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Contents

Recommendations from the Arctic Biodiversity Workshop

The Arctic Biodiversity Workshop had two distinct programs. The first was to determine interest and need for a biodiversity study in the Arctic, while the second discussed the joining of the longitudinal and latitudinal NaGISA transects with a transect that would cross the North Pacific/Bering Sea at the Aleutian Islands.

Discussions during the Arctic biodiversity portion of the workshop identified what is known and what is unknown but knowable about diversity in the Arctic Ocean. An Arctic Biodiversity Transect was identified as being urgent since changes in environmental conditions have already happened, and Arctic biological communities are expected to have disproportionate responses to global climate change. The dependency of Native peoples on the Arctic ecosystem for subsistence lifestyle adds social and cultural urgency.

How will the changes in the Arctic impact the biodiversity of sea ice communities on regional and temporal scales? For the sea ice system it was identified that delicate groups such as protozoan and metazoan meiofauna inhabiting the sea ice are among the least known groups. Little to no information is available on their species richness, distribution, and abundance. The sea ice community is also subject to dramatic seasonal changes, and information on these community structures in the winter compared to spring and fall is sorely needed. Also, most studies so far have focused on annual ice or fast ice while the significance of biological communities in multiyear ice—the majority of the sea ice present in the Arctic—is unknown. One way of combining multiyear ice studies with seasonal investigations is the establishment of permanent ice floe stations that can be revisited at intervals until 2010. It was proposed to establish ice stations in the Transpolar Drift and in the Beaufort Gyre.

Within the plankton, the major gaps in knowledge are delicate groups such as the gelatinous plankton, and nektonic groups such as cephalopods that are either destroyed or escape the traditional net sampling. Although copepods are reasonably well studied, knowledge on several small species is lacking for a comprehensive biodiversity understanding. Among the phytoplankton, morphological and physiological characteristics may vary within a species. A better understanding of species composition will improve our understanding of their ecology and physiology as well as interactions and processes in the ecosystem. A combination of microscope and molecular techniques were suggested to help eliminate ambiguities.

For benthic communities, patterns of floral and faunal biodiversity in the Arctic Ocean need to be related to hydrological processes and primary production to predict effects of climate change. Most efforts have traditionally been invested in shallow water benthic systems on the continental shelves. The Chukchi, Bering, Laptev, and Kara shelves have been most studied, while the Eastern Siberian Shelf is still comparatively under-explored. The extent to which infauna and epibenthic megafauna have been studied so far varies among the different shelf regions, but common to all areas, meiofaunal communities including Foraminifera are the most unknown. Also, among the coastal regions, the fjord systems of the Canadian Archipelago and of Greenland are among the least well known. The shelf breaks and the deep-sea basins of the Arctic Ocean are not well studied, with the deep Canada Basin being the least known of all. Since the Canada Basin is a long-time separated system with little exchange to other deep-sea basins, this will be a particularly interesting area to study within an Arctic transect. Benthic, pelagic, and sea ice systems are not isolated and the connectivity between these realms has to be the focus to understand biodiversity in the Arctic Ocean. Especially the ice/air and ice/water interfaces present unique but biologically unfamiliar habitats.

Agreement was reached that standardized sampling techniques would be necessary to ensure compatibility of data collected along a pan-arctic biodiversity transect. Image systems associated with ROVs or AUVs are appropriate for benthic megafauna and gelatinous plankton, while epibenthic sleds, grabs, and cores are reliable quantitative tools for smaller and often infaunal macrofauna and meiofauna. Live microscopy in the field is the only tool to analyze and identify ice protozoa. Hard bottom coastal areas should be sampled using the already established standardized NaGISA (Natural Geography in Shore Areas) protocols. Cooperation and coordination of sampling methods with those applied in other Census of Marine Life (CoML) projects, such as MarEco (Mid-Atlantic Ridge Ecosystem Project), GoMe (Gulf of Maine Program), and CeDAMar (Census of Diversity of Abyssal Marine Life) is desirable. Several CoML projects have already expressed interest in an Arctic component, e.g., ChEss (Biogeography of Deep-Water Chemosynthetic Ecosystems) in the ultra-slow spreading Gakkel Ridge. Sampling metazoans from all Arctic Ocean realms for DNA barcoding, a newly evolving program within CoML, is highly recommended.

Conducting a biodiversity transect across the Arctic Ocean is only feasible as a multinational, multidisciplinary program. The next steps in initiating this program are advocating the Arctic Transect to a broader scope of scientists in follow-up workshops. Regional workshops in the United States, Russia, and Europe are the best way to reach and involve a broad range of scientists with Arctic interests. The idea of an Arctic Biodiversity Transect should also be presented at appropriate scientific conferences. Efforts are also being made to obtain funding for an Arctic OBIS (Ocean Biogeographic Information System) node. There is a tremendous wealth of data and information from Russian investigations that is not accessible for the general scientific community. It will be a key issue to translate and organize these data to reveal a more complete picture of what is already known about marine life in the Russian Arctic. Also, old samples are available and could be re-analyzed on a more detailed taxonomic level. For this, and for the Arctic Biodiversity Transect work in general, the need for taxonomic expertise was expressed, as it is crucial to the success of describing life in the Arctic Ocean. The production of new keys, and translation of existing keys, should have high priority.

For the second program of the workshop, the extension of the NaGISA field project across the North Pacific and Bering Sea was discussed. Several biogeographic breaks are suggested along the Aleutian Chain, the Commander Islands, and the Kamchatka Peninsula. A series of NaGISA transects was suggested to test the existence of a biogeographic break at Samalga Pass and between the Aleutians and the Commander Islands while at the same time linking the longitudinal and latitudinal NaGISA gradients. A major outcome of this cooperation is a joint proposal between the Far Eastern Branch of the Russian Academy of Science in Vladivostok, the Zoological Institute of the Russian Academy of Science (ZIN) in St. Petersburg, and the University of Alaska Fairbanks, which was submitted to the National Science Foundation.

Introduction: Arctic Biodiversity Transect

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Among the major oceans on Earth, the Arctic Ocean is the smallest, least accessible, and indisputably the least studied. This is largely due to its remote location, which does not allow routine sampling, and its inaccessibility for most of the year because of heavy sea ice coverage. On average, ice cover of the Arctic Ocean varies from 6×10^6 km^2 in summer to 7×10^6 km^2 in winter. Only a small margin along the continental coasts becomes ice-free during summer, while mostly multiyear ice permanently covers the majority of the ocean (Horner 1985). This permanent ice cover plays a vital role in the Earth's climate with respect to heat exchange between the ocean and the atmosphere. Sea ice extent and thickness are parameters critical in climate modeling (Bitz et al. 2001). Because of positive feedback mechanisms such as ice albedo connected to snow and cloud cover, reactions to climate variability and climate change are strongly amplified in the Arctic (Manabe and Stouffer 1980). This polar amplification can lead to a much larger and faster surface warming and ocean circulation changes (Rind et al. 2001). Thermohaline circulation patterns in the Arctic Ocean respond to changes in atmospheric circulation, which is likely to be responsible for the recently observed increased presence of Atlantic water in the western Arctic (Zangh and Hunke 2001). This can lead to a warming of surface water, which in turn can increase thinning of Arctic Sea ice (Manabe and Stouffer 1995). In the Barents Sea a weakening in thermohaline circulation patterns could lead to significant cooling of water temperatures. A collapse of the thermohaline circulation might cause global changes in precipitation, air moisture, and ocean currents (Broecker 1994, Vellinga and Wood 2002). A change in sea ice extent would thus not only have significant local but worldwide consequences. As it is, recent investigations have estimated a decadal loss in Arctic sea ice of 2-3% (Parkinson et al. 1999) and a reduction in sea ice thickness of an average of 1 m in the Chukchi and Beaufort seas (Rothrock et al. 1999).

