Dynamics and History of the Laptev Sea and its Continental Hinterland: A Summary

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Abstract - Russian and German scientists have investigated the extreme environmental system in and around the Laptev Sea in the Siberian Arctic. For the first time a major comprehensive research program combining the efforts of several projects addressed both oceanic and terrestrial processes, and their consequences for marine and terrestrial biota, landscape evolution as well as land-ocean interactions. The primary scientific goal of the multidisciplinary program was to decipher past climate variations and their impact on contemporary environmental changes. Extensive studies of the atmosphere, sea ice, water column, and sea-floor on the Laptev Sea Shelf, as well as of the vegetation, soil development, carbon cycle, permafrost behaviour and lake hydrology, and sedimentation on Taymyr Peninsula and Severnaya Zemlya Archipelago were performed during the past years under a framework of joint research activities. They included land and marine expeditions during spring (melting), summer (ice free), and autumn (freezing) seasons. The close bilateral cooperation between many institutions in Russia and Germany succeeded in drawing a picture of important processes shaping the marine and terrestrial environment in northern Central Siberia in Late Quaternary time. The success of the projects, which ended in late 1997, resulted in the definition and establishment of a new major research effort which will concentrate on establishing a better understanding of the paleoclimatic and paleoenvironmental record of the area. This is important because it allows to be able to judge rates and extremes of potential future environmental changes.

Introduction

Mankind has an eminent interest in establishing forecasts within whose ranges its own living conditions may change in the foreseeable future. Geological synoptic reconstructions and climate modelling have shown independently that the polar latitudes of the northern hemisphere, in particular its marginal seas and adjacent continents, are apt to drastic and fast changes. There is growing concern about the reaction of the Arctic system to global environmental change and the impact of this change on future climate development. In this sense the shallow Laptev Sea Shelf, ice free only during few summer months, and its Siberian hinterland are of particular interest, because here riverine outflow acts as important freshwater source for the halocline and sea-ice cover in the Arctic Ocean proper. Climate dependent environmental changes in the Laptev Sea itself are strongly controlled by changes in the terrestrial environment of its

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hinterland, particularly via the quantity and quality of the riverine water and sediment transport. Reversely, sea-level and ice-cover changes in the marine environment have direct influence on the precipitation and temperature regime on land, both of which have a strong impact on the vegetation and permafrost behaviour and thus on the water and carbon balances.

In order to address the complexity and interdependencies of processes both in the marine and in the terrestrial environment, three bilateral research projects were established in Russian-German collaboration in northern Central Siberia. Whilst part of the cooperation specifically focuses on the reconstruction of the Late Quaternary climatic and environmental history of the Laptev Sea Shelf and Taymyr Peninsula/Severnaya Zemlya Archipelago, other investigations were devoted to the study of modern processes, describing ecosystems and different environmental settings of the study area.

Strategy and history

Marine studies

The drastic and fast environmental reaction on climate change in the Arctic (e.g. CLIMAP, 1976; Broecker, 1994; Imbrie and Imbrie, 1980) is potentially of great importance because the modes and rates of present deep- and intermediate-water renewal of the Norwegian Greenland Sea and the Arctic Ovean have an important control on the global environment, while the heat exchange between the Arctic Ocean and North Atlantic Ocean generates a regional anomaly of the northern hemisphere climatic zonation resulting in habitable areas in northwestern Europe, including its highest North.

The sensitivity of the Arctic sea-ice cover to climate change is well established and provides a strong motivation for research in this area. Furthermore, however, the recent record minima in summertime ice extent observed over the Siberian shelves in the early and mid-1990's (Maslanik et al., 1996) underscore the importance of the Laptev Sea as an indicator as well as an agent of change. While the Laptev Sea is most remote from Atlantic and Pacific oceanographic influences, its importance as the prime ice production area in the Arctic Basin and as source area of the Transpolar Drift (Rigor and Colony, 1997) provides a linkage that reaches as far as the freshwater budget of the Greenland Sea (Figure 1). Global climate change potentially amplified by anthropogenic emission of greenhouse gases is assumed to considerably affect the Arctic Ocean's oceanographic circulation and the waxing and waning of its sea-ice cover (Wadhams, 1995). Unfortunately, the knowledge about present and past processes driving these changes is limited, and it is not entirely clear to what an extent such regional processes are tied into a global picture. We believe that the interpretation of paleoclimatic records in conjunction with the study of modern processes will further the understanding and prediction of the Arctic System.

Scientific investigations within the scope of the bilateral projects were planned as part of a system approach. They comprise marine and terrestrial investigations, and a suite of modelling experiments and theoretical considerations. While studying a complicated system such as the Laptev Sea region, it is expedient to divide it into subsystems. It will be most natural to delineate the modern (e.g., hydrophysical, chemical, biological) and past subsystems which are constrained by both marine and terrestrial boundary conditions. The boundary conditions of these subsystems are quite variable. They can be treated as constant (in as far as modern processes are concerned), faintly varying (interannual and climatic variations) and strongly varying (paleoclimatic variations) depending on temporal scales. While describing marine system evolution, its boundaries can be considered as a subsystem. Parameters of this subsystem play different roles depending on the temporal scale of process integration.

