Glukhoye Lake: Middle to Late Holocene environments of Kunashir Island (Kuril Archipelago, Russian Far East)

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A multiproxy analysis of a sediment core from Glukhoye Lake in the southern Kuril Islands indicates that the basin originated c. 8.2 cal. ka BP as a brackish lagoon with the subsequent development of a freshwater lake (c. 4.0 to 3.3 cal. ka BP), a bog (c. 3.3 to 2.4 cal. ka BP) and a second lake (c. 2.4 cal. ka BP to present). The basin history primarily reflects local coastal dynamics and is not related to proposed Archipelago-wide changes in sea level. Between c. 8.2 and 8.0 cal. ka BP, the vegetation of southern Kunashir Island was characterized by Betula–Quercus forest with a secondary component of temperate broadleaf trees. Quercus broadleaf forest established c. 8.0 to 6.5 cal. ka BP and represents the Holocene thermal maximum. The remainder of the record shows a gradual decrease in temperate and an increase in conifer taxa, indicating a gradual cooling from the Holocene thermal maximum to c. 2.3 cal. ka BP. Maxima in Picea and Abies pollen between c. 2.3 and 1.1 cal. ka BP suggest conditions that were slightly cooler than present. Palaeoecological changes in the Kuril Islands as inferred from lake and section data differ in the timing and/or composition of the vegetation communities, although results from the two types of sites become more similar as the number of sections increases. The lake results do not support a previous conceptual model developed for the southern Russian Far East, which linked changes in sea levels to Holocene climate fluctuations. Rather the depositional environments in the lake cores seem more related to coastal dynamics that are independent of fluctuations in sea levels or climate. The difficulty in developing accurate age models for sites with multiple depositional environments may be the most important obstacle for documenting and understanding the Archipelago’s vegetation and climate histories.

The Kuril Archipelago, spanning ~1200 km between the Kamchatka Peninsula of northeastern Russia and Hokkaido Island of northern Japan (Fig. 1A), encompasses the northern Circumboreal and southern East Asian floristic zones (Pietsch et al. 2003). Located on the eastern edge of the southern Russian Far East (SRFE), the islands lie within a tectonic convergence zone, resulting in a long history of intensive volcanic and seismic activity (Bourgeois et al. 2006). Today ~160 volcanos are found in the Kurils, of which 40 are still active (Pietsch et al. 2003). The island chain separates the relatively warmer Okhotsk Sea from the cool North Pacific Ocean (Gorbarenko et al. 2014; Fig. 1B). Additionally, the Soya Current brings warmer waters from the Japan Sea to the Okhotsk Sea, thereby ameliorating conditions on the western shores of the southern Kurils. The regional climate of the Archipelago is formed by the interaction of the Siberian High and Aleutian Low in winter and the Asiatic Low and the North Pacific High in summer (Martyn 1992; Mock 2002). Additionally, the SRFE is located at the northeastern limit of the modern East Asian Monsoon (Ding & Chan 2005).

This suite of geological, oceanic and atmospheric influences illustrates the range of factors that have shaped the landscapes and climates of the Kuril Islands. The temporal and spatial scales of these factors, as represented in the palaeorecords, also vary greatly from local, short-term events (e.g. volcanic eruptions and tsunamis) to longer, regionwide changes (e.g. atmospheric circulation). Thus, the dynamic geological setting and the Archipelago’s position at the intersection of three major atmospheric features make the Kuril Islands a challenging area for unravelling the regional vs. local palaeoecological patterns and ultimately for describing Holocene climates based on the palaeoanatomical data.

Palaeoenvironmental investigations in this intriguing area of northeastern Asia were few (e.g. Pryanulkhina 1961; Jouze 1962; Alexandrova, 1971) prior to the late 20th century, when expeditions led initially by A.M. Korotky (Korotky et al. 1988, 1996, 2000; Korotky 2002) and later by N.G. Razjigaeva (Razjigaeva et al. 2013 and references therein) provided ground-breaking information on late Quaternary environments of the Archipe-
Their work with sections from both the Pacific and Okhotsk sides of the islands provided a rich database for inferring past landscape changes, documenting the impact of volcanos and tsunamis on local landscapes and exploring the influences of local vs. regional factors on the palaeoenvironmental record (Razjigaeva et al. 2004, 2011a, 2013, 2017). These investigations, when coupled with data from the mainland, also revealed an intriguing and complex climate history, one that was linked closely to sea level changes (Korotky et al. 1988, 1996, 2000, 2005; Razjigaeva et al. 2004).

While greatly informative, palaeodata from sections have potential shortcomings, particularly in developing reliable age models for sediments with discontinuous depositional histories or using palynological data, which potentially is biased by the input of the local vegetation, to interpret the palaeovegetation or palaeoclimate (Prentice 1988; Davis 2000). Because variations in site
lithologies and vegetation have been used as the main proxies for inferring Holocene climate fluctuations in the Kuril Islands (e.g. Korotky et al. 1996; Razjigaeva et al. 2004), a further evaluation of the section data as applied to broader trends in past vegetation and ultimately in the palaeoclimate seems appropriate. To that end, a north–south transect of lakes was sampled as part of the Kuril Islands Biocomplexity Project with the goals of (i) improving the understanding of the nature and chronology of events that shaped the Holocene landscapes of the Kuril Islands through the multiproxy analyses of lacustrine records and (ii) assessing whether the Kuril vegetation and depositional histories in this geologically dynamic region were primarily influenced by local factors (e.g. local changes in coastal dynamics; impact of volcanic eruptions on local vegetation) or whether more regional signals have been preserved in the palaeorecords. Our discussion focuses on the Greater Kuril Ridge, composed of Kunashir through Paramushir Islands (Fig. 1A), and does not include the Lesser Kuriles, a group of six islands which are located ~75 km to the east of Kunashir Island (see Razjigaeva et al. 2008 for a discussion of the environmental history of this smaller group of islands).

In this paper, we report on a multiproxy study of sediments from Glukhoye Lake, southeastern Kunashir Island (43°54′25″N 145°38′8″E; ~4 m a.s.l., Fig. 1B, C). It is the last of the lacustrine cores analysed for the Biocomplexity Project (note: we refer to sites that are currently freshwater basins as ‘lakes’, even though other depositional environments characterized the site in the past). We explore the evolution of the Glukhoye basin, and as with the other lake records (Lozhkin et al. 2010, 2017, 2020; Anderson et al. 2015), we evaluate the potential influence of local depositional factors on the palynological record. We then consider the suitability of lacustrine and non-lacustrine records for use in defining local vs. regional vegetation patterns and the relationship of changes in vegetation, climate and sea levels in the Greater Kuril Ridge during the Middle and Late Holocene.

Study area

Kunashir Island

Kunashir Island is the southernmost island in the Kuril Archipelago (Fig. 1A). It is ~123-km long and varies between 4 and 30 km in width (Goldfarb 2014). The north–south trending Dokuchaev Range (Fig. 1B), which was formed by eruptive craters and their ejecta (Kotlyakov et al. 2009; Ganzei 2011), is the island’s main topographic feature. To the south of Mendeleev Volcano, a broad lowland dominates the Okhotsk side and central areas of the island (elevations generally <100 m a.s.l.). Within this lowland, the Sernovodsky Isthmus cross-cuts Kunashir from east to west (Fig. 1C). The isthmus is mostly occupied by Peschanoye Lake and otherwise is characterized by boggy landscapes. Volcanic terrain is found on the southeastern coast dominated by the presence of Golovnin Volcano.

The bedrock geology of Kunashir Island reflects a relatively young history dominated by volcanic activity and marine, riverine and aeolian processes (Kotlyakov et al. 2009). The bedrock includes two Neogene suites characterized by volcanic and sedimentary rocks. Poorly defined Quaternary deposits (e.g. alluvium, slope deposits, marine, lacustrine, peats, aeolian sand, gravels, boulders) overlie the volcanic material. The south-central island is characterized by Quaternary sediments, which are similar to deposits found in the north. Palaeotsunami deposits extend up to 1 km inland on the Pacific side of the island, with a splash height of up to ~7 m. These deposits are dated to 1.0, 1.4 to 1.6, 1.7 to 1.8 and 2.0 to 2.1 cal. ka BP and appear to be associated with strong earthquakes (Razjigaeva et al. 2017).

Meteorological data from Yuzhno-Kurilsk (Fig. 1B) indicate mean annual, January and July temperatures of 5.0, ~4.6 and 12.5 °C, respectively, with the warmest conditions in August (15.8°C; http://climatebase.ru/station/32165). Mean annual, January and July precipitation values are 1245.2, 58.8 and 126.6 mm, with September being the wettest month (171.1 mm). Kunashir experiences distinctive cold (January to March, ~6.0 to ~3.2 °C), warm (July to September 12.615.8 °C), dry (January to April, 49–93 mm) and wet (August to October 122–175 mm) seasons. February is the driest and coldest month (49 mm, ~6.0 °C). The sum of degree-days across Kunashir averages ~1700°C, which is the maximum for the Kuril Archipelago (Ivanova 1990).

In addition to the atmospheric circulation patterns, marine currents originating in the North Pacific and Japan Sea influence the Kuril Island climates (Gorbarenko et al. 2004, 2014). The warm Soya Current, which enters the southern Okhotsk Sea from the Japan Sea, flows northeastward, paralleling the western coastlines of the southern Kuril Islands (Fig. 1A). The current enters the Pacific Ocean through Bussol’ Strait to the north of Urup Island. The Soya and the cooler East Kamchatka currents join on the Pacific side of the Archipelago to form the cool Oyashio Current. This circulation pattern results in warmer conditions in the southern as compared with the northern islands. The north–south-oriented volcanic ridges on the Kuril Islands provide an effective barrier to the cool fogs and winds associated with the Oyashio Current, which is an additional factor causing relative warmth along the western coasts of the southern Archipelago (Razjigaeva et al. 2002).

