Global and Planetary Change xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Global and Planetary Change

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

Evidence of global pollution and recent environmental change in Kamchatka, Russia

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ARTICLE INFO

Article history:
Received 30 September 2014
Received in revised form 5 February 2015
Accepted 10 February 2015
Available online xxxx

Keywords:
Kamchatka
Pollution
Diatom
Chironomid
Mercury
Spheroidal carbonaceous particles

ABSTRACT

Kamchatka is a remote, isolated and understudied area and is presumed to be pristine. Here we present the first high-resolution palaeolimnological investigation of the recent past. A short core representing the last 250 years was taken from Olive-backed Lake situated in central Kamchatka. Lead-210 dating revealed that sediment accumulation has increased at the site since the 1960s and may be related to greater rates of catchment erosion associated with wetter winters in the region. Mercury and spheroidal carbonaceous particle (an unambiguous indicator of fossil fuel combustion) concentrations are low but clearly detectable indicating that both regional and global pollution sources are observed at this site. The recent increase in the flux of mercury is more related to catchment sources and catchment erosion than increases from regional or global sources. The diatom and chironomid populations are stable and do not show any statistically significant changes related to either the low levels of pollution, or to temperature and precipitation changes. The lake is not pristine since anthropogenic contamination has occurred but since there have been no significant effects on the flora and fauna the lake can be considered to be unimpacted. Olive-backed Lake may be a suitable reference site to benchmark the natural variability of a lake ecosystem.

1. Introduction and aims

In many regions of the world, lakes are now more controlled by anthropogenic forcing than by natural drivers (Wilkinson et al., 2014) and it has even been suggested that stratigraphic changes observed in lake sediments such as changes in isotopic or diatom composition could be used to characterise the start of the proposed Anthropocene era (Wolfe et al., 2013; Dean et al., 2014). While we do not want to enter here into the wider debate of whether a 'golden spike' can be defined it is useful to consider the extent to which remote lakes are impacted by human activity and whether any can still be considered 'pristine'. This is especially true in understudied regions such as much of South America, Africa, South East Asia, the Polar Regions and the Russian Far East.

Definitions of 'pristine' are varied but for a lake ecosystem we suggest that it should describe a situation where there is little detection of local or long-range anthropogenic contamination sources and no significant anthropogenic impacts on sensitive elements of the flora and fauna and upon ecosystem functioning. However, there is a need to acknowledge that the pristine state is not static but varies naturally on a range of timescales due to internal and external forcings, and therefore sometimes changes are difficult to attribute solely to either natural or anthropogenic causes (Bennion et al., 2011a).

Palaeolimnological reconstructions have been an important means of both defining reference conditions, and measuring deviations from them (Bennion et al., 2011a). In Western Europe reference conditions are usually defined as those existing around 1800–1850 CE (all subsequent dates are CE; Common Era), prior to the first evidence of major human impact. In areas where human influence has occurred for millennia these reference conditions are not the same as the pristine state of a lake but are acknowledged as a pragmatic and realistic target for lake restoration (Bennion et al., 2011a). The study of lakes from areas where there are no direct anthropogenic influences in their catchments can help inform the benchmarks of natural variability as well as assessing impacts of global and regional pollution.

In the absence of monitoring data this palaeolimnological approach may also be helpful to determine whether there is a pollution signal in the lakes and if there has been an impact of that pollution on the aquatic ecosystem (Smol, 2008). Indeed stratigraphical analyses may be the only way of determining if changes have occurred, their magnitude and the time-scale (Simola et al., 1991). Therefore there is a role of exploratory studies to determine the extent to which lakes in an

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http://dx.doi.org/10.1016/j.gloplacha.2015.02.005

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understudied region may have been impacted by pollution and/or climate change and to assess baseline conditions.

Since the adoption of the European Water Framework Directive (WFD) (European Union, 2000) there has been an expansion of freshwater ecosystem research and palaeolimnological studies devoted to the establishment of 'reference conditions'. These can be seen as a measure of 'biological integrity' (Karr, 1991) and an assessment of the baseline state of a lake in the absence of human activity. Reference conditions are defined by the WFD as having only very minor anthropogenic impacts and are used to "anchor judgements of change" (Bennion et al., 2011b:416).

The Kamchatka region is remote; until 1990 it was a closed area inaccessible to both foreigners and Russians, and our knowledge of recent environmental change there, is almost non-existent. There have been no published palaeolimnological studies of recent environmental change, and pollution studies are scant. The Kamchatka area is considered to be 'pristine' by van Zoelen (2002) who attributes the preservation of an 'ecologically pristine wilderness area' to the consequences of it being a closed area for many decades allowing for example, large populations of the Kamchatkan brown bear (*Ursus arctos beringianus*) to persist.

1.1. Pollution sources and recent climate change in Kamchatka

There are few air quality monitoring stations in Russia and peer-reviewed pollution studies are limited (Henry and Douhovnikoff, 2008). Henry and Douhovnikoff (2008) suggest that there is a consensus amongst experts that the official estimates of pollutants are lower than independently derived values and they also point to a dichotomy between evaluations of most of Russia not being affected by humans, to Russian cities being amongst the most polluted in the world. The persistent gap between Russia's strong environmental protection laws on paper and their weak enforcement in practice has been a frequent criticism since the Soviet period (Henry and Douhovnikoff, 2008). Characterising Russia's current environmental status as well as determining which environmental problems are the most important, is thus of wide interest.

Most local industrial activity in Kamchatka is concentrated in the Avacha Bay area where about 70% of the population lives (see Jones this issue), mainly in the city of Petropavlovsk–Kamchatsky and the nearby ports and naval bases. Local sources of pollution include nuclear wastes from shipyards and naval bases (Moltz et al., 2004) and wastes from fish processing and mining. The extensive use of geothermal energy means that fossil fuel burning is not common, for example the village of Esso has geothermal central heating for the homes (Gledhill, 2007) and anthropogenic nitrogen (NOx) and sulphur emissions from the area are estimated from models to be low (Ryaboshapko et al., 1998). There is limited evidence of pollution effects on the coastal macrobenthos (Klotchkova and Berezovskaya, 2000), but information about local pollution impacts is scant and limnological data for this vast region is limited (Henry and Douhovnikoff, 2008). Halmer et al. (2002) suggest that Kamchatka's volcanoes emit considerable amounts of sulphur, important in terms of global budgets, but the local impacts of these are unknown.