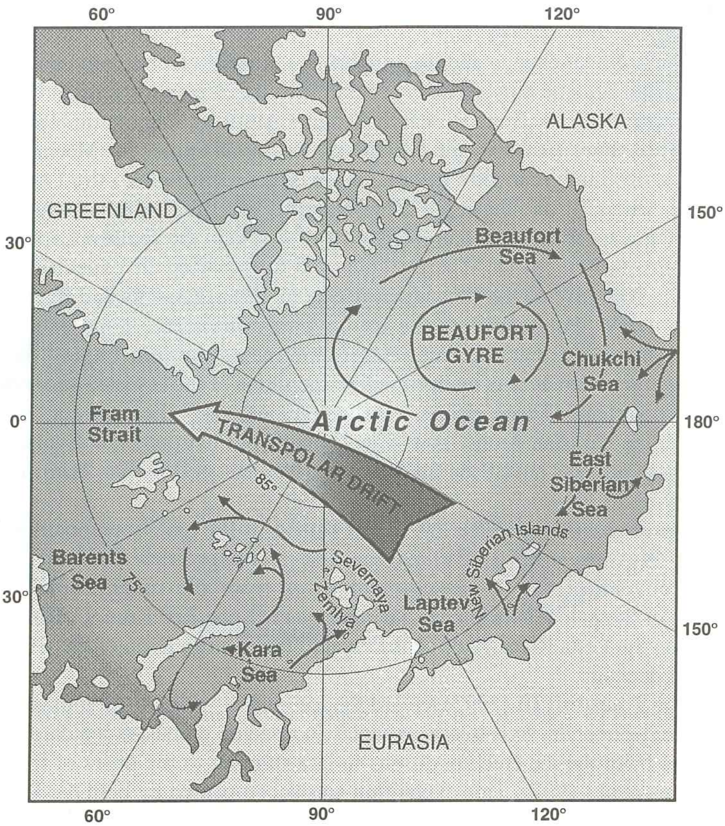

Figure 1: Major sea-ice drift paths in the Arctic Ocean. The Laptev Sea, at the tail of the Transpolar Drift, is considered a major ice factory for the Arctic Ocean.

Many properties of the water mass boundaries of the Laptev Sea are dependant on the interaction of the Laptev Sea with the continental hinterland. The hydrography of the Laptev Sea water masses and the extent of its sea-ice cover are controlled by the interaction of the open Arctic Ocean water masses and the influx of freshwater from a number of major river systems. The sea floor sediments in the Laptev Sea consist chiefly of biogenic and terrigenous components, and their distributional pattern directly depends on the water mass boundaries. The biogenic components consist in part of materials derived from freshwater organisms living in the rivers draining into the Laptev Sea and detrital plant remains, as well as of marine/brackish organisms specialized to the highly variable living conditions in the Laptev Sea. The terrigenous components consist of fine-grained sediments which can be linked to several major sources: Detrital suspended material transported to the Laptev Sea by the rivers draining its continental hinterland, and products of coastal and sea floor erosion.

All of these variables allow to define biological and sedimentological provinces in the Laptev Sea, and to determine the source regions. Detailed investigations of the riverine depositional environments as well as of the lacustrine sedimentary sequences and experiments on land adjacent to the Laptev Sea have additionally contributed to a comprehensive understanding of the entire Laptev Sea system. The compilation of results described in this book as well as the scientific approach of the investigations are henceforth of considerable general interest, even though they are based mainly on the bilateral Russian-German efforts under the projects mentioned above.

Due to both the political change and the support from modern technology, the Laptev Sea as well as its hinterland became only recently accessible to the international scientific community. In close cooperation with the State Research Center - Arctic and Antarctic Research Institute (AARI) in St. Petersburg (Russia), the GEOMAR Research Center for Marine Geosciences, Kiel (Germany), originally carried out two land-based expeditions to the Laptev Sea. Both expeditions, the Ameis '91 and the Esare '92 (Dethleff et al., 1993), were conducted during the early spring of the respective years and focussed on the role of the shallow Laptev Sea shelf in sediment entrainment into sea ice. These studies and furthermore the expeditions Transdrift I aboard RV "Ivan Kireyev" to the inner Laptev Sea in 1993 (Kassens and Karpiy, 1994) and Arctic 93 aboard RV "Polarstern" to the ice-covered continental slope of the Laptev Sea (Fütterer, 1994) revealed that the complex environmental system Laptev Sea required a multidisciplinary approach as was realized within the scope of the research program devoted to the "Laptev Sea System". These efforts were supplemented by the projects "Ecology of the Marginal Seas of the Eurasian Arctic" and "Late Quaternary Environmental Evolution of Central Taymyr". All these projects have been funded by the Russian and German Ministries of Science and Technology.

In 1994, activities continued in the line of the Transdrift II expedition aboard RV "Professor Multanovskiy" (Kassens et al., 1995a) and the first river expedition Lena 94 (Rachold et al., 1995). The recovery of few long sediment cores from the inner Laptev Sea allowed reconstructions of the paleoenvironment, i.e., changes in Lena River runoff. Contemporaneous investigations on the Lena River itself contributed to the identification of the river's fingerprint within the shelf deposits.

The expedition Transdrift III (1995) aboard the icebreaker "Kapitan Dranitsyn" met the most difficult logistical demands, since research topics focused on processes which occur during the extreme change from the ice-free conditions in late summer to the onset of freeze-up during autumn (Kassens et al., 1997). This expedition was accompanied by both the RV "Polarstern" ARK-XI/1 expedition (Rachor, 1997) and the land-based Lena-Yana expedition (Rachold et al., 1997a). RV "Polarstern" completed investigations during July to September 1995 within the pack ice of the northernmost Laptev Sea, the adjacent deep-sea basin and on the Lomonosov Ridge, thereby addressing relationships between shelf areas and adjacent deep-sea basins. The river studies attempted to quantify the river's contribution to the sedimentary, chemical, and hydrodynamic balance of the Laptev Sea (Rachold et al., 1996).

The primary objective of the Transdrift IV expediton was to study the Lena River break-up and its influence on the environmental system of the Laptev Sea (Kassens et al., 1996). The international biological Station "Lena-Nordenskiöld", located in the eastern Lena Delta, was the base for the scientists of the expedition. From here the field program in the Lena Delta and the Laptev Sea was carried out. The river investigations were completed during the Khatangar 96 expedition in 1996 (Rachold et al., in press).

All joint research activities were performed in a close formal cooperation between many Russian and German scientific institutions (but with liaisons to many international programs and institutions) and succeeded to draw a detailed picture of most important processes shaping the Laptev Sea system (Figure 2). Beside national efforts, the multinational expedition "Spaciba" (Martin et al., 1996) and the US-Russian expedition aboard the RV "Smirnitsky" in 1995 (Johnson, 1996) are the most important ones.

