

## SHORT ARTICLE ON PRELIMINARY RESEARCH

**Climatic potential of  $\delta^{18}\text{O}$  of *Abies spectabilis* from the Nepal Himalaya**

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**Abstract**

A 50-year tree-ring  $\delta^{18}\text{O}$  chronology of *Abies spectabilis* growing close to the tree line (3850 masl) in the Nepal Himalaya is established to explore its dendroclimatic potential. Response function analysis with ambient climatic records revealed that tree-ring  $\delta^{18}\text{O}$  is primarily governed by rainfall during the monsoon season (June–September), and the regression model accounts for 35% of the variance in rainfall. Extreme dry years identified in instrumental weather data are detected in the  $\delta^{18}\text{O}$  chronology. Further, tree-ring  $\delta^{18}\text{O}$  is much more sensitive to rainfall fluctuations than other tree-ring parameters such as width and density typically used in dendroclimatology. Correlation analyses with Niño 3.4 SST reveal time-dependent behavior of ENSO–monsoon relationships.

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**Introduction**

The Indian sub-continent is one of the most heavily populated regions in the world, and therefore understanding the potential impact of regime shifts in monsoon rainfall is crucial (Pant and Rupa Kumar, 1997). Proxy climate records dating back to the pre-instrumental era (before AD 1850) enable comparison of natural climate variability and anthropogenic impact, and creating such records is essential to accurately predict future monsoon changes (e.g., Bradley and Jones, 1992). In the view of this, climate variations for the last several centuries have been reconstructed using annual tree rings of conifers growing

in the Indian Himalaya (e.g., Hughes, 1992; Borgaonkar et al., 1994; Yadav et al., 2004; Singh et al., 2006). However, ring widths mostly used in the previous studies are generally influenced by pre-monsoon (spring) climate, and therefore reconstructions of precipitation and temperature in the monsoon season are very few. In spite of the limitation, reconstructions of precipitation reveal an unprecedented wet period of the late 20th century (Singh and Yadav, 2005; Singh et al., 2006), whereas those of temperature show a notable cool phase of that period (Hughes, 1992; Yadav et al., 2004).

In contrast to the quantity and quality of the dendroclimatic studies from the Indian Himalaya, those from the Nepal Himalaya are rather few. Reduced climate sensitivity resulting from relatively abundant rainfall in the Nepal Himalaya is at least partially responsible for fewer published climate reconstructions being available. Therefore, robust reconstructions for this region can be achieved only by

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increasing the number of chronologies (predictors), obtained from multiple sites (Cook et al., 2003) and by measuring multiple parameters, i.e., ring width and intra-annual densities (Sano et al., 2005). In addition, the reconstructed proxy climatic variable in these studies is only temperature, and rainfall in Nepal is yet to be reconstructed. Here we describe the dendroclimatic potential of stable oxygen isotope composition ( $\delta^{18}\text{O}$ ) derived from *Abies spectabilis* growing near the tree line in the Nepal Himalaya. Our analyses of oxygen isotopes in tree rings correlated with climatic records of this region over the past half a century show that  $\delta^{18}\text{O}$  of tree cellulose is a potential indicator of monsoon rainfall.

## Materials and methods

Tree-ring samples were collected from *A. spectabilis* growing close to the tree line of 3850 masl along the northeast-facing slope in Humla District, western Nepal (Fig. 1). The sampling site was dominated by *A. spectabilis*, while associated species were *Betula utilis* D. Don and *Rhododendron* spp. Firs in the site are considered to grow from March through September on the basis of climatic responses of their ring width and densities previously analyzed (Sano et al., 2005). Paired increment cores were bored at breast height (1.3 m above ground) from each of 23 trees for a total of 46 core samples.

Cross-dating was performed in the laboratory by matching ring-width variations for all cores to determine the absolute year of each ring. Cross-dating was then cross-checked by the software COFECHA (Holmes, 1983), with which individual ring-width series were tested on the basis of correlation against a master series derived by averaging all the series. Of the 40 cores precisely dated, 10 cores from 5 trees were selected for isotope analysis. Criteria for sample selection were ring size, stem circumference, and high inter-correlations among ring-width series. Every annual ring of those

cores over the last 50 years (AD 1951–2000) was split with a scalpel, and the resultant shavings were pooled for each year in order to obtain representative stable isotope records at the site. After the samples were finely milled, cellulose was extracted by a modified method based on protocols of Brendel et al. (2000) and Anchukaitis et al. (2008). Oxygen isotope ratios ( $^{18}\text{O}/^{16}\text{O}$ ) of cellulose samples were determined by an isotope ratio mass spectrometer (Delta Plus, ThermoFinnigan, Germany) interfaced with a pyrolysis-type elemental analyzer (TC/EA, ThermoFinnigan, Germany). The  $^{18}\text{O}/^{16}\text{O}$  ratios were conventionally expressed as  $\delta^{18}\text{O}$  (‰), deviation relative to the VSMOW international standard. The standard deviation derived from repeatedly measured standard material was 0.3‰.

