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Russian and German Scientists Explore the Arctic's Laptev Sea and Its Climate System

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River runoff into the Laptev Sea in the Siberian Arctic (Figure 1) causes dramatic environmental changes in the sea, influencing not only the entire Arctic climate but global climate as well, a 4-year study suggests. The study, known as the Laptev Sea System program, was conducted by a joint group of Russian and German scientists. It marked the first time a major comprehensive research program looked at the extreme environmental system of the Laptev Sea, addressing both oceanic and terrestrial processes.

The work focused on mechanisms involved in past and ongoing climate variations in the Laptev Sea region (Figure 2) with an emphasis on the interaction between the sea and the Lena River in the summer, autumn, and spring. In the summer, river water spreads over the sea as a low-salinity surface layer carrying much of the river's suspended load. In the fall, during ice formation, the low-salinity layer controls the fast-ice edge and, consequently, the Laptev Sea polynya or ice clearing.

However, the most dynamic interaction occurs in the spring, researchers found, as river ice breaks up. This results in a sudden influx into the cold, ice-covered sea of relatively warm freshwater and high amounts of dissolved and particulate matter, drastically altering the environment. Though less than a month long, this period of time is also of great importance for the formation of underwater ice in the sea and for sediment dynamics around the Lena Delta, according to the study.

The findings were the result of extensive multidisciplinary studies—funded by the German and Russian Ministries for Sciences and Technology—of the atmosphere, the ice, the water column, and the seafloor on the Laptev Sea Shelf and its hinterland. In addition to the land and marine expeditions (Figure 3), workshops were conducted and scientists were exchanged.

In the context of growing concerns about the response of the Arctic regions to environmental change and its impact on global climate, the Laptev Sea and its Siberian hinterland are of particular interest. River discharge into the Laptev Sea constitutes a key source for the Arctic halocline's freshwater budget, and the shallow Laptev Sea Shelf is a major ice-production area, linking the Siberian shelves to the Arctic Ocean and the Nordic seas.

For more information, contact Secretariate, Laptev Sea System Program, GEOMAR Research Center for Marine Geosciences, Wischhofstrasse 1-4, 24148 Kiel, GERMANY; (http://www.geomar.de/sci_dpmt/paloz/laptev/proj_laptev.html), or the State Research Center of the Russian Federation, Arctic and Antarctic Research Institute, 38 Bering St., St. Petersburg, 199397, RUSSIA.

