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Characterizing the Qinghai Lake watershed using oxygen-18 and deuterium stable isotopes

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ABSTRACT

Isotope mass balance models have been widely applied for assessing the water balance of closed and open lake systems in remote regions with sparse monitoring gauges. The role of evaporation in determining the water balance of Qinghai Lake has been unclear in recent decades, when the lake level has continued to rise. In the current study, stable water isotopes ($\delta^{18}O$ and δ^2H) from precipitation, river water, and lake water were investigated and used to model the evaporation:inflow (E/I) ratio of Qinghai Lake between 2013 and 2014. The results revealed that the relationship between $\delta^{18}O$ and δ^2H in lake water ($\delta^2H = 4.58\delta^{18}O - 1.4$, $R^2 = 0.836$) differed from that in precipitation ($\delta^2H = 8.17\delta^{18}O + 16.2$, $R^2 = 0.967$). The $\delta^{18}O$ and δ^2H values in lake water with low mean deuterium excess values ($-7.23‰ \pm 0.34‰$) were more positive than those in precipitation and river water, implying that lake water had experienced stronger isotopic enrichment. Quantitative analysis using an isotope mass balance model showed that mean E/I ranged from 0.57 to 1.04 in Qinghai Lake during the study period. The interannual variability of E/I was mainly related to the changes in inflow water and isotopic compositions in atmospheric vapor. The changes in E/I indicated that both inflow and runoff have dominated the water balance of Qinghai Lake in recent years, partly explaining the recent increase in water level in the lake and the resulting expansion in its surface area. These results facilitate a better understanding of the current and future status of the water balance of lakes on the Tibetan Plateau and regional hydrological processes based on limited instrumental observations.

Introduction

Lakes are widely distributed over the Tibetan Plateau (TP) and interact closely with water storage components including melt water, rivers, and groundwater, that act as their main recharge sources. However, the roles of these lakes in the regional water cycle are not clearly understood. TP has experienced rapid warming that has resulting in a series of hydrological, environmental and ecological changes, including changes in lake water balances. Recently published reports revealed that lakes on the TP have substantially expanded as a result of recent climate change, but so far there is no clear consensus on the mechanisms driving these responses. Hence, there is a real need to understand the water balance in lake systems on the TP for quantifying regional hydrological cycles. However, conventional hydrological and meteorological observations on the TP are sparse because of its remoteness and harsh environment, which constrains the systematic and extensive evaluation of the water balance in lakes on the plateau.

Stable water isotopes ($\delta^{18}O$ and δ^2H) can provide information about both the current and hisotrical climate (Jonsson et al., 2010; Leng and Marshall, 2004; Schoell-Barna, 2011; Yuan et al., 2011) and hydrological cycles (e.g., moisture source and recycling) (Friedman et al., 2002; Shi et al., 2014; Tian et al., 2008), and can also be used to determine water balances of lakes (Turner et al., 2010; Wolfe et al., 2007). The evaporation:inflow ratio of a lake (E/I) is a key indicator that can be used to evaluate the water balance for open or closed water bodies via the water isotopic approach; E/I has been applied widely to study lake evaporation in different geographical and climatic scenarios (Biggs et al., 2015; Brock et al., 2009; Gibson and Reid, 2014). The evaporation from lakes in low-altitude regions shows wide variations attributable to the influence of groundwater, lake morphemetry and catchment vegetation (Brock et al., 2009; Isokangas et al., 2015; Turner et al., 2010). At the high altitudes, many lakes exhibit patterns of evaporation that are unique to particular climatic and hydrological regimes (Gibson and Reid, 2014;

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Shi et al., 2014). For example, lake water can become isotopically enriched, and this can be detected based on meteorological parameters and the isotopic composition of input water (e.g., surface and subsurface flow) (Yuan et al., 2011). On the southern TP, isotopes in lake water differed in a closed lake and a through-flow lake despite similar climatic conditions (Shi et al., 2014). Hence, it is not possible to make generalizations regarding the water balance in lakes on the TP. In addition, E/I can potentially vary with lake hydrological processes and the watershed landscape; for example, the evaporation-dominated lakes have high E/I compared with flood-dominated and through-flow lakes on floodplain deltas (Turner et al., 2010; Wolfe et al., 2007), and even adjacent lakes with distinct E/I have been reported on the TP (Yuan et al., 2011). These variations highlight the complex hydrological regime that occurs in high-elevation regions and, thus, the need for site-specific research.

Qinghai Lake is a large, intermontane, hydrologically closed watershed on the northeastern TP, and is important for ecological integrity of the entire northeast region. In recent years, almost half of the rivers flowing into the lake have dried up as a result of climate change and anthropogenic disturbances (Li et al., 2007), and the lake water level decreased from 3196.55 m (in 1959) to 3194.97 m (in 2004) (Fig. 1). Drawdowns of water from the lake have resulted in a series of ecological-environmental problems such as desertification, erosion, loss of grasslands, and deterioration of water quality and quantity (Chen et al., 2008; Qin and Huang, 1998). Curiously, the water level in the lake steadily increased from 3192.97 m (in 2004) to 3194.08 m (in 2012), with an annual increase of 13.9 cm within eight years (Hao, 2008; Jin et al., 2013). These changes of water level largely depend on climate change and the water balance (Jin et al., 2013; Qin and Huang, 1998). Previous studies using conventional techniques (e.g., meteorological and hydrological observation) demonstrated that evaporation was an important deciding factor of the water balance of Qinghai Lake, based on 2000-year-old hydrometric and climatic data (Li et al., 2007; Qin and Huang, 1998). However, it is still challenging to assess the recent water balance of Qinghai Lake because of a reduction in the continuous monitoring observations (Chen et al., 2008). These insufficient records could result in increasing uncertainty in understanding and predicting the relationships between hydrologic budget and water level, and the potential causes of changes in the most recent years. Given the likelihood of significant changes in the hydrology of Qinghai Lake because of climate change, it is imperative to assess the water balance of the lake and to identify reasons for the changes in lake level.

