Watanabe *et al. Geoscience Letters* (2023) 10:28
https://doi.org/10.1186/s40562-023-00282-x

Geoscience Letters

RESEARCH LETTER

Open Access

Assessments of tree-ring intra-annual $\delta^{18}O$ record for reconstructing hydroclimate with high temporal resolution

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Abstract

Tree-ring cellulose oxygen isotopic ratios have been widely studied as a hydrological proxy in monsoonal Asia. There has been, however, little attempt to perform proxy assessment of the intra-annual isotopic data to reconstruct hydroclimate with higher temporal resolution. We presented new intra-annual cellulose oxygen isotopic records of Japanese cedar trees spanning A.D. 1918 to 2017, and validated it as a hydrological proxy by comparing with meteorological data. There are significant negative correlations between intra-annual isotopic ratios and summer precipitation/relative humidity, as similar to annual-resolution data of earlier studies. Notably on intra-annual scales, the period showing the highest correlation gradually shifted from May to August, in corresponding to the location within the annual ring. Principal component regression analyses show the regression was more accurate over a wider duration than single regression analysis using the annual data, therefore indicating that the subdivision of the annual ring could contribute to reconstruct higher-resolution hydroclimate.

Keywords Tree ring, Cellulose, Isotope, Proxy, Paleoclimate, Precipitation

Introduction

Tree-ring cellulose oxygen isotope composition ($\delta^{18}O$) is recognized as a powerful tool for reconstructing ancient precipitation in the Asian monsoon region. The $\delta^{18}O$ has been validated as a hydrological proxy, and thus it shows a significant negative correlation with summer precipitation/relative humidity (e.g., Xu et al. (2011) for Laos; Sano et al. (2012) for Vietnam; Xu et al. (2013) for southeast China; Li et al. (2015), Sakashita et al. (2016) and Nakatsuka et al. (2020) for central Japan; Pumijumnong et al. (2020) for Thailand). According to a forward model of tree-ring cellulose $\delta^{18}O$, a so-called proxy system model, the values are controlled by source water $\delta^{18}O$ and relative humidity. Precipitation, which is assumed as source water, is negatively correlated with the $\delta^{18}O$ of rainfall due to the "amount effect" at mid-latitudes (Dansgaard 1964; Kurita et al. 2009). Accordingly, cellulose $\delta^{18}O$ exhibits a negative correlation with summer precipitation. On the other hand, relative humidity is also negatively related to rainfall $\delta^{18}O$ because relative humidity and precipitation are linked. Furthermore, under dry conditions (low relative humidity), soil water evaporation is more likely to occur, resulting in heavier isotope enrichment in soil water. That evaporation promotes a negative trend between relative humidity and source water $\delta^{18}O$. Transpiration in leaves also changes leaf water $\delta^{18}O$, which is related negatively to relative humidity by the Craig–Gordon equation (Craig and Gordon 1965). As a result, relative humidity is negatively correlated with the isotopic ratios of source water and leaf water. Therefore, the tree-ring cellulose $\delta^{18}O$ is negatively

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correlated with relative humidity in summer. Consequently, tree-ring isotopic record is influenced by summer precipitation/relative humidity at mid-latitude of Asia. Previous studies reconstructed hydroclimate variabilities primarily based on interannual cellulose $\delta^{18}O$ (e.g., Xu et al. 2011; Sano et al. 2012; Sakashita et al. 2016; Nakatsuka et al. 2020; Pumijumnong et al. 2020). Annual-resolution data may miss heavy rains and droughts that occur over shorter periods of time, and higher-resolution isotopic information by dividing the annual ring to several segments is required. However, intra-annual cellulose $\delta^{18}O$ has not been established as a hydrologic proxy because earlier studies are limited.

Only a few previous studies so far published evaluated intra-annual isotopes as hydrological proxies in the Asian monsoon region, as discussed below. Zhu et al. (2012) presented cellulose $\delta^{18}O$ within annual rings for Cambodia pine trees over the past 140 years (A.D. 1867–2006). Because the intra-annual isotopic patterns of tree ring are similar to those found for precipitation and the isotopic minimum of annual ring correlates with isotopic ratios in precipitation of October, they described the hydrological cycle in the late rainy season based on the isotopic minimum of tree rings (Zhu et al. 2012). Xu et al. (2016) also presented intra-annual cellulose $\delta^{18}O$ for *Fokienia hodginsii* and *Cryptomeria fortunei* in southeastern China, respectively, for the past 23 years (A.D. 1988–2011) and the past 15 years (A.D. 1996–2011). Correlations between the $\delta^{18}O$ variations of tree rings and those of precipitation suggest that cellulose $\delta^{18}O$ could reconstruct precipitation with higher resolution (Xu et al. 2016). In addition, Xu et al. (2020) presented intra-annual cellulose $\delta^{18}O$ in *Pinus massoniana* collected from southeastern China during 115 years (A.D. 1900–2014). The isotopic minimum of annual rings was influenced by the soil water supply and source water isotopes in July–September, whereas the maximum of latewood was mainly influenced by relative humidity in October (Xu et al. 2020).

