Invited Research Article

Low oxygen isotope values of fossil cellulose indicate an intense monsoon in East Asia during the late Oligocene

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ABSTRACT

The late Oligocene is an important deep-time analog for understanding future changes in the strength of the East Asian monsoon: it represents a climate warmer than today, yet follows the nascent uplift of the Tibetan-Himalayan orogeny during the Eocene Epoch. Here we quantify monsoon strength based on new oxygen isotope measurements on cellulose (δ18Ocell) extracted from modern and fossil wood from southern China. Tree-ring δ18Ocell values have previously been used to track Holocene climate variations in East Asia, as δ18Ocell values are primarily controlled by meteoric water δ18O (δ18Ometeoric) and relative humidity. We find the δ18Ocell values measured on the modern samples (25.7 to 29.1‰ VSMOW) are consistent with other δ18Ocell records from trees growing in southern China under the present-day monsoon climate. However, fossil wood δ18Ocell values (21.0 to 24.1‰ VSMOW) are significantly lower than those from living trees in the region, and instead overlap with values from modern high latitudes and high elevations. We show that these low δ18Ocell values are best explained by much higher rainfall amounts in southern China during the late Oligocene, with monthly wet-season rainfall that may have been ~60% greater than today based on modern relationships. These data represent the first seasonal rainfall estimates for southern China during the late Oligocene and signify an intensification of the region’s current monsoonal rainfall patterns. We speculate that significantly greater monsoon rainfall is therefore possible in the region under a warmer climate.

1. Introduction

Strong seasonality in precipitation, with wet summers and dry winters, characterizes the monsoon climate across East Asia today. Models indicate that monsoon intensity, measured as the amount of summer rainfall, may increase with global warming (Takahashi et al., 2020), but projected changes have large uncertainties and substantial intermodel variability (Chevuturi et al., 2018), and the role of anthropogenic activity (i.e., aerosol emission) on monsoon strength is still highly debated (Bollasina et al., 2011; Dong et al., 2019; Kim et al., 2016; Mu and Wang, 2021). Paleoclimate records from intervals of warmer global climate may therefore be informative for understanding monsoon dynamics in a warmer world. Analysis of paleo-monsoon strength is commonly inferred from oxygen isotope measurements of speleothems (Cheng et al., 2016; Cosford et al., 2008; Liu et al., 2020), but these records are limited to the Quaternary, when CO2 levels were lower than today. Studies of monsoon strength in deep time (pre-Quaternary) indicate a strong link between CO2 and rainfall dating back to the Eocene (Licht et al., 2014), while others highlight the important role of paleogeography on monsoon intensity (Farnsworth et al., 2019). Although the mechanism is debated, recent work provided firm evidence for an East Asian Monsoon-style system, with wet summers relative to winters, prior to the Neogene (Vornlocher et al., 2021), but quantitative estimates of the amount of wet-season rainfall in the late Oligocene are lacking. Here we provide new measurements of the oxygen isotope value of cellulose (δ18Ocell) extracted from modern and late Oligocene fossil wood in order to determine how monsoon rainfall during the late Oligocene compares to today. The late Oligocene is an ideal period to study the effect of global temperature on monsoon intensity because it represents the likely trajectory for Earth’s climate system as CO2 emissions continue to rise unabated (Westerhold et al., 2020). It also represents a critical period in central Tibetan uplift (Fang et al., 2020; Su et al., 2019), and therefore is

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an essential yet understudied interval of time for investigating Asian monsoon dynamics in deep-time.