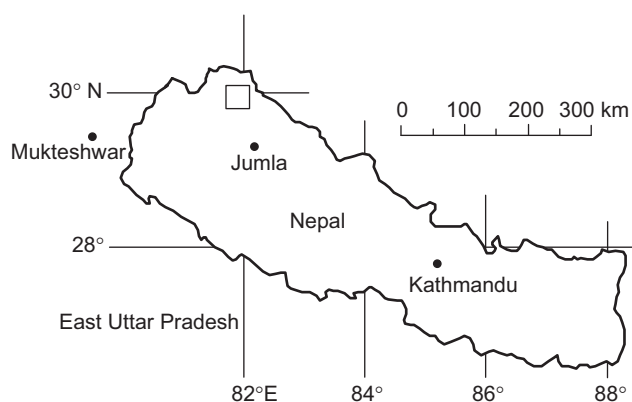
To identify the climatic response of the tree-ring  $\delta^{18}\text{O}$ , meteorological records from stations close to the sampling site are required. In this study, the rainfall records (AD 1957–1996) of the Jumla station (Fig. 1; 70 km south of the site) nearest to the site were used. However, the 18 years of temperature observations at the Jumla station were too short for a meaningful response function analysis, and therefore the temperature records (AD 1889–1991) from Mukteshwar (200 km west of the site) were used instead. The lack of proximal instrumental station data is a chronic problem in the Nepal Himalaya and, indeed, in many parts of the world where remote tree ring sites are sampled, and is not unique to this study. The mean annual precipitation is 796 mm, 66% of which falls in the summer monsoon months of June through September. Rainfall in the pre-monsoon (March–April) and post-monsoon (October–November) seasons together contributes 24% of annual precipitation, while the remaining 3 months (December–February) comprise the dry season. The mean annual temperature is 13.5 °C with a maximum of 18.7 °C in June and a minimum of 6.2 °C in January.

Linear correlations of oxygen isotope ratios with monthly rainfall and temperature were calculated for the period of AD 1957–1991, being common to both variables. We also correlated the  $\delta^{18}\text{O}$  chronology with Niño 3.4 SST, which is area-averaged sea surface temperatures over the equatorial Pacific (120°W–170°W, 5°N–5°S) (NOAA Climate Research Center, 2008), and EQWIN, which is the negative of the zonal surface wind averaged over the equatorial Indian Ocean (60°E–90°E, 2.5°S–2.5°N) (Gadgil et al., 2003, 2004), to identify large-scale forcing effects on  $\delta^{18}\text{O}$  and the local climate.

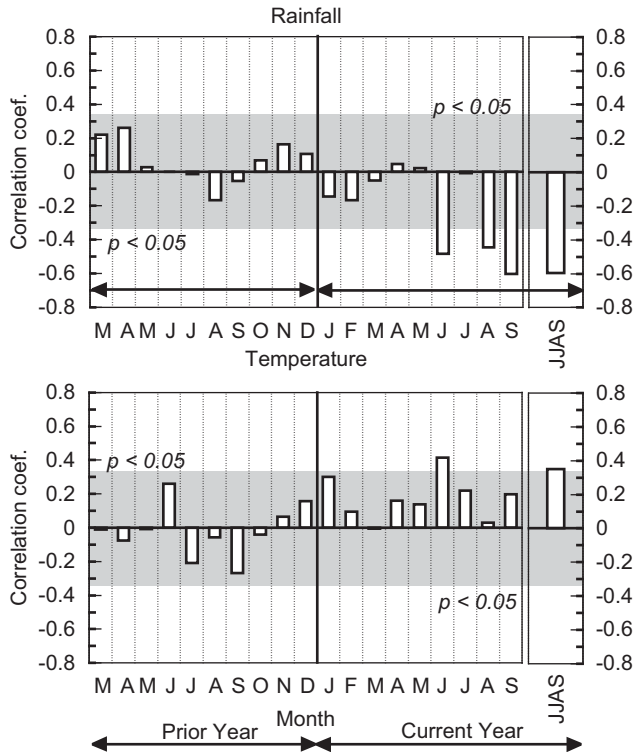
## Results and discussion

### Climatic signal in tree-ring $\delta^{18}\text{O}$

Response of the tree-ring  $\delta^{18}\text{O}$  to monthly rainfall and temperature is shown in Fig. 2 (the bars beyond the



**Fig. 1.** Map of the study region, showing the locations of study site (square: 29°51'N and 81°56'E), and Jumla and Mukteshwar meteorological stations.



