

# Impact of recent climate change on Lake Kanas, Altai Mountains (N.W. China) inferred from diatom and geochemical evidence

Xueru Lin · Patrick Rioual  · Wei Peng · Handong Yang · Xiaozhong Huang 

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**Abstract** Glacier shrinkage and melting of snow patches caused by the current phase of warming is having a profound impact on lake ecosystems located in glacierized environments at high altitude and/or latitude because it alters the hydrology and the physico-chemistry of the river discharges and catchment runoff. These changes, in turn, have a major impact on the biota of these lakes. In this study, we combined geochemical and diatom analyses of a sediment core retrieved from Lake Kanas (N.W. China) to assess how climate change has affected this ecosystem over the past ~ 100 years. Our results show that the aquatic ecosystem of Lake Kanas was

sensitive to changes in the regional climate over that period of time. The lake has been affected by change in hydrology (e.g. influx of glacier meltwater, variations in precipitation) and change in hydrodynamics (water column stability). The variations in abundance and composition of the diatom assemblages observed in the sedimentary record have been subtle and are complex to interpret. The principal changes in the diatom community were: (1) a rise in diatom accumulation rates starting in the AD 1970s that is coeval with changes observed in temperate lakes of the Northern Hemisphere and (2) an increase in species diversity and assemblage turnover and a faster rate-of-change since ~ AD 2000. The diatom community is expected to change further with the projected melting of the Kanas glacier throughout the twenty-first century.

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X. Lin · W. Peng · X. Huang (✉)  
MOE Key Laboratory of Western China's Environmental System, Lanzhou University, Lanzhou 730 000, China  
e-mail: xzhuang@lzu.edu.cn

P. Rioual (✉)  
Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100 029, China  
e-mail: prioual@mail.iggcas.ac.cn

H. Yang  
Environmental Change Research Centre, University College London, Pearson Building, Gower Street, London WC1E 6BT, UK

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## Introduction

Air temperatures in temperate latitudes of the Northern Hemisphere have increased over the last century, with an amplification of this warming trend over the past 30–40 years that is unprecedented in the last ~ 1300 years (Jansen et al. 2007). Climate

warming has a significant impact on the function and biodiversity of the natural ecosystems, including lakes, which represent an important component of the global ecosystem. Lakes are effective sentinels for environmental change because they integrate biogeochemical inputs from aquatic and terrestrial landscapes. As a result, lake sedimentary records provide important information about past environmental conditions in the lakes themselves and their surrounding catchment (Adrian et al. 2009; Mills et al. 2017).

Among lakes, those that are fed by glacier or snow meltwaters and located at high elevation in alpine regions or at high latitudes in Polar Regions, are among the most vulnerable to climate change. This is due to the interconnections between atmospheric forcing, snowpacks/glacier mass-balance, stream flow, water quality and hydrogeomorphology (Milner et al. 2009). More specifically, variations in the quantity and quality of glacier and snowpack meltwaters strongly impact the hydrology, the chemistry and water transparency of lakes in alpine and arctic regions. These changes have obvious repercussions on the aquatic biota of these lakes, including on primary producers that are particularly sensitive to variations in light conditions and in the concentration of nutrients, i.e. mainly nitrogen and phosphorus (Slemmons et al. 2015).

Diatoms, which are important primary producers in lakes, are often used as proxies in paleoclimatic reconstructions because of their sensitivity to changes in their aquatic environment and the characteristics of their siliceous frustules that allow their identification to the species level and also promote their preservation in the sediment record of lakes (Battarbee et al. 2001). Diatoms are particularly useful proxy indicators in alpine and/or subarctic regions as some terrestrial-based paleoecological techniques reach their methodological limits at sites beyond the tree line (Lotter et al. 2010). Although the responses of diatoms to climate change is often complex, it has been demonstrated that shifts in diatom assemblage composition, when considered carefully, represent a powerful signal for climate-related regime shifts (Rühland et al. 2015).

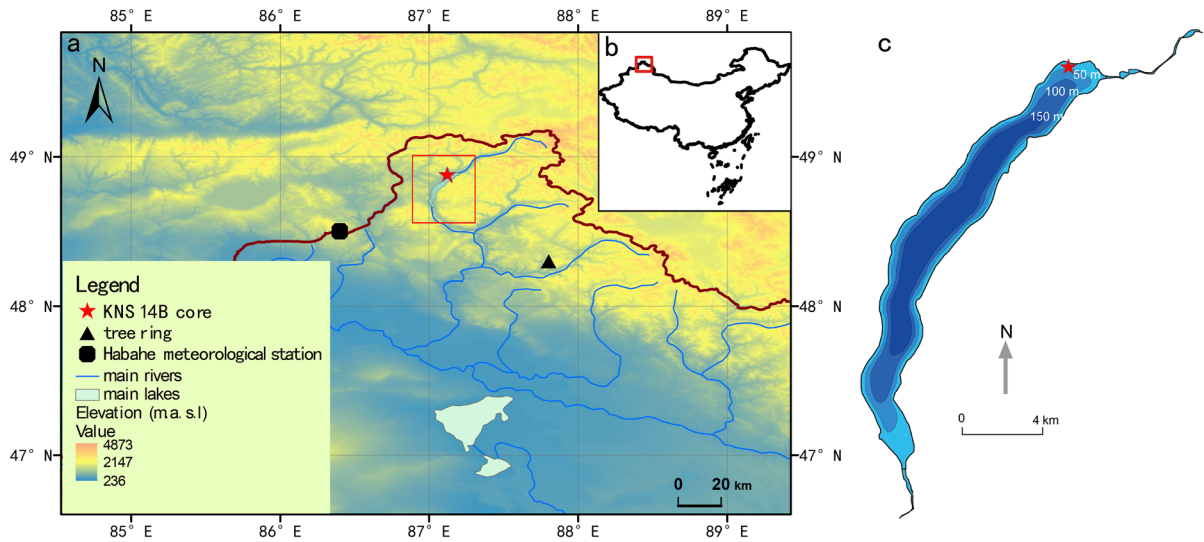
Paleolimnological studies that focused on meltwater fed lakes have revealed that in the recent past abrupt changes occurred in the diatom communities of these lakes. However, the effects on the sedimentary diatom assemblages can be very variables. For example, Sienkiewicz et al. (2017) found in the sedimentary

record of Revvatnet Lake (Svalbard) that the abundance of diatoms typical of rivers and streams increased in frequency at the end of the Little Ice Age due to an increase in running waters caused by the melting of nearby glaciers associated with higher temperature while planktonic diatoms almost completely disappeared. Similarly, Vorobyeva et al. (2015) who analyzed the diatom records of several proglacial lakes in East Siberia (Russia), found a strong decline in the abundance of diatoms when the glaciers in the catchment of these lakes actively melted after the Little Ice Age and they associated these changes with the high supply of clastic material with meltwater that increased water turbidity, which is detrimental to both planktonic and benthic diatoms. Slemmons et al. (2015, 2017a, b) also found pronounced shifts in diatom assemblages in the glacier-fed lakes of the Rocky Mountains (USA), but there the changes were expressed by the increase in the percentages of planktonic species indicative of moderate nitrogen enrichment that started about 100 years ago. These authors interpreted these diatom shifts as the results the rapid melting of the glaciers combined with the increase in atmospheric nitrogen deposition (due to human activities). In Bunny Lake in East Greenland, Slemmons et al. (2017a) also inferred that glacially derived nitrogen subsidies caused the shifts observed in the diatom record, although in that lake, fluctuations in water level also had an impact on the diatom assemblages.

