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Reconstruction of soil water oxygen isotope values from tree ring cellulose and its implications for paleoclimate studies

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ABSTRACT

We present here a rationale for estimation of soil water oxygen isotope values (δ_{sw}) from tree ring cellulose oxygen isotope data and examine, for the first time, its (δ_{sw}) efficacy as a tool to obtain paleoclimate information. We analyzed pre-dated tree ring cellulose samples collected from a site at Western Himalaya for oxygen isotopes, used similar dataset of overlapping time period from 12 different locations across the world, reconstructed δ_{sw} for 1901–2004 CE, compared the data with available observations and examined implications of this technique. Our study shows (a) good agreement in spatial ranges between observed and estimated δ_{sw} data suggesting its suitability for a representative parameter, and (b) reconstructed δ_{sw} largely depend on soil moisture content modulated by regional evaporation regimes. Considering a growing importance of measurement of recycled soil moisture and its ensuing role in rainfall amount, a method to reconstruct soil moisture isotope as presented in this work will enable application of land hydrological models to the past.

1. Introduction

Recent studies have shown, in addition to the ocean, various recycled sources also contribute significant amount of moisture to global precipitation (Rozanski et al., 1993; Gat et al., 1994; Schär et al., 1999; Wirmvem et al., 2014), i.e. evaporation from soil, water bodies like lakes, dams, rivers etc and transpiration from plant leaves (Salati et al., 1979; Brubaker et al., 1993; van der Ent et al., 2010; Ren et al., 2013). Soil evaporation and plant transpiration generate ~40–50% of total moisture for precipitation in any tropical rain-forest and are therefore crucial components in regional moisture budget (Salati et al., 1979; Njitchoua et al., 1999; Worden et al., 2007). Considering significant changes in recent temporal trends of rainfall amount (Almazroui et al., 2012; Hulme, 1992; Fauchereau et al., 2003; Pasquini et al., 2006; Li et al., 2010) long term measurement of recycled moisture has gained importance (Brubaker et al., 1993; van der Ent et al., 2010). However, precise estimation of recycled moisture and knowledge of its local variability remain poorly constrained due to the lack of observational network across the globe (Dirmeyer et al., 2009).

Evapotranspiration (ET) is conventionally measured by various indirect observations, such as: catchment water balance, energy balance (Dirmeyer et al., 2009). Both these methods rely on hydrometeorological equations or mass balance techniques instead of direct measurement of the physico-chemical properties of soil water (Allen, 1996; Malek and Bingham, 1993). This is likely to contribute a substantial error in ET estimation both in global as well as in regional atmospheric circulation models (Allen, 1996). Direct measurement of soil water content is possible by lysimeter (Allen et al., 2007) although measurement through lysimeter is difficult. Evaporation causes isotopic enrichment in water (Craig et al., 1963), which implies that soil water isotope values are significantly enriched compared to rain due to evaporation (Hoffmann and Heimann, 1997; Hsieh et al., 1998; Li et al., 2007; Gibson et al., 2008). Studies have shown, in addition to measurement of weight loss of moist soil column through lysimeter, routine measurement of oxygen isotope ($\delta^{18}O$) of soil water (δ_{soilw}) can give additional information on soil water evaporation (Brubaker et al., 1993). However, due to the lack of longterm (>100 yr) δ_{soilw} data, this technique has limited application for understanding long term trend of soil evaporation. This necessitates search for a suitable proxy to estimate the δ_{soilw} of the past.

As soil water is the primary source of water for trees, tree ring cellulose isotopic values preserve signatures of the source water. Trees translate the isotopic composition of source water (δ_{sw}) to

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Terminology used

δ_c	Tree ring cellulose oxygen isotope ($\delta^{18}O$) values (‰ VSMOW)
δ_{soilw}	Instrumentally measured $\delta^{18}O$ of soil water (‰ VSMOW)
δ_{sw}	Reconstructed $\delta^{18}O$ of soil water (‰ VSMOW) from δ_c using biogeochemical model
δ_{rw}	$\delta^{18}O$ of rain water (‰ VSMOW)
δ_{soilwg}	Estimated $\delta^{18}O$ of soil water (‰ VSMOW) from a simple box model with δ_{rw}, R_f and E_f
δ_{ah}	$\delta^{18}O$ values of atmospheric humidity (‰VSMOW)
T_a	Air temperature (°C)
R_{hf}	Relative humidity, in fraction
ΔT	Difference between air temperature to that of leaf (°C)
R_f	Precipitation flux (mm/month)
E_f	Evaporation flux (mm/month)
P	Atmospheric Pressure (kPa)
e	Vapor pressure (kPa)
α_k	Water liquid-vapor kinetic fractionation in air
α_{kb}	Water liquid-vapor kinetic fractionation of boundary layer
g_s	Stomatal conductance (mol m^{-2} s^{-1})
g_{bl}	Boundary layer conductance (mol m^{-2} s^{-1})

