Quaternary Science Reviews 177 (2017) 340–356

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Mid- to late Holocene climate-driven regime shifts inferred from diatom, ostracod and stable isotope records from Lake Son Kol (Central Tian Shan, Kyrgyzstan)

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A R T I C L E I N F O

Article history:
Received 28 June 2017
Received in revised form
20 September 2017
Accepted 7 October 2017

Keywords:
Holocene
Central Asia
Stable oxygen and carbon isotopes
Diatoms
Ostracods
Conductivity reconstruction
Regime shift
Seasonality

A B S T R A C T

Arid Central Asia represents a key region for understanding climate variability and interactions in the Northern Hemisphere. Patterns and mechanisms of Holocene climate change in arid Central Asia are, however, only partially understood. Multi-proxy data combining diatom, ostracod, sedimentological, geochemical and stable isotope analyses from a ca. 6000-year-old lake sediment core from Son Kol (Central Kyrgyzstan) show distinct and repeated changes in species assemblages. Diatom- and ostracod-inferred conductivity shifts between meso-euhaline and freshwater conditions suggest water balance and regime shifts. Organism-derived data are corroborated by stable isotope, mineralogical and geochemical records, underlining that Son Kol was affected by strong lake level fluctuations of several meters. The $\delta^{13}C_{carb}/\delta^{18}O_{carb}$ correlation shows repeated switchovers from a closed to an open lake system. From 6000 to 3800 and 3250 to 1950 cal. yr BP, Son Kol was a closed basin lake with higher conductivities, increased nutrient availability and a water level located below the modern outflow. Son Kol became again a hydrologically open lake at 3800 and 1950 cal. yr BP. Comparisons to other local and regional paleoclimate records indicate that these regime shifts were largely controlled by changing intensity and position of the Westerlies and the Siberian Anticyclone that triggered changes in the amount of winter precipitation. A strong influence of the Westerlies ca. 5000–4400, 3800–3250 and since 1950 cal. yr BP enhanced the amount of precipitation during spring, autumn and winter, whereas cold and dry winters prevailed during phases with a strong Siberian Anticyclone and southward shifted Westerlies at ca. 6000–5000, 4400–3800 and 3250–1950 cal. yr BP. Similarities between variations in winter precipitation at Son Kol and records of the predominant NAO-mode further suggest a tele-connection between wet (dry) winter climate in Central Asia and a positive (negative) NAO-mode. Thus, this study identifies climate fluctuations as the main driver for hydrological regime shifts in Son Kol controlling physicochemical conditions and consequently causing abrupt species assemblage changes. This emphasizes the importance of multi-proxy approaches to identify triggers, thresholds and cascades of aquatic ecosystem transformations.

1. Introduction

Regime shifts in lake ecosystems are characterized by abrupt and persistent responses to changes in catchment area, hydrology, anthropogenic influence and climate (Lees et al., 2006; Andersen

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https://doi.org/10.1016/j.quascirev.2017.10.009

et al., 2009; Randsalu-Wendrup et al., 2014, 2016). Paleoecological methods applied to lake sediments have successfully been used to detect such regime shifts (Laird et al., 2003; Smol et al., 2005; Reuss et al., 2010; Cartier et al., 2015). Especially multi-proxy approaches are effective to identify early warning signals and triggers of aquatic ecosystem transformation as well as potential impacts of future environmental change (Battarbee, 2000; Reuss et al., 2010; Randsalu-Wendrup et al., 2012; Wang et al., 2012). Aquatic microfossils, especially diatoms and ostracods, are generally well preserved in the sedimentary archive and are among the best and most frequently used indicators of past and present environmental and climatic changes (Battarbee, 2000; Battarbee et al., 2001; Holmes, 2001; Pérez et al., 2013).

Climate, one of the main drivers of regime shifts, may shift abruptly and cause changes in species composition of aquatic biota after internal ecosystem thresholds are crossed (Randsalu-Wendrup et al., 2016). For example, air temperature, wind speed and solar radiation directly affect the lake's physical conditions and influence vertical mixing and stratification, duration of the growing season as well as potential ice cover, and thus, indirectly light and nutrient availability for diatoms (Gerten and Adrian, 2002; Adrian et al., 2009; Dreβler et al., 2011; Rühland et al., 2015). Ostracods react sensitively to fluctuations in water temperature, salinity, nutrient supply, water depth and therefore oxygen availability, which might be caused by changes in air temperature, precipitation and evaporation (Horne, 2007; Lord et al., 2012).