Lake Kanas (48°11′–49°11′N, 86°23′–88°05′E, 1370 m a.s.l.) has great potential for studying the way aquatic ecosystems respond to climate change as it is fed by a river with glacier meltwater inputs and it is located in the Altai Mountains (also spelled Altay), a region that has been so far little affected by human activities. There are, however, few studies about lakes in the Altai Mountains (Rudaya et al. 2009; Li et al. 2017) and in particular about Lake Kanas to build upon. In this study, we investigate how Lake Kanas is responding to the recent climate change by analyzing the diatom assemblage and geochemical record of a short sediment core that spans the last ~ 100 years.

#### Study site

Lake Kanas (latitude 48°11′–49°11′N, longitude 86°23′–88°05′E, altitude 1370 m a.s.l.) is a lake surrounded by the boreal coniferous forests of the



**Fig. 1** Geographical location of Lake Kanas: **a** Regional setting, **b** location in NW China, **c** simplified lake bathymetry and position of the coring site

Altai Mountains (Fig. 1). It is a large and deep lake with a surface area of 45.73 km<sup>2</sup>, about 24 km long and 2 km wide and its maximum and mean water depths are 197 m and ~ 100 m, respectively (Wu et al. 2014). It is located at the junction between the Burqin and Habahe counties, in the most northern part of Xinjiang Province and is 60 km away from Khüiten Peak (altitude 4374 m), the highest peak of the Altai Mountains (Gao 1986). The lake basin was excavated by ancient glaciers and dammed by the glacier end moraine. It formed during Marine Isotope Stage 6 with the outermost moraine dated at 167 ± 16 ka (Zhao et al. 2013).

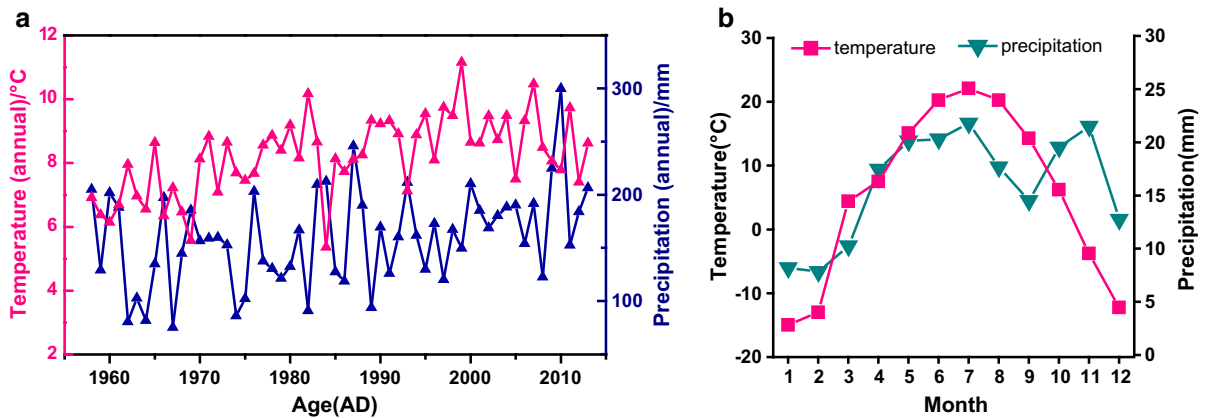
There are 210 active modern glaciers in the Kanas River valley. These glaciers occupy a total area of about 210 km<sup>2</sup> and represent an ice volume of 13.34 km<sup>3</sup>. Among these glaciers, the most notable is the Kanas glacier with a length of more than 5 km. In 1980, the Kanas glacier was about 10.8 km long, had an area of about 30 km<sup>2</sup> and an ice volume of 3.92 km<sup>3</sup>, and had its terminus at 2416 m a.s.l. (Liu et al. 1982). In 2009, Zhao et al. (2013) observed that the terminus of the Kanas glacier was at 2460 m a.s.l., i.e. more than 40 m higher by comparison with the 1980 position, as a result of about 800 m of glacier retreat.

The Kanas River flows into the lake from the northeast to the southwest (Fig. 1). The lake surface

water is slightly alkaline (pH 7.23), weakly mineralized (conductivity = 46 μS cm<sup>-1</sup>) and dominated by calcium-carbonates with the following sequence of dominant cations Ca<sup>2+</sup> > Na<sup>+</sup> > Mg<sup>2+</sup> > K<sup>+</sup> and anions HCO<sub>3</sub><sup>-</sup> > Cl<sup>-</sup> >> SO<sub>4</sub><sup>2-</sup> > NO<sub>3</sub><sup>-</sup> (Zhu et al. 2013). The lake volume and surface area of this open system have been stable in the recent past (Wu et al. 2014).

Historically Lake Kanas has been barely influenced by anthropogenic disturbances. However, in recent years the number of tourists visiting the area has increased rapidly: from ~ 9000 visitors per year in 1997 when the area became opened to tourism to ~ 1 million tourists in 2013, with 5000 tourists a day during the peak of the tourism season in the summer months (Han et al. 2011; Yang et al. 2014; Shi and Shi 2016). The impact of tourism is however limited to the southern part of the lake. Core KNS14B was retrieved from the upper reaches of the lake, near the west shore and the estuary, from a position that can be considered as unaffected by direct human impact.

Present climate conditions are determined by the Westerlies which brings water vapor and precipitation in summer. In winter this area is influenced by the Asian anticyclone that causes cold but sunny conditions. The polar air from the north penetrates along the valley of the Erqis River (Bai 2012). The temperature and precipitation recorded from AD 1958–2014 at the



**Fig. 2** Meteorological data from Habahe station in the Altai Mountains. **a** Time-series for the annual mean temperature and annual precipitation from 1957 to 2014; **b** Ombrothermic

diagram showing the monthly mean temperature and precipitation from the same time interval as in (a)

Habahe meteorological station, the nearest to Lake Kanas, are shown in Fig. 2. The average annual temperature is 5.5 °C while the average annual precipitation is 160 mm. Maximum rainfalls occur in July (21.7 mm) and November (21.5 mm) while the minimum precipitation is in February (2.8 mm). Monthly mean temperature varies from 22.1 (July) to −14.9 °C (January).

## Materials and methods

### Sediment sampling and chronology development

In September 2014, a sediment core was retrieved from a water depth of about 15 m near the northern shore of the lake, closed to the estuary of the River Kanas (48°53′34.01″N, 87°7′50.47″E) using a Uwitec® modified piston corer (Fig. 1c). The core, KNS14B, was 51 cm long and sliced in the field at 1 cm interval. Fifty samples from core KNS14B were analyzed for  $^{210}\text{Pb}$  and  $^{137}\text{Cs}$  at the  $\gamma$  Radiation Laboratory of the Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing. The chronology was established based on the constant rate of supply (CRS) model (Appleby and Oldfield 1978). Error in the sediment chronologies was determined from the uncertainty in the  $^{210}\text{Pb}$  gamma counts as described in Appleby (2001).

### Geochemical analysis

The grain size and total organic carbon (TOC) of the sediments were measured in the Key Laboratory of Western China's Environmental Systems, Ministry of Education (MOE) in Lanzhou University. Variations in grain size may be related to changes in inputs from the river, runoff from the lake catchment and the hydrodynamic of the lake. The grain size was measured with a Mastersizer 2000 laser granularity analyzer (Malvern Instruments Ltd, UK). Details of the analytical method are given in Peng et al. (2005). TOC, that relates to the content in organic matter of the sediment and may indicate changes in biological productivity, was measured using a TOC Analyzer (Analytik Jena AG, Germany). Details of the method are given in Liu et al. (1996) and Bao (2000).

