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Editorial

Arctic Siberian shelf environments—an introduction

1. Why study the Arctic?

Although the Arctic region is a unique environment in its own respect, as it comprises a number of very specific features which altogether form an integral part of the regional climate, the Arctic also plays a central role in the global climate system through its influence on ocean–atmosphere heat balance and circulation. It is generally accepted that temperature-related processes in the Arctic are some of the most sensitive environmental elements. Obviously, these are being considered in terms of their response to climate warming. In recent years, concern is growing about the rapidity and extent of a global change in temperature and the impact it might exert on the Arctic system in the near future (Johannessen et al., 1995; Grotefendt et al., 1998; Dickson, 1999).

The present Arctic climate is highly influenced by regional weather patterns and ocean currents. The latter play a fundamental role in the circulation of water in the oceans of the world. When warm, salty North Atlantic water reaches the cold Arctic around Greenland and Iceland, it becomes denser as it cools, thereby sinking to greater depths to become part of global deep ocean circulation (Fig. 1). The warming effect of the Norwegian Current, the northern extension of the Gulf Stream, pushes the surface ocean isotherm north of the Arctic Circle and to the edge of the sea ice. Most of the marine water in the Arctic Ocean comes from the Atlantic Ocean via Fram Strait and the Barents Sea, with some additional inflow from the Pacific through Bering Strait. The main outflow from the Arctic Ocean is along East Greenland (Fig. 1), with a minor portion flowing through the Canadian Archipelago west of Greenland.

Sea ice is the dominating surface feature of the Arctic Ocean. The total area covered by sea ice changes with season, reaching its peak in March–May and its low during August–September. The ice is in constant motion partly due to wind stress, but following in general the major ocean currents underneath (Fig. 1) and growing in thickness as it drifts along. Therefore, ice originating from the perennially covered areas in the central Arctic Ocean is several years older and considerably thicker than the ice from the marginal seas, which is newly formed every year again after the ice-free summer season.

Oceanographic studies in the Arctic Ocean have shown that a certain part of the low salinity in the near surface layer below the sea ice, the Arctic halocline, is of riverine origin (Bauch et al., 1995; Ekwurzel et al., 2001). Especially in the eastern Arctic Ocean, this connection between Eurasian rivers draining onto the Siberian shelves and the young sea ice produced there becomes evident, when looking at the circulation system that causes the ice to drift toward Fram Strait within a few years (Fig. 1).

The Arctic Ocean has a vast continental shelf. All the Eurasian marginal seas are located over this shelf, which has a width of up to 900 km off the coast of Siberia. Along the north American side, the shelf size is smaller, extending only between 50 and 100 km from the coast. A similar difference between the two continents is found in annual river runoff volumes, which is much larger due to the many more rivers located on the Siberian side (Fig. 2). In the Siberian Arctic, the severe cold climate during the long winter period causes even larger rivers to vertically freeze completely for several months. In the short summer season, thawing processes of the uppermost perma-

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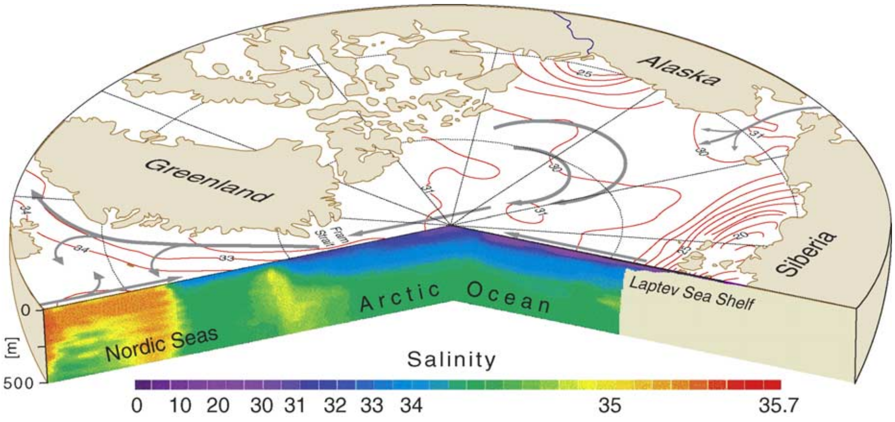