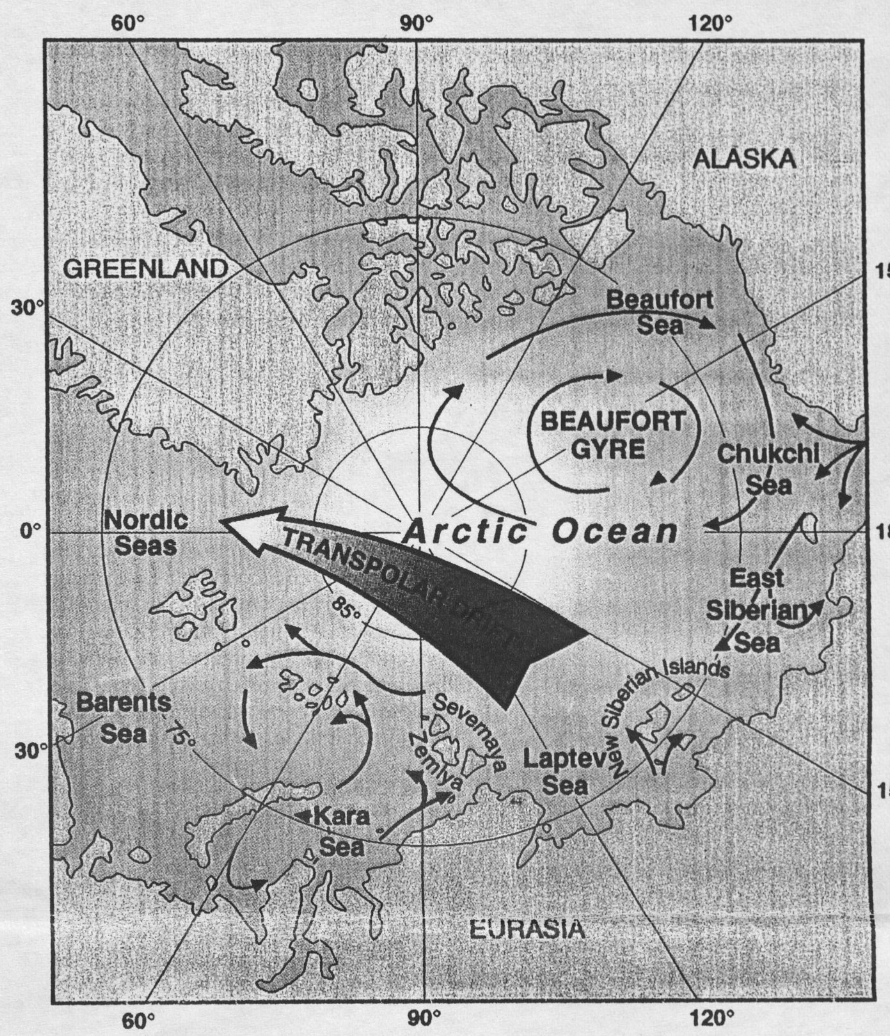

Fig. 1. Major sea-ice drift paths in the Arctic Ocean. The Laptev Sea, at the tail of the Transpolar Drift, is considered a major ice factory for the Arctic Ocean.

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 (Figure 4). 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 project collected data between 1992 and 1996. This time period 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 melt due to advection of warm air masses from central Siberia. As a result of advective heat transport and storage of solar short-wave energy in the water column, fall freeze-up was 2 weeks later than the long-

Laptev Sea (cont. on page 322)

Ozone Layer Is on Slow Road to Recovery, New Science Assessment Indicates

The good news, according to a new report about ozone depletion, is that the ozone layer will recover in 50 years—if parties to the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer fully adhere to the treaty, and if other conditions that could affect the atmosphere remain stable.

The "Scientific Assessment of Ozone Depletion: 1998," a report prepared by the scientific assessment panel of the Montreal Protocol, states, "The stratospheric abundance of halogenated ozone-depleting substances is expected to return to its pre-1980 (that is, "unperturbed") level of 2 ppb chlorine equivalent by about 2050 assuming full compliance with the Montreal Protocol and its Amendments and Adjustments."

The maximum ozone depletion is expected to occur within the next 2 decades, according to the report—although unambiguous identification and evidence for the recovery of the ozone layer could take longer, and the most vulnerable period for ozone depletion will be extended into the coming decades.

In addition, the report states that ozone depletion and climate protection are interconnected, and that recovery in the Arctic region could be delayed by the cooling of the lower stratosphere through changes in greenhouse gases. The report also notes increased levels of UV-B (ultraviolet B) radiation (280-315 or 320 nm), and a strengthening of the understanding of the inverse correlation between increasing surface UV-B irradiance and decreasing ozone column amounts.

The treaty already has spared the world from a frightening future during which levels of ozone depletion could have risen 10 times higher than currently forecast, the report continues. The United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) released the executive summary on June 22; the full report will be released later this year.

"The good news is the future. The vulnerable story is now," says Daniel Albritton, cochair of the scientific assessment panel. He adds that "it's the first report that shows a downward trend in the total set of ozone-depleting compounds in the lowest part of the atmosphere."

The science panel, along with the environmental effects panel and technology and economics panel, provide major quadrennial reports to the parties to the Montreal Protocol, and all three panels will issue their reports later this year.

Other major findings of the report include:

- Natural events such as major volcanic eruptions could enhance the loss from ozone-depleting chemicals. Potential future increases or decreases in other gases important in ozone chemistry (such as nitrous oxide, methane, and water vapor) and climate change also will influence the recovery of the ozone layer.
- The combined abundance of ozone-depleting compounds in the troposphere peaked around 1994 and is now slowly declining. The combined abundance of chlorine and bromine in the stratosphere is expected to peak before the year 2000, which takes into account the time for gases to rise higher into the atmosphere.
- The link between the long-term build-up of chlorine and the decline of ozone in the upper stratosphere has been firmly established.
- The austral springtime Antarctic ozone hole continues unabated, with ozone within the Antarctic lower stratosphere during springtime nearly completely destroyed.
- Methyl bromide may play less of a role as an ozone-depleting compound than previously estimated, according to new information about ocean removal, soil uptake, and other factors.

