THE GLOBAL COASTAL OCEAN

INTERDISCIPLINARY REGIONAL STUDIES AND SYNTHESES

PART A: PANREGIONAL SYNTHESES AND THE COASTS OF NORTH AND SOUTH AMERICA AND ASIA

PART B: THE COASTS OF AFRICA, EUROPE, MIDDLE EAST, OCEANIA AND POLAR REGIONS

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Chapter 28. LAPTEV AND EAST SIBERIAN SEAS (23,P)

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1. Introduction

Key words usually used to characterize the environment of the Laptev and East Siberian seas are: shallow, ice-covered, and extremely cold. However, the Arctic bitter cold and heavy ice could not stop the first polar explorers from discovering and describing for us that wonderful and rich world. Russian Cossacks, followed by

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navy officers and hydrographers, explored the Arctic seas, no doubt with the main aim to discover new lands, new transport routes, to annex new territories to the Russian Empire, and they described the environment of the seas, coasts, and islands. They left their names on the maps and charts and on the many graves, which were scattered along the coast. Besides the Russians, the eastern Arctic seas were explored by the Sweden (Nordenskøeld, *Vega,* 1878–1879), American (De Long, *Jannette,* 1879–1881), and Norwegian (Nansen, *Fram,* 1893; Amundsen, *Maud,* 1922–1924) polar expeditions.

The Soviet Union organized many interdisciplinary polar expeditions after the Great October Revolution. The main purposes were to ensure a security of navigation through the Northern Sea Route and to explore mineral resources. Many stationary observatories and scientific stations were founded on the coasts of the Arctic seas. The main efforts were focused on ice studies in conjunction with hydrographic conditions. Physical, chemical and biological properties of ice and water column were studied intensively. The observations obtained became a foundation for future studies. Many famous Russian (soviet) professors published a great number of papers and books concerning hydrography, climate, ice conditions, bottom sediments and biota in the Arctic seas and in the Eastern sector in particular at that time (see the reviews in the *Problems of the Arctic and Antarctic,* Vol. 70, 1995).

The studies of the Laptev and East Siberian seas were continued after the Second World War. The Golden Era of Russian Arctic research was from 1950 till 1990. Two or three expeditions worked in each sea every summer and winter. These were, so called, *Ice Patrols* at sea in summer, the airborne expeditions *Sever* in winter, and ice camps all year round. Unfortunately, it is not possible to describe these expeditions as interdisciplinary because oceanographers, biologists and geologists explored the seas separately. The Arctic and Antarctic Research Institute (AARI) studied sea ice, hydrometeorological conditions, and some nutrients as indicators of water mass origin, and to monitored pollutants distributions. Zoological and Biological Institutes (ZIN and BIN) and Shirshov Institute of Oceanography of the Russian Academy of Science studied biological processes. The All-Union Research Institute for Geology and Mineral Resources of the World Ocean (VNIIO) studied bottom sediments and geological processes. But, unfortunately inter-institutional cooperation was not a priority. There were many examples, when biologists or geologists tried to explain their own interesting findings by complexity of oceanography and regretted that appropriate observations had not been collected. Nevertheless, the Russian scientific community has a long tradition in working on the Eurasian shelf seas because of oil, gas and mineral resources found there and the economic advantages of the Northern Sea Route. Relevant institutions have accumulated a tremendous amount of experience in Arctic research. Much data and numerous papers about the Siberian shelf seas have been published, but they have appeared primarily in Russian reports or journals, which have not easily been available for the Western world. These areas were closed to international exploration for a number of decades.

Actually, real interdisciplinary studies at the Eastern shelf began ten years ago, thanks to international cooperation. Very interesting new results were obtained in the international expeditions SPASIBA (1989–1991). Multidisciplinary team studied river influx into the Laptev Sea and then published their results in a special volume of the *Marine Chemistry.* The Russian-German ESARE (1992) expedition operated in the eastern part of the Laptev Sea in winter (Dethleff et al., 1993). The great progress in interdisciplinary studies in the Laptev Sea was achieved owing to the bilateral research project *Laptev Sea System* (1993–2003) that was aimed to the interpretation of paleoclimatic records in conjunction with the study of modern processes for better understanding and prediction of the Arctic System (Thiede et al., 1999). The project comprised marine and terrestrial observations as well as a suite of modeling experiments and theoretical considerations. Ten expeditions to the inner Laptev Sea in the frame of the multi-disciplinary research program were carried out. These expeditions were accompanied by both RV *Polarstern* cruises and the land-based Lena-Yana expeditions (Fütterer, 1994; Rachor, 1997; Rachold, 1999). Some of them were unique. For example, the expedition TRANSDRIFT III (1995) aboard the icebreaker *Kapitan Dranitsyn* 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), and the TRANSDRIFT IV (1996) expedition studied the Lena River break-up and its influence on the environmental system of the Laptev Sea (Kassens et al., 1998). For the first time, a major comprehensive research program combined the efforts of many Russian and German institutions and addressed both oceanic and terrestrial processes, and their consequences for marine and terrestrial biota, landscape evolution as well as land-ocean interactions. 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 behavior and lake hydrology were performed during the recent years (Thiede et al., 1999).

2. Geographical location, bottom topography, climate, ice, river run-off, key physical processes

2.1. Geographical location and bottom topography

The Laptev and East Siberian seas are marginal open seas of the Arctic Ocean and occupy the central and eastern parts of the vast Siberian (Eurasian) shelf, which is the broadest one on Earth (Fig. 28.1). Northern boundaries of the seas are conventional. That is why the Laptev Sea includes the continental slope and a part of the deep Arctic Basin, while 72% (Timokhov, 1994) of the sea is located on the extremely shallow shelf. The total area of the sea is 662,000 km^2 (Atlas of the Arctic, 1985). The East Siberian Sea shelf makes up 96% of the sea area (913,000 km^2). Both of the seas are located within the Polar Circle. The coastal line is indented with many gulfs. The largest of them are Khatanga, Anabar, Olenek, Buor-Khaya, Yana gulfs in the Laptev Sea, and Khroma, Indigirka, Kolyma and Chauna gulfs in the East Siberian Sea.

The Laptev Sea shelf is very shallow. Depths less than 50 m dominate over the southern part of the shelf. Submarine valleys are the main and very important relief features of the sea because they control water mass redistribution and sedimentation rate. They comprise a series of depressions 25–45m in depth. A vast shoal (bank) separates the Lena and Yana underwater valleys in the eastern part of the Laptev Sea. This shoal comprises the remains of eroded and recently submerged islands. The islands were mapped and named only a little more than one hundred years ago (Zigarev and Sovershaev, 1984). This is an example of the intensive erosion of the shore, which is an object of interdisciplinary studies nowadays (Are, 1999; Are et al., 2002).

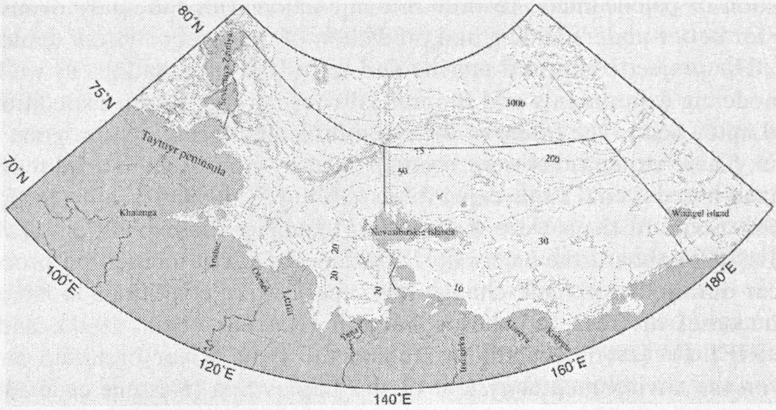

Figure 28.1 Geographical boundaries and bottom topography of the Laptev and East Siberian seas. Thin solid lines with numbers indicate isobaths according to IBCAO (International Bathymetric Chart of the Arctic Ocean) bathymetry data (Jakobsson et al., 2000). Thicker solid lines show conventional boundaries of the seas according to the Atlas of the Arctic (1985). Coastlines and bathymetry were taken from the Ocean Data View software (Schlitzer, 2002).