Although there has been only certain attempt that intra-annual $\delta^{18}O$ evaluated as a hydrological proxy, it is desirable to perform proxy assessment with a spatial and tree species spread. In particular, intra-annual $\delta^{18}O$ of Japanese cedar has not been validated, although it is an important tree species on dendroclimatology and dendrochronology. Therefore, this study aims to perform proxy assessment of the intra-annual $\delta^{18}O$ to reconstruct hydroclimate with higher temporal resolution. In this study, we report new intra-annual cellulose $\delta^{18}O$ records of Japanese cedar (*Cryptomeria japonica*) from the Kyoto prefecture in western Japan spanning A.D. 1918 to 2017. First, we confirmed the reproducibility of intra-annual (six segments within annual layers) isotopic analysis, their seasonal patterns, and correlations among isotopic ratios of six segments. We examined the possibility that the six segment data function as a hydrological proxy with higher resolution, by performing correlation analysis and multiple regression analysis with meteorological observation data. We also discussed the temporal change of radial growth phenology based on intra-annual $\delta^{18}O$ data.

Material and methods

Study site and tree-ring sample

The study site is located in the northeastern part of Kyoto Prefecture, Japan (Fig. 1a). The nearest meteorological observatory is the Maizuru District Meteorological Station (35°27′N, 135°19′E, 2.4 m a.s.l.). The meteorological data are available from the Japan Meteorological Agency (http://www.data.jma.go.jp/obd/stats/etrn/index.php). Figure 1b is a climograph calculated from the data during A.D. 1991–2020 at Maizuru station. The average monthly temperature varies from 3.7 ℃ to 27.1 ℃. The annual precipitation is 1941 mm/year, with monthly precipitation of more than 150 mm during the rainy season (known as the Baiu; June–July), typhoon season (September–October), and winter snow season (December–January).

A wood disk of Japanese cedar (*Cryptomeria japonica*) was provided by the xylarium of Kyoto University. The disk was collected in autumn of A.D. 2017 from Chojidani (640 m a.s.l.) of the Ashiu Forest Research Station and registered as KYOw20512 (Fig. 1c). Based on the tree-rings counting, we confirmed that it is approximately 200 years old. Cellulose oxygen isotopic ratios were measured for the annual ring and for the six divisions of the annual rings over the last 100 years (i.e., the outermost 100 tree rings immediately below the bark). For intra-annual isotopic analysis, the annual rings were divided into six equal widths. The average width of the annual ring was 2.9 mm, and thus the average width of six segments was estimated as 0.48 mm. To confirm the exact year of tree-ring formation, cross dating was performed between the measured annual oxygen isotopic ratios and the master chronology of central Japan (Nakatsuka et al. 2020).

Cellulose extraction and oxygen isotopic ratios measurement

After cutting the disk in the traverse from pith to bark and then preparing laths (1 cm wide, 1 mm thick; Fig. 1c), we extracted cellulose from laths on the "cross-section" method by Kagawa et al. (2015) with a few modifications. Cellulose-extracted tree rings were divided on annual and intra-annual (six segments per annual ring) scales with an ophthalmic scalpel under a stereomicroscope and then were packed into silver