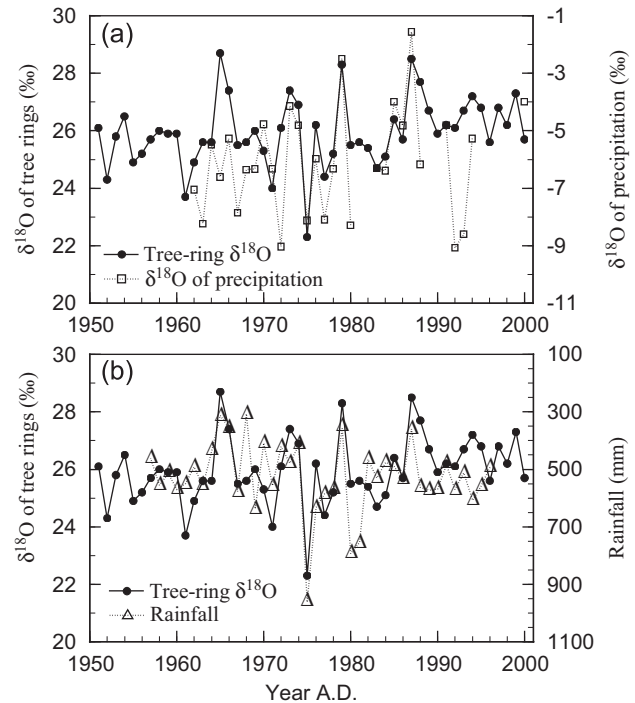
**Fig. 2.** Response of tree-ring  $\delta^{18}\text{O}$  to monthly rainfall and temperature in terms of correlation coefficient. All bars that exit the shaded area indicate significance at 5%.

shaded area indicate 95% significance level; the same level of confidence applies henceforth unless mentioned otherwise).  $\delta^{18}\text{O}$  was correlated negatively with rainfall in June, August and September, and positively with temperature in June. Based on the results, we also correlated the  $\delta^{18}\text{O}$  with seasonal records, i.e., June–September (monsoon) rainfall and temperature, to simplify climate signals in the  $\delta^{18}\text{O}$  chronology. It turned out that the  $\delta^{18}\text{O}$  was correlated negatively with monsoon rainfall (linear correlation coefficient,  $R = -0.59$ ;  $p < 0.001$ ) and positively with temperature ( $R = 0.35$ ;  $p < 0.05$ ) (Fig. 2). We further scrutinized the relative effects of monsoon rainfall ( $r$ ) and temperature ( $t$ ) on the  $\delta^{18}\text{O}$  variations by conducting multiple regression analysis. To compare the coefficients of climatic parameters directly, all variables including  $\delta^{18}\text{O}$  were standardized individually to have mean 0 and variance 1 for each time series. The following equation was then obtained:

$$\delta^{18}\text{O} = -(0.55 \pm 0.33)r + (0.10 \pm 0.33)t$$

$$[R = 0.61; F = 8.97; p < 0.001]$$

where  $r$  and  $t$  are June–September rainfall and temperature, respectively. The confidence intervals for the coefficients represent the 95% level. This equation indicates that the  $\delta^{18}\text{O}$  was primarily controlled by



**Fig. 3.** Plots of inter-annual variations in (a) weighted mean  $\delta^{18}\text{O}$  of June–September precipitation at New Delhi (Global Network of Isotopes in Precipitation, [http://www-naweb.iaea.org/naweb/ih/GNIP/IHS\\_GNIP.html](http://www-naweb.iaea.org/naweb/ih/GNIP/IHS_GNIP.html)) and tree-ring  $\delta^{18}\text{O}$ , and (b) June–September rainfall and tree-ring  $\delta^{18}\text{O}$ . The gaps in (a) represent missing data, and rainfall axis in (b) is reversed.

June–September rainfall, with a negative association. The temperature dependence is less significant.

