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A Reconstruction of the Climate and Vegetation of Northeastern Siberia Based on Lake Sediments

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Abstract—Detailed palynological analysis of glacial, tectonic, and crater lakes of northeastern Siberia reveals continuous records of the changing vegetation during one or several climatic cycles of the Pleistocene and in the Holocene. The most continuous records in the mountain areas of the region are those of Lake Elikchan-4 (northern Okhotsk Sea Region). Pollen records of Lake El'gygytgyn, which was formed by the impact of a meteorite in the northern Chukchi Peninsula, reflect the response of land vegetation to the global climatic impact during the last 300 ka.

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Key words: continuous palynological records, Pleistocene, Holocene, lacustrine sediments.

INTRODUCTION

Continuous palynological records of lacustrine sediments reflect the response of vegetation to the climatic changes during the Quaternary. These climatic records, supported by chronological control, are obtainable from sediments of crater, glacial, and fault lakes.

For the reconstruction of Quaternary climate and vegetation, core samples were collected in several phytogeographical zones of northeastern Siberia: northern Chukchi Peninsula (including Wrangel Island), Anadyr River Basin, southern Chukchi Peninsula, regions of mountain-valley glaciers in the Kolyma and Indigirka river basins, and the northern Okhotsk Sea Region (*The Late Quaternary* …, 2002; *The Glaciation* …, 2005).

METHODS AND RESULTS OF THE STUDY

One of the most complete continuous palynological records known, showing the evolution of the climate and vegetation in northeastern Siberia during the Late Pleistocene and Holocene, was discovered in the sediments of Lake Elikchan-4 (60°44′ N, 151°52′ E, 798.9 m above sea level). Lake Elikchan-4 gives rise to the Maimandzha River, which flows into the Okhotsk Sea. The lake, 4 km long and up to 1.3 km wide, is situated in a deep valley near the divide with the Kolyma River basin. Its formation was related to a fault zone transecting the Okhotsk–Kolyma interfluve in a northwesterly direction. Forests of *Larix dahurica* Turcz. with *Duschekia fruticosa* (Rupr.) Pouzar and *Betula middendorffii* Trautv. et Mey. grow on the slopes of the Maimandzinskie Mountains surrounding the lake.

At the center of the lake 945-cm-long cores were taken from a depth of 9 m, showing the complete thickness of the sediments, composed of silts with thin horizontal bedding, plant remains, and sublayers of fine-grained sand. In an interval of 213–214.5 cm a band of volcanic ash was revealed and dated 7650 ± 50 BP (Lozhkin et al., 2004). It is a marker of the lacustrine deposits in the northern Okhotsk Sea–Kolyma-Indigirka Region. The pollen record of the sediments of Lake Elikchan-4 embrace an interval of at least 70 ka and includes isotope stages 4–1 (Fig. 1). The contribution of each pollen taxon is shown as a percentage of the sum total of all pollen grains, and that of spores as a relative value of the total number of pollen grains individually for each spore taxon. In the diagram, two herb pollen zones are distinct (EL1 and EL3), which are characterized by persistent composition of the pollen spectra. The spectra of the lower zone, EL1 (945–882 cm), which was assigned to the Zyrianka glacial stage of the Late Pleistocene (isotope stage 4), were produced by tundra associations and reflect a very profound cooling. The dominating pollen grains of the Poaceae (48%) and Cyperaceae (35%) indicate a wide occurrence on the floors of mountain valleys of cereal and sedge associations with *Polygonum aviculare* L., *P. amphibium* L., *Koenigia islandica* L., *Pedicularis, Sanguisorba, Allium, Cardamine*, Ranunculaceae (9%), Polemoniaceae, and Apiaceae on wet soils of riverbanks and lakeshores, damp meadows, and streamside pebbles. The abundant spores of *Selaginella rupestris* (L.) Spring (60% of the sum total of all pollen grains); relatively abundant pollen grains of *Artemisia* (11%), Asteraceae (5%), Brassicaceae (10%), and Ericales