The East Siberian Sea floor is a smooth plain dipping gently to the north and east. The shelf break occurs at the water depth of 50–60 m as far as 350–400 km from the coast. The submarine valley of the Indigirka River stretches northward in the western part of the sea. The relatively narrow and deep underwater valley of the Kolyma River extends along the Siberian coast and turns northward as it widens near Wrangel Island.

2.2. *Climate*

The severe arctic climate of the seas is characterized by a long and extremely cold winter (mean January air temperature is up to -32 °C) and a short and rather cold summer (mean August air temperatures are from 0 to 5 °C). Cyclones visit this region rarely in winter, and they are not active and deep. An average wind speed over the seas is about 5 m s^{-1}. The region is calm even in summer when atmospheric circulation is weak with storms occurring for two or three days per month. Cloudiness is slight in winter, but it usually covers the entire sky in summer. The precipitation rate is low, 150–300 mm per year with most of the precipitation falling in summer. The relative humidity is rather high, 95–98% so fogs are quite frequent, especially in the ice-covered regions (Timokhov, 1994; Pavlov, 1998).

2.3. *Ice conditions*

Sea ice influences the climate, oceanography, biology as well as the geology of the area to a high degree. Ice significantly reduces the heat flux between ocean and atmosphere; through its high albedo it has a strong influence on the radiation budget. It controls the thermohaline circulation driven by ice formation and melting. Sea ice is a key geological agent in the Arctic, it transports large amounts of the sediments incorporated into the ice in the shelf area (Pfirman et al., 1990; Lindemann et al., 1999). Sea ice cover is one of the most sensitive expressions of the modern climate regime with its extreme seasonal fluctuations being a good indicator of potential instability (Thiede, 1996).

New ice formation depends on hydrometeorological and ice conditions present at the beginning of the fall. The dates of the onset of freezing vary dramatically; ice can be formed even in summer among the remaining ice patches. As a rule, new ice appears at the edge and among the existing ice floes, in shallow near shore areas and estuaries. It means that freeze-up starts both from the north and south of the seas at the same time. Autumn storms play a key role in ice formation. Strong winds induce a vertical mixing and a rapid cooling of the surface layer. Ice formation is more intensive and occupies larger areas after the storms. Air temperature and hydrographic conditions, which are changing in space and time, control the ice growth. At the end of winter, ice thickness reaches 2 m (Zakharov, 1996). The shallow parts of the seas (depth less than ca. 20 m) are covered by fast ice. The width of the fast ice depends on bottom topography and is controlled by offshore winds (Zakharov, 1966; 1996). A perennial polynya, hundreds of kilometers wide, borders the very smooth fast ice (Fig. 28.2). *In this body of open water, rapidly forming ice is continuously advected offshore, making the Laptev Sea the single the major ice factory for the Arctic Ocean and Transpolar Drift* (Reimnitz, 1994). Ice outflows from the Laptev and East Siberian seas are 540 and 150 km^3 respectively (Timokhov, 1994). *With summer warming, this winter factory turns into an area of heat gain, aiding the retreat of the ice edge to a much higher latitude and greater distance (500 km) from the mainland than in the Beaufort Sea* (Reimnitz et al., 1993; Reimnitz, 1994). The fast ice massifs thaw at the same places where they have been formed. A huge amount of ice, comparable with the riverine freshwater influx, melts in the seas in summer (Zakharov, 1996; Rigor and Colony, 1997).

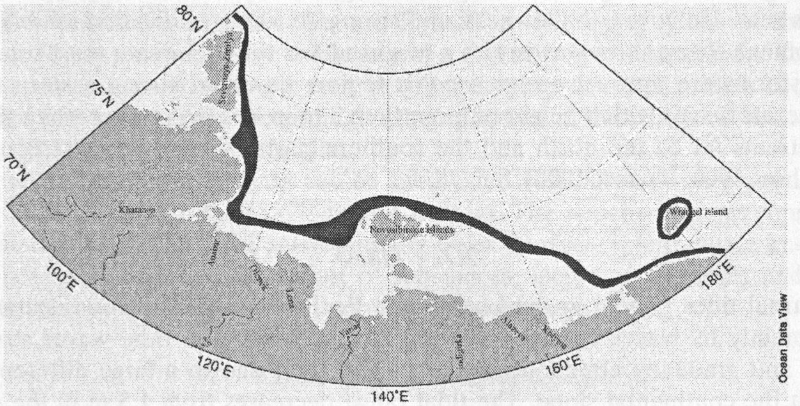

Figure 28.2 Location of the Great Siberian polynya in the Laptev and East Siberian seas according to Zakharov (1996).

2.4. *River run-off*

Pulsing river run-off impacts the seas. This freshwater input together with melt water from the sea ice is of critical importance in influencing the circulation pattern, ecosystem, sediment dynamic, and geochemistry of the seas. The most important contributors are the Siberian rivers Lena (520 km^3), Khatanga (105 km^3), Anabar (25.2 km^3), Olenek (40 km^3), Yana (37.5 km^3), Indigirka (56.7 km^3), Alazeya (10.2 km^3), and Kolyma (102 km^3) (Atlas of the Arctic, 1985; Ivanov and Piskun, 1999). Total river run-off is estimated to be about 1000 km^{3}per year. These rivers transport millions of tons of dissolved and particulate material (i.e., chemical elements, nutrients, siliciclastic and organic matter, etc.) onto the shelf where it is accumulated or further transported by different mechanisms (sea ice, icebergs, turbidity currents, etc.) (Stein et al., 2001). The river influx changes dramatically in seasonal circles. Small, medium, and even some branches of the large rivers are completely frozen down to the bottom in winter. From 70 up to 95% of the river influx occurs during a short Arctic summer (Ivanov and Piskun, 1995).

2.5. *Water circulation*

The surface circulation pattern is extremely variable in the shallow Laptev and East Siberian seas both in summer and in winter, and it is intimately connected with atmospheric processes. In spite of large mesoscale variability in surface currents caused by changes in the wind field, it is possible to identify permanent currents in the seas. In general, a very slow counterclockwise (cyclonic) water circulation is observed at the surface of the seas in summer (Pavlov, 1998). There are more or less permanent coastal currents directed eastward along the shore. Very little is known about the currents in the Intermediate and Bottom Structural Zones.

2.6. *Waves*

Wave heights are usually small along the navigation route in the Laptev and East Siberian seas. Ice cover, shallowness, and strong density stratification inhibit wave development. Steep short waves with a height of less than 1.5 m are most common. Heavy storms are unusual events for this region, however, strong eastern winds can generate waves with a height of more than 3 m in late September when the ice edge retreats far to the north and the southern parts of the seas are free of ice (Timokhov, 1994; Pavlov, 1998).

2.7. *Tides*

Semidiurnal tides prevail in the Laptev and East Siberian seas. The tides are induced mainly by waves coming from the Arctic Basin. The tidal waves strongly deform and gradually attenuate in the shallow shelf due to a large difference of depth at the continental slope. The tidal range decreases from 1.5 m in the north (near the New Siberian Islands and Wrangel Island) to 0.1m near the coast of mainland. So, as a rule, the tidal range is very small at the shore. Tidal current velocities are usually less than 0.2 m s^{-1}. However, there are some exceptions. According to Earth's rotation, the tidal waves deviate to the right from the direction of propagation that induces an increasing tidal range along the western coasts of these seas. Tidal range increases up to 2.5 m near the entrance of the Khatanga Gulf (the western part of the Laptev Sea). Enhanced tidal range is observed in the western part of the East Siberian Sea near the Sannikov and Dmitry Laptev Straits (Timokhov, 1994).