In terms of longer distance pollution sources, Kawamura et al. (2012) found an abrupt increase in the concentration of total organic carbon from the late 1970s to the early 1990s in an ice core from the Ushkovsky ice cap in central Kamchatka. This abrupt increase may have been caused by increased anthropogenic activity in East Asia, followed by long-range atmospheric transport to Kamchatka. The industrial development of east Russia (e.g., Siberia and the Far East) started at the beginning of the 20th century, with for instance, the completion of the Siberia railroad in 1905. Economic growth in east Russia and northeast China has accelerated in recent years which suggests that there may be enhanced deposition in the region of organic matter from forest fires and biomass burning (Kawamura et al., 2012).

An ethnographic study based on interviews of inhabitants from two remote rural areas in Kamchatka (Esso and Anavgai villages) suggested that people are concerned about the worsening of environmental conditions and environmental degradation (Graybill, 2013). For example, people mentioned changes in the quantity, quality and location of salmon; changing berry abundances, and difficulty in locating ferns (paparatniki) in the forest. Some of these observations were related by the interviewees to anthropogenic environmental change that they had noted (e.g., pollution and degradation), but most people felt that most changes they perceived to be happening on Kamchatka were natural and not related to human influences or climate change (Graybill, 2013).

Over the period covered by ^{210}Pb dating (the last c. 150 years), climate change is inferred from glaciological and dendrochronological evidence (Solomina et al., 2007; Sano et al., 2009) indicating warming temperatures and glacial retreat during the 20th century. Tree-ring data suggest that the 1860s–1880s comprised the longest coldest interval in the last 350 years (Solomina et al., 2007) with an early summer cooling of about 1.5 °C compared to the mid 20th century (Gostev et al., 1996). The latest part of this period (1880s) coincided with increased precipitation, a positive glacier mass balance and glacier advances and moraine deposition (Solomina et al., 2007). See Jones this issue and Solomina this issue for further details of past climate variation.

1.2. Rationale for this study

Lakes and their catchments respond to changes in climate and pollution inputs and some of these responses are recorded in the sediment record. Well-dated and well-resolved stratigraphic records can thus provide a natural archive of anthropogenic pollutants deposited to a lake and its catchment. The analysis of spheroidal carbonaceous particles (SCPs) and mercury (Hg) in lake sediments can give valuable records of atmospheric contamination; with Hg giving a global pollution signal and SCPs reflecting regional industrial fossil fuel combustion.

Mercury is a volatile element and has been shown to be subject to long range transport (Mason et al., 1994). Due to its long atmospheric life-time, mercury is a global pollutant and has been found at contamination levels in recent sediments in remote lakes around the world (Fitzgerald et al., 1998; Biester et al., 2007; Yang et al., 2010a) where a three-fold increase in Hg deposition since preindustrial times has been observed in isolated areas (Lindberg et al., 2007; Yang et al., 2010b). However, there is an absence of lake sediment Hg records in many parts of the world including some remote areas such as Kamchatka and therefore our confidence in historical Hg accumulation trends can be improved by including such new sites. Although Hg is a global pollutant it may also be affected by local or regional sources and its distribution in lake sediments can provide basic information to assess Hg pollution history and possible sources. These additional empirical data from remote areas are needed to extend our knowledge by for example, confirming current estimates and providing ground truth for global models.

Spheroidal carbonaceous particles (SCPs) are a component of fly-ash, the particulate product of the incomplete combustion of coal-series fuels and heavy oil at industrial temperatures. SCPs have no natural sources, are morphologically distinct, and therefore provide unambiguous evidence for contamination from high-temperature fossil-fuel combustion (Rose, 2001). In sediment studies, SCPs have been extensively used to identify spatial and temporal patterns of atmospherically deposited contamination, and show good correlations with the distributions of other atmospherically deposited pollutants (e.g. Rose and Juggins, 1994; Fernandez et al., 2002). Despite their size (typically 2–20 μm), their presence has been recorded in the sediments of many remote lakes in both northern and southern hemispheres (e.g., Bindler et al., 2001; Rose et al., 2004, 2012) where they have proved useful in identifying anthropogenic influences while their large, and frequently porous, surface areas result in them being

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considered an important means by which toxic pollutants such as trace metals and persistent organic pollutants (Wey et al., 1998; Ghosh et al., 2000) may be atmospherically transported and deposited.

The impact of changing pollution and climate can also be seen on biotic components preserved in lake sediments. Diatoms (Bacillariophyceae) are often abundant and well-preserved in lake sediments because their siliceous outer shells, or frustules, are resistant to decay. They are amongst the most widely used biological indicator species having well-documented ecologies and being sensitive to changes in habitat and lake water chemistry, for example pH, nutrients and salinity (Jones, 2013). In Europe and North America diatoms have been widely used to assess whether lakes have been affected by anthropogenic acidification or eutrophication (Bennion et al., 2004; Battarbee et al., 2010) and have been used to determine reference conditions for lakes (Leira et al., 2006; Bennion et al., 2011a). Recently there has been greater realisation of the importance of multiple stressors, including climate change, acting on lakes (Smol, 2010), which may complicate diatom responses and make simple interpretations difficult.

The chitinous head capsules of chironomid larvae (Insecta: Diptera) are also often abundant and well-preserved in lake sediments. Their records have been used to infer past temperatures in Western Europe and North America (see reviews in Brooks, 2006; Walker and Cwynar, 2006) and more recently in northern Russia (Nazarova et al., 2011; Self et al., 2011) and Kamchatka (Nazarova et al., 2013). Multiple stressors, such as changes in nutrient availability, anoxia or pH, may also cause changes in chironomid assemblages (Velle et al., 2010, 2012) and thus the chironomid record needs to be interpreted within a multiproxy framework, using autoecological data (Brooks et al., 2012).

