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When to conduct an isotopic survey for lake water balance evaluation in highly seasonal climates

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Abstract

One-time or short-term lake water isotopic surveys are often employed to evaluate regional lake water balance. However, it can be difficult to determine the optimal time-window for sampling to obtain a representative long-term perspective of lake water balance in settings influenced by seasonal variations in precipitation, evaporative loss, glacial/snow meltwater, and larger seasonal shifts in isotopic composition of precipitation. This is especially true for areas of the Tibetan Plateau that are influenced by the summer Indian monsoon. Although high-frequency sampling is always preferred as the most rigorous approach to characterize the water budget of lakes or watersheds, this may be impractical in remote regions and over large spatial scales. To assess the potential sensitivity of isotope balance characterization to seasonal variability, we used a weekly lake water isotope data set acquired over a period of 3 years on the Tibetan Plateau to evaluate the potential inaccuracies that might have arisen from using isotopic data collected during narrower time-windows. For this assessment, we use weekly isotopic data collected during the study and assume that these sampling events were stand-alone one-time surveys. We then demonstrate the sensitivity of the isotope balance method in this setting, particularly for the rainy season that significantly underestimated the evaporation/inflow. In contrast, isotopic composition of the lake water was found to be more representative of long-term conditions when sampled in October on the Tibetan Plateau. To broaden our evaluation of seasonality effects over a range of climatic zones, published high-frequency isotopic data were also compiled, and a similar assessment was carried out for selected regions of the world. The synthesized data and model outputs, which confirm pronounced variations in lake water isotopic composition and evaporation/inflow across a range of seasonal climates, were used to determine optimal sampling windows for these specific regions.

KEYWORDS

isotopic survey, lake water balance, optimal sampling date, seasonal climate

1 | INTRODUCTION

During the process of evaporation from surface water bodies, the lighter isotopic molecules of water preferentially evaporate to the atmosphere, whereas heavier isotopic molecules tend to be retained in the liquid phase (Clark & Fritz, 1997; Craig & Gordon, 1965). As a result, surface water bodies such as lakes and wetlands often become enriched in the heavier isotopic species and, hence, are distinctly labelled relative to lake input sources such as snow, rain, streamflow, and groundwater. Quantitative tracing of water balance using $\delta^{18}O$ and $\delta^{2}H$ enrichment in lake water has been shown to be a useful tool for regional studies including, for example, assessment of evaporation/inflow (E/I) ratio (Gat, 1978), water yield (Gibson, Birks, Jeffries, & Yi, 2017), residence time (Brooks et al., 2014), and lake–groundwater interactions (Sacks, Lee, & Swancar, 2014). Among all isotope-based water balance indicators, E/I ratio is among the most commonly applied as it requires only basic knowledge of the isotopic separation between lake water and inflow and supplementary climate data, yet it informs on the essential liquid–vapour partitioning of lake outflows and has been shown to be highly variable across different climate zones and hydrologic regions (Brooks et al., 2014; Gat, 1978; Gibson, Edwards, Bursey, & Prowse, 1993; Gibson, Birks & Yi, 2016; Skrzypek et al., 2015; Zuber, 1983).

Water stable isotopes have also been widely used to evaluate regional lake water balance and water quality (Brooks et al., 2014; Gibson, Birks, Yi, Moncur & McEachern, 2016; Wolfe et al., 2007; Yuan et al., 2011). However, it is logistically challenging and costly to conduct long-term, high-frequency isotope monitoring over large spatial regions. This is especially true in remote regions, such as the Tibetan Plateau and Pan-Arctic. In practice, one-time or short-term isotopic surveys are employed in the summer season when it is logistically convenient to visit and sample the sites (Brooks et al., 2014; Yuan et al., 2011). Ideally, the collected samples should be a representative of an individual lake's average isotopic composition. Previous studies have shown that quantification of lake water balance parameters such as water yield can be significantly influenced by the timing of lake water isotope sampling and may also be complicated by factors such as seasonality and stratification (Cui, Tian, Biggs, & Wen, 2017; Gibson et al., 2017; Gibson et al., 1993). Consequently, the representativeness of one-time isotopic surveys during a specific season may vary significantly from region to region and certainly will depend on sampling strategy.