In addition, Albritton says the report describes the effect of global warming on ozone depletion as "an area of very active research."

According to David Rind, a climate research scientist with NASA's Goddard Institute for Space Studies in New York, "global warming is a new component in intensifying the Arctic ozone hole." He says climatic modeling indicates that global warming can allow a buildup of chlorine above the Arctic, which in turn "is a recipe for getting an ozone hole."

The science report also suggests that earlier elimination or phase-out of some chemicals could lead to somewhat speedier remediation.

Stephen Andersen, cochair of the technology and economics panel, says the science report also draws attention to the remaining major sources of ozone-depleting chemicals. "Where is the big enchilada? It's the developing countries. It's not MDIs [metered dose inhalers]. It's not essential uses," he says, referring to the need to focus more on excess production in certain countries, rather than on some usages allowed under the treaty for essential purposes, such as MDIs used for treating asthma and other medical conditions.

Albritton adds that while the science report purposely conveys information rather than concern, he is eager to read the environmental effects panel's upcoming findings about the consequences of ozone depletion.

Edward De Fabo, a research professor of dermatology at George Washington University in Washington, D.C., and a reviewer for the upcoming health panel assessment, calls the scientific assessment "almost surreal." He says the report heralds the success of the protocol in reducing ozone-depleting chemicals and avoiding a global catastrophe, but also states that UV-B levels will continue well above pre-1980 baseline levels for 50 more years, if there are no complications.

"What will increased levels of radiation do to the biosphere and the inhabitants of the biosphere?" he asks.

De Fabo, who chairs UV radiation impact committees of the International Council of Scientific Unions and the International Arctic Science Committee, says ultraviolet radiation is absorbed by many important biomolecules in cells, including DNA, proteins, and urocanic acid. He says the implications of increased UV-B radiation to biomolecules in the human body and in the biosphere are largely unknown. He says the biomolecules are wavelength-dependent and have evolved under fairly stable levels of ozone. The impacts to humans, he says, could include increased cases of skin cancer and cataracts. Other organisms also could be severely

Ozone Layer (cont. on page 318)