Determination of δ¹⁸Ocell value from living trees has long been used to quantify recent climate change (Brienen et al., 2012; Knorre et al., 2010; Loader et al., 2010; Loader et al., 2007; McC Carroll and Loader, 2004; Pousart et al., 2004; Rinne et al., 2013; Saurer et al., 2008; Treydte et al., 2006; Young et al., 2015), including in monsoon regions of East Asia (e.g., Sakashita et al., 2016; Xu et al., 2016). Application of these techniques to well-preserved fossil wood collected from pre-Quaternary sediments has allowed for new quantitative climate data in deep time (Jahren and Sternberg, 2002, 2003, 2008; Richter et al., 2008b; Wolfe et al., 2012). These studies all rely on empirical relationships between the stable oxygen isotope composition of tree-ring cellulose (δ¹⁸Ocell) and that of meteoric water (δ¹⁸OMW) (Csank et al., 2013; Olson et al., 2020; Richter et al., 2008b; Saurer et al., 2016; Sternberg et al., 2007; Waterhouse et al., 2002), which can then be related to precipitation or temperature depending on the environment in which the plant grew: δ¹⁸OMW values in low-latitude sites respond more to rainfall amount (Araguás-Araguás et al., 1998; Brienen et al., 2012; Dayem et al., 2010; Gonfiantini et al., 2001; Xie et al., 2011), while δ¹⁸OMW values in middle to high-latitude sites are affected more by changes in temperature (Bowen, 2008; Dansgaard, 1964; Schubert and Jahren, 2015). We leverage these earlier works to present the first estimates for wet-season rainfall in southern China during the late Oligocene based on the δ¹⁸Ocell value of well-preserved wood fossils, thus providing data on seasonal rainfall intensity in this monsoon region under a warmer climate state.

2. Materials and methods

Mummified fossil wood samples were collected from the upper Yongning Formation near Nanning in the Guangxi Zhuang Autonomous Region of South China (22°52′50″N, 108°25′2″E; elevation = ~80 m; Fig. 1) (Quan et al., 2016). The upper Yongning Formation is a lacustrine deposit dated to the late Oligocene based on palynology and mammalian fossils (Quan et al., 2016). For this study, we selected 64 mummified wood samples representing the genus Castanopsis (Huang et al., 2018) for cellulose extraction and oxygen isotope analysis. This genus is considered an important paleoecological indicator of subtropical evergreen forests (Gee et al., 2003), and are currently restricted to regions of east and southeast Asia (Huang et al., 2018). Living Castanopsis trees growing in the region have maximum rooting concentrations within the upper 0.3 m of the soil (Hao et al., 2006). Such shallow rooted trees may better record annual variations in δ¹⁸OMW (McCarroll and Loader, 2004; Waterhouse et al., 2002) than more deeply rooted species or trees growing in drier climates (e.g., Huang et al., 2019a; Huang et al., 2019b).

Radial cores (QXS21A and QXS24A, Fig. 1) were also collected from two living Pinus massoniana trees growing at nearby Qingxiushan Hill, Nanning (22°47′23.35″N, 108°23′4.26″E, elevation = 223 m). The site has a humid, monsoon climate, with 63% of the total annual rainfall falling in only four months (May through August) (Fig. 2). Annual growth rings (entire earlywood and latewood) were sampled by hand using a razor blade across the years 1990–2000 to produce an annually resolved δ¹⁸Ocell record. This period was chosen because it: 1) represented a wide range of wet-season rainfall (482 to 1267 mm), and 2) avoided potential juvenile effects on δ¹⁸Ocell value in the early portion of the trees’ growth (Büntgen et al., 2020; Duffy et al., 2019). A total of 22 annual growth rings (11 per tree) were collected for stable isotope analysis.

We extracted α-cellulose from bulk samples of the fossil wood and individual tree rings of the modern wood following a method modified from Brendel et al. (2000). Because of the low cellulose yields in the fossil wood relative to the modern wood, we increased the amount of fossil wood starting material and proportionally adjusted the volume of reagent used. Lignin was removed by nitric acid and acetic acid, and lipids were removed by ethanol and acetone, and then treated with 17% sodium hydroxide solution to obtain α-cellulose. Dry α-cellulose samples were then weighed into silver capsules, and δ¹⁸Ocell values were determined using a High–Temperature–Conversion Elemental Analyzer.