The vegetation of Kunashir Island can be classified into three forest types: (i) cool-temperate broadleaf; (ii) boreal conifer; and (iii) a mix of boreal conifer and cool-temperate broadleaf (Vorobiev 1963; Alekseeva, 1983; Barkalov 2009). The southern part of the island, where
Glukhoye Lake is located, supports both cool-temperate broadleaf forest and mixed conifer–broadleaf forest. Broadleaf taxa include Quercus crispula, Quercus dentata, Acer mayrii and Acer ukurunduense, with Kalopanax septemlobus, Ulmus lacintata and Ulmus japonica, while less common, thermophilus species, such as Magnolia hypoleuca, Fraxinus manshurica, Betula maximowicziana, Alnus japonica and Syringa amurensis, are also present. Conifers in the southern part of the island are Abies sachalinensis, Picea glehnii, Picea ajanensis, Larix leptolepis and Taxus cuspidata. Boreal conifer forest in northern Kunashir is dominated by Abies sachalinensis but also includes the evergreen species found in the southern conifer communities.

The Kunashir vegetation is also characterized by five altitudinal zones, although their geographical distribution varies across the island. These zones include: (i) cool-temperate broadleaf forest (~0–400 m a. s. l. in the south; restricted to river valleys and elevations below 200 m a. s. l. in the north); (ii) boreal conifer forest (~200–700 m a. s. l. in the northern and central island); (iii) Betula ermanii forest (~400–600 m a. s. l. in the north); (iv) Pinus pumila shrub tundra (typically ~600–800 m a. s. l. but can extend to 1500 m a. s. l. in the southern and central island) – note that Pinus pumila also grows in thickets that are scattered in both the conifer and broadleaf forests; and (v) alpine tundra, found at the highest elevations beyond Pinus pumila shrub tundra. In addition, coastal forb or forb–graminoid meadows can be extensive, often covering large, stabilized dune fields. Ericales occur as shrubs or subshrubs in all of the vegetation zones as well as in meadows found in moist, lowland areas (~0–200 m a.s.l.) and along marine terraces, coastal cliffs and the flanks of volcanoes. These taxa are also a component of lowland forb–graminoid meadows. The most common ericaceous species include Empetrum sibiricum, Rhododendron aureum, Phyllocladus spp., Arctica nana and Cassiope lycopodioides. Sasa kurilenis is a dominant taxon on lower to mid-elevation slopes (i.e. below 400 m a.s.l.) throughout the island. Additionally, numerous microhabitats, which are related to the influences of marine currents, topography and hot spring activity, can be found on the island (Alekseeva, 1983).

Glukhoye Lake

Glukhoye Lake is located on the Pacific side of southern Kunashir Island (Fig. 1C) on the eastern edge of the Sernovodsky Isthmus. The lowland around the lake is composed of a mix of unconsolidated Quaternary sediments of multiple origins, as described above. A small hill (~40 m a.s.l.) separates Glukhoye Lake from the Sernovodka River, the present-day Peschanoye Lake outlet. The hill itself is part of the Danilov Upland (maximum elevation of ~150 m a.s.l.), which borders the isthmus to the north and west. Glukhoye Lake is elongated along a north–south axis with a maximum length of ~700 m, a maximum width of ~325 m and an elevation of ~2 m a. s. l. A bathymetric survey of Glukhoye indicated two separate basins of ~2.4 m water depth in the south/south-central part of the lake with a shallow shelf of ≤1.5 m water depth to the north (Fig. 1D). The lake has two small streams (~140 and 440 m in length) that drain to the north. They terminate in the boggy terrain that characterizes much of the lowland and are not part of the larger Sernovodka River drainage. Small seasonal streams flow into the lake from the western upland. Lemnaceae and Nymphaea, the latter being particularly dense in the northern part of the lake, are the major aquatic plants.

Meadows border much of the Glukhoye basin, with relatively extensive boggy areas in the southern and northeastern ends of the lake. Poaceae spp. dominate these meadows, and wetter areas support Eriophorum gracile, Eriophorum vaginatum, Juncus spp. and a variety of wet-to-mesic forbs (e.g. Iris, Polygonum bistorta, Rumex spp., Equisetum, Comarum palustre, Menyanthes trifoliata, Symppocarpus renifolius, Lilium lancifolium and Ranunculus spp.). Disturbed and/or better drained areas are relatively scarce at lower elevations near the lake, but these micro-habitats support more drought-tolerant forbs (e.g. Artemisia and other Asteraceae) and graminoids.

Duschekia maximowiczii, often in association with shrub Salix, is abundant on lower hillslopes on both sides of Glukhoye Lake, achieving heights of 2–3 m. Myrica, while present along the shore, is not common. Betula–broadleaf–conifer forest is found below 200 m a. s. l. on slopes that border the lake to the east and west. The main taxa of the mixed forest include Quercus crispula, Alnus japonica, Alnus hirsuta, Betula ermanii, Sorbus commixta, Abies sachalinensis and Picea ajanensis. Sasa kurilenis is locally abundant on slopes. Acer ukurunduense, Hydrangea and Actinidia are present but not common. Pinus pumila occurs as isolated individuals near the lake, but the conifer is more abundant regionally, often forming dense thickets at higher elevations (>200 m a.s.l.).

Material and methods

In summer 2007, a 562-cm-long sediment core (G-1; Fig. 1D) was recovered from one of two central basins in Glukhoye Lake at a water depth of ~260 cm. A plexiglass tube was used to collect the upper, water-rich sediments and a modified Livingstone piston corer (Wright et al. 1984) retrieved the remaining sediments. Core sections were split and photographed. Diatom and palynological samples were taken every 10 cm, and samples for geochemical analyses were taken every 20 cm. Radiocarbon analyses were performed in the laboratories at the Interdisciplinary Science Research Institute N.A. Shilo, Far East Branch, Russian Academy of Sciences, Maga-
dan. The lithology was described through visual inspection.

Standard methods were followed to process 1 cm³ subsamples for pollen analysis following standard procedures for sediments from arctic and sub-arctic lakes (PALE 1994). Samples from the upper part of the Livingstone core were correlated with the plexiglass core using the decline in Pinus subg. Haploxylon pollen at ~30 cm; 0–30 cm samples are from the plexiglass core and the remaining samples were taken from the Livingstone core. The individual arboreal and non-arboreal pollen taxonomy are shown as a percentage of the sum of all identified and unknown terrestrial pollen grains (ΣP). The percentages of spores and aquatics are calculated using ΣP. Palynomorphs were grouped into three subsum categories: Trees & Shrubs; Herbs (terrestrial and aquatic); and Spores. The percentages for each subsum were based on the sum of ΣP + aquatics + spores. Both pollen and diatom data were converted to percentages and plotted using Tilia and Tilia Graph (http://www.tilia-it.com), then divided into zones and subzones using the constrained incremental sum of squares method (CONISS). All pollen sums exceeded 300 identified arboreal and non-arboreal taxa with most samples having sums between 500 and 700 grains. The plant taxonomy follows Czerepanov (1995). Pinus s/lg Haploxylon pollen represents Pinus pumila. The distribution of palaeovegetation types is inferred from the relationships between the modern topography and ecology (Vorobiev 1963; Urusov & Chipizubova, 2000; Pietsch et al. 2003; Barkalov 2009).

Preparation of diatom samples followed the standard method described by Gleser et al. (1974). A 2-g sample was boiled in a solution of sodium tripolyphosphate with 30% hydrogen peroxide solution. After decantation in distilled water, 100 mL of distilled water was poured into the resulting precipitate. A 0.06 mL aliquot of this mixed suspension was applied to an 18×18 mm cover slip. Identification of the diatom algae and the calculation of diatom valve concentration in the sediment (numbers of valves per 1 g of dry sediment) were performed with an Axioplan 40 light microscope at a magnification of 1000× using immersion oil. The calculation of diatom valve concentration was based on valves per slide transect following the methods described in Avramenko et al. (2015). More than 300 valves were counted in each of the prepreparations. Diatom classification follows AlgaeBase (http://www.algaebase.org). Ecological characteristics of the taxa are taken from Barinova et al. (2006).

Organic matter δ¹³C, sedimentary δ¹⁵N, elemental TOC (total organic carbon) and TN (total nitrogen) samples were acid washed (1 M HCl), rinsed five times in deionized water and freeze dried. The samples were then analysed using an elemental analyser to determine TOC and TN concentrations, coupled with a Finnigan Delta plus isotope ratio mass spectrometer for δ¹³C and δ¹⁵N measurements. All isotope values are reported in per mil units (‰) according to the relationship δX = [(Rsample/ Rstandard) − 1]×1000‰, where X is the element of interest and R is the measured isotopic ratio. Carbon isotope measurements are relative to the Vienna Peedee Belemnite standard, and all nitrogen measurements are relative to atmospheric nitrogen. Replica measurements of internal standards, which were run along with TOC, TN, sedimentary δ¹³C and sedimentary δ¹⁵N samples, yielded uncertainty in the isotopic measurements of <0.2‰ and coefficients of variation of <5% of the value for the C and N‰ data.

Radiocarbon dates were converted to calibrated ages using the IntCal13 calibration curve (Reimer et al. 2013) in CALIB 7.1 (Reimer et al. 2013; Stuiver et al. 2020). An age–depth model was then constructed using BACON ver. 2.3 (Blaauw & Christen, 2011; Blaauw & Heegaard 2012). This program divides the palaeorecord into a specified number of sections, based on user-defined core characteristics, and estimates accumulation rates using Bayesian statistics. All ages in the text are presented as calibrated kiloyears before present (cal. ka BP).

Results

Lithology

The 5.62-m-long core (G1), while variable in its sedimentology, has been divided into three lithological units (Table 1). Unit 1 (564–141 cm) has a complex stratigraphy, but it is mostly dominated by silt, which often is mixed with pebbles, gravel and/or sand. Unit 2 (141–107 cm) is composed of peat that includes gravel and sand. Unit 3 (107–0 cm) caps the peat with a layer of silt; the upper 102 cm are characterized by a water-rich gyttja.