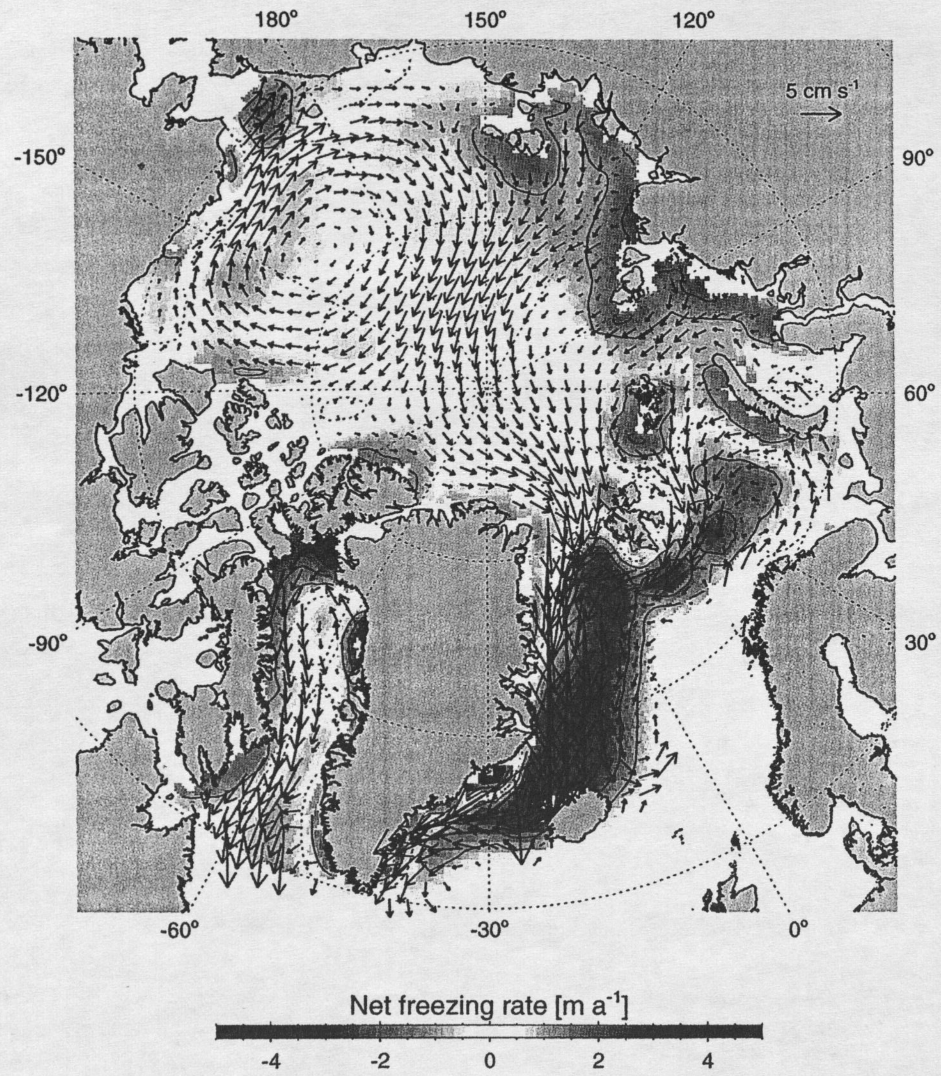

Fig. 4. Average ice velocity field and net-ice production rates for the period from 1979 to 1995, as predicted by a large-scale, dynamic-thermodynamic sea ice model. Note the high net production in the Laptev Sea, with ice being transported by the Transpolar Drift to the Nordic Seas within 2 to 3 years

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 investigations (for instance, on Sr isotope) and mineralogical investigations (on heavy and clay minerals) 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, the Laptev Sea Shelf, 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 seafloor sediments in the western Laptev Sea can be distinguished from those in the eastern Laptev Sea by the dominance of pyroxene (in contrast to amphibole-rich sediments in the eastern part), higher amounts of the clay mineral smectite, and significantly lower $^{87}Sr/^{86}Sr$ isotope ratios. In addition, seafloor sediments of the Arctic Ocean indicate that Sr isotope ratios and heavy mineral assemblages can be used to identify sediment pathways from central Siberia to the Arctic Ocean.

The Lena River is considered to be the main sediment source for the Laptev Sea. Measurements of suspended sediment transport were made during the past decades about 150 km upstream from the Lena Delta. But the quantitative evaluations of suspended sediment discharge made by different investigators using the same datasets 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 are difficult to estimate. However, data on suspended sediments along a transect from the southeastern Lena Delta to the Laptev Sea showed no concentration gradient during the onset of river breakup 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 because of erosion are of the same order as data on sediment discharge of the rivers feeding the Laptev Sea [*Are*, 1996]. Reliable estimates for land-ocean sediment transport will be a 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. In general, 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 (for example, long-chain n-alkanes and wax esters, light $\delta^{13}C_{org}$) 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 (for instance, 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 g C cm^{-2} ky^{-1}, decreasing to 0.02 g C cm^{-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 offshore.

The Laptev Sea Since the Last Glacial

Paleoceanographic investigations based on radiocarbon datings (accelerator mass spectrometry ^{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 because of low global sea level. Sedimentation was mainly governed by 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 $\delta^{18}O$ at 11,000 years B.P., which seems to correlate in age with the onset of the Younger Dryas cold spell. A major change towards marine conditions on the shelf because of rising sea level is noted at 9500 years B.P. with increasing $\delta^{13}C$ 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 (≥70 m water depth) are marked by an abrupt decrease in sedimentation rates at 9000 years B.P. In the inner-shelf areas, the sea level continued to rise until flooding of the shelf terminated near 6000 years B.P., accompanied by a major drop in sedimentation rates between paleodepth 30 to 50 m.