It is well known that  $\delta^{18}\text{O}$  of tree cellulose is mainly influenced by two factors, i.e.,  $\delta^{18}\text{O}$  of source water, and relative humidity (e.g., Ramesh et al., 1986; Saurer et al., 1997; Anderson et al., 1998; Robertson et al., 2001; Waterhouse et al., 2002). With regard to the former, a negative correlation between  $\delta^{18}\text{O}$  of precipitation and the amount of rainfall is observed in tropical regions, which is termed as the “amount effect” (Dansgaard, 1964; Rozanski et al., 1993; Araguás-Araguás et al., 1998; Yadava and Ramesh, 2005). The significantly negative correlation of the  $\delta^{18}\text{O}$  with rainfall indicates that our sampled trees clearly record  $\delta^{18}\text{O}$  of precipitation. This is further supported by a significant correlation ( $R = 0.49$ ;  $p < 0.01$ ) between weighted mean  $\delta^{18}\text{O}$  of June–September precipitation at New Delhi and  $\delta^{18}\text{O}$  of the tree rings analyzed (Fig. 3a). On the other hand, relative humidity was not taken into account for the present study due to the lack of instrumental records, and therefore we cannot evaluate the effect of humidity on  $\delta^{18}\text{O}$ . However, humidity may be correlated with rainfall, and may not be an independent parameter.

Inter-annual variations in the  $\delta^{18}\text{O}$  and June–September rainfall are plotted in Fig. 3b. The relationship with

**Table 1.** Extreme years of  $\delta^{18}\text{O}$  and monsoon (June–September) rainfall for Jumla, E. Uttar Pradesh, and all-India.

Tree rings			Jumla (Nepal)		E. Uttar Pradesh		All-India	
	Year	$\delta^{18}\text{O}$ (‰)	Year	$R$ (mm)	Year	$R$ (mm)	Year	$R$ (mm)
<b>Highest 5 years</b>			<b>Driest 5 years</b>					
1st	1965	28.7	1968	307	1979*	465	1972	653
2nd	1987	28.5	1965*	313	1965*	566	1987*	697
3rd	1979	28.3	1966*	356	1987*	607	1979*	708
4th	1988	27.7	1979*	357	1959	626	1965*	709
5th	1966	27.4	1987*	360	1966*	639	1982	735
<b>Lowest 5 years</b>			<b>Wettest 5 years</b>					
1st	1975	22.3	1975*	962	1980	1433	1961*	1020
2nd	1961	23.7	1980	793	1955	1277	1956	983
3rd	1971	24.0	1981	755	1953	1251	1975*	963
4th	1952	24.3	1969	637	1971*	1183	1988	961
5th	1977	24.4	1976	634	1975*	1114	1983	956

The asterisk indicates the year shared with  $\delta^{18}\text{O}$  extreme.

**Table 2.** Response of tree-ring parameters to seasonal rainfall and temperature in terms of correlation coefficient.

Tree-ring parameter	Rainfall		Temperature	
	March–May	June–September	March–May	June–September
$\delta^{18}\text{O}$	0.00	−0.59**	0.35*	0.11
Ring width	0.31	0.20	−0.39*	−0.26
Max. density	−0.12	−0.17	0.11	0.17
Min. density	−0.28	−0.27	0.38*	0.58**
Mean density	−0.23	−0.32	0.33	0.43*

\* $p < 0.05$ .

\*\* $p < 0.01$ .

monsoon rainfall is clear, with drier conditions corresponding to increased  $\delta^{18}\text{O}$  and vice versa, especially for such extreme dry/wet years as 1965, 1975, 1979 and 1987. We further explored how these extreme dry (wet) conditions correspond to high (low)  $\delta^{18}\text{O}$  values, using rainfall records from the Jumla station and also the regionally averaged rainfall dataset for East Uttar Pradesh (south of the sampling site; a part of the Ganges plains) and all-India (Sontakke et al., 1993; Pant and Rupa Kumar, 1997). For this purpose, the driest (wettest) 5 years and the  $\delta^{18}\text{O}$  highest (lowest) 5 years are listed in Table 1. The years marked with an asterisk for rainfall records are shared with the  $\delta^{18}\text{O}$  extremes. The driest years are apparently recorded in our tree-ring  $\delta^{18}\text{O}$  chronology (3–4 out of the 5 isotope maxima), while the wettest years poorly correspond to the  $\delta^{18}\text{O}$  extremes (1–2 out of the 5 isotope minima).