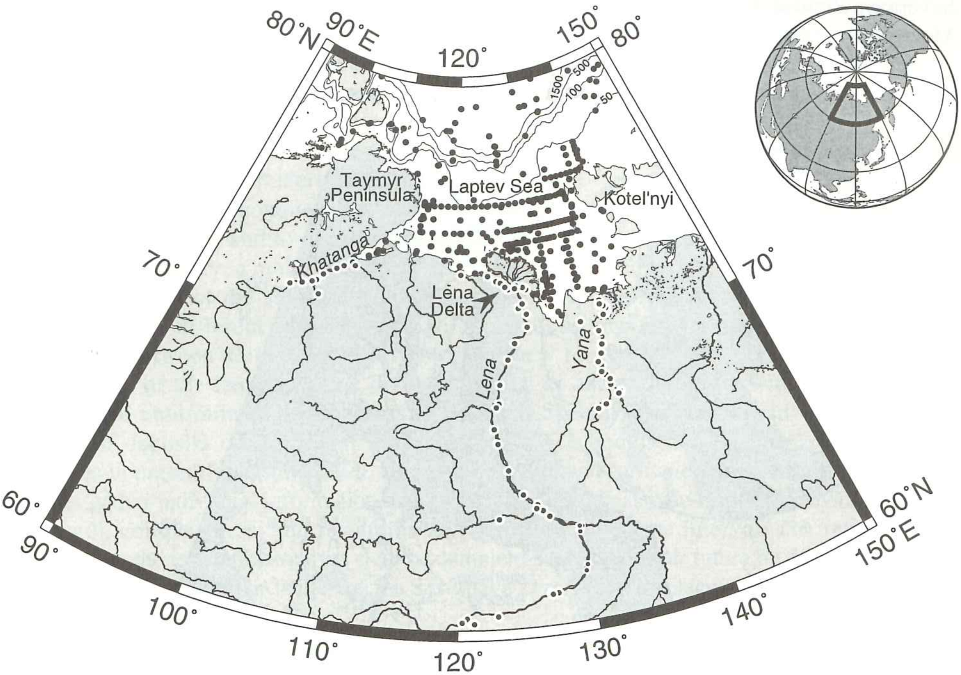

Figure 2: Station map of the Laptev Sea System Project. For the past six years, a multidisciplinary working program was carried out at almost 500 stations in the Laptev Sea and along the Siberian rivers draining into the Laptev Sea.

Terrestrial studies

The terrestrial investigations were carried out within the scope of the Russian-German research project "Late Quaternary Environmental Evolution of Central Taymyr" (Taymyr), which was established in 1993. Following a pilot phase, funding by the German Ministry of Education, Science, Research, and Technology was provided from 1994 to 1997. During these years, five expeditions with more than fifty participants from six Russian and five German institutions were carried out in the project study area: Norilsk/Taymyr 1993 (Melles et al., 1994), Taymyr 1994 (Siegert and Bolshiyanov, 1995), Taymyr 1995 (Bolshiyanov and Hubberten, 1996), Taymyr/Severnaya Zemlya 1996 (Melles et al., 1997), and Norilsk 1997 (Melles et al., in prep.).

The overall objective of the Taymyr project was the reconstruction of the Late Quaternary climatic and environmental history of the Taymyr Peninsula and the Severnaya Zemlya Archipelago (Figure 3). For a number of reasons, this region is a key area for understanding the modern and past environmental dynamics of northern Siberia.

For example, the Taymyr region is located in the transition zone between the West Siberian marine and East Siberian continental climates. The higher precipitation in West Siberia and Europe during Late Quaternary glacial times led to the formation of the Eurasian ice sheet, whilst large areas in East Siberia, despite lower temperatures, remained unglaciated. The eastern extension of the Eurasian ice sheet is still under discussion - for the Last Glacial Maximum, a maximalistic hypothesis with almost complete ice coverage of the Taymyr region (Grosswald, 1998) contradicts with a minimalistic hypothesis with glaciations being restricted to the

Severnaya Zemlya Archipelago and high-altitude areas of the Putoran Plateau and the Byrranga Mountains (Velichko et al., 1997, 1997a). In the Taymyr region, therefore, both the Late Quaternary changes in relative influences of the West and East Siberian climates and their influences on the kind and extension of the Eurasian glaciation can be investigated.

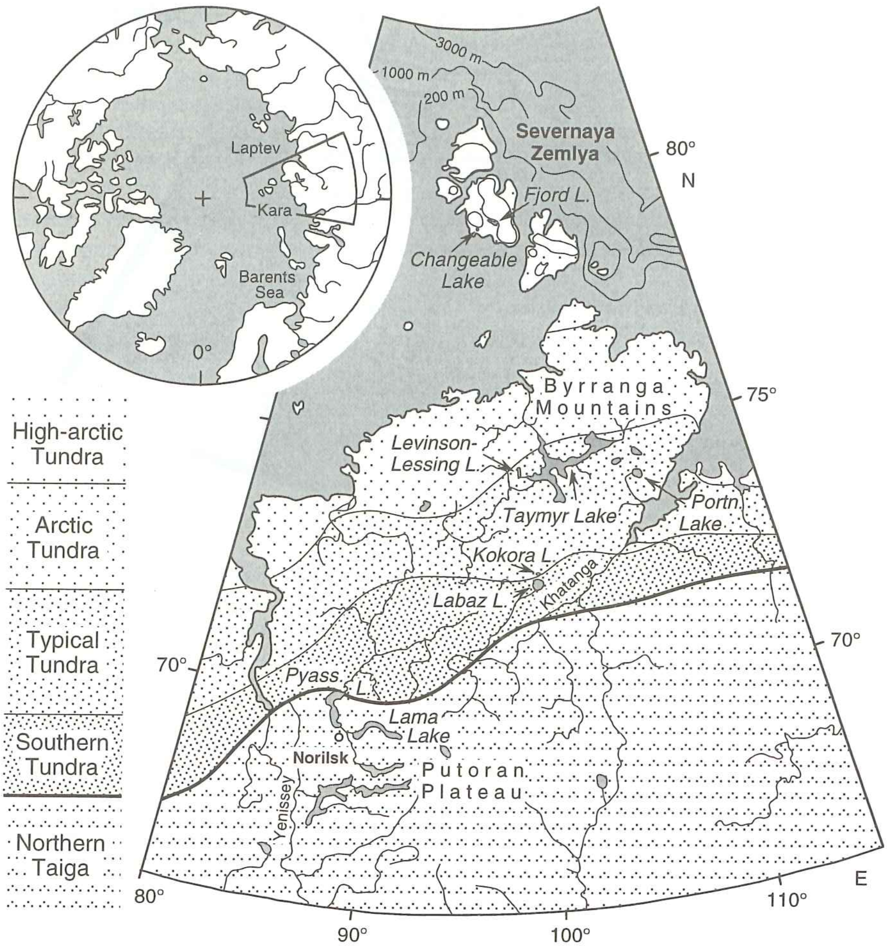

Figure 3: Location and map of the Taymyr Project study area in Central Siberia showing the modern distribution of the vegetation zones and geographic terms mentioned in the text.