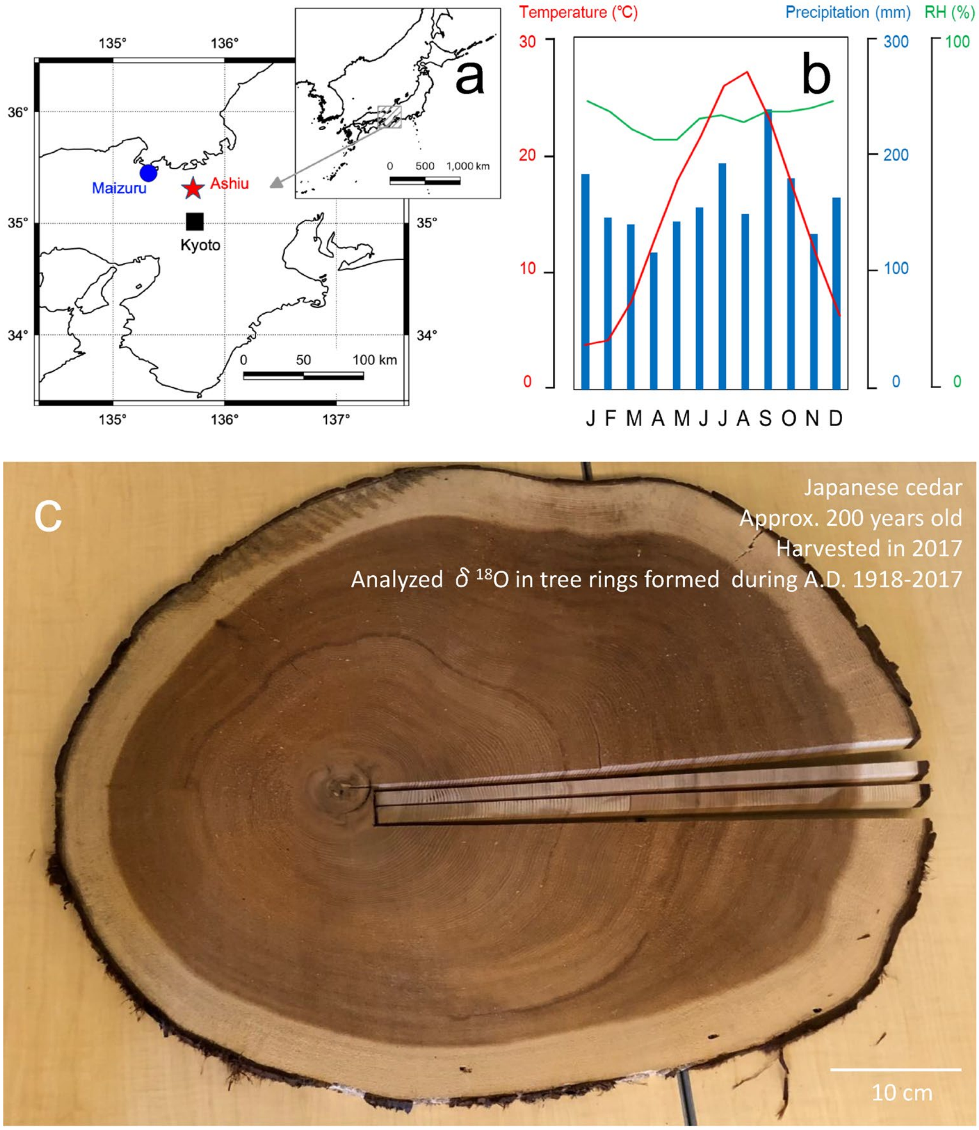

Fig. 1 **a** Location of Ashiu Forest Research Station, Kyoto Prefecture in western Japan. **b** Monthly temperature, precipitation, and relative humidity (RH) at Maizuru District Meteorological Station (calculated by using A.D. 1991–2020 data from the Japan Meteorological Agency; http://www.data.jma.go.jp/obd/stats/etrn/index.php). **c** Photograph of analyzed wood disk

foil for oxygen isotopic measurements. Cellulose samples were measured for oxygen isotopic ratios using a mass spectrometer (Delta Plus XP; Thermoquest Corp.) interfaced with a pyrolysis-type elemental analyzer (TCEA; Thermoquest Corp.). The isotopic values of Merck cellulose, which was used as an in-house standard, were measured for every eight samples. Acquired isotope ratios were presented as $\delta^{18}O$ values against VSMOW. The internal reproducibility of oxygen isotopic analysis is typically 0.20‰ or less at the 2σ level, which is estimated by multiple analyses of the cellulose standard.

Results and discussion

Cross-dating with master tree-ring oxygen isotope chronology

Cellulose $\delta^{18}O$ variations of Ashiu cedar is shown in Fig. 2a, and the annual values vary from 25.8‰ to 28.8‰. To date tree-ring formation exactly, we performed cross dating by comparing between the measured cellulose $\delta^{18}O$ with the master chronology of central Japan (Nakatsuka et al. 2020). The correlation coefficients were calculated with sliding year-by-year, and thus the highest value of the correlation coefficient was obtained when the formation year of the outermost ring was A.D. 2017