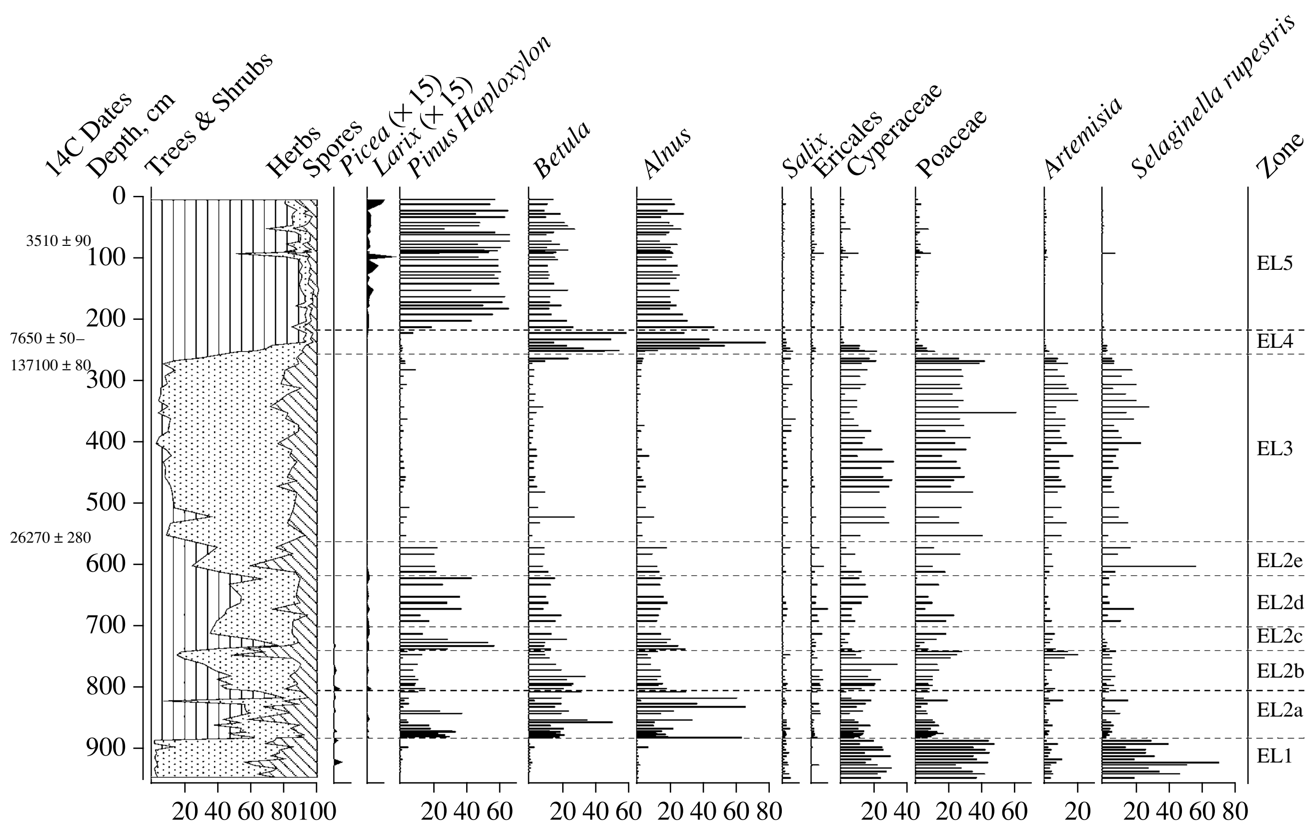

Fig. 1. Proportions of vegetation groups and main pollen and spore taxa in the spectra of sediments of Lake Elikchan-4. The left part of the diagram shows radiocarbon dates. The lower horizontal line shows relative proportions of pollen and spores as percentages of the total pollen grains.

(4%); and pollen grains of Cichoriaceae, Caryophyllaceae, Fabaceae, Saxifragaceae, Papaveraceae, *Corydalis, Rosaceae*, *Draba, Potentilla, Dryas*, and *Claytonia acutifolia* Pall. ex Schult. indicate the development of rubbly and stony tundras on mountain slopes, taluses, and wet areas with snow patches persisting throughout summer. All samples constantly contain (up to 1%) pollen grains of *Claytoniella vassilievii* (Kuzen.) Jurtz., a species that is more characteristic of the Middle Pleistocene. In all likelihood, willows were the most common shrub of the mountain tundra: pollen grains of *Salix* make 5%. In the lower course of the Maimandzha River, *Pinus pumila* (Pall.) Regel, *Betula middendorffii, Duschekia fruticosa*, and *Picea obovata* Ledeb. could have grown as relicts of Late Pleistocene interglacial forests, also growing there today. Although computer extrapolation of radiocarbon dates disregards, for example, the compression of lacustrine sediments at the base of the core, it does not contradict the dating of the upper boundary of the Zyrianka stage as 60 ka BP.