Arid Central Asia (ACA) represents a key region for understanding climate change in the Northern Hemisphere, as it is located at the intercept between the influences of the mid-latitude Westerlies, the Siberian Anticyclone and partially also the Asian monsoon system (Aizen et al., 2001; Cheng et al., 2012). Small changes in these systems thus might have relatively large consequences for regional precipitation and temperature patterns. In addition, the high-altitude ecosystems of the Tian Shan and the Tibetan Plateau are particularly sensitive to climate change. There, the current warming trend potentially has severe impact on permafrost and glaciers (Cheng and Wu, 2007; Zhang and Wu, 2012) and related effects (e.g. groundwater lowering, soil destabilization, changing amount and seasonality of precipitation) will most probably result in shifts of the hydrological regime of rivers and lakes (Aizen et al., 1997). The patterns and mechanisms of climate change in ACA are, however, only partially known so far. Uncertainties in hydrological conditions and thresholds of local ecosystems, in sensitivity and specificity of proxy parameters and in the chronology of paleorecords hamper the clear identification of past climatic and environmental changes (Battarbee, 2000; Laird et al., 2003; Lauterbach et al., 2014; Chen et al., 2016), making data comparison and synthesis difficult. Past climate development in ACA apparently differed from that in southern and eastern Asia due to different dominating atmospheric circulation systems (Herzschuh, 2006; Chen et al., 2008; Aichner et al., 2015; Stebich et al., 2015), but also within ACA, Holocene climate development seems to have differed regionally (Rudaya et al., 2009; Aichner et al., 2015; Lu et al., 2015). Further paleoclimate records are thus needed to provide information about moisture sources, precipitation amount and temperature to understand the spatial and temporal patterns of climate dynamics in ACA during the Holocene, which are apparently influenced by climatic teleconnections to the North Atlantic (Chen et al., 2008, 2010; Aichner et al., 2015; Feng et al., 2017).

Previous paleoclimate records from ACA based on diatom and ostracod used species compositions to reconstruct trophic status, productivity, lake level fluctuations, surface runoff and wind conditions in connection with temperature and moisture variability (Mischke and Wünnemann, 2006; Prokopenko et al., 2007; Rudaya et al., 2009; Mischke and Zhang, 2011; Watanabe et al., 2012; Felauer et al., 2012; Chiba et al., 2016). In contrast, quantitative conductivity records from arid Central Asia are still scarce (Shinneman et al., 2010; Rioual et al., 2013), although such quantitative salinity or conductivity reconstructions would strengthen the paleoclimate interpretation based on species composition and help to assess the extent of climate change effects by providing the key to detect climate-driven water balance changes (Mischke et al., 2010; Reed et al., 2012). The aim of the present study is to (1) detect diatom and ostracod assemblage shifts and their potential drivers in the Kyrgyz lake Son Kol (also transcribed Son Kul, Sonkul or Song-Kul) during the last 6000 years, (2) quantify conductivity shifts by applying a combination of diatom- and ostracod-based transfer functions and (3) contribute to a better understanding of Holocene climate development and associated ecosystem changes in Central Asia. By evaluating the organism-based salinity data against stable isotope records of hydrological system shifts, we double-check information on inferred water-budget changes. By comparison with other proxy data from Son Kol (Huang et al., 2014; Lauterbach et al., 2014; Mathis et al., 2014; Pacton et al., 2015), we further aim at inferring information on precipitation seasonality changes. Due to the high spatial heterogeneity of precipitation seasonality in arid Central Asia, such information will provide important insights into Holocene moisture development and seasonality, allowing to integrate apparently conflicting records of past climate change.

2. Study site

With a surface area of ~273 km^2 and a maximum water depth of ~13 m, Son Kol (app. 41° 50′ N, 75° 10′ E, 3016 m a.s.l.) is by size and volume the second largest natural lake in the Republic of Kyrgyzstan (Fig. 1). The lake is located in the central Tian Shan within a large intermontane basin (catchment area ~1130 km^2) bounded by mountain ranges reaching peak elevations of 3800–4000 m a.s.l. (Shnitnikov, 1980; Academy of Science of the Kyrgyz SSR, 1987). These are composed of Carboniferous sedimentary rocks and Permian granitoids (east and south) as well as Cambro-Ordovician granitoids, sedimentary rocks and tuffs (north) while the plains directly surrounding the lake are mainly covered by eroded bedrock material (De Grave et al., 2011). At present, the catchment lacks glaciers. As the present-day equilibrium line altitude (ELA) of glaciers in the Central Tian Shan of Kyrgyzstan is ~3850–4150 m a.s.l. (Narama et al., 2007; Koppes et al., 2008) and the ELA depression during the Holocene did not exceed ~270 m (Savoskul and Solomina, 1996), it appears likely that glaciers did not exert significant influence on the Son Kol catchment since the early Holocene.

The water balance of the currently exorheic lake is determined by inflow of surface runoff through several small, mostly perennial tributaries, rainfall on the lake surface as well as groundwater inflow and drainage through a single major outlet (Lauterbach et al., 2014). The average water temperature ranges between about 16 °C in summer and 0–2 °C in winter, and almost no stable thermal stratification develops (vertical variations <2 °C) throughout the year, characterizing Son Kol as a polymictic lake. Due to constant mixing, the water body is at present permanently well oxygenated down to the lake bottom (Lauterbach et al., 2014; Huang et al., 2014). The lake is usually ice-covered between October and late April with ice thickness reaching 1.0–1.2 m. Conductivity throughout the water column (measured with YSI 6600 V2 and YSI CastAway CTD multi-parameter water probes) ranged between 0.515 and 0.530 mS cm^{-1} in late summer 2012.

The local climate is characterized by short temperate summers and severely cold winters. Annual mean air temperature close to