Biological marine systems will naturally respond to changes in ocean dynamics. It is important to be able to understand the influence that naturally occurring climate variations have on the diversity of Arctic marine systems, variations such as El Niño/Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), and the Pacific Decadal Oscillation (PDO) which are major sources of seasonal and interdecadal variability in the global atmosphere (Wanner et al. 2001). Only if we understand natural variation, we can start to understand changes caused by anthropogenic forces, such as changes in CO_2 concentration and the increase in greenhouse gases (Broecker 1997) or oil spills and commercial fish trawling.

About 30% of the Arctic Ocean's surface area is situated on continental shelves, mainly in the Russian sector, where freshwater from large river systems mixes with seawater to form extensive plumes of brackish water. This hydrological complexity and the pronounced seasonality in sea ice cover, light regime, and food availability lead to strong regional and temporal variations within the Arctic seas (Smith 1990). The high degree of adaptation of organisms to these environmental conditions leaves them particularly susceptible to climatic changes. In light of the recurring natural climate fluctuations (e.g., ENSO, NAO), the effects of human activities on global climate change, and the rapidly increasing melting of the permanent Arctic ice cap (Comiso 2002), it is especially important and urgent to increase our understanding of the abundance, distribution, and diversity of Arctic organisms. It is essential to know what lives in the Arctic Ocean to be able to monitor and evaluate shifts, and to relate them to natural variability or large-scale changes. Typically, the Arctic is viewed as being less diverse than tropical regions or the Southern Ocean (e.g., Clarke and Crame 1997; Rex et al. 1993, 1997; Gray 1997), which is probably due to its younger geological age, its relatively small area, and its low structural heterogeneity (Gray 2001). Although current data generally support the concept of a latitudinal gradient of decreasing biodiversity toward high northern latitudes, in part this view may be skewed by sporadic sampling efforts and insufficient coverage. A true and comprehensive understanding of Arctic biodiversity can only be gained from more investigations on increasing spatial scales from local to regional scales to biogeographic provinces, using consistent methodology.

From a biological perspective, the Arctic marine environment can be distinguished as various habitat types: the sea ice cover, the pelagic environment, the nearshore benthos, the continental shelf, and the deep-sea benthic habitat. Although each habitat type comprises an abundance of biodiversity of unique organisms, all compartments also interact strongly on various physical, chemical, and biological scales.

The Arctic sea ice is inhabited by organisms that are adapted to the physiologically challenging conditions of low temperatures, ice crystallization, and high salinities in brine. Sea ice communities consist in part of pelagic organisms that spend part of their life associated with the sea ice. The majority of sea ice organisms are sympagic (ice-associated), a specialized group of protozoans, microalgae, and small metazoans (Horner 1985), which are well adapted to the variable conditions in this habitat (Smith et al. 1989, Medlin and Priddle 1990, Carey 1992, Ikävalko and Gradinger 1997, Poltermann 1998, Gradinger et al. 1999). Sea ice also serves as a platform for larger marine mammals like polar bears and seals to feed and breed (Stirling 2002).

Phytoplankton production can be severely constrained by snow and ice cover, low light angles despite constant sunlight in summer, the high seasonality of the growing season, and often low nutrients in Arctic waters (Wheeler et al. 1997). Large phytoplankton blooms can form along the ice edge during melting season due to stable stratification of the water column. Depending on season and physical conditions (light, nutrients), one can often see a change in the composition of phytoplankton blooms from pennate to centric diatoms (von Quillfeldt 2000). The high phytoplankton biomass in marginal ice zones is mainly consumed by herbivorous mesozooplankters, dominantly copepods of the genus *Calanus* (Smith and Schnack-Schiel 1990, Mumm et al. 1998, Thibault et al. 1999). Large-scale and depth distribution patterns of dominant copepod species are reasonably well known for certain areas (Longhurst et al. 1984, Falk-Petersen et al. 1999). Much less is known about the abundance, diversity, and ecological significance of other planktonic organisms, such as gelatinous plankton (medusae, ctenophores, larvaceans), bacteria, small fishes, and cephalopods that may prey on copepods or be otherwise substantial in cycling and recycling organic matter (e.g., Skagshaug 1994, Nesis 2001).

Within the benthic realm some areas of the Arctic have been studied more intensely than others, due to accessibility or national interests. Traditionally, most work has been done in the shallow continental shelf regions. Factors such as depth, salinity grain size, and carbon availability are reported to strongly influence benthic community structure and spatial variability (Grebmeier et al. 1989, Grebmeier and McRoy 1989, Grebmeier and Barry 1991, Wassman et al. 1996, Dahle et al. 1998, Jewett et al. 1999). Due to tight coupling between pelagic and benthic production in shelf areas (e.g., Grebmeier et al. 1995, Piepenburg et al. 1997), faunal biomass in productive shelf regions can be impressively high (Feder and Jewett 1981, Stoker 1981, Grebmeier et al. 1989, Highsmith and Coyle 1992). In some areas high epifaunal biomass is connected with low overall diversity due to the dominance of few species, e.g., of ophiuroids (Piepenburg and Schmid 1997). In some places, natural disturbance from grounding icebergs, or feeding activity of walruses and gray whales, can be a major structuring factor of diversity of benthic communities in shallow regions (Nerini and Oliver 1983, Oliver et al. 1985, Gutt et al. 1996, Conlan et al. 1998). These coastal shallow water, nearshore regions are often dominated by deposit feeders and are low in diversity due to high influence of freshwater and sedimentation (Wlodarska et al. 1996, Hop et al. 2002). In areas with hard substrates, macroalgal communities occur and increase diversity by offering food and substrate for associated macrofauna (Dunton et al. 1982, Lippert et al. 2001).

Less information on biodiversity is available from Arctic deep-sea regions. From individual studies it seems that dominant macrofauna groups are polychaetes, bivalves, and crustaceans (Paul and Menzies 1974). Diversity patterns vary between various Arctic deep-sea regions, with the highest diversity found at intermediate depths (Kröncke 1998) or along ridges under the influence of lateral transport of matter (Kröncke 1994). Microfauna—bacteria, protozoa, and meiofauna—are of increasing importance in abundance and diversity compared to macrofauna with increasing depth and latitude (Soltwedel and Schewe 1998, Schewe and Soltwedel 1999, Kröncke et al. 2000). Small-scale biogenic structures from bioturbation or organisms increase habitat heterogeneity and can increase bacterial biomass and abundance in the upper sediment layers (Soltwedel et al. 2001).

This present knowledge on biodiversity in the Arctic Ocean leaves us with a picture of high diversity in local areas and habitats against a background of generally low biodiversity. There is indication that the high diversity patches are found on varying spatial and temporal scales, and that to date sampling efforts have not resolved these scales sufficiently to develop a clear picture. The need for a unified approach that is not hampered by different sampling techniques is needed to support and further develop our knowledge on Arctic biodiversity. Especially in light of a changing climate and its consequences for a changing world, it is ever so important to know the natural resources of our oceans. It is evident that only the combined efforts, expertise and resources of many nations can take up the effort to design and complete a transect across the Arctic Ocean and the different habitats. Therefore, the Sloan Foundation is funding an international workshop as a new initiative within the Census of Marine Life program (CoML, http://www.coml.org) to gather the expertise from scientists from countries of the Circumpolar North to advance the study of biodiversity in the Arctic Ocean. CoML is a major international research program assessing and explaining the diversity, distribution, and abundance of marine organisms throughout the world's oceans.

