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The relative influences of climate and volcanic activity on Holocene lake development inferred from a mountain lake in central Kamchatka

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ABSTRACT

A sediment sequence was taken from a closed, high altitude lake (informal name Olive-backed Lake) in the central mountain range of Kamchatka, in the Russian Far East. The sequence was dated by radiocarbon and tephrochronology and used for multi-proxy analyses (chironomids, pollen, diatoms). Although the evolution of Beringian climate through the Holocene is primarily driven by global forcing mechanisms, regional controls, such as volcanic activity or vegetation dynamics, lead to a spatial heterogeneous response. This study aims to reconstruct past changes in the aquatic and terrestrial ecosystems and to separate the climate-driven response from a response to regional or localised environmental change. Radiocarbon dates from plant macrophytes gave a basal date of 7800 cal yr BP. Coring terminated in a tephra layer, so sedimentation at the lake started prior to this date, possibly in the early Holocene following local glacier retreat. Initially the catchment vegetation was dominated by *Betula* and *Alnus* woodland with a mosaic of open, wet, aquatic and semi-aquatic habitats. Between 7800 and 6000 cal yr BP the diatom-inferred lake water was pH 4.4–5.3 and chironomid and diatom assemblages in the lake were initially dominated by a small number of acidophilic/acid tolerant taxa. The frequency of *Pinus pumila* (Siberian dwarf pine) pollen increased from 5000 cal yr BP and threshold analysis indicates that *P. pumila* arrived in the catchment between 4200 and 3000 cal yr BP. Its range expansion was probably mediated by strengthening of the Aleutian Low pressure system and increased winter snowfall. The diatom-inferred pH reconstructions show that after an initial period of low pH, pH gradually increased from 5500 cal yr BP to pH 5.8 at 1500 cal yr BP. This trend of increasing pH through the Holocene is unusual in lake records, but the initially low pH may have resulted directly or indirectly from intense regional volcanic activity during the mid-Holocene. The chironomid-inferred July temperature reconstruction suggests cool periods between 3200–2800 cal yr BP and 1100–700 cal yr BP and a warmer period between 2800 and 1100 cal yr BP. Chironomid and diatom DCA scores decline from ca. 6000 cal yr BP, indicating compositional changes in these aquatic assemblages. In comparison declines in pollen PCA scores are delayed, starting ca. 5100 cal yr BP. The results suggest that while catchment vegetation was responding primarily to climate change, the biota within the lake and lake water chemistry were responding to localised environmental conditions.

1. Introduction

The climate and environmental history of Beringia (northeast Russia, Alaska, and northwestern Canada), and Kamchatka in particular, is poorly known at present due to a lack of records from this region. This is a serious gap in our understanding of past climate change and the nature of climatic teleconnections between the North Atlantic and the North Pacific. Sea surface temperature suggests a close atmospheric coupling between the North Pacific and North Atlantic until 10,000 cal yr BP, as evidenced by similarities in the NGRIP oxygen isotope record and reconstructed sea-surface temperatures from the western Bering Sea, NW Pacific and Sea of Okhotsk (Max et al., 2012). However, during the last 7000 years sea surface temperatures in the North Pacific have shown more complex variations, suggesting a strong regional overprint (Max et al., 2012). Climate models suggest that while evolution of the Beringian climate through the Holocene was largely driven by global forcing mechanisms, such as the amplified seasonal

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cycle of Northern Hemisphere insolation and changes in global ice volume and atmospheric composition, regional-scale controls strongly mediated these responses and generated considerable spatial heterogeneity (Bartlein et al., 2015). Furthermore models indicate that the replacement of tundra by deciduous woodland produces additional widespread warming, whereas the development of thaw lakes produces modest and localised cooling in summer and warming in winter (Bartlein et al., 2015). In addition, many areas of Beringia are, or have been, volcanically active during the Holocene (Barr and Solomina, 2014). Volcanic ash falls influenced vegetation development on a local scale by arresting or delaying forest expansion which may obscure the climate response (Dirksen and Dirksen, 2009). The interaction of these controls, acting at differing spatial and temporal scales, leads to a complex and spatial heterogeneous climatic response during the Holocene and problems in generalising palaeoclimatic trends from a limited number of sites (Mock et al., 1998; Yamamoto et al., 2007). These results also highlight the importance of reconstructing past changes in the aquatic and terrestrial ecosystems to separate the climate-driven response from a response to regional or localised environmental change.

The Kamchatka Peninsula, in the far east of Russia, protrudes into the North Pacific Ocean and is ideally situated to be responsive to climatic fluctuations driven by ocean and atmospheric currents. The modern climate of Beringia is influenced mainly by the relative strength and position of the Siberian High and Aleutian Low (Mock et al., 1998). In summer it is also influenced by the intensity of the North Pacific High and sea ice in the Sea of Okhotsk which brings cold air and competes with the summer monsoonal influence (Kurita et al., 2003). Until recently palaeoenvironmental and palaeoecological studies in Kamchatka have been limited to reconstructions of Pleistocene and Holocene vegetation dynamics (Dirksen and Uspenskaia, 2005; Dirksen and Dirksen, 2008, 2009; Dirksen et al., 2013 and references therein) and glacial dynamics (Zech et al., 1997; Savoskul, 1999). Changes in the late Holocene climate have been inferred from tree rings, marginal moraines and ice-core records (Solomina et al., 2007; Barr and Solomina, 2014). Many of these records (Mock et al., 1998; Yamamoto et al., 2007; Dirksen and Dirksen, 2009) and climate models (Renssen et al., 2009) have highlighted the complexity and spatial heterogeneity of responses to climate and environmental change in Kamchatka over the Holocene.