In addition, the Taymyr Peninsula forms the northernmost region of the Eurasian continent, being widely unpolluted by human activities. Together with the Severnaya Zemlya Archipelago, it covers the entire spectrum of Arctic landscapes and vegetation zones, leading from the Northern Taiga in the south via different tundra zones on the central and northern peninsula to the high-Arctic tundra in the north. This ca. 1400 km long transect reflects a summer temperature gradient of more than 10°C (Matveyeva, 1998). Hence, the Taymyr region is predestined for reconstructing the development and changes in the location and extension of the vegetation zones in dependence on the Late Quaternary climatic variations.

Due to the proximity to the Laptev Sea, the results from the Taymyr region can directly be linked to the marine geological data. From this, a better understanding of the often problematic correlation of land and ocean records is expected. In addition, the comparison may supply comprehensive information concerning the interaction of the marine and terrestrial histories. The effects of sea-level and marine ice-cover changes on the precipitation and temperature development on land, both of which have strong impact on the vegetation and permafrost behaviour are of particular interest are.

In order to adress the complexity of climate dependent processes in the permafrost landscape of the Taymyr region and to obtain a most comprehensive understanding of the climatic and environmental history, a multidisciplinary approach was applied to the Taymyr Project (Figure 4). Investigations of the seasonal processes operating in the lithosphere, hydrosphere, and biosphere in the different climatic and environmental settings of the study area indicate the interaction between climate and permafrost. They form the basis for interpreting the development of the landscape and the composition of ancient deposits with respect to the climatic and environmental conditions in the past. Special emphasis is put on syngenetic permafrost deposits on land with included ground ice bodies and on unfrozen sediment sequences in presently existing lakes. Due to their individual formation processes, these natural archives gather individual information concerning the kind of paleoenvironmental evidence, and the length, completeness, and resolution of the documented time interval. The information derived from the terrestrial archives shall be complemented in the near future by data from an ice core which is planned to be drilled on the Severnaya Zemlya Archipelago.

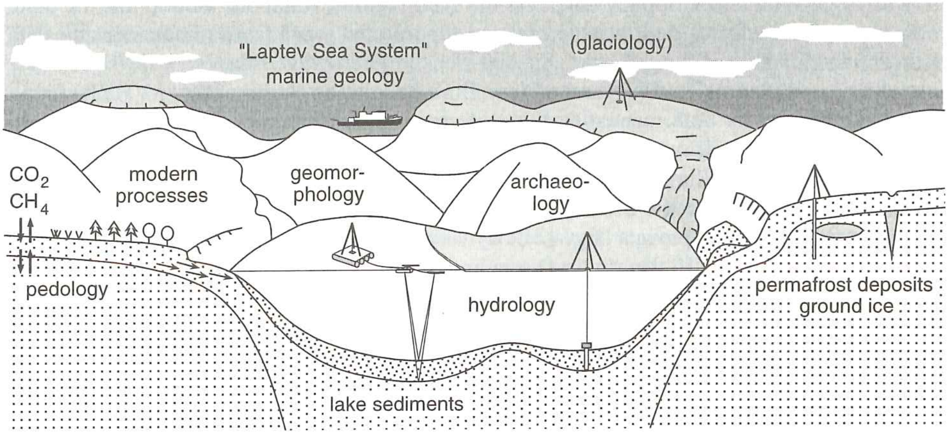

Figure 4: Schematic section through the permafrost landscape of northern Siberia illustrating the multi-disciplinary character of the Taymyr project in the neighbourhood of the System Laptev Sea project. Complex investigations of the modern seasonal dynamic processes, taking place in the different landscapes and climates of the study area, form the basis for interpreting the composition of ancient deposits with respect to past environmental and climatic conditions. Major natural data archives, investigated for the Late Quaternary history, are the sediment fill in presently existing lakes and syngenetic permafrost sequences on land with incised ground ice bodies. Additional information comes from geomorphological and archaeological work. An ice core drilling on the Severnaya Zemlya Archipelago is planned to complement the existing data sets in the coming years.

Major results of marine and terrestrial investigations in the Siberian Arctic

On the following pages some of the major scientific results of the projects are summarized (see also Kassens et al., 1995; 1998; Melles et al., 1996). Many of these are described in the subsequent papers of this volume. Some of the discoveries are providing first insights into the different processes controlling Arctic climate and linking the land and shelves to the deeper basins.

Modern sea-ice and ocean processes

The Laptev Sea is one of the regions with the highest net-ice production rates in the Arctic Ocean (Rigor and Colony, 1997). One of the aims of the project was to assess the spatial patterns and variability of ice growth in the Laptev Sea including its linkage to atmospheric and oceanic processes as well as its importance for sediment transport through the entrainment of particulate matter.

The time period 1992 - 1996 is of particular interest since summer ice extent attained a record minimum in 1995. As shown by meteorological data and a large-scale sea ice model, this minimum is mostly a result of atmospheric circulation anomalies and their impact on ice dynamics, along with enhanced ice melting due to advection of warm air masses from central Siberia (Kolatschek et al., 1996). As a result of advective heat transport and storage of solar short-wave energy in the water column, the fall freeze-up 1995 was delayed by two weeks compared to the long-term mean of ice-formation onset. This is corroborated by hydrographic measurements which detected a warm water layer in the eastern Laptev Sea in the fall of 1995 (Kassens et al., 1997).