Variations in the concentrations of geochemical elements down-core can indicate changes in inputs from the river and/or the catchment but also changes in lake productivity and hydrodynamics. The elemental composition of KNS14B core was investigated by X-ray fluorescence spectrometry (XRF-SR) for the quantitative analysis of 36 trace elements and major constituents. All collected samples were dried by air and pulverized into powder. A volume of 5 g of powdered material was pressed into a bead, 4–6 mm thick and 30 mm in diameter, under 30 t m<sup>-2</sup> of pressure. Elemental concentrations ranging from 0.1 ppm to 100% can be measured by the spectrometer. The measuring errors for reported elements

are < 10%. These analyses were carried out at the MOE Key Laboratory of Western China’s Environmental System in Lanzhou University. The coefficients of correlation ( $r$ ) were computed between down-core variations in these elements in order to identify significant geochemical associations (Beaudoin et al. 2016).

### Diatom analysis and taxonomy

All 51 samples from core KNS14B were analyzed for diatoms. Diatom samples were prepared in test tubes from approximately 0.05 g of freeze-dried sediment using hot H<sub>2</sub>O<sub>2</sub> to remove organic matter (Renberg 1990). Diatom concentrations (valves per g of dry matter) were calculated by the addition of divinylbenzene microspheres (Battarbee and Kneen 1982). Diatom fluxes (in valves cm<sup>-2</sup> yr<sup>-1</sup>) were then calculated by multiplying the diatom concentration by the dry bulk density (in g cm<sup>-3</sup>) and the sediment accumulation rate (in cm yr<sup>-1</sup>). Subsamples of the homogenized suspension were diluted by adding distilled water and left to settle onto glass coverslips until dry (Gao et al. 2016). The coverslips were fixed onto glass slides with Naphrax<sup>®</sup>. For all samples at least 300 valves were counted under a Leica DM6000 light microscope using oil immersion phase-contrast at 1000× magnification. Diatom identification and taxonomy were mainly based on Krammer and Lange-Bertalot (1986, 1988, 1991a, b) and Hofmann et al. (2011). We also used other taxonomic publications to aid with the identification of difficult groups of diatoms, like Kling and Håkansson (1988) for *Cyclotella gordonensis* H.J. Kling & Håkansson (recently renamed *Pantocsekiella gordonensis* (H.J. Kling & Håkansson) K.T. Kiss & Ács). Light microscope and scanning electron microscope photographs of *P. gordonensis* are shown in the appendix.

### Numerical analyses on diatom data

Diatom assemblage zones (DAZ) were delimited by optimal partitioning (Birks and Gordon 1985) based on the diatom percentage data using the unpublished program ZONE (version 1.2) (Lotter and Juggins, pers. commun.).

The planktonic:benthic ratio (P:B ratio) was calculated for each core depth based on the habitat of the species as indicated in the main flora used for diatom

identification (Krammer and Lange-Bertalot 1986, 1988, 1991a, b; Hofmann et al. 2011). Variations in the P:B ratio are interpreted as reflecting alterations in the lake habitat conditions.

To estimate the down-core diatom compositional turnover or beta-diversity, of the core diatom assemblages, relative abundances were analyzed using detrended canonical correspondence analysis (DCCA) constrained to time. The larger the beta-diversity value obtained over the interval under consideration, the greater the assemblage turnover. Beta-diversity is estimated in units of standard deviations (SD), which correspond with units of compositional turnover (Birks 2007; Hobbs et al. 2010). The DCCA analysis was performed using the program CANOCO 5 (ter Braak and Šmilauer 2012) and the protocol included square-root transformation of the diatom relative abundance data, no down-weighting of rare species, detrending by segments and non-linear rescaling (Smol et al. 2005; Hobbs et al. 2010). In addition, to estimate the rate at which compositional change is occurring we determine the rate-of-change. This was done by calculating the down-core diatom species turnover as the Bray–Curtis distance between adjacent samples, and the down-core rate of change as this measure divided by the time interval between samples (Juggins et al. 2013). The rate-of-change is therefore measured in yr<sup>-1</sup>.

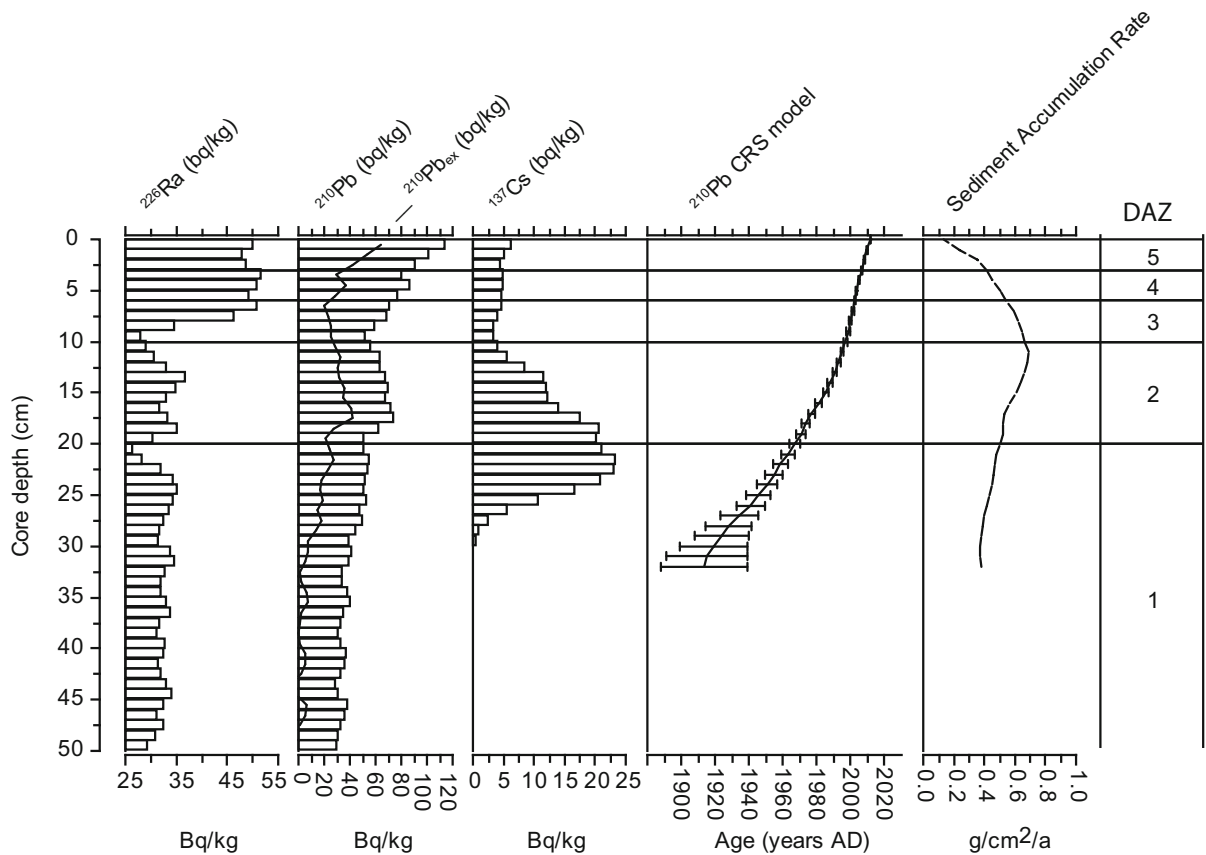
Although biodiversity assessments would ideally require complete samplings (i.e. an inventory of all the species present in a sample), only partial samplings are ordinarily achieved when species abundances distributions are highly heterogeneous within a community which is often the case with micro-organisms such as diatoms (Béguinot 2015a). In this study, we used Jack-2, a nonparametric estimator of species richness (Béguinot 2015a, b) defined according to the following formula (Eqs. 1–4):

$$R(N) = S \left( 1 - k''/N - k'''/N^2 \right) \tag{1}$$

$$S = Ro + 2f_{1(N)} - f_{2(N)} \tag{2}$$

$$k'' = \frac{(3f_{1(N)} - 2f_{2(N)}) N_0}{R_0 + 2f_{1(N)} - f_{2(N)}} \tag{3}$$

$$k''' = \frac{(f_{1(N)} - f_{2(N)}) N_0^2}{R_0 + 2f_{1(N)} - f_{2(N)}} \tag{4}$$



