Impact of recent climate change on Lake Kanas, South of the Altay Mountains (Xinjiang, N.W. China) inferred from diatom and geochemical evidence

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Abstract Global warming is one of the most important environmental problems the world is facing and the changes it is causing on ecosystems is drawing great attention from scientists. In particular, how lake ecosystems, which are an important part of continental ecosystems, will change is a problem that needs to be investigated. 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 the past ~100 years. The lake has been affected by change in its hydrology (e.g. influx of glacier meltwater, variations in precipitation) and change in its 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.

Introduction

Global warming is one of the most important environmental problems that the world is facing. 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). Global warming is having a significant impact on the functioning and biodiversity of the natural ecosystems, including lakes, which represent an important component of the global ecosystem. Lakes are effective sentinels for climate change because they are sensitive to climate, respond rapidly to change, and integrate information about changes in their catchment (Adrian et al. 2009; Mills et al. 2017). Diatoms, which are among the most important primary producers in lakes, are often used as proxy indicators in paleoclimatic reconstructions because of their sensitivity to changes in their aquatic environment and the characteristics of their siliceous frustules that promote their preservation in the sediment record of lakes. Moreover, they can be identified to the species level based on the shape and ornamentations on the valves (Battarbee, 1986). Many arctic freshwater ecosystems have experienced dramatic and unidirectional regime shifts within the last ~150 years. In shallow lakes, these shifts can be characterized by taxonomically diverse and increasingly productive aquatic ecosystems, with more complex community and trophic structures. In deeper lakes, plankton development has been enhanced (Smol et al., 2005). In subarctic regions of Finland and Canada, under the forcing of global warming, the relative abundances of small-sized diatoms, such as *Cyclotella* spp., increased sharply, and was concurrent with decreases in heavily silicified *Aulacoseira* species and/or small, benthic taxa belonging to the *Fragilariaceae* (Sorvari and Korhola, 1998; Sorvari et al., 2002; Rühland et al., 2003; Rühland and Smol, 2005).

Regarding diatom species diversity, it seems that the response to climate change differs from lake to lake, as it appears to increase in some situations and decrease in others. This may be because the effects of recent temperature increases on freshwater ecosystems are blurred at temperate latitudes, as these regions are typically subjected to multiple stressors that can mask or override climatic signals (Smol, 2008). However, in remote regions where extensive anthropogenic disturbances are reduced, the effects of climatic fluctuations on physical, biological and chemical processes of freshwater ecosystems are more clearly evident (Schindler et al., 1996; Gerten and Adrian, 2002).

Lake Kanas (48°11'~49°11'N, 86°23'~88°05'E, 1370m) has great potential for studying the way aquatic ecosystems respond to climate change as it is located in the deep forests of the Altay Mountains and has been so far little affected by human activities. There are, however, few studies 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 of a short sediment core that spans the last ~100 years.

Study area

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 deep forests of the Altay Mountains (Fig. 1). It is a large and deep lake with a surface area of 45.73 km^2, about 24 km long and 2 km wide and its maximum and mean water depths are 188.5 m and ~100 m, respectively (Li, 1987). It is located at the junction between the Burqin and Habahe counties, in the most northern part of Xinjiang Province (Li, 1987) and is only 60 km away from Khüiten Peak (altitude 4374 m), the highest peak of the Altay 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). 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 $\mu S.cm^{-1}$) and dominated by calcium-carbonates with the following sequence of dominant cations $Ca^{2+}>Na^{+}>Mg^{2+}>K^{+}$ and anions $HCO_3^{-}>Cl^{-}>>SO_4^{2-}>NO_3^{-}$ (Zhu et al. 2013). The lake volume and surface area of this open system have been stable in the recent past (Wu et al. 2012).

As an alpine lake surrounded by the deep forests of the Altay Mountains, historically Lake Kanas has been barely influenced by human activities. 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 (Han et al. 2011; Yang et al. 2014; Shi & 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 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 over the period AD 1958-2014 recorded at the 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. Most of the rain falls 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 (48°53'34.01"N, 87° 7'50.47"E) using a Uwitec® modified piston corer. 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}Pb and ^{137}Cs at the γ 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}Pb gamma counts.

Geochemical analysis

The grain size and the content in 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. 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 was measured using a TOC Analyzer (Analytik Jena AG, Germany). Details of the method are given in Liu et al. (1996) and Bao et al. (2000).

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^2 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 (e.g. 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_2O_2 to remove organic matter (Renberg, 1990). Diatom concentrations (valves per g of dry matter) were calculated by the addition of divinyl-benzene microspheres (Battarbee and Kneen 1982). Diatom fluxes (in valves/cm^2/yr) were then calculated by multiplying the diatom concentration by the dry bulk density (in g/cm^3) and the sediment accumulation rate (in cm/yr). 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®. 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 & Lange-Bertalot (1986, 1988, 1991a, 1991b) 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* (recently renamed *Pantocsekiella gordonensis*). 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 & Gordon 1985) based on the diatom percentage data using the unpublished program ZONE (version 1.2) (Lotter & Juggins, pers. comm.).

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)(Hobbs et al., 2010). The DCCA analysis was performed using the program CANOCO 5 (ter Braak and Šmilauer 2012). 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).

Although biodiversity assessments would ideally require complete samplings, 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:

$$R(N) = S(1 - k''/N - k'''/N^2)$$

$$S = R\text{o} + 2 f_{1(N)} - f_{2(N)}$$

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

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

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.

4. Results

4.1 Chronology of the sequence

Unsupported ^{210}Pb activity ($^{210}Pb_{ex}$), which was calculated by substracting supported ^{210}Pb (as ^{226}Ra) activity from the total ^{210}Pb activity, declines irregularly with depth (Fig. 3). Equilibrium between the total ^{210}Pb activity and the supported ^{210}Pb is reached at the level 32-33 cm. Small irregularities in $^{210}Pb_{ex}$ 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 $^{210}Pb_{ex}$ is 64.4 ± 6.3 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 19XX by this method. The ^{137}Cs activity reaches a maximum value of 23.4 ± 0.6 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 AD 1962.8 ± 3.9.

There are considerable changes in sediment accumulation rates in the upper part of the core so it was not appropriate to extrapolate the ^{210}Pb chronology into the deeper part of the core using the average sediment accumulation rate (Appleby 2000).

4.2 Geochemical analyses

Core KNS14B was retrieved closed to the estuary of the River Kanas and also near the shore (Fig. 1c). Thus, 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. 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 and by fine silt (< 4 μm) in the upper part of the sequence. TOC of core KNS14B varied from 0.3 to 0.7% (mean value of 0.45%). nIts 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_2O, 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_2) and the Zr/Rb ratio are strongly and positively correlated with coarse particles ($r > 0.8$, $p < 0.01$, $\alpha = 0.001$). K_2O and to a lesser extend Fe_2O_3 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 AD1970s, 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.

4.3 Diatom analysis

In total, 300 species of diatoms were identified in the 51 samples. Only species with relative percentages >2% and that appeared in more than 3 samples are shown in the diatom stratigraphy in Fig. 4. In total, 25 species fulfilled these criteria, including 7 species of planktonic diatoms *Pantocsekiella gordonensis*, which is largely dominant throughout he sequence, *Aulacoseira ambigua*, *Discostella stelligeroides*, *Asterionella edlundii*, *Fragilaria gracilis*, *Fragilaria tenera* and *Fragilaria nanana* and 18 species of benthic diatoms including *Achnanthidium minutissimum* (which is the dominant benthic species), *Diatoma mesodon*, *Encyonema silesiacum*, *Encyonema minutum*, *Staurosirella pinnata*, *Fragilaria capucina*, *Gomphoneis pseudookunoi*, *Hannaea arcus var. amphioxys*, *Hannaea recta*, *Staurosira venter*, *Cocconeis placentula var. euglypta*, *Reimeria sinuata*, *Nitzschia perminuta*, *Fragilaria vaucheriae*, *Meridion circulare*, *Psammothidium subatomoides*, *Staurosira construens* and *Gomphonema sp.#1.* The sequence was divided into 5 DAZ using optimal partitioning on the percentage data. The maximum DCCA axis-1 score is 1.90 standard deviation. This indicates that the diatom community of Lake Kanas has a medium scale assemblage turnover. Such turnover value is considered as significant in diatom ecology (Smol et al., 2005; Hobbs et al., 2010). It indicates that over the last ~100 years, the aquatic ecosystem of Lake Kanas is sensitive to environmental change.

A summary diagram of diatom abundance plotted against core depth is shown in **Fig. 5**. Diatom flux, species diversity (observed and expected) and the results of rate-of-change analysis and the DCCA are shown in Fig. 6.

HERE MENTION THAT FULL NAMES WITH AUTHORITIES ARE LISTED IN A TABLE, IN APPENDIX.

DAZ 1: 51 – 20.5 cm, before ~AD 1916- to 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, S. pinnata, E. silesiacum, G. pseudookunoi* and *D. mesodon*. 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. stelligeroides* 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 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).

5. Discussion

Interpretation of geochemical proxy

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 palaeoenvironmental changes

Zone 1 (from before ~AD 1916- to 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 large (?) 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. These data indicate higher clay content and increased river input (Possibly(?)=meltwater). This is consistent with temperature reconstructions for the Northern Hemisphere that show that the AD 1940s were a warm interval (e.g. IPCC 2014). Simultaneously 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 & Håkansson 1988) and has also been found in similar settings in Europe (Wunsam et al. 1995; Hausmann & Lotter 2011) and the Far-East (Genkal & 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, 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, 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. Simultaneously, in the geochemical data we observed increases in Cu, Mn and Fe, elements that are indicators of bio-productivity and diagenesis (Fedotov et al. 2005; Stepanova et al. 2005). 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. This geochemical data suggest an increase in the influx of fine particules 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. 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 ± 0.02 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. 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. In the diatom record, only a slight decrease in the percentages of *P. gordonensis* occurred in that interval.

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}Ra. High ^{226}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 Fe_2O_3 would suggest increased weathering. The meteorological data indeed show that this interval had high precipitation and high summer temperature. 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 and there is an increase in species diversity, rate-of-change and turnover (DCCA). The slight decrease in diatom flux may reflect the "dilution" of diatom concentration in the sediment caused by the large 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.* 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 NO_3-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. 2915, 2016). The meteorological data, which indicate continuing high summer temperature and high precipitation for this zone, 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 ± 0.13 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.

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. The flux data however, indicate that the productions of both planktonic and benthic diatoms actually decline. In that interval meteorological data indicate that summer temperature generally remained high and that precipitation increased further. 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 global 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 Altay Mountain (Yang et al. 2017), while summer temperature remain 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. 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 so overall the species diversity increases.

Finally, the high TOC and Mn content recorded in the uppermost sample 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 Mn has been affected by redox changes in the surface sediments and enriched there.

6. 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. It 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. Global warming is the main force that drives the ecological change of Lake Kanas but its impact on the ecosystem is complex as it affects the hydrology, through the melting of the Kanas glacier and of snow patches on the lake catchment as well as the lake hydrodynamic by its effects on key limnological processes such as the duration of ice-cover and the intensity of mixing and thermal stratification of the water column. 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 (Rühland et al. 2008). Geochemical data showed some corresponding changes. Over the last ~20 years, the diatom community has changed further, although in the 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.

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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