Given the importance of sea ice circulation and export (Dmitrenko et al., this volume), a more detailed study of the ice circulation regime in the Laptev Sea was carried out in the period of 1979 to 1995. With a lack of buoy data over the shelf regions, where ice motion may be quite complex, the ice velocity field was determined for selected years from remote-sensing data (Russian Okean Side-looking Radar, Special Sensor Microwave/Imager (SSM/I) 85 GHz passive microwave data, and Advanced Very High Resolution Radiometer (AVHRR) data). This was achieved by both manual tracking of conspicuous features in the ice pack (leads, boundaries between multi-year and first-year sea ice as visible in Okean and AVHRR data) as well as automated tracking using maximum-likelihood correlation techniques (for SSM/I scenes). Comparison with the available buoy data showed consistent results and these were utilized to validate and improve a large-scale dynamic-thermodynamic sea-ice model. From the model, the areal ice flux to the Arctic Ocean and the adjacent shelf seas was derived for the period of 1979 to 1995. Except for the summer months of 1979 and 1981, total net export during summer and winter is positive for the entire period, ranging between 3 and 7 x 10^5 km^2 in winter (October-May). Along the northern boundary, ice was imported into the Laptev Sea during the summer period of 12 out of 18 years. Export into the East Siberian Sea is considerable, with mean winter values of approximately 1 x 10^5 km^2.

Freshwater input through river discharge is an important component of the freshwater balance of the Laptev Sea and the Arctic Ocean (Bareiss, 1996; Dmitrenko et al., this volume; Golovin et al., this volume). Hydrographic surveys carried out between 1993 and 1996 have been able to trace the influence of the plume from the Lena River throughout the eastern Laptev Sea. Historical data indicate that salinity anomalies in the Transpolar Drift may also be directly affected by continental runoff. While a study based on remote-sensing and hydrological data has shown that the impact of river discharge (through its effect on short-wave radiation balance and heat advection) on summer ice retreat is of importance only in the near-delta regions (Bareiss, 1996), river discharge considerably affects the ice freeze-up.

We were able to show that the establishment of a fast-ice cover and its areal extent are mainly controlled by the dispersal of river water in the eastern Laptev Sea (Dmitrenko et al., this volume). High resolution studies also indicate that frazil-ice production in the boundary layer between the river plume and water of higher salinity may constitute an important component of the ice-mass balance and play a role in sediment entrainment and transport (Dmitrenko et al., 1998; Golovin et al., this volume). Given the variability on decadal and in particular on longer timescales, the dispersal and the fate of river discharge and its impact on the ice regime are a central issue in understanding the long-term changes in the Laptev Sea and the Arctic Ocean.

Ice export from the Laptev Sea is of great importance for sedimentation processes on the shelf, in the central Arctic Ocean and the Nordic Seas (e.g. Wollenburg, 1993; Nürnberg et al., 1994; Pfirman et al., 1995; Eicken et al., 1997). Field studies have shown that substantial quantities of sediments are entrained into sea-ice growing over the broad, shallow Siberian shelves. Part of this ice grows throughout the winter season in a system of coastal polynyas and flaw leads (Dethleff et al., 1993; 1995; Rigor and Colony, 1997). To date, the relative contribution of polynyas, both to total ice export and transport of sediments, has not yet been fully understood, however. These sediments are transported with the ice and released during ice melting, most of which occurs in the Greenland Sea area. A major entrainment event was identified in the eastern Laptev and western East Siberian Sea in 1994. Through a combination of remote-sensing and field measurements, the evolution and drift of this ice field were studied. Estimates of the total sediment load from this single event, surviving ice melt in 1995 and hence exported to the Arctic Basin, amount to between 7 and 10 million tons. In conjunction with entrainment of sediments over the remaining shelf areas, sea ice transport may represent an important component of the Laptev Sea sediment budget, in particular with respect to short-term, long-range transport.

The marine ecosystem

Biological studies focused on the abundance and community structure of phytoplankton (Juterzenka and Knickmeier, this volume; Cremer, this volume), on zooplankton and benthos (Abramova, this volume; Petryashov et al., this volume; Bauch, this volume) as well as on benthic life in relation to environmental changes (Grahl et al., this volume). Three distinct faunal and floral provinces have been identified by multivariate analysis in the central, the northern, and the southeastern part of the Laptev Sea. The overall phytoplankton biomass during the summer period (August/September 1993) given by carbon content of the different taxa was relatively low compared to other Arctic shelf regions, despite a maximum of chlorophyll *a*, revealing the influence of the Lena river runoff. The late freezing period in autumn 1995 was characterized by a locally high chlorophyll *a* biomass, which can be used by zooplankton as a last food source before the winter period.

In newly formed sea ice, pigment concentrations varied considerably. However, total algal biomass within the new and young ice was relatively high and within the range of the water column standing stock in October 1995. Therefore, this algal biomass may serve as food for the developing micro- and meiofaunal ice community. Endoscopic observations showed significant differences in the three-dimensional small-scale ice morphology as well as enclosures of biotic and abiotic origin, which are characterizing the habitat.

Zooplankton on the Laptev Sea Shelf is dominated by *Calanus glacialis* and *C. finmarchicus*, but in areas of freshwater influence in the south and east, brackish water taxa contributed as much as 27% of the total biomass. The export of *Calanus* species from the Nansen Basin onto the Laptev Shelf appears to be of great importance for the shelf communities. On the other hand, the eastern outer shelf and slope area of the Laptev Sea are thought to have a pronounced effect on the deep basin, modifying the populations entering the central Arctic Ocean (Kosobokova et al., 1998).

Benthic faunas can be abundant but show little diversity. Except for some shallow areas (< 20m) with low bottom water salinity (< 30), the brittle star *Ophiocten sericeum* dominates the megabenthic shelf assemblage and reaches a maximum density of more than 500 individuals per

m^2 in river valleys (> 30m water depth). Gross estimates of brittle star respiration, productivity, and organic carbon demand suggest that a substantial portion of the energy flow is channeled through these dense brittle star assemblages (Piepenburg and Schmid, 1997). In large isopods *(Saduria entomon* var. *sibirica)*, respiration rates as indicators of metabolic activity were significantly higher at low salinities, indicating metabolic costs of osmotic stress in a seasonally changing brackish environment. The findings show that energy flow models of this highly variable environment must be based on the occurrence of different biological communities, which also represent regional differences in biomass and, therefore, most likely, productivity and carbon demand.

Pathways of nutrients, trace elements and chlorinated biphenyls

Nutrients, trace elements, and chlorinated biphenyls were studied in sea ice, water column and surface sediments of the Laptev Sea and in river water in order (i) to trace shelf-ocean pathways of river discharge and sea ice, (ii) to study processes of ice formation, and (iii) to estimate the natural and anthropogenic input into the Laptev Sea (Hölemann et al., this volume; Lara et al., 1998; Utschakowski, 1998; Pivovarov et al., this volume). Input and distribution of nutrients, trace elements, and chlorinated biphenyls are controlled by river runoff. Remarkable is a strong increase in the content of chlorinated biphenyls and metals and a corresponding decrease in dissolved silicon in Lena River water during the onset of spring break-up, as shown by daily concentration measurements in 1996. As a result, approximately half of the annual discharge is drained into the Laptev Sea during this short period of less than one month. The most important factor controlling the transport of dissolved and suspended matter during spring break-up is the pronounced density stratification of the water column in the Laptev Sea due to freshwater input via river runoff. Working much like a conveyor belt driven by the intensity of river runoff, dissolved and particulate matter are transported offshore to the north (Hölemann et al., this volume; Ivanov and Piskin, this volume; Pivovarov et al., this volume). Therefore, possible depositional centers, although not clearly identified, are far away from the Lena Delta.

Another important process affecting the transport pathways of particles was studied in the autumn of 1995. During freeze-up, particulate matter was effectively incorporated into newly forming ice off the Lena Delta. Unexpectedly high concentrations of dissolved Fe, Mn, Zn, Cd, and Pb were measured in the sediment laden new ice (Hölemann et al., this volume). For instance, the concentration of Fe was up to 25 times higher as compared to the average concentration of Lena River water. We suggest that this is caused by a redox controlled remobilization of metals from ice-bound sediments. Further geochemical investigations of sea ice and surface sediments from different regions in the Laptev Sea have also shown that the chemical signature can be directly related to different fluvial sources: e.g., high Mg/Al ratios found in sea ice sediments in the southwestern Laptev Sea reflect the geochemical signature of flood basalts in the catchment area of the Khatanga River. Dissolved and particulate heavy metals and chlorinated biphenyls in sediments, water column, and sea ice are at very low levels. In particular, the content of heavy metals in sea ice and surface sediments are comparable to those found in unpolluted marine sediment and thus give no indication of anthropogenic pollution. High contents of As in surface sediments along the river valleys are caused by strong suboxic diagenesis.

Land-ocean transfer of sediments

To identify modern and past sediment transport from the Siberian hinterland across the Laptev Sea to the Arctic Ocean, geochemical, i.e., major, trace, and rare earth element (Hölemann et al., this volume; Rachold, this volume) and Sr isotope (Rachold et al., 1997b), and mineralogical, i.e., clay and heavy mineral (Behrends et al., this volume; Rossak et al., this volume), investigations were performed. These analyses concentrated on river suspended particulate matter as well as on surface sediments from all major river systems draining into the Laptev Sea and the adjacent Arctic Ocean. In addition, ice samples from the Laptev Sea and the Arctic Ocean were studied. Accordingly, the Laptev Sea can be divided into two different sedimentary provinces. While the eastern part is controlled by Lena River discharge, the western part is controlled by sediments supplied by the Khatanga River. Sea ice and sea-floor sediments from the western Laptev Sea can be distinguished from those from the eastern Laptev Sea by (i) the dominance of pyroxene in contrast to the amphibole-rich sediments of the eastern Laptev Sea, (ii) high amounts of the clay mineral smectite, which are lower in the eastern Laptev Sea, and (iii) significantly lower $^{87}Sr/^{86}Sr$ isotope ratios. In addition, sea-floor sediments of the Arctic Ocean indicate that Sr isotope ratios and heavy mineral assemblages can be used to identify sediment transportation pathways from Central Siberia to the Arctic Ocean.

The Lena River is considered to be the main sediment source for the Laptev Sea. About 150 km upstream from the Lena Delta measurements of suspended sediment transport were made during the past decades. But the quantitative evaluations of suspended sediment discharge made by different investigators using the same data sets range from 11.8 to 21 million tons per year. Hence, the exact amounts of sediment actually accumulating in the Lena Delta and finally reaching the sea is difficult to estimate. However, data on suspended sediments along a transect from the southeastern Lena Delta to the Laptev Sea have shown no concentration gradient during the onset of the river break-up in 1996.

Another important sediment source for the Laptev Sea is coastal erosion. Field investigations as well as air and satellite images indicate that coastal retreat varies between 2.5 and 6 m per year. Rough estimations of the amount of sediments released to the sea due to erosion are of the same order compared to data on sediment discharge of the rivers feeding the Laptev Sea (Are, 1996; Are, this volume). However, reliable estimates for land-ocean sediment transport will be the focus of further investigations in the Lena Delta.

The modern organic-carbon cycle

To understand the processes controlling organic-carbon flux and composition in the Laptev Sea, biological, micropaleontological, organochemical, and sedimentological investigations were performed on water samples and surface sediments of the Laptev Sea (Fahl and Stein, 1997; Stein et al., this volume). Data from the water column indicate a higher biological activity in the eastern Laptev Sea. This is also reflected in surface sediments, with increased contents of organic matter in this area. Micropaleontological parameters and specific biomarkers can be used to distinguish between marine and terrigenous sources of organic matter of surface sediments. Organic carbon maxima off the river mouths correlate with increased abundances of freshwater algae, plant debris, and terrigenous biomarkers (e.g., long-chain n-alkanes and wax esters, light $\partial^{13}C_{org}$) as well as high clay content. This points to the terrigenous source of this organic matter. Concentrations of terrigenous markers decrease with increasing distance from the source. The distribution of the marine biomarkers (e.g., short-chain fatty acids) correlates with sea ice distribution. The lowest concentrations of short-chain fatty acids are in ice-covered areas, whereas the highest amounts are located near the ice edge. Fatty-acid distribution correlates with the distribution of chlorophyll *a* and biogenic opal content, indicating increased surface-water productivity near the ice edge (Fahl and Stein, 1997).

To understand the modern organic carbon cycle, variations in modern organic carbon accumulation (flux) rates must also be considered. Accumulation rates of total organic carbon may reach 0.2 to 2 $gCcm^{-2}\,ky^{-1}$, decreasing to 0.02 $gCcm^{-2}\,ky^{-1}$ at the lower slope. A decrease in accumulation rates from the Laptev Sea towards the lower slope reflects a decrease in terrigenous organic matter supply in offshore direction.

The Laptev Sea since the Last Glacial

Paleoceanographic investigations based on radiocarbon datings (AMS ^{14}C) of bivalve shells in sediment cores (up to 5 m) have provided new insights into the history of the Laptev Sea since the last glacial. The history of the Laptev Sea can be subdivided into various phases inherently linked to sea level rise following the last glaciation.

During the last glaciation, large parts of the Laptev Sea Shelf were dry due to low global sea level. Sedimentation was probably governed by the deposition of syngenetic sediments (ice complexes), although light planktic oxygen isotope ratios from the central Arctic Ocean may indicate continuing river runoff during this time (Nørgaard-Pedersen et al., 1998). During deglaciation, records from the Laptev Sea continental slope reveal a major depletion in $\partial^{18}O$ at 11,000 years before present (yBP), which seems to correlate in age with the onset of the Younger Dryas cold spell. A major change towards marine conditions on the shelf due to rising sea level is noted at 9,500 yBP with increasing $\partial^{13}C$ values for organic matter and marine biomarker concentrations. This is coeval with an onset in the lateral distribution of heavy minerals from east to west on the shelf and along the continental slope. The outer parts of the Laptev Sea Shelf ($\geq$70 m water depth) are marked by an abrupt decrease in sedimentation rates at 9,000 yBP. In the inner-shelf areas, the sea level continued to rise until flooding of the shelf terminated near 6,000 yBP, accompanied by a major drop in sedimentation rates between paleodepth 30 to 50 m (Bauch et al., in press).

The later Holocene (since 6,000 yBP) situation appears to be rather stable in that sedimentation rates varied between 1.2 mm per year in the Lena Valley and 0.1 mm per year in the Khatanga Valley (Bauch et al., in press). This is about 5 times lower in comparison to the continental slope. Surface sediments, freshwater diatoms, and chlorophycean algae dominated the eastern shelf, whereas marine diatoms and dinoflagelate cysts are prominent on the western parts of the shelf (Cremer, 1998; this volume; Kunz-Pirrung, 1998; this volume). Ice algae species become more abundant particularly towards the north, along the average position of the summer ice edge. Grounding ice contributed considerably to sediment transport on the Laptev Sea Shelf. Side-scan sonar records and 30 kHz echograms indicate that at some locations (e.g., north of the Lena Delta) sediments are disturbed as a result of grounding ice (Benthien, 1995; Lindemann, 1995). These plough marks can be as deep as ten meters. Such grounded icebergs were actually occasionally observed between 15 and 25 m water depth in summer.

Another interesting feature of the Laptev Sea is the existence of offshore permafrost, which was verified by ice-bonded Holocene sediments found in areas as shallow as 12 cm below surface in the central Laptev Sea (Kassens and Karpiy, 1994; Romanovskii et al., 1997). The impact of offshore permafrost on the environmental system is unknown and will be a primary goal during further investigations.

Modern processes in permafrost landscapes

In Arctic regions, hydrological, geochemical, and biological processes are directly controlled by the presence of permafrost and the seasonal thawing of the active layer. Most of the processes occur during the short summer season from May to August and cease during the winter. As the active layer thaws with the progress of summer, the infiltration and storage capacity of the ground are increased. Consequently, geochemical, biological, and hydrological activities in the active layer are enhanced and influence the hydrology and geochemistry of surface and ground waters.

Modern seasonal dynamic processes were studied on various scales in the different climatic settings of the Levinson-Lessing and Labaz Lake catchments, and of northern Bolshevik Island, Severnaya Zemlya (Figure 3). For example, pedological and biological studies were conducted and replenished by seasonal measurements of CO_2 and CH_4 fluxes. In addition, the temporal and spatial variations in active layer hydrological and thermal processes and solute fluxes were quantified and compared with climatological data. A complete spring to autumn record of water and sediment discharge by streams entering Levinson-Lessing Lake and of the sedimentation in the lake, was measured in order to get an impression of the seasonal dynamic processes of sediment transport and accumulation under the present environmental and climatic conditions. The representative field data were put into a wider context by landscape mapping and subsequent connection with remote sensing data from Landsat TM images in order to extrapolate the field data to larger areas.

The results discussed in this book were obtained in the catchment of the Levinson-Lessing Lake. Mapping of vegetation, soils, and geomorphology in the field, supported by interpretations of air photos, enabled Anisimov and Pospelov (this volume) to classify 34 landscape units. Surface hydrological investigations were carried out by Zimichev et al. (this volume). They quantified seasonal fluxes of water and sediment for a typical high Arctic-nival streamflow regime entering the Levinson-Lessing Lake. The temporal dynamic of water, heat, and solute fluxes in the active layer was studied for a complete freeze-thaw cycle by Boike and Overduin (this volume) using Time Domain Reflectometry. The results indicate that the dominant heat sinks during spring and summer are the sensible and latent heat fluxes into the atmosphere. The soil heterogeneity strongly impacted hydrologic and thermal processes in the active layer.

The role of permafrost affected soils as sinks or sources of carbon is determined by labile balance between the production and the decay of organic matter. The relationship between the carbon-cycle and soil substrate, hydrological and thermal regime of the active layer, vegetation, and relief, was studied at different polygonal tundra sites. Seasonal trace gas emission of CH_4 and CO_2 was quantified (Sommerkorn et al., this volume) and, using carbon isotopes, the recent decomposition processes of carbon in permafrost-affected soils were studied (Samarkin et al., this volume). Such data are important for the understanding of soil generation and carbon accumulation processes in the present and past and thus for knowledge about the development of the Siberian Tundra.