Lakes in high elevation, high latitude, and monsoon regions are influenced by seasonal precipitation or glacial and/or snow meltwater input or evaporative loss (Gibson & Reid, 2010; Tian et al., 2008; Tyler, Leng, & Arrowsmith, 2007; Wolfe et al., 2007). For example, more than 90% of precipitation falls between May and September over most of the Tibetan Plateau. Isotopes in precipitation, glacier ice, and snow often have very depleted heavy isotope signatures compared to that of lake water that is often subject to continuous or seasonal evaporation (see Gat, 1996). Thus, lake water samples collected during the rainy season may be a poor representation of long-term lake water balance. Lakes in northern Canada are subjected to a spring pulse of melt inflow and then arid summers with high rates of evaporation, resulting in a pronounced seasonal variation in lake water isotopes (Brock, Yi, Clogg-Wright, Edwards, & Wolfe, 2009; Gibson & Reid, 2014). Therefore, selection of sampling date in these seasonal climatic regions should be with caution when to conduct short-term and large-scale lake isotopic surveys.

To date, no systematic evaluation of the influence of seasonal variations on lake isotope balance has been conducted to determine optimal sampling dates for specific regions including the Tibetan Plateau. To evaluate this effect, we first performed a test by using a 3-year data set of weekly isotope samples from Cona Lake on the Tibetan Plateau. We then evaluated the representativeness of individual weekly isotopic data collected throughout the year by examining the influence of sampling date on the calculated E/I ratios. Then, calculated E/I for specific weeks was compared with calculated annual averages to determine optimal sampling dates. Finally, we synthesized published isotope data sets with high-frequency and long-term sampling to offer new insight into the optimum season for conducting representative, large-scale lake water isotope surveys in different climatic regions around the world. The objectives of this study are as follows: (a) to characterize the seasonal variations of lake water isotopes in Cona Lake on the Tibetan Plateau, (b) to test the influence of seasonal variations of lake water isotopes on derived E/I ratios, and (c) to review and assess pre-existing data sets to determine the optimal sampling date for various regions of the world.

1.1 | Study area and climate

We first performed the test for Cona Lake, with a surface area ~190 km^2 and a watershed area of 4,140 km^2, located on the central Tibetan Plateau (31°55′–32°07′ N, 91°25′–91°32′ E, 4,590 m a.s.l, Figure 1). As a throughflow lake, there are five tributaries, which generally enter the lake from the north, and water finally outflows via a single southern outlet. The area is characterized by a semi-arid monsoonal climate, with vegetation in the watershed consisting mainly of alpine meadow dominated by small hills. The mean annual air temperature and precipitation

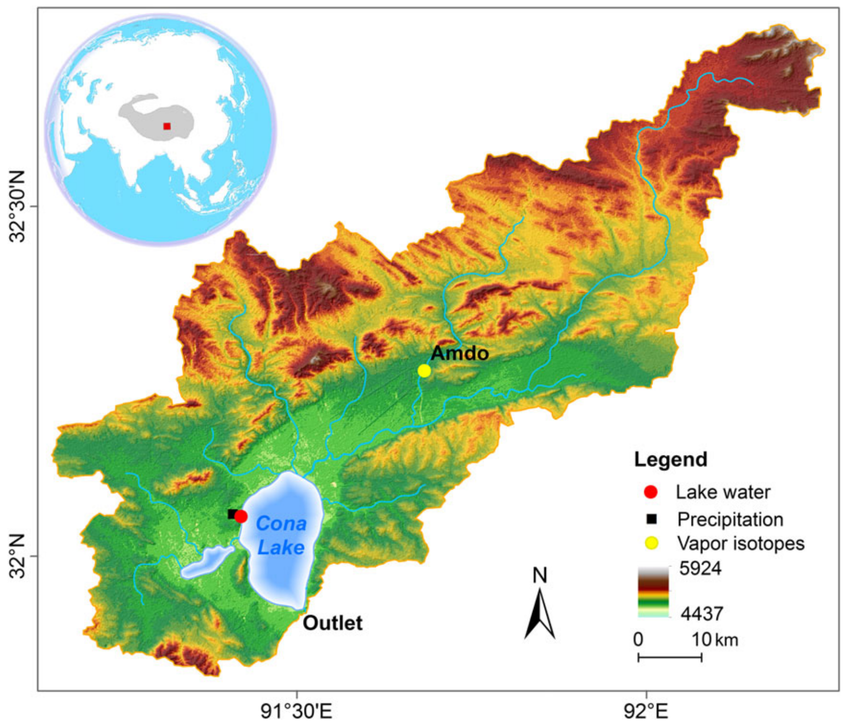

FIGURE 1 Location of Cona Lake Basin and sampling sites

are −2.3 °C and 466 mm, respectively, recorded at nearby Amdo meteorological station (1980–2015). About 94% of precipitation falls during the lake ice-free period (May–October; Figure 2). The glacier coverage of Cona Lake Basin is ~0.2% during the ice-free period.