Fig. 1. Surface ocean circulation and average summer surface water salinities (1960s to 1980s) in the Arctic Ocean, its shelf seas, and in the adjacent Nordic Seas. The cross-section shows the structure of the upper 500 m revealing the characteristic low-saline halocline in the Arctic Ocean and the more saline deep convection sites in the Nordic Seas (map compiled by T. Mueller-Lupp; data from EWG, 1998).

frost fosters vast wetland areas and erosion. In fact, the character of Arctic rivers is also directly linked to the permafrost, because little water can be stored in the ground. The erratic spring flood then leads to extensive erosion along the river flow paths carrying substantial amounts of dissolved and particulate

Fig. 2. Circum-arctic configuration of major rivers and their annual freshwater contribution (km^3/year) to the Arctic Ocean (adopted from AMAP, 1998). Note that, unlike the discharge from Ob and Yenisey rivers into the semi-enclosed Kara Sea, the Lena water has open access to the eastern Arctic Ocean.

matter that eventually end up in the wide deltas and inner-shelf zones.

There are many bays and deltas on the Siberian shelves. These estuarine, semi-enclosed water bodies are important links between the terrestrial environment and the shelf because they act as natural sediment traps. Moreover, since the riverine freshwater released into these marginal seas every early summer is much warmer than the ambient cold shelf waters, it not only introduces a lot of additional heat that influences the ice cover at this time, it also leaves a strong imprint on biological life and productivity due to the low salinity. During the long winter season, which usually starts with the freezing in October, wind is the main factor that creates strains and stresses on the newly formed ice. Persistent offshore winds during this time cause patches of open water on the shelf which become areas of high energy exchange between the ocean and the atmosphere. These so-called leads or flaw polynyas often separate the pack ice on the outer shelf from the landfast ice.

Over the past decade or so, a large body of new evidence, from observation and numerical modeling, has been accumulated by scientists from many disciplines that underscore the notion of a greatly changing Arctic environment during the 20th century. A substantial portion of the Arctic climate variations can be described in terms of one or more characteristic spatial patterns (Moritz et al., 2002). One of these characterizes the oscillating nature of the Arctic atmospheric pressure regime, Arctic Oscillation (AO), which indicates a rather systematic change over the last 30 years (e.g., Thompson and Wallace, 1998; Monahan et al., 2000; Mysak, 2001) directly influencing, for instance, the spatial distribution of Arctic sea ice and water masses (Maslowski et al., 2000; Rigor et al., 2002). But in general, this pattern is part of a complex of interrelated atmospheric, oceanic, and terrestrial processes. This complex comprises several environmental variables, such as precipitation and seasonal sea-ice extent and thickness as well as ground, air and water temperature and other factors. Satellite imagery and other observational means have unveiled reducing trends in seasonal sea-ice extent and volume (e.g., Rigor et al., 2002; Serreze et al., 2003), while increasing trends in temperature regimes is noted over most of the Arctic (Proshutinsky and Johnson, 1997; Rigor et al., 2000; Jones and Moberg, 2003; Nelson, 2003; Comiso and Parkinson, 2004). On the basis of long-term monitoring data, an increase of river discharge from the six largest Eurasian rivers to the Arctic Ocean has been recognized (Peterson et al., 2002). Because this riverine discharge is closely related to the meteoric precipitation over much of Siberia, atmospheric changes in this region are thus tied also to thermohaline circulation and deep water formation processes outside the Arctic, through the riverine freshwater and its effect on the surface salinity in the Arctic Ocean (Bauch et al., 2000; Delworth and Dickson, 2000). Many of the changes already evident in the Arctic should be even more noticeable around its margin in the future, because of the much larger seasonal contrasts occurring here. The circum-arctic shelves, which cover nearly 50% of the area of the Arctic Ocean, are such a key margin. It therefore is important to have a satisfactory understanding of the coupled land, ocean, and atmospheric components of the arctic hydrological cycle.