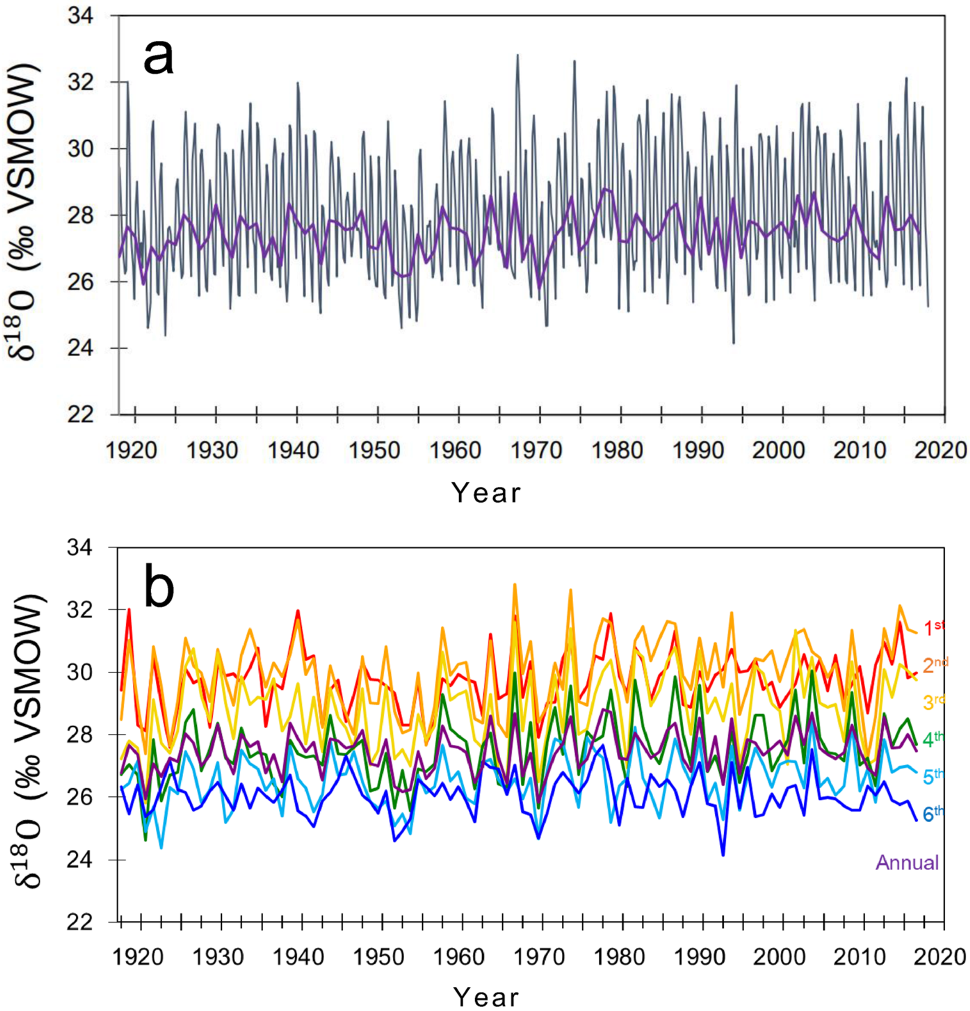

Fig. 2 **a** Cellulose oxygen isotopic time series of Japanese cedar from Kyoto Prefecture. Bold and thin lines respectively represent annual and intra-annual isotopic data. **b** Arranged time series in a sequence by each segment in the annual rings. Colors denote the respective segments: red for the first segment, orange for second, yellow for third, green for fourth, light blue for fifth, blue for sixth, and violet for the annual ring

($r = 0.76$), which is consistent with the year of tree cutting. We were able to confirm that the outermost ring was formed in A.D. 2017. An age model of measured tree rings was constructed by counting the annual rings, with A.D. 2017 as the year of formation of the outermost ring.

Reproducibility of intra-annual isotopic analysis

After dividing annual rings into six segments using an ophthalmic scalpel under a stereomicroscope, we analyzed oxygen isotopic ratios using a mass spectrometer. To evaluate the reproducibility of the procedure, we conducted duplicate analyses. As shown in Fig. 3, the repeated isotopic data agree within error (i.e., 0.20‰ or less), confirming that the partitioning and analysis are reproducible.

Intra-annual isotopic pattern and correlation among six segments of divided annual rings

The variations of cellulose δ^{18}O are presented in Fig. 2a for annual and intra-annual scales (Additional file 1). Intra-annual cellulose δ^{18}O vary in the range of 24.1–32.8‰, which is a larger range than the annual variation. Figure 2b presents a sequentially arranged time series by segment in the annual ring. Intra-annual isotopic pattern have high values early in the growing season; then decline to a seasonal minimum (Fig. 2b). In other Asian sites, cellulose δ^{18}O values are known to be higher near the ring boundary and lower near the center of the annual rings (e.g., Managave et al. (2011) for India; Poussart et al. (2004) for Thailand; Zhu et al. (2012) for Cambodia; Xu et al. (2016) for southeastern China). Our intra-annual pattern documents an isotopic minimum at the

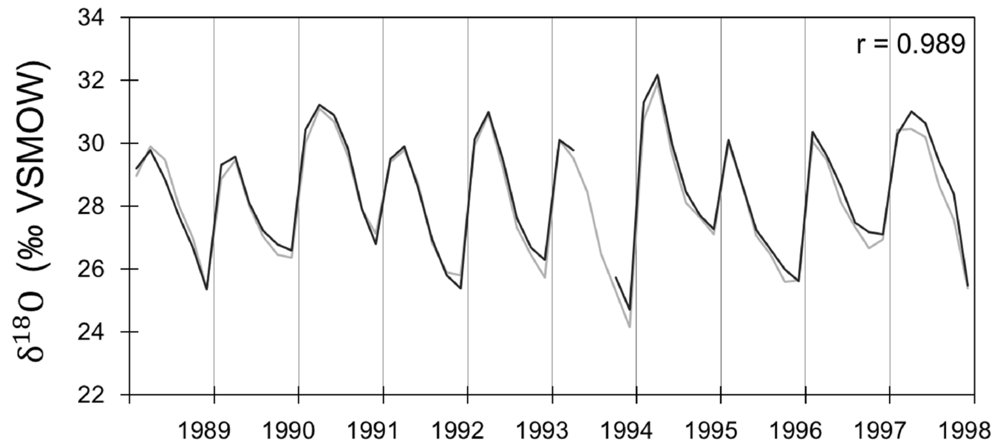

Fig. 3 Reproducibility of intra-annual isotopic analysis. Grey and black lines respectively represent first and second analysis. Duplicated samples are cut out of the same tree rings from the same cellulose-extracted plate. Repeated isotopic data agree within error (i.e., 0.20‰ or less at the 2σ level), confirming that the partitioning and analysis were reproducible

final formed part of latewood, implying that the growing period of Japanese cedar at this site is more limited than those of earlier studies.