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The Census of Marine Life: Advancing Our Understanding of Marine Biodiversity

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Abstract

As an overview, this article presents the unique collaborative approach of the Census of Marine Life (CoML) to increasing our knowledge of the abundance, distribution, and diversity of marine life throughout the world's oceans. Five elements comprise the foundation of the research program, providing information and methods useful for enhancing our understanding of marine biodiversity, both historically and today, and making sound predictions of biological diversity in the future. (1) A series of initial field projects will demonstrate techniques or technologies to be applied to future studies. Some of these will test new technologies in well-known areas of the ocean, but most will take place in poorly known regions where both new and existing methods of surveying marine life will yield new information. (2) The Ocean Biogeographic Information System will make CoML and independent biological data accessible by serving as a single entry point to a distributed federation of databases. It will also provide tools for all users to create visualizations of the distribution and abundance of organisms together with environmental parameters in three dimensions. (3) Through the History of Marine Animal Populations, the historical component of the CoML, biologists and marine historians will mine and analyze historical records dating before human impact on the ocean became significant. (4) Exploring and documenting the multitude of ocean life accessible today requires advanced technology, and the CoML is working with the Scientific Committee on Oceanic Research Working Group on New Technologies for Observing Marine Life to move recent technological advances for observing marine life into the field. (5) The Future of Marine Animal Populations program will demonstrate and develop modeling approaches to hindcasting

and forecasting changes in global biodiversity in response to fishing, pollution, and climate change.

1. Introduction

Throughout the development of modern society, the oceans have been routinely treated as limitless sources and sinks for human consumption and waste. By the end of the twentieth century, it had become clear that the oceans were changing in response to intense fishing, pollution, and climate change (NRC 1995). Continuous discoveries of new species and habitats highlighted the lack of basic information required to fully understand the more complex interactions in marine ecosystems. Recognition that science has sampled less than 0.1% of the volume of the oceans led to the convening of a series of workshops focused on the question of whether it is possible to document what lives there, so that the changes can be monitored and understood (Ausubel 1999). The outcome was a recommendation for a comprehensive international research program called the Census of Marine Life (CoML). The purpose of the CoML is to assess and explain the diversity, distribution, and abundance of marine organisms throughout the world's oceans (Ausubel 2001). It is organized around the questions: What did live in the oceans? What does live in the oceans? What will live in the oceans?

The oceans occupy over 70% of the Earth's surface and 90% of the volume of its biosphere and pose a huge challenge for documenting the diversity life that exists there. The two hundred international scientists who participated in the workshops, however, agreed that new technologies available at the turn of the millennium have made it plausible to ask and answer these questions. In addition, awareness of the need for more information has already led to the development of distributed individual efforts by governments, industry, and international monitoring and observing organizations. Therefore, the key to conducting a global census of life in the oceans will lie not only in the generation of new studies but also in cooperation, collaboration, and a willingness to share by all users of marine biological information.

Based on these recommendations, the Census of Marine Life was launched in 2000. Although the precision of the census cannot be predetermined and costs are estimated to be in the billion-dollar range, major advances are possible within a decade that can contribute usefully to the knowledge base necessary to manage an environment under increasing pressure. The CoML's unique niche among global marine research programs comes from its focus on diversity at the higher levels of food webs, the consequent requirement for extensive taxonomic expertise to characterize undescribed species, and special interests in timelines extracted from non-traditional sources in the field of marine science. The detailed planning approach integral to the program is centered on assembling what is known, assessing what is knowable and, therefore, avoiding barriers to our goals by seeking the unknowable.

2. Elements of the program

A group of eleven senior marine scientists from around the world forms the Scientific Steering Committee (SSC) for the Census of Marine Life. The SSC agreed on the steps necessary for the initiation of a successful program with far-reaching impact on our understanding of marine biodiversity. The first steps were the assembly of existing data and the development of a data management system to make this information accessible to scientists around the world. The next step was the development of a series of field studies to collect new information on life in the oceans. Finally, the use of these new and historical data will be combined with mathematical ecosystem models to provide predictions of the future state of marine communities.

In recognition of the need for reliable baseline information on marine ecosystems, the first project initiated by the CoML was the History of Marine Animal Populations (HMAP). Historians, ecologists, and biologists formed an international consortium to “rescue” historical records on changes in distribution and abundance of marine organisms before the era of modern fisheries management. This rescued history will create a new vision of ocean life as it existed before major human impacts and will provide a context for new information collected.

All of the data collected by the CoML would need a place to reside and remain accessible, leading to the establishment of the Ocean Biogeographic Information System (OBIS), a global network of interoperable databases. This internet-based, distributed system accesses not only species-level data on the distribution and abundance of living organisms but also on the chemical and physical characteristics of the environment in which they live. In addition, OBIS provides visualization tools to facilitate interpretation by all users of marine biological information. The online portal launched in early 2002 and has since successfully demonstrated the benefits of such a system. As it continues to link a growing number of taxonomic, environmental, and fisheries-related databases, it will become a powerful tool for science, management, and education.

The SSC also supported the development of a series of initial field projects (Fig. 1) to demonstrate new quantitative approaches for sampling a full spectrum of life forms in the major ocean habitats. These

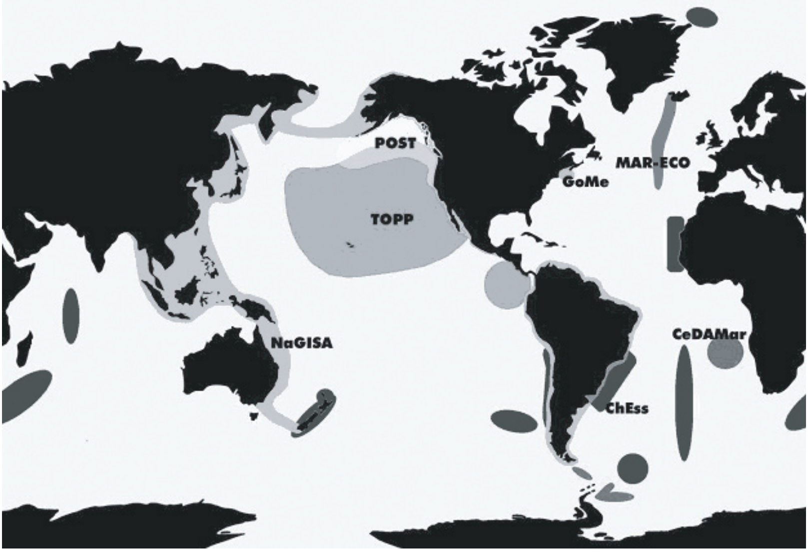

Figure 1. Global distribution of the seven planned CoML demonstration projects. Symbols indicate site of CoML workshops and meetings.

projects are the initial phase in a series of projects to be conducted worldwide in a variety of habitats. All of the data from these—and future—projects will be assembled in and made available through OBIS. There are seven such initial projects under way.

The project Natural Geography In Shore Areas (NaGISA) is intended to develop a simple, standardized approach to describe the biodiversity from the shore to a depth of ten meters at selected reference sites along coastlines (IBOY 2002). Much of the coastline around the Pacific is already planned, with the ultimate goal to expand this project to similarly cover the millions of kilometers of coastline around the world.

The regional project in the Gulf of Maine (GoMe) brings together teams of U.S. and Canadian scientists to develop an integrated view of marine life and its environment in an already well-studied marginal sea, taking advantage of advanced technologies and monitoring systems already operating there.

The Mid-Atlantic Ridge Ecosystem project (MAR-ECO) is addressing the challenge of measuring diversity and abundance in the water column of the deep ocean over one of the largest physical features in the ocean. This project will combine state-of-the-art sampling gear with high-resolution bathymetric surveys to characterize the communities and bottom topography along selected areas of the ridge.

The most recently discovered and poorly characterized ecosystems associated with deep-sea hydrothermal vents, cold seeps, whale falls, and wood debris are the targets for the Biogeography of Chemosynthetic Ecosystems project (ChEss). This study will examine already-discovered and new communities to form a global biogeographic understanding of their composition and distribution (Van Dover et al. 2002).