The later Holocene (since 6000 years B.P.) situation appears to be rather stable in that sedimentation rates vary between 1.2 mm per year in the Lena Valley and 0.1 mm per year in the Khatanga Valley. This is about 5 times lower than at the continental slope. Freshwater diatoms and chlorophycean algae dominate the eastern shelf, whereas marine diatoms and dinoflagelate cysts dominate the western parts of the shelf. Ice algae species become more abundant particularly towards the north, along the average summer ice edge. Grounding ice contributes considerably to sediment transport on the Laptev Sea Shelf. Side-scan sonar records and 30 kHz echograms indicate that at some locations (for example, the southwest of Kotelneyy Island (Figure 2) and north of the Lena Delta) sediments are disturbed as a result of grounding ice. These plough marks can be as deep as 10 m. 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 very low seafloor temperatures (up to -2.3°C), and ice-bonded Holocene sediments found in areas as shallow as 12 cm below the surface in the central Laptev Sea [*Romanovskii et al.*, 1997]. The impact of offshore permafrost on the environmental system is unknown and will be a primary focus during further investigations.

More detailed information about the Laptev Sea System will be published soon in *Land-Ocean Systems in the Siberian Arctic: Dynamics and History*, edited by H. Kassens, et al., to be released by Springer-Verlag this year.

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Laptev Sea (cont. from page 317)

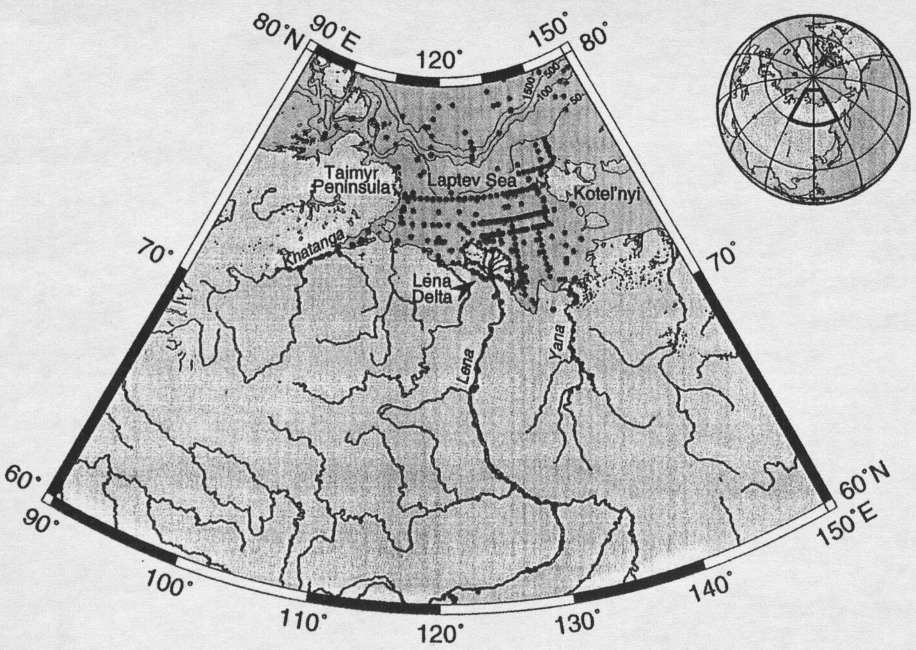

Fig. 2. Station map of the Laptev Sea System Project. For the past 4 years, a multidisciplinary working program was carried out at almost 500 stations in the Laptev Sea and along the Siberian rivers draining into the Laptev Sea.