Chronology

A total of 13 radiocarbon samples were analysed from Glukhoye Lake (Table 2). Because the core had few plant macrofossils in Unit 1, which comprises the greatest portion of the core, we took four paired macrofossil–bulk sediment samples to compare the age results. In all cases, the paired samples yielded the same age (115 cm, 325–339 cm) or ages that were within one standard error (470 cm, 545–546 cm). These results indicate that there is minimal offset between sample types. However, the age–depth distribution of the median calibrated ages indicates that the results for 40, 139–141 and 250 cm are probably in error, as they do not follow the generally linear pattern evident in the age–depth (Fig. S1) and BACON plots (Blaauw & Christen, 2011; Fig. 2). Where similar ages of paired macrofossil and bulk samples occurred, bulk sediments were used in the age model so that sample type was consistent with the bulk ages used to constrain the upper part of the core. Note that the ages
The use of Early (c. 8.2–4.2 cal. ka BP), Middle (c. 4.2–2.2 cal. ka BP), and Late (c. 2.2–1.1 cal. ka BP to present) Holocene follows Walker et al. (2019).

Diatoms

The sediments of Glukhoye Lake yielded a rich and diverse diatom flora (Figs 3, 4, Table S1). The core includes 453 taxa that belong to different ecological groups (e.g., marine, brackish-water, freshwater, bog, benthic, tychoplanktonic, planktonic). The changes in valve concentrations and the ratios of representatives of the ecological groups formed the basis for the identification of the four diatom zones (DZ; Table 3). DZ1 is characterized by assemblages with a high species richness of marine and brackish taxa. DZ2 shows some of the highest valve concentrations in the Glukhoye record. It is also characterized by high species richness within the freshwater planktonic and tychoplanktonic diatom categories. DZ3 is marked by a clear decrease in the concentration of diatom valves and the predominance of bog taxa. The species richness of freshwater tycho-planktonic taxa and valve concentrations again increases in DZ4. Variations in diatom percentages within some zones have resulted in the delineation of two subzones in DZ2 and three subzones in DZ1. DZ2.1 is characterized by high percentages of the freshwater tychoplanktonic Staurastrum var. exigua and the planktonic Aulacoseira italica. DZ1.1 and DZ1.3 are marked by high percentages of the marine taxon Paralia sulcata.

Table 1. Sediment description, Glukhoye Lake.

| Depth (cm) | Age (cal. ka BP) | Sediment description |
|-----------|------------------|----------------------|
| Unit 3    |                  |                      |
| 0–100     | 0–2.34           | Watery, organic rich gyttja; large bivalve 27–32 cm and 78–80.5 cm |
| 100–102   | 2.34–2.39        | Organic-rich gyttja with peaty inclusions |
| 102–107   | 2.39–2.51        | Silt |
| Unit 2    |                  |                      |
| 107–141   | 2.51–3.31        | Peat; 139–141 cm peat includes gravel and sand |
| Unit 1    |                  |                      |
| 141–170   | 3.31–3.98        | Silt |
| 170–174   | 3.98–4.04        | Silt–sand mix with pieces of gravel |
| 174–193   | 4.04–4.31        | Silt |
| 193–250   | 4.31–5.16        | Silt with scattered sand |
| 250–251   | 5.16–5.17        | Sand |
| 251–253   | 5.17–5.20        | Organic-rich silt |
| 253–379   | 5.20–6.74        | Silt with scattered sand and gravel; sand layer at 254.5–255.3 cm; rock fragment 341.5–343 cm; 369–369.5 gravel layer |
| 379–404   | 6.74–6.95        | Silt with scattered organic material |
| 404–448   | 6.95–7.46        | Silt |
| 448–454   | 7.46–7.53        | Pebble layer |
| 454–466   | 7.53–7.67        | Silt |
| 466–564   | 7.67–8.17        | Silt with scattered small rock fragments |

younger than 2590 cal. ka BP (0–115 cm) presented in the text and figures are based on a linear extrapolation of the age model. As the sediment type does not change over this interval, we believe that this is a reasonable approach to provide a provisional age scheme for the latest Holocene. Nonetheless, ages in this part of the core are to provide a provisional age scheme for the latest Holocene. Nonetheless, ages in this part of the core are considered as tentative and should be used with caution. The use of Early (c. 11.7 to 8.2 cal. ka BP), Middle (c. 8.2 to 4.2 cal. ka BP), and Late (c. 4.2 cal. ka BP to present) Holocene follows Walker et al. (2019).

Geochemistry

Changes in organic carbon content and its δ13C composition generally follow the major lithological change at ~140 cm (Fig. 5). Organic carbon contents range from 1 to 29% and are significantly higher in the upper 140 cm. The highest organic content occurs between ~140 and 80 cm. The δ13C values are relatively high (~25 to ~21‰) below ~200 cm, with maximum values occurring between 200 and 250 cm. Values decline between ~200 and 160 cm, above which they average ~29‰. The TOC/TN weight ratios range between ~12 and 20. There is no strong trend in the data, but the highest values occur between ~80 and 120 cm. The δ15N values range between ~1 and 5‰. These values are

Table 2. Radiocarbon and calibrated ages, Glukhoye Lake. Dates not used in the age model are indicated by an asterisk.

| Depth (cm) | Material dated | Date (14C a BP) | Median calibrated age (cal. a BP) | 2σ calibrated age (cal. a BP) | CAMS laboratory number |
|-----------|----------------|----------------|----------------------------------|-----------------------------|------------------------|
| 40        | Bulk           | 5160±30        | 5920                             | 5890–5990                   | 152311                 |
| 115       | Bulk           | 2505±30        | 2590                             | 2490–2735                   | 152312                 |
| 115       | Bulk           | 2506±30        | 2590                             | 2490–2735                   | 152313                 |
| 139–141   | Plant macrofossil | 1150±40        | 1065                             | 970–1175                    | 136956                 |
| 170       | Bulk           | 3680±35        | 4020                             | 3900–4090                   | 143084                 |
| 250       | Bulk           | 6970±100       | 7800                             | 7620–7970                   | 152314                 |
| 325–330   | Bulk           | 5615±30        | 6390                             | 6310–6450                   | 153935                 |
| 325–339   | Plant macrofossil | 5610±35        | 6380                             | 6310–6460                   | 153938                 |
| 393       | Plant macrofossil | 5950±35        | 6780                             | 6680–6860                   | 136957                 |
| 470       | Bulk           | 7120±35        | 7980                             | 7930–8030                   | 153939                 |
| 470       | Plant macrofossil | 7165±35        | 7980                             | 7930–8020                   | 153937                 |
| 545–546   | Bulk           | 7145±35        | 7970                             | 7930–8020                   | 153937                 |
| 545–546   | Plant macrofossil | 7085±35        | 7915                             | 7840–7970                   | 153940                 |
relatively low in Unit 3 (~2%) but are higher (> ~4%) between 220 and 330 cm.

**Palynology**

Six pollen zones (PZ) were defined for the Glukhoye record (Fig. 6). Zone boundaries do not correspond to changing depositional environments, as indicated by the diatom data (Table 3). Thus, the variations in the palynological record reflect changes in the palaeovegetation. Tree and shrub pollen dominate in zones PZ2–PZ6, and the percentages of total herb taxa vary between 20 and 40% of total pollen and spores below ~230 cm and from 40 to 50% in samples from 230 to 0 cm. The total percentages of spores decline in PZ4–PZ6, caused mostly by the decrease in Polypodiaceae. PZ1–PZ3 are characterized by broadleaf deciduous species with *Quercus* being the most dominant taxon. The role of *Quercus* is less in assemblages of the upper three zones, but *Betula* becomes an important component of these spectra. Conifer taxa are more common in PZ4–PZ6, although *Pinus* s/g Haploxylon shows modest values in PZ1. The rise in conifer pollen is gradual in PZ4 with the *Picea* sect. *Eupicea* and *Abies* pollen reach maximum percentages in PZ5. Both taxa decline sharply in PZ6, where *Pinus* s/g Haploxylon shows a second percentage peak. *Larix* occurs in trace amounts throughout the record. *Ulmus* pollen is found in all zones but generally is <5%; *Juglans* pollen occurs consistently in PZ1–PZ4 with maximum values (~5 to 7%) in PZ2 and PZ3. Graminoids dominate the herb taxa; maximum Poaceae percentages (~15–30%) occur in the lower two zones. Saxifragaceae, Polygonaceae, Primulaceae, Lamiaceae and *Iris* have the highest percentages within the minor taxa group, but they do not exceed 5%. Aquatic pollen is restricted to sporadic occurrences as trace amounts in PZ3–PZ6, with *Nymphaeaceae* being the most common taxon. *Polyopodiaceae* spores are abundant in PZ1–PZ3 (up to 50%) but are reduced to ~5% in the remaining zones. *Osmundaceae* is also highest in the lower zones, but the spores are generally <10% with decreasing values up-core. *Sphagnum* occurs consistently in all zones but is <10%.

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*Fig. 2.* Age model for Glukhoye (G-1) using Bacon age-modelling software (Blaauw & Christen, 2011). Bacon Manual – v. 2.2. [http://www.chron.qub.ac.uk/blaauw/bacon.html](http://www.chron.qub.ac.uk/blaauw/bacon.html). The bottom panel shows the calibrated ages and the age–depth model. The black curve indicates the optimal model based on weighted mean ages, whereas the grey stippled portion reflects 95% confidence intervals. The upper panels indicate the following: left = history of Markov Chain Monte Carlo iterations; middle = distributions for the accumulation rate illustrating prior (grey line) and posterior (grey infilled curve) distributions; right = distributions for memory illustrating prior (grey line) and posterior (grey infilled curve) distributions.
Discussion

In this section, we will first describe the varying depositional environments represented in the Glukhoye core and the probable origin of the basin. We next will consider Middle to Late Holocene vegetation as inferred from the Glukhoye data and compare these results with the palaeovegetation as interpreted from the sections for the Greater Kuril Ridge. Finally, we will re-examine the palaeoclimate model proposed by Korotky et al. (1996, 2000) in light of the data provided by the lacustrine records in the Kuril Islands.

Depositional environments of the Glukhoye basin

The DZ1 diatom assemblage indicates that the Glukhoye basin was a brackish lagoon c. 8.2 to 4.3 cal. ka BP, as shown by the moderate to high percentages of Actinocyclus octonarius, Cocconeis scutellum, Melosira discigera, Paralia sulcata, Thalassiosira b partly exposed spit, which would inhibit the penetration of marine diatom taxa into the lagoon. A marine transgression of several metres would affect local coastal processes, and in southern Kunashir Island the rise in sea level probably caused a redistribution of eroded coastal sediments and/or of sediments carried to the ocean by the Sernovodka drainage (Korotky et al. 1996, 2000). Under such conditions, the build-up of a spit, which restricted the inflow of marine waters to the Glukhoye basin, might be expected.