Fig. 1. a) Location of Nanning, China (circle) and Guangzhou, China (square) within the present-day monsoon region (pink: as reported within (Ramage, 1971) and (Wang and Ding, 2008)). Note this area includes the East Asia summer monsoon, western North Pacific summer monsoon, and Indian summer monsoon (Wang and LinHo, 2002). All of these locations experience high rainfall seasonality today. b-c) Photographs of mummified fossil wood samples: b) NNW015 and c) NNW037, respectively. d-e) Photographs of the two modern cores: d) QXS21A and e) QXS24A. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
coupled with a Delta-V Advantage Mass Spectrometer (Thermo Fisher Scientific, Inc., USA). Samples were analyzed with three internal laboratory reference materials (ACell = 32.33 ± 0.06‰, JCEL-01 = 17.64 ± 0.09‰, and SigmaCell = 28.46 ± 0.07‰) calibrated against International Atomic Energy Agency (IAEA) benzoic acid reference materials: IAEA 601 (23.24 ± 0.19‰) and IAEA 602 (71.28 ± 0.36‰). A quality assurance sample (JCcell 02, δ18O = 20.44 ± 0.10‰) was analyzed within each batch and analyzed as an unknown. The δ18Ocell values had an analytical error of ±0.3‰ and ±0.1‰ for the fossil and modern samples, respectively. The δ18Ocell values are reported in units of per mil (%) relative to the VSMOW standard.

3. Results

We recovered α-cellulose from 67% of the fossil wood samples (43 out of 64 samples); the remaining 21 samples (33%) contained no recoverable α-cellulose, and are not discussed further. The δ18Ocell value of the 43 fossils ranged from 21.0 to 24.1‰ with a mean (± 1σ) = 22.4 ± 0.7‰ (Table 1). The measured variance in the δ18Ocell values across the 43 fossil specimens was small (0.5‰), consistent with a common water source and common environment during growth (Csank et al., 2013; Sternberg et al., 2007). Because the δ18Ocell value of seawater during the late Oligocene was lower than today (Westerhold et al., 2020), we added 2.5‰ to the fossil values to allow for an unbiased comparison with modern δ18Ocell values. The δ18Ocell value of the modern samples averaged 27.4 ± 1.0‰ (n = 22) (Table 2), which was similar to the most recent 30 years of δ18Ocell values measured independently on Pinus massoniana and Picea schrenkiana trees growing in monsoon regions of southern China (Shi et al., 2020; Xu et al., 2013) (Two-sample t-test, t = 0.6, p = 0.53). The different sampling resolution of the modern (annual) and fossil (bulk wood) samples do not allow for comparison of variance between the late Oligocene and present-day; however, the δ18Ocell values of the modern samples is significantly higher than both the raw (22.4 ± 0.7‰) and seawater-corrected (24.9 ± 0.7‰) fossil δ18Ocell values (two-sample t-tests, t = 20.8 and 10.3, respectively; p < 0.0001, for each). We note that all further analysis and discussion of the fossil δ18Ocell data use the seawater corrected values.

4. Discussion

When examining our results within the context of published δ18Ocell values, we find that all our measured δ18Ocell values (both fossil and modern) were within the range of δ18Ocell values reported for trees growing across the planet today (δ18Ocell = 14 to 34‰; Fig. 3). The δ18Ocell values of the modern samples are similar to other records in southern China (Cai et al., 2018; Shi et al., 2020; Xu et al., 2013). However, our measured fossil δ18Ocell values are lower than δ18Ocell values from the modern trees in the Nanning Basin, and are more similar to values reported for trees growing at high elevation sites (2500 m) in Nepal (Xu et al., 2018); high latitude, cold sites near Lake Baikal in central Russia (Tartakovsky et al., 2013) and arctic Siberia (Holzskamper et al., 2008); and areas that receive higher summer rainfall amounts than southern China (e.g., Bangladesh, Islam et al., 2021). Nevertheless, the paleolatitude (Wu et al., 2017) and paleogeography (Quan et al., 2016) of Nanning Basin during the late Oligocene are incompatible with very low MAT and/or high elevation, suggesting the low δ18Ocell values measured in our fossil wood samples are unlikely caused by these factors. This is also supported by similar δ18Ocell values reported for...
Oligocene age fossils from interior Siberia (Fig. 3), which further preclude temperature (Richter et al., 2008b), vapor transport distance (Jahren and Sternberg, 2002), or continentality (i.e., distance from coast) (Rozanski et al., 1993) as viable explanations for the low δ18O values measured in the fossil wood from Nanning Basin. Intriguingly, similarly low δ18O values to our fossil wood have also been measured in modern wood growing within monsoon climates of east and south Asia that see greater precipitation amounts than present-day Nanning Basin (Islam et al., 2021; Schollaen et al., 2014; Zhu et al., 2012). For example, Zhu et al. (2012) reported δ18O values of 22.3 to 25.9‰ (mean ± 1σ = 24.1 ± 0.78‰) for Pinus merkusii growing in southern Cambodia and Islam et al. (2021) reported δ18O values of 24.2 to 27.2‰ for Chukrasia tabularis (25.6 ± 0.8‰) and Lagerstroemia speciosa (25.9 ± 0.5‰) growing in Bangladesh; both of these studies reported data from sites with greater wet-season precipitation than our study site in Nanning.