The aim of this paper is to provide the first assessment of the extent and temporal scale of atmospherically deposited contamination and ecological change in this remote area of Kamchatka using lake sediments as a natural archive.

2. Regional setting

Olive-backed Lake (informal name) (56° 12.0740 N; 158° 51.4930 E) is a shallow (maximum depth 3 m) small (ca. 2 ha) lake located ca. 350 km north of Petropavlovsk in the centre of Kamchatka. It lies at an altitude of 704 m in the valley of the Kuyul River a tributary of the Kamchatka River and is surrounded by mountains which reach elevations of about 1000 m (Fig. 1). The nearest settlement is the small village of Esso (population 2560, Russian Census 2010) which lies about 32 km to the SSW. The lake is remote; there is a dirt track about 0.5 km away which ultimately joins the road that leads to Esso, but the lake can't be accessed by vehicles. The site was visited and sampled by Dan Hammerlund (University of Lund) and colleagues who arrived by helicopter. They report no signs of human activity in the catchment or in the vicinity. The catchment geology is characterized by Quaternary basalts, andesites and their tuffs. The site is remote with no anthropogenic activities in the catchment or nearby. The area is very volcanically active and the volcano Anaun, active during the Holocene, lies 12 km to the north and reaches up to 1829 m. Tephra analyses of Holocene sediments show the presence of Ksudach and Khangar ash deposits (see Plunkett this issue, see Jones et al. this issue) but no tephra studies were completed on the recent core. Although situated in an area of low relief the catchment itself has some relatively steep 'active' slopes with scree and rock (Klimaschewski, 2010) especially in the area to the east of the lake (Fig. 1b) on an end moraine. The catchment is dominated by arctic–alpine vegetation of the mountain tundra and taiga zone and by pine and alder–pine mixtures of the brushwood zone (Klimaschewski, 2010). There is a fairly wide littoral with fringing macrophytes; mainly Cyperaceae. The lake is closed, lacking any obvious inflow or outflow and δ^{18}O analysis of lake-water showed moderate isotopic enrichment in summer (Hammarlund et al. this issue). During fieldwork in July 2005, spot measurements showed that the lake water was circum-neutral (pH 6.70) and dilute (conductivity 8 μScm^{-1}) with a water temperature of 20.5 °C. An exposed shore zone due to lake-level drawdown of maybe 0.5 m was also observed at this time.

The climate is sub-continental to sub-maritime. The nearest meteorological station is at Esso about 30 km to the south; but this station only has limited data. Between 1983 and 2005 mean air temperature at Esso for the warmest month (July) was 14.6 °C and −19.6 °C for the coldest month (January) (http://meteo.ru/english/index.php) accessed in 30/09/14). However, longer records (1907–present) are available at Kluchy, 139 km north of Esso. Here precipitation varied between 32 and 66 mm/month for the period 1961–90 and is fairly uniformly distributed throughout the year but with a minimum between April and June. There has been about a 20% increase in winter (DJF) precipitation in central Kamchatka since the 1930s (Solomina et al., 2007). Temperature records from Kluchy also show slightly increasing summer (JJA) temperatures since the 1980s with a coherence in the smoothed temperature records with the Pacific Decadal Oscillation (PDO) showing a period of colder temperature between ca. 1940–1980 (Solomina et al., 2007).

3. Materials and methods

A 20 cm core (Fig. 1c) was taken in 2005 from the middle and deepest part of the lake using a gravity corer, extruded at 1 cm intervals, and stored in a cold room at 4 °C. Samples were weighed, dried at 105 °C, and reweighed to obtain the water content, heated for 2 h at 550 °C, cooled and reweighed to measure the % loss-on ignition (%LOI), an estimate of the organic content of the sediment.

Lead-210 (half-life is 22.3 year) is a naturally-produced radionuclide, derived from atmospheric fallout (termed unsupported ^{210}Pb). Caesium-137 (half-life is 30 years) and Americium-214 are artificially produced radionuclides, introduced to the study area by atmospheric fallout from nuclear weapons testing, and which have been extensively used in the dating of recent sediments. Dried sediment samples were analysed for ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am by direct gamma assay in the Environmental Radiometric Facility at UCL, using ORTEC HPGe GWL series well-type coaxial low background intrinsic germanium detector. Lead-210 was determined via its gamma emissions at 46.5 keV, and ^{226}Ra by the 295 keV and 352 keV gamma rays emitted by its daughter isotope ^{214}Pb following three weeks storage in sealed containers to allow radioactive equilibration. Caesium-137 and ^{241}Am were measured by their emissions at 662 keV and 59.5 keV (Appleby et al., 1986). The absolute efficiencies of the detector were determined using calibrated sources and sediment samples of known activity. Corrections were made for the effect of self absorption of low energy gamma rays within the sample (Appleby et al., 1992).

For mercury analysis freeze-dried samples were digested with 8 ml *aqua regia* at 100 °C on a hotplate for 2 h in rigorously acid–leached 50 ml polypropylene digestion tubes. Standard reference material, stream sediment GBW07305 (certified Hg value is 100 ng g^{-1}; our measured mean value is 108 ng g^{-1} RSD = 1.5 ng g^{-1} (n = 2)) and sample blanks were digested with every 20 samples. Digested solutions were analysed for Hg using cold vapour–atomic fluorescence spectrometry (CV–AFS) following reduction with $SnCl_2$. Standard solutions and quality control blanks were measured in every five samples to monitor measurement stability.