2.8. Surges

Sea level fluctuations caused by surges are very common along the coast of the seas. Surges increase sea level up to 2 m and more. The wind surge effect is inversely proportional to depth. The largest surges are observed in shallow regions of the eastern Laptev Sea and in the Kolyma estuary. Their ranges are five to twenty times greater than tidal fluctuations of sea level. Surges decrease to the north along the coasts of islands and the mainland. The sea level fluctuations caused by surges are a little more than 1m at the coasts of the Taymyr Peninsula and the New Siberian Islands but they exceed the tidal range there nevertheless (Timokhov, 1994; Pavlov, 1998).

3. Water column structure

A clear understanding of a water body structure is necessary for modeling and prediction of entire sea ecosystem. It was mentioned earlier that there are thermohaline, hydrochemical, biological, and other structures. It is now obvious that a water column has only one structure, and it should be studied in a interdisciplinary manner, combining physics, chemistry, geochemistry and biology.

As a result of changeable hydrometeorological, ice, and biological conditions, a multilayered and mosaic water column structure is formed in the Laptev and East Siberian seas. Water mass (a volume of water having *common formation history* (Tomczak, 1999) and *possesses for a long time almost constant and continuous distributions of physical, chemical, and biological characteristics, constituting a united complex* (Dobrovolsky, 1961)) is a basic element of the water column. Water masses with different properties are formed in the same regions of the seas during different seasons. Small volumes and a short life span characterize the water masses in the shallow Arctic seas. A great number of water masses could be separated into several types according to their position in the structural zones, and the place, and time of their formation.

The water column in the seas can be subdivided vertically into three structural zones, namely: Surface, Intermediate and Bottom. The structural zones consist of water masses appurtenant to corresponding types (surface, intermediate and bottom). Transport and transformation of substances, including nutrients and contaminants, in these structural zones occur in different ways.

3.1. Surface Structural Zone (SSZ)

The SSZ is the most active area where energy and material is transformed by interactions between sea, ice, and atmosphere, and is a region where biological processes are very important. It is the most dynamic as well because of its own characteristics change during the annual cycle and the movements of water masses caused by winds, tides, gravity, and the Earth's rotation. The thickness of the SSZ in the well-stratified seas is usually 5–10 m and changes seasonally.

Two different regions in the Laptev Sea can be distinguished according to temperature and salinity distributions, and chemical and biological properties of the surface water masses. River plumes occupy the southern and eastern regions of the sea while the Arctic Basin influences the northwestern part of the sea. It is considered that the silicate distribution at the surface (Fig. 28.3a) is a good indicator of the river plume in summer (Rusanov et al., 1979). The 10 μmol l^{-1} silicate isoline is accepted to be a boundary of the river plume that is also characterized by low salinity (less than 25), low oxygen saturation (95 – 100%), and high concentrations of suspended matter (0.5–0.8 mg l^{-1} at the outer shelf and up to 70 mg l^{-1} near the Lena River Delta). They can be distinguished by many other physical, chemical and biological properties (e.g. water color and smell). Bottom sediment composition and distribution of benthic species reflect an average location of the river plume.

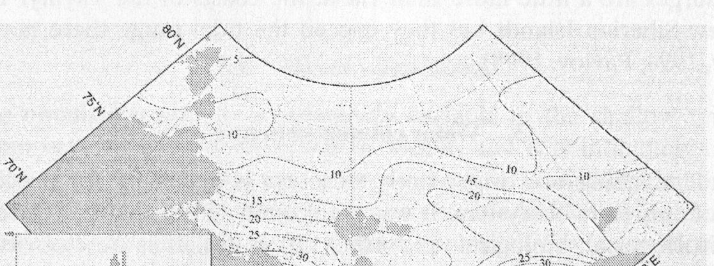

Figure 28.3 Averaged silicate (μmol l^{-1}) distributions at the surface of the Laptev and East Siberian seas in summer (August-September) (a), and in winter (March-May) (b) for the years 1922–2000. Thin solid lines with numbers indicate isolines of silicate concentrations. High silicate concentrations at the surface of the seas in summer indicate a riverine influence. Black points show locations of the oceanographic stations data of which were used for averaging and gridding. Data source is the US-Russian Hydrochemical Atlas of the Arctic Ocean (Colony et al., 2002). Windows at the lower left corners of the maps show temporal distributions of the stations. Ocean Data View software (Schlitzer, 2002) was used for gridding and map construction.

According to the silicate distribution (Fig. 28.3a), the East Siberian Sea is influenced by river run-off to a high degree too. The Kolyma River plume is visible on the map, however huge amounts (ca. 250 km^3) of fresh water are imported from the Laptev Sea.

Nitrate and phosphate are almost consumed in the SSZ in summer. Nitrate concentrations are near zero in the both parts of the Laptev Sea though phosphate concentrations range between 0 and 0.2 µmol l^{-1}. Increased nitrate (up to 1 µmol l^{-1}) and phosphate (up to 0.5 µmol l^{-1}) concentrations can be observed near river mouths in summer.

Ice margins are special regions where surface water masses are characterized by extremely high oxygen saturation (more than 120%), and pH, and alkalinity anomalies caused by continuous phytoplankton bloom. These regions are of great ecological significance because of high primary production and special conditions for marine inhabitants. However it should be noted that the geographical location of an ice margin changes dramatically in summer.

The SSZ is enriched by nutrients in winter as a result of mixing with intermediate waters. An average silicate concentration at the sea surface in winter is higher than in summer (Fig. 28.3). Water-cooling and the brine injection accompanying ice formation cause deep convection, which increases the thickness of the surface mixed layer. The convection is able to destroy the halocline in some shallow regions and penetrate down to the bottom. In this case bottom sediments and nutrient rich pore waters are involved in the effects of mixing. Winter water masses formed under fast ice, in polynya, and under drift ice are characterized by different physical, chemical and biological properties. A polynya is a natural ventilator for the seas, and their water masses are very well saturated by oxygen since ice does not hinder gas exchange between sea and atmosphere.

3.2. *Intermediate Structural Zone (ISZ)*

The ISZ in the shallow Arctic seas consists of just the halocline, a layer up to 20 m of thickness with strong salinity gradients. It has a multi-layered structure itself and consists of water masses of different origin. Data of the summer oceanographic surveys show that it is possible to recognize in the halocline the intermediate water masses, which have been formed in winter, in spring, and in summer according their temperature and chemical properties. Extremely low temperature (less than -1.5 °C) is a distinguishing characteristic of the intermediate winter water masses. The intermediate spring water masses are characterized by low temperature (sometimes less than -1.0 °C), very low nutrient concentrations, and high oxygen saturation (more than 100%). An intermediate oxygen maximum indicates the location of the spring water masses, which are formed at the surface of the sea before ice melting. The intermediate summer water masses are characterized by relatively high positive temperatures (up to 5 °C), low nutrient concentrations, and sufficient oxygen saturation (up to 95%). They are formed at the surface and penetrate to the intermediate depth at the frontal zone that separates the river plume from surrounding water masses. An intermediate temperature maximum is a remarkable feature of the river plume region in the late summer and autumn when the surface mixed layer is cooled.