The pollen spectra of the second herb pollen zone, EL3 (560–255 cm), which corresponds to the Sartan Glacial (isotope stage 2), pollen of the Poaceae (62%), Cyperaceae (87%), *Artemisia* (20%), and the Brassicaceae (15%) dominate; and pollen of the Caryophyllaceae (9%), Ranunculaceae (10%), *Thalictrum* (8%), Saxifragaceae (3%), Ericales (2%), Scrophulariaceae (3%), and the Cichoriaceae (10%) is prominent. Such shrubs as *Pinus pumila, Duschekia fruticosa,* and *Betula middendorffii* are usually represented by single specimens, but pollen grains of *Salix* are constantly present (up to 6%). We believe that the vegetation of the Sartan Glacial was a combination of various tundra communities: from dry stony slopes with discontinuous plant cover of herbs and *Selaginella rupestris* (28%) to typical tundra sedge-moss communities with creeping dwarf willows. A comprehensive series of radiocarbon dates from 27.4 to 13.7 ka BP obtained in different phytogeographic regions of northeastern Siberia allowed us to date the boundary between the Sartan Glacial and the preceding interglacial (isotope stage 3) to about 27.4 ka BP (Lozhkin, 1991). This does not contradict the date 26270 ± 280 BP (CAMS 5166) shown in the diagram for the lower layers of zone EL3.

Zone EL2 (882–560 cm) is situated between two herb pollen zones and reflects vegetation change during the Karga Interglacial (isotope stage 3). The pollen spectra are characterized by abundant pollen grains of *Pinus* subgen. *Haploxylon* (up to 57%), *Alnus* (up to 64%), *Betula* (up to 50%); pollen grains of *Larix* constantly occur; pollen grains of *Picea* are present.

Among pollen grains of herbs, the Poaceae (28%), Cyperaceae (33%), *Artemisia* (20%), Brassicaceae (12%), and Caryophyllaceae (10%) predominate. Pollen grains of the Ericales (9%) are more prominent than in the spectra of EL1. The taxonomic composition of secondary herbaceous taxa, with various ecological preferences, is very diverse: pollen grains of the Liliaceae, *Polygonum* (at least three species), Chenopodiaceae, *Claytonia acutifolia, Claytoniella vassilievii, Thalictrum* (4%), Papaveraceae, *Corydalis, Cardamine, Draba*, Saxifragaceae (2%), Rosaceae, *Spiraea, Potentilla, Dryas, Sanguisorba*, Fabaceae, Onagraceae, Apiaceae, Primulaceae, Plumbaginaceae, Gentianaceae, Polemoniaceae, Lamiaceae, Scrophulariaceae, *Pedicularis*, Rubiaceae, Valerianaceae, Asteraceae (2%), Cichoriaceae (1%), and others. The spectra of this zone provide a fair indication of the development of open larch forests in valley bottoms and low mountain slopes, supposedly with the participation of spruce, which alternate with forest, low-shrub, and herbaceous dwarf-shrub tundras. It is very possible that a belt of mountain pine forests formed over the boundary of larch forests during the Karga Interstadial.

Very considerable changes in the proportions of vegetation groups and main pollen taxa that are reflected in the pollen spectra of zone EL2 testify to significant climatic fluctuations during the Karga Interstadial. This allows five subzones to be identified within zone EL2 (Fig. 1). Subzone EL2a corresponds to the Early Karga warming, which we call Elikchan-4. This warming obviously embraces an interval of 60–44 ka BP. It is not excluded that a short but sufficiently profound cooling episode took place during this warming, manifested by a peak of pollen grains of herbs. The cooling episodes that are revealed in the palynological diagram in the intervals of 800–740 cm (subzone 2b) and 700–620 cm (subzone 2d) may correspond to the Kirgilyakhskii and Konoshchelskii coolings (Shilo et al., 1983), when the mountain areas occupied by low-shrub and herbaceous dwarf-shrub tundras considerably expanded, and open larch forests were restricted to valley bottoms. Therefore, palynological analysis testifies that the climate of the Karga Interstadial was more severe than the modern climate, which is characterized by a cool and relatively humid summer.