SCPs were extracted following the method developed by Rose (1990). Sediment samples were subjected to sequential chemical attack using HNO_3, HF and HCl to remove organic material, silicate and carbonate minerals, respectively. A known fraction of the resulting suspension was evaporated onto coverslips and mounted on microscope slides. The number of SCPs was counted under a light microscope at 400 times magnification using the identification criteria described in Rose (2008). The concentrations of SCPs in the sediment were calculated as 'number of particles per gram dry mass of sediment' (g DM^{-1}) and fluxes as the 'number of SCPs per square centimetre per year'

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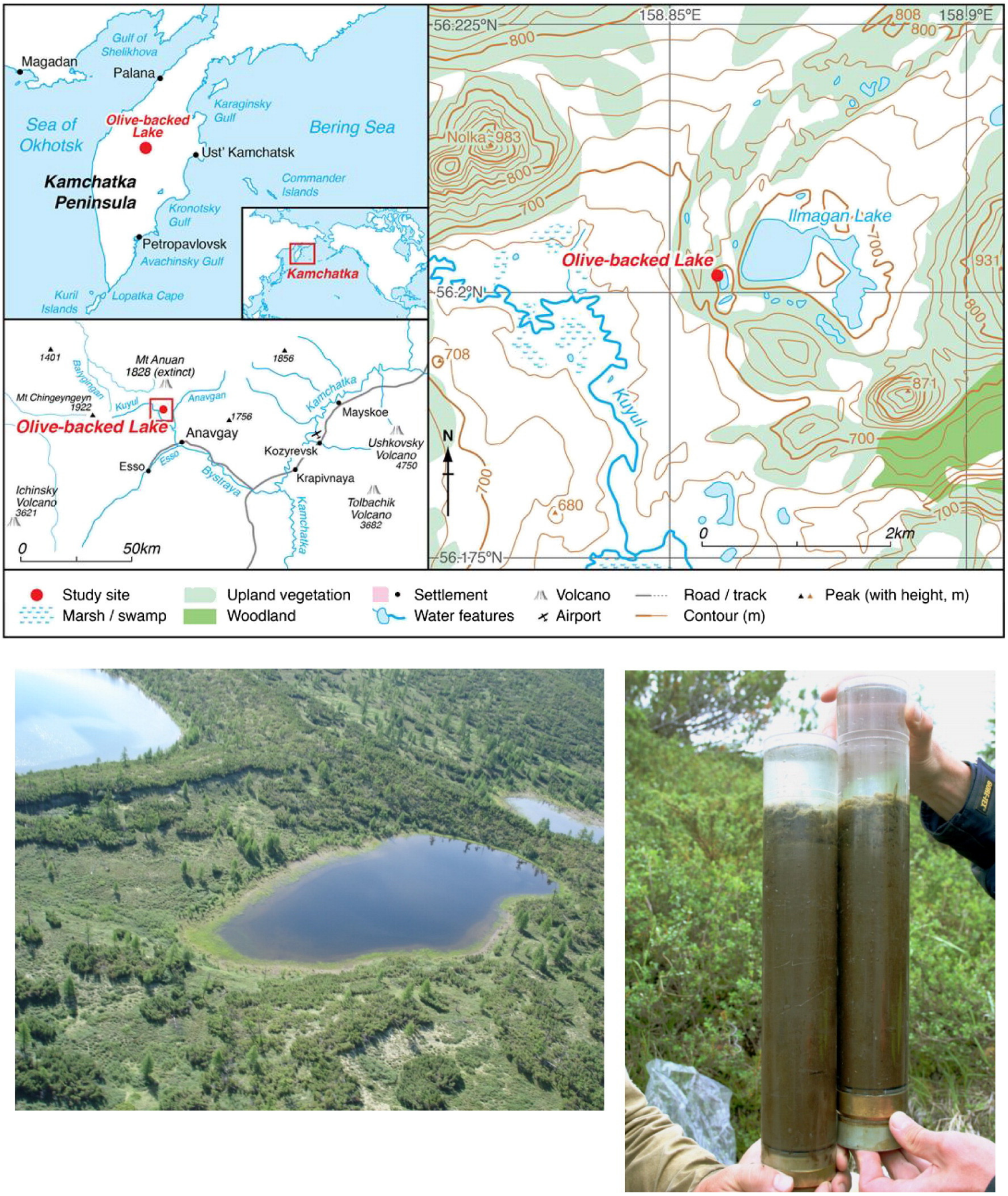

Fig. 1. a. Location of Olive-back Lake. 1b Aerial photograph of Olive-backed Lake 1c Gravity cores from Olive-Backed Lake (photo credit Elinor Andrén). Colour figure on the web and in print.

(SCP cm^{-2} yr^{-1}). The detection limit of the method is typically 50–80 SCPs per gram dry mass (gDM^{-1}) with a mean recovery of 95.2%. Sample blanks and SCP reference material (Rose, 2008) were included in all preparations.

Chironomid subfossils were prepared and slides mounted following standard techniques (Brooks et al., 2007) for each 1 cm sample interval. Chironomids were identified with reference to Weiderholm (1983), Rieradevall and Brooks (2001) and Brooks et al. (2007). Mean July air temperatures were inferred using a chironomid-based temperature inference model (WA-PLS, 2 component, $R^2_{jack} = 0.81$, $RMSEP_{jack} = 1.3$, range of sample specific errors = 1.42–1.47 °C) (Nazarova et al. this issue) based on a modern calibration data set of 88 lakes from eastern Russia covering a mean July air temperature range of 1.8–13.3 °C. BSTICK (Bennett, 1996) was used to assess the statistical significance of zones in ZONE version 1.2 (Juggins, 1991).

Diatoms were prepared according to standard methods (Battarbee and Kneen, 1982; Battarbee et al., 2001) and counted and identified under a light microscope at 1000× magnification using phase contrast. Three hundred valves were analysed per sample. Diatoms were identified mainly using Krammer and Lange-Bertalot (1986–1991). In the absence of any local model to infer past pH the AL:PE diatom-based pH inference model (WA-PLS, 2nd component, $R^2_{jack} = 0.78$ $RMSEP_{jack} = 0.34$) (Cameron et al., 1999) was chosen. This consists of a diatom-pH calibration data-set consisting of surface–sediment diatom assemblages from 118 lakes from high-altitude or high-latitude lakes in the Alps, Norway, Svalbard, Kola Peninsula, UK, Slovenia, Slovakia, Poland,

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Portugal, and Spain with a pH range from 4.5–8.0. It was found to be suitable due to the modern pH of the lake (pH 6.7) and the good representation of the fossil diatom assemblages (>85%).