The abyssal plains are the largest habitat on the planet and the least well known. The Census of Diversity of Abyssal Marine Life (CeDAMar) project will explore benthic life in the deep basins, beginning in the South Atlantic Ocean. The abyssal plains may be the last place where science can study biodiversity patterns before major human impacts are felt.

Two projects in the Northeast Pacific use advanced telemetry techniques. These techniques make it possible for the animals themselves to report on their movements and the rapidly changing environments in which they live and on whose associated organisms they depend. The Pacific Ocean Salmon Tracking (POST) project uses coded acoustic tags in animals as small as 25 grams to record migrations along the highly productive continental shelf of western Canada and the U.S. The Tagging of Pacific Pelagics (TOPP) project uses satellite telemetry to track movements of large predators across the entire Pacific Ocean basin (Boustany et al. 2002). These new approaches should make it possible to identify and sample biological hot spots and to estimate abundances on ocean scales from limited, but strategic, direct sampling.

As mentioned, a Census of Marine Life is feasible today because of the emergence of new technologies for observing the ocean and the organisms that live there. The CoML is primarily interested in the implementation of technologies ready to be tested and calibrated in the field, rather than development of new technologies. The initial field projects of the CoML demonstrate and integrate these quantitative sampling techniques to better reach areas of the oceans that have not been well sampled before. To assist, they work in collaboration with Working Group 118 of the Scientific Committee on Ocean Research (SCOR), which meets regularly to review and recommend new technologies for use in the field.

The final element of the CoML, the Future of Marine Animal Populations (FMAP), is focused on data management to maximize the coverage and precision of the data acquired through all elements of the program and to make available through OBIS the data and appropriate mathematical models. It was developed in response to the need for broader understanding of ecosystems to improve our ability to predict the biological impacts of climate change, harvesting, and other human interventions. However, to have any hope of predicting the unknown future, models must be able to predict the known past, so OBIS will also provide data and a testing ground for biodiversity hindcasting using these tools.

3. Organizing the community

The oceans form a large global system in which biological, chemical, and physical processes are closely linked. Understanding biodiversity requires comprehensive coverage at various scales of both space and time. The goal of global coverage is fundamental to the CoML concept, not just the dream of over-ambitious scientists.

In order to achieve this goal, it is crucial that the CoML integrate with existing programs and form new cooperative efforts around the world to make the most efficient use of resources and to obtain the data needed to characterize life in the world's oceans. The CoML is actively seeking and building partnerships among the many national and international organizations, industry, and research programs to share information and collaborate on projects.

A worldwide research program aimed at collecting new information on marine species cannot be designed and implemented by a single central committee such as the SSC. To obtain global coverage from field programs, they must be developed on an ecosystem basis and funded at a local level. Therefore, the CoML is also supporting the formation of national and regional committees around the world to promote marine biodiversity research and to facilitate development of and support for new field projects, first at the national level in countries with major ocean research capacity to establish project and funding priorities and second at the regional level to strengthen the collaborative efforts where large ocean areas are associated with countries having limited research capacity.

Canada, with CoML field projects on both its Atlantic and Pacific coasts, held a workshop in February 2002 to form a national committee. The major products were a review of existing biodiversity information in three oceans to meet commitments to the UN Convention on Biological Diversity and a commitment to incorporate the Department of Fisheries and Oceans Canada long-term survey data into OBIS. This proved a successful model, which Japan, Australia, the United States, the European Union, and South America followed in the establishment of their national implementation committees.

4. Access to information

Without access to accurate information about marine life and its environments, the scientific and societal needs to understand and predict the effects of changes in communities or habitats cannot be addressed. While contributing new knowledge, the CoML is building relationships with national and intergovernmental organizations, industry, and other groups already collecting taxonomically resolved biodiversity information that should be made accessible through OBIS.

In 2001 OBIS became the marine associate for Global Biodiversity Information Facility (GBIF), established in Copenhagen under the Organisation for Economic Cooperation and Development. In this role, OBIS will be the primary means of access to marine data for GBIF. The CoML is working closely with international and intergovernmental organizations, such as the International Council for Exploration of the Seas, the North Pacific Marine Science Organization, and the Food and Agriculture Organisation of the United Nations. Efforts with these organizations should result in access to all the fisheries survey data available around the world.

Industry is also an important retainer of marine biological information. The most successful collaboration that CoML has developed in this arena has been a joint effort between the Oil and Gas Producers Association Deep Water Environmental Taskforce and United Nations Environment Programme's World Conservation Monitoring Centre (WCMC). British Petroleum has agreed to provide all of its environmental data to the WCMC. An agreement between the WCMC and OBIS has begun the integration and linkage of this information through OBIS. A CoML investigator recently illustrated the value of scientific access to industry archives by discovering a new species of 10 m long deep-sea squid from videos generated by the oil and gas industry from around the world (Vecchione et al. 2001).

5. Societal benefits

The concept for a Census of Marine Life grew out of scientific and societal recognition that declining biodiversity has been a consequence of climate change and human impacts on ecosystems. Good examples of direct economic impact from this decline, previously limited to the terrestrial realm, have become clear in the oceans and have called us to action to improve our knowledge of marine biodiversity. Other international ocean stakeholders also recognize this need and are beginning to integrate CoML biodiversity information for management of commercial fisheries, conservation of marine habitats, and prediction of the potential impacts of climate change.

Single-species management of fisheries around the world has failed to provide sustainability because it does not accommodate the shift by fishermen from harvest of heavily exploited, regulated species to poorly studied species of lower trophic levels. Most major fisheries agencies are moving toward multispecies or ecosystem management, which requires information about the non-commercial and rare species—a focus of the CoML—and their function in their ecosystem. In many cases, there are no taxonomic experts available to these agencies to even describe the species making up the system with the detail required, let alone monitor it routinely.

One example of unanticipated effects of biocomplexity emerged from climate change studies such as the Global Ocean Ecosystem Dynamics Program. On Georges Bank in the Gulf of Maine, USA, blooms of planktonic jellyfish consumed small planktonic grazers that would normally have been food for larval fish. These blooms are thought to be related to changes in water conditions as a result of climate change; the impact of this on the future populations of adult fish are unknown (Madin et al. 1996). Under some conditions such massive removal of species by large predators overwhelms changes in primary production and carbon dioxide fixation that would have been predicted from the availability of sunlight and nutrients. In this case, the details of the biological diversity proved critical to understanding and modeling ecosystem performance.

The CoML is well prepared to provide special expertise to meet these newly recognized needs in exchange for access to sampling opportunities. All new and existing data will be merged into OBIS. Cooperation with resource management agencies should increase the geographical coverage and, therefore, amount of information available for characterizing biodiversity patterns. As the amount of data, visualization tools, and FMAP model approaches accessible through OBIS increases, so will our ability to manage sustainable fisheries and to recognize and predict the effects of both natural and human impacts on ecosystems (Myers and Worm 2003).

6. The future

The primary goal of CoML is to explore within the next decade poorly known and even well studied areas of the world's oceans to gather reliable, quantitative data on the distribution and abundance of marine species, both new and already described. The knowledge collected will significantly increase our ability to understand the importance of marine biodiversity, past, present, and future. Other legacies of the CoML will also last far into the future. As long as it is maintained, OBIS will provide a single, easily updated entry point to a network of databases containing new and historical data and tools for interpreting the complex relationships between biology, geology, physics, and chemistry in the oceans. A second legacy will be a set of new sampling technologies and techniques, for use in both field and laboratory, and a set of analytical models that have been tested and calibrated for routine use in the assessment and explanation of marine biodiversity. In addition, they will provide an economical basis for ongoing biological monitoring, combining shipboard techniques with satellite and other modern ocean observation methods. The third legacy of CoML will be the working relationships that will have been established among all marine sectors and a recognition that it is to everyone's benefit to share our understanding of the oceans to better preserve them as the common heritage of humanity.