3.3. Bottom structural zone (BSZ)

Many different types of water masses can be distinguished in the BSZ according to their physical, chemical and biological properties. For example, stagnant bottom water masses are formed in the river plume areas of the Arctic seas under fast ice in winter. Low temperature (-1.2 – -1.5 °C), extremely low oxygen saturation (30–50%), and high nutrient concentrations characterize them. The intensive influx of riverine organic matter and limited ventilation are the reasons for the oxygen deficit. In winter, the fast ice prevents gas exchange with the atmosphere; in summer, the halocline insulates the bottom water masses from the surface waters. In the BSZ of the Buor-Khaya Bay (the Laptev Sea), even hydrogen sulfide has been found in certain years and these conditions negatively affect the benthic community (Sidorov and Gukov, 1992). Generally, the water masses accumulate in small pits, underwater valleys, and other seabed depressions where advective ventilation is suppressed. They are not really stagnant water masses. When the water masses overfill the seabed depressions, they spread according to their density and can penetrate into different structural zones. Oceanographic transects across underwater valleys in the Laptev seas showed that, as a rule, the water masses spread toward the shelf edge along the eastern slopes of the valleys as a result of the Earth's rotation (Fig. 28.4). Two different water masses can be found at the same depth in the Bottom Structural Zone in the underwater valley. They spread in opposite directions. The data obtained during the Russian-German multidisciplinary expedition TRANSDRIFT-V in the Laptev Sea in the summer 1998 (Kassens et al., 1998) allowed us to trace the stagnant bottom water masses from the region of their formation to the continental slope (Fig. 28.5). Strikingly, there is a possibility of upwelling of these nutrient rich water masses near the shelf break. According to their density, the bottom water masses first rise to the Intermediate Structural Zone and then to the Surface Structural Zone where physical, chemical, and biological properties of the water masses change rapidly. The remains of these nutrient rich bottom water masses, after such transformation, serve as an additional source of nutrients for phytoplankton in the ice marginal zone where nutrients are completely consumed in summer.

In the East-Siberian Sea, oxygen-depleted bottom water masses also settle in depressions on the sea floor. However, the mechanism of their formation has not been adequately studied yet. It is possible that the organic matter that consumes the bottom-layer dissolved oxygen enters the sea from the Pacific Ocean through the Chuckhi Sea or it is produced in large quantities at the shelf and at the edge of the drift ice. Bottom water masses of this type are denser than the stagnant bottom water masses in the Laptev Sea. They spread from the regions of their formation and penetrate into the Intermediate Structural Zone of the Canadian and Makarov Basins as a part of a very complex assembly of the Pacific waters. Physical, chemical and biological properties of the Pacific water masses are preserved in the ISZ for a long time. That allows tracing them from the Chukchi Sea up to the Fram Strait (Rusanov et al., 1979, Jones et al., 1991, Jones et al., 1998).

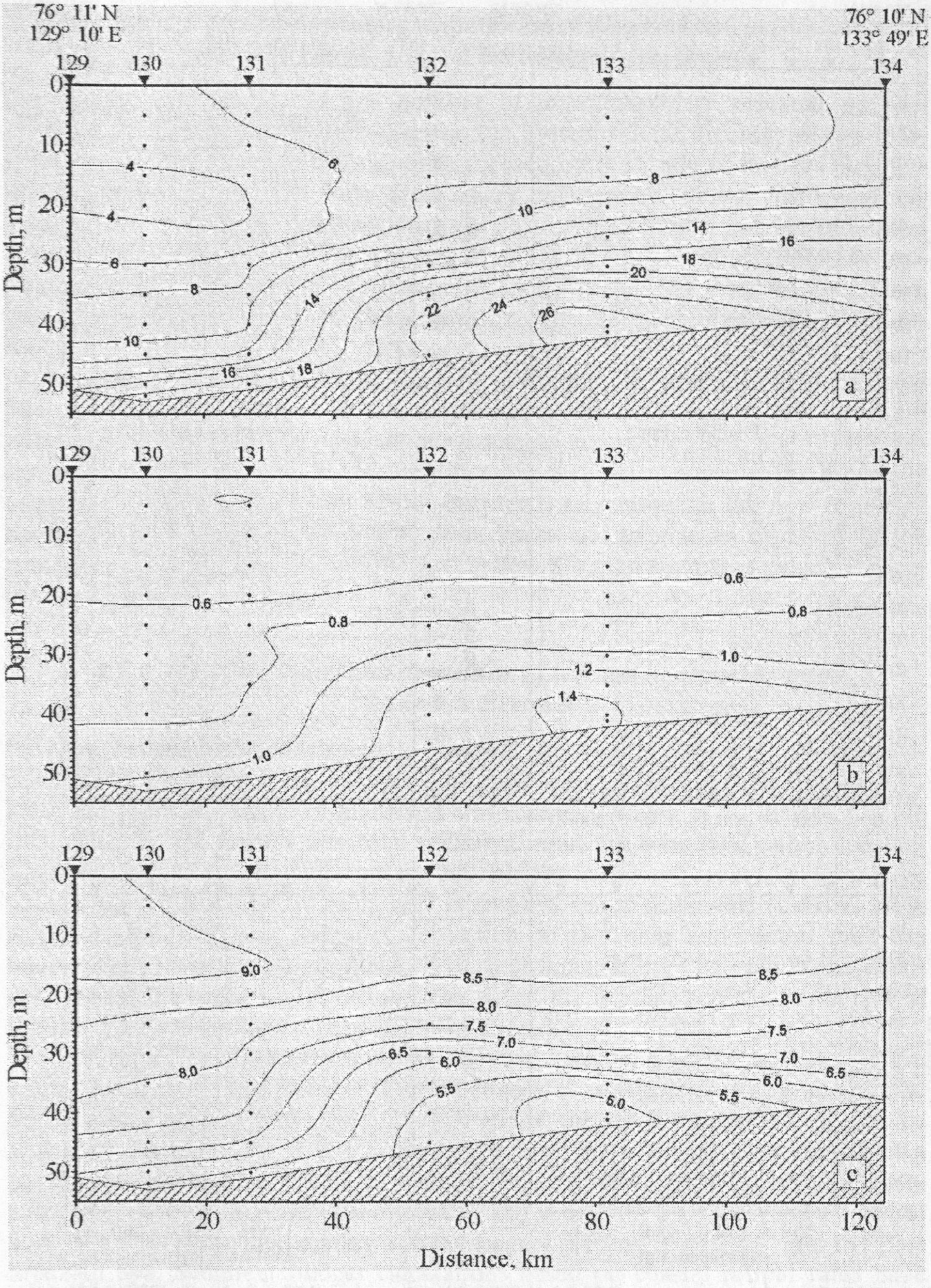

Figure 28.4 Silicate (μmol l^{-1}) (a), phosphate (μmol l^{-1}) (b), and oxygen (ml l^{-1}) distributions in the transect across the Lena underwater valley in the Laptev Sea. RV Polarstern, RK14/1b, 10–11 September 1998. High nutrient concentrations and low oxygen concentrations near the bottom indicate a location of the stagnant bottom water masses.