The current study aimed to characterize stable water isotopes in precipitation, river water entering Qinghai Lake, as well as in the lake water itself, in 2013 and 2014, and to evaluate the roles of evaporation and inflow in the annual water balance of Qinghai Lake. These results may provide the basis for explaining the change in water level in Qinghai Lake, and for understanding the current and future status of the lake water balance and regional hydrological processes.

Materials and methods

Study site description

Qinghai Lake, the largest inland closed lake in China (99°36′—100°47′E, 36°32′—37°15′N; 3194 m; Fig. 2), is situated in a cold, high-altitude climate zone dominated by the East Asian monsoon, with moisture derived mainly from the low-altitude oceans, the cold, dry polar airflow from the Siberian high-pressure system and the westerly jet stream. The annual mean temperature of the drainage basin is 0.1 °C, and the mean annual precipitation is approximately 400 mm with more than 65% falling between June and September (An et al., 2012). The mean annual evaporation is approximately 1300 mm, and this occurs mainly during the warmer summer season. Throughout November to March, the lake surface is often frozen, with a maximum ice thickness of 0.8 m. The lake has no visible surface flow and any output is primarily controlled by evaporation loss, which has resulted in a Na^+—Mg^{2+}—SO_4^{2-}—Cl^- type water with a mean salinity of 14.1 g/L and a pH range of 9.1–9.4 (Lister et al., 1991; Zhang et al., 1989).

The lake has a surface area of approximately 4264 km^2 (in 2005), within a catchment area of 29,699 km^2. Approximately 40 rivers flow into the lake, accounting for 46% of the total lake input volume. River Buha, the longest and largest river in the watershed, drains an area of 14,337 km^2, accounting for approximately half of the total runoff volume. By contrast, River Shaliu is the second largest river flowing into the lake, but only drains an area of 1442 km^2 (Henderson et al., 2010; Li et al., 2007).

Isotope mass balance model based on $\delta^{18}O$ and δ^2H in natural waters

Stable isotope compositions were used to analyze the water balance (E/I) for Qinghai Lake. The method was derived from the water mass balance and isotope mass balance according to the equations from Gibson and Edwards (2002) and Gonfiantini (1986). The E/I can be expressed using the isotopic compositions of each water budget component as follows (Eq. (1)):

$$\frac{E}{I} = \left[\frac{\delta_L - \delta_I}{(\delta^* - \delta_L)^* m}\right] \tag{1}$$

where δ_L and δ_I represent the isotopic compositions in the lake and in water flowing into the lake, respectively. δ_I is considered to the weighted average isotopic composition of both precipitation and runoff water, and is estimated by the intersection of LMWL (local meteoric water line) with LEL (local evaporation line) (Gibson and Edwards, 2002). m represents the isotopic enrichment slope determined by the relative humidity and total isotope fractionation factor ($\varepsilon = \varepsilon^*/\alpha^* + \varepsilon_k$) (Eq. (2)). The equilibrium (ε^*) fractionation separation is defined as $\varepsilon^* = (\alpha^* - 1) * 1000$. The equilibrium ($\alpha^*$) fractionation factors

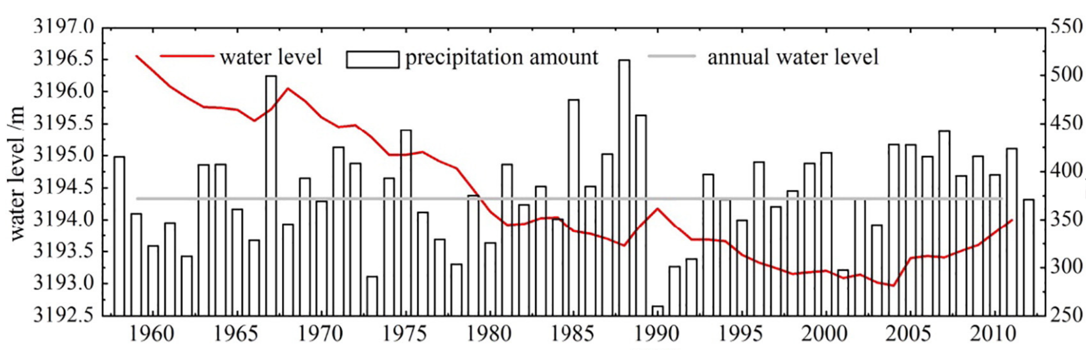

Fig. 1. Variations in lake water level and annual precipitation amount from 1959 to 2012 in Qinghai Lake.

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