All ordinations were performed using program CANOCO 4.5 for Windows (ter Braak and Šmilauer, 2002). Detrended canonical correspondence analysis (DCCA) was used to develop quantitative estimates of compositional turnover for diatoms and chironomids as beta-diversity, expressed as standard deviation (SD) units or beta-diversity, along the temporal gradient with age being the only constraining environmental variable (Hill and Gauch, 1980).

4. Results

4.1. Lithostratigraphy and dating

The sediment is relatively organic (LOI 550 is between 20–30%) with very low (<1%) carbonate values (%LOI 950) throughout and slightly higher organic values (>40%) towards the top of the core (Fig. 2).

Total ^{210}Pb activity reaches equilibrium depth with the supported ^{210}Pb activity at ca. 11 cm. Unsupported ^{210}Pb activities, calculated by subtracting supported ^{210}Pb activity from total ^{210}Pb activity, decline irregularly with depth, and the unsupported ^{210}Pb profile can be divided into two sections: from the surface to 5 cm and from 6 to 10 cm section (Fig. 3b). Unsupported ^{210}Pb activities decline more or less exponentially with depth in each individual section, suggesting different but relatively uniform sedimentation rates within each section.

The ^{137}Cs activity versus depth profile (Fig. 3c) has a well resolved peak at 6.5 cm. This peak is almost certainly derived from the maximum fallout of the atmospheric testing of nuclear weapons in 1963, and just below this depth, a trace of ^{241}Am was detected, confirming this. Relatively high ^{137}Cs activities in the samples shallower than 6.5 cm might be due to the inwash of catchment material.

^{210}Pb dates were calculated using the CRS (constant rate of ^{210}Pb supply) model as use of the CIC (constant initial concentration) model was precluded by the non-monotonic features in the unsupported ^{210}Pb profile (Appleby, 2001). The CRS dating model places 1963 at ca. 5 cm, which is shallower than the depth suggested by the ^{137}Cs and ^{241}Am records. Corrected chronologies and sedimentation rates (Fig. 4) were calculated by the CRS model using the ^{137}Cs peak at 6.5 cm for 1963 as reference level.

From the 1880s to the 1930s sediment accumulation rates were low and relatively uniform with a mean at 0.006 g cm^{-2} yr^{-1}, increasing about 5 fold to 0.0345 g cm^{-2} yr^{-1} in the 1980s, thereafter staying relatively uniform for about 20 years with a mean of 0.033 g cm^{-2} yr^{-1}, with lower sediment accumulation rates in the most recent past (Fig. 4).

4.2. Records of pollution

Below 12 cm Hg concentrations are relatively constant with a background level of around 60 ng g^{-1} (Fig. 2). From the mid-19th century to the present day, Hg concentrations have gradually increased to about twice background. Mercury fluxes have increased around seven-fold from the mid-19th century to the present day reaching a maximum around 1980 (Fig. 2).

Mercury fluxes to lake sediments are derived from a combination of atmospheric deposition and in-wash from the catchment. At Olive-backed Lake Hg fluxes are considerably higher than the three-fold increase observed during the same time period in many other remote lakes around the world (Yang et al., 2010b). Lead-210 data show that the mean ^{210}Pb fluxes were 86 and 114 Bq m^{-2} yr^{-1} before and after 1963, respectively, indicating an increase in ^{210}Pb fluxes in the coring location in recent years. Atmospheric ^{210}Pb deposition flux in a region should be relatively constant through time thus increased ^{210}Pb fluxes in the core are likely to be derived from higher catchment in-wash. This increase in catchment in-wash was probably responsible for

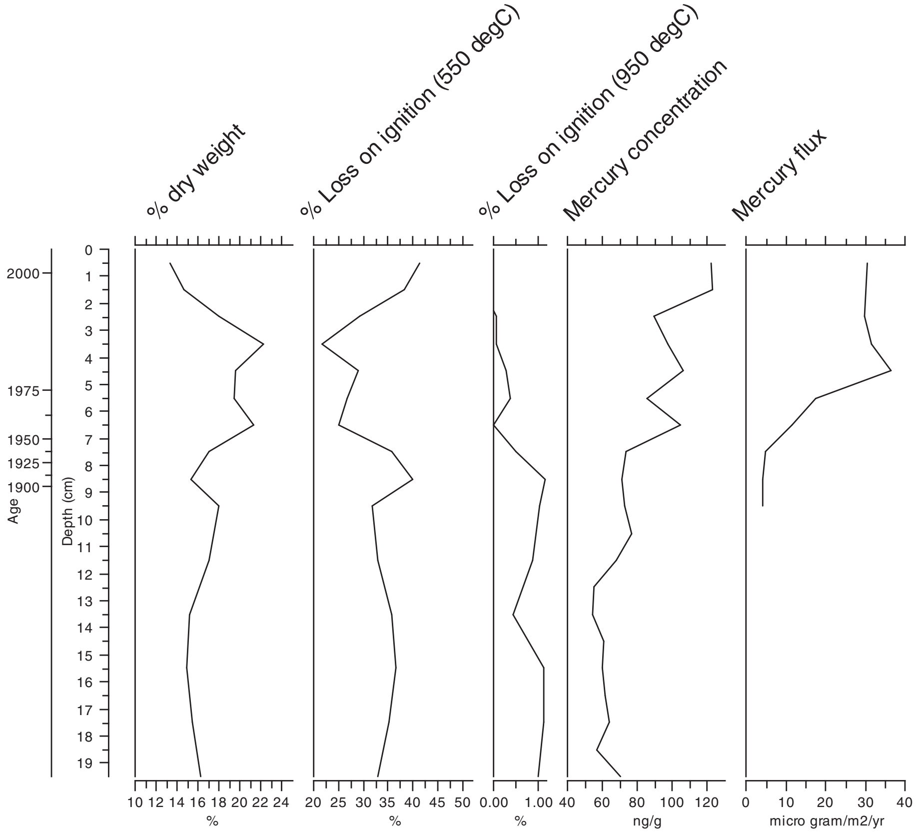

Fig. 2. Olive-backed Lake % Dry weight %LOI at 550 °C and 950 °C concentration and flux of mercury (Hg).