There are two ways in which the CoML expects to move forward on research activities—expansion of existing projects and development of new concepts for projects. Each of the seven initial field projects is demonstrating the use of a new technology or technique for collecting data on distribution, abundance, or diversity. Since the use of new technologies plays a key role in the projects that make up the CoML, the plan is to expand the sampling methods developed in these projects into other areas of the ocean. Thus, the initial development costs are borne by nations that have this capacity and expertise. Expansion of the projects will benefit other nations by providing tested methods and experts who can train others. Industry will benefit from the ability to sell technology that has been tested and approved for routine research use.

Expanded coverage of the ocean using the methods of the initial projects has already started. There is a funded prototype project in Australia based on the POST approach and TOPP technology is being applied in a corridor from the Cocos to Galapagos Islands in the South Pacific. The NaGISA project, initiated in the western Pacific, has been extended along Alaska and there is considerable interest to use the protocols along the coastlines of the contiguous United States, South America, and Antarctica.

The initial projects were designed to initiate and provide a basis for growth of the field phase of the CoML. They do not preclude the identification and support of additional new project concepts. There are still many habitats for which sampling approaches are lacking, and the CoML is eager to encourage the development of concepts for future support by the program. Project concepts are in development for marine observations under Arctic ice. A workshop to explore potential new projects on seamounts and canyons will be held in August 2003.

In order for the CoML to truly succeed, new field projects must be carried out in all regions of the world, with collaboration from many nations and organizations, using money, equipment, and expertise from many sources. The CoML program has already significantly advanced scientific understanding based on its activities to date. To reach its full potential, however, it will require much more direct financial support of its field activities, as well as extensive collaboration to increase data assembly and new sampling opportunities. The new CoML national and regional implementation committees will be primarily responsible for identifying new project concepts, as well as promoting financial support from both traditional and non-traditional sources at the national levels. The efforts to create these committees are aimed at broadening interest in the program and in promoting the vision of distributed costs and responsibility.

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ChEss: Biogeography of Deep-Water Chemosynthetic Ecosystems, Census of Marine Life

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Chemosynthetic systems: The known

Most of the deep-sea benthos is heterotrophic, depending on the deposition of surface photosynthetically produced organic matter. But photosynthesis is not the only base for the development of life. Locally, in discrete locations such hydrothermal vents on mid-ocean ridges and cold seeps on continental margins and subduction zones, fluids charged with reduced chemicals seep from the ocean floor. At these sites, dense invertebrate communities develop based on chemosynthesis where chemoautotrophic bacteria are at the base of the trophic chain. These microorganisms biosynthesize organic carbon compounds from CO_2 using reduced chemicals such as H_2S and methane as a source of energy. The bacteria are found both free-living and in symbiotic associations with the invertebrate fauna.

Hydrothermal vents were first discovered in 1977 along the Galapagos Rift on the Eastern Pacific (Corliss et al. 1979) (Fig. 1). The fauna at these newly discovered vents was dominated by tubeworms (*Riftia pachyptila*), clams (*Calyptogena magnifica*), mussels (*Bathymodiolus thermophilus*) and a variety of gastropods and polychaetes. Since then, an increasing number of hydrothermal vents have been discovered and studied on almost each oceanic basin (Fig. 1).

In the last 25 years, more than 400 morphological species have been described from vents, with a high degree of endemism. In a recent review, Cindy Van Dover and colleagues (2002) recognized six biogeographic regions for hydrothermal vent communities (Fig. 1). These are:

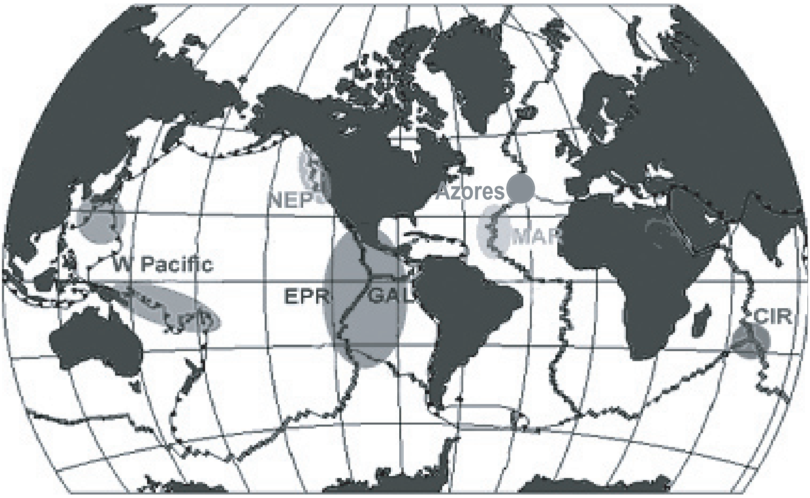

Figure 1. The mid-ocean ridge system and biogeographical regions of hydrothermal vent communities. Azores: Azores region; MAR: Mid-Atlantic Ridge; EPR: East Pacific Rise; GAL: Galapagos Rift; NEP: North East Pacific; W Pacific: West Pacific; CIR: Central Indian Ridge.

1. Azores region, dominated by bathymodiolid mussels, amphipods and caridean shrimp (Desbruyères et al. 1994a, Van Dover 1995, Van Dover et al. 1996, Tunnicliffe et al. 1998).
2. Mid-Atlantic Ridge region (MAR) dominated by caridean shrimp—mainly *Rimicaris exoculata*—and bathymodiolid mussels (Galkin and Moskalev 1990, Segonzac 1992, Murton et al. 1995, Van Dover 1995, Tunnicliffe et al. 1998).
3. EPR and Galapagos Rift, dominated by vestimentiferan tubeworms, bathymodiolid mussels, vesicomyid clams, amphipods and crabs (Hessler et al. 1985, Fustec et al. 1987, Van Dover and Hessler 1990, Shank et al. 1998, Tunnicliffe et al. 1998).
4. NE Pacific region dominated by vestimentiferan tubeworms, vesicomyid clams, polychaetes and gastropods (Tunnicliffe 1991, Tunnicliffe et al. 1998).
5. Western Pacific back-arc basins dominated by bathymodiolid mussels, “hairy” gastropod, vesicomyid clams and shrimps

(Hessler and Lonsdale 1991, Desbruyères et al. 1994b, Tunnicliffe et al. 1998).

6. Central Indian Ridge (CIR) dominated by the shrimp *Rimicaris* cf *exoculata* and mussels, scale gastropods and anemones (Van Dover et al. 2001).

The interest in large chemosynthetic environments was strengthened by the discovery of a chemosynthetic-based fauna in the cold seeps at the base of the western Florida Escarpment in 1983 (Paull et al. 1984). Cold seeps are distributed globally along both continental margins and subduction zones (Sibuet and Olu 1998). Cold seeps are characterized by the seepage of cold fluids with a high concentration of methane. Sulfide concentrations can also be important as a result of sulfate reduction in the sediments. Over 200 morphological species have been described from cold seeps. At high taxonomical levels, the seep fauna is similar to the fauna of Pacific vents, but there are significant differences in species composition, diversity and abundances (Sibuet and Olu 1998). Chemosynthetically driven communities have also been described from other systems such as whale falls, sunken wood or ocean minimum zones (OMZ). These systems have been interpreted as stepping-stones for the dispersal of vent and seep fauna and are thought to play an important role in the global distribution of vent and seep species (Smith et al. 1989).

Chemosynthetic systems: The unknown

The exploration and study of deep-water chemosynthetic systems depends on long oceanographic cruises involving large research vessels and state of the art technology such as towed mapping vehicles, specific sensors mounted on deep-towed vehicles, autonomous underwater vehicles (AUV), remote operated vehicles (ROV) and manned submersibles. The financial and logistics implications are considerable and have constrained research on deep-sea vents and seeps to evolve at slower pace compared to coastal research.