Pollen grains of *Alnus* (77%) and *Betula* (66%) dominating in the spectra of zone EL4 (255–215 cm) allow us to describe it as a birch-alder zone that reflects the replacement of herbaceous tundra communities by tundras with big shrubs and, later, by larch forests. The upper boundary of EL4 zone coincides with the *Pinus-peak* (the first pine peak since the Sartan Glacial) at the boundary between the Boreal and Atlantic intervals of the Holocene. The maximum percentage of pollen grains of *Pinus* (66%) was registered in zone EL5, where *Larix* constantly occurs (up to 2%), and the proportions of *Alnus* and *Betula* reach 47 and 28%, respectively. Radiocarbon dating indicates that zone EL5 was formed during the Atlantic, Sub-Boreal, and Boreal of the Holocene, when the vegetation became similar to the modern vegetation.

The first convincing evidence of a considerable warming in the beginning of the Late Pleistocene (marine isotope stage 5) is provided by pollen records of crater Lake El'gygytgyn, which was formed about 4 Ma BP by the impact of a meteorite in the northern Chukchi Peninsula (67°30′ N and 172°05′ E). The records that now characterize the upper 1283 cm in the center of the lake at a depth of 169 m include the time of extreme changes of the global climate from the Middle Pleistocene until now (Fig. 2). The antiquity of the records can compete with data on the Greenland ice sheet, and the location of the lake in a different sector of the Arctic enables changes in ancient climates of the Northern Hemisphere to be traced throughout a broader area. Unlike ice core samples, sediments of Lake El'gygytgyn provide a continuous picture of the response of land vegetation to global climatic impact during the last 300 ka, or marine isotope stages 8–1.

The palynological diagram of the sediments of Lake El'gygytgyn is subdivided into 13 pollen zones showing the alternation of three main vegetation types: the domination of shrubs, prevailing of herbs, and the mixed type that is represented by herbaceous low-shrub communities. We unite pollen zones with similar characteristics in several groups. Shrub-dominating communities include zones E13, E12, E8, E7, and E6. Zone E13 reflects the development of the modern vegetation of the Anadyr Upland. *Betula* was supposedly the most common shrub, and the abundance of *Duschekia fruticosa* and *Pinus pumila* varied depending on the microlandscape. About 9600 BP *Pinus pumila* became the main element of modern regional vegetation communities. Zone E12, which includes Late Glacial and Early Holocene, shows a common occurrence of tundra with dominating *Betula middendorffii* and *Duschekia fruticosa.* The increased percentage of pollen grains of *Betula* testifies to the regional development of birch 12 800 BP. The wide occurrence of alder forests is dated to 10 700 BP.

The maximum of the last interglacial (isotope substage 5e) is reflected in the spectra of pollen zone E6 with peaks of *Betula* and *Alnus* (Fig. 2). It is very possible that at this time *Betula, Alnus*, and *Salix* developed into trees and large shrubs, and the landscape of the northern Chukchi Peninsula was dominated by birch forest-tundra. Although *Larix* was not detected in the spectra, it is possible that larch forests grew in the upland surrounding the lake. According to these reconstructions, about 116–128 ka BP the boundaries of the ranges of *Larix dahurica* and arboreal *Betula* were situated 600 km to the north of their current position. A very high percentage of *Pinus pumila* in the spectra of zone E7 (isotope substage 5d, 104–116 ka BP) indicates that mountain pine formed tundra with high shrubs within the basin. In the regional landscape, the vegetation resembled modern phytocenoses of the