1.2 | Samples collection and analysis

Precipitation samples were collected on the west bank of Cona Lake (32°04′ N, 91°24′ E, 4,623 m a.s.l, Figure 1) using an evaporation-preventing collector. The collector has a "V-shape" tube in inlet to prevent water re-evaporation and a 1 m long internal tube for pressure equilibration, modified slightly from the design of Groning et al. (2012). Samples were collected at 20:00 hr (Beijing time) in each rainy day, sealed in 15 ml polyethylene terephthalate bottles, and wrapped with parafilm to avoid evaporation. Snow samples were collected and melted thoroughly at room temperature in plastic bags, then transferred to polyethylene terephthalate bottles. One hundred sixty-two daily precipitation samples were collected between 2011 and 2013. Weekly water samples at surface and 20 cm depth were taken 1 m from the shoreline using a clean plastic bottle. A sampling location on the steep west bank was selected for ease of access and to avoid potential for incomplete mixing related to surface stream inlets. The isotopic composition of surface lake water in this study was found to be consistent with that of outlet water and central lake water, indicating that the west bank location was fairly representative of lake-average isotopic composition under well-mixed conditions (Cui et al., 2017). In total, there were 110 surface lake samples collected on the west bank from June 2011 to December 2013.

All liquid samples were stored frozen before analysis and transported frozen to the Key Laboratory of Tibetan Environment Changes and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences. Samples were then completely melted prior to analysis for both $\delta^{18}O$ and δ^2H using a Picarro L2130-i analyser (Picarro Inc., Sunnyvale, CA, USA) with a precision of 0.05‰ ($\delta^{18}O$) and 0.4‰ (δ^2H). Isotopic ratios are expressed in per mil (‰) relative to Vienna Standard Mean Ocean Water.

Atmospheric water vapour isotopes were measured at Amdo station (Figure 1) and Nagqu station (70 km in southeast) using a high-frequency (1 Hz) Picarro L2130-i analyser, together with a standard delivery module and a vaporizer module for both $\delta^{18}O$ and δ^2H. Measured isotopic values were corrected for humidity dependence and instrument drift before calibrating to Vienna Standard Mean Ocean Water, following Steen-Larsen et al. (2013) and Cui et al. (2017). The precision of vapour measurements was estimated to be 0.2‰ for $\delta^{18}O$ and 0.5‰ for δ^2H in vapour isotope measurement.

Relative humidity and evaporation flux were recorded by an automatic weather station and evaporation pan at Amdo station. A HOBO RG3-M data logger on the west bank was used to monitor air temperature and precipitation. Lake water temperature was recorded at 30-min intervals using Onset HOBO water-level data loggers installed separately along the west bank and at the outlet.

We also collected published data on lake water isotopes. The following criteria were used for data selection in our synthesis: (a) at least one tracer out of $\delta^{18}O$ and δ^2H was measured; (b) at least one whole year of sampling was carried out; (c) monthly or higher sampling frequency was employed; and (d) pronounced seasonal variations (or amplitude) of lake water isotope were detected. Although many lake water isotope studies have been conducted worldwide, high-frequency and long-term sampling programmes have been few. Twelve data sets met these criteria and so were employed in this synthesis. Based on the seasonal variations of lake water isotopes, we determined the optimal sampling month by matching the weekly or monthly isotope values to the annual mean value. Where available, E/I was included to evaluate the bias potentially introduced due to noncharacterization of isotopic seasonality. Ancillary information including location, area, and sampling information was also recorded. We extracted $\delta^{18}O$, δ^2H, and E/I values directly from tables or text in original papers or indirectly from figures.

Precipitation seasonality and air temperature seasonality from WorldClim Version 2 (http://worldclim.org/bioclim) were used to map the global distribution of climatic seasonality. The data set is gridded climate data with a spatial resolution of 10 min (~18 km). Precipitation seasonality was calculated from coefficient of variation of monthly precipitation amounts (1970–2000). The grids with high values indicated strong precipitation seasonality, whereas low values suggested weak seasonality. Air temperature seasonality was calculated from standard deviation of monthly air temperature (1970–2000). Isotherms were extracted from the original gridded map to divide globe into zones with different intensities of air temperature seasonality.