Hoff et al. (2012) and Nazarova et al. (2013) studied diatoms and chironomids respectively in lakes within central Kamchatka, approximately 100 km north-east of the current study area. Chironomid assemblages have been widely used to infer late-glacial and Holocene temperature trends (Brooks, 2006). However their response to temperature can be confounded by changes in catchment vegetation and/or lake water chemistry, such as pH (Nyman et al., 2008; Velle et al., 2010). Diatoms are valuable quantitative indicators of lake water chemistry, especially pH and total phosphorus (TP), as well as providing valuable information on the duration of the ice-free period and summer temperatures (Korhola et al., 2000; Clarke et al., 2005). The records derived from the two proxies are therefore complementary. The diatom record also helps to disentangle any responses to volcanic ash falls, which may have resulted in changes to water chemistry, light availability and habitats, from a response to climate change. While pollen and spore analyses are used to determine changes in catchment vegetation. Therefore our multiproxy study enables us to interpret both terrestrial vegetation dynamics and lacustrine responses to catchment maturity and multiple stressors, such as climate change and volcanic eruptions.

Olive-backed Lake (693 m.a.s.l) was selected for study as it lies close to the lower altitudinal limit of Siberian dwarf pine, *Pinus pumila* (Pallas) Regel. *P. pumila* is a key species for studies of past climate changes in western Beringia, particularly precipitation amount and seasonality dynamics (Anderson et al., 2010; Lozhkin and Anderson, 2011; Hammarlund et al., 2015-in this issue). This coniferous shrub is the dominant species in the subalpine zone of the Sredinny and Eastern Mountain Ranges of the Kamchatka Peninsula (Krestov, 2003). In these ranges it occurs as a continuous shrub belt or scattered thickets at an altitudinal range of 700–1200 m a.s.l., reaching maximum altitudes of approximately 1400 m a.s.l. in the slightly more continental climatic setting of the interior (Khomentovsky, 2003). Its abundance in Kamchatka is assumed to reflect the generally cool and maritime subarctic climate, which typically produces a thick and late-melting snow cover that favours the species by protecting its leaves and branches from desiccation and wind damage during the winter and spring seasons before the onset of photosynthesis (Okitsu and Ito, 1984, 1989). The location of Olive-backed Lake near the ecotonal boundary of *P. pumila* suggests the vegetation in its catchment is likely to be sensitive to shifts in vegetation zones and/or climate. This study forms part of a larger project to document Holocene climate change across Kamchatka Peninsula (Brooks et al., 2015-in this issue). Here we present the results of a multiproxy study of a lake sediment record from central Kamchatka which includes analyses of pollen, diatoms and chironomids to infer past changes in catchment vegetation, lake water chemistry and primary productivity and past summer temperature.

2. Regional setting

Olive-backed Lake is situated approximately 30 km north of the settlement of Esso, in the valley of the Zapadnyi Range, within the central Sredinnyi Range (56° 12.0740 N; 158° 51.4930 E, Fig. 1a). The lake lies at an altitude of 693 m a.s.l. with surrounding mountains reaching elevations of c. 1000 m. Olive-backed Lake consists of a single closed basin c. 200 x 100 m with a maximum water depth of 3 m. During fieldwork in July 2005, a single measurement showed the lake water was circum-neutral (pH 6.7) and dilute (conductivity 8 μS) with a water temperature of 20.5 °C. The catchment geology consists of Pleistocene basalts, andesites and tuffs. The volcano Anaun, active during the late Quaternary, lies 12 km north of the lake and geochemical analyses have revealed the presence of Opala, Ksudach and Khangar ash deposits in the sediments of Olive-backed Lake (Plunkett et al., 2015-in this issue). These three volcanoes are located approximately 350 and 190 km respectively to the south of the study site. The surrounding region of Kamchatka has 24 clusters of hydrothermal springs (Murcott, 2012) with the closest hot geothermal springs located 4 km north of Esso. The geothermal waters are weakly acidic or weakly alkaline (pH 5.9-7.8) with average mineralisation of 3.7-12 g l^{-1} (Murcott, 2012).

The central interior regions have a relatively dry climate with strong seasonal variations in temperature (Ivanov, 2003). Between 1983 and 2005 mean air temperature at Esso (55° 55′N, 158° 42′E, 479 m.a.s.l) for the warmest month (July) was 14.6 °C and −19.6 °C for the coldest month (January) (http://kamchatka-meteo.ru). Mean monthly precipitation at Klyuchi, 139 km north of Esso, varied between 32 and 66 mm/month for the period 1961–1990 (http://climexp.knmi.nl). This is fairly uniformly distributed throughout the year with a minimum between April and June.

In Kamchatka, forests generally occupy the land up to 600–880 m.a.s.l., with *P. pumila* and *Alnus viridis* thickets extending to 1200–1400 m.a.s.l (Khomentovsky, 2003). This is succeeded by alpine meadows, mountain tundra and volcanic landscapes. However the distribution of vegetation is dependent on the local climate which shows strong longitudinal variation between the coastal and central regions. Within the altitudinal shrub belt *P. pumila* dominate in sunny dry areas and *A. viridis* in shady and moist areas (Ivanov, 2003). At Olive-backed Lake the surrounding vegetation is dominated by arctic-alpine species of the mountain tundra and taiga zones (Klimaschewski, 2010). *P. pumila* dominates the sheltered slopes of the catchment, with pine and pine-alder mixtures at lower altitudes, and scattered larch stands (Fig. 1b).

3. Material and methods

Sediment cores were collected in July 2005 from a rubber raft situated in the central part of the lake, at 3 m water depth, using a 5 cm piston