We therefore interpret our low δ18O values in terms of the amount effect, consistent with interpretations made at other low-elevation tropical and sub-tropical sites (Schollaen et al., 2014; Shi et al., 2020; Zhu et al., 2012), in which intense monsoon precipitation becomes depleted in 18O in summer months (Araguás-Araguás et al., 1998; Dansgaard, 1964). We achieve this by first demonstrating the utility of these relationships for quantifying growing season precipitation in monsoon climates using our modern δ18O values, and then applying these relationships towards inferring wet-season rainfall during the late Oligocene using our fossil δ18O dataset.

### 4.1. Quantifying monsoon precipitation from δ18O

In order to quantify monsoon rainfall from δ18O, we first demonstrate the ability for δ18O to accurately record the δ18O 90% value of monsoon rainfall in present-day Nanning. We did this by calculating δ18O 90% from δ18O using the following relationship developed by Sternberg et al. (2007) from both needle leaf and broadleaf tree species growing across a wide climate gradient:

\[
\delta^{18}O_{\text{cell}} = 0.60 \times \delta^{18}O_{90\%} + 31.9
\]

This relationship excluded samples from Arizona, USA (after Sternberg et al., 2007) because they grew under exceptionally low relative humidity (26%) that is known to affect δ18O, and contrasts with the consistently high relative humidity of Nanning Basin today (80%) (Fig. 2). We note, however, that given the strong relationship between δ18O and δ18O 90% and large sample size of this dataset \((n = 34)\), the slope \((m)\) and intercept \((b)\) do not change substantially if the data from Arizona are included \((m = 0.61, b = 32.4\)‰, Sternberg et al. (2007)).

Using Eq. (1) and the δ18O 90% values measured here for the modern trees growing in Nanning, we calculate median δ18O 90% = −7.5 ± 1.7‰ \((n = 22)\). These values are consistent with predicted δ18O 90% values for summer monsoon precipitation at this site, which today range from −6.5 to −8.0‰ (Fig. 2), and demonstrate the utility of Eq. (1) for estimating monsoon δ18O 90% values using δ18O cell.

Next, we calculated average monthly monsoon precipitation using the following relationship developed by Xie et al. (2011) for nearby Guangzhou, China:

\[
P_{\text{mon}} = -30.4 \times \delta^{18}O_{\text{cell}} - 0.5
\]

where \(P_{\text{mon}}\) is mean monthly precipitation, and δ18O 90% is calculated using Eq. (1). Using our annual δ18O cell values from each tree core and Eqs. (1) and (2), we calculate mean \(±1\sigma\) \(P_{\text{mon}}\) in Nanning today of 230 ± 51 mm \((\text{range} = 141–314 \text{ mm})\). These values are consistent with average monthly rainfall amount during the wettest four months of each calendar year represented by our δ18O cell dataset, i.e., “Pwet” (1990–2000: \(P_{\text{wet}} = 216 ± 46 \text{ mm}, \text{range} = 158–317 \text{ mm}\) (Fig. 4)). This result highlights the importance of rainfall in the wettest months on tree growth in this subtropical monsoon climate, and suggests δ18O cell values as an accurate proxy for monsoon precipitation in the region.