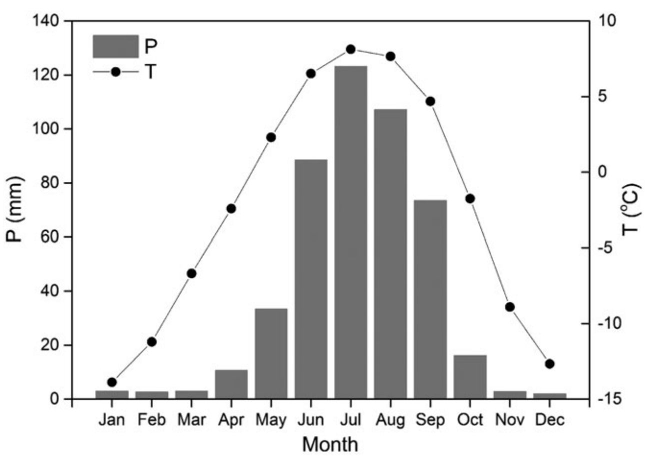

FIGURE 2 Monthly precipitation (P) and air temperature (T) from 1980 to 2015 at the Amdo station

2 | METHODS

$\delta^{18}O$ and δ^2H were separately used to constrain the lake water balance of Cona Lake. Based on the isotope and water mass balance, the E/I ratio can be determined as (Gibson & Edwards, 2002; Skrzypek et al., 2015)

$$\frac{E}{I} = \frac{\delta_I - \delta_L}{\delta_E - \delta_L}, \tag{1}$$

where I is inflow to the lake including precipitation, surface runoff, and subsurface inflow; E is lake surface evaporation; δ_L, δ_I, and δ_E are the stable isotope compositions ($\delta^{18}O$ or δ^2H) of lake water, inflow, and the evaporation flux from the lake surface, respectively. δ_E was calculated by the Craig–Gordon model (Craig & Gordon, 1965; Gibson, Birks & Yi, 2016):

$$\delta_E = \frac{(\delta_L - \varepsilon^+)/\alpha^+ - h\delta_A - \varepsilon_K}{1 - h + 10^{-3}\varepsilon_K}, \quad (2)$$

where α^+ (>1) is the equilibrium liquid–vapour isotope fractionation factor and is a function of temperature (Horita & Wesolowski, 1994); $\varepsilon^+ = (\alpha^+ - 1) \times 10^3$ is the equilibrium enrichment factor; ε_K is the kinetic enrichment factor; h is the relative humidity of ambient air normalized to the saturation vapour pressure at the temperature of the water surface; and δ_A is the isotopic composition of ambient atmospheric moisture. ε_K is calculated by the following:

$$\varepsilon_K = C_K(1 - h). \quad (3)$$

C_K was 14.2‰ for oxygen (Gonfiantini, 1986). For hydrogen, we used the ε_K–h relationship presented in Zuber (1983) to calculate ε_K, which produced a better match between E/I from $\delta^{18}O$ and δD than the ε_K–h relationship in Gonfiantini (1986) in regions with low humidity. The ε_K–h relationship of Zuber (1983) has been successfully used in previous studies (Biggs et al., 2015; Cui et al., 2017). Temperature, h, and δ_A were weighted by monthly evaporation flux according to Gibson, Birks, and Edwards (2008). The isotopic compositions of lake inflow were represented by precipitation isotopes as the consistent isotopic values of precipitation, surface water inlets, and groundwater in this area (Cui et al., 2017).

To evaluate the influence of sampling season and to determine the optimum month to sample across the Tibetan Plateau, weekly lake water isotopes were assumed as model input of δ_L. E/I ratios for each week were calculated and compared with the mean E/I value of each year. Based on synthesized isotopic data and E/I, optimal sampling dates were determined in different regions over the world.

3 | RESULTS

3.1 | Seasonality of water isotopes in Cona Lake

The Tibetan Plateau is mainly influenced by two large-scale atmospheric circulation systems: Indian monsoon in summer (June–September) and westerlies in winter (October–May; Tian et al., 2007; Yao et al., 2013). Precipitation isotopes in summer were conspicuously lower than in other seasons (Figure 3). Due to the influence of intense precipitation and isotopically depleted inflow in the summer monsoon season (Tian et al., 2002), lake water isotopes decreased in summer. According to the measurement, the average isotopic composition of Cona Lake water was −9.7‰ for $\delta^{18}O$ and −85.1‰ for δ^2H during the 3 years. Minimum values for lake water $\delta^{18}O$ and δ^2H were −10.7‰ and −91.8‰, respectively. Lake water isotopes were significantly enriched relative to the amount-weighted isotopic composition of concurrent precipitation in the area of −15.2‰ for $\delta^{18}O$ and −110.8‰ for δ^2H, indicating the influence of lake-surface evaporation. Evaporation can also be inferred from the deviation of lake water isotopes from local meteoric water line (please see Figure S1). Seasonally, lake water isotopes were stable in winter, but slightly larger fluctuations were measured in summer. In 2013, the fluctuations of lake water isotopes clearly follow the variations of precipitation isotopes, but this effect is reduced for 2011 and much weaker in 2012. This may be due to distinct precipitation amounts and intensities of the 3 years. Precipitation was greatest in 2013 (542 mm) with the strongest intensity, whereas amount and intensity were lower for 2011 (529 mm) and 2012 (403 mm; Figure 3). Consequently, the transient variability of lake water isotopic compositions in summer likely biases estimates of E/I ratio if isotopic results in this period are used in the lake water balance estimation.