Hydrothermal vents have been discovered along every mid-ocean ridge section and back-arc spreading center that has been methodically studied, from fast spreading ridges such as the EPR to slow spreading ridges such as the MAR. Recently, it has been demonstrated that venting occurs even at ultra-slow spreading ridges such as the Gakkel Ridge (Edmonds et al. 2003). Similarly, the number of known cold seep sites is increasing. The economical potential of cold seeps through the exploitation of oil and gas has also increased the interest of national governments in cold seep research. However, with mid-ocean ridges extending for ~60,000 km and continental margins and large organic matter falls covering vast extensions of the ocean seafloor, most of the potential chemosynthetic regions and their associated faunal communities remain still unexplored.

In a study of the biogeography of chemosynthetic communities of the world's oceans, it is imperative that the taxonomic status of all the individuals be determined. Traditionally, this has been done by morphological methods. To date, molecular techniques are rapidly developing and are one of the most innovative aspects of deep-sea research. The molecular approach offers the possibility, not only to identify cryptic species and discriminate between populations and metapopulations, but also to measure gene flow and to analyze the phylogeography, evolution and possible origin of the present genetic types. This, in parallel with the traditional morphological techniques for taxonomy will significantly add to our understanding of the biogeography of chemosynthetic fauna. Furthermore, the discovery of new species can lead to findings of specific physiological adaptations with valuable implications for the biochemical and medical sectors.

Life history components such as fecundity, egg size, fertilization success and larval patterns play a central role in the dispersal and distribution of a species (Ramirez-Llodra 2002). This is of special relevance in discrete and ephemeral habitats such as vents and seeps. However, the reproductive and larval patterns of only a very small number of vent and seep species have been studied to date (reviewed in Tyler and Young 1999). In addition to the biological analysis, it is necessary to improve our understanding of the geographical barriers and physical forces affecting dispersive processes, as well as the historical vicariant processes that have affected the global distribution of vent and seep species.

ChEss: The program

ChEss is a pilot project within the Census of Marine Life initiative. ChEss aims to improve our knowledge of the biogeography of deep-water chemosynthetically driven ecosystems by promoting an international field phase of discovery and exploration. The main objectives are to assess and explain the diversity, distribution and abundance of species from chemosynthetic systems at a global scale and to understand the forces driving these ecosystems. For this, ChEss will follow two approaches:

1. To develop a relational database for all chemosynthetic species. This database will be bio- and geo-referenced and will include information on the taxonomy, basic biology, geographical

distribution, characteristics of the sites, photos and short videos. ChEssBase will be available on the Web through the ChEss Web page (http://www.soc.soton.ac.uk/chess) and through OBIS (Ocean Biogeographic Information System, http://www.iobis.org).

2. To develop a long-term field program for the discovery and exploration of new chemosynthetic sites. Because of the vast dimensions of potential target areas, a number of key locations were agreed upon during the first ChEss steering committee meeting in January 2003 (Fig. 2). The intention is to identify the maximum scientific return that could be achieved from detailed investigation of the minimum number of sites at key locations.

ChEss in the Arctic

Gakkel Ridge

The central Arctic Ocean is covered by a permanent layer of ice. Photosynthesis under the ice is reduced and therefore the deposition to the seafloor of organic matter used by the benthic fauna is near to inexistent. However, communities sustained by chemoautotrophic bacteria can develop, and evidence of hydrothermal vent systems and cold seeps have been found in the Arctic.

Evidence of hydrothermal venting has recently been found over the Gakkel Ridge in the eastern Arctic Basin (Edwards et al. 2001, Edmonds et al. 2003). The Gakkel Ridge is an ultra slow spreading ridge (spreading rate = 0.6-1.3 cm year^{-1}) along which the North American and Eurasian plates diverge. In 2001, a joint cruise (AMORE) with the icebreakers USCGC *Healy* and PS *Polarstern* conducted mapping, sampling and geophysical surveys along the Gakkel Ridge. During the program, several hydrothermal plumes were observed and fresh sulfide chimneys, hydrothermally altered rocks and invertebrates were recovered, giving further evidence of the presence of hydrothermal systems (Edmonds et al. 2003).

In addition to being an ultra-slow spreading ridge with its characteristic geological processes, the Gakkel Ridge is under permanent ice cover and hydrographically isolated within the Arctic Basin. The exchange of water with other oceans is limited to shallow sills. This has important implications for the evolution and ecology of deep-water hydrothermal fauna. The endemic vent fauna has been characterized in discrete sites at all ocean basins except for the Arctic. There is therefore no knowledge of the relationships between Arctic vent fauna and Atlantic and Pacific vent fauna, and on how Arctic

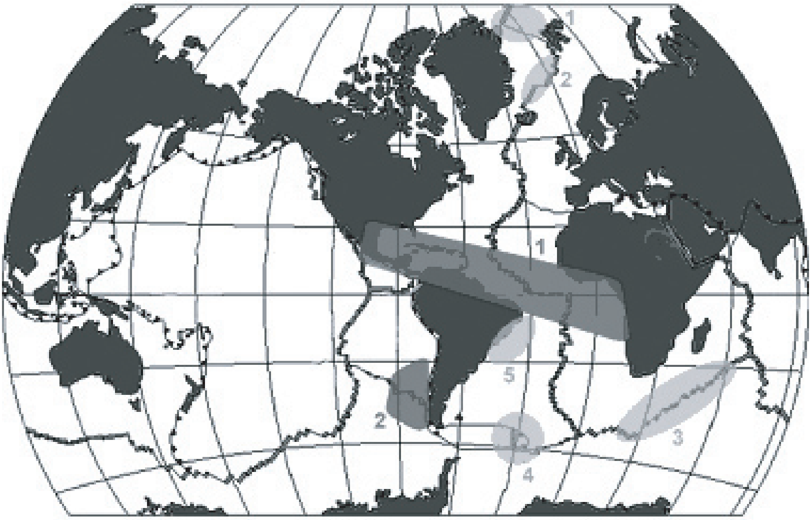

Figure 2. Key target areas for the ChEss field program. Yellow: 1-Gakkel Ridge, 2-SW Indian Ridge, 3-Scotia Arc, 4-continental margin off Brazil. Red: Area 1- region comprising the seeps off Costa Rica and Gulf of Mexico, the Cayman Trough, the Barbados Prism, the continental margin off north Brazil, the MAR north and south of the Chain Fracture Zone and the continental margin off Angola; Area 2- region comprising the Chile rise and the cold seeps and OMZ off southern Chile.

vent fauna has evolved and adapted at an ultra-slow spreading ridge isolated from all other ridge systems.

A comprehensive set of geological, chemical, hydrographical and biological data is needed in order to understand the ecology and evolution of Arctic vent fauna set in the global scale. Understanding how these isolated communities have evolved and adapted to their habitat would help understand the general patterns of biogeography and biodiversity of vent species around the globe.

For such a study, however, the use of the latest technologies is necessary. With the Gakkel Ridge under a permanent cover of ice, the use of Roves or towed vehicles is not feasible unless two ships are used (see AMORE program). Auks such as ABE (WHOI, U.S.A.) or AUTOSUB (SOC, U.K.) are a way of sidestepping the difficulties of operating on ice-covered locations and could be used successfully to study a site such as the Gakkel Ridge.

Haakon Mosby mud volcano

Cold seep communities based on metamorphic bacteria were found on the Haakon Mosby mud volcano in 1995-1996 (Milkov et al. 1999, Vogt et al. 1999). The Haakon Mosby mud volcano is on the continental margin west of the Barents Sea at 1,250 m depth. It is 1 km in diameter and is covered with white mats of thiobacteria. The mud volcano sustains a diverse community based on the production of methanotrophic bacteria.