2. The Siberian shelf seas as sensitive "environmental recorder"

In this context of Arctic change, the North Siberian shelf with its vast hinterland is of particular interest (Kassens et al., 1999). For more than a decade now, a multidisciplinary approach, lead by Russian and German scientists, is being carried out to investigate the processes behind short- and long-term changes in the Laptev Sea. Because the methods are applied to much different time scales, the resulting data sets provide important new insight into the causes, impacts, and feedback mechanisms which determine the ongoing and past environmental changes in this shelf sea. The existence of a tremendous amount of data was the central motivation to put together a comprehensive scientific volume that would cover nearly all major aspects of a changeable arctic shelf environment.

Because the Laptev Sea is nearly completely frozen for about 9 months each year, the ice cover is the most prominent feature in the Arctic winter. During this long season, rather persistent southerly winds maintain open water areas, up to a hundred kilometer wide, between the landfast ice and the drifting pack ice (Fig. 3). This flaw polynya is one of

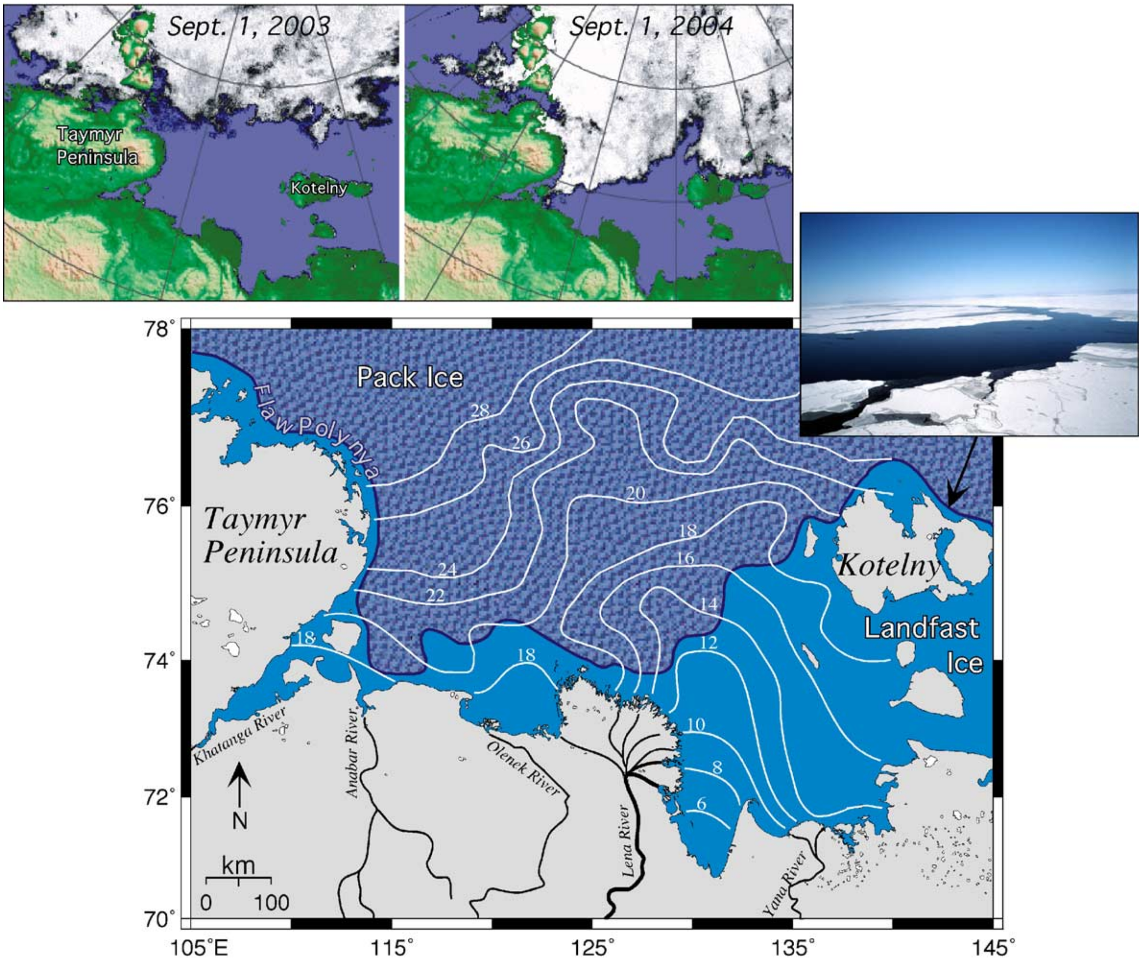

Fig. 3. Major features of the Laptev Sea for various seasons. The average position of the flaw polynya separates the pack ice from the landfast ice (after Dmitrenko et al., 1998). Diatom assemblage studies from surface sediments have shown (Bauch and Polyakova, 2000) that the pack ice area is typically associated with enhanced abundance of sea-ice species, whereas the landfast ice zone is characteristical for abundant freshwater species. The two microwave images (top left) reveal quite contrasting distribution of sea-ice concentration (source: http://iup.physik.uni-bremen.de:8084/amsr/amsre.html). The open sea areas, in particular in summer 2004, correlate well with the average summer surface salinity (white isolines; adopted from Bauch and Polyakova, 2003) and the landfast ice distribution in winter, both underscoring the strong influence of the Lena river water on the physical conditions in the Laptev Sea. Photograph top right shows the flaw polynya in spring 1999 (courtesy: T. Mueller-Lupp).

the key elements of the Siberian shelf system and it is regarded an important area where ice is constantly being formed. Using a 20-year long salinity record, Dmitrenko et al. estimate the production rate of sea ice for this open water lead in the Laptev Sea. While in the central parts of the polynya deep-reaching convective mixing seems to be a dominant feature, near the margins the observed spatial alignment of sea-ice crystals is probably caused by a quasi-stationary cellular circulation.

On the basis of satellite observations, spatial size variations of the ice cover in summer can be investigated nowadays in great detail (Fig. 3). Using a times series that spans back to 1979 combined with a thermodynamic sea-ice model, an overall decreasing trend in sea-ice extent is recognized for the summer, alongside with an extension of the length of the summer melt season (Bareiss and Görgen).