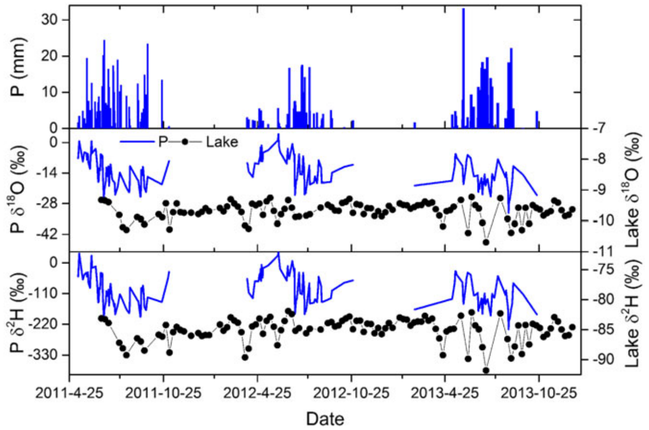

FIGURE 3 Daily precipitation amount (blue columns), precipitation $\delta^{18}O$ and δ^2H (blue lines), and weekly Cona Lake water $\delta^{18}O$ and δ^2H (solid dots) from 2011 to 2013

3.2 | Influence of seasonality of water isotopes on lake water balance evaluation

The distinct isotopic signals of δ_L, δ_I, and δ_E make it feasible to use Equation 1 to calculate the E/I ratios for each specific week during the 3 years based on the observed lake water isotopes. Figure 4 presents the calculated E/I as a comparison with the estimated annual mean E/I values (dashed lines). Annual mean E/I calculated from both $\delta^{18}O$ and δ^2H in the 3 years were 0.23, 0.25, and 0.27, close to the results from deuterium excess-based estimation (Cui et al., 2017). $\delta^{18}O$- and δ^2H-based E/I were very similar with a mean difference of 0.01. E/I calculated from summer sampling events was clearly lower than annual mean E/I. The maximum bias was more than 0.07, larger than the interannual variability of E/I from 2011 to 2013. Given that an earlier study showed that E/I signal across the Tibetan Plateau ranged between 0.38 and 0.65 (±1 standard deviation; Yuan et al., 2011), the E/I noise induced by seasonality as calculated here (−0.07–0.04) may potentially mask about half of the E/I signal in this region. No clear bias was found for the summer of 2012, probably due to reduced precipitation in this dry year. As illustrated in a histogram (Figure 5), we find that E/I values fell close to annual mean values in the majority of cases, whereas large E/I anomalies were accompanied by a high percentage of summer precipitation (6–9 months), implying the use of isotope data collected in the summer rainy season most likely introduce a poorer representation of mean lake conditions. In contrast, E/I evaluated for winter periods was typically more stable with smaller anomalies. The slightly higher E/I values in winter may be related to prewinter evaporation and reduction in isotopically depleted

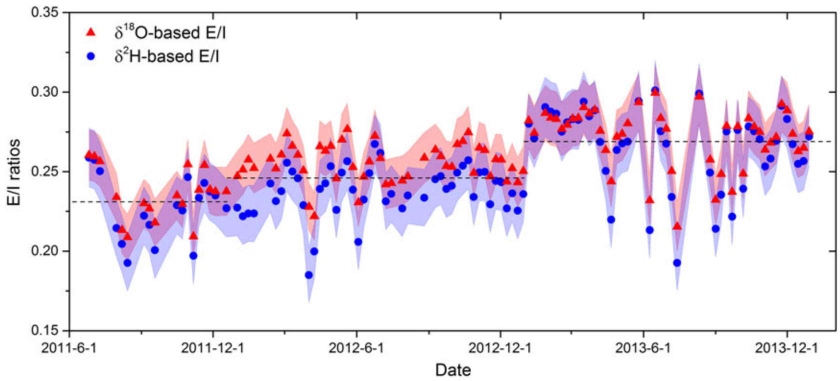

FIGURE 4 Evaporation/inflow (E/I) ratios calculated using weekly lake water isotopes as input. The dot lines represent annual mean E/I values calculated from both $\delta^{18}O$ and δ^2H. Shaded area represents E/I uncertainties induced by uncertainties of input parameters