### 4.2. Quantifying monsoon precipitation during the late Oligocene

Applying Eqs. (1) and (2) to our fossil wood data allows for...
estimation of monsoon precipitation during the late Oligocene. We note that this approach can be affected by changes in the δ¹⁸O cell value of source water and potential changes in δ¹⁸O_SSW gradients through time (Fricke and O’Neill, 1999). If we assume a similar amount effect in the late Oligocene as today, we can use our seawater-adjusted fossil δ¹⁸O_{cell} values to calculate average P_{wet} = 349 ± 35 mm (n = 43), which suggests late Oligocene rainfall was approximately 60% greater than present-day (P_{wet} = 220 ± 46 mm, 1951 to 2012) (note, without the correction, P_{wet} = 476 mm, or 2.2× present-day, which is untenably large). Today, similar monthly precipitation amounts are found at coastal sites only 400 km to the southeast of Nanning (e.g., P_{wet} = 354 mm at Yangjiang, China) as well as large portions of northern central Vietnam and central Laos (P_{wet} = 339 mm, range = 315 to 383 mm) and central Bangladesh (P_{wet} = 348 mm, range = 314 to 384 mm). We note that our significantly lower δ¹⁸O_{cell} values in the late Oligocene compared with today cannot be reconciled with an increase in rainfall compared to present, even if the specific relationship represented by Eq. (2) differed in the past (e.g., steeper or shallower slope). Although the exact amount of this increase is here calculated as 60%, larger and smaller increases cannot be ruled out without knowing δ¹⁸O_{SW}/P_{wet} Spatial patterns in the late Oligocene.

Recent efforts have aimed to improve our understanding of spatial patterns in precipitation during the late Oligocene (Utescher et al., 2021). Plant macrofossil data indicate less wet-season precipitation in northern China during this time (Li et al., 2018), in contrast with the greater wet-season rainfall we calculate here for southern China. These regional differences are consistent with observations and models indicating diminished rainfall in northern China (Li et al., 2017) and increased rainfall to the south (Bryan et al., 2019; Sooraj et al., 2015) in response to modern global warming, and lend support to our interpretation of high rainfall inferred by the low δ¹⁸O_{cell} values. The increased average wet season rainfall calculated here for the late Oligocene further supports hypotheses that warmer temperatures in the future will increase the amount of precipitable water thereby intensifying rainfall in southern China (Takahashi et al., 2020). This interpretation is supported by multiple models that indicate a 50% to 100% increase in extreme precipitation frequency in southern China and southeast Asia in response to warming of only 1.5 to 2 °C (Chevuturi et al., 2018).

The Oligocene paleoflora at Nanning has previously been interpreted to reflect tropical, monsoon climate conditions similar to areas that receive higher summer rainfall than modern Nanning (e.g., Thailand and eastern India; Huang et al., 2018; Ying et al., 2018). The results of the current study and these independent lines of evidence suggest that the East Asian monsoon was at least as strong as modern conditions—with likely higher summer rainfall levels—during the late Oligocene, and indicates that the East Asian monsoon may strengthen as CO₂ levels and global temperatures approach those of the Oligocene (Tierney et al., 2020).

5. Conclusions

We show that δ¹⁸O_{cell} values can be used to provide information on summer rainfall within monsoon regions. We find that δ¹⁸O_{cell} values were 5% lower during the late Oligocene than today, half of which is attributed to lower δ¹⁸O values of seawater and half to changes in climate. Comparison to Oligocene δ¹⁸O_{cell} data from Siberia confirms the low δ¹⁸O_{cell} values cannot be reconciled by lower temperatures because it is unlikely both sites experienced the same temperatures. Agreement between δ¹⁸O_{cell} and rainfall in modern monsoon regions supports our interpretation of low fossil δ¹⁸O_{cell} values inferring elevated rainfall during the late Oligocene. Using modern relationships, we calculate a 59% increase in monsoon rainfall during the late Oligocene compared to present (349 mm/month versus 220 mm/month). Such heavy rainfall in a single month is not unprecedented in Nanning at present: from 1951 to 2012, nearly 10% of the monsoon months (May through August) have experienced at least 349 mm of rainfall; however, no single year has averaged at least 349 mm across four months (i.e., P_{wet} ≥ 349 mm, the late Oligocene average value). This result is consistent with fundamentally higher monsoon rainfall in the late Oligocene than today and indicates potential for greater monsoon rainfall in a warmer climate. We therefore conclude that continued global warming beyond 2 °C may lead to enhancement of wet-season rainfall in southern regions of the East Asian monsoon.

Acknowledgments, samples, and data

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The research data required to reproduce the work reported in this manuscript are included in Tables 1 and 2 and within the PANGAEA data publisher (https://doi.org/10.1594/PANGAEA.930777). Literature data compiled and presented in Fig. 3 are provided in Table S1.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.palaeo.2021.110556.

References