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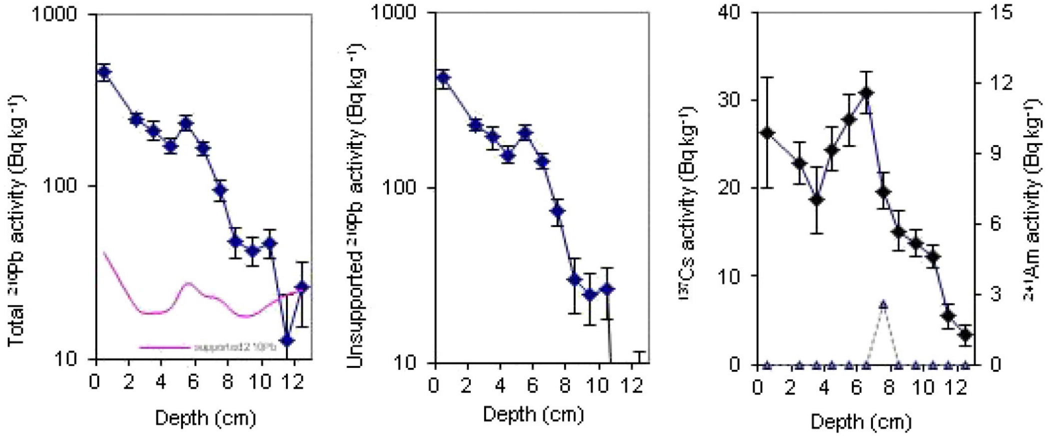

Fig. 3. Fallout radionuclide concentrations in core GC-3 taken from Olive Backed Lake, Russia, showing from right total ^{210}Pb, unsupported ^{210}Pb, and ^{137}Cs and ^{241}Am concentrations, versus depth.

bringing into the lake more Hg which had previously been stored in the soils, making an important contribution to the higher than three-fold Hg flux increase in the core.

A low but detectable level of SCP contamination was only seen in the upper 3 cm (post-1990) of the core. Concentrations of 290–350 gDM^{-1} were observed which convert to flux values of around 10 SCP cm^{-2} yr^{-1}, levels equivalent to those observed in sub-Antarctic islands (Rose et al., 2012). Below 3 cm, SCP concentrations fall below the limit of detection.

4.3. Lake biology

The chironomid fauna is dominated throughout the sequence by *Ablabesmyia*, *Psectrocladius septentrionalis*-type, *Psectrocladius sordidellus*-type *Sergentia coracina*-type and *Tanytarsus mendax*-type which are generally indicative of relatively warm, shallow, productive lakes with abundant aquatic macrophytes (Fig. 5). The chironomid fauna remains relatively stable throughout the sequence and no statistically significant biostratigraphic changes were identified. The chironomid-inferred July air temperatures show a gradual decline from 10 °C to 9 °C, however this variation is within the prediction error of the model (+/— 0.3 °C). Taxa with warmer temperature optima such as *Dicrotendipes nervosus*-type and *Microtendipes pedellus*-type are most abundant near the base of the core (17–19 cm depth). These decline from 17 cm depth and taxa, including *Sergentia coracina*-type, *Ablabesmyia* and *Parakeifferiella bathophila*-type, with cooler, intermediate temperature optima increase. *Cricotopus* type C and *Tanytarsus glabrescens*-type increase in the uppermost two samples (0–1, 1–2 cm depth). *T. glabrescens*-type is associated with warm shallow, nutrient-rich lakes with high dissolved organic carbon and high organic matter (%LOI) in Swiss lakes (Heiri and Lotter, 2005), so its increase in abundance may be associated with increased productivity in the lake.

Diatom assemblages from the surface sediments are typical for slightly acidic peaty lakes commonly found in granite bedrock lakes from, for example, Fennoscandia and the Kola Peninsula in Russia (Weckström and Korhola, 2001; Solovieva and Jones, 2002). The assemblages are dominated by benthic epiphytic or epilithic species such as *Frustulia rhomboides* v *saxonica*, several *Brachysira* and *Eunotia* species. *Eunotia incisa*, which is a characteristic taxon of acidic waters, appears in the bottom of the core at low abundance, 4.4%. Other benthic taxa, common in slightly acidic waters, for example, *Encyonema lunatum*, *C. gaemanii*, *Encyonema perpusillum*, *Kobayasiella subtilissima* and *Navicula leptostriata* are present throughout the core at a relative

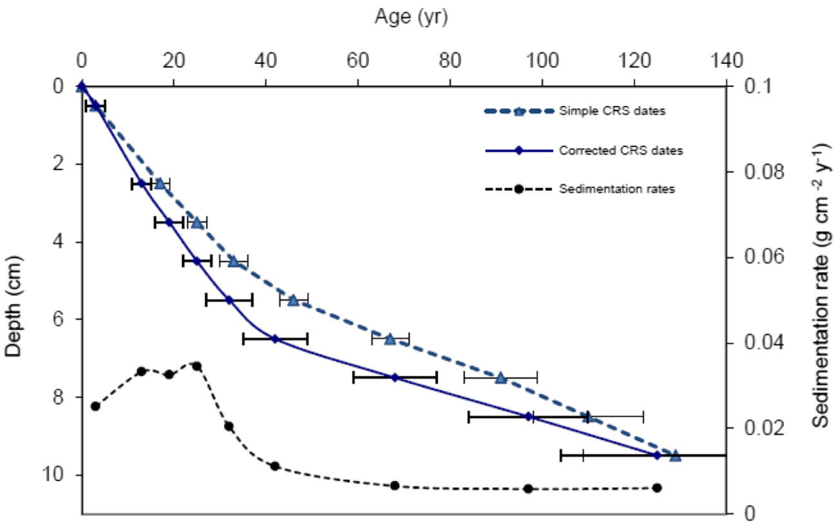

Fig. 4. Radiometric chronology of core GC-3 taken from Olive Backed Lake, Russia, showing the CRS model ^{210}Pb dates and sedimentation rates. The solid line shows corrected age. The dashed line with dots indicates sedimentation rate.

