and surface/groundwater is affected by the relative degree of influence from these two monsoon systems (reviewed by Wei, 1997). Based on a large number of observations, China has been divided into isotopic zones (Fig. 1). Zones I and III_1 are mostly influenced by the SE and SW monsoons, respectively. Zone IV is not significantly affected by monsoon climates, and the remaining large area, in which our study site is located, is affected by both the SE and

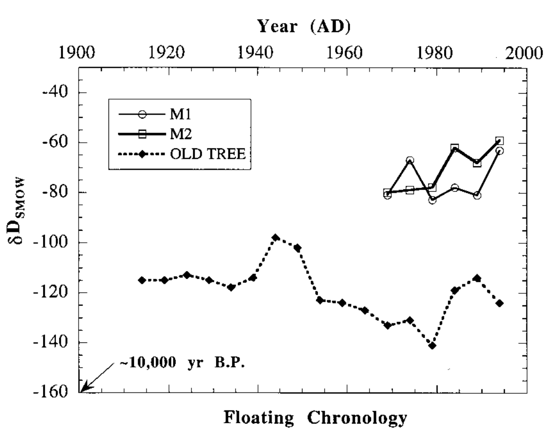

FIG. 2. Hydrogen isotopic compositions of tree rings from two modern and one ancient *Picea.* The open symbols are for two modern trees and the diamonds are for the old tree dated 10,040 ± 100 yr B.P. The isotopic values of the modern trees are significantly greater than those of the ancient tree, indicating a change in climatic conditions between these two time periods.

SW monsoons. Given the study location (Fig. 1), precipitation carried by the SW monsoons experiences more of a continental effect than with the SE monsoons. Therefore, the isotopic composition of the precipitation reaching the location from the SW is more depleted in ^{18}O and deuterium than that coming from the SE. This isotopic contrast may be further amplified by an additional altitude effect of the SW monsoons along the mountainous pathway of Burma and the southeast part of the Tibetan Plateau, as can be seen by comparing the isotopic composition of meteoric water for Tengchong and Xian, China (Fig. 1). These two locations are nearly equidistant from the coast, and Xian is 10° north of Tengchong. Tengchong is considered to be influenced mostly by the SW monsoons and Xian by both the SW and the more dominant SE monsoons. The oxygen isotopic analyses of the summer precipitation of 1980 yielded −11.1‰ for Tengchong and −8.9‰ for Xian (Wei and Lin, 1994). Therefore, it is possible that with an increase in monsoon intensity, SW monsoons would travel further inland, increasing their chance or frequency of reaching our site. This pattern would result in a decrease of weighted $\delta^{18}O$ and δD values in meteoric water.

In summary, with an increase in summer monsoonal intensity, the amount of annual precipitation increases. The δD of meteoric water decreases accordingly because of the increase in ratios of summer/winter precipitation and/or SW/SE monsoonal influence. The integrated effect of these two mechanisms is that δD of meteoric water is inversely related to the amount of precipitation. We believe that the 46‰ depletion in the δD values of tree rings 10,000 yr ago was caused by the greater intensity of Asian summer monsoons during the early Holocene, a finding that is consistent with other paleoclimatic reconstructions mentioned earlier.

The predicted inverse relationship between the amount of precipitation and the δD of meteoric water should be tested from modern observations. Unfortunately, most isotopic time series from IAEA stations are not sufficiently long ($<$ 5 yr) to provide meaningful statistical analysis for correlation between δD and annual precipitation under modern conditions. The precipitation data we have for the timber farm do not significantly correlate with the δD values of the 5-yr-long tree ring segments of the two modern trees. Therefore, our interpretation needs to be confirmed with long-term isotopic studies of precipitation in the monsoon-affected regions.

We note that the above interpretation was made assuming that the δD values for both ancient and modern trees can be directly related to the δD of precipitation. However, many nonclimatic factors can affect the isotopic composition of tree rings. For example, δD differed by up to 25‰ along the circumference of a single growth ring for a tree that grew asymmetrically (Ramesh *et al.,* 1985). We always used the least compressed side of a tree to obtain more wood for cellulose extraction. However we can not rule out the possibility that some of the observed variations between the modern and the ancient samples are caused by such a sampling artifact. Within-site variations can also be significant. Feng and Epstein (1994) found an average of about 35‰ difference in δD for two pieces of bristlecone pine wood from the same area that overlapped in age by 600 years. Without additional wood samples, especially for the ancient period, we can only assume that the range of values we obtained represents the average growing conditions.

Any quantitative reconstruction of paleomonsoon intensity using stable isotopes of meteoric water is premature for this preliminary study. This reconstruction would require the calibration of isotopic distributions of modern meteoric water as a function of monsoon intensity at different isotopic zones of China. We hope that the work presented here will act as a springboard for futher investigation

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