DZ1 has been divided into three subzones, suggesting some variations in the lagoon environment during the Middle Holocene. The first notable feature of this assemblage is the trace appearance of Terpsinoë americana in the earlier and later parts of the zone. This warm-water tropical species is not found today in the coastal waters off Kunashir Island. It is considered a tropical epiphyte that lives in salty and brackish waters to the south of 45°N (Alhonen et al. 1984). Its appearance in the Glukhoye record is evidence for warmer sea temperatures between c. 8.0 and 7.7 cal. ka BP and between c. 5.7 and 4.5 cal. ka BP. These intervals correspond to times of maximum summer temperatures as inferred from the pollen data. Moreover, geochemical and diatom analyses of marine cores from the southern Okhotsk Sea and the northwestern Pacific Ocean indicate that sea surface temperatures were warmer than present from c. 8.0 to
4.5 cal. ka BP (Harada et al. 2004, 2014; Okazakia et al. 2005; Inagaki et al. 2009). The fact that Terpsinoë americana occurs sporadically and in only trace amounts in DZ1 suggests that this species was not abundant in the waters off Kunashir Island and that the increase in sea surface temperatures was more modest as compared with other nearby regions (e.g. Terpsinoë americana in marine cores off eastern Honshu Island registers up to 60%; Sato et al. 1983).

The second feature common to all the subzones is the importance of the freshwater tycho planktonic diatoms Staurosira venter and Staurosira construens var. exigua. These taxa often occur in sediments as colonies, formed by two to 10 valves (Fig. 4), which may indicate their allochthonous nature in the Glukhoye record. They possibly were transported to the lagoon by freshwater inflow, which today is limited to short, ephemeral streams. If the 30 cm sample can be taken as an approximation of a diatom assemblage associated with the ‘modern’ drainage pattern, percentages of Staurosira venter and Staurosira construens var. exigua in DZ1 are generally lower or are similar to the modern value. This comparison suggests that if the species were transported to the lagoon via streams, then it is probable that the Middle Holocene inflow to the basin was like that seen today. This similarity further suggests that there was no significant alteration of the drainage patterns in this part of the Sernovodsky Isthmus. However, the formation of lagoons and embayments associated with a proposed marine transgression (Korotky et al. 1996, 2000) logically would result in some changes to the drainage patterns within the Isthmus. The pollen data do not indicate an
increase in annual or seasonal precipitation (see the section below on the vegetation history). Thus, if the ancient drainage systems were altered, they were related to shifts in stream gradients and perhaps sediment load caused by rising sea levels, rather than by increased runoff associated with changes in precipitation. Because other freshwater taxa are few and are represented by single valves, it is possible that currents carried *Staurosira venter* and *Staurosira construens* var. *exigua* to the coring site from more desalinated parts of the lagoon.

The third common feature in DZ1 is the low total concentrations of diatom valves (TCD), excepting a modest increase in the lower part of DZ1.2. Low diatom concentrations can indicate a high-energy hydrological setting, which is reasonable given the deposition of coarse sediments in the lagoon (Unit I; Table 1). The low percentages of TOC and δ³¹C throughout DZ1 also are consistent with a high-energy environment under the influence of marine carbon sources (e.g. more wave action within the basin would result in less deposition of material of low density and small size). The decrease in the planktonic sublittoral species *Paralia sulcata* and a slight increase in sublittoral benthic diatoms (e.g. *Cocconeis scutellum*, *Opephora mutabilis*, *Planolithidium hauckianum*), particularly in the lower part of DZ1.2, indicate a slight decline in water levels in the lagoon c. 5.8 to 4.5 cal. ka BP. This reconstruction seems inconsistent with the Glukhoye data, which indicate the persistence of a brackish lagoon, albeit one that was perhaps slightly shallower than previously.

**Table 3. Comparison of ages and depths of pollen and diatom zones.**

| Pollen zones | PZ | Age, cal. a BP | DZ | Age, cal. a BP | Diatom zones and subzones (DZ) |
|--------------|----|---------------|----|---------------|-------------------------------|
| PZ6          | 0–1125 | 0–2400 | DZ4          |
| PZ5          | 1125–2250 | 2400–3275 | DZ3          |
| PZ4          | 2250–4050 | (96–175) | (140–195) | 3275–4340 | DZ2          |
| PZ3          | 4050–6470 | (175–345) | 4340–8170 | (195–562) | DZ1          |
| PZ2          | 6470–7940 | (345–505) | 4340–5820 | (195–295) | DZ1.3        |
| PZ1          | 7940–8170 | (505–545) | 5820–7770 | (295–475) | DZ1.2        |
|              |       |           | 7770–8170 | (475–562) | DZ1.1        |

The cause of the lowered water levels is somewhat puzzling. The decline in the percentages of *Paralia sulcata*, the absence of *Terpsinoë americana* and a slight increase in the abundance and diversity of freshwater allochthonous diatoms in lower DZ1.2 may reflect greater river runoff into the Glukhoye basin. However, the palynological data do not indicate an increase in precipitation, suggesting that the shift in the diatom complex is most likely related to a change in drainage within the Glukhoye catchment. Korotky *et al.* (1996, 2000) noted a slight marine regression c. 6.5 to 6.2 cal. ka BP. Although the timing is not exactly that of lower DZ1.2, perhaps a coastline reconfiguration or shift in coastal sediment load (e.g. from coastal inflow of redeposited sediments from the Sernovodka drainage and/or the influx of coastal shelf sediments) as related to a modest change in sea level may have contributed to the build-up of the barrier bar and the consequent lowered water levels within the lagoon.

Like DZ1.1, DZ1.3 (c. 5.8 to 4.3 cal. ka BP) is characterized by low concentrations of diatom valves, an increase in percentages of the sublittoral, brackish-marine species *Paralia sulcata*, and a more consistent appearance of *Terpsinoë americana*. The frequency of taxa (e.g. *Cocconeis scutellum*, *Opephora mutabilis*, *Planolithidium hauckianum*) that grow on macroalgae also increases. These data indicate a decreasing water level in the Glukhoye basin. The sea level history proposed by Korotky *et al.* (2000) indicates a regression to modern levels or slightly below modern between c. 5.7 and 4.5 cal. ka BP. This reconstruction seems inconsistent with the Glukhoye data, which indicate the persistence of a brackish lagoon, albeit one that was perhaps slightly shallower than previously.

DZ2 (c. 4.3 to 3.3 cal. ka BP) marks the transformation of the brackish lagoon into a freshwater basin. DZ2.1 (c. 4.3 to 4.0 cal. ka BP) is characterized by the highest frequency of *Staurosira venter*, indicating the increased importance of freshwater flow to the basin. Marine (e.g. *Pinnunavis yarrensis*, *Paralia sulcata*, and *Diploneis smithii*) and brackish (e.g. *Rhopalodia gibberula*, *Navicula pergirina*) taxa are present in low frequencies in DZ2.1, indicating the continued but minor influx of saline water to the basin (e.g. during highest tides). DZ2.2 (c. 4.0 to 3.3 cal. ka BP) is distinguished by the dominance of the freshwater planktonic diatom *Aulacoseira italica*. The presence of *Aulacoseira* suggests an increase in eutrophicity (Donar *et al.* 1996; Gibson *et al.* 2003; Juracek, 2003; Kirilova *et al.* 2010). By this time, the Glukhoye basin no longer had any connection to Pacific waters. The occurrence of *Aulacoseira*, the richness of the diatom taxa and the presence of the large-valved *Iconella* taxa indicate a continued warming of the basin’s waters. The palynological data suggest that the onset of lake formation corresponds to a climate that, while still warmer than present, was beginning to cool, as
indicated by the introduction of conifer trees into the forest.

According to Korotky et al. (2000), the DZ2 interval encompasses sea levels that were both slightly lower and slightly higher than present (+1.2 to 1.5 m p.s.l.), the latter occurring c. 4.5 to 3.6 ka cal. BP. Rising sea levels are inconsistent with a shift from a brackish lagoon to a freshwater lake, presuming that the marine waters simply flooded the present-day lowlands surrounding the Glukhoye basin. If the age models are accurate for both the lake core and the sections, then the Glukhoye data suggest that coastal processes (e.g. accumulation of a larger and/or higher barrier bar to block marine incursion, blockage of the lagoon inlet with the formation and/or shifts in coastal dune localities) were the main influences in changing the depositional environments in the Glukhoye basin during DZ2.

The organic geochemistry associated with DZ2 reflects an increase in the preservation of organic matter (δ13C), sedimentary nitrogen (δ15N); carbon (C%) and nitrogen (N%) weights and weight ratios (C%/N%). δ13C and δ15N are expressed as parts per mil (‰). C, N and C/N are shown as weight percentages. See Fig. 3 for the key to the lithology. Note that the ages younger than 2590 cal. ka BP (0–115 cm) are based on a linear extrapolation of the age model and should be considered as tentative.

The diatom complex in the lower part of DZ3 (c. 3.3 to 2.4 cal. ka BP) reflects the transition from a lake to a bog as indicated by Aulacoseira crassipunctata, Eunotia glacialis, Pinnularia major and S. construens var. exigua. The upper part of the zone with Chamaepinnularia hassiaca, Chamaepinnularia begeri, Nitzshia perminuta and Pinnularia subrostrata marks the establishment of a bog ecosystem, with the presence of Humidophila contenta, Nitzschia terrestris and Hantzschia amphyoxis indicating the occurrence of soil-forming processes. A reduction in Polypodiaceae spores and the appearance of trace amounts of Nymphaceae and Sparganium pollen in PZ4 and PZ5 (Fig. 6) also suggest a shallowing of the freshwater basin with an expansion of boggy environments near the lake. The higher organic content c. 3.3 to 2.6 cal. ka BP shown by the high C/N percentages is consistent with the presence of peaty sediments in the Glukhoye core. Additionally, δ13C values are in accord with a non-marine setting.