The Haakon Mosby mud volcano is not covered by permanent ice, but there is no reason why similar systems should not be found on the central deep Arctic Ocean. The characterization of cold seep Arctic fauna would again provide very valuable data for a thorough understanding of the biogeographical patterns of chemosynthetic ecosystems at a global scale. It would also provide information on the relationships and barriers between discrete vent and seep systems across ocean basins.

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Natural Geography in Nearshore Areas (NaGISA): The Nearshore Component of the Census of Marine Life

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Introduction

The potential loss of marine biodiversity has recently spurred an increasing number of studies to identify the importance of biodiversity for ecosystem functioning. (Loreau et al. 2001, Pachepsky et al. 2001, Pfisterer and Schmidt 2002). Biodiversity is one potential measure of ecosystem health, though criteria are not always clear; high biodiversity may not necessarily represent the natural state of an ecosystem. But biodiversity can definitely be a measure of biological interactions such as competition, disturbance, facilitation, predation, recruitment, and productivity of a system (Petraitis et al. 1989, Worm et al. 1999, Mittelbach et al. 2001). On a larger scale, biodiversity measurements can serve as an indicator of the balance between speciation and extinction (McKinney 1998, Rosenzweig 2001).

Apart from our increasing appreciation of marine biodiversity in coral reefs and deep-sea regions (Grassle and Maciolek 1992, Stone et al. 1996, Gray 1997, Small et al. 1998, Knowlton 2001, and Roberts et al. 2002), biodiversity in coastal areas other than coral reefs has started to receive more and more attention (Gray et al. 1997). Coastal marine biodiversity can be very high (Ray 1996) particularly because the three-dimensional structure of macroalgal habitats and seagrass communities supports and enhances species richness (van Oppen et al. 1996, Walker and Kendrick 1998, Duarte 2000, Engelhardt and Ritchie 2001, Duffy et al. 2001, Somerfield et al. 2002). Shallow water coastal areas, however, are also the areas most impacted by humans, and human impact such as industrial use, oil exploration, fisheries, pollution, invasive species, recreational activities, and habitat fragmentation can have severe effects on nearshore biodiversity (Gray 1997, Walker and Kendrick 1998, Bax et al. 2001, Tilman and Lehman 2001, Barnes 2002). On a larger scale, human-induced global climate change can also have a significant impact (Scheffer et al. 2001).

Within the last decade the need for nearshore biodiversity studies on a large spatial or even global scale has become increasingly obvious for the intent of conservation and establishment of Marine Protected Areas (Norse 1995, Costello 1998, Zacharias and Roff 2000, Eiswerth and Haney 2001, Shaffer et al. 2002). We have now started to understand that biologically diverse communities are more resilient to environmental and ecological stress and disturbances, e.g., from invasive species (Kennedy et al. 2002). The sustainable use of coastal biodiversity has to be one of the major efforts in our conservation and management efforts (Gray 1997, Price 2001). “The extent, cause and maintenance of biodiversity are among the most important biological issues of our time” (Diversitas Systematics Agenda 2000). Although many attempts have been made to measure and evaluate biodiversity, small- and large-scale comparisons are hampered because varying methods have been applied (France and Rigg 1998). For a comparative biodiversity assessment on multiple scales, within an area, between areas, or among global gradients, a unified approach is needed (e.g., Rabb and Sullivan 1995, Mikkelsen and Cracraft 2001). The Census of Marine Life, and its associated projects such as NaGISA, is such a framework for the global study of biodiversity.

CoML and NaGISA

The Census of Marine Life (CoML) is a major international research program assessing and explaining the diversity, distribution, and abundance of marine organisms throughout the world’s oceans (expected to be completed by 2010). Technical and political barriers, as well as the vastness of the oceans, have kept these areas of the globe largely unexplored. New technologies, the end of the Cold War, and increased concerns about the health of life in the oceans are among the factors that combined make the concept of a census feasible and necessary. During 1999 a group of scientists from many countries committed themselves to making CoML happen, and the CoML is now active around the world. The History of Marine Animal Populations (HMAP) project, the Future of Marine Animal Populations (FMAP), and a series of Initial Field Projects are being combined together in the Ocean Biogeographic Information System (OBIS) database, which is becoming a powerful and accessible tool for viewing, understanding, and predicting the future of life in the oceans.

NaGISA (Natural Geography in Shore Areas) is one of the initial field projects within CoML that focuses on biodiversity in intertidal and shallow subtidal communities. The land and sea meet along millions of kilometers around the world, where the combination of solar, tidal, and wave energy have fueled the evolution of some of the earth's most complex ecosystems, from temperate rocky intertidal to tropical coral reefs. A project studying nearshore areas has special challenges because it focuses on the zone most heavily affected by humans. It is also the zone most studied by humans, but because it is so diverse and so subject to influences from pollution to global warming and changing sea levels, baseline studies are critically needed over most of the world's coasts. NaGISA is the Census of Marine Life project specifically designed to meet these challenges globally by standardizing a simple, economical but powerful protocol for comprehensive coverage of shore zones out to 20 m depth. At present, NaGISA targets sampling in rocky shore/large macrophyte areas, and in seagrass soft substratum communities that are very complex and are less well characterized than coral reef communities. Providing complex three-dimensional structure, macroalgal rocky communities and seagrass communities are important habitats for many fish species (e.g., nursery or refuge areas) and an abundance of invertebrates. By employing a standard set of protocols (see below) in many areas, large-scale and even global comparisons can be made.

The NaGISA project was initiated by Yoshihisa Shirayama (Seto Marine Biological Laboratory, Kyoto University, Japan), and the Sloan Foundation has funded the establishment of NaGISA centers in Japan and Alaska. The Japan center is working to establish sampling in the Western Pacific, and it aims to complete an equatorial longitudinal gradient from the east coast of Africa to the Palmyra Atoll. The Alaska center (ANaGISA) is organized by Brenda Konar and Katrin Iken (University of Alaska Fairbanks, USA) and is working toward a pole-to-pole latitudinal transect along the Eastern Pacific coast and possibly the Western Atlantic coast. Recently, a South American branch, NaGISA-SA, was established and is working under the direction of Miriam Fernandez (University of Santiago, Chile).

NaGISA sampling protocol

The NaGISA sampling protocol is intentionally basic in design and is intended to yield baseline data for the sampling sites. This will allow for the most flexibility of individual scientists to use the NaGISA protocol in conjunction with other ongoing projects, or to expand on the NaGISA baseline data for conservation, monitoring programs, or for testing ecological hypotheses. The economic design of the sampling protocol allows many countries to join. The protocols are published in Shirayama et al. (2002).

It is suggested that at least three core areas are sampled in each 20º bin along the proposed latitudinal and longitudinal transects. A core area is a larger geographic area with similar physical and environmental influences. An example of a core area in a recently funded NaGISA project in Alaska is Kachemak Bay (Fig. 1). Each core area comprises several (ideally three or more) study sites, which will be sampled in replicates of five transects. In the example of Kachemak Bay, study sites would be Outside Beach, Jakolof Bay, Elephant Island, and Cohen Island (Fig. 1). Replicate transect samples at each site will be collected at the high, mid-, and low intertidal and at 1, 5, and 10 m subtidal water depth, with optional sampling at 15 and 20 m depth. Targeted community types at present are large macroalgal/rocky shore communities and seagrass soft substrate communities. There are two levels of target sampling of increasing difficulty: (1) Non-destructive sampling of five quadrats for macro-algal and/or seagrass soft-bottom communities (counts and photographic imaging); and (2) Destructive sampling of five quadrats for each sampling strata at each site for standard identification of macrophyte, small macrobenthos, and meiobenthos.

Area and site selection criteria

Ideally, core areas and study sites are selected by the following criteria:

Existing infrastructure—Nearby laboratory facilities are suited to accommodate sample processing and will likely facilitate planning and coordination of research efforts. A major benefit of locating monitoring sites near a research facility is that routine measurements of biodiversity and physical variables can often be carried out relatively cheaply using student labor or other on-site/near-site human resources. Laboratory infrastructure is particularly desirable for those locations that are likely to develop into long-term monitoring sites.