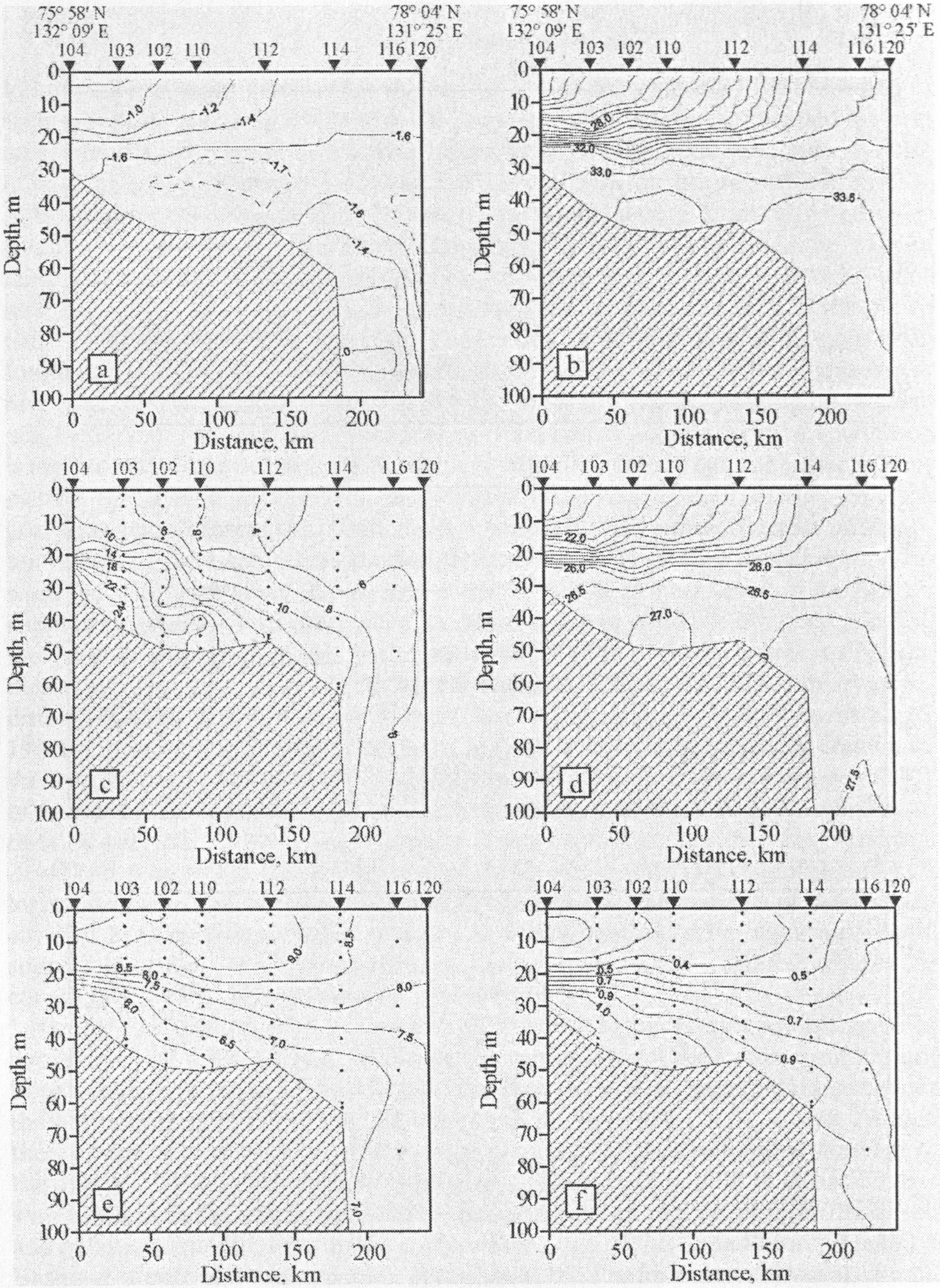

Figure 28.5 Potential temperature (°C) (a), salinity (b), silicate (μmol l^{-1}) (c), density (SIGMAT) (d), oxygen (ml l^{-1}) (e), and phosphate (μmol l^{-1}) (f) distributions in the transect across the continental slope in the Laptev Sea. RV Polarstern, ARK14/1b, 05–08 September 1998.

4. Sources and present-day transport pathways of dissolved and particulate matter on the Laptev Sea and East Siberian Sea shelves

During the last few decades a number of interdisciplinary research projects (SPASIBA, Laptev Sea System, Laptev Sea System - 2000; Ecology of the Marginal Seas of the Eurasian Arctic) have focused on the study of modern environmental processes and the Late Quaternary paleoenvironmental history of the Laptev Sea. Overviews of the results have been published in a number of articles and books (Martin et al., 1993, Kassens et al., 1995; Kassens et al., 1999). In contrast only little information has been published for the East Siberian Sea. Thus, this chapter focuses mainly on the scientific results that were obtained in the Laptev Sea.

Recently published articles on modern environmental processes in the Laptev Sea were mainly addressed to two major issues: (1) the transport processes and pathways of dissolved and particulate substances across the shelf, and (2) the importance of shelf processes for the modification of chemical constituents, especially organic carbon. The main aim of this chapter is to summarize the new results of the scientific research connected to these issues and to give an overview of the transport processes that are unique for shallow Siberian shelf seas, which are ice-covered for nearly ten months a year.

4.1. Input, transport and deposition of sediments, organic carbon and trace elements

Paleoenvironmental reconstructions revealed that the modern depositional environment of the Laptev Sea was probably established no earlier than 5000 yr B.P., after the Holocene sea level highstand was reached (Bauch et al., 2001a). On the inner shelf of the Laptev Sea total sediment input has remained rather constant since about 4000 yr B.P. (Bauch et al., 2001b). The inundated areas now form large shoals that are covered by relict and palimpsest sandy sediments (Gukov, 1999; Klenova, 1962). Recent sediment deposition on the inner and central shelf has been mainly connected to depressions in shelf topography. But even in the depocenter near the major outlet of the Lena River, the average sedimentation rate of the last 5 ka was not higher than 30 cm/ky (Bauch et al., 2001b).

Modern sedimentary environments of the Laptev and East Siberian seas are controlled by sediment input from rivers (reviewed in Gordeev, 2000), and coastal and seafloor erosion (Are, 1999). In particular, the riverine input to the Laptev and East Siberian seas is characterized by a strong seasonal variability with a maximum discharge of freshwater and sediments during June (Ivanov and Piskun, 1999; Pivovarov et al., 1999). Gordeev (2000) estimated a total riverine input of $25.1 \cdot 10^6$ t a^{-1} of suspended matter into the Laptev Sea and 33.610^6 t a^{-1} into the East Siberian Sea. Sediment budget calculations based on coastal retreat rates have shown that sediment input due to shore erosion can exceed 5010^6 t a^{-1} (Rachold et al., 2000).

Environmental forcing factors, i.e. atmospheric circulation, sea ice cover and river runoff, mainly affect the shallow water environment of the Laptev Sea. Especially the predominance of cyclonic or anticyclonic atmospheric circulation over the Arctic influences the current system and the distribution of river runoff on the shelf (Proshutinsky and Johnson, 2001). As a consequence the transport of sediments and the sedimentation processes are also strongly affected by different regimes of atmospheric circulation and ice cover. New data show that this effect starts as soon as the Laptev Sea flow polynya opens up during winter (Dmitrenko et al., 2001). New long-term measurements with bottom-moored instruments provide strong evidence for the assumption that modern shelf sediment transport is mainly wind-forced and connected to the N-S running submarine valleys on the shelf of the eastern Laptev Sea (Wegner et al. 2003; Wegner et al., accepted). In these submarine valleys suspended sediments are transported in a distinct bottom nepheloid layer, a layer of increased suspended matter concentration (SPM) with up to 12 m thickness, which is strongly influenced by the prevailing atmospheric circulation and the ice cover (Burenkov et al., 1997; Dmitrenko et al., 2001; Wegner et al., 2003). Calculations of the net horizontal sediment flux during the ice-free period revealed that the main transport within the bottom nepheloid layer in the submarine valleys is directed towards the inner shelf (Wegner et al., 2003) (Fig. 28.6). With respect to the sediment export from the eastern Laptev Sea shelf into the deep Arctic Ocean, Wegner et al. (accepted) assume that during the ice-free period most of the material derived from riverine input is trapped within a quasi-estuarine circulation system. This pattern of sediment transport might also explain the low average sedimentation rates that were observed on the outer shelf and the slope of the Laptev Sea (<10 cm/ky).

If the net sediment transport in the bottom nepheloid layer is directed towards the central and inner shelf and if we further take into account that large areas of the Laptev Sea are covered by relict sediments and lag deposits (Viscosi-Shirley et al., 2003b) with no present-day sediment deposition, we can draw the conclusion that the sediment input into the Laptev Sea is not balanced by sediment deposition on the shelf and long-range export through the water column to the Arctic basins. This discrepancy in sediment budgets may be explained by an eastward sediment transport to the East Siberian Sea that follows the Siberian Coastal Current (Viscosi-Shirley et al., 2003b) and a long-range transport of sediments by sea ice (Wegner et al., accepted).