The establishment of boggy terrain may indicate a shift in larger-scale climatic forcings that caused a decrease in precipitation, which in turn resulted in a decline in river and/or overland flow into the lake. The shift in hydrology would lead to the lake’s desiccation, and ultimately the formation of a bog in the Glukhoye basin. The moderate
increases in Picea and Abies pollen, if representing Picea glehnii and Abies sachalinensis, are consistent with the presence of cold, wet soils associated with boggy terrain. The occurrence of cool fogs would also favour these conifers and indirectly provide additional moisture to the local landscape. The diatom data suggest that soils ultimately formed on the bog’s surface as moisture input decreased and/or substrates became better drained. Here again the palynological record does not indicate any significant decline in effective moisture, although conditions were cooling. Thus, the changes from a lake to a bog to a soil, while reflecting a regional shift to cooler and perhaps slightly wetter climates, appear most likely to have been the result of local changes related to overland or groundwater flow.

DZ4 (c. 2.4 cal. ka BP to present), as indicated by Staurosira venter, S. construens var. exigua, Aulacoseira crassipunctata, Aulacoseira subarctica and Discostella pseudostelligera, indicates a second interval of freshwater dominance and the establishment of the present-day Glukhoye Lake. Depleted values of δ13C in the core’s organic remains are consistent with freshwater sources of carbon being used by the aquatic plants. The palynological data suggest the presence of cooler and moister summer climates between c. 2.3 and 1.1 cal. ka BP (note: here and in other parts of the Discussion ages that are
younger than c. 2.6 cal. ka BP should be considered tentative as they are based on a linear extrapolation from the last radiocarbon date at 115 cm to the core top). The increase in summer precipitation perhaps led to the flooding of the Glukhoye basin and the formation of a freshwater lake. If lake formation is linked directly to climate, then seasonal water source perhaps shifts from primarily a spring (c. 2.4 to 1.1 cal. ka BP) to a winter (c. 1.1 cal. ka BP to present) runoff, reflecting the inferred change to an increased snow cover during the latest Holocene as indicated by the pollen data. The appearance of Iconella tenera in DZ4 indicates warm waters within the basin over the past c. 2.4 cal. ka BP. Although there was moderate climate cooling over the past c. 1.1 cal. ka BP, the continued presence of this species suggests that this cooling did not affect the temperature of the lake water. A slight decline in percentages of TOC % and TOC%/TN% could indicate a modest deepening of the lake between c. 1.9 and 1.4 cal. ka BP.

**Genesis of the Glukhoye basin**

Based on preliminary work, Anderson *et al.* (2009) proposed three alternative hypotheses for the genesis of the Glukhoye basin: (i) Glukhoye was once part of a larger Peschanoye Lake, which covered most of Sernovodsky Isthmus (Fig. 1C); (ii) Glukhoye and Peschanoye lakes are both remnants from a time when sea level was higher than present and the isthmus was flooded by marine waters; or (iii) the elongated Glukhoye basin is an abandoned river channel that once drained an older Peschanoye Lake. As described below, a history of the Middle to Late Holocene geomorphology of Kunashir Island (Korotky *et al.* 1996; Razjigaeva *et al.* 2011a, b) describes changes in the timing and types of landforms that are both consistent and inconsistent with the Glukhoye record.

The section-based data indicate that sea levels began to rise starting c. 8.9 cal. ka BP, reaching a high stand of c. +2.5–3.0 m p.s.l. The final flooding of the land bridge which connected Kunashir Island to northern Japan occurred c. 6.9 cal. ka BP (Sato *et al.* 1998; Korotky *et al.* 2005). This marine transgression resulted in the eventual formation of large open bays and lagoons on the Pacific and Okhotsk sides of Kunashir Island, respectively. The flooding of Sernovodsky Isthmus is believed to have occurred at this time. In other areas of the island, the erosion of coastlines related to the transgression resulted in the build-up of barrier bars and numerous coastal lakes. Eventually, storm ridges developed, causing the demise of most of the lakes. A minor regression, indicated by the formation of large dunes (up to 20 m high), occurred c. 5.4 cal. ka BP. At this time, the marine strait was still present in the area of the modern Sernovodsky Isthmus, but it was divided by narrow ‘land bridges’. Two additional transgressions, from c. 4.5 to 3.6 and from c. 3.1 to 2.8 cal. ka BP, are marked by the erosion of coastal dunes and the formation of large sandy beaches and small estuarine lagoons. Two intervals of sea level lowering led to coastal dune formation and infilling of lagoons, the latter resulting in the closure of the coastal bays on each end of Sernovodsky Isthmus at c. 2.3 to 1.5 cal. ka BP. This period is also characterized by the subsequent development of freshwater lakes on the island.

The palaeodata preserved in the Glukhoye core indicate a simpler environmental history (i.e. a brackish lagoon, followed by a freshwater lake, a bog, and again a freshwater lake; Fig. 7) as compared with that reconstructed from the Kunashir sections. Nonetheless, the Glukhoye data are consistent with the proposed pattern of marine incursion and subsequent formation of coastal lakes and peats. The lithological and diatom data from the sections indicate the development of lagoons and then freshwater lakes between c. 4.5 and 1.5 cal. ka BP, whereas the Glukhoye data suggest that a lagoon phase ended by c. 4.3 cal. ka BP. Such differences in timing are to be expected given the piecemeal nature of the palaeoenvironmental record preserved in the sections and the relatively few radiocarbon dates and the limited spatial distribution of both lacustrine and section sites. Nonetheless, there are clear parallels in both data types that can be used in evaluating the genesis of the modern Glukhoye Lake.

Revisiting the first of the three hypotheses about the history of the Glukhoye basin, the low-lying topography of the Isthmus would not limit the size of Peschanoye Lake, and modern elevations are similar (~2.0 m a.s.l.) between Peschanoye and Glukhoye lakes. Tectonic activity may have altered the relative elevations over time, but there is no evidence to suggest that the area was not a lowland throughout the Middle to Late Holocene (Korotky *et al.* 1996; Razjigaeva *et al.* 2017). However, large shifts in precipitation and increased river inflow to the Isthmus would be needed to connect both freshwater lakes. The palynological data from Glukhoye and from the Kunashir sections (Razjigaeva *et al.* 2011a, 2013) do not support such a large increase in either rain or snow fall.

Turning to the second hypothesis, the Glukhoye diatom record indicates that the basin initially was filled with brackish water, reflecting some inflow from the Pacific. The occurrence of a lagoon between c. 8.2 and 4.3 cal. ka BP might support the idea that the Isthmus was once flooded, forming a strait between the Pacific Ocean and the Okhotsk Sea. The formation of exposed areas cross-cutting the isthmus c. 5.4 cal. ka BP possibly represents the initial separation of the Peschanoye and Glukhoye basins. However, if a true marine strait were established during the Middle Holocene, the Glukhoye diatoms should reflect greater salinity and would include taxa associated with a greater marine influence (e.g. an open bay as opposed to a brackish lagoon, the latter probably formed by a barrier bar). Unfortunately, we do...
not have a core from the larger lake (whose maximum depth is 36 m) nor any material from exposures near the lake. Thus, we cannot establish whether marine waters once filled the Peschanoye basin. However, the Glukhoye data do not support the establishment of a marine strait nor the presence of a large open bay, at least on the Pacific side of Kunashir Island.

The third hypothesis suggested that the Glukhoye basin was once part of the Peschanoye drainage. The current Peschanoye outlet flows to the north of Glukhoye Lake. Glukhoye Lake and the Peschanoye outlet are separated by boggy terrain and a small hill (~40 m a.s.l.). Given the modern topography, the outlet could once have included Glukhoye Lake. However, we lack evidence of alluvial terraces that would suggest an ancient river that once flowed through the Glukhoye basin to the Pacific and then was subsequently abandoned. Although diatoms indicate a period when the basin supported a boggy landscape, thus suggesting changes to the local hydrology (e.g. drainage pattern, groundwater), there is no evidence in the diatom complex nor the sedimentology of the Glukhoye core that the basin was part of a riverine system. Rather it seems that the history of the Glukhoye basin mainly records the interactions of coastal dynamics and local changes in hydrology rather than being formed by any of the processes we originally considered in our hypotheses.

The Middle and Late Holocene vegetation of southern Kunashir Island

The earliest vegetation represented in the Glukhoye record was *Betula–Quercus* forest with an understory of *Alnus* and *Pinus pumila* shrubs (PZ1; c. 8.2 to 8.0 cal. ka BP; Fig. 6). Other broadleaf trees, such as *Ulmus, Juglans* and *Fagus*, were present but not common. *Pinus pumila* also grew at higher elevations. Graminoid species were an important element on the landscape, most likely associated with lowland meadows. Although its pollen is not distinguishable from that of other Poaceae, *Sasa* was probably present by the early Middle Holocene. Today *Sasa kurilensis* forms dense thickets in open areas of the
forest. Like *Pinus pumila*, it requires sufficient snow cover to protect its leaves from frost damage (Suslov 1961; Andreev 1980). The occurrence of *Sasa* is supported indirectly by the establishment of *Pinus pumila*, implying sufficient snow cover, and by Polypodiaceae, which indicates openings in the forest canopy. The presence of *Sphagnum* and Polypodiaceae suggests the occurrence of mesic to boggy substrates and forested habitats near the lake. Temperatures were more moderate than present, with the steady increase in *Quercus* pollen in PZ1 suggesting a gradual warming between c. 8.2 and 8.0 cal. ka BP. Section data from southern Kunashir Island indicates the establishment of a similar vegetation to that inferred from the Glukhoye record. However, the sections indicate that *Betula–Quercus* forest persisted until c. 7.5 cal. ka BP and that climates were warmer than modern during the Early to Middle Holocene transition (Razjigaeva et al. 2013).