As it is evident from long-term monitoring of surface salinities in the Laptev Sea, the spread of the riverine freshwater on the shelf during summer strongly determines the extent of the landfast ice during winter (Fig. 3). By using a different mean of remote sensing data together with hydrographic observations and ice core studies, Eicken et al. have mapped out the distribution of freshwater and brackish ice as influenced by river discharge from the Lena and Yana rivers. Because the methods applied not only allow to distinguish between the different types of ice, they offer also the opportunity to actually better interpret the scatterometer data obtained by remote sensing. Using this information, in combination with stable isotope data from the landfast ice, it is estimated that a fourth of annual riverine runoff in the eastern Laptev Sea is stored in this type of ice.

Although five major rivers empty into the Laptev Sea every year, the volume of the Lena discharge is by far the largest of all, mainly affecting the eastern shelf where most of the discharge is distributed (Figs. 2, 3). An analysis of the discharge rates over the last 65 years indicates seasonal as well as interannual variations (Berezovskaya et al.). While some of the observed variability may be due to certain man-made actions in the catchment area, other changes appear to be partly associated with dynamical processes of the active layer of the permafrost. Indeed, a long-term study of the stream temperature of the entire Lena River basin shows quite consistent seasonal warming trends, for instance, in the early open water season (Liu et al.). This evidence may indicate a response to earlier snowmelt over the Lena River watershed and, furthermore, has implication also for the energy budget of the Laptev Sea, since the relatively warm riverine freshwater has a significant impact on shelf water mass temperature.

It is evident that the large Lena runoff is also a primary mechanism that, especially during the late spring flood when the river ice breaks causing the freshwater to pulse onto the still ice-covered shelf, leads to a transfer of various dissolved and particulate matters to the delta and the adjoining shelf area. A study of the concentration of dissolved metals implies a strong variability of trace metals in the Lena river and the surrounding shelf during summer, and that river water pH needs to be considered when estimating the trace metal flux of the Lena river (Hölemann et al.).

An all-season, 1-year long study using turbidity, current and temperature data from monitoring stations on the sea floor indicates that most of the input of suspended matter to the shelf takes indeed place during the spring high flow (Wegner et al.), while in the ice-free season enhanced resuspension of bottom material occurs during and after storm events, clearly indicating the atmospheric forcing as a principle component of sediment transport.