Evidence has accumulated over the past two decades demonstrating that the entrainment of sediments into sea ice is a common phenomenon on the shallow Siberian shelves (Reimnitz, 1993; Eicken et al., 1997). It was shown that even under calm weather conditions, the freeze-up during October seems to be an important time period for sediment transport by sea ice from the shallow shelf areas of the Laptev Sea towards the Arctic Basin (Lindemann et al., 1999). Combining field measurements, remote sensing and numerical modelling, Eicken et al. (2000) could identify the shallow shelf near the New Siberian Islands as a key site for ice entrainment and a basin-wide dispersal of sediments by sea ice. They documented a total ice-bound sediment export of 18.510^6 t for one entrainment event in 1994/95. Another possible mechanism for the formation of sediment-laden sea ice is the resuspension of fine-grained bottom sediments in the polynya area and the subsequent entrainment of these sediments into the newly forming ice (Pfirman et al., 1990; Nürnberg et al., 1994; Rigor and Colony, 1997, Eidsvik, 2000). Recent studies have shown that the Laptev Sea is one of the major source areas for sea ice in the transpolar drift system (Rigor and Colony, 1997; Alexandrov, et al., 2000) and a center of sediment entrainment by ice (Pfirman et al., 1990; Darby, 2003). However, the general idea that suspension freezing during sea ice formation in the winter polynya is the dominant sediment entrainment process in the Laptev Sea is in conflict with the field observations of Dmitrenko et al. (2001) who have shown that even during winter the strong density stratification of the water column especially in the eastern Laptev Sea prevents convection to penetrate down to the seafloor. Thus resuspension of fine-grained bottom sediments accompanied by suspension freezing beneath the polynya is unlikely to occur in the eastern Laptev Sea. This supports the hypothesis that the fall freeze-up (October) might also be an important and yet underestimated period for the formation and export of sediment-laden sea ice.

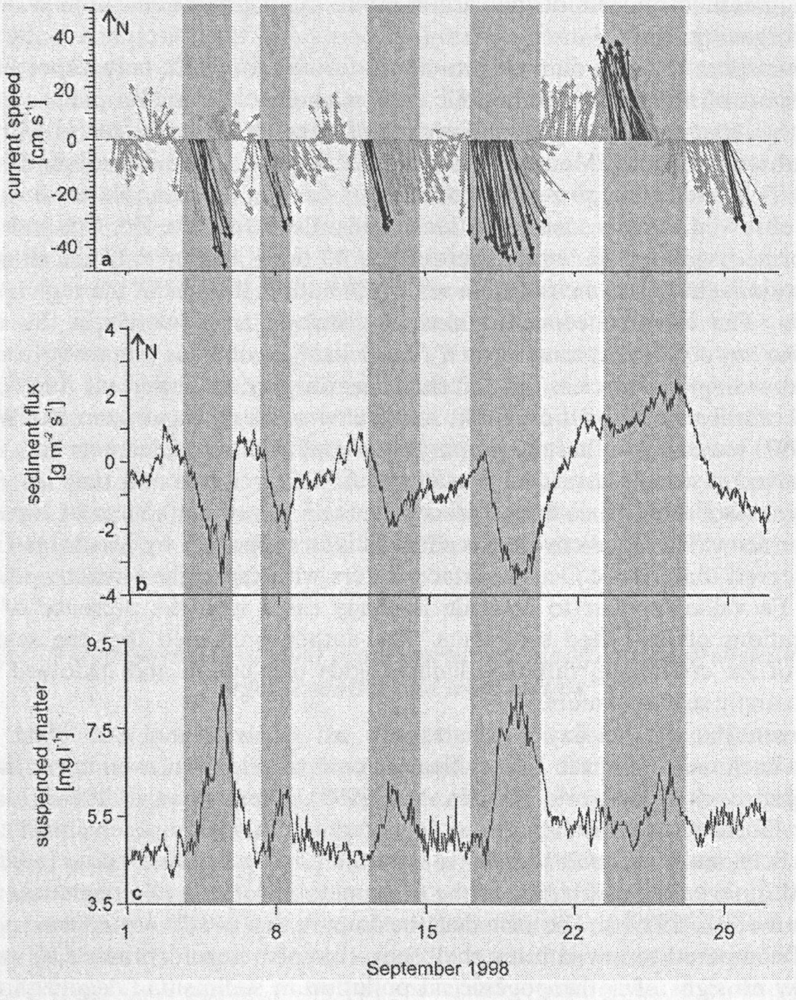

Figure 28.6 Bottom current speed (a), with the black vectors indicating current speeds exceeding the threshold velocity for incipient grain motion, sediment flux (b), and suspended matter concentration (c) at 4 m above bottom at a bottom-mooring station (75°09' N, 130°50' E) in the Eastern Lena Valley on the Laptev Sea shelf during September 1998. The grey bars indicate periods of wind-induced bottom currents.

The role of sea ice as a transport vehicle for the basin wide dispersal of sediments is also one of the unknown key characteristics of the Laptev Sea and East Siberian Sea budget of organic carbon. The average riverine input of total organic carbon (TOC) is about 5.1610^6 t a^{-1} in the Laptev Sea and 1.7810^6 t a^{-1} in the East Siberian Sea (Gordeev, 2000). The contribution of coastal erosion to the input of organic carbon is still unknown. Biomarker studies (Peulvé et al., 1996; Fahl and Stein, 1999, Bauch et al., 1999) and maceral analysis (Boucsein and Stein, 2000) of sediments and suspended matter from the Laptev Sea have shown that the particulate organic carbon is predominantly of terrigenous origin (Kattner et al., 1999). Although recent studies have accumulated new information about various sources and pathways of organic carbon in arctic shelf seas, we are still far away from establishing detailed budgets of the carbon input, cycling and deposition of allochthonous organic carbon.

The incorporation of sediments into newly formed ice is not only important for the transport of sediments and organic carbon. Arctic sea ice also plays a crucial role for the large-scale transport and cycling of trace elements (Rigor and Colony, 1997) and radionuclides (Meese et al., 1997). Within the framework of an interdisciplinary field study of freeze-up processes in the Laptev Sea, Hölemann et al. (1999b) observed that the concentrations of dissolved Mn, Fe, Zn, Cd, and Pb in newly formed sediment-laden ice were up to 40 times higher than the dissolved concentrations that were measured in sea water and freshwater in the region of ice formation. The elevated concentrations of dissolved trace metals in the newly formed ice were probably caused by a remobilization of trace elements from the ice-rafted sediment particles. This mechanism can play an important role for the dispersal of trace elements through the arctic environment. As an example, Winter et al. (1997) have shown that the primary source of rare earth elements and Pb for the dissolved reservoir in arctic seawater is not river water and that ice rafted debris, by dissolution or exchange processes, is an important source of trace elements for seawater in ice-covered oceans. This is supported by Measures (1999) who observed that Arctic Ocean surface waters with the highest reactive Al and reactive Fe values appear to coincide in many cases with the presence of high concentrations of ice-rafted sediments. The author presumed that the seasonal melting of ice containing rafted sediments adds particulate and dissolved trace metals to arctic surface waters.

However, the present-day concentrations of dissolved and particulate trace elements in the waters of the Laptev Sea are comparable to or even lower than in most major rivers of the world (Martin et al., 1993; Hölemann et al., 1995; Guieu et al., 1996; Gordeev, 2000; Hölemann et al., accepted). Also, the geochemical analysis of surficial and ice-bound sediments from the Laptev Sea showed no indication of an anthropogenic perturbation of the trace metal inventory (Nolting et al., 1996; Hölemann et al., 1999b). The fact that the Laptev Sea is still a pristine environment - if compared to low-latitude shelf seas - has also been confirmed by studies that show no signs of anthropogenic oil pollution in sediments (Zegouagh et al, 1998), only low levels of polychlorinated biphenyls and chlorinated pesticides (Utschakovski, 1998), and also low levels of dissolved and particulate anthropogenic radionuclides (Pavlov et al., 1999).