Between c. 8.0 and 6.5 cal. ka BP (PZ2), broadleaf forest became more widespread in the vicinity of Glukhoye Lake. These communities were dominated by *Quercus* but also included *Juglans*, *Ulmus*, tree *Betula* and *Acer*. The reduction in *Pinus s/g* Haploxylon pollen indicates the disappearance or rare occurrence of *Pinus pumila* in the region. Meadows probably persisted in wet low-lying areas but may not have been as prevalent as previously (e.g. slight reductions in *Sphagnum* spores and Poaceae pollen). Polypodiaceae continued to be an important element in the forest groundcover. The increase in more temperate tree taxa (e.g. *Juglans* and to a lesser extent *Ulmus*; consistently high percentages of *Quercus*) indicates a continuation in the trend towards increased warmth noted for zone PZ1. However, zone PZ2 reflects the warmest climate in the Glukhoye record. The decline in *Pinus pumila* suggests drier conditions during the cold season (Andreev 1980; Kozhevnikov 1981). During this interval, section data indicate that a cool-temperate *Quercus–*broadleaf forest spread throughout Kunashir Island, extending northward to Iturup Island and southward into the Lesser Kuriles (Korotky et al. 1996, 2000; Razjigaeva et al. 2002, 2004, 2011a; Lyaschevskaia & Ganzei 2011; Lozhkin et al. 2017). In contrast to the Glukhoye record, Korotky et al. (1996, 2000) concluded that the entire Archipelago experienced maximum Holocene warmth between c. 7.5 and 5.7 cal. ka BP.

While the c. 8.0 to 6.5 cal. ka BP interval marks the warmest part of the Glukhoye record, warmer than modern conditions continued in PZ3 (c. 6.5 to 4.1 cal. ka BP). *Quercus*, *Juglans* and *Ulmus* were common elements of the broadleaf forests, which also included *Fagus*, *Tilia*, *Acer*, *Magnolia* and *Shizandra*. Low percentages of *Picea* sect. *Eupicea* pollen, representing *Picea ajanensis* and/or *Picea glehnii*, suggest expansion of the conifers into the region. The modest presence of the conifers indicates a decline in summer temperatures as compared with the previous zone. Korotky et al. (2000) suggested that a weak cooling, associated with a slight marine regression, occurred at c. 6.5 to 6.2 cal. ka BP on Kunashir Island. The lake records from both Kunashir and nearby Iturup islands (Lozhkin et al. 2017) do not indicate such a brief climatic reversal.

*Quercus–*broadleaf forests persisted in the lowlands and along the coast c. 4.1 to 2.3 cal. ka BP (PZ4). The modest increase in *Abies* and *Picea* pollen indicates an expansion of conifer forest on hill and mountain slopes and provides additional evidence for the continued cooling trend initially noted for zone PZ3. The moderate but consistent increase in *Betula* pollen as compared with PZ3 reflects its greater role in the vegetation. During this interval, the Glukhoye record is in good agreement with the sections.

Palynological spectra from PZ5 (c. 2.3 to 1.1 cal. ka BP) differ from the assemblages in the earlier zones by the maxima in *Abies* and *Picea* pollen, consistent but trace percentages of *Larix* pollen and the final reduction in pollen from broadleaf taxa. This zone marks the increase in dark coniferous forests, which were dominated by *Picea* and *Abies*. This change probably included both an upslope and a downslope expansion of the conifer communities. Broadleaf trees such as *Quercus*, *Ulmus*, *Juglans* and *Acer* were probably present, but were reduced to minor elements in the lowland forests, the latter probably dominated by *Betula*. The increased importance of *Abies* and *Picea* suggests the occurrence of moist climates, if *Abies sachalinensis*, *Picea ajanensis* and *Picea glehnii*, which are present today, are the conifers represented by the pollen (Suslov 1961). Although the first two species require well-drained, mineral-rich soils, *Picea glehnii* needs a mesic substrate. The low percentages of *Pinus s/g* Haploxylon pollen suggest that the increased moisture was limited to the warm season. Razjigaeva et al. (2004) described a major climatic deterioration c. 3.2 to 2.6 cal. ka BP associated with the southward shift of mixed conifer–broadleaf forests and the dominance of *Picea* on most of Kunashir Island. Although the Glukhoye spectra reflect the increase in *Picea*, the timing (c. 2.3 to 1.1 cal. ka BP) is younger than documented in the sections. Such a difference probably reflects problems in the chronologies and related age models in both site types. A peak in Late Holocene cooling (c. 1.6 to 1.2 cal. ka BP), seen in the section data, was also noted in the Glukhoye record. However, the timing of the cool event differs (c. 2.3 to 1.1 cal. ka BP, again probably related to age models) and is not as intense as suggested in the sections.

The palynological spectra from PZ6 (c. 1.1 cal. ka BP to present), excepting *Pinus s/g* Haploxylon, suggest that modern vegetation was in place by c. 1.1 cal. ka BP, an age that approximates that noted by Razjigaeva et al. (2013) for the southern Kuril Islands. The increased presence of *Pinus pumila* in the middle of PZ6 suggests snowier conditions c. 0.8 to 0.5 cal. ka BP and is perhaps associated with Little Ice Age (LIA) climates. A LIA
Sections and lacustrine cores: reliability of palaeovegetation records from the Kuril Islands

Although analyses of lake and peat cores are now more common in areas of the SRFE (Bazarova et al. 2008; Lozhkin et al. 2010, 2021; Dirksen et al. 2013, 2015; Hammarlund et al. 2015; Hoff et al. 2015; Leipe et al. 2015), the current ideas about Holocene vegetation and climate change still rely heavily on data from sections. This is particularly true for the Kuril Islands. Palynological data extracted from sections usually represent differing depositional environments (e.g. soils, peats, lakes, alluvium) that can vary in their representation of local vs. regional vegetation (sensu Prentice 1988; see also Jacobson & Bradshaw, 1981). Furthermore, sections have a discontinuous depositional history, which complicates the formulation of reliable age models. Although lacustrine records are generally considered reliable sources for defining broader-scale patterns in the vegetation (Jacobson & Bradshaw 1981; Prentice 1988; Davis 2000), the coastal lakes in the Kuril Islands also have a complex depositional history (Fig. 7).

Despite these complications, some general conclusions can be drawn about pollen–vegetation and pollen deposition–vegetation relationships for the Kuril lacustrine records. A qualitative comparison of pollen spectra from surficial lake sediments to the modern vegetation showed that the lakes register variations in the major vegetation communities (i.e. the broadleaf forests of the southern Kurils, the transitional *Betula* forests of the central Kurils and the shrub tundra of the northern islands; Anderson & Lozhkin 2017). Korotky et al. (2000) and Razjigaeva et al. (2013) also noted that modern pollen samples from both lacustrine and non-lacustrine sediments reflect the main vegetation types of the Archipelago. However, these studies did not discuss any variations in the pollen spectra as related to differences in depositional setting, nor are brackish lagoons included in the modern data set. A visual inspection of stratigraphic boundaries based on palynological, diatom and lithological data from coastal lake cores in both the Kuril Islands and the SRFE mainland shows that times of change in the pollen data do not correspond to times when the depositional environment had altered (Anderson et al. 2015; Lozhkin et al. 2017, 2021). This simple comparison suggests that shifts in the pollen assemblages are the result of changes in vegetation and not in the depositional setting. In a more quantitative approach, Azuara et al. (2019) adapted the REVEALS model (Sugita 2007), which was initially applied to lakes, to evaluate pollen–vegetation relationships as recorded in coastal lagoons. They concluded that the model that had been developed to account for the dispersal and deposition of pollen, pollen source areas and estimation of regional vegetation in lakes is applicable to coastal lagoons. They also noted that changes to a basin’s geometry did not affect any of the above parameters. The model, thus, provides additional support that shifts from a lagoon to a lake should not significantly impact the Kuril pollen records.

Another problem for interpreting the palaeovegetation of the Kuril Islands is the paucity and uneven spatial distribution of the sites. Although the modern samples suggest that the different site types record broadscale vegetation patterns, combining palynological data from lacustrine and sections indicates that the palaeorecords are not as straightforward (Fig. 7, Table 4; the material presented in Table 4 is adapted from Razjigaeva et al. 2013). The best-case scenario is that of Kunashir Island. Here the palaeovegetation changes described in the previous section indicate a general agreement in the sequence of vegetation types between the sections and the Glukhoye record, although there is some discrepancy in timing. The latter most likely reflects problems in chronologies from both site types. Comparisons of lacustrine and section reconstructions from Iturup Island, located to the north of Kunashir Island (Fig. 1A), and from the northern Kurils (Onekotan Island, sections; Paramushir Island, lake) show more variation (Table 4, Fig. 7). The Maloye Lake record from central Iturup Island indicates the initial presence of *Betula*–conifer forest (c. 8.2 to 7.4 cal. ka BP) followed by the establishment of *Betula*–*Quercus*–broadleaf forest (c. 7.4 to 6.1 cal. ka BP), which marks the Holocene thermal optimum (Lozhkin et al. 2017). In contrast, the sections show the presence of a mix of broadleaf–*Betula* forest and *Betula*–conifer forest between c. 8.1 and 5.4 cal. ka BP (Razjigaeva et al. 2013). The Maloye record suggests a gradual change in the vegetation as climate cooled with the modern vegetation established over the past 200–400 years. The sections indicate a more abrupt cooling with the presence of *Betula*–*Quercus* forests c. 5.4 to 4.3 cal. ka BP followed by *Betula* forest with a minor component of *Quercus* and the establishment of modern vegetation at c. 1.4 cal. ka BP. The Holocene optimum is placed at c. 6.8 to 5.7 cal. ka BP. Even greater differences are seen in the Onekotan and Paramushir records, where the interval of *Pinus pumila–Duschekia* shrub tundra differs between c. 9.2 and 8.6 cal. ka BP in the sections (note: 9.2 cal. ka BP represents the bottom of the section data) and from c. 9.1 to 6.5 cal. ka BP in the lakes. Modern vegetation established c. 3.2 cal. ka BP (section) and c. 5.5 cal. ka BP (lake). The section data that show major discontinuities related to volcanic deposits are found only in the sections.

Conclusions that can be drawn from the above comparisons are limited by the small number of lakes and the uneven numbers of sections from any island. However, some tentative inferences can be made. For
example, the closest similarity in records from the different site types is from Kunashir Island, where the number of analysed sections is the greatest (Razjigaeva et al. 2013). The Onekotan–Paramushir comparison clearly shows that the section data are more sensitive to volcanic activity on the landscape. In contrast the lacustrine cores, while containing dispersed tephra, show no discrete ash layers. Thus, the differences in the lake and section records seem to have more to do with the number of section sites per island, the number of radiocarbon dates per site and the development of site age-models than they do with pollen representation issues related to the depositional environment. Although data from different site types can be combined with some caution for the Southern Kurils, insufficient numbers of sites exist at this time to provide a definitive vegetation or climate history for the Middle to Late Holocene of the central and northern Kuril Archipelago.