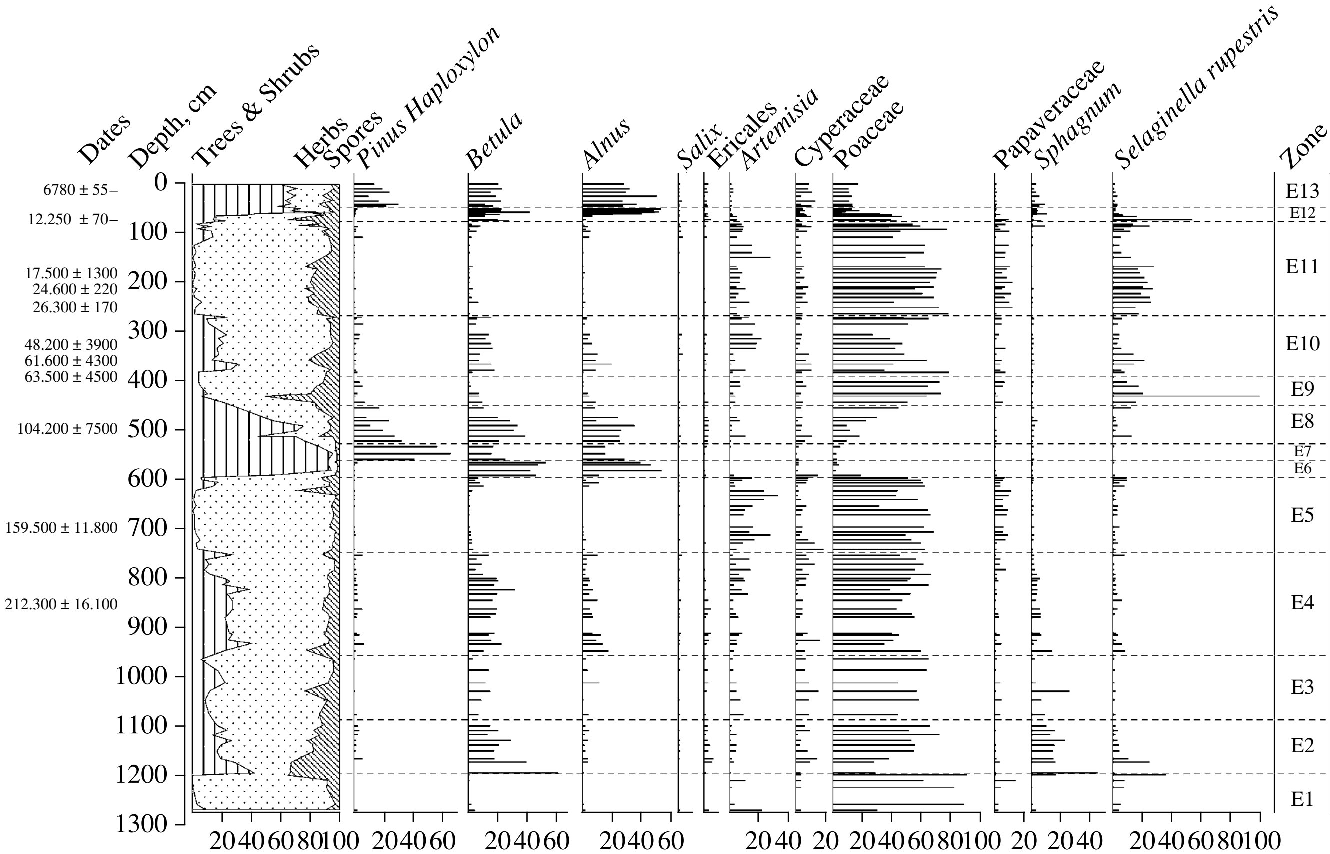

Fig. 2. Proportions of vegetation groups and main pollen and spore taxa in the spectra of sediments of Lake El'gygytgyn. The left part of the diagram shows radiocarbon and luminescence dates. The lower horizontal line shows relative proportions of pollen and spores as percentages of the total pollen grains.

southern Chukchi Peninsula, which are transitional between tundra and taiga. Zone E8 most probably embraces isotope substages 5a, 5b, and 5c (74–104 ka BP) and reflects regional and local plant communities: from low-shrub birch tundra with the locally increased proportion of *Duschekia fruticosa* and *Pinus pumila* to tundra with high shrubs of *Pinus pumila, Duschekia fruticosa*, and *Betula middendorffii.* Larch possibly grew during the early phase of this stage.

Boreal larch forests that predominated in the Late Quaternary Interglacial in mountain regions of the Kolyma and Indigirka rivers included *Picea obovata* Ledeb. and *P. ajanensis* Fisch. Their composition was close to that of the forest communities that nowadays grow 1000 km further south. The discovery of cones and large trunks of *Larix dahurica* in pseudomorphs along Yeadomian ice veins show that larch intruded into the Yana-Kolyma lowland of northeastern Siberia, which is currently occupied by herbaceous low-shrub tundra.

Communities with domination of herbs are typical of the glacials (zones E11, E9, E5, and E1). The spectra of zone E9, which is referred to as isotope stage 4 (60–74 ka BP, Zyrianka Glacial), were undoubtedly produced by grass-and-herb tundras. The spectra of zone E11, assigned to isotope stage 2 (27.4–12.3 ka BP, Sartan Glacial), clearly show the predominance of xerophytic tundras. The Middle Pleistocene age of zone E5 is confirmed by luminescence dating as 163600 ± 12200 BP (UIC–675). The peaks of *Artemisia,* the Papaveraceae, and Poaceae that are characteristic of this zone indicate the development of arctic tundras with discontinuous cover under relatively dry climatic conditions. A fairly profound cooling reflected in the spectra allows this zone to be correlated with isotope stage 6. Zone E11 may correspond to isotope stage 8. The spectra of this zone showing peaks of pollen of the Poaceae, the abundance of *Artemisia* and *Selaginella rupestris*, and a low proportion (or absence) of pollen grains of shrubs reflect the development of arctic mosaic tundras with discontinuous herb cover under extreme climatic conditions.

Mixed herbaceous and shrubby communities are reflected in pollen zones E10, E4, E3, and E2. Palynological data belong to the Late Pleistocene Interstadial (zone E10) and isotope stage 7 of the Middle Pleistocene (zones E2–E4). The spectra of zone E10 show that the regional and local vegetation were probably dominated by dry Poaceae–*Artemisia* tundra with *Salix* as a dominating shrub, developed under more severe

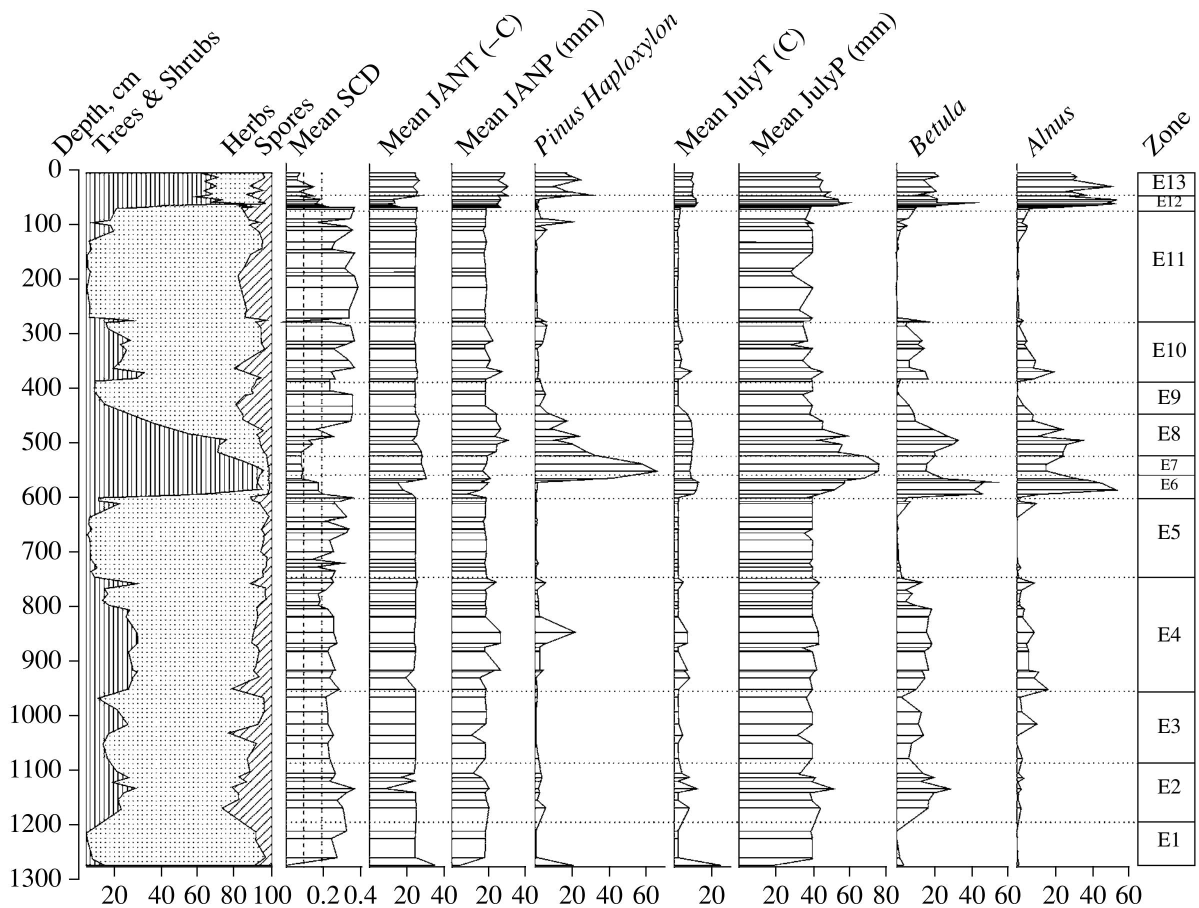

Fig. 3. Climatic reconstruction based on the pollen spectra of the sediments of Lake El'gygytgyn and their analogues among modern pollen spectra of northeastern Siberia and the Alaska Peninsula. Legend: (Depth) depth, cm; (Trees & Shrubs, Herbs, Spores) ratio of vegetation groups in the spectra of sediments of Lake El'gygytgyn; (Mean SCD) mean statistic coefficients; (Mean JanT (C)) mean January temperatures, °C; (Mean JanP (mm)) mean January precipitation, mm; (*Pinus Haploxylon*) relative proportion of mountain pine in the spectra; (Mean JulyT (C)) mean July temperatures, °C; (Mean JulyP (mm)) mean July precipitation, mm; (*Betula*) relative proportion of birch in the spectra; (*Alnus*) relative proportion of alder in the spectra; (Zone) pollen zones.

conditions in comparison to the modern climate. We correlate this zone with the Karga Interstadial (isotope stage 3). By contrast to the pollen records of Lake Elikchan-4, the spectra of zone E10 show certain small differences between the vegetation of glacial and interglacial stages in higher latitudes. It is conceivable that the lower layers of zone E11 should also be assigned to isotope stage 3.

In general, the pollen spectra of zone E2, E3, and E4 have "interstadial" characteristics. In the Middle Pleistocene samples, the proportion of pollen grains of *Betula* is high, and that of the Poaceae is very high (Fig. 2). Zone E3 shows grass-and-sedge tundra that was supposedly more moderately humid than in zone E10, as is testified by smaller proportions of pollen grains of *Artemisia*. *Salix* was the most common shrub. *Betula* most probably formed small disjunctive populations. The proportion of *Betula* in the spectra of zones E4 and E2 is generally comparable or exceeds its contribution to the modern spectra, but other characteristics of the assemblages differ significantly: high proportions of the Poaceae in the spectra of zones 4 and 2 and low proportions in the modern spectra, and low proportion of *Pinus* in the spectra of zones 4 and 2 contrast to its abundance in the modern spectra. The significant contribution of *Betula* to the pollen spectra of these zones most probably proves that it grew in the Anadyr Upland in the vicinity of Lake El'gygytgyn. The maximum abundance of *Betula* in the spectra of the lower part of zone E2 indicates the development of productive high-shrub birch tundra. Therefore, the spectra reflecting the vegetation development during isotope stage 7 show repeated alternation between herbaceous-birch low-shrub tundras and herbaceous or herbaceous-alder-birch tundras, caused by climatic fluctuations.

CLIMATIC RECONSTRUCTIONS

We used the results of our palynological analysis of the bottom sediments of Lake El'gygytgyn in one of the first attempts at paleoclimatic reconstruction based on statistical comparison between modern and fossil pollen spectra, and the evaluation of the modern climatic conditions of each locality, where samples of bottom lacustrine sediments were collected at the water-sediment interface (Fig. 3). Paleoclimates were interpreted using software. The first program we used was called "Program of Analogues." It is used in statistical coefficient dissimilarity (SCD), which allows one to reveal the closest modern analogue of a fossil spectrum (Overpeck et al., 1985). The program contains data from about 310 modern spectra of northeastern Siberia and the Alaska Peninsula, as well as geographical coordinates and elevations of each modern sample and data about pollen spectra from fossil samples. The statistical coefficients for the evaluation of pollen analogues have the following values: A very strong similarity <0.095; strong similarity 0.096–0.185; possible similarity 0.186–0.4; and no similarity >0.4 (Fig. 3). When the search for modern analogues of fossil spectra was performed, the climatic parameters were determined for the sites where relevant modern samples were collected. For this purpose a computer program was used that processed climatic data distributed on a global coordinate grid having 0.5°-units of latitude and longitude. This grid is based on data from meteorological stations.

Modern climatic conditions were established within zone E13 about 6–7 ka BP. The warmest conditions, with JulT from +11 to +12.4°C and JanT from –12 to –18°C, existed between 8.6 and 19.7 ka BP. January temperatures (from –24 to –25°C) showed small differences between the glacials and interstadial in the Late Pleistocene (zones E11–E9). During the Late Pleistocene Interstadial (zone E10), July temperatures mostly changed from +2.5 to +4°C, testifying that this interstadial was only slightly warmer than the preceding and subsequent glacials (Fig. 3). The driest conditions were between 22.6 and 24.3 ka.