Baseline information—The existence of historical data for a site allows closer comparisons between former and current states, and may help in the process of site selection. In addition such information would be useful for future compilation of biological information.

Pristine-ness—It is desirable that monitoring should be carried out in areas that are as natural as possible, e.g., in reserves, within marine protected areas, or otherwise pristine areas.

Long-term stability of the site—It needs to be ascertained that a proposed sampling site is likely to remain the same during the

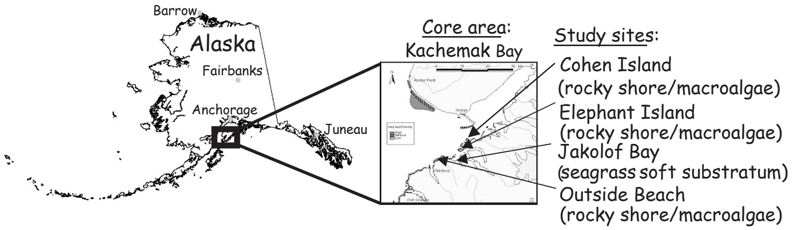

Figure 1. Example of a core area and study site distribution in South-central Alaska.

monitoring period. Thus it may be necessary to determine if coastal development is intended. It is important to eliminate human-caused variables as far as possible.

Accessibility—Sites that are more pristine are frequently the most remote and difficult to access. Some coasts are also subject to greater wave exposure and are less able to be regularly sampled. This also could be a potential safety hazard for scientists and local community people involved in sampling.

Biological character—Pre-selection criteria can include known biodiversity values. It is also important that the target habitats, i.e., “homogeneous” macroalgae (hard) and/or seagrass (soft) substratum habitats have a shoreline extent of 20-200 m to allow replicate sampling.

Sampling protocol

Sampling of rocky substrates/macroalgal cover

At each study site a stratified random sampling strategy will be employed, with strata representing vertical heights above and below low water datum. That is, for each site, five random replicate samples will be taken at high, mid-, and low intertidal positions and 1, 5, and 10 m subtidal water depths (15 and 20 m depth strata are optional). The most expedient randomization procedure should be adopted. Sampling of each study site should take place at least once a year, during the period of expected highest diversity. It is recommended that sampling be repeated over two years to yield a minimum temporal resolution. A higher sampling frequency per year or over more than two years is encouraged where feasible.

For rocky substrates, three different quadrat sizes will be used at each sample location: 1 × 1 m, 50 × 50 cm, and 25 × 25 cm (Fig. 2).

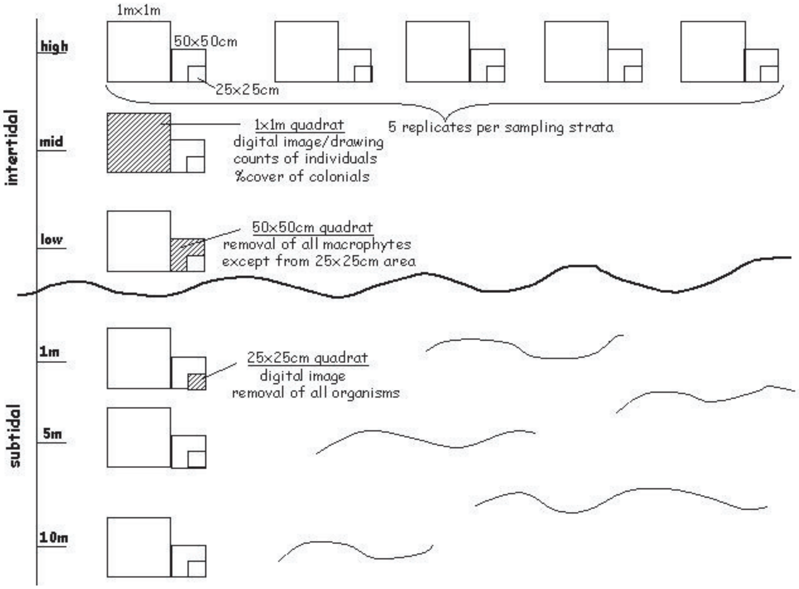

Figure 2. Sampling design for rocky shore/macroalgal habitats. Shown is vertical and horizontal quadrat sample design (only one row each shown as example) within a study site.

Within each 1 × 1 m quadrat, a photographic image record (digital or film) will be made immediately prior to sampling. If conditions do not permit such a photographic record to be made (e.g., poor visibility) then a hand-drawn map should be constructed as an alternative. All macrophytes and conspicuous macrofauna (>2cm length) within the 1 × 1 m quadrat will be identified in situ, and either counted or an estimate of percent cover made using a standard technique. Counts will be made of solitary macroflora and macrofauna while percent cover will be used for species whose individuals cannot be differentiated (e.g., colonial organisms).

Adjacent to the 1 × 1 m quadrat, a 50 × 50 cm quadrat will be placed. Within each 50 × 50 cm quadrat, a 25 × 25 cm quadrat shall be placed (always the same position within the larger sample). Within the 50 × 50 cm quadrat all macroalgae shall be completely removed, except for the 25 × 25 cm area. This 50 × 50 cm sample is taken in order to ensure sufficient algal reference material to support the in situ observation.

In each 25 × 25 cm quadrat, a photographic image record (digital or film) should be made immediately prior to sampling. All macrophytes and fauna within the quadrat will be carefully and completely removed and placed into a 63 μm mesh bag. Hand scrapers will be used to facilitate removal of attached organisms.

Sampling of seagrass soft substratum

At each study site five random replicate samples are to be taken in the center of the seagrass bed. The most expedient randomization procedure should be adopted. Sampling of each study site should take place at least once a year, during the period of expected highest diversity, but more frequent sampling is encouraged where feasible.

For seagrass communities, two different quantitative samples will be taken at each location: a 50 × 50 cm quadrat and a 15 cm diameter cylindrical core.

In each 50 × 50 cm quadrat, counts will be made of solitary fauna, flora, and seagrass shoots. Percent cover estimates (using a standard technique) will be made for encrusting colonial organisms.

In each 15 cm diameter cylindrical core (to 10 cm substrate depth), a photographic image record (digital or film) will be made immediately prior to sampling. All macrophytes and fauna within the core sample will be carefully and completely removed. All organisms will be transferred to a 63 μm mesh bag. If possible, cores will be sieved in the field using a 63 μm mesh sieve.

Physical descriptions

When possible, the surface and bottom seawater temperature should be measured at each sample location. In addition, the substratum should be visually classified according to the standard Wentworth convention for the description of sediments. GPS coordinates should be taken of all study sites. If possible, data loggers should also be placed at each study site to acquire temperature information. These loggers can be retrieved in year two of the sampling.

Initial processing of direct samples

Resulting samples should be sieved on nested meshes of 0.5 mm and 63 μm. Macrophytes remaining on the 0.5 mm sieve should be carefully washed (and if necessary scraped) over the mesh to remove associated macrofauna. Both the floral and faunal component of the 0.5 mm sample are to be retained, but should be stored separately. The material retained on the 63 μm sieve will largely comprise meiofauna. All portions of the sample should be separately fixed and preserved using 5% neutralized concentrated formalin (35% formaldehyde) saturated with borax (sodium hexaborate) seawater formalin (2% formaldehyde).

Secondary processing of direct samples

All macrophytes will be sorted for species and a wet weight determined. For each macroalgal species a wet weight–dry weight ratio will be established. For this, wet weight of a small subsample per species will be taken, and then the sample will be dried at 60ºC for 24 h and weighed again. Dried samples will be re-weighed every 24 h until a constant weight is reached. Selected samples will be pressed and vouchers made. All macrofauna also will be sorted by species and wet weight determined. