Polarforschung 75 (2–3), 83 – 90, 2005 (erschienen 2006)

High-Resolution Reconstruction of Lena River Discharge during the Late Holocene Inferred from Microalgae Assemblages

by Yelena I. Polyakova[1], Tatyana S. Klyuvtkina[1], Ekaterina A. Novichkova[2], Henning A. Bauch[3] and Heidemarie Kassens[4]

Abstract: On the basis of a detailed study of the diatom and aquatic palynomorph assemblages and a detailed radiocarbon chronology of sediment cores obtained from the south-eastern inner Laptev Sea shelf adjacent to the Lena Delta the spatial and temporal variability in the Lena River discharge during the last 6 cal. ka were reconstructed. It was shown that in the area adjacent to the Lena Delta variations in surface water salinities, reconstructed using freshwater diatoms as a proxy, were mainly caused by changes in the volume of the Lena River runoff through the major riverine channels Trofimovskaya, Bykovskaya and Tumatskaya. Several paleohydrological phases are recognized: (i) establishment of modern-like conditions within the eastern Lena River Valley occurred from 6-4.2 cal. ka; (ii) Lena River outflow increased in north-eastward direction via the Trofimovskaya or Bykovskaya channels from 4.2-2.7 cal. ka, coeval with a reduction of runoff toward the north via the Tumatskaya Channel; (iii) generally stable hydrological conditions northward of the Tumatskaya Channel and variations in riverine discharge north-eastward of the Trofimovskaya and Bykovskaya channels prevail since 2.7 cal. ka. Using indicator species of dinocysts as principle marine proxy, an influence of Atlantic water to the southeast inner Laptev Sea shelf could be inferred, possibly along the Eastern Lena paleovalley, brought into this area by wind-driven reversed bottom currents.

Zusammenfassung: Untersuchungen von Diatomeen- und aquatischen Palynomorphen-Vergesellschaftungen wurden an Radiokohlenstoff datierten Sedimentkernen aus der inneren südöstlichen Laptevsee nahe des Lenadeltas durchgeführt. Anhand dieser Daten wurde die zeitliche und räumliche Veränderlichkeit des Flusswasserausstromes der Lena für die letzten 6 ka (Kalenderjahre) rekonstruiert. Zeitliche Veränderungen in den Häufigkeiten von Süßwasserdiatomeen sind begründet durch Wechsel in der Menge des Lenaausflusses durch die drei großen Haupkanäle im Delta: Trofimovskaja, Bykovskja, sowie Tumatskaja. Darauf basierend konnten prinzipiell drei große paläohydrologische Phasen unterschieden werden: (1) heutigen Verhältnissen vergleichbare Bedingungen wurden östlich des Lenadeltas zwischen 6 und 4.2 ka etabliert; (2) Erhöhung des Flusswasseraustrags in nordöstliche Richtung über die Kanäle Trofimovskaja und/oder Bykovskaja zwischen 4.2 und 2.7 ka bei gleichzeitiger Reduzierung Richtung Norden via Tumatskaja; (3) Ausbildung relativ stabiler Bedingungen nördlich des Deltas sowie Auftreten wechselhafter Flusswasserausträgen in östliche Richtung nach 2.7 ka. Das Auftreten von marinen Dinocysten in den Sedimenkernen belegt den Einfluss von Wassermassen mit vermutlich atlantischem Ursprung. Es ist zu vermuten, dass diese durch windgetriebene Bodenströmungen entlang der alten versunkenen Flusstäler auf den östlichen inneren Schelf verfrachtet werden.

[1] Lomonosov Moscow State University, Geographical Faculty, Vorobievy Gory, 119899 Moscow, Russia; <ye.polyakova@mail.ru>, <t.klyuvitkina@mail.ru>
[2] Shirshov Institute of Oceanology RAS, 36, Nakhimovsky ave., 117851 Moscow, Russia; <egolovnina@inbox.ru>
[3] Mainz Academy of Sciences, Humanities and Literature, c/o Leibniz Institute for Marine Sciences IFM-GEOMAR, Wischhofstraße 1-3, 24148 Kiel, Germany; <hbauch@ifm-geomar.de>
[4] Leibniz Institute for Marine Sciences IFM-GEOMAR, Wischhofstr. 1-3, 24148 Kiel, Germany; <hkassens@ifm-geomar.de>

Manuscript received 02 Januar 2006, accepted 20 April 2006

INTRODUCTION

Due to its unique geographical position, constituting the central part of the wide Eurasian Arctic Shelf, the Laptev Sea is a key area for studying the influence of river systems on the Arctic Ocean (KASSENS et al. 1998, 1999). The many rivers draining onto the Laptev Sea shelf comprise about 25 % of the total annual riverine input into the Arctic Ocean (AAGAARD & CARMACK 1989). The main portions of freshwater are transported annually through the Lena River, the second largest river in northern Eurasia in terms of water discharge (GORDEEV 2000). Moreover, the Laptev Sea polynya is an important production area of arctic sea ice, which, together with the fluvial runoff, has a profound influence on the surface-water hydrology and the sea-ice regime in the Arctic Ocean (ZAKHAROV 1997, KASSENS et al. 1998). From this point of view, understanding the history of Lena River discharge is a critical but yet insufficiently understood component of the Arctic Ocean paleohydrology and sea-ice regime.

Owing to ample shallow sediment coring carried out in recent years on the Laptev Sea shelf, the Holocene development of paleoenvironments in this region during the postglacial sea-level rise is quite well understood (e.g., BAUCH et al. 1999, 2001, MUELLER-LUPP et al. 2000). However, the paleohydrology of the shallow Laptev Sea shelf and riverine outflow through time have not yet been completely reconstructed, in particular the Lena River discharge as the major source of freshwater input into the Laptev Sea. Micropaleontological studies indicate that diatoms and aquatic palynomorphs offer the opportunity to reconstruct past water salinities, sea-ice conditions and riverine discharge (POLYAKOVA et al. 2000, BAUCH & POLYAKOVA 2000, 2003, KUNZ-PIRRUNG 2001, POLYAKOVA 2003).

The main goal of this study is to reconstruct short-term variability of the Lena River discharge to the Laptev Sea during the late Holocene. Selected sediment cores obtained from the shallow inner Laptev Sea shelf region (water depth up to 32 m) near the Lena Delta (Fig. 1) have been studied with micropaleontological means. Acoustic data and detailed radiocarbon chronologies of the recovered sediments from this region indicate high sedimentation rates during the Holocene (KLEIBER & NIESSEN 1999, 2000, BAUCH et al. 1999, 2001). The investigated sediments provide high-resolution data for reconstructing the Lena River discharge during the late Holocene.