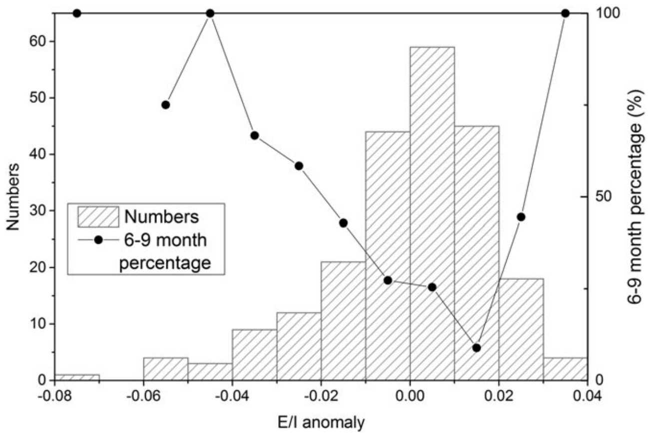

FIGURE 5 Histogram of weekly evaporation/inflow (E/I) anomalies with respect to annual mean E/I value from 2011 to 2013 (columns) and E/I percentage between 6 and 9 months (dots). Both $\delta^{18}O$- and δ^2H-based E/I are included

inflow. Nevertheless, in winter, lakes are usually covered by thick ice and are significantly more difficult to sample within the context of a regional survey. Sampling in late autumn, such as in October, is therefore likely the most representative of average lake conditions and can be a more appropriate time to conduct regional surveys.

Outside of the Tibetan Plateau, lake water isotope data reported from other regions also showed variability due to the seasonal pattern of precipitation, glacial and/or snow meltwater, and/or seasonal evaporative enrichment. The synthesized data are summarized in Table 1. Both lake water isotopes and E/I showed significant variations in seasonal climates. Lake water isotopes departed from mean values from −7.2 to 3.6 for $\delta^{18}O$ ($\Delta\delta^{18}O$_Max) and −37.6 to 19.0 for δ^2H ($\Delta\delta^2H$_Max), whereas E/I departed from mean values from −0.07 to 0.64 (ΔE/I_Max). This level of noise potentially masks a great part of the spatial signal of lake water isotopes and E/I from the regional to global scales (Brock et al., 2009; Brooks et al., 2014; Gibson, Birks, Yi, Moncur & McEachern, 2016; Wolfe et al., 2007; Yuan et al., 2011). To reduce introduction of noise, we propose optimal sampling periods for each region based on the seasonality of the water isotopes.

3.3 | Optimal sampling date across the world

Figure 6 summarizes various climatic information and calculated optimal sampling date in different regions across the world. Climatic seasonality was indicated by air temperature seasonality (lines) and precipitation seasonality (shadows). It was found that all lakes with high seasonality of water isotopes are located in climates with high precipitation or air temperature seasonality. Obviously, the optimal sampling date is different across the globe, indicating the influence of distinct climatic or hydrological regimes. However, optimal sampling date is consistent within specific regions. For example, we suggest that October is optimal on the Tibetan Plateau and closer to July/August within the selected regions of North America. Hence, the determination of optimal sampling date of a representative lake is expected to be a useful guide for planning large-scale isotopic surveys in specific regions.

4 | DISCUSSION

4.1 | Factors driving seasonality of lake water isotopes

Seasonality in climatic parameters such as precipitation and air temperature is a common character of continental climates and cold regions (Figure 6). The seasonal signals transmit to lake inflow and also the isotopic composition of inflow, driving the variations of lake water isotopes. Volume of the reservoir is also a primary factor controlling the magnitude of seasonal fluctuations. Seasonality of water isotopes in Cona Lake as described in this study was mainly controlled by precipitation amount and isotopic composition of precipitation in summer (Figure 3), which was similar in this respect to Lochnagar Lake in Scotland (Tyler et al., 2007). Although seasonal snowmelt and glacial meltwater can be major drivers of seasonal variations in lake isotopic composition, this was not significant for Cona Lake due to minimal glacier coverage in this area (~0.2%). Glacier meltwater is likely important in other regions (Brock et al., 2009; Shi et al., 2014).

Some lakes located in seasonal climates showed a weak seasonality (or amplitude) of lake water isotopes, such as Potrok Aike and Laguna Azul Lake in Argentina (Mayr et al., 2007), Bangong Co Lake in the western Tibetan Plateau (Wen, Tian, Liu, & Qu, 2016), and Garda Lake in Italy (Longinelli et al., 2008), implying a significant influence of other factors such as residence time of water in the lakes and degree of reliance on groundwater sources. It is well known that groundwater and lake water can actively interact in a range of settings, including subtropical (Sacks et al., 2014) and subpolar lakes (Isokangas, Rozanski, Rossi, Ronkanen, & Kløve, 2015). The isotopic composition of river

TABLE 1 Water isotopes, E/I, and sampling information of selected lakes for optimal sampling date determination

Lake	Location	Area (km^2)	$\delta^{18}O$ mean (‰)	$\Delta\delta^{18}O$_Max (‰)	δ^2H mean (‰)	$\Delta\delta^2H$_Max (‰)	E/I mean	ΔE/I_Max	Sampling frequency	Period	Data source
Pocket	Yellowknife, Canada	0.05	−11.3	−2.2	−119.1	10.8	1.25	0.64	Biweekly to monthly	1997–2008	Gibson and Reid (2010)
Lochnagar	Lochnagar, UK	0.1	−9	−1.2	−59.6	−8	/	/	Biweekly	2000–2005	Tyler et al. (2007)
Clifton Pond	Nottingham, UK	0.19	−2.4	−1.8	−24.1	−9.8	0.28	0.26	Monthly	2005–2009	Jones et al. (2016)
Sandy	Salmita, Canada	1.2	−16.2	−2	−143.5	−20	0.26	/	Weekly to monthly	1991–2010	Gibson and Reid (2014)
Ihotry	SW Madagascar	68–115	1.2	−7.2	−1.2	−37.6	/	/	Weekly to monthly	1995–1997	Vallet-Coulomb et al. (2017)
Cona	Tibet, China	190	−9.7	−1	−85.5	−6.3	0.25	−0.07	Weekly	2011–2013	This study
Pyramid	Nevada, USA	490	−0.7	−1	/	/	/	/	Monthly	1985–1992	Benson (1994)
Yamdruk-tso	Tibet, China	621	−5.9	−3.2	/	/	/	/	Weekly	2003–2004	Tian et al. (2008)
Taihu	Jiangsu, China	2,400	−4.8	−1.7	−35	−13.4	0.15	0.2	Daily and quarterly	2012–2014	Xiao et al. (2016)
Qinghai	Qinghai, China	4,264	0.8	−3.8	1.1	−22	0.33	/	Biweekly	2009–2012	Wu et al. (2015)
Great Salt	Utah, USA	4,400	−6.9	−2	−65.3	−18.6	/	/	Biweekly	2006	Nielson and Bowen (2010)
Chad	Chad	26,200	8.2	3.6	45	19	0.82	0.18	Monthly	1968–1970	Bouchez et al. (2016)

Note. $\Delta\delta^{18}O$_Max, $\Delta\delta^2H$_Max, and ΔE/I_Max are maximum seasonal disparities of $\delta^{18}O$, δ^2H, and E/I relative to the mean values, respectively.

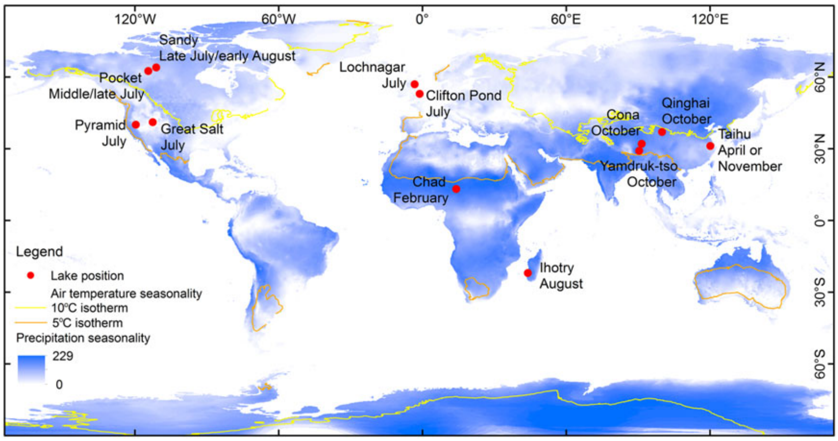

FIGURE 6 Positions for lakes with pronounced seasonal variations in water isotopes and the corresponding determined optimal sampling date. Isotherms represent air temperature seasonality. Blue shadows represent precipitation seasonality. Isotherms with higher value indicate stronger air temperature seasonality, whereas darker colours indicate stronger precipitation seasonality