**Fig. 3** Radioisotopic activities of  $^{210}\text{Pb}$ ,  $^{137}\text{Cs}$  and  $^{226}\text{Ra}$  in core KNS14B and the age-depth model and sediment accumulation rate derived from the CRS model. The zonation corresponds to the diatom assemblage zones (DAZ)

Here,  $f_{1(N)}$  and  $f_{2(N)}$  are the numbers of singletons (i.e. the species for which only one individual was counted) and doubletons (i.e. the species for which two individuals were counted) among the  $R(N)$  recorded species within a sample of size  $N$  (Béguinot 2015b).  $N_0$  is the number of counted valves and  $S$  represents the expected total richness (Béguinot 2015a).  $R_0$  is the number of recorded species, which for this study corresponds with a valve count of 300.

## Results

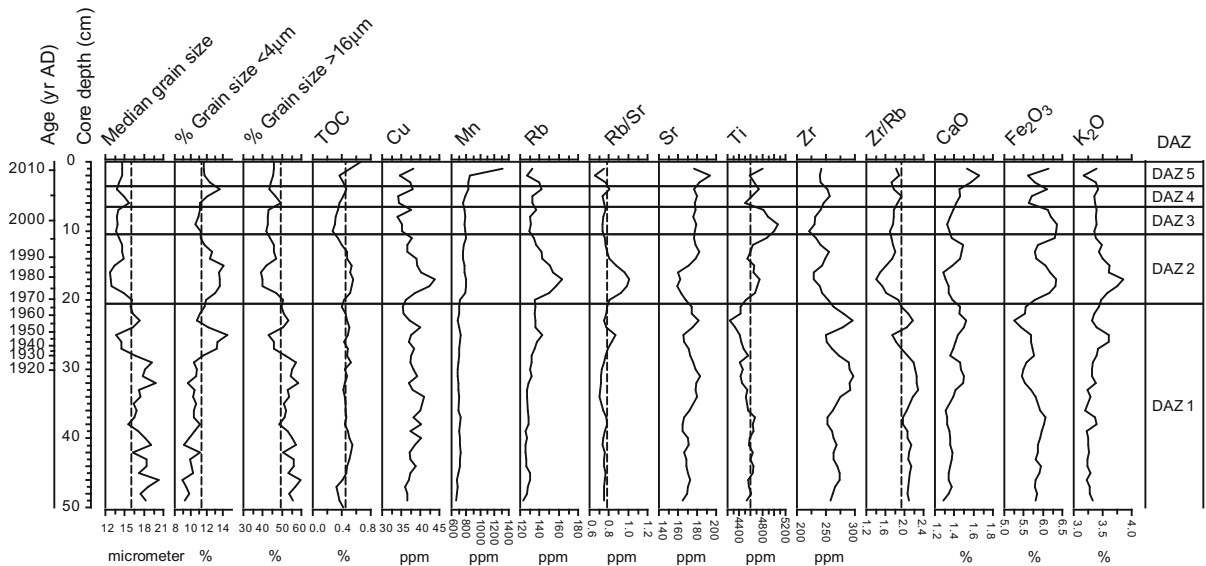
### Chronology of the sequence

Unsupported  $^{210}\text{Pb}$  activity ( $^{210}\text{Pb}_{\text{ex}}$ ), which was calculated by subtracting supported  $^{210}\text{Pb}$  (as  $^{226}\text{Ra}$ ) activity from the total  $^{210}\text{Pb}$  activity, declines

irregularly with depth (Fig. 3). Equilibrium between the total  $^{210}\text{Pb}$  activity and the supported  $^{210}\text{Pb}$  is reached at the level 32–33 cm. Small irregularities in  $^{210}\text{Pb}_{\text{ex}}$  below this depth are probably not significant as they are in the same order of magnitude as the uncertainties in the measured activities. The maximum for  $^{210}\text{Pb}_{\text{ex}}$  is  $64.4 \pm 6.3 \text{ Bq kg}^{-1}$  measured in the uppermost sample (0–1 cm).

The chronological error increased from 0.2 years at the top to 25.6 years at 33 cm, where sediments are dated to AD 1914 by this method. The  $^{137}\text{Cs}$  activity reaches a maximum value of  $23.4 \pm 0.6 \text{ Bq kg}^{-1}$  in the core sample 21–22 cm. This corresponds to the large fallout from the atmospheric testing of nuclear weapons in AD 1963. It is in good agreement with the CRS model that dates this layer as  $\text{AD } 1962.8 \pm 3.9$ . There are considerable changes in sediment accumulation rates in the upper part of the core so it was not





**Fig. 4** Variations in geochemical proxies in core KNS14B plotted against core depth (with age as secondary y-axis) including grain-size, TOC and selected elements and element

ratios measured by XRF. The zonation corresponds to the diatom assemblage zones (DAZ)

appropriate to extrapolate the <sup>210</sup>Pb chronology into the deeper part of the core using the average sediment accumulation rate (Appleby 2000).

**Geochemical analyses**

The median grain size varies from 12 to 20 µm with a mean value of ~ 16 µm for the whole profile. Grain size is dominated by coarse silt (> 16 µm) below 29 cm while the percentages of fine silt (< 4 µm) increase in the upper part of the sequence. TOC of core KNS14B varied from 0.3 to 0.7% (mean value of 0.45%). Its value is mostly stable from the bottom (51 cm) to ~ 20 cm. From that point, TOC fluctuates reaching its minimum value for the whole sequence at 10 cm before rising sharply up to the top of the sequence. The variations of TOC and median grain size are shown in Fig. 4.

Among the elements derived by XRF analysis, only those that exhibit trends considered to be significant variations in elemental composition of the sediment core are mentioned in this paper (Fig. 4, Table 1). Variations in the core of Rb, Rb/Sr ratio and K<sub>2</sub>O, that are generally associated with feldspars and clay minerals follow those of the fine particle (< 4 µm) as shown by their strong positive correlations ( $r > 0.8$ ,  $p < 0.01$ ,  $\alpha < 0.001$ ). By contrast Zr, which is

associated with weathering-resistant, coarse mineral particles such as zircon (ZrO<sub>2</sub>) and the Zr/Rb ratio are strongly and positively correlated with coarse particles ( $r > 0.8$ ,  $p < 0.01$ ,  $\alpha = 0.001$ ). K<sub>2</sub>O and to a lesser extend Fe<sub>2</sub>O<sub>3</sub> and Ti are strongly negatively corrected with the Zr/Rb ratio. CaO and Sr are positively correlated with each other ( $r > 0.7$ ,  $p < 0.01$ ,  $\alpha = 0.001$ ). A peak in Cu is observed in the AD 1970s, between 17-19 cm core depth, and matches with high TOC content. The curve for the Mn content is marked by a modest increase at ~ 19 cm and a sharp rise in the uppermost sample.