Environmental history of the permafrost landscape

The development of permafrost is a characteristic process in non-glaciated regions with cold, continental climate. The deposits formed in permafrost landscapes contain complex information concerning the regional and local environmental conditions of the time of sediment accumulation and freezing. Besides chronological, sedimentological, mineralogical, geochemical, and paleontological data, specific information can be obtained from the cryostructure of syngenetic permafrost sequences as well as the kind and composition of ground ice bodies.

Widely continuous permafrost development takes place in lowland areas where accumulation distinctly exceeds denudation and where sufficient moisture leads to well expressed ground ice formation. Investigations of permafrost sequences in the Taymyr region, therefore, have focused on the Taymyr lowland being bordered by the Putoran Plateau to the south and the Byrranga Mountains to the north. Early work in the western and southwestern lowland had supplied first important information concerning the climatic history and paleogeography of the region (e.g., Karpov, 1986; Tumel, 1985). On the central and northern lowland, in contrast, permafrost data were restricted to some geothermic measurements in boreholes. The latter areas, therefore, were the major focus for permafrost investigations within the scope of the Taymyr Project. Special attention was drawn to the surroundings of the Labaz Lake, to Cape Sabler at the western shore of the Taymyr Lake, and to the western rim of the Putoran Plateau, where running work was continued. Additional information was obtained from paleogeographic, geomorphologic, and archaeologic work carried out in the foreland of the western Putoran Plateau, in the western Byrranga Mountains, and on the Severnaya Zemlya Archipelago.

First results from permafrost deposits and ground ice bodies at the Labaz Lake have shown that the last glaciation of the area predates the Middle Weichselian and that the East Siberian anticyclon had gained in significance during Middle and Late Weichselian times, leading to a distinctly higher continentality of the climate (Melles et al., 1996; Derevyagin et al., 1996; Chizhov et al., 1997). Evidence for a restricted ice advance during the Last Glacial Maximum was also found on the Severnaya Zemlya Archipelago, based on geochronological and paleogeographic investigations (Bolshiyanov and Makeev, 1995).

A more detailed presentation and discussion of the permafrost development in the Labaz Lake area, and its dependence on the Late Quaternary climatic history, is presented in this book by Siegert et al. (this volume). The results support the suggestion that the last ice advance to the central Taymyr lowland took place prior to the Middle Weichselian. The preservation of fossil glacier ice in near-surface permafrost deposits evidence a strongly retarded deglaciation of this territory with continuous, low-temperature permafrost. Climate warming during Middle Weichselian interstadials and at the Pleistocene/Holocene transition led to distinct vegetation changes and enhanced thermokarst processes, and subsequent peat accumulation. Following an early Holocene climatic optimum, climatic deterioration since about 3 ka led to the drying of the lakes and a gradual increase of permafrost aggregation. Additional information concerning the latest Holocene climate and environment comes from the archaeological findings on the northern Taymyr Peninsula (Pitul´ko, this volume). Limited information about the pre-Weichselian history, in contrast, is available from the sampled permafrost deposits. Some data about the fluctuations in relative sea level were obtained by ESR dating and lithostratigraphic studies of marine deposits (Bolshiyanov and Molodkov, this volume).

Paleoenvironmental reconstructions by lake sediments

The sediment fill in lakes functions as one of the best natural data archives for paleoenvironmental reconstructions because lakes act as sediment traps. Limnic sediments generally represent more complete depositional sequences than other terrestrial deposits. With multi-proxy data from lake sediments, complex information concerning the environmental setting both in the catchment area and in the water column of lakes can be obtained. In addition, detailed age determinations can often be achieved by radiocarbon dating of organic matter. Hence, lake sediments may supply high-resolution reconstructions of the environmental history, with good stratigraphic control.

Within the scope of the "Taymyr" Project, long sediment cores were recovered from the lakes Lama (18.9 m), Pyassino (6.0 m), Kokora (5.2 m), Portnyagino (4.0 m), Taymyr (14.3 m), Levinson-Lessing (22.4 m), Changeable (12.7 m), and Fjord (3.2 m). These lakes cover the entire project study area (Figures 3 and 4). In the lakes Lama, Taymyr, and Levinson-Lessing, in addition, the large-scale sediment architecture was investigated by sub-bottom profiling. With the existing sample and data set, therefore, both spatial and temporal variations of the climatic and environmental histories can be reconstructed.

The analytical work on the lake sediment cores is manifold, being used irregularly in dependence on individual objectives and core qualities. Special emphasis is put on the sediment chronology, sedimentology, palynology, micropaleontology, geochemistry, and mineralogy. First results, obtained on sediment cores from the Lama Lake and the Levinson-Lessing Lake, had shown that palynological analyses supply comprehensive information on the climatic evolution and related vegetation history (Hahne and Melles, 1997) and that investigations of lake sediment cores in the Taymyr region ideally complement investigations of permafrost profiles and ground ice bodies on land (Melles et al., 1996).

Results from sub-bottom profiling in the lakes Taymyr and Levinson Lessing, presented in this book, indicate that glaciers were present in the western Byrranga Mountains for the last time during the Early Weichselian glacial (Niessen et al., this volume). In addition, the seismic data are discussed with respect to the postglacial depositional histories of these lakes, with particular attention to their dependence on lake-level fluctuations. Sedimentological data from the Levinson-Lessing Lake core support the seismic interpretation and supply more detailed information concerning the kind and temporal variations of sedimentary processes since late Middle Weichselian time (Ebel et al., this volume).

Palynological analyses on sediment cores from four lakes, forming a transect from the southern Taymyr Peninsula to Severnaya Zemlya, were employed to reconstruct the vegetation history in the catchment areas of the lakes since Middle to Late Weichselian times (Hahne and Melles, this volume). The palynological results, compared with published ice core isotope data from Severnaya Zemlya, give a first impression of the development and of spatial and temporal variations of vegetation zones in dependence on climatic changes since the latest Pleistocene. The Holocene climatic evolution at the Lama Lake is also mirrored by the planktonic to benthonic diatom ratio in the lake sediments (Kienel, this volume). In addition, the diatom assemblages enable to reconstruct variations in the trophic conditions in the lake water. Hagedorn et al. (this volume) used ^{210}Pb dating and measurements of heavy metal concentrations in near-surface sediments of the Lama Lake to determine geogenic and anthropogenic sources and calculate recent accumulation rates.

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