water (Shi et al., 2014) and permafrost (Yang, Wu, Yun, Jin, & Zhang, 2016) may also exert an influence on isotopic variations in lake water. We acknowledge that a complete characterization of hydrological controls on lake water balance is essential for full understanding and prediction of isotopic variations (Jones et al., 2016; Steinman, Rosenmeier, Abbott, & Bain, 2010). However, our analysis is useful for identifying potential bias due to use of discrete surveys and offers optimal sampling dates in different regions by using limited lake water isotopes. Lake morphology may also have an effect on the seasonal variations of lake water isotopes. Large and deep lakes with longer residence times such as the Laurentian Great Lakes (Jasechko, Gibson, & Edwards, 2014) may have weak seasonal cycles, in which case sampling date may not be as important. We expect small, shallow lakes with shorter residence times to be more susceptible to shorter-term variability of water balance parameters (Brooks et al., 2014; Jonsson, Leng, Rosqvist, Seibert, & Arrowsmith, 2009). In regions with a range of lake sizes, careful attention needs to be given to lake-to-lake comparisons as the isotopic signals may reflect different time domains. Comparing long-term isotope values and E/I in this situation seems to be the most conservative approach for determining regional variability in water balance. An essential caveat of our evaluation is that it does not account for site-specific influences. Lakes may be out of hydrological synchronicity with one another in nearby areas due to differences in lake area/watershed area ratios, volume, or ice cover duration, inflow lag due to elevation gradients, differential groundwater connectivity, localized melting of permafrost, autochthonous water inputs, or regulatory influences as well as other factors.

4.2 | Optimal sampling date and its implications

The seasonal variations of lake water isotopes were pronounced in highly seasonal climates, including the Tibetan Plateau and many other regions around the globe (Table 1 and Figure 6). The calculated dates for optimal sampling of Cona Lake were interannually consistent and also consistent with results from other lakes such as Yamdruk-tso Lake and Qinghai Lake located on the Tibetan Plateau (Figure 6). Our calculated time-window for sampling is also consistent with previous evaluations, such as that of Gibson and Reid (2014), who discussed uncertainties related to lake sampling date as part of short-term sampling campaigns.

The results from Cona Lake and our data synthesis both show that noise induced by seasonality of lake water isotopes can mask a large part of the spatial E/I signal, biasing the evaluation of lake water balance (Table 1). For example, if the lake isotopic survey was conducted in the summer rainy season on the Tibetan Plateau, lake water isotopes would typically be more depleted than mean annual values and thus would significantly underestimate E/I. The optimal sampling date in this study has significant implications for lake water balance evaluation in short-term lake isotopic surveys (Brock et al., 2009; Brooks et al., 2014; Gibson et al., 2017; Gibson & Edwards, 2002; Henderson & Shuman, 2009; Kebede, Travi, & Rozanski, 2009; Wolfe et al., 2007; Yuan et al., 2011). Similarly, Gibson et al. (2008) found that it was necessary to account for the seasonality of climate to accurately predict δ_A and evaporation slopes of lakes and soil water in cold regions. In addition, the optimal sampling date calculated in this study was also useful for studies of other water pools, such as river water. Careful determination of optimal sampling date has also been shown to be important for large-scale river water isotopic surveys in seasonal climates (Li & Garzione, 2017), which was consistent with the date calculated in this study.

It is important to note that no lakes fitted our preselection criteria in North Asia and Australia. Although long-term lake water isotope measurements have been made in Argentina (Mayr et al., 2007), the amplitude of lake water isotopes was small and thus appeared to be potentially less influential on isotope balance determinations. Given the clear spatial heterogeneity, caution should be taken if results are extrapolated to other regions. Higher sampling frequency, such as weekly in this study and daily in Xiao et al. (2016), is expected to significantly improve the evaluation of optimal sampling dates.

5 | CONCLUSION

A 3-year lake water isotope data set was used in an effort to evaluate the influence of one-time or short-term sampling on lake water balance estimations in regions with high climate seasonality. Our finding is that the isotopic surveys conducted in the rainy season on the Tibetan Plateau significantly underestimated E/I of a typical lake. In terms of representativeness and logistical considerations, October is suggested as the optimal period to sample lake water regionally on the Tibetan Plateau. Based on similar data compiled for other regions, optimal sampling periods were evaluated for selected regions around the globe. We emphasize that determining the optimal sampling period prior to conducting large-scale regional surveys may be a useful guideline for field work in remote areas but essentially requires that lakes across the region are morphologically similar and driven by the same basic hydrological processes that may vary in relative magnitude due to climatic gradients.

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