Table 1 presents the correlation coefficients of cellulose $\delta^{18}O$ among six segments of divided annual rings. Significant positive correlations has been identified between adjacent samples in the six divisions of the annual rings. Additionally, for the outermost part of the latewood (i.e., sixth segment), the correlation is weak with those of proceeding period, suggesting that the growth periods are significantly different.

Correlation between tree-ring isotopic ratios and meteorological data

We examined the relationship between annual/intra-annual cellulose $\delta^{18}O$ and meteorological data during the growing season (i.e., March–August; Nanami et al. 2010; Nishizono et al. 2018) and the result shows in Fig. 4. From the inner (earlywood) to the outer (latewood) side of six segments, we found a slight shift from May to August in the time of highest inverse correlation with precipitation (Fig. 4a). A similar seasonal progression of correlation peaks was recognized by Xu et al. (2016), and our study clearly confirms this correlation. The isotopic values in the first, second, and third segments show the highest correlation with precipitation from late May to mid-June (Fig. 4a). Those of fourth and fifth segments are shifted gradually by about 10 days (Fig. 4a). The sixth segment is shifted by about 40 days from the fifth, during late July to mid-August (Fig. 4a). Overall the growth period of cedar trees is from March to August (Nanami et al. 2010; Nishizono et al. 2018). Significant correlation between intra-annual cellulose $\delta^{18}O$ and precipitation is also observed during the period. It is noteworthy that the peak delay of the sixth segment (the outermost latewood) is consistent with growing later than the other segments.

The annual cellulose $\delta^{18}O$ are found to have significant inverse correlations with precipitation during mid-May to early July (Fig. 4a). Similar correlations with summer precipitation were described in reports of previous studies of eastern and southeastern Asia (e.g., Xu et al. 2011, 2013; Sano et al. 2012; Li et al. 2015; Sakashita et al. 2016; Nakatsuka et al. 2020; Pumijumnong et al. 2020). The results of this study are consistent with those earlier

Table 1 Correlations of oxygen isotopic ratios among six segments divided annual rings

	1st	2nd	3rd	4th	5th	6th	Annual
1st		**0.750***	0.551	0.469	0.251	0.047	0.622
2nd			**0.859****	0.683	0400	0.138	**0.768***
3rd				**0.844****	0.507	0.177	**0.773***
4th					**0.720***	0.339	**0.798***
5th						0.465	0.674
6th							0.525

Asterisks denote significance levels (**p* < 0.05, ***p* < 0.01)

Bold numbers denote statistical significance (*p*-value less than 0.05)