$R_{xy} = \frac{N_x}{N_y}$, where N_x and N_y are the abundances of heavier isotope (x) and lighter isotope (y) of a given element (e.g. O^{18} and O^{16})

$\delta^{sample}_{standard} = \frac{R_{sample} - R_{standard}}{R_{standard}} 1000‰$ The standard for $\delta^{18}O$ is standard mean oceanic water (SMOW/VSMOW) hence,

$$\delta^{18}O = \frac{R_{sample} - R_{SMOW}}{R_{SMOW}} 1000‰$$

$$\Rightarrow R_{sample} = R_{SMOW}\left(1 + \frac{\delta^{18}O}{1000}\right)$$

where,

$$R_{sample} = \frac{N_{^{18}O}}{N_{^{16}O}}$$

R_{smow} = Oxygen isotope ratio of SMOW = 0.0020052

that of cellulose (δ_c) via a complex non-linear physiochemical processes (Ballantyne et al., 2006). This process, common among plants which undergo C_3 metabolic pathway for carbon fixation in photosynthesis (including all trees) for different locations and situations was modeled by Roden et al. (2000) to estimate δ_c from δ_{sw}, temperature (T_a), relative humidity (R_{hf}, in fraction) and physiological parameters (e.g. temperature difference between Air and Leaf 'ΔT', Stomatal Conductance 'g_s'etc.).

Tree ring cellulose $\delta^{18}O$ (δ_c) have been used to reconstruct paleo temperature, rainfall and humidity (e.g. Sakashita et al., 2016). These studies have mostly relied on linear statistical models between δ_c and meteorological parameters instead of biochemical models of isotope fractionation (Schleser et al., 1999; Barbour, 2007). Those reconstructions have assumed that δ_c was related to $\delta^{18}O$ of the source water (δ_{sw}), which in turn, related to temperature (Libby et al., 1976; Gray and Thompson, 1977), relative humidity (Burk and Stuiver, 1981; Ramesh et al., 1986; Loader et al., 1995) or both (Danis et al., 2006; Holzkämper et al., 2008). Extensive studies carried out by Evans and his group showed that cyclic oxygen isotopic signatures of α-cellulose obtained from both ring bearing trees from tropical rain forest (Costa Rica) and non rain bearing trees from Temperate region (Massachusetts, USA) represent corresponding annual cycle of rainfall and relative humidity (Evans and Schrag, 2004). Interestingly, this study also showed a ~10 ‰ trough (indicating a dry and warm event) in cellulose oxygen isotope during ENSO event at 1998 from a ten year old (1992–2002) plantation tree of Peru. High resolution measurements from non ring bearing trees of Monte Verde rain forest at Costa Rica by Anchukaitis et al. (2008) and Anchukaitis and Evans (2010), further confirmed a coherence between corresponding annual cycles of oxygen isotopes from tree cellulose and dry season moisture associated with ENSO. Based on sixteen years meteorological data (1986–2001), Evans (2007) parameterized forward modeling of oxygen isotopes in wood cellulose. This model results in a stronger negative isotope anomaly associated with a positive JAS (July-August-September) rainfall anomaly during ENSO. Subsequent studies considered that δ_{sw}-rainfall correlation may be extrapolated well in the past (Holzkämper et al., 2008) and δ_{sw} is nearly similar to isotopic composition of rain water (δ_{rw}) (Managave et al., 2011). In contrast, soil moisture studies have shown that isotopic composition of rain (δ_{rw}) and δ_{soilw} (specially in deeper levels where most large trees have their roots) can be significantly different (~4–6‰) (Liu et al., 2010; Weltzin and McPherson, 1997). Therefore, temporal correlations of δ_{soilw} with meteorological parameters may not be applicable in paleo time-scales. Further, the correlation between rainfall amount and δ_{rw} (amount effect) which is considered to be main pathway for reconstruction of rainfall from cellulose isotope, is not visible in all sites of rainfall isotope observations (e.g. Chakraborty et al., 2016; Lekshmy et al., 2015; Scholl et al., 2009; Risi et al., 2008). Hence, relationships of rainfall amount with δ_c or δ_{rw} are site specific and subjective to the type of statistical analysis. The relationship between δ_c and δ_{sw}: (1) is based on known physiochemical processes and hence is stable in space and time; (2) can be modeled in terms of isotopic fractionations.

In the present study, we have transformed Roden et al. (2000) model with δ_c as an independent variable, and estimated δ_{sw} by the resulting equation. Our derivation (Section 3) does not add any further simplifications in terms of physico-chemical processes to the Roden et al. (2000) model. The effect of the presence of unenriched water (péclet effect) in the leaf (as a possible deviation from the Roden et al. model) on the isotopic composition of cellulose have been tested and found negligible in annual or higher time ranges. We have generated a tree ring cellulose oxygen isotopic time series from the western Himalayan region and used it as an input parameter to the transformed model i.e. Soil water reconstruction model (SWRM). Additionally, we use 12 other $\delta^{18}O$ datasets of trees from across the world and several meteorological parameters from the gridded datasets. The sensitivity of the SWRM