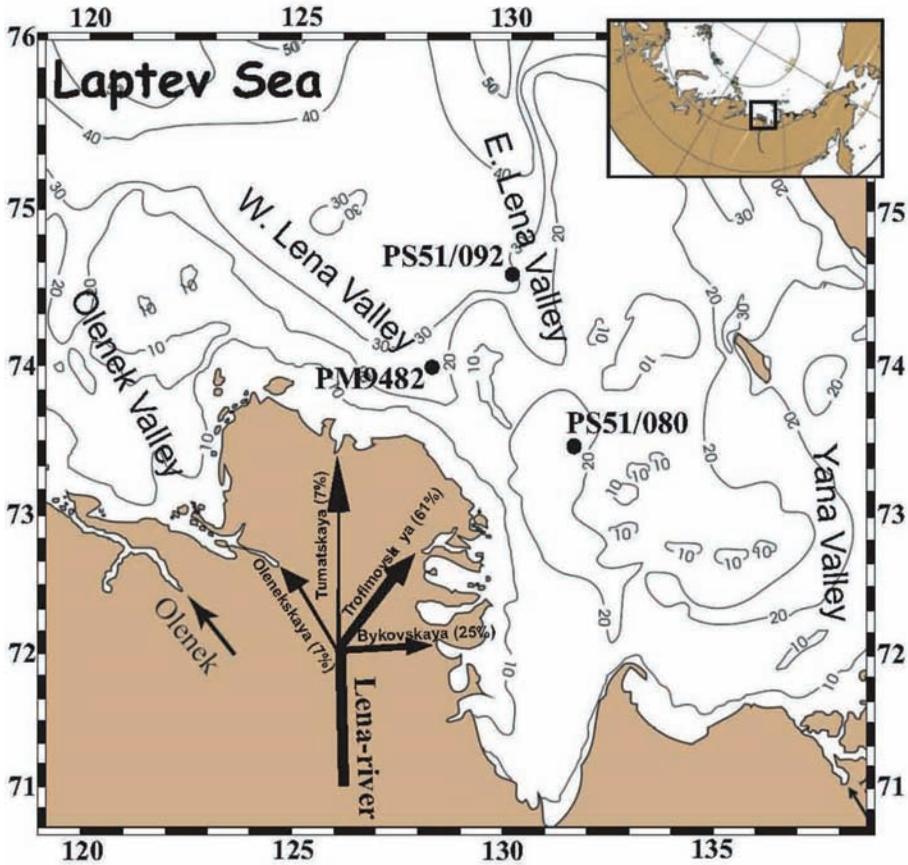

Fig. 1: Bathymetric map of the inner Laptev Sea showing the major river channels in the Lena Delta and locations of studied cores PS51/080-13 (21 m water depth), PS51/092-12 (32 m water depth) and PM94/82-2 (27 m water depth).

Abb. 1: Bathymetrische Karte der inneren Laptewsee, des Lenadeltas mit seinen Hauptarmen sowie die Positionen der bearbeiteten Sedimentkerne PS51/080-13 (21 m Wassertiefe), PS51/092-12 (32 m Wassertiefe) und PM94/82-2 (27 m Wassertiefe)

MATERIAL AND METHODS

In order to estimate the variability in the Lena River discharge during the late Holocene, we selected cores located close to the Lena Delta (Fig. 1). Cores PS51/092-12 and PS51/080-13 (32 m and 21 m water depth) and PM94/82-2 (27 m water depth) were obtained from the eastern and western Lena River paleo-valleys during Russian-German TRANSDRIFT II (1994) and TRANSDRIFT V (1998) expeditions (Fig. 1). The cores PS51/092-12 and PS51/080-13 consist of organic-rich (total C_{org} ~1.5-2 %, (Mueller-Lupp et al. 2004), rather homogeneous clayey-silty sediments. Core PM94/82-2 is composed of dark greenish-gray silty clay to clayey silt (below 180 cm core depth).

Diatom and aquatic palynomorph assemblages were studied in core PS51/080-13 (total sediment recovery 1.9 m) in 5 cm intervals. In addition to previously obtained diatom records (Bauch & Polyakova 2000, 2003) aquatic palynomorphs were studied in core PM94/82-2 (total sediment recovery 3.5 m) and in the upper 2 m of core PS51/092-12. For diatom analyses the bulk sediment was treated with H_2O_2 (30 %) and HCl (10 %) according to Gleser et al. (1974) after freeze-drying. Diatom valves were then concentrated by decantation with a settling time of three hours using distilled water. Residues were mounted in Naphrax (refraction index 1.68) on glass slides (Battarbee 1973). Diatom valves were examined under a light microscope at 1000 magnification. Generally, approximately 300-400 specimens were counted in each sample, following the procedures of Schrader & Gersonde (1978). Results were calculated as percentages and concentrations (number of valves g^{-1} of dry sediment).

Standard preparation techniques (Kunz-Pirrung 1998, 2001) were applied to sample treatment for aquatic palynomorph study. Cold hydrochloric and hydrofluoric acids were used to dissolve carbonates and silicates. Wet sediment was sieved after chemical treatment through a 6 μm mesh-size sieve to eliminate fine silt and clay particles. A minimum of 100 dinoflagellate cysts per sample were identified and counted under a light microscope at a magnification of 400 x and 1000 x. Individual palynomorph taxa were counted if more than half a specimen was present. Concentrations of palynomorphs (individuals g^{-1}) are calculated according to the marker grain method of Stockmarr (1971). For each sample, one or two tablets with *Lycopodium* spores were added. The relative abundance of dinoflagellate cysts is calculated based on the sum of all cysts counted.

To examine temporal and spatial patterns of paleohydrological changes, a precise chronology is necessary. Our age models are based primarily on bivalves, with AMS ^{14}C dates done at Leibniz-Lab, Kiel University (see Bauch et al. 2001). Original radiocarbon dates were converted into calendar years (cal. ka) using CALIB 4.3 (Stuiver et al. 1998), and a regional reservoir correction of 379 +49 years (Bauch et al. 2001).

ENVIRONMENTAL SETTING

The modern hydrological situation of the shallow marginal Laptev Sea results from the advection of Arctic water masses from the north and the extensive riverine discharge from the south (Ivanov & Piskun 1995, Gordeev 2000). The Atlantic water mass is restricted to the continental slope near the 100 m isobath, and its sporadic appearance on the shelf is governed by atmospheric circulation and reversal up-welling currents (Proshutinsky & Johnson 1997, Dmitrenko et al. 2001a, b).

The Lena River discharge, which comprises approximately 70 % of the total water and suspended matter input to the Laptev Sea, strongly affects hydrological and sedimentation processes, especially in its eastern part (e.g., Kassens et al. 1998, 1999). On annual average, 416-632 km^3 of water and 16.6-25.2 Mio. t of suspended sediments are recorded in the Lena Delta head (Korotaev 1991, Ivanov & Piskun 1995, Gordeev 2000). Most of the water is discharged at the end of May and beginning of June, when ice in the rivers breaks up while the Laptev Sea is still covered by ice (Gordeev 2000, Kassens et al. 1998).

The Lena River runoff is distributed along numerous delta arms, and the main division of the water flow between four major branches occurs in the apex of the delta. The largest branches, Trofimovskaya and Bykovskaya, trend toward the northeast and east, and receive ~61 % and 25 % of the total annual freshwater. Only a very small amount of (~ 7 % each) is received by the northward directed Tumatskaya branch and the westward directed Olenekskaya branch. In general, the distribution of the runoff of suspended sediments by the delta arms follows the water runoff distribution (Korotaev 1991, Ivanov & Piskun 1995, Alabyan et al. 1995). The transformation of water and sediment yield along the delta branches is important for understanding the sediment transport to the Laptev Sea and the evolution of the delta. According to Korotaev (1991) and Alabyan et al. (1995) only 30 % of their initial discharge reaches the sea through the main eastern Trofimovskaya and Bykovskaya, and northern Tumatskaya channels. The main water volume disseminates into second order arms and transverse distributaries. The water discharge dynamics of the western main delta branch, the Olenekskaya channel, is characterized by a different regime. Its water discharge does not change significantly along the channel, and only 10 % of its initial discharge flows into second-order arms.

Several studies present evidence for a significant loss of suspended load (up to 70-90 %) on the sub-aerial parts of the Lena Delta before reaching the sea (Korotaev 1991, Alabyan et al. 1995, Kuptsov & Lisitzin 1996), however, the exact amounts of suspended sediment load actually introduced into the sea by the Lena River are still uncertain (Are & Reimnitz 2000, Are et al. 2002, Rachold et al. 2002). Overall, the bed load is expected to exceed the suspended load and appears to be deposited mostly in the sub-aerial delta. It mainly fills the Lena Delta channels and forms river mouth bars, which border the major channels along the 2 m isobath (Mikhailov 1997, Mikhailov et al. 1986, Korotaev 1991, are et al. 2002, Rivera et al. 2006). Radiocarbon dating shows that the modern Lena Delta was built during the second half of the Holocene, and the total advance of the delta during this time was about 120-150 km (Are & Reimnitz 2000, Are et al. 2002, Pavlova & Dorozhkina 2002). However, evolution of the delta was irregular, and while some parts of the delta advance rapidly (58 m y^{-1}), other parts erode (Are et al. 2002).

According to the distribution of water discharge in the Lena Delta, approximately 80-90 % of the Lena water enters the eastern and north-eastern Laptev Sea shelf at present (Ivanov & Piskun 1995, Alabyan et al. 1995). The influence of the Lena River outflow on the Laptev Sea hydrology is well manifested in the distribution patterns of summer surface-water salinity and dissolved silicon content. The lowest values of salinity (down to 2) and the maximum content of dissolved silicon (>2000 g l^{-1}) are recorded on the south-eastern Laptev Sea shelf on the basis of the measurements of the last 50 years (Dmitrenko et al. 1999, Pivovarov et al. 1999). Although it is obvious from recent research that the current regime is significantly complicated in the Laptev Sea, the sea bottom relief has a considerable influence on the distribution of Lena River waters, which generally flow in the direction of the eastern Lena Valley (Dmitrenko 1995, Dmitrenko et al. 2001a, b). Most sediment transport on the eastern Laptev Sea shelf during the ice-free period is assumed to take place in the low-relief cross-shelf valleys (Wegner et al. 2005). During winter, the flaw polynya is an important factor for the hydrography, sea-ice formation and sedimentation processes in the Laptev Sea (Dmitrenko et al. 2005, Eicken et al. 2000, Pfirman et al. 1997, Zakharov 1997). A seasonal volume of 218 km^3 of new ice is produced within these long (~2000 km) open-water areas in the arctic winter sea-ice cover (Dethlef et al. 1998), and is exported to the Siberian branch of the Transpolar Drift. The total ice-bound sediment export through entrainment is of the same order of magnitude as the annual Lena River sediment supply (Eicken et al. 2000).

DOWNCORE DISTRIBUTION PATTERNS OF DIATOMS AND AQUATIC PALYNOMORPHS

Core PS 51/080-13

According to radiocarbon dating, this core encompasses the time interval between roughly 1 and 6 cal. ka (Fig. 2).

Diatoms

Diatom assemblages are taxonomically diverse (about 230 species and varieties) and abundant (30,000-770,000 valves g^{-1} dry sediment). The total concentration of diatom valves is generally higher (up to 770,000 valves g^{-1}) in the upper part of the core. Maximum accumulation rates of diatom valves (up to 2.2 Mio. valves cm^{-2} y^{-3}) correspond to a sharp increase in sedimentation rates observed between 1.5 and 0.9 cal. ka (Fig. 2).

In order to establish temporal changes in riverine discharge, diatom species were combined into two main groups according to their ecological preferences: freshwater diatoms, and marine and brackish-marine diatoms. The group of marine and brackish-marine diatoms in this core assemblages consists largely (up to 50 %) of euryhaline species (*Thalassiosira baltica, T. hyperborea* and others) typical of freshened areas of the arctic shelf (Polyakova 1997, 2003, Cremer 1999). Other marine diatoms are represented mainly by cold-water, arctic-boreal and bipolar planktic types (*Thalassiosira antarctica, T. gravida,* spores of *Chaetoceros* genus). Their total relative abundances do not exceed 15 % in diatom assemblages. The marine diatoms also include a specific group of sea-ice species represented by *Fossula arctica, Fragilariopsis oceanica, F. cylindrus* and other species, indicating the presence of sea ice (Polyakova 1997, Cremer 1999). It was revealed that

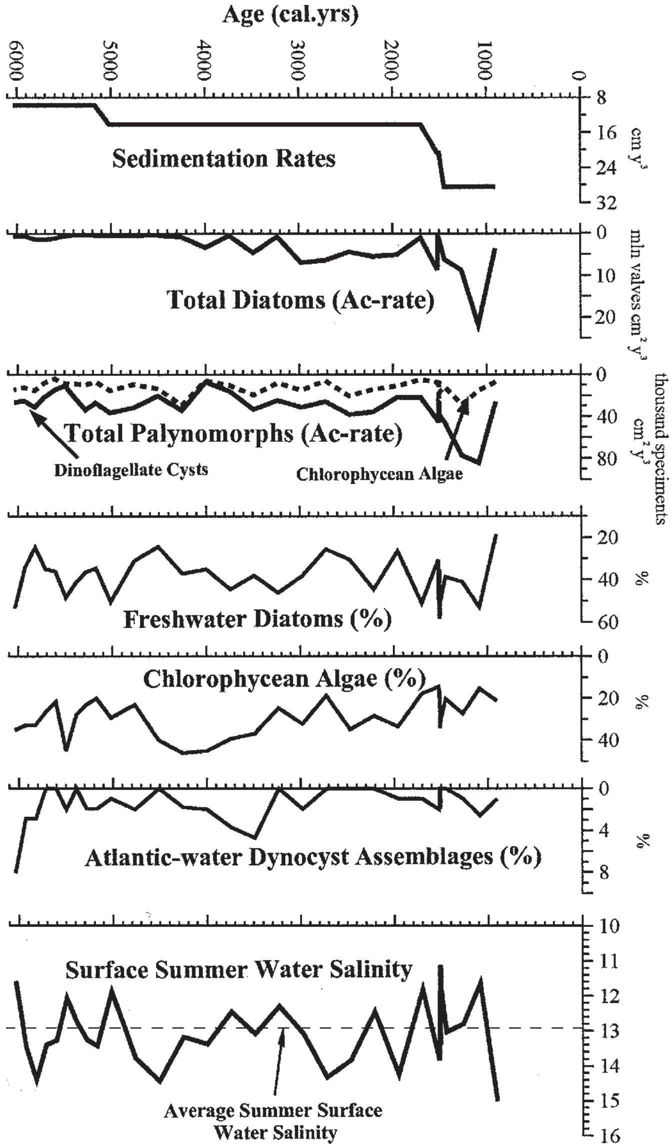

Fig. 2: Sedimentation rates (cm ka^{-1}), accumulation rates of total diatom valves (106 valves cm^{-2} y^{-3}) and aquatic palynomorphs (n x 1000 spec. cm^{-2} y^{-3}), down-core distribution of the main ecological groups of algae, and reconstructed summer surface water salinity from core PS51/080-13.

Abb. 2: Gesamtsedimentationsrate (cm ka^{-1}) sowie die Akkumulationsraten von Diatomeenschalen (106 Schalen cm^{-2} y^{-3}) und aquatischen Palynomorphen (n x 1000 cm^{-2} y^{-3}) von Sedimentkern PS51/080-13. Dargestellt ist auch die Unterteilung der Algen in ökologische Gruppen und die rekonstruierten Oberflächensalinitäten (Sommer).

the steep increase (>10-20 %) in relative abundance of sea-ice diatoms corresponds to the mean inter-annual position of the winter polynya (Polyakova et al. 2000, Bauch & Polyakova 2000, Polyakova 2003). Total relative abundance of sea-ice species in this core diatom assemblage does not exceed 10 %, thus indicating a more distal and seaward location of the polynya. The freshwater diatoms are represented by riverine and boggy taxa (*Aulacoseira italica, A. islandica,* species of *Eunotia, Pinnularia, Fragilaria* genus) transported by rivers to the shelf zone. Their total relative abundances vary around 40 % indicating a constant riverine supply to the study area.

Reconstructed summer surface water salinities with freshwater diatoms as a proxy (Polyakova 2003) provide evidence for a salinity range at this site of 11-15 during the last 6 cal. ka, with an average value of approximately 13. It was revealed that the surface water salinities at the study site remained mainly higher than its average value before 4.2 cal. ka. A marked decrease in summer surface water salinities (average ~12.5) is observed between 4.2 and 2.8 cal. ka, which reflects temporal changes in the Lena River outflow. From 2.9 to 0.9 cal. ka reconstructed surface summer water salinities show a tendency to decrease (down to 11). These changes may be interpreted as the result of variation in the Lena River runoff connected to climate fluctuations or as the result of channel migration within the delta.

Aquatic palynomorphs

Aquatic palynomorph records extracted from core PS 51/080-13 are in good accordance with diatom data (Fig. 2). Maximum accumulation rates of aquatic palynomorphs, reaching between 1.5 and 0.9 cal. ka in this core, correspond to the sharp increase in rates of sedimentation and accumulation rates of diatom valves. Aquatic palynomorph assemblages are dominated by marine dinoflagellate cysts (up to 85 %). The group of freshwater chlorophycean algae is represented by *Pediastrum* spp. and *Botryococcus* cf. *braunii* species, which are regarded as indicators of riverine discharge to the shelf area (Matthiessen 1995, Kunz-Pirrung 2001). Their total relative abundances in dynocysts and chlorophycean algae assemblages vary between 15 and 45 % (average value ~27 %) providing evidence for river-proximal environments. Maximum percentages of chlorophycean algae correspond to the interval of the lowest surface summer water salinity reconstructed for the time between 4.2 and 2.8 cal. ka.

Generally, the dinocyst assemblages in this core consist (average 80 %) of cold and shallow water species (*Islandinium minutum, Echinidinium karaense*) which are typical for the freshened waters on the inner Laptev Sea shelf (Kunz-Pirrung 2001). Dinocyst species indicating relatively warm Atlantic water (e.g., *Operculodinium centrocarpum,* Matthiessen 1995, Kunz-Pirrung 2001) were of low abundance in most of the studied sediment assemblages (<2 %), with the maximum abundance (up to 5 %) observed between 3.9 and 2.9 cal. ka (Fig. 2). However, their occurrence provides evidence for the Atlantic water inflow to the south-eastern inner Laptev Sea shelf through the eastern Lena paleo-valley during the last 6 cal. ka possibly due to reversed currents (e.g., Dmitrenko et al. 2001 a, b).

Core PS 51/092-12

Aquatic palynomorphs

Aquatic palynomorph records from the upper part of the core corresponding to the last 6 cal. ka are in a good agreement with previously obtained diatom records from this core (Bauch & Polyakova 2003). Reconstructed summer surface water salinities with freshwater diatoms as a proxy provide evidence for a salinity range at this site between 12.5 and 15.2 (average value ~14, Fig. 3). Two events of relatively high salinity (average values ~14.3 and 14.5) were revealed for the time intervals before 3.9 and after 1.0 cal. ka, respectively (Fig. 3). A short-time event of low salinity (13.2) occurred

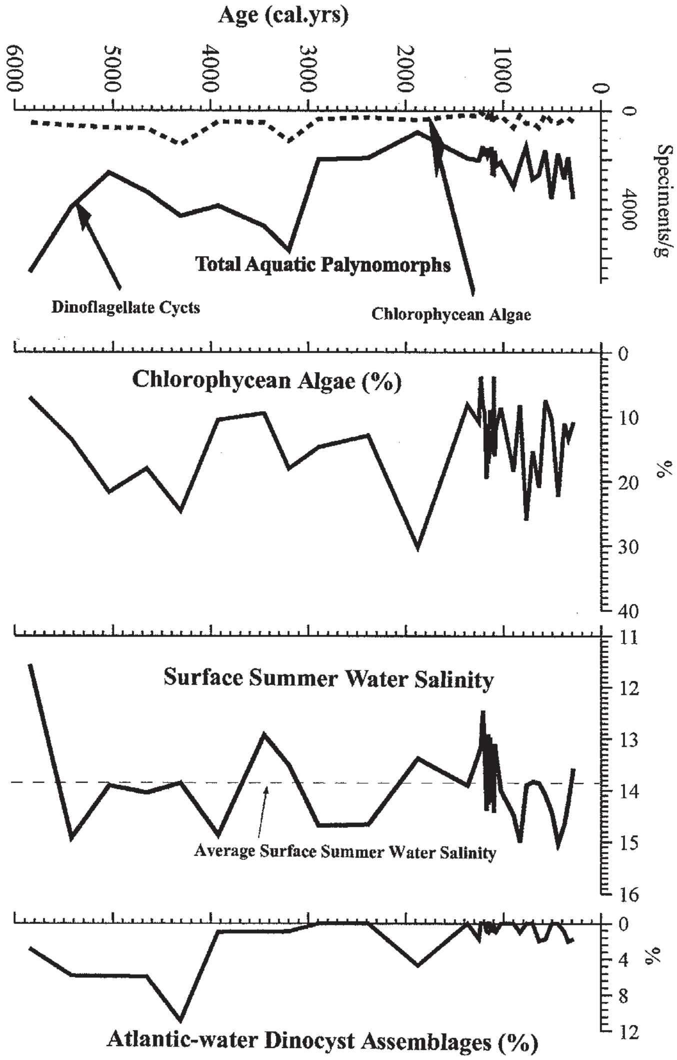

Fig. 3: Distribution of total dinoflagellate cysts and freshwater chlorophycean algae, relative abundances of the main ecological groups of algae and reconstructed summer surface-water salinity from core PS51/92-12.

Abb. 3: Verteilung von Dinoflagellatenzysten und Süßwasseralgen in Sedimentkern PS51/080-13 sowie die Unterteilung der Algen in ökologische Gruppen und die rekonstruierten Oberflächensalinitäten (Sommer).

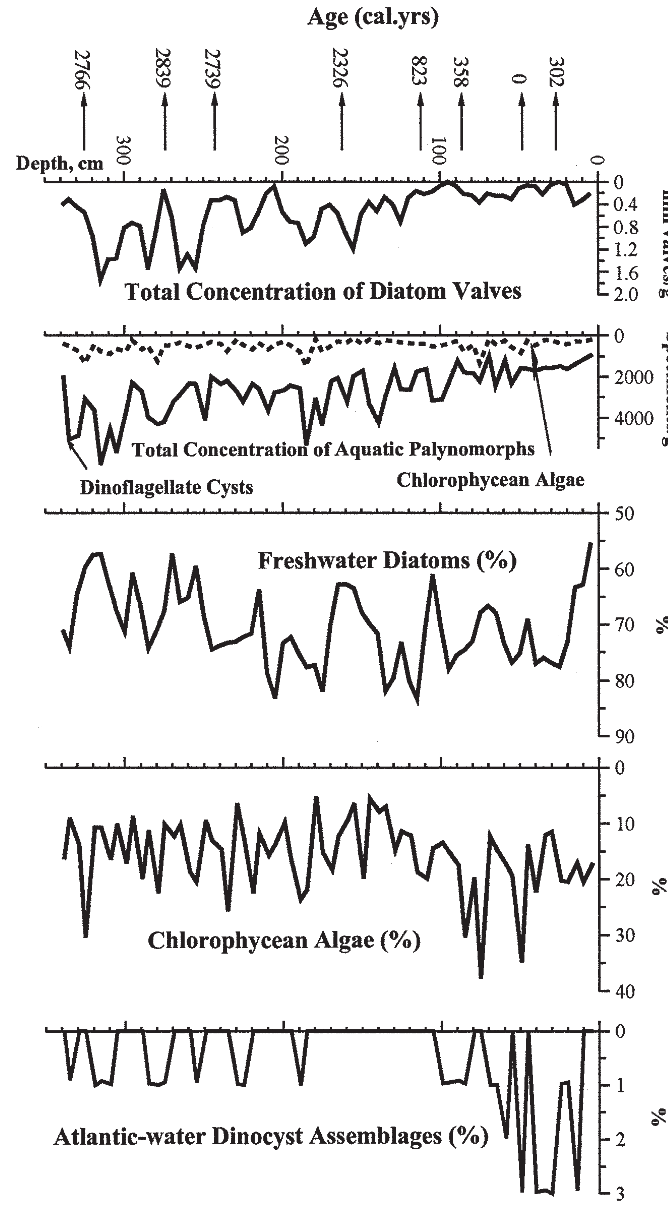

Fig. 4: Distribution of total diatoms, dinoflagellate cysts, freshwater chlorophycean algae and the main ecological groups of algae from core PM94/82-2.

Abb. 4: Häufigkeit der Diatomeen, Dinoflagellatenzysten und Süßwasseralgen im Sedimentkern PM94/82-2 sowie die Unterteilung der Algen in ökologische Gruppen.

between 3.9 and 3.2 cal.ka.

Total concentrations of marine dinocysts along with diatoms generally decrease up-core (down to approximately 1000 cyst g^{-1}), with the maximum concentrations of dinocysts (up to approximately 6200 cyst g^{-1}) observed in the sediments dated back to 4 cal. ka (Fig. 3). The concentrations of freshwater chlorophycean algae represented by *Pediastrum kawraiskii, P. boryanum* and *Botryococcus* cf. *braunii,* vary between 0 and 1000 algae g^{-1}. Their relative proportions show a lower value (average ~13.5 %) in comparison with their abundances in core PS51/080-13 (average ~27 %), which is in good agreement with the more distal location of core PS51/092-12 from the Lena River as a major source of freshwater for this site. The pronounced decrease in relative abundances of freshwater chlorophycean algae (generally <20 %) observed in the uppermost part of the core (after 1.2 cal. ka) is in good accordance with the reconstructed increase of summer surface water salinity indicating a possible reduction of the riverine runoff to this site (Fig. 3).

Dinoflagellate cyst assemblages from this part of the core show a species composition comparable to that of the modern Laptev Sea (KUNZ-PIRRUNG 2001). These assemblages consist of 10 species or species groups, but *Islandinium minutum, Echinidinium karaense* and *Islandinium cezare* s.l., dominating the inner shelf assemblages, constitute up to 100 % of the dinocyst group in most of the core samples. The total relative abundances of *Operculodinium centrocarpum* and the cyst *Pentapharsodnium dalei,* which are regarded as indicators of comparatively warmer Atlantic waters in the Siberian Arctic seas (e.g., MATTHIESSEN 1995, SCHAUER et al. 1997), vary between 0 and 12 %, and are generally decreasing in the upper part of the core. Their occurrence in most of the core samples confirms a constant influence of Atlantic waters onto the inner Laptev Sea shelf through the Eastern Lena paleo-valley (Fig. 1) during the last 6 cal. ka.

Core PM9482-2

Aquatic palynomorphs

In addition to the previously obtained diatom records from the core PM 94/82-2 (Bauch & Polykova 2000) aquatic palynomorphs were studied in this core as well (Figs. 1 and 4). According to radiocarbon dating, the core encompasses approximately the last 3 cal. ka. Although reconstructed summer surface water salinities show fluctuations between 9 and 11.6, they mainly remain higher than the average value (~10) before 2.7 cal. ka.

Aquatic palynomorph assemblages are dominated by dinoflagellate cysts. Their concentration varies between 1000 and 6000 cysts g^{-1}, overall decreasing up-core. In general, the dinocyst assemblages in this core are largely comprised (average 80 %) of cold and shallow-water species (*Islandinium minutum, Echinidinium karaense*) which are typical for the freshened waters on the inner Laptev Sea shelf (Kunz-Pirrung 2001). Species indicating Atlantic-water (e.g., *Operculodinium centrocarpum*) were observed mainly in the upper part of the core (after approximately 0.7-0.5 cal. ka, up to 3.5 %). But they sporadically also occurred in the lower part of the core (before 2.3 cal. ka), thus providing evidence for the influence of Atlantic waters on this Laptev Sea region through the western Lena River paleo-valley. Relative abundances of freshwater algae in dinocyst and chlorophycean algae assemblages remain mainly lower than 20 %.

DISCUSSION

The rapidly increasing postglacial sea level was the factor, most strongly influencing the paleo-hydrographical changes in the Laptev Sea (e.g., Bauch et al. 2001, Bauch & Polyakova 2003, Polyakova et al. 2005, Mueller-Lupp et al. 2004). Due to the continuing southward retreat of the coastline and the Lena River mouth salinities of both surface and bottom waters, the modern values were approached on the inner Laptev Sea shelf around 7.4 cal.ka (Bauch & Polyakova 2003, Polyakova et al. 2005, Mueller-Lupp et al. 2004). Since approximately 6-5 cal. ka, when the sea level eventually came to a stable position (Bauch et al. 2001), spatial and temporal variations of riverine discharge apparently became the dominating factor on paleohydrological conditions in the Lena River proximal areas. Our microalgae records obtained from the sediment cores from the inner Laptev Sea shelf (<32 m water depth) adjacent to the Lena Delta show stepwise changes in summer surface water salinity northward and north-eastward of the Lena Delta during the last ~6 cal. ka. These changes may be interpreted as the result of variation in the Lena River runoff connected to climate fluctuations or as the result of channel migration within the delta.

Therefore, a paleogeographical interpretation on the basis of reconstructed surface water salinities remains incomplete without discussing the evolution of the Lena Delta. The Lena Delta area is the largest delta in the Arctic, which is a composite of erosional remnants from different late Pleistocene to Holocene fluvial stages and deltaic sedimentation (Korotaev 1984, 1991, Grigoriev 1993, Are & Reimnitz 2000, Schwamborn et al. 2002). The latest investigation provides evidence for a shift of the major river runoff direction from the west towards the north, and then to the northeast and east during the Late Pleistocene and Holocene. It is expected that this lateral shift was caused by the differential neotectonics with uplift and back-filling and flooding of the paleochannels due to postglacial sea-level rise (Are & Reimnitz 2000, Schwamborn et al. 2002, Pavlova & Dorozhkina 2002).

According to the reconstructed seawater salinity patterns and composition of diatom and aquatic palynomorph assemblages, the following major paleo-hydrological phases could be outlined for the inner Laptev Sea region adjacent to the Lena Delta for the last 6 cal. ka (Figs. 1, 2 and 3). The studied sites located eastward and north-eastward of the Lena Delta are strongly influenced by Lena River discharge mainly via Trofimovskaya and Bykovskaya channels, which currently receive ~90 % of the annual Lena River discharge, while the northern site is under the effect of the outflow via Tumatskaya Channel, which currently receives ~7 % of the Lena discharge (Dmitrenko 1995, Dmitrenko et al. 2005, Alabyan et al. 1995).

Our microalgae records from the eastern region (cores PS51/080-13 and PS51/092-12) suggest that hydrological conditions comparable to the modern ones existed at the studied sites between 6 and 4.2 cal. ka. This is in good accordance with previously obtained results, indicating establishment of modern-like environments on the south-eastern inner shelf approximately 7.4 cal. ka (Bauch & Polyakova 2003, Polyakova et al. 2005, Mueller-Lupp et al. 2004).

A distinct decrease in the mean summer surface water salinities is observed at the site PS51/080-13 eastward of the Lena Delta within the Eastern Lena RiverValley for the time interval 4.2-2.8 cal. ka (site PS51/080-13). Farther northeast, along the Eastern Lena River Valley (core site PS51/092-12), the slight decrease in surface water salinities generally coincided with the same short-time event. It is particularly remarkable that at the site of core PM94/82-2, which is located just northeast of the Tumatskaya Channel, the maximum salinities were observed before 2.7 cal. ka (Bauch & Polyakova 2003). The discrepancy in the tendency of salinity fluctuations observed for two inner shelf regions adjacent to the Lena Delta allows us to assume an increase in the Lena River outflow in the north-eastward direction via Trofimovskaya or Bykovskaya channels during the time between 4.2 and 2.7 cal. ka, and a coeval reduction of runoff toward the north via Tumatskaya Channel. This assumption is corroborated by geological-geomorphologic studies in the Lena Delta (Are & Reimnitz 2000, Korotaev 1984, 1991, Pavlova & Dorozhkina 1999, 2002, Schwamborn et al. 2002). According to their models, accumulation of alluvial deposits in the area of the modern Tumatskaya Channel, which initially represented the paleo-estuary, started in the early Holocene (~8.5 cal. ka). This vast area is now being filled by a multi-lobate delta, prograding into the open sea. Radiocarbon dating of floodplain outcrops from the Tumatskaya Channel area give evidence for pronounced changes in the conditions forming the alluvial deposits around 2.7 and 1.3, which are assumed to be caused by neotectonic activity (Pavlova & Dorozhkina 1999, 2002).

During the following paleo-hydrological phase (2.8-1.2 cal. ka) microalgae records (site of cores PS51/092-12 and PS51/080-13) show a general decreasing trend in summer surface water salinities north-eastward of the Lena Delta after a considerable increase in water salinity around 2.8-2.7 cal. ka in both cores (Figs. 1 and 3). The latest phase (last 1.2 cal. ka) was characterized by the highest salinity values observed in core PS51/092-12 from the Eastern Lena River Valley. The lack of sediments in the upper part of core PS51/080-13, corresponding to the time interval after 1 cal. ka, make it impossible to trace this event in the eastern offshore region. However, a sharp increase revealed in sedimentation rates and accumulation rates of diatoms and aquatic palynomorphs (1.3 and 0.9 cal. ka) suggests possible changes in hydrological and sedimentation processes in the Eastern Lena River Valley since this time.

Northward of the Tumatskaya Channel area summer surface water salinities have varied around average values since 2.7 cal. ka indicating a relatively constant riverine discharge through this channel. This fact also allow us to assume that the Tumatskaya part of the Lena Delta was generally formed before 2.7 cal. ka. Recorded variations in water salinity most likely were caused by dissemination of the water volume into second-order channels and transverse distributaries.

Therefore, two major patterns can be recognized in the Lena River discharge through the main delta channels during the late Holocene. A comparison of reconstructed variations of Lena outflow allows us to assume that the stepwise changes in discharge along the Eastern Lena River Valley are possibly connected to climate fluctuation. But this remains speculative at present due to the weak correlation of long-term changes between meteoric precipitation in the Lena basin and the actual Lena River runoff into the Laptev Sea (Berezovskaya et al. 2004).

In order to determine the influence of the Atlantic water inflow on the south-eastern inner Laptev Sea shelf hydrology we used indicator species of dinocyst (e.g., *Operculodinium centrocarpum*) as a proxy. According to Dmitrenko et al. (2001 a, b) the appearance of Atlantic waters on the shelf mainly along the submarine valleys is governed by atmospheric circulation resulting in reversed bottom currents. The common occurrence of this group of dinocysts at the site of cores PS51/092-12 and PS51/080-13 gives evidence for Atlantic water advection onto the inner Laptev Sea shelf along the Eastern Lena River Valley during the last 6 cal. ka, and their sporadic occurrence at the site of core PM94/82-2 indicates at least episodical input of Atlantic Waters through the Western Lena Valley during the last 3 cal. ka.

CONCLUSION

The spatial and temporal variability in the Lena River discharge during the last 6 cal. ka was reconstructed on the basis of a detailed study of diatom and aquatic palynomorph assemblages and a detailed radiocarbon chronology of sediment cores obtained from the southeastern inner Laptev Sea shelf adjacent to the Lena Delta. Using freshwater diatoms as a proxy, temporal changes of the summer surface-water salinity in the regions was influenced by the particular riverine outflow pattern via the major delta channels (Trofimovskaya, Bykovskaya, Tumatskaya) during the last 6 cal. ka. These records confirm to the distribution patterns of freshwater chlorophycean algae, which are transported together with diatoms come to the shelf area with the riverine discharge. The following peculiarities of the Lena River discharge during the last 6 cal. ka could be determined:

• Variations in surface water salinities in the area adjacent to the Lena Delta were mainly caused by changes in volume of Lena River runoff through the major riverine channels Trofimovskaya, Bykovskaya and Tumatskaya .

• Micro-algae records from the region north-eastward of the Lena Delta suggest that hydrological conditions comparable to modern ones existed at the studied sites between 6 and 4.2 cal. ka.

• Between 4.2 and 2.7 cal. ka a marked increase in the Lena River outflow in the north-eastward direction via the Trofimovskaya or Bykovskaya channels and coeval reduction of runoff toward the north via Tumatskaya Channel were established.

• Since 2.7 cal. ka summer surface water salinities northward of the Tumatskaya Channel area have varied around its average value indicating a relatively constant riverine discharge through this channel, while north-eastward of Trofimovskaya and Bykovskaya channels a general increasing trend in riverine discharge is observed between 2.7 and 1.2 cal. ka followed by a steep decrease in outflow during the last 1.2 cal. ka.

• A relatively constant Atlantic water influence on the south-eastern inner Laptev Sea shelf through the Eastern Lena paleovalley due to reversed currents during the last 6 cal. ka, and a sporadic input onto the inner shelf through the Western Lena paleovalley, is interpreted on the basis of indicator species of dinocysts.

ACKNOWLEDGMENTS

This research was supported through grants provided by the German Ministry of Education and Research (BMBF; Otto Schmidt Laboratory, OSL grant 02-22 and 06-18, project Laptev Sea Systems, RFBR grant 06-05-65267) and INTAS (03-51-6672). The authors deeply appreciate the reviews of A.A. Andreev and T. Mueller-Lupp and D.K. Fütterer for providing critical and fruitful comments on the manuscript. We are also grateful to K. Volkmann-Lark for correcting the text.

References

Aagaard, K.A. & Carmack, E.C. (1989): The role of sea ice and other freshwater in the Arctic circulation.- J. Geophys. Res. 94 (C10): 14485-14498.

Alabyan, A.M., Chalov, R.S., Korotaev V.N., Sidorchuk, A.Yu. & Zaitsev, A.A. (1995): Natural and technogenic water and sediment supply to the Laptev Sea.- Rep. Polar Res. 182: 265-271.

Are, F., Grigoriev, M.N., Hubberten, H.-W., Rachold, V., Razumov, S. & Schneider, W. (2002): Comparative shoreface evolution along the Laptev Sea coast.- Polarforschung 70: 135-150.

Are, F. & Reimnitz, E. (2000): An overview of the Lena River Delta setting: Geology, tectonics, geomorphology, and hydrology.- J. Coastal Res. 16 (4): 1083-1093.

Battarbee, R.W. (1973): A new method for estimation of absolute microfossil numbers, with reference especially to diatoms.- Limnol. Oceanogr. 18: 647-653.

Bauch, H., Kassens, H., Erlenkeuser, H., Grootes, P.M. & Thiede, J. (1999): Depositional environment of the Laptev Sea (Arctic Siberia) during the Holocene.- Boreas 28: 194-204.

Bauch, H.A., Mueller-Lupp, T., Spielhagen, R.F., Taldenkova, E., Kassens, H., Grootes, P.M., Thiede, J., Heinemeier, J. & Petryashov, V.V. (2001): Chronology of the Holocene transgression at the northern Siberian margin.- Global Planet. Change 31: 125-139.

Bauch, H.A. & Polyakova, Ye.I. (2000): Late Holocene variations in Arctic shelf hydrology and sea-ice regime: Evidence from north of Lena Delta.- Internat. J. Earth Sci. 89 (3): 569-577.

Bauch, H.A. & Polyakova, Ye.I. (2003): Diatom-inferred salinity records from the Arctic Siberian margin: implications for fluvial runoff patterns during the Holocene.- Paleoceanography 18(2): 501-510.

Berezovskaya, S., Yang, D. & Kane, L.D. (2004): Compatibility analysis of precepitation and runoff trends over the large Siberian watersheds.- Geophys. Res. Letters 31 (L21 502): doi 10 1029/2004GL021277.

Cremer, H. (1999): Distribution patterns of diatom surface sediment assemblages in the Laptev Sea (Arctic Ocean).- Mar. Micropal. 38: 39-67.

Dethleff, D., Loewe, P. & Kleine, E. (1998): The Laptev Sea flaw lead – Detailed investigation on ice formation and export during 1991/92 winter season.- Cold Region Sci. Technol. 27 (3): 225-243.

Dmitrenko, I.A. (1995): The distribution of river run-off in the Laptev Sea: The environmental effect.- Rep. Polar Res. 182: 114-120.

Dmitrenko, I.A., Gribanov, V.A., Volkov, D.L. & Kassens, H. (1999): Impact of river discharge on the sea land fast ice extention in Russian Arctic shelf area.- In: J. TUHKURI & K. RISKA (eds), Proc. 15th Internat. Conf. Port and Ocean Enginering under Arctic conditions, Espoo, Finland, August 23-27, 1: 311-321.

Dmitrenko, I.A., Hoelemann, J.A., Kirillov, S.A., Berezovskaya, S.L., Eicken, H. & Kassens, H. (2001a): The role of barotropic changes of sea-level in formation of regime of currents on the shelf in the eastern part of the Laptev Sea.- Doklady Earth Science, translated from Doklady Akademii Nauk 377 (1): 1-8.

Dmitrenko, I.A., Hoelemann, J.A., Kirilov, S.A., Wegner, C., Gribanov, V.A., Berezovskaya, S.L. & Kassens, H. (2001b): Thermal regime of the Laptev Sea bottom layer and affecting processes.- Cryosphere of the Earth 3: 40-55 (in Russian).

Dmitrenko, I.A., Tyshko, K.N., Kirillov, S.A., Eiken, H., Hoelleman, J.A. & Kassens, H. (2005): Impact of flaw polynyas on the hydrography of the Laptev Sea.- Global Planet. Change 48: 9-27.

Eiken, H., Kolatschek, J., Freitag, J., Lindeman, F., Kassens, H. & Dmitrenko, I. (2000): A key source area and constraints on entrainment for basin scale sediment transport by Arctic sea ice.- Geophys. Res. Lett. 27(13): 1919-1922.

Gleser, S.I., Jousé, A.P., Makarova, I.V., Proshkina-Lavrenko, A.I. & Sheshukova-Poretzkaya, V.S. (1974): The diatoms of the USSR.- Nauka, Leningrad, 1-403 (in Russian).

Gordeev, V.V. (2000): River input of water, sediment, major ions, nutrients and trace metals from Russian territory to the Arctic Ocean.- In: E.L. LEWIS et al. (eds), The freshwater budget of the Arctic Ocean, Kluwer, Amsterdam, 297-322.

Grigoryev, M.G. (1993): Cryomorphogenesis of the Lena Delta mouth area.- Permafrost Institute, Academy of Science USSR, Siberian Branch, Yakutsk, 1-176.

Ivanov, V.V. & Piskun, A.A. (1995): Distribution of river water and suspended sediments in the river deltas of the Laptev Sea.- Rep. Polar Res. 182: 142-153.

Kassens, H., Bauch, H.A., Dmitrenko, I.A., Eicken, H., Hubberten, H.-W., Melles, M., Thiede, J. & Timokhov, L. (eds) (1999): Land-Ocean system in the Siberian Arctic: dynamics and history.- Springer-Verlag, Berlin Heidelberg, 1-711.

Kassens, H., Dmitrenko, I.A., Rachold, V., Thiede, J. & Timokhov, L. (1998): Russian and German scientists explore the Arctic's Laptev Sea and its climate system.- EOS 79: 317-323.

Kleiber, H.P. & Niessen, F. (1999): Late Pleistocene paleoriver channels on the Laptev Sea shelf-implications from sub-bottom profiling.- In: H. KASSENS, H.A. BAUCH, I.A. DMITRENKO, H. EICKEN, H.-W. HUBBERTEN, M. MELLES, J. THIEDE & L.A. TIMOKHOV (eds), Land–ocean system in the Siberian Arctic: Dynamics and history, Springer-Verlag, Berlin Heidelberg, 657-666.