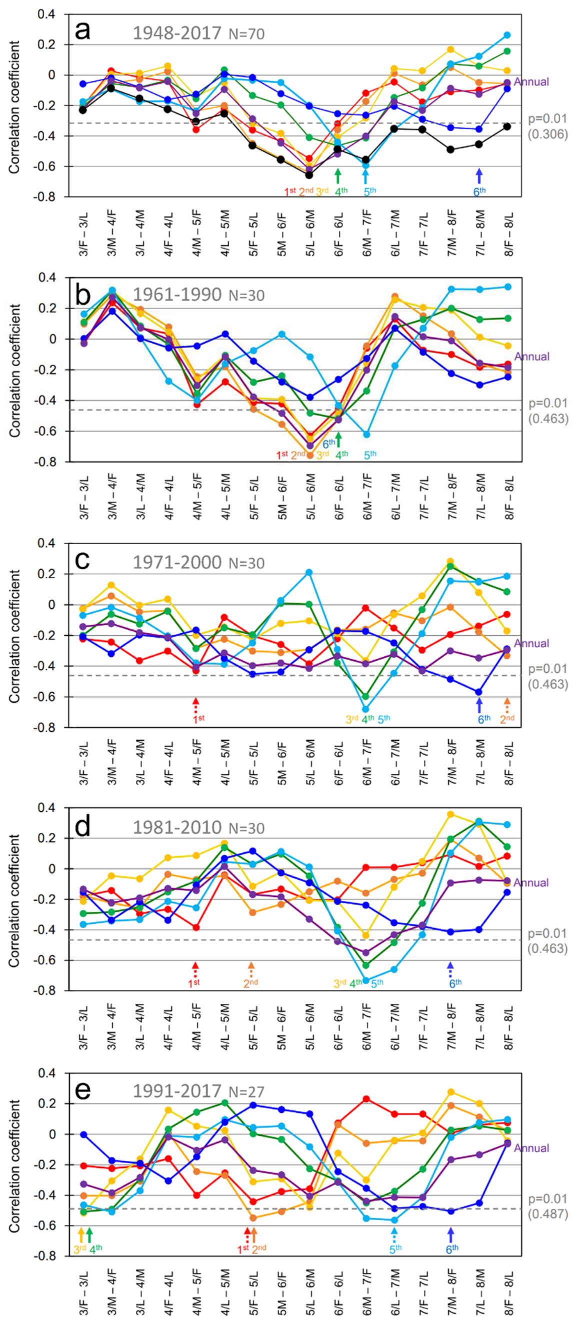

Fig. 4 Correlation between cellulose oxygen isotopic ratios and precipitation during the growing season (i.e., March–August). Analytical durations are as follows; all duration (A.D. 1948–2017) for **a**; duration I (A.D. 1961–1990) for); duration II (A.D. 1971–2000) for **c**; duration III (A.D. 1981–2010) for **d**; duration IV (A.D. 1991–2017) for **e**. Colors denote the results of each segment: red for the first segment, orange for second, yellow for third, green for fourth, light blue for fifth, blue for sixth, and violet for the annual ring. Black shows the results of principal component regression. The correlation coefficient is calculated every 30 days for meteorological data, and F, M, L on horizontal axis respectively represent the first 10 days of a month, the middle of a month, and the last 10 days of a month. The dashed line presents the *p*-value of 0.01. Arrows and dashed arrows denote the strongest correlations with and without statistical significance (*p*-value < 0.01)

studies. Moreover, compared to the conventional annual isotopic data, intra-annual isotopic data yield significant correlations over a wider period of time (Fig. 4a).

Correlations between cellulose $\delta^{18}O$ and relative humidity are summarized in Fig. 5. Because the data of relative humidity are only available since A.D. 1961, correlation coefficients with relative humidity were calculated for 57 years from A.D. 1961 to A.D. 2017 (Fig. 5a). The annual oxygen isotopic ratios showed significant inverse correlations with relative humidity during mid-May to early July (purple of Fig. 5a). On intra-annual data, a tendency can be identified with the highest peaks of the correlations appear in segment order during mid-May to mid-August (Fig. 5a). Accordingly, intra-annual isotopic data obtain significant correlations with relative humidity over a wider period than conventional annual data, as similar to the results of precipitation.

Multiple regression analysis using cedar intra-annual oxygen isotopic ratios

A multiple regression analysis was performed using meteorological data (i.e., precipitation, relative humidity, or air temperature) as objective variables and cedar intra-annual cellulose $\delta^{18}O$ as explanatory variables. In multiple regression analysis, multicollinearity is known to occur when correlation among explanatory variables is considerable, which can engender inaccurate regression. To avoid multicollinearity, a principal component analysis was performed first for intra-annual cellulose $\delta^{18}O$, and thus six new variables were synthesized as principal components. The first three of the new six variables (i.e., the first, second, and third principal components) were used as explanatory variables for the multiple regression analysis. Precipitation or relative humidity was used as the objective variable. The sign-reversed multiple correlation coefficients are shown as black lines in Figs. 4a and 5a.

For most of the period, the multiple regression analysis is more accurate than a single regression analysis using the annual cellulose $\delta^{18}O$ data (Figs. 4a and 5a). The difference is particularly pronounced for the period after July, with no significant correlation between annual cellulose $\delta^{18}O$ and precipitation/relative humidity (purple of Figs. 4a and 5a), whereas the multiple regression yields significant correlations of less than 1% (black of Figs. 4a