**Diatom analysis**

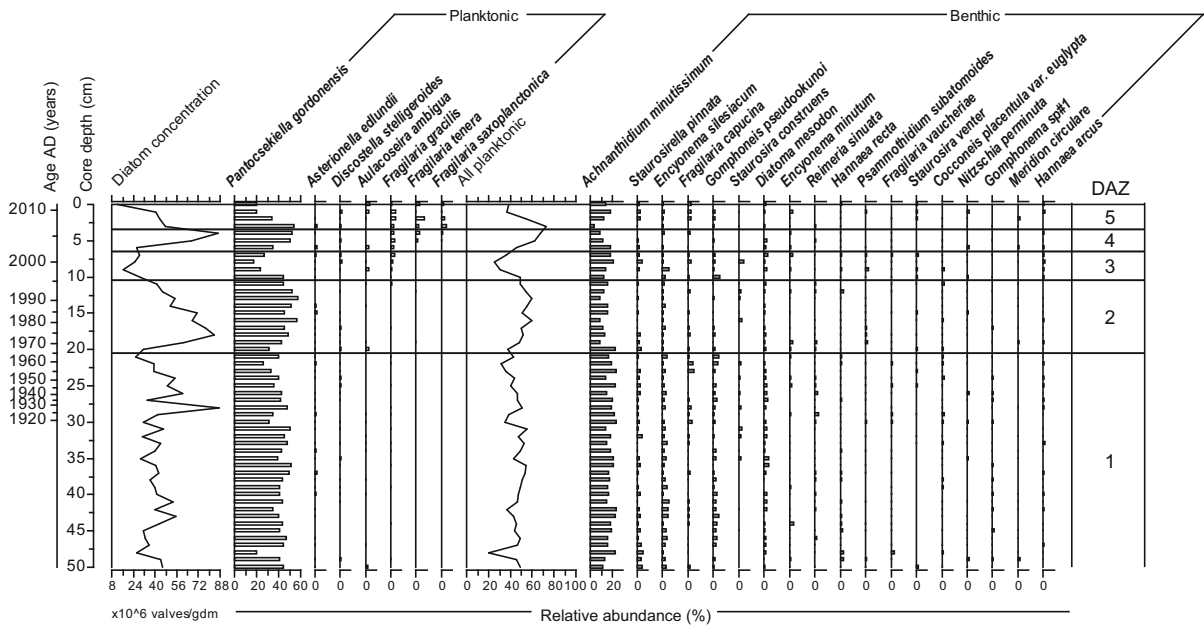
In total, 300 species of diatoms were identified in the 51 samples. Only 25 species reached relative percentages > 2% and appeared in more than 3 samples (Fig. 5). A list of these diatoms with their taxonomic authorities and habitat preference is given in Electronic Supplementary Material. The species that fulfilled these criteria include seven species of planktonic diatoms such as *P. gordonensis*, which is largely dominant throughout the sequence, *Aulacoseira ambigua* (Grunow) Simonsen, *Discostella stelligeroides* (Hustedt) Houk & Klee, *Asterionella edlundii* Stoermer & Pappas, *Fragilaria gracilis* Østrup, *Fragilaria*

**Table 1** Coefficient of correlation ( $r$ ) between the main geochemical variables measured for core KNS14B

TOC	Grain size		Cu	Mn	Rb	Sr	Ti	Zr	Fe <sub>2</sub> O <sub>3</sub>	CaO	K <sub>2</sub> O	Rb/Sr	Zr/Rb		
	Median	< 4 $\mu$ m												> 16 $\mu$ m	
TOC	1														
Median	0.07	1													
<4 $\mu$ m	0.31	-0.83	1												
>16 $\mu$ m	0.08	0.99	-0.81	1											
Cu	0.66	-0.07	0.24	-0.08	1										
Mn	0.08	-0.48	0.31	-0.48	0.00	1									
Rb	0.40	-0.67	0.82	-0.69	0.46	0.23	1								
Sr	-0.41	0.05	-0.17	0.05	-0.44	0.17	-0.30	1							
Ti	-0.37	-0.50	0.06	-0.54	-0.06	0.46	0.09	-0.05	1						
Zr	0.26	0.79	-0.47	0.81	0.04	-0.48	-0.43	0.19	-0.74	1					
Fe <sub>2</sub> O <sub>3</sub>	-0.09	-0.54	0.21	-0.58	0.25	0.41	0.33	-0.39	0.90	-0.78	1				
CaO	-0.01	-0.04	0.17	-0.02	-0.30	0.31	-0.03	0.76	-0.36	0.23	-0.58	1			
K <sub>2</sub> O	0.30	-0.68	0.80	-0.69	0.40	0.21	0.91	-0.43	0.12	-0.48	0.36	-0.14	1		
Rb/Sr	0.49	-0.54	0.70	-0.55	0.56	0.10	0.90	-0.68	0.10	-0.42	0.43	-0.36	0.88	1	
Zr/Rb	-0.01	0.89	-0.75	0.90	-0.17	-0.45	-0.79	0.25	-0.54	0.89	-0.67	0.14	-0.78	-0.72	1

Values of  $r > |0.24|$  indicate significant correlations at  $p < 0.01$ , with  $\alpha < 0.001$  and degree of freedom  $n - 2 = 46$





**Fig. 5** Summary diagram of diatom relative abundance plotted against core depth (with age as secondary y-axis) and local diatom assemblage zones (DAZ)

*tenera* (W. Smith) Lange-Bertalot and *Fragilaria saxoplanctonica* Lange-Bertalot & Ulrich and 18 species of benthic diatoms including *Achnantheidium minutissimum* (Kützing) Czarnecki (which is the dominant benthic species). The sequence was divided into 5 DAZ using optimal partitioning on the percentage data (Fig. 5).

The species turnover, as expressed by the difference between the minimum and maximum sample scores on DCCA axis-1 is 2.98 standard deviation units. The uppermost sample has the lowest score for the whole sequence (Fig. 6). The rate-of-change is low throughout DAZ 1 and 2 during which it remains mostly below  $0.1 \text{ yr}^{-1}$  and increases from the top of DAZ 2 from ~ AD 1995. The maximum value for rate-of-change is for the sample 2–3 cm (AD 2007–2008) with  $0.32 \text{ yr}^{-1}$  (Fig. 6). Diatom flux peaks at the level 5–6 cm (AD 2003–2004) with a value of  $\sim 75 \times 10^6 \text{ valves cm}^{-2} \text{ yr}^{-1}$  (Fig. 6). Species diversity (observed and expected) is highest in the uppermost sample (Fig. 6).