The quite contrasting distribution of salinity over the Laptev shelf, with far more marine conditions found in the west than in the east, has a profound influence on the shelfwide distribution, activity and community structure of phytoplankton and zooplankton. Results from 12 years of sampling reveal a seasonally but also interannually varying abundance in populations of copepods (Abramova and Tuschling). The work emphasizes the need to continue collecting such biological time series data in the future as this will be an important aspect in the context of arctic environmental change.

The strong seasonal and interannual variability imparted by the riverine freshwater on the shelf salinity not only affects the plankton distribution, the waters oxygen isotopic composition leaves a clear signature that can be used to trace the different water masses across the shelf. Because circum-arctic rivers have a distinct isotopic signature, the movement of the riverine freshwater and its interaction with the marine waters become evident when applying such tracer studies (Bauch et al.). Moreover, since the oxygen isotope composition of the ambient water is locked up in biogenic $CaCO_3$, this geochemical proxy can be used to test whether such data sets would support the concept of some of the described recent climate trends and natural variations in the Arctic. A first major step forward in addressing this question of natural variability is carried out by resolving the seasonal and annual variations in shelf salinity as reflected in the annual growth layers of bivalve shells (Mueller-Lupp and Bauch).

Because water depths are less than 100 m, the Laptev Sea was part of a much larger landmass during the last glacial maximum (LGM) when global sea level was lowered by more than 100 m. During this time, the shelf was transected by the north-flowing Siberian rivers that emptied directly at the continental shelf break, leaving topographic features on the shelf itself, today recognizable as distinct paleovalleys (Fig. 4). A large number of radiocarbon-dated gravity