Virtually all climatic parameters reached their maxima in the Late Pleistocene Interglacial (zones E8, E7, and E6). During isotope substages 5a, 5b, and 5c (zone E8), average January temperatures changed from –23.4 to –27.4°C, and July temperatures were from +9 to +10°C. Even lower winter temperatures are reconstructed for zone E7 (isotope substage 5d): from –27.2 to –29.4°C. Summer temperatures were about +9°C. Zone E7 is characterized by the most humid conditions in the climatic record of Lake El'gygytgyn (July precipitation 73–75 mm). The high percentage of pollen grains of *Pinus pumila* in the spectra implies a deep snow cover that was formed during autumn and a relatively dry January (16–23 mm) that did not affect the pine.

Zone E6 reflects an interglacial climatic optimum (isotope stage 5e) with January temperatures varying from –16 to –24.7°C and July temperatures from +10.6 to +12.7°C. January approximated to the glacials in its precipitation (7.5–20 mm), and July precipitation was less abundant (36.5–57.5 mm) than in zone E7.

Middle Pleistocene glacial zones E5 and E1 are characterized by January temperatures varying from –24 to –25°C and July temperatures varying from +2 to +3°. The Middle Pleistocene Interstadial significantly differs from the Holocene and the warming period of the last interglacial. The maximal temperatures of zone E2 vary between +8.1 and +10.3°C. The maximal temperatures represented by some peaks in the diagram (Fig. 3) are supposedly related to small anomalies in the pollen spectra. Cold July temperatures in zones E4–E2 are between +2.3 and +2.5°C and resemble the modern temperatures of Wrangel Island; January temperatures vary between –23.7 and –24.8°C.

CONCLUSIONS

There were only two periods during 300 ka when the climate of northeastern Siberia was warmer than nowadays: (1) the Early Holocene thermal maximum and part of the Late Dryas (8600–10700 BP, radiocarbon dating) and (2) the climatic optimum of the Late Pleistocene Interglacial (isotope substage 5e). All pollen records of the transitional Pleistocene–Holocene period show a sharp and fast warming 12.4 ka BP, when the herbaceous tundras dominating over the entire region were replaced by uniform shrubby birch tundra, and, later, by birch-alder tundra. As early as 11.6 ka BP, open larch forests already occupied vast areas in mountain regions of the Kolyma and northern Okhotsk Sea regions. Mountain pine became significant in the plant cover 8 ka BP and formed pure stands over the forest boundary. In the southern Chukchi Peninsula, high-shrub tundras with *Pinus pumila* and *Duschekia fruticosa* spread out. The majority of Beringia pollen records (including Wrangel Island that is influenced by the Arctic Ocean) do not reflect the Late Dryas cooling of 11–12 ka BP. A "Younger Dryas" is determined in pollen lacustrine records of the western margin of Beringia in mountain regions of the Indigirka River (*The Late Quaternary* …, 2002) and in the southern Chukchi Peninsula (*The Glaciation* …, 2005), by a considerably increased participation of the Poaceae and *Artemisia* in the pollen spectra. These data show that Arctic regions do not necessarily respond to each relatively rapid climatic change, as is the case at lower latitudes. The expansion of arboreal birches and alder forests into the zone currently occupied by herbaceous tundra is related in northeastern Siberia to the postglacial thermal maximum 8–9.5 ka BP (Boreal Interval). It is explained by both climatic warming and lower (in comparison to the modern) sea level. The second maximum warming of the Holocene is related to the Atlantic Interval, when the upper limit of mountain larch forests was situated at least 200 m higher than nowadays.

The analysis of the pollen records of northeastern Siberia, Alaska Peninsula, and northwestern Canada within every 1000-year interval since 21 ka BP to the present has shown that trees and shrubs such as *Betula, Alnus, Populus, Pinus*, and *Picea* had persisted in Beringia during the glacial in small populations rather than having migrated from southern regions following the warming. These data show that northeastern Siberia, as well as the western part of Beringia, were refugia not only for arctic herbs and subshrubs, but also for boreal trees and shrubs (Brubaker et al., 2005). During global warming conditions, it was larch-alder-birch-poplar forests, rather than those of evergreen coniferous, that were able to expand into the modern tundra zone.

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