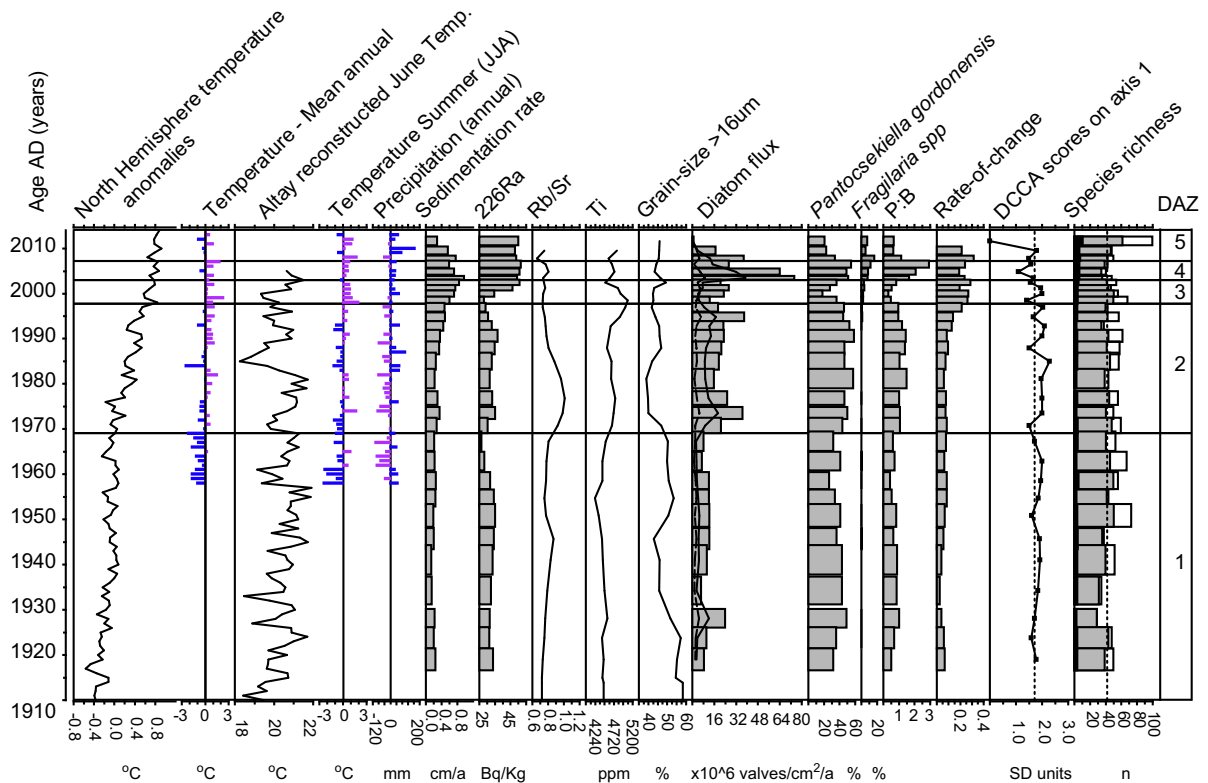
**DAZ 1:** 51–20.5 cm, before ~ AD 1916–1969 From the start of the record to ~ AD 1969 diatom assemblages change little in composition and are largely dominated by the planktonic species *P.*

*gordonensis*. The most abundant benthic species are *A. minutissimum*, *Staurosirella pinnata* (Ehrenberg) D. M. Williams & Round, *Encyonema silesiacum* (Bleisch) D. G. Mann, *Gomphoneis pseudookunoi* Tuji and *Diatoma mesodon* (Ehrenberg) Kützing. Diatom flux is low throughout the zone but diatom diversity is variable ( $29 < S < 73$ , mean = 48).

**DAZ 2:** 10.5–20.5 cm, AD 1969–1998 This zone is characterized by an increased in the percentages of *P. gordonensis* and a decrease in benthic diatoms. Compared with the previous zone, the diatom flux and planktonic:benthic ratio increase. Diatom diversity is generally higher than in the previous zone ( $38 < S < 62$ , mean = 53).

**DAZ 3:** 6.5–10.5 cm, AD 1998–2003 The rate-of-change increases markedly at the transition between this zone and the previous one. There is a drop in the percentages of *P. gordonensis* but those of other planktonic species such *A. ambigua*, *D. stelligeroidea* and *F. gracilis* increase. The diatom flux and planktonic:benthic ratio decrease. Diatom diversity increase further ( $47 < S < 68$ , mean = 56).

**DAZ 4:** 3.5–6.5 cm, AD 2003–2007 The percentages of *P. gordonensis* and that of other planktonic



**Fig. 6** Comparison between selected proxy data derived from Lake Kanas core KNS14B, the meteorological data from Habahe station and other records of recent climate change, plotted against time. From left to right: Globally averaged combined land and ocean surface temperature anomaly (IPCC 2014); mean annual temperature from Habahe Station (deviation from the mean 1957–2014); June temperature for the Altai reconstructed from tree-ring data (Shang et al. 2010); Summer temperature and annual precipitation from Habahe station (deviation from the mean 1957–2014); and proxy data from core KNS14B including: sedimentation rate,  $^{226}\text{Ra}$  activity, Rb/Sr

Sr ratio, Titanium content, grain-size, diatom fluxes (total diatoms = bars, *P. gordonensis* = plain line, *A. minutissimum* = dashed line), relative percentages of *P. gordonensis* and planktonic *Fragilaria*, planktonic:benthic ratio, rate-of-change, detrended DCCA scores on axis-1 (the dotted line indicates the mean for the sequence), species richness (black = observed number of planktonic spp, grey = obs. number of benthic spp, white = expected richness, the dotted line indicates the mean observed richness for the sequence). Note that for the core data the width of the bars corresponds with the time interval covered by each sample

species increase sharply as well as the diatom flux and the planktonic:benthic ratio. The decrease in benthic is associated with a decrease in diatom diversity ( $41 < S < 48$ , mean = 44).

**DAZ 5: 0–3.5 cm, AD 2007–2014** This zone is characterized by a sharp drop in the planktonic:benthic ratio and the diatom flux. Besides *P. gordonensis*, planktonic *Fragilaria* species such as *F. gracilis*, *F. tenera* and *F. saxoplanctonica* and *A. ambigua* are also abundant. The uppermost sample is characterized by a sharp increase in species diversity ( $S = 100$ ).

## Discussion

### Interpretation of geochemical proxy

Due to the coring location, near the shore and the estuary of the Kanas River, we can assume that the grain size characteristics of core KNS14B are influenced by inputs from the river, runoff from the lake catchment and the hydrodynamic of the lake. As discussed by Liu et al. (2014), variations in the lake sediment record in grain size and in some elements can be used to indicate glacial erosion and the downstream transport of particles and therefore reflect glacier activity. In particular, abrasion by glaciers is known to

produce large quantity of silt-sized particles in periods of glacier advances. The Zr/Rb ratio traces grain size changes with high Zr/Rb ratios indicating coarse-grained and inversely, low Zr/Rb ratios indicating fine-grained material. In the context of Lake Kanas, high Zr/Rb ratios reflect glacier advance.

Sr is normally associated with autochthonous precipitation of carbonates in lake, itself associated with summer thermal stratification. In a glaciolacustrine context such as Lake Kanas, however, seasonal melting of the glacier caused by high air temperature result in high input of glacier meltwater, which is unfavorable to the precipitation of carbonates and therefore cause low content of Sr. Sr content is therefore a mixed signal, driven by the opposite effects of summer stratification and meltwater input. In the lower part of the core, the Rb/Sr ratio mainly depends on the amount of Rb ( $r > 0.9$ ,  $p < 0.01$ ,  $\alpha = 0.001$ , Table 1). In such conditions, high values of the Rb/Sr ratio indicate glacier retreat (Liu et al. 2014).

Ti is typical of clastic material primarily transported as suspended particulates (Stepanova et al. 2015) that can be considered as indicator of detrital sediment input and of a water body strongly influenced by river runoff (Biskaborn et al. 2012).  $K_2O$  and  $Fe_2O_3$  on the other hand are considered as highly mobile and closely associated with the intensity of weathering (Stepanova et al. 2015). Mn is also a highly mobile element but additionally it is susceptible to reduction and mobilization in sediments (Engstrom et al. 1985; Kauppila et al. 2012). Cu is autochthonous in origin and high content of this element indicates high lake productivity due to an increase in the rate of supply of nutrients into the lake from the catchment area at a high soil water saturation (Fedotov et al. 2015).

