ARTICLE IN PRESS

Quaternary Science Reviews xxx (2015) 1–16

Contents lists available at ScienceDirect

Quaternary Science Reviews

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

Late Quaternary vegetation and lake system dynamics in north-eastern Siberia: Implications for seasonal climate variability

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A R T I C L E I N F O

Article history:
Received 17 April 2015
Received in revised form
27 July 2015
Accepted 6 August 2015
Available online xxx

Keywords:
Diatoms
Pollen
Summer and winter temperature
Holocene Thermal Maximum
Aquatic and terrestrial ecosystems
Lake-ice cover

A B S T R A C T

Although the climate development over the Holocene in the Northern Hemisphere is well known, palaeolimnological climate reconstructions reveal spatiotemporal variability in northern Eurasia. Here we present a multi-proxy study from north-eastern Siberia combining sediment geochemistry, and diatom and pollen data from lake-sediment cores covering the last 38,000 cal. years. Our results show major changes in pyrite content and fragilarioid diatom species distributions, indicating prolonged seasonal lake-ice cover between ~13,500 and ~8900 cal. years BP and possibly during the 8200 cal. years BP cold event. A pollen-based climate reconstruction generated a mean July temperature of 17.8 °C during the Holocene Thermal Maximum (HTM) between ~8900 and ~4500 cal. years BP. Naviculoid diatoms appear in the late Holocene indicating a shortening of the seasonal ice cover that continues today. Our results reveal a strong correlation between the applied terrestrial and aquatic indicators and natural seasonal climate dynamics in the Holocene. Planktonic diatoms show a strong response to changes in the lake ecosystem due to recent climate warming in the Anthropocene.

We assess other palaeolimnological studies to infer the spatiotemporal pattern of the HTM and affirm that the timing of its onset, a difference of up to 3000 years from north to south, can be well explained by climatic teleconnections. The westerlies brought cold air to this part of Siberia until the Laurentide ice-sheet vanished 7000 years ago. The apparent delayed ending of the HTM in the central Siberian record can be ascribed to the exceedance of ecological thresholds trailing behind increases in winter temperatures and decreases in contrast in insolation between seasons during the mid to late Holocene as well as lacking differentiation between summer and winter trends in paleolimnological reconstructions.

1. Introduction

The Arctic is experiencing unprecedented warming (PAGES 2k consortium, 2013). During the Anthropocene warming has greatly exceeded the global average temperature increase, due to a mechanism called "Arctic amplification" (IPCC, 2013; Miller et al., 2010a). In northern Asia, the effect of recent climate warming is most intense in eastern Siberia (Jones et al., 1999). There, biosphere responses to climate change include not only shifts in geographical distribution but also extinction of species unable to adapt fast enough to new environmental conditions (MacDonald et al., 2008). Subrecent short-term climate changes are also associated with societal reactions, such as the disappearance of northern or alpine

Supplementary data are available at http://dx.doi.org/10.1594/PANGAEA.848906.

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http://dx.doi.org/10.1016/j.quascirev.2015.08.014

Please cite this article in press as: Biskaborn, B.K., et al., Late Quaternary vegetation and lake system dynamics in north-eastern Siberia: Implications for seasonal climate variability, Quaternary Science Reviews (2015), http://dx.doi.org/10.1016/j.quascirev.2015.08.014

human populations during historical cooling events (Grove, 2004; Kotlayakov et al., 2014; Wanner et al., 2011) or to the present threat to northern communities caused by permafrost degradation, increasing forest fires and other extreme events (AMAP, 2012). However, the climate at northern latitudes since the late-glacial period has been spatially variable and complex (Kaufman et al., 2004; Miller et al., 2010b) and modern Arctic landscapes are affected by recent climate change with varying severity (IPCC, 2014). A precise understanding of the spatial and temporal variability of the environmental history of the Arctic is thus necessary for the sustainment of favourable ecological and economic conditions and the better prediction of future scenarios.

Past climate change at a supra-millennial scale was driven by insolation anomalies, which resulted from cyclic changes to orbital parameters known as Milankovich cycles, whereas natural and anthropogenic controlled land-surface characteristics and greenhouse-gas emissions are the drivers of sub-millennial scale changes (Jones et al., 2009; Miller et al., 2010b; Wanner et al., 2011). Profound research on Holocene climate variability inferred from lake sediments has been reviewed and reported during the last decade (e.g. Kaufman et al., 2004; Kaufman et al., 2009; Miller et al., 2010b; Sundqvist et al., 2014; Wanner et al., 2008, 2011). Investigations of sediment cores from lakes in north-eastern Siberia are known from the Lena Delta area (Andreev et al., 2004; Biskaborn et al., 2013a; Laing et al., 1999; MacDonald et al., 2004; Pisaric et al., 2001; Porinchu and Cwynar, 2002) and its hinterland (Biskaborn et al., 2013b, 2012; Herzschuh et al., 2013; Müller et al., 2009, 2010; Popp et al., 2006). Synthesising these reports shows that climate development, especially in the early and mid Holocene, varied at local to regional scales and the so-called Holocene Thermal Maximum (HTM) is strikingly different across space and time. Temperature reconstructions during the mid to late Holocene in the Northern Hemisphere are, however, often based on summer proxies and biased due to insufficient differentiation between summer and winter temperatures (Meyer et al., 2015). In the literature cited above, climate reconstructions for Siberia are mainly based on terrestrial and aquatic bioindicators, but to understand better the role of winter and summer temperatures in the sedimentary and fossil record palaeolimnological studies should integrate the tight and complex hydrologic coupling between terrestrial and aquatic environments in boreal lake ecosystems (Engstrom et al., 2000).