**Implications of the lacustrine records from the Kuril Islands for a section-based model of Holocene climate change**

Korotky et al. (1996, 2000) proposed a conceptual model of Holocene climate fluctuations based on lithological and palaeobotanical data from sections in both the SRFE mainland and the Kuril Islands, the latter area relying primarily on data from Kunashir Island. They linked regional changes in climate to sea level (warmer climates and higher sea levels; cooler climates and lower sea levels). Times of regression/cool climate were marked by indicators of shallow straits (e.g. marine molluscs and brackish to saline diatom assemblages) within the low-lying isthmuses that characterized the southern Kuril Islands and the presence of elevated marine terraces along the coasts. Rising sea level also resulted in large amounts of detrital material being deposited in the coastal zones, in some areas causing the development of coastal lakes. According to this model, the Middle and Late Holocene climate fluctuations were characterized by three intervals of dune formation and cool climates (c. 5.4 to 5.2 cal. ka BP, c. 1.6 to 1.2 cal. ka BP, LIA), a major warm/transgressive period (c. 7.4 to 6.8 cal. ka BP; +2.5 to 3.0 m p.s.l.), a second transgression with conditions only slightly cooler than during the HTM (c. 4.5 to 3.5 cal. ka BP; +1.25 to 2.5 m p.s.l.), and two occurrences of more modest warming/transgressions (c. 3.1 to 2.7 and c. 1.2 to 0.7 cal. ka BP). As their model relies heavily on changes in coastal conditions, the lake records, although few, add further information with which to evaluate the proposed palaeoclimate scheme.

Comparisons of lithological and palynological data from present-day lakes in coastal areas of Iturup and Paramushir Island (Anderson et al. 2015; Lozhkin et al. 2017) to the Glukhoye record do not support the linkage of region-wide sea level fluctuations and climate change as proposed by the Korotky et al. model (Fig. 7). Although the lacustrine records do indicate that sea levels were higher during the Middle Holocene (i.e. presence of brackish lagoons), the timing of these high stands varies among the sites (Glukhoye Lake high sea levels present by at least c. 8.2 and persisting to c. 4.3 cal. ka BP; Maloye Lake present by at least c. 8.2 cal. ka BP and persisting to c. 7.1 cal. ka BP; Pernatoye Lake c. 10.1 to 6.0 cal. ka BP). Furthermore, none of these records indicate additional high stands (i.e. re-establishment of lagoons) during the Late Holocene. Each of the lake

### Table 4. Summary of Middle to Late Holocene vegetation, Kuril Islands, from section data.

| Location          | Age (cal. ka BP) | Vegetation description                                      |
|-------------------|------------------|------------------------------------------------------------|
| Southern Kurils   |                  |                                                            |
| Kunashir Island   | 8.9–7.5          | Mixed *Betula* forest and meadows                          |
|                   | 7.5–5.7          | Cool temperate *Quercus*– broadleaf                       |
|                   | 5.7–2.3          | Mixed *Quercus*– broadleaf forest with conifers            |
|                   | 2.3–0.7          | Mixed conifer– *Quercus* broadleaf forest with decrease in broadleaf species and increase in tree *Betula*, meadows and bogs as compared with the previous interval |
|                   | 0.7–0            | Modern mix of *Quercus* broadleaf and conifer forest       |
| Central Kurils    |                  |                                                            |
| Rasshua Island    | 9.1–8.1          | Mixed shrub *Betula* tundra and graminoid meadows          |
|                   | 8.1–7.6          | Gramminoid–forb meadows and bogs                           |
|                   | 7.6–6.8          | Mixed *Pinus pumila*– *Duschekia* shrub                    |
|                   | 6.8–5.5          | *Duschekia* shrub tundra and graminoid–forb meadows        |
|                   | 5.5–4.5          | Heath with *Pinus pumila*– *Duschekia* thicket             |
|                   | 4.5–3.1          | Mixed *Pinus pumila*– *Duschekia* shrub                    |
|                   | 3.1–1.9          | Heath and graminoid–forb meadows                           |
|                   | 1.9–1.4          | Modern *Pinus pumila*– *Duschekia* shrub                   |
|                   | 1.4–0            | Heath with scattered shrub thickets of *Betula* and *Duschekia* |
| Northern Kurils   |                  |                                                            |
| Onekotan Island   | 9.5–8.6          | Heath with scattered shrub thickets of *Betula* and *Duschekia* |
|                   | 8.6–8.3          | Gramminoid–forb meadows, succession of pioneering communities following eruption of *Tao-Rusyr* volcano at c. 8.3 cal. ka BP |
|                   | ?                |                                                            |
|                   | 5.6–3.2          | *Pinus pumila* shrub tundra with greater bogy areas as compared with the previous interval |
|                   | 3.2–2.3          | *Pinus pumila*– *Duschekia* shrub tundra                   |
|                   | 2.3–0            | Modern mix of *Pinus pumila*– *Duschekia* shrub tundra, graminoid–forb meadows and wetlands |
paramushir islands (lozhkin et al. 2015; lozhkin et al. 2017), might reflect the development of coastal dunes during times of regression/cool climate (fig. 7). maloye and pernatoye lakes include four sand layers, whereas glukhoye lake has only two. all three records have a sand deposit c. 4000 cal. ka bp, a time of transgression in the palaeoclimate scheme. only maloye and pernatoye lakes show a c. 1000 cal. ka bp event, which is also proposed as a cool interval in the model. temporal offsets within and between lacustrine and section data can be attributed to the uncertainties in the age models. nonetheless, the inconsistencies in the numbers of ‘cool’ events among the lacustrine cores and between these records and the palaeoclimate model suggest that the sand layers in the lakes are not related to cool conditions associated with sea regression and coastal dune formation. it seems more likely that the sandy deposits reflect local processes, such as erosion of sandy deposits along inflowing streams or from embankments bordering the basin.

palynological data from the lacustrine sites indicate a gradual cooling from a holocene thermal maximum, again in contrast to the varying climates suggested by korotky et al. (1996, 2000) for the middle and late holocene. the interval of maximum warmth in all the lacustrine sites partially overlaps the c. 7.4 to 6.8 cal. ka bp age for the htm as proposed in the model for the entire archipelago, but the lakes show greater temporal variability (glukhoye lake c. 8.0 to 6.5 cal. ka bp; maloye lake c. 7.0 to 6.1 cal. ka bp; pernatoye lake c. 9.0 to 6.6 cal. ka bp). here again some temporal offset for the holocene optimum probably represents the quality of chronological control. however, a late holocene pattern of gradual cooling (lakes) and one with fluctuations between relatively cool and warm conditions (sections) is difficult to reconcile based solely on dating.

conclusions

previous results from lacustrine cores from iturup and paramushir islands (lozhkin et al. 2010, 2017; anderson et al. 2015) and from a coastal lake on the mainland (lozhkin et al. 2021) indicated that changes in palynological assemblages were independent of shifts in depositional environments, even in cases of significant differences, such as the shift from marine lagoons to freshwater lakes. the glukhoye record also confirms these findings and underscores the usefulness of the coastal lacustrine records for palaeovegetation interpretations.

comparisons of palaeovegetation changes based on the lacustrine cores (fig. 7) vs. the composite sections (table 4) indicate that the greatest similarity between the two data types occurs in the kunashir records. kunashir is also the island with the largest number of radiocarbon-dated sections, suggesting that: (i) there is an extra local vegetation signal that can be gleaned from the sections; (ii) the ability to understand the regional over the local vegetation history improves as the number of analysed sections increases; and (iii) at least qualitative palaeoclimate trends can be inferred for well-sampled islands. however, the timing of the vegetation changes differs between the two data types, reflecting the challenge for developing accurate age models in either discontinuous records or records with significant changes in depositional environments.

in previous publications, lozhkin and colleagues (anderson et al. 2015; lozhkin et al. 2017, 2021) noted that multiple changes in sea level, which had been proposed by korotky et al. (1996, 2000) as correlating to middle and late holocene climate fluctuations, were not supported by the diatoms or lithology, nor the geochemistry of the coastal lake records. this conclusion also holds true for glukhoye lake. in the palaeoclimate model proposed, periods of intense dune formation corresponded to intervals of relative cooling c. 5.4 to 5.2 and c. 1.6 to 1.2 cal. ka bp, and during the lia. lozhkin and colleagues considered that the sand layers preserved in the lake cores were possible indicators of coastal dune formation and/or greater aeolian input associated with lowered sea levels and a broader exposure of shelf sediments. although maloye (iturup island) and pernatoye (paramushir island) lakes include middle to late holocene sand layers, the timing and numbers do not correspond to episodes of sea level regression as proposed in the model. the glukhoye core has fewer and thinner sand layers as compared with the other lakes, and the ages of the glukhoye sands do not coincide with the proposed times of lowered sea levels. rather the histories of the lake basins seem to be related to local coastal dynamics that are independent of climate change.

in addition to the basin history, the palynological data from the lake records indicate gradual changes in vegetation and climate from an interval of maximum warmth to modern conditions. this pattern contrasts with the korotky et al. (1996, 2000) model, where the middle and late holocene were punctuated by intervals of warmer and cooler climates. although the palaeovegetation interpretations of palynological data in both lakes and sections indicate a thermal optimum during the middle holocene, this interval varies from c. 7.5 to 5.7 cal. ka bp (for the entire kuril islands based on sections; razgjaeva et al. 2013), from c. 8.0 to 6.5 cal. ka bp (kunashir island, lake data; this paper), from c. 7.0 to 6.1 cal. ka bp (iturup island, lake data; lozhkin et al. 2017) and from c. 9.0 to 6.6 cal. ka bp (paramushir island, lake data; anderson et al. 2015). such variation again speaks to the difficulties of age modelling, which may be the more important obstacle for documenting and understanding causes of the archipelago’s palaeoenvironmental history than are the
influences of sea levels or of subregional factors, such as volcanic eruptions or tsunamis.

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References

Alekseeva, L. M. 1983: Flora of Kunashir Island (Vascular Plants). 129 pp. Far East Regional Center of the USSR Academy of Sciences, Vladivostok (in Russian).