#### Lake Kanas recent paleoenvironmental changes

Zone 1 (from before ~ AD 1916–1969). The geochemical data for the lowermost zone 1 in core KNS14B suggest 3 periods of glacier advance that are characterized by high values for the coarse grain-size and Zr/Rb ratio. On the other hand, there is also a noticeable ~ 10-year interval centered around AD 1940 in which the median grain size markedly decreased while the Rb/Sr ratio and  $K_2O$  content increase (Figs. 4, 6). These data indicate higher clay content and increased river input, possibly associated with glacier meltwater. This is consistent with the

record of the globally averaged combined land and ocean surface temperature anomaly (IPCC 2014) that shows that the AD 1940s were a warm interval (Fig. 6). During the same interval in the diatom record there is an increase in the planktonic:benthic ratio associated with low values for the observed and expected species richness. The diatom response to this climate shift is rather muted, and the lack of large change in the composition of diatom assemblages in zone 1 suggests that no ecological threshold was crossed during the time interval covered by this zone. The large dominance of the planktonic freshwater diatom *P. gordonensis* in Lake Kanas is in accordance with what is known about the ecology and distribution of this species that was described from deep oligotrophic lakes in Canada (Kling and Håkansson 1988) and has also been found in similar settings in Europe (Wunsam et al. 1995; Hausmann and Lotter 2001) and the Far-East (Genkal and Lepskaya 2014). The most abundant benthic diatom, *A. minutissimum*, is one of the most frequently occurring freshwater diatom species all over the world with a broad ecological spectrum (Krammer and Lange-Bertalot 1991b). Its continuous large abundance in the assemblages of the core reflects the fact that the core was retrieved near the shore, at only 15 m water depth.

In the Habahe meteorological record the interval from AD 1958 to 1969, that corresponds with the uppermost part of DAZ 1 (Fig. 6), was characterized by colder and drier conditions compared to the average values obtained for the whole period covered by the meteorological record (i.e. AD 1958–2013). In agreement with drier conditions, the geochemical data in this interval is characterized by very low content of Ti and  $Fe_2O_3$  (Fig. 4), which are detrital indicators associated with river input (Biskaborn et al. 2012). Yet, for that interval too, there was no obvious response in the diatom assemblage.

Zone 2 (AD 1969–1998). At the start of this zone, the simultaneous increases in diatom flux, in the abundance of planktonic diatoms and in the TOC content suggest a more productive aquatic system (Figs. 4, 6). Simultaneously, in the geochemical data (Fig. 4) we observed increases in Cu, Mn and Fe, elements that are indicators of bio-productivity and diagenesis (Fedotov et al. 2015; Stepanova et al. 2015). The rise in Mn in particular may have come from reduced sediments on the slope of the lake basin (where the core was taken) associated with summer

stratification and increased redox cycling across the sediment-water interface (Engstrom et al. 1985).

The transition between the zones 1 and 2 is also marked by a sharp increase in the Rb/Sr ratio and in the content of  $K_2O$  and Ti (Fig. 4). This geochemical data suggest an increase in the influx of fine particles by meltwater input. The local meteorological data indicate that this period was generally less cold than the previous one, while precipitation was generally higher albeit variable (Fig. 6). In summary, warmer temperature may have promoted more stable thermal stratification for the whole euphotic zone, conditions that promote the growth of planktonic species such as *P. gordonensis* (Tolotti et al. 2007), while at the same time causing melting of the Kanas glacier. These observations match with the findings of Wei et al. (2015) who estimated the changes in glacier volume in the Chinese Altai using geodetic methods. In particular, their results indicate a glacier mass loss of  $0.43 \pm 0.02 \text{ m a}^{-1}$  water equivalent during the interval 1959–1999. Interestingly, the changes that occurred in Lake Kanas in the AD 1970s are coeval with the onset of biological responses to warming reported in temperate lakes throughout the Northern Hemisphere (Rühland et al. 2008, 2015).

This warming trends is however interrupted in the mid-1980s, which are characterized in the Habahe meteorological record by 4 years colder than average (Fig. 6). This cold spell is clearly marked in the tree-ring record for the Chinese Altai (Shang et al. 2010). It is well expressed in the geochemical record of Lake Kanas by an increase in the percentage of coarse particles, a decrease in the Rb/Sr ratio and a sharp rise in the Zr/Rb ratio (Figs. 4, 6). In the diatom record, only a slight decrease in the percentages of *P. gordonensis* occurred in that interval (Figs. 5, 6).

Zone 3 (AD 1998–2003). The sedimentation rate increases steadily from the start of this zone which is also marked by high Ti content (an indicator of clastic material) and a sharp rise in the concentration of  $^{226}\text{Ra}$  (Fig. 6). High  $^{226}\text{Ra}$  is also an indicator of enhanced delivery of bedrock material (Brenner et al. 1994). High concentrations in radium are also found in the very fine powdered abrasion material from glaciers (Kies et al. 2011). These geochemical proxies may suggest a steady influx into the lake of glacier meltwater. Yet, the Rb/Sr ratio decrease in this zone while we would expect an increase with the melting of glaciers in agreement with what we observed in DAZ 2

and what we know from the literature (Liu et al. 2014; Vorobyeva et al. 2015). An alternative explanation is that the influx of clastic material was not only caused by glacier meltwater but also by increased precipitation. The significant increase in  $\text{Fe}_2\text{O}_3$  (Fig. 4) would suggest increased weathering. The meteorological data indeed show that this interval had high precipitation and high summer temperature (Fig. 6). Simultaneously, in the diatom assemblages there is a drop in the percentages and flux of *P. gordonensis* but other planktonic species such *A. ambigua*, *D. stelligeroides* and *F. gracilis* increase (Fig. 5) and there is an increase in species diversity, rate-of-change and turnover (as shown by DCCA axis-1 scores, Fig. 6). The slight decrease in diatom flux (Fig. 6) may reflect the “dilution” of diatom concentration in the sediment caused by the increased sedimentation rate rather than a decrease in diatom primary production.

Zone 4 (AD 2003–2007). The diatom assemblages of this short interval are characterized by the highest percentages and fluxes of planktonic species observed in the whole sequences with increased abundance of *P. gordonensis* and planktonic *Fragilaria* such as *F. gracilis*, *F. tenera* and *F. saxoplanctonica* (Fig. 5). In lakes of the Italian Alps, increased abundances of planktonic *Fragilaria* spp. has been found to be positively correlated with the relative thermal stability of the euphotic zone, an increase in total water inflow and lake water level and with nutrient concentrations (especially  $\text{NO}_3\text{-N}$ ) (Tolotti et al. 2007). Planktonic *Fragilaria* species have also been linked to nitrogen enrichment from glacial meltwater in various remote lakes (Slemmons et al. 2015, 2017a). The meteorological data, which indicate continuing high summer temperature and high precipitation for this zone (Fig. 6), suggest that conditions similar to the ones observed by Tolotti et al. (2007) prevailed in Lake Kanas during that interval. It is interesting to note that the mass loss of the Kanas glacier continued and even accelerated during that interval according to Wei et al. (2015), reaching  $-0.54 \pm 0.13 \text{ m a}^{-1}$  water equivalent during the period 1999–2008. This is not clearly reflected in the geochemical record of Lake Kanas that shows only small variations in grain-size and the Rb/Sr ratio (Figs. 4, 6).

Zone 5 (AD 2007–2014). The diatom record is marked by the sharp decline in the abundance of *P. gordonensis* and to a lesser extent that of the planktonic *Fragilaria* spp. while the relative percentages of

benthic species increased (Fig. 5). The flux data however, indicate that the productions of both planktonic and benthic diatoms actually declined (Fig. 6). In that interval meteorological data indicate that summer temperature generally remained high and that precipitation increased further (Fig. 6). It is therefore unlikely that the decline in diatoms was caused directly by a return to cold conditions that would have limited diatom production. Large amounts of suspended minerogenic particles (= glacier flour) associated with glacier meltwater would be detrimental to algal production due to its very low temperature and turbidity that affects light conditions. This is however unlikely to have occurred in Lake Kanas, because like in the previous zone, the geochemical evidence do not indicate a large influx of clastic material into the lake, while the sedimentation rate and sediment accumulation rate are even decreasing.

An alternative explanation for the diatom decline is a change in lake water chemistry, and in particular nutrient concentrations such as silica. A strong decline in the abundance of diatoms was also observed by Vorobyeva et al. (2015) who studied the impact of climate warming on proglacial lakes in East Siberia. These authors linked that decline to the large supply of dilute freshwater from the increased melting of snow patches and seasonal snow cover. Snow meltwater is very nutrient-poor and much less chemically enriched than glacier meltwater (Brown 2002). The significant increase in January precipitation (= snowfall) detected in the Southern Altai Mountain (Yang et al. 2017), while summer temperatures remained high, supports the hypothesis of increasing influx of snowmelt water to the lake.

Although the flux of diatoms decreased in DAZ 1, diversity of benthic species increase markedly, especially in the uppermost sample in which the expected species richness reaches its maximum for the whole profile (Fig. 6). Simultaneously, the uppermost sample is characterized by an abrupt change in DCCA axis-1 score that drops to 0 compare to an average score of 1.72 for the whole sequence (Fig. 6). Such big change in turnover value is considered as very significant in diatom ecology (Smol et al. 2005; Hobbs et al. 2010). Such increase in diversity may be a response to the warming trends as increased temperature leads to a longer growing season and more diverse micro-habitats in the lake. These changes provide more ecological niches for diatoms in both

temporal (seasonal) and spatial terms and so cause an overall increase in species diversity.

Finally, the high TOC and Mn content recorded in the uppermost sample (Fig. 4) do not signal that the lake has become eutrophic but most likely, reflect the fact that biochemical decomposition and diagenesis had not yet fully taken place and that Mn content has been affected by redox changes and enriched in the surface sediments. Similar peaks in Mn content at the sediment-water interface have been reported in previous studies. These peaks are due to the diffusion upwards from the deeper sediment of  $Mn_{(II)}$  and its re-oxidation to  $Mn_{(IV)}$  at the active redox interface where it can precipitate as rhodochrosite ( $MnCO_3$ ) and accumulate (Schaller et al. 1997; Torres et al. 2014).

#### Comparison with other diatom-based paleolimnological studies from China

To our knowledge there are only two diatom-based paleolimnological records that span the past 100 years from sites that are located at relatively short distance from Lake Kanas. The closest one was studied by Rudaya et al. (2009) who presented pollen and diatom analyses from Hoton-Nur Lake, also located in the Altai Mountains but in NW Mongolia. This study spans the whole Holocene and the resolution for the upper part of the sequence is much lower (one sample for every  $\sim 500$  years in the upper part of their sequence) than the one achieved here for Lake Kanas. The only element of comparison with the sequence from Lake Kanas, is the absence of diagnostic anthropogenic indicators in the Hoton-Nur diatom records which indicates that human disturbance of soils and vegetation cover was not significant in that region. The second study is that on Bosten Lake by Zhang et al. (2010). Again, the time resolution of the diatom record from that study is much lower for the last 100 years than the one achieved for Lake Kanas. In addition, Bosten Lake is located in the arid area of Xinjiang and is very different from Lake Kanas as it is a large shallow lake (mean water depth of 8 m) that is sensitive to change in temperature-controlled evaporation. Consequently, the diatom record in Bosten Lake reflects change in lake water salinity. Nevertheless a climate signal was deduced from this record as the large increase in the percentages of brackish diatoms that characterizes the uppermost section of the



record was interpreted as indicating warmer conditions.

From other regions of China in general, there are few diatom-based paleolimnological studies that span the same time interval and with a comparable sampling resolution as our study on Lake Kanas. One of them is the study by Liu et al. (2017) from Lake Gonghai that is located on the loess plateau in northern central China. The diatom record for this lake shows that in the 1960s took place a nearly complete shift in species dominance from large celled and heavier *Lindavia* taxa to the abrupt arrival and dominance of more buoyant *Cyclotella ocellata* and *Fragilaria tenera*. This shift among diatom taxa with similar nutrient optima, but different ecophysiological traits, was interpreted as indicative of the rise in mean air temperatures and concomitant increases in the lake water column thermal stability and attendant changes in resource availability.

The diatom sequences from lakes Erlongwan (Wang et al. 2012) and Xiaolongwan (Panizzo et al. 2013), two volcanic lakes located in NE China, also show increases in small planktonic diatoms (*Discostella* spp.) that are consistent with increased temperatures leading to strong thermal stratification of the water column.

Finally, the diatom sedimentary sequence from Lake Chenghai in Yunnan, SW China, also displays large shifts in assemblage for the recent past that may be related to solar forcing (Li et al. 2015). However, Wang et al. (2016) who studied the diatom assemblages from Lugu Lake, another lake on the Yunnan Plateau, found opposite species shifts compared to that observed in Lake Chenghai and therefore cautioned against generalizing among lake sites in relation to climate forcing. In addition, the diatom record in Lugu Lake is in part affected by a rise in nutrient supply associated with anthropogenic activities.

## Conclusions

The diatom and geochemical data presented here for Lake Kanas core KNS14B provide a detailed record of climatic and environmental change during the last ~ 100 years and reveals the water ecosystem response to the regional climate change. The aquatic ecosystem of Lake Kanas appears sensitive to the climate change with little direct human impact.

Regional warming is the main force that drives the ecological change of Lake Kanas. Its impact on the ecosystem is complex, however, as it affects not only the hydrology but also the lake hydrodynamic. The lake hydrology is mainly affected through the melting of the Kanas glacier and of snow patches on the lake catchment, while the effects of climate change on key limnological processes such as the duration of ice-cover and the intensity of mixing and thermal stratification of the water column impact the lake hydrodynamic. In addition to the complexity of Lake Kanas glaciolacustrine setting, planktonic diatoms such as *P. gordonensis*, the dominant species in Lake Kanas, do not respond directly to climate but to proximal growing conditions (a combination of nutrients, light, temperature, mixing regimes), which can appear or disappear under different combinations of factors forcing the lake system (Catalan et al. 2013). Nonetheless, the increase flux of *P. gordonensis* observed in Lake Kanas around AD 1970 matches with the average timing of ecological change observed in temperate lakes of the Northern Hemisphere in general (Rühland et al. 2008) and in some Chinese lakes in particular (Wang et al. 2012; Panizzo et al. 2013; Liu et al. 2017). Geochemical data showed some corresponding changes. Over the last ~ 20 years, the diatom community has changed further, although in a subtle way. The assemblages have remained dominated by *P. gordonensis* and *A. minutissimum* but species diversity and assemblage turnover has increased while the rate-of-change accelerated. Planktonic *Fragilaria* spp. have also become more abundant and suggest that the thermal stability of the euphotic zone was strengthened and/or that the delivery of nutrients such as nitrogen has increased (Tolotti et al. 2007; Holm et al. 2012; Slemmons et al. 2017a, b; Wolfe et al. 2013; Johnson et al. 2017).

Considering that the Altai Mountains are projected to experience significant warming throughout the century and that the Altai glaciers are predicted to continuously lose mass throughout the twenty-first century with large variations in meltwater discharge (Zhang et al. 2016) we should expect larger change in Lake Kanas ecosystem, and in particular its diatom community.

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