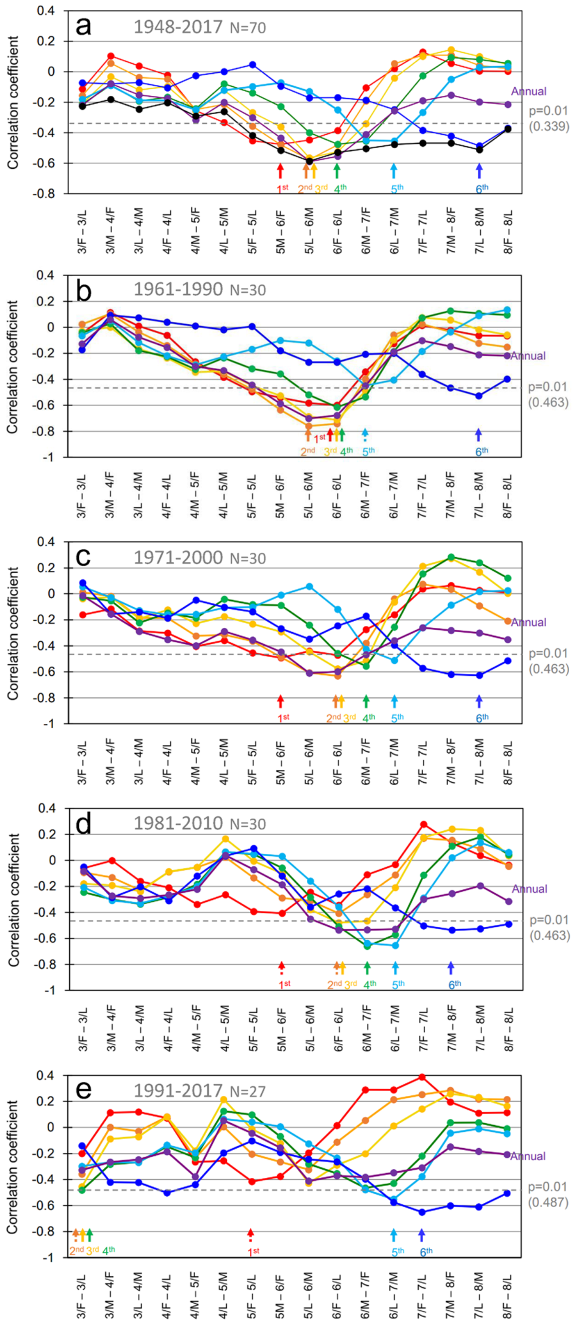

Fig. 5 Correlation between cellulose oxygen isotopic ratios and relative humidity during the growing season (i.e., March–August). Analytical durations are as follows; all duration (A.D. 1961–2017) for **a**; duration I (A.D. 1961–1990) for **b**; duration II (A.D. 1971–2000) for **c**; duration III (A.D. 1981–2010) for **d**; duration IV (A.D. 1991–2017) for **e**. Colors and abbreviations are same as Fig. 4

and 5a). The results therefore suggest that more detailed information related to past precipitation can be obtained by dividing annual rings into six segments.

Temporal change of radial growth phenology

In order to investigate the temporal change on the correlation between tree-ring intra-annual isotopic ratio and meteorological data, we attempted to divide the time series data into several intervals and perform a correlation analysis. The correlation coefficients of four periods are shown in Figs. 4b–e and 5b–e: A.D. 1961–1990 for I; A.D. 1971–2000 for II; A.D. 1981–2010 for III; and A.D. 1991–2017 for IV.

In analytical duration I, all segments within the annual ring have highest correlations with precipitation/relative humidity from late May to early July (Figs. 4b and 5b; except sixth segment), suggesting that most segments are prominently influenced by photosynthetic products formed in June. In analytical durations II and III, the first segment has the highest correlation earlier (Figs. 4c, d and 5c, d), showing that tree-ring formation begins earlier than in analytical duration I. In analytical duration IV, there is a clear difference among the seasons with highest correlation between intra-annual isotopic ratios and meteorological data (Figs. 4e and 5e). This finding suggests that the photosynthetic products used for each segment are not blended enough and it increases the influence of photosynthetic products formed in the preceding season before June. According to previous studies, heating of cedar stems promotes end of winter dormancy and cambial reactivation (Oribe & Kubo 1997; Begum et al. 2010), and thus the temperature rise accelerates the initiation of radial growth. Additionally, according to Nishizono et al. (2018), the onset of radial growth of Japanese cedar is strongly influenced by mean annual temperature, with higher mean annual temperatures leading to earlier growth initiation. This study agrees with the results of previous studies as our isotopic records indicate that radial growth starts earlier than June after the 1990 s with higher annual mean temperatures (Figs. 4c–e and 5c–e). Particularly, spring temperatures have increased since the 1990 s (Fig. 6), suggesting that those conditions promote early radical growth. It is worth noting that the present study is novel in that it demonstrates the temporal change in radial growth phenology response to ongoing warming based on intra-annual isotopic data.

Cellulose $\delta^{18}O$ of the third to fifth intra-annual divisions are characterized by higher correlations with March precipitation (Fig. 4e). According to previous study of ecosystem modeling by Hirano et al. (2021), temperature from winter to spring preceding radial growth affects photosynthesis of Japanese cedar and then the amounts of stored photosynthates, thereby leading to the variation of earlywood width. The results of this study are further consistent with the results of Hirano et al. (2021). Our results can be interpreted as follows: photosynthetic products using March rainwater are utilized to produce

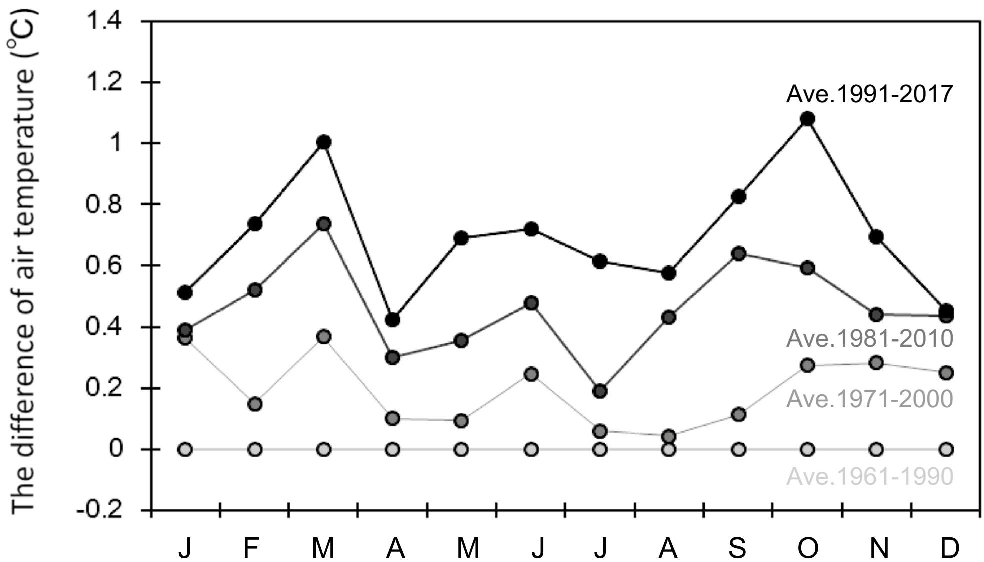

Fig. 6 Temporal change of monthly average air temperatures at Maizuru (the data from the Japan Meteorological Agency; http://www.data.jma.go.jp/obd/stats/etrn/index.php). The difference of temperature was calculated as the difference from A.D. 1961–1990