Alexandrova, A. N. 1971: Some questions of Quaternary stratigraphy of Iturup. Reports of the Sakhalin Department of the USSR Geographical Society 2, 74–81 (in Russian).

Alhonen, P., Heino, A. & Tynni, R. 1984: Multiproxy record of Holocene vegetation dynamics and climate change in Kamchatka Peninsula, Russian Far East. Review of Palaeobotany and Palynology 95, 48–65.

Anderson, P. M., Minyuk, P. S., Lozhkin, A. V., Cherepanova, M. V., Pakhomov, A. Y. & Alexsandrova, A. N. 1971: Some questions of Quaternary stratigraphy of Iturup. Reports of the Sakhalin Department of the USSR Geographical Society 2, 74–81 (in Russian).

Anderson, P. M., Minyuk, P. S., Pakhomov, A. Y. & Solomatkin, T. B. 2009: Pollen record and sediment ages from lakes of Kunashir and Iturup islands (Southern Kurils). In Blakonov, P. Ya. (Chairman of Editorial Board): Environment Development of East Asia in the Pleistocene-Holocene (Boundaries, Factors, Stages of Human Mastering), 13-16. Proceedings of International Scientific Conference, September 14-18, 2009. Dalnauka, Vladivostok.

Anderson, P. M., Minyuk, P. S., Lozhkin, A. V., Cherepanova, M. V., Borkhodoev, V. & Finney, B. P. 2015: Multiproxy record of Holocene environmental changes from the northern Kuril Islands (Russian Far East). Journal of Paleolimnology 54, 379–393.

Andreev, V. N. 1980: Some data about lichen-free tundra. In Andreev, V. N. (ed.): Vegetation and Soils of Subarctic Tundra, 201–205. Siberian Branch Yakutia Subdivision Biological Institute USSR Academy of Sciences, Novosibirsk (in Russian).

Avramenko, A. S., Cherepanova, M. V., Pushkar, V. S. & Yarusova, S. B. 2015: Diatom characteristics of the Far East siliceous organogenic deposits. Russian Geology and Geophysics 56, 947–958.

Aznara, J., Mazier, F., Lebretón, V., Sugita, S., Viovy, N. & Combouvier-Nebout, N. 2019: Extending the applicability of the REVEALS model for pollen-based vegetation reconstructions to coastal lagoons. The Holocene 29, 1109–1112.

Barinova, S. V., Medvedeva, L. A. & Anisimova, O. V. 2006: Diversity of Algal Indicators in Environmental Assessment. 498 pp. Plüies, Tel-Aviv (in Russian).

Barkalov, V. Y. 2009: Flora of the Kuril Islands. 135 pp. Dalnauka, Vladivostok (in Russian).

Bazarova, V. B., Klimin, M. A., Mokhova, L. M. & Orlova, L. A. 2008: New pollen records of Late Pleistocene and Holocene changes of environment and climate in the last 23,000 years. Environmental changes during the last deglaciation. Journal of Oceanography 65, 847–858.

Blaauw, M. & Christen, J. A. 2011: Bacon Manual – v. 2.2. http://www.cron.qub.ac.uk/blaauw/bacon.html.

Blaauw, M. & Heegaard, E. 2012: Estimation of age-depth relationships. In Birks, H. J. B., Lotter, A. F., Juggins, S. & Smol, J. P. (eds.): Tracking Environmental Change Using Lake Sediments: Data Handling and Numerical Techniques, 379–413. Springer, Amsterdam.

Bourgeois, J., Pignéna, T. K. & Zaretkaia, N. 2006: Holocene tsunami in the southwestern Bering Sea, Russian Far East, and their tectonic implications. Geological Society of America 118, 449–463.

Czerepanov, S. K. 1995: Vascular Plants of Russia and Adjacent States (the Former USSR). 516 pp. Cambridge University Press, Cambridge.

Davis, M. B. 2000: Palynology after YER – Understanding the source area of pollen in sediments. Annual Review of Earth and Planetary Sciences 28, 1–18.

Ding, Y. H. & Chan, C. L. 2005: The East Asian summer monsoon: a review. Meteorology and Atmospheric Physics 99, 117–142.

Dirksen, V., Dirksen, O., van den Bogaard, C. & Dickmann, B. 2015: Holocene pollen record from Lake Sokoch, interior Kamchatka (Russia), and its paleobotanical and palaeoclimatic record. Global and Planetary Change 134, 129–141.

Dirksen, V., Dirksen, O. & Dirksen, B. 2013: Holocene vegetation dynamics and climate change in Kamchatka Peninsula, Russian Far East. Review of Palaeobotany and Palynology 195, 48–65.

Donar, C. M., Needy, R. K. & Stoermer, E. F. 1996: Diatom succession in an urban reservoir system. Journal of Paleolimnology 15, 237–243.

Ganzei, K. 2011: Landscape Forming Factors of Kurile Islands (North-Western Pacific). 94 pp. Lambert Academic Publishing, Saarbrücken.

Gibson, C. E., Anderson, N. J. & Haworth, E. Y. 2003: Aulacoseira subarctica: taxonomy, physiology, ecology and palaeoecology. European Journal of Phycology 38, 83–101.

Gleser, Z. I., Jousé, A. P., Makarova, I. V., Proshkina-Lavrenko, A. I. & Sheshukova-Poretskaya, V. S. (eds.) 1974: Diatoms of the USSR: Fossil and Modern. 403 pp. Nauka, Leningrad (in Russian).

Goldfarb, S. I. 2014: Geographical Encyclopedia of the Kuril Islands. 254 pp. Publishing House Komsomolskaya Pravda, Moscow (in Russian).

Gorbarenko, S. A., Artemova, A. V., Goldberg, E. L. & Vasilenko, Y. P. 2014: The response of the Okhotsk Sea environment to the orbital-millennium global climate changes during the Last Glacial Maximum, deglaciation and Holocene. Global and Planetary Change 116, 76–90.

Gorbarenko, S. A., Southon, J. R., Keigwin, L. D., Cherepanova, M. V. & Grozdeva, I. G. 2004: Late Pleistocene-Holocene oceanographic variability in the Okhotsk Sea: lithological and paleontological evidence. Palaeogeography, Palaeoclimatology, Palaeoecology 209, 281–301.

Hammarlund, D., Klimaschewski, A., St. Amour, N. A., Andren, E., Seif, A. E., Solovieva, N., Andreev, A. A., Baraevk, L. & Edwards, T. W. D. 2015: Late Holocene expansion of Siberian dwarf pine (Pinus pumila) in Kamchatka in response to increased snow cover as inferred from lacustrine oxygen-isotope records. Global and Planetary Change 134, 91–100.

Harada, N., Akagon, N., Uchida, M. & Murayama, M. 2004: Northward and southward migrations of frontal zones during the last 40 kyr in the Kuroshio-Oyashio transition area. Geochimie, Geophysie, Geosystems 5, Q00904, https://doi.org/10.1029/2004GC007040.

Harada, N., Katsuki, K., Nakagawa, M., Matsumoto, A., Seki, O., Addison, J. A. & Finney, B. P. 2014: Holocene sea surface temperature and sea ice extent in the Okhotsk and Bering Seas. Progress in Oceanography 126, 242–253.

Heyerdahl, T., Biskaborn, B. K., Dirksen, V. G., Dirksen, O., Kuhn, G., Meyer, H., Nazarova, L., Roth, L. & Dickmann, B. 2015: Holocene environment of Central Kamchatka, Russia: Implications from a multi-proxy record of Two-Yurts Lake. Global and Planetary Change 134, 101–117.

Inagaki, M., Yamamoto, M., Igarashi, Y. & Ikehara, K. 2009: Biotracker records from core GH02-1003 off Tokachi in the Northwestern Pacific over the last 23,000 years. Environmental changes during the last deglaciation. Journal of Oceanography 65, 847–858.

Inagaki, M., Yamamoto, M., Igarashi, Y. & Ikehara, K. 2009: Biotracker records from core GH02-1003 off Tokachi in the Northwestern Pacific over the last 23,000 years. Environmental changes during the last deglaciation. Journal of Oceanography 65, 847–858.
Sato, H., Kumano, S., Maeda, Y., Nakamura, T. & Matsuda, I. 1998: The Holocene development of Kushu Lake on Rebun Island in Hokkaido, Japan. *Journal of Paleolimnology* 20, 57–69.

Sato, H., Maeda, Y. & Kumano, S. 1983: Diatom assemblages and Holocene sea level changes at the Tamatsu site in Kobe, western Japan. *The Quaternary Research (Japanese Association for Quaternary Research)* 22, 77–90.

Stuiver, M., Reimer, P. J. & Reimer, R. W. 2020: *CALIB 8.2* (WWW program) at http://calib.org. Accessed 20/6/2020.

Sugita, S. 2007: Theory of quantitative reconstruction of vegetation I: pollen from large sites REVEALS regional vegetation composition. *The Holocene* 17, 229–241.

Suslov, S. P. 1961: *Physical Geography of Asiatic Russia*. 594 pp. W.H. Freeman and Co, San Francisco.

Urusov, V. M. & Chipizubova, M. N. 2000: *Vegetation of Kuril Islands Questions of Dynamics and Origin*. 303 pp. Russian Academy of Sciences, Far East Branch, Vladivostok (in Russian).

Vorobiev, D. P. 1963: *Vegetation of the Kurile Islands*. 92 pp. USSR Academy of Sciences Press, Moscow (in Russian).

Walker, M., Head, M. J., Lowe, J., Berkelhammer, M., Bjorck, S., Cheng, H., Cwynar, L. C., Füger, D., Gkinis, V., Long, A., Newnham, R., Rasmussen, S. O. & Weiss, H. 2019: Subdividing the Holocene Series/Epoch: formalization of stages/ages and sub-series/subepochs, and designation of GSSPs and auxiliary stratotypes. *Journal of Quaternary Science* 34, 173–186.

Wright, H. E., Mann, D. H. & Glaser, P. H. 1984: Piston corers for peat and lake sediments. *Ecology* 65, 657–659.

**Supporting Information**

Additional Supporting Information to this article is available at http://www.boreas.dk.

Fig. S1. Age–depth plot of calibrated ages for Glukhoye Lake.

Table S1. Dominant and common diatoms, Glukhoye Lake.