Kleiber, H.P. & Niessen, F. (2000): Variations of continental discharge pattern in space and time: Implications from the Laptev Sea continental margin, Arctic Siberia.- Internat. J. Earth Sci. 89: 605-616.

Korotaev, V.N. (1984): The formation of the hydrographic network of the Lena Delta in the Holocene.- Vestnik MSU 5 (6): 39-44 (in Russian).

Korotaev, V.N. (1991): Geomorphology of river deltas.- Moscow, MSU: 1-223 (in Russian).

Kunz-Pirrung M. (1998): Rekonstruktion der Oberflächenwassermassen der östlichen Laptevsee im Holozän anhand der aquatischen Palynomorphen.- Ber. Polarforsch. 281: 1-117.

Kunz-Pirrung, M. (2001): Dinoflagellate cyst assemblages in surface sediments of the Laptev Sea region (Arctic Ocean) and their relationship to hydrographic conditions.- J. Quat. Sci. 16 (7): 637-649.

Kuptsov, V.M. & Lisitsin, A.P. (1996): Radiocarbon of Quaternary along shore and bottom deposits of the Lena and the Laptev Sea sediments.- Marine Chemistry 53: 301-311.

Matthiessen, J. (1995): Distribution patterns of dinoflagellate cysts and other organic-walled microfossils in recent Norwegian-Greenland sediments.- Mar. Micropal. 24: 307-334.

Matthiessen, J., Kunz-Pirrung, M. & Mudie, P.J. (2000): Freshwater chlorophycean algae in recent marine sediments of the Beaufort, Laptev and Kara seas (Arctic Ocean) as indicators or river runoff.- Internat. J. Earth Sci. 89: 470-485.

Mikhailov, V.N. (1997): Mouths of Russian rivers and contiguous countries: Past, future and present.- GEOS, Moscow, 1-413 (in Russian).

Mikhailov, V.N., Rogov, M.M. & Chistyakov, A.A. (1986): River deltas.- Leningrad, Gidrometizdat, 1-280 (in Russian).

Mueller-Lupp, T., Bauch, H. & Erlenkeuser, H. (2004): Holocene hydrographical changes of the eastern Laptev Sea (Siberian Arctic) recorded in $\delta^{18}O$ profiles of bivalve shells.- Quat. Res. 61:32-41.

Mueller-Lupp, T., Bauch, H.A., Erlenkeuser, H., Hefter, J., Kassens, H. & Thiede, J. (2000): Changes in the deposition of terrestrial organic matter on the Laptev Sea shelf during the Holocene: evidence from stable carbon isotopes.- Internat. J. Earth Sci. 89: 563-568.

Pavlova, E. Yu. & Dorozhkina, M.V. (1999): Geological-geomorphological studies in the northern Lena River Delta.- In: V. RACHOLD & M.N. GRIGORIEV (eds), Expeditions in Siberia in 1999.- Rep. Polar Res. 315: 112-128.

Pavlova, E. Yu. & Dorozhkina, M.V. (2002): The Holocene alluvial delta relief complex and hydrological regime of the Lena River Delta.- Polarforschung 70: 89-100.

Pfirman, S.L., Colony, R., Nürnberg, D., Eicken, H., & Rigor, I. (1997): Reconstructing the origin and trajectory of drifting Arctic seas ice.- J. Geophys. Res. 102(12): 12.575-12.586.

Pivovarov, S.V., Hölemann, J.A., Kassens, H., Antonov, M. & Dmitrenko, I. (1999) Dissolved oxygen, silicon, phosphoros and suspended matter concentrations during the spring breakup of the Lena River.- In: H. KASSENS, H.A. BAUCH, I.A. DMITRENKO, H. EICKEN, H.-W. HUBBERTEN, M. MELLES, J. THIEDE & L.A. TIMOKHOV (eds), Land–ocean system in the Siberian Arctic: Dynamics and history, Springer-Verlag, Berlin Heidelberg, 251-265.

Polyakova, Ye.I. (1997): Eurasian Arctic seas during the Late Cenozoic.- Scientific World, Moscow, 1-145 (in Russian).

Polyakova, Ye.I. (2003): Diatom assemblages in the surface sediments of the Kara Sea (Siberian Arctic) and their relationship to oceanological conditions.- In: R. STEIN, K. FAHL, D.K. FÜTTERER, E.M. GALIMOV & O.V. STEPANETS (eds), Siberian river run-off in the Kara Sea: Characterization, quantification, variability, and environmental significance, Proceed. Mar. Sci., Elsevier, Amsterdam, 375-399.

Polyakova, Ye.I., Bauch, H.A. & Kassens, H. (2000): Ice-hydrological regime changes in the Late Holocene Laptev Sea.- Doklady Earth Sciences, translated from Doklady Akademii Nauk 370(5): 686-688.

Polyakova, Ye. I., Bauch, H.A. & Klyuvitkina, T.S. (2005): Early to middle Holocene changes in Laptev Sea water masses deduced from diatom and aquatic palynynomorph assemblages.- J. Global Planet. Change 48: 208-222.

Proshutinsky, A.Y. & Johnson, M.A. (1997): Two circulation regimes of the wind-driven Arctic Ocean.- J. Geophys. Res. 102: 12,493-12,514.

Rachold, V., Grigoriev, M.N. & Bauch, H.A. (2002): An estimation of the sediment budget in the Laptev Sea during the last 5000 years.- Polarforschung 70: 151-157.

Rachold, V., Grigoriev, M.N., Are, F.E., Solomon, S., Reimnitz, E., Kassens, H. & Antonov, M. (2002): Coastal erosion vs riverine sediment discharge in the Arctic Shelf seas.- Internat. J. Earth Sci. 89: 450-460.

Rivera, J., Karabanov, E., Williams, D.F., Buchinskyi, V. & Kuzmin, M. (2006): Lena River discharge events in sediments of Laptev Sea, Russian Arctic.- Estuarine, Coast. Shelf Sci. 66: 185-196.

Schauer, U., Muenche, R.D., Rudels, B. & Timokhov, L.A. (1997): Impact of eastern Arctic shelf waters on the Nansen Basin intermediate layers.- J. Geophys. Res. 102: 3371-3382.

Schrader, H.J. & Gersonde, R. (1978): Diatoms, Utrecht Micropal. Bull. 17: 129-176.

Schwamborn, G., Rachold, V. & Grigoriev, M.N. (2002): Late Quaternary sedimentation history of the Lena Delta.- Quat. Internat. 89: 119-134.

Stockmarr, J. (1971): Tablets spores used in absolute pollen analysis.- Pollen Spores 13: 616-621.

Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W.,Burr, G.S., Hughen, K.A., Cromer, B., McCormic, G., van der Plicht, J. & Spurk, M. (1998): INTCAL 98 radiocarbon age calibration, 240000 cal. BP.- Radiocarbon 40: 1041-1083.

Wegner, C., Hölemann, J.A., Dmitrenko, I., Kirillov, S. & Kassens, H. (2005): Seasonal variations in Arctic sediment dinamics – evidence from 1-year records in the Laptev Sea (Siberian Arctic).- Global Planet. Change 48: 126-140.

Zakharov, V.F. (1997): Sea ice in the climate system.- WMO, WCRP, Arctic Climate System Study, Geneva, 1-80.