the third to fifth segments. It also might be a distinctive feature after the 1990 s, because there is no significant correlation between isotopic data and March precipitation prior to the 1990 s (Fig. 4b).

Based on the correlation analysis between intra-annual cellulose δ^{18}O and meteorological data, we discussed the temporal change of radial growth phenology. Temperature rise around the 1990 s (Fig. 6) may have change the growth phenology of Japanese cedar in this site. The tree-ring phenology response to ongoing global warming has attracted much attention and investigated by many studies (e.g., Moser et al. 2010; Wang et al. 2015; Rossi et al. 2016; Nishizono et al. 2018), but little is known about temporal variation in the past several decades because of the difficulty to acquire reliable data. Our results point towards the potential that intra-annual isotopic records could be one of useful approach to assess tree-ring phenology response on global warming, because it is widely available across tree species and regions.

Conclusions

In this study, we report new intra-annual cellulose δ^{18}O records of Japanese cedar from northeast Kyoto spanning A.D. 1918 to 2017. Based on the results presented above, we reached the following conclusions.

1. To evaluate the reproducibility of the isotopic analysis by dividing the annual layer into six segments, we conducted duplicate analysis. Results of repeated analyses are consistent within error, thereby confirming that the data of six divisions are reproducible.
2. We examined the relationship between cellulose δ^{18}O in the six divisions of the annual ring and meteorological data (i.e., precipitation and relative humidity). As the results, the isotopic data of six divisions show significant negative correlation with each meteorological data over a longer period of time, compared to annual isotopic data.
3. Multiple regression analysis was performed using intra-annual cellulose δ^{18}O as explanatory variables and meteorological data (i.e., precipitation, relative humidity and air temperature) as objective variables. Results indicated that multiple regression analysis is more accurate than single regression analysis using annual isotopic data in all periods during March–August. Especially during July–August, a prominent difference can be identified between single regression analysis using annual isotopic data and multiple regression analysis. Accordingly, this study suggests that intra-annual tree ring analysis enables hydroclimate reconstruction with higher resolution than a conventional annual analysis.
4. We investigated the temporal change on the correlation between tree-ring intra-annual δ^{18}O and meteorological data (i.e., precipitation, relative humidity). Before the 1990 s highest correlations for most segments accumulate around June, whereas those after the 1990 s distinctively extend from spring to summer. This result implies that radial growth phenology of Japanese cedar has changed during A.D. 1948–2017.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40562-023-00282-x.

Additional file 1: Table S1 Cellulose oxygen isotopic data.

Acknowledgements

We are indebted to Prof. T. Tagami (EPS, Kyoto Univ.) and to Prof. J. Sugiyama (Faculty of Agriculture, Kyoto Univ.) for generous support to this study. We are deeply grateful to Mr. A. Adachi and Mr. H. Sorimachi (RISH, Kyoto Univ.) for processing the wood samples and to Prof. M. Ishihara (AFRS, Kyoto Univ.) for providing meteorological data of this study site. We would also like to thank Prof. H. Zwingmann (EPS, Kyoto Univ.) for reading our original manuscript and correcting the English usage. Thanks are extended to Dr. K. Nakajima (EPS, Kyoto Univ.) for his warm and continual encouragement for our study and to Mr. H. Nishimine (EPS, Kyoto Univ.) for analytical support. This work was financially supported by JSPS KAKENHI [Grant Number 21K12208] to YW, and in part by the Exploratory Research Project, RISH, Kyoto University.

Author contributions

YW and YK: Sampling, measurement of cellulose $\delta^{18}O$, analysis, interpretation, and writing the manuscript. ZL: Measurement of cellulose $\delta^{18}O$. TN: Measurement of cellulose $\delta^{18}O$ and interpretation. ST: Sampling and wood processing. All authors read and approved the final manuscript.

Funding

This investigation was supported by the Japan Society for the Promotion of Science (JSPS) KAKENHI program (Grant Numbers 21K12208). This research was also funded in part by the Exploratory Research Project, RISH, Kyoto University.

Availability of data and materials

Tree-ring cellulose $\delta^{18}O$ data are available from the supplementary material.

Declarations

Ethics approval and consent to participate

We consent to participate and have no competing interests.

Consent for publication

All authors agree for this publication.

Competing interests

The authors declare that they have no competing interests.

Received: 28 December 2022 Accepted: 2 June 2023
Published online: 21 June 2023

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