We compared climatic sensitivity between  $\delta^{18}\text{O}$  and previously measured tree-ring parameters, i.e., width, and minimum, maximum, and mean bulk densities, based on 20 individual trees from the same site (Sano et al., 2005). These parameters were correlated with the

same climate data used in the  $\delta^{18}\text{O}$  response analysis. The results indicate that the overall climatic response is less in ring width and densities than in  $\delta^{18}\text{O}$  (Table 2). This could stem from the fact that ring width and densities are usually affected by endogenous disturbance pulses, such as competition with neighboring trees (Fritts, 1976; Ramesh et al., 1985). In fact, Nakatsuka (2007) reported that variations in  $\delta^{18}\text{O}$  of larch trees showing uneven ring-width trends are notably consistent among themselves. Another noteworthy feature is that  $\delta^{18}\text{O}$  was mostly controlled by rainfall, whereas ring width and densities were more sensitive to temperature. We therefore conclude that  $\delta^{18}\text{O}$  of *A. spectabilis* in the study area is useful to reconstruct rainfall variability, as an alternative proxy to ring width and densities widely used in dendroclimatology.

### Links with the remote oceans

It is widely recognized that El Niño/Southern Oscillation (ENSO) influences rainfall patterns in



regions quite remote from its main stage of the tropical Pacific (e.g., McBride and Nicholls, 1983; Ropelewski and Halpert, 1987). For example, Rasmusson and Carpenter (1983) demonstrate that summer monsoon rainfall over India is suppressed during El Niño phases. However, the influence of ENSO on monsoon rainfall is shown to be both temporally and spatially variable. Krishna Kumar et al. (1999) found that Indian summer monsoon rainfall is negatively correlated with El Niño significantly for the 100 years before the 1980s, but with no correspondence in the post-1980s period. This time dependence results at least in part from a shift in the location of the descending limb of the Walker circulation (Krishna Kumar et al., 1999). Our results with the  $\delta^{18}\text{O}$  chronology are consistent with their findings that El Niño-like anomalies result in reduced rainfall at the study area and then our sampled trees record increased  $\delta^{18}\text{O}$  of precipitation, as indicated by a significant positive correlation ( $R=0.40$ ;  $p<0.05$ ) of our chronology with the June–September Niño 3.4 SST for the period of 1951–1980. Further, the significant correlation of the  $\delta^{18}\text{O}$  chronology with the Niño 3.4 SST disappears during 1981–2000 ( $R=0.11$ ).

The Indian summer monsoon rainfall is also linked to the equatorial Indian Ocean (e.g., Ashok et al., 2001; Gadgil et al., 2003, 2004). Gadgil et al. (2004) found that Equatorial Indian Ocean Oscillation (EQUINOO), which is the atmospheric component of the Indian Ocean Dipole mode, is closely related to the Indian monsoon. More specifically, equatorial Indian Ocean zonal wind index (EQWIN) is correlated significantly with the Indian summer monsoon rainfall ( $R=0.42$ ; 1958–1997) (Gadgil et al., 2004). On the other hand, correlation analyses of the tree-ring  $\delta^{18}\text{O}$  and local rainfall (Jumla station) with EQWIN turned out to be non-significant ( $R=-0.08$  and  $0.01$ , respectively). Our results coupled with the above studies suggest that while the Indian monsoon rainfall is affected by EQUINOO, its influence does not reach as far northward as the present study region.

Although our findings in the present study are limited spatially and temporally, the results suggest that tree-ring  $\delta^{18}\text{O}$  is of great use to assess the ENSO forcing effects on monsoon rainfall. Himalayan  $\delta^{18}\text{O}$  chronologies in combination with other proxy ENSO records (e.g., Stahle et al., 1998; D'Arrigo et al., 2005) are expected to shed more light on the relationships between monsoon rainfall and ENSO over the past several centuries.

## Conclusions

The present study suggests that tree-ring  $\delta^{18}\text{O}$  of *A. spectabilis* is notably promising for reconstruction of monsoon rainfall in the Nepal Himalaya. Furthermore,

the extreme dry years found in regionally averaged data from India were consistent with those in the tree-ring  $\delta^{18}\text{O}$  chronology, giving hope for large-scale reconstruction of deficient monsoon rainfall. Correlation analyses with Niño 3.4 SST provide a valuable avenue for future research. Continued effort toward the development of a tree-ring  $\delta^{18}\text{O}$  network across the Himalaya would lead us to robust reconstruction of rainfall, and help us to understand the dynamics and causes of monsoon variability.

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