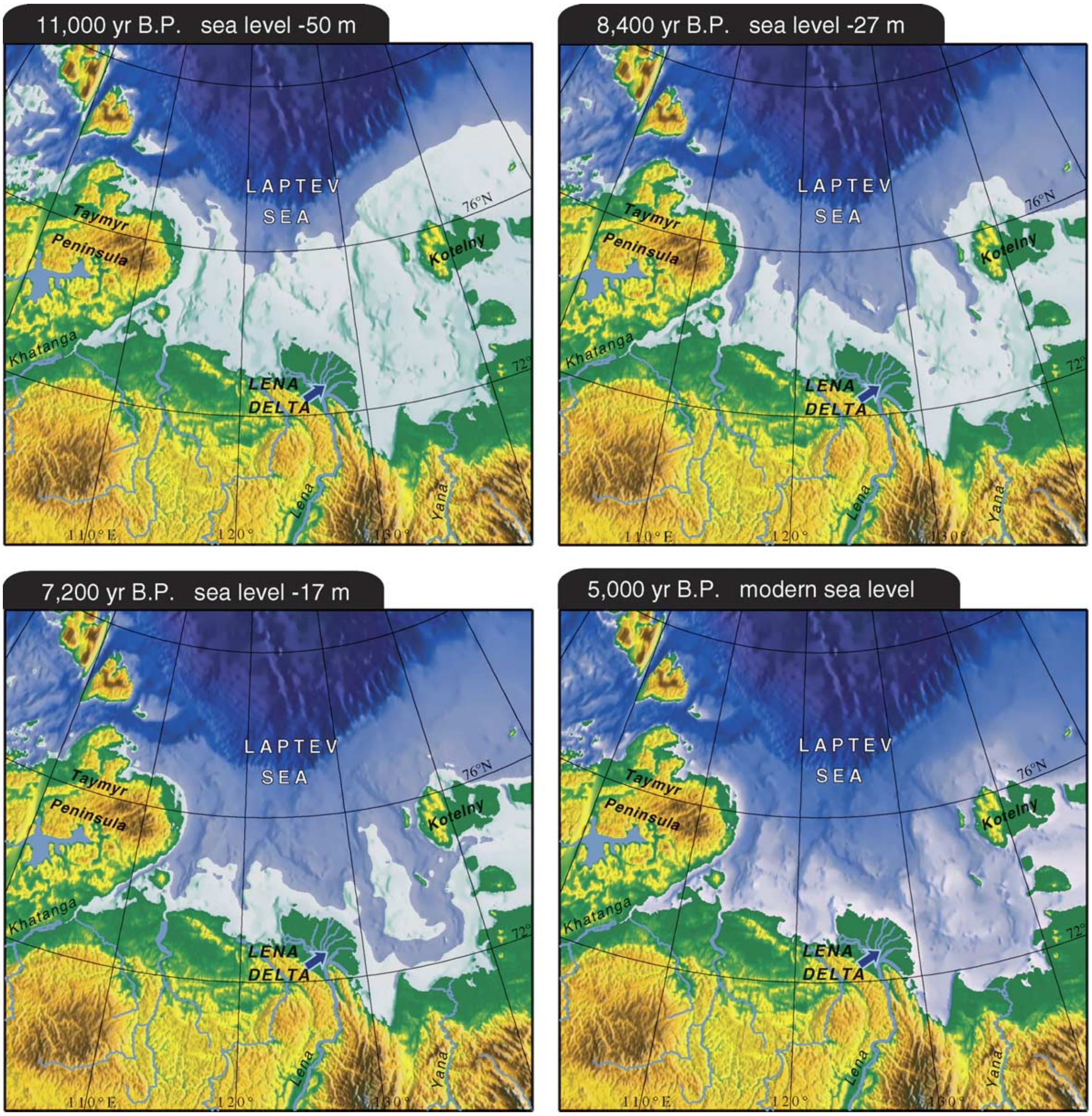

Fig. 4. Time-slice reconstruction of the Holocene transgression for the Laptev Sea shelf showing the retreat of the coastline (map compiled by T. Mueller-Lupp, after Bauch et al., 2001); note the south-north running paleovalleys on the shelf incised by the rivers during times of low sea level.

cores of up to 9 m in length have been recovered from different water depths of these paleovalleys and the continental slope. The sedimentation history of these cores allowed for a time-slice reconstruction of the Laptev Sea inundation since early Holocene times.

On the basis of a sediment core from a water depth below the continental shelf break, Spielhagen et al. use a planktic oxygen isotopic record to make assumptions on the river runoff during late glacial times. A very distinctive spike is identified around 13,000 years BP, implying the existence of a nearby riverine freshwater source at this time. The nature of this isotopic feature let the authors assume that a major riverine freshwater outburst influenced the

North Siberian margin at a time when the Younger Dryas cold spell commenced.

In order to interpret the major environmental changes that occurred on the Laptev Sea shelf during the Holocene sea-level rise, paleontological tools offer a wealth of possibilities. Based on modern analogues which are applied to evaluate crucial ecological preferences (Fig. 3), various fossil groups, such as diatoms, aquatic palynomorphs, ostracods, foraminifers, and bivalves all provide ample evidence of the transformation phase of the Laptev Sea shelf from a terrestrial to a marine environment (Polyakova et al.; Taldenkova et al.). In addition, interpreting both planktic and benthic fossil communities allows to make relevant assumptions on past water depths, the specific depositional setting as well as the variable influence of paleoriver discharge on the shelf salinity during the last 11,000 years.

3. Outlook

There is little doubt that the ongoing global changes will have far-reaching and more profound consequences for the Arctic than for many other environments. The new research strategies which combine satellite-based observations with ground-based continuous recording and conventional data collecting of crucial environmental parameters will increase our in-depth knowledge of how this impact will affect the Arctic environment. At present, a satisfactory understanding of naturally and anthropogenically forced variability of Arctic changes remains elusive, but substantial progress has already been made over the past 10 years by means of statistical and dynamical analysis of historical observations, paleoclimate reconstructions, physical theories, and numerical climate modeling. Especially the information available from paleoclimate archives will contribute useful additional insight for predictive purposes, since these records provide a longer time frame within which to evaluate natural variability and a means to examine the response of the system to future changes. As indicated by the wide range of different topics covered in the manuscripts of this volume, a key region to conduct such studies in the Arctic are the broad Siberian shelves like the Laptev Sea.

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Henning A. Bauch
Mainz Academy of Sciences, Humanities and Literature c/o IFM-GEOMAR, Wischhofstrasse 1-3, 24148 Kiel, Germany
E-mail address: hbauch@ifm-geomar.de
Corresponding author.

Heidemarie Kassens
IFM-GEOMAR, Wischhofstrasse 1-3, 24148 Kiel, Germany