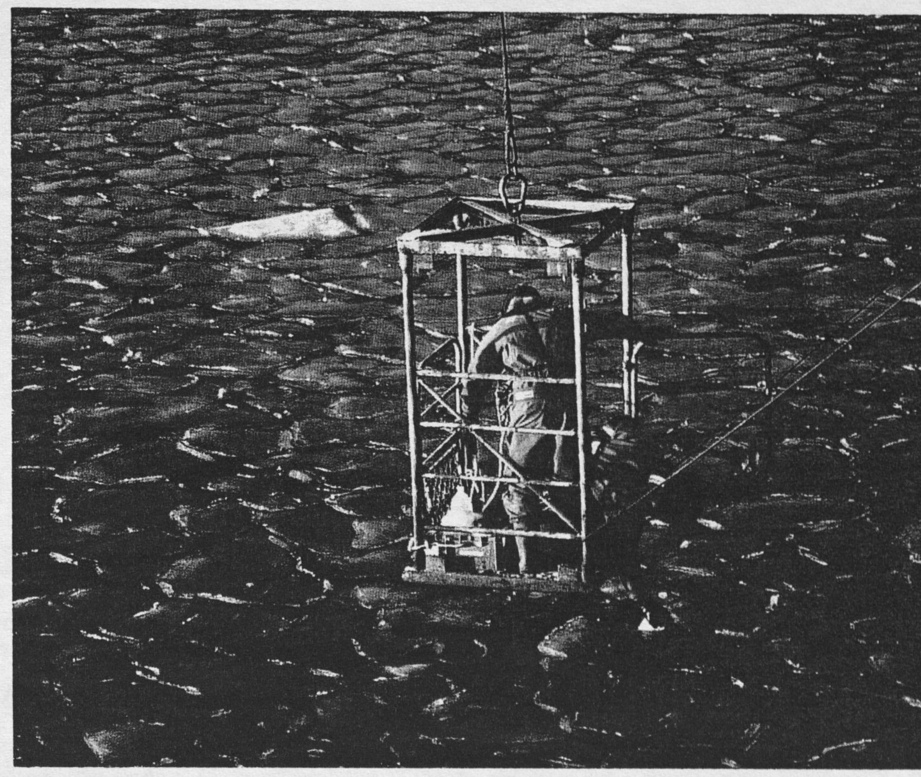

Fig. 3. Sampling of young sea-ice during freeze-up using the ice lift of Kapitan Dranitsyn in the autumn of 1995.

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, a more detailed study of the ice-circulation regime in the Laptev Sea was carried out for the period from 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 multiyear 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). Comparisons with the available buoy data showed consistent results and 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 from 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 for 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. Hydrographic surveys carried out between 1993 and 1996 were 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 (Figure 1) 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 only of importance in the near-delta regions, river discharge affects ice freeze-up considerably. 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. 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]. Given the variability on decadal and, in particular, on longer timescales (as suggested by paleoceanographic studies based on foraminiferal isotopic composition), the dispersal and fate of river discharge and its impact on the ice regime are a central issue in understanding 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 in the Nordic seas. Field studies have shown that substantial amounts of sediments are entrained into sea ice growing over the broad, shallow Siberian shelves [*Eicken et al.*, 1997]. Part of this ice grows throughout the winter season in a system of coastal polynyas and flaw leads [*Dethleff et al.*, 1993]. The relative contribution of polynyas, both to total ice export and to transport of sediments, is not yet fully understood, however. These sediments are transported with the ice and released during ice melt, most of which occurs in the Greenland Sea area. A major entrainment event was identified in the eastern Laptev and western East Siberian Sea (Figure 1) 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. Work is now under way to improve these estimates and link them to the long-term perspective of Arctic sedimentation processes.

The Marine Ecosystem

Biological studies focused on the abundance and community structure of phytoplankton, zooplankton, and benthos as well as on benthic life in relation to environmental changes. Three distinct faunal and floral provinces were identified by multivariate analysis in the central, the northern, and the southeastern parts 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 forming sea ice (Figure 3), 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 microfaunal 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 fauna can be abundant, but show little diversity. Except for some shallow areas (<20 m) 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 square meter in river valleys (>30 m 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. 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

Nutrients, trace elements, and chlorinated biphenyls were studied in sea ice, water column, and surface sediments of the Laptev Sea in order to trace shelf-ocean pathways of river discharge and sea ice, determine processes of ice formation, and estimate the natural and anthropogenic input into the Laptev Sea. 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 breakup, 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 breakup is the pronounced density stratification of the water column in the Laptev Sea due because of 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. Therefore possible depositional centers, although not clearly identified, are far away from the Lena Delta (Figure 2).

Another important process affecting the transport pathways of particles was studied in 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. For instance, the concentration of Fe was up to 25 times higher than its average concentration in Lena River water. Researchers suggested 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 also showed that the chemical signature can be directly related to different fluvial sources. For example, 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.

In general, dissolved and particulate heavy metals and chlorinated biphenyls in sediments, water column, and sea ice are at very

Laptev Sea (cont. on next page)

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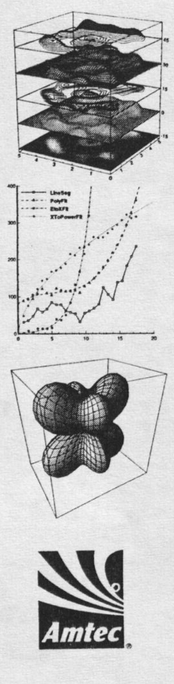

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