4.2. *Geochemical and geological characteristics of surficial sediments as indicators for modern transport processes*

Geochemical and mineralogical characteristics of surficial sediments indicate that the present-day sedimentary regime on the Laptev Sea shelf is dominated by the fluvial input of the rivers draining the Siberian platform (Hölemann et al, 1999b; Wahsner et al., 1999; Viscosi-Shirley et al., 2003a; Viscosy-Shirley et al., 2003b). The sediment input by the rivers Lena in the eastern and Khatanga in the western Laptev Sea especially control the mineralogical and geochemical compositions of surficial sediments. The main geochemical difference between both rivers is caused by the differing geology of the hinterland. The Khatanga River, like the Yenisei River, drains a plateau with basalts. Basalts have a different mineralogical and geochemical composition if compared to average crustal abundances (Rachold, 1999; Eisenhauer et al., 1999). The Lena River drains an area with different sedimentary, metamorphic, and magmatic units. Thus the geochemical composition of sediments from the Lena River resembles a more or less average crustal signal.

Interdisciplinary studies using the difference between both river systems as an indicator for transport pathways pointed out that the suspended matter discharge from the Lena River is mainly deposited on the southeastern Laptev Sea shelf (Silverberg, 1972; Wahsner et al., 1999; Lisitzyn, 1996; Hölemann et al., 1999a; Peregovich et al., 1999; Fahl et al., 2001; Viscosi-Shirley et al., 2003a). This conclusion is also supported by the relative abundance pattern of freshwater diatoms (Cremer, 1999) and chlorococcalean algae (Kunz-Pirrung, 2001) in surficial sediments, which also point to the conclusion that the deposition of riverine material is highest in the southeastern Laptev Sea near the delta of the Lena River. On the other hand, as a result of the strong density stratification of the water column of the Laptev Sea the riverine suspended matter is dispersed above the pycnocline over large areas of the eastern Laptev Sea shelf, especially during the high discharge period in June (Létoille et al., 1993; Burenkov et al., 1997; Pivovarov et al., 1999; Wegner et al., accepted).

4.3. The importance of shelf processes for the modification of dissolved organic matter and trace metals

River runoff widely determines the signatures of dissolved trace elements and dissolved organic matter (DOM) in the Laptev Sea. But only few studies have focused on the biogeochemical and sedimentological processes in the mixing zone of the Lena River waters and the Laptev Sea waters (Guieu et al., 1996; Garnier et al., 1996; Cauwet and Sidorov, 1996; Kattner et al., 1999; Levasseur et al., 2000; Hölemann et al., accepted). Cauwet and Sidorov (1996), Kattner et al. (1999) and Dittmar and Kattner (2003) pointed out that the distribution of dissolved organic carbon (DOC) in the Laptev Sea is largely controlled by conservative mixing between freshwater and marine waters. A conservative mixing was also observed for dissolved Zn (Guieu et al., 1996). All other elements showed a decrease (Fe) or a strong increase (Cu, Ni, Cd) in dissolved concentration within the mixing zone. Guieu et al. (1996) stated that this behaviour is mainly controlled by particle-dissolved phase interaction. Also, the behaviour of dissolved osmium, which rapidly decreases in the mixing zone of the Lena River, was explained by the fact that the osmium becomes adsorbed to suspended particles (Levasseur et al., 2000).

A general drawback of the studies on the mixing process in arctic seas is that the river discharge is highly variable during the year and that most of the observations were carried out during the ice-free period in the late summer, nearly two months after the high-discharge period in June. Thus, more detailed studies on the mixing behaviour of various chemical constituents should be carried out during the high-discharge period. One of the first studies on discharge and transport of trace elements during the high-discharge period was carried out by Hölemann et al. (accepted). The authors showed that in the Lena River during the spring high flow (freshet) dissolved concentrations of metals were significantly higher than those reported during the rest of the year (Fig. 28.7). The dissolved metals were transported within the Laptev Sea in an under-ice fresh water layer spreading seaward and resulting in a long-range transport without mixing processes.

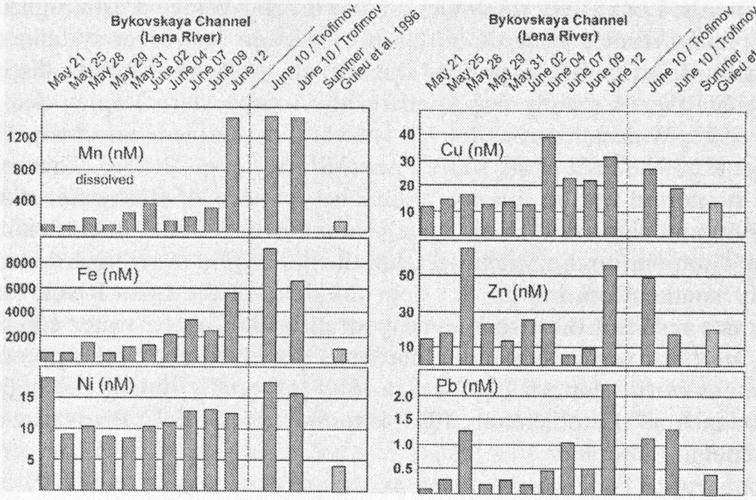

Figure 28.7 Dissolved concentrations of Mn, Fe, Ni, Cu, Zn, and Pb in the Lena River water (Bykovskaya and Trofimovskaya channels in the Lena Delta) before (21 and 25 May) and during the initial phase of the spring freshet (after May 25). The light grey bars indicate summer concentrations published by Guieu et al. (1996).

5. Recent studies of the Laptev and East-Siberian seas ecosystems

5.1. *Distribution and development of the microalgal community in the Laptev Sea kryo-pelagic system during autumnal freeze-up*

During the autumnal freeze-up period, sea ice formation in the shallow Laptev Sea results in the development of a coastal belt of fast ice and a zone of pack ice, separated from each other by a polynya. Several mechanisms such as wave pumping or scavenging by ice crystals are considered to be responsible for the incorporation of suspended matter and organisms into the newly forming ice sheet.

During the TRANSDRIFT III expedition in October 1995 (Kassens et al., 1997; Juterzenka and Knickmeier, 1999; Tuschling, 2000), samples were taken from the water column as well as various types of newly forming sea ice and analyzed for Chlorophyll *a* as an indicator of algal biomass as well as abundance and species composition of microalgae. *In situ* fluorescence measurements were carried out along two transects from the coast east of the Lena Delta towards the central Laptev Sea east of Kotelnyy. At the beginning of the sampling period, the Laptev Sea was ice-free and subsequently freezing up, to be almost entirely ice-covered at the end of October. Ice samples analyzed for Chlorophyll *a* included grease ice, nilas and young ice (≤ 25 cm). Biomass, as expressed by integrated pigment concentrations, varied considerably in the water column as well as in new and young ice samples, although the Chl *a* content increased as soon as ice floes were formed. At some stations, *in situ* fluorescence showed near-bottom maxima, which may be related to resuspension processes within the bottom nepheloid layer.

Phytoplankton community studies revealed distinct differences between the three investigated seasons. Phytoplankton blooms could already be observed at the northern stations during spring, whereas Chl *a* concentrations at the southern stations were low. Most of the phytoplankton species were euryhaline forms with an arctic-boreal distribution. In spring and summer diatoms prevailed in the area. The percentage of dinoflagelates grew higher during the seasons and peaked in autumn. A distinct correlation between the biomass of the smaller phytoplankton species, Chl *a* contents and primary production rate could be proven by means of a factor analyses. The influence of the river water is evident for species composition and distribution as well as biomass and production rates.

5.2. *Zooplankton communities in the Laptev Sea*

The distribution and population structure of zooplankton (abundance, biomass, ontogenetic stages) in the Laptev Sea were studied during the Russian-German TRANSDRIFT I expedition in August/September 1993 and during TRANSDRIFT III in October 1995 (Kassens and Karpiy, 1994; Kassens et al., 1997). In late summer 1993 and autumn 1995 a total of 42 zooplankton species/taxa were identified. Copepods contributed 17 species (calanoids, cyclopoids, poecilostomatoids, harpacticoids). Other crustacean taxa were amphipods, decapods, ostracods, mysids and cumaceans. Additional taxa included hydrozoans, ctenophores, appendicularians as well as juvenile stages of polychaetes and echinoderms (Kosobokova et al., 1998). Both expeditions showed maximum abundances in the northeast of the Lena Delta. This zooplankton was dominated by *Drepanopus bungei, Acartia* sp. and *Limnocalanus grimaldii. D. bungei* was also the most important biomass species in this area. Other areas of the investigated region exhibited a high local variability in abundance and biomass. Multivariate analyses separated three main clusters for the zooplankton in late summer 1993 (provinces *Southeast, Northeast* and *Northwest*), while two major clusters were distinguished for autumn 1995 (provinces *East* and *West*). In conclusion, the results demonstrate the strong impact of abiotic factors on the zooplankton communities in this unique ecosystem.

5.3. *Distribution and ecology of selected Zooplankton species*

The distribution, abundance and composition of smaller zooplankton species has been investigated and discussed within the context of main abiotic factors. Samples have been taken in August/September 1999. Overall abundances have been high in the eastern Laptev Sea but exhibited variations of 815 individuals m^{-3} and 9,177 m^{-3} near the Lena River mouth. Biomasses were highest in the south western part of the Laptev Sea (25.3 mg dry mass m^{-3}) and lowest in the east (1.6 mg dry mass m^{-3}). This discrepancy in high abundances but low biomasses in the east is due to smaller neritic species as *Drepanopus bungei, Pseudocalanus major* and *Acartia longiremi,* whereas in the west large copepods of the genus *Calanus* prevail. It is noticeable that regionally the Laptev Sea can be highly productive. The combination and analyses of abundance, biomass and distribution of the zooplankton with hydrographical parameters such as salinity and temperature in addition to Chlorophyll *a* revealed a governing influence of the fluvial Lena waters on the distribution of the zooplankton.

Biochemical analyses helped to investigate the feeding ecology of selected zooplankton species. It is known that many organisms develop adaptations to the relatively long period of short food supply. Copepods are capable of building and storing high concentrations of wax esters or other lipids during summer when the nutrient supply is high. Copepods revealed high concentrations of wax esters, other zooplankton like amphipods, mysids or chaetognaths stored energy as triaclglycerines. Total lipid contents as well as the high concentration of wax esters pointed to a considerable accumulation of lipids already in August/September. Marker lipids revealed a diatom-dominated diet of the investigated zooplankton species. While the Calanus species seem to be mostly herbivorous, other copepods seem to have an opportunistic lifestyle.

5.4. *Benthos*

As a result of six joint expeditions to the Laptev Sea in 1993, 1994 and 1995, 150 invertebrate species were added to the known list of species from this high-Arctic region, comprising now 1235 species in total (Petryashov et al., 1999; Piepenburg and Schmid, 1997). Most of these species (987) are macrozoobenthic. The geographic distribution of macrobenthic species numbers and biomass exhibited a pronounced increase to the north up to 77 °N. In terms of biogeographic composition, Boreal-Arctic species accounted for most of the species, primarily widespread Boreal-Arctic species in the southern and central Laptev Sea at depths from 10 to 75 m and primarily Atlantic Boreal-Arctic species in the northern Laptev Sea at depths of 90 to 1100 m. Only in depths of more than 2000 m, as well as in estuarine and brackish coastal waters, Arctic forms had significant species shares. On sandy and silty bottoms, nine major communities and two trophic zones were distinguished. The distribution of species numbers, biomass and faunal composition is discussed in relation to water depth, seabed sedimentology and near-bottom water salinities. The latter are supposed to be the major environmental factors regulating the distribution and structure of macrobenthic communities. An ecological-biogeographical zonation scheme is proposed, combining the current information about the distribution of macrobenthic communities and brackish water masses (Sirenko, 1999).

The depth zonation of the communities is presumably governed by depth correlated environmental factors. The faunistic composition in the shallower part of the Laptev Sea is determined mainly by physical disturbances such as freshwater and sediment input or by direct ice scouring from anchor ice or small icebergs. Low species numbers and diversity indicate the existence of physical disturbances. Communities of the intermediate and deeper parts seem to be influenced mainly by sediment structure and hydrographical conditions. The more estuarine conditions in the south with low salinity and high sediment loaded waters supported mostly detritovorous bivalves. It is assumed that high sedimentation rates affect the existence of suspension-feeding organisms. Highest diversities were found in areas where two water masses meet.

The epibenthic megafauna of the high-Arctic Laptev Sea shelf was investigated in August/September 1993 and October 1995 (Kassens et al., 1997; Piepenburg and Schmid, 1997). At 13 stations in water depths between 14 and 45 m, a series of 5 to 29 photographs, each depicting about 1 m^2 of the seabed, was taken to assess epifaunal distribution patterns and abundances. Furthermore, the population biomass of dominant brittle stars was estimated by combining abundance values with size-mass relationships and size frequencies established by measuring specimens on scaled photographs. A total of 13 epibenthic species were identified. Species numbers per station were low, ranging between one and six. Total epibenthic abundances, averaging 173.7 ind m^{-2}, ranged considerably between 0.1 and 579.5 ind m^{-2}. Except for some stations on shallow shelf banks < 20 m that were characterized by bottom-water salinities < 30 due to fluvial dilution, the brittle star *Ophiocten sericeum* dominated the megabenthic shelf assemblages. At the flanks of sunken Pleistocene river valleys in depths > 30 m, they reached maximum density and biomass values of 566 ind m^{-2} and 1.5 g ash-free dry mass m^{-2}, respectively. At some sites, the brittle star *Ophiura sarsi* occurred in abundances of up to 35 ind m^{-2} and attained a biomass of 3.8 g AFDM m^{-2}. Of local importance were the sea cucumber *Myriotrochus rinckii* (up to 70 ind m^{-2}) and the bivalve *Arctinula greenlandica* (up to 33 ind m^{-2}). All other species were recorded with distinctly lower densities (≤ 1 ind m^{-2}). Gross estimates of population respiration and production of dominant brittle stars suggest that their organic carbon demand may amount to a pooled average of about 4 mg C m^{-2} d^{-1} in the Laptev Sea, locally even to a maximum of > 10 mg C m^{-2} d^{-1}. This finding indicates that a substantial portion of the energy flow in this high-Arctic shelf ecosystem may be channelled through dense brittle star assemblages (Piepenburg, 2000).

Due to its remoteness and 8-month ice coverage, knowledge has been limited on ecology, turnover processes, coupling of marine communities in the Laptev Sea. Taxonomic and zoogeographical questions have been addressed and (several hundred benthic and zooplankton species could be identified) abundance and biomass composition wherever possible gave valuable insights about community structure and distribution patterns. Community structure analysis revealed three distinct faunal provinces in the western, northwestern and the Lena Delta region. Those provinces showed in the phytoplankton and zooplankton communities as well as in the benthos giving a first clue about a tight benthic-pelagic coupling (see also above chapters). In a second step, process-oriented studies have been carried out to investigate biological carbon sources as phytoplankton production, its transformation in the pelagial, and degradation in the benthos. High chlorophyll *a* contents in the sediment hint to rapid sinking of phytoplankton blooms to the benthos making high quality food available for benthic organisms as well. Already early in the year phytoplankton production is possible in the polynya region which is dividing the fast and sea ice from east to west app. 200 km north of the Lena Delta. Hence this year round ice-free water is very important for all biological processes.

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