The timing of climate changes, as reported for the western and eastern Arctic, is spatially asynchronous and knowledge gaps in millennial-scale climate variability still exist, particularly for large areas in north-eastern Siberia. In this paper we present a multi-proxy study combining sediment geochemistry, and diatom and pollen data from a lake-sediment archive in the lower Lena River area in north-eastern Siberia. Our objectives are (i) to reconstruct the depositional environment and to constrain the timing of major palaeoenvironmental changes during the last ~38,000 years at Lake Kyutyunda, (ii) to assess the influence of summer and winter climate conditions on terrestrial and aquatic indicators, and (iii) to reveal spatiotemporal patterns of major Holocene climate events by comparing our results with other palaeolimnological reconstructions from north-eastern Siberia.

2. Regional setting

Lake Kyutyunda (N 69°38′, E 123°38′, 66 m a.s.l.) is located 320 km south of the Lena Delta in the Molodo River valley and 45 km west of the Lena River in Yakutia, north-eastern Siberia, Russia (Fig. 1). The lake extends 2.2 km from north to south and 3 km from east to west, with a surface area of about 4.9 km^2. The deepest part in the centre of the smooth lake basin is ca. 3.5 m. The estimated average water depth is ca. 2.5 m.

Lake Kyutyunda is on the central Siberian Plateau near the transition to the Verkhoyansk mountain region. The study area is situated in the northern taiga zone, approximately 120 km south of the present treeline. The vegetation is characterised by an open *Larix* forest intermixed with shrub-tundra. According to the geological map of Yakutia (Prokopiev et al., 1999) the bedrock of the catchment mainly consists of Middle Jurassic sandstone and unconsolidated sands (Kystatymskaya suite). The western and northwestern shore of the lake is underlain by Pliocene and Lower and Upper Pleistocene sands and gravels (Prokopiev et al., 1999). These deposits are identified as alluvium – the remains of flood-plain terraces of the Molodo River (Geological map of the USSR, Vysotsky (1970)). Clear evidence of a former river bed identified from LANDSAT imagery (Fig. 1) and confirmed by field observations, as well as the lake's close proximity to the Molodo River, indicate a fluvial-erosion thermokarst lake (Pestryakova et al., 2012). Soils in this area are predominantly north-taiga gley and gleyic undifferentiated soils (Agricultural Atlas of the Yakut ASSR, Matveev (1989)). We observed dune sands west of the lake and different peat generations at the southern and western shoreline. Permafrost in this region reaches down to a maximum of 700 m (Kondratieva, 1989). During fieldwork in summer 2010, the active layer was about 50 cm deep.

The recent climate in northern Siberia is strongly influenced by the track of the westerlies. During winter, the region lies roughly between the 'Siberian High' and the Laptev Sea coast (MacDonald et al., 2000).

The area is characterised by a pronounced continental climate. Present-day mean July and January temperatures for the Lena hinterland are at the coast 8 °C and −36 °C, respectively with a mean annual temperature of about −14 °C; maximum July and minimum January temperatures are 30 °C and −60 °C (Shahgedanova, 2002). Southwards, at the town of Yakutsk, with increasingly continental climate mean July and January temperatures are 19.5 °C and −38.6 °C, respectively, with a mean annual temperature of about −8.8 °C. However, modern temperatures based on MODIS satellite imagery and the interpolated WORLDCLIM data at the study location indicate mean July temperatures between 13 °C and 15 °C (Duguay et al., 2012; Hijmans et al., 2005). Annual precipitation in the Lena Delta region is mainly represented by summer rainfall of about 200 mm (Boike et al., 2008). Direct precipitation, run-off, and one small inflow coming from a smaller lake 4.5 km east feed the lake. One small outflow drains from the south-western side of the lake towards the Molodo River, 3.4 km to the west. During summer it is likely that the lake is permanently mixed (polymictic).

3. Materials and methods

3.1. Field work

Sediment cores were taken during a helicopter expedition to Lake Kyutyunda between August 17 and September 3, 2010. Lake basin bathymetry was measured with a portable Depthmate SM-5 Echo Sounder to locate the appropriate coring site at a deep and undisturbed part of the basin. Water samples for hydrochemical analyses of the water column were collected from the core site before and after sediment coring, to avoid biased data due to suspension load. Immediately after collection, the water samples were analysed using a WTW Multilab 340i for pH, conductivity, and oxygen values. A sub-sample of the original water was passed through a 0.45 µm filter, and then stored and transported in 60-ml Nalgene polyethylene bottles for subsequent anion and cation analyses. Cation samples were acidified with HNO_3 in the field.

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