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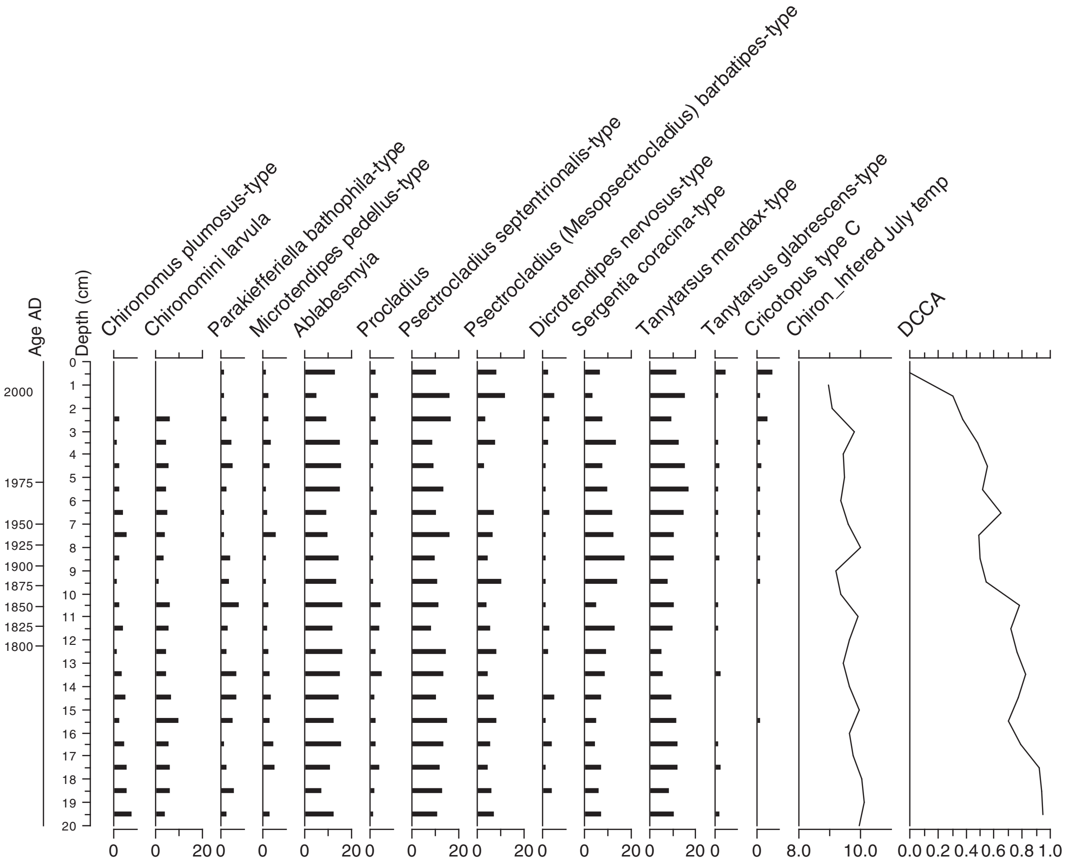

Fig. 5. Olive-backed Lake Percentage abundance of chironomids (expressed as % total chironomids) inferred July temperature (deg C) and DCCA.

abundance of about 5–10%. Amongst the few planktonic diatoms present, *Cyclotella rossii* is the most prominent and it reaches its highest relative abundance of 5.5% at the depth of 2 cm (Fig. 6). The diatom–reconstructed pH shows little variation with average values around 5.8–5.9, which an underestimation of the measured pH (6.7), but little reliance should be put on a single pH measurement. The diatom concentrations show no apparent stratigraphic trend and ranges from about 125 to 200 × 10^5 diatoms/mg dry sediment (Fig. 6).

Both diatoms and chironomids show insignificant ($p = 0.144$ diatoms and $p = 0.074$ chironomids) DCCA changes of about 1SD over the period represented by the short core (Figs. 5 and 6).

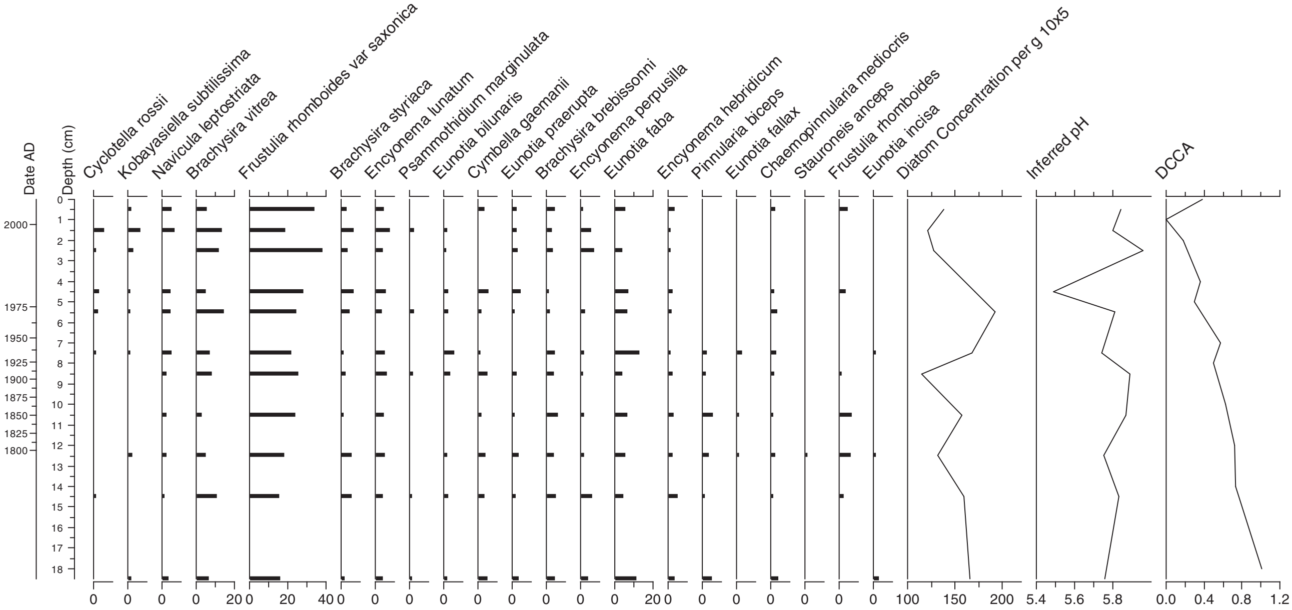

Fig. 6. Olive-backed Lake Percentage abundance of Diatoms (expressed as % total diatoms) inferred pH and DCCA.

Please cite this article as: Jones, V.J., et al., Evidence of global pollution and recent environmental change in Kamchatka, Russia, Glob. Planet. Change (2015), http://dx.doi.org/10.1016/j.gloplacha.2015.02.005

5. Discussion

Lead-210 fluxes to the sediments in the core are similar to those estimated from atmospheric deposition in the region, which suggests sediment focussing in the coring location is limited. However, there is an increase in sediment accumulation after the 1960s with a rapid increase in the 1980s lasting for about 20 years where the sediment increases about 5 fold with lower sediment accumulation rates in the most recent past (Fig. 4). This increase in sediment accumulation rate may be related to the increased winter precipitation observed at Kliuchy station since the 1930s which was more marked after about 1960 (Solomina et al., 2007), this might have caused greater catchment erosion.

Mercury concentrations are low and comparable to low levels of Hg recorded in particulate material from Siberian rivers, and in deep marine sediments (Cox and McMurtry, 1981; Coquery et al., 1995). Although the cause of the increased sediment accumulation is speculative it altered the flux of Hg to the sediment. Hg fluxes before the 1970s (<10 ugm^{-2} yr^{-1}) are similar to the mean Hg fluxes found in lakes from many other remote areas where catchment inputs are negligible (Swain et al., 1992; Yang et al., 2010b e.g. lakes in the Northern Tibetan Plateau have around a flux of about 10 ugm^{-2} yr^{-1} Yang et al., 2010a), suggesting that Hg in this area of Kamchatka is mainly derived from a global source. However, after the 1970s, Hg input to Olive backed lake increased considerably probably due to increased catchment erosion, and thus the fluxes reflect this catchment source.

SCP contamination is very low in this core. Concentrations are only above the limit of detection in the very uppermost sediment levels and only reach levels equivalent to the cleanest sites in the northern hemisphere and sub-Antarctic islands in the south (Rose et al., 2012). Although the historical SCP record may be curtailed in such low contamination areas, the cumulative SCP inventory may be calculated to provide an estimate of total deposited contamination. Here again, Olive-backed lake shows contamination equivalent to lake sites in Greenland, arctic Canada and sub-Antarctic islands. Interestingly, while SCP concentrations and fluxes at Olive-backed Lake are similar to the only other reported SCP data for northern Siberia (Schuchie Lake; Rose et al., 2012) and northern Lake Baikal (Rose et al., 1998), cumulative fluxes are lower in Olive-backed lake due to the shorter SCP record. Sources for the deposited SCPs at Olive-backed and Schuchie Lake remain unknown but are most likely to be associated with long-range transport from industrial sources remote from these lakes and may possibly represent a northern hemisphere background level (Rose, 1995).

Although the biological proxies; diatoms and chironomids show some variations, these are not statistically significant and are not related to the limited evidence for atmospheric pollution, or to recent climate change. Smol et al. (2005) argue that the DCCA of diatom and chironomid communities gives a reliable measure of the amount of species turnover in a lake ecosystem. At Olive-backed Lake both diatoms and chironomids show insignificant DCCA changes of about 1SD which are equivalent to those recorded by Smol et al. (2005) and Hobbs et al. (2010) from unimpacted lakes in temperate regions. Similarly Barr et al. (2013) argue low turnover is indicative of a very stable system in a lake in Australia and Wischnewski et al. (2011a, 2011b) working on the Tibetan plateau noted diatom compositional change was minimal over a recent 200-year period (DCCA $= 0.85$ SD, $p = 0.59$) showing stability of the system despite climate warming.

6. Conclusions

Clearly though Olive-backed Lake is a remote site and unimpacted by direct anthropogenic activity, atmospheric contamination can still be detected and global sources implicated. We suggest that the lake is not pristine but that it is unimpacted. Background concentrations and fluxes of both SCPs and Hg are similar at Olive-backed compared to other remote sites but the recent increased flux of Hg needs to be interpreted more as a consequence of increased soil erosion than increased atmospheric deposition. These changes though have no discernible effect on either diatom or chironomid communities. In addition, rather minor changes in the recent climate have not influenced the biology of the lake.

Unimpacted lakes are rarely studied, and their number is hard to estimate. These lakes may be extremely valuable in terms of biodiversity and ecosystem functioning. Human–environment interactions in the Holocene are of key interest (Seddon et al., 2014) and palaeolimnology does give us an insight into whether lakes have changed.

Acknowledgements

This work was funded by NERC (NE/H008160/1) (Influence of Glocal teleconnections on Holocene Climate in Kamchatka). We acknowledge logistic support to the Beringia 2005 expedition by the Swedish Polar Research Secretariat and its Russian collaboration partners. We would also like to thank Keith Bennett, Elinor Andrén, Lena Barnekow, Veronika Dirksen, Andrei Andreev and Dan Hammarlund for collecting the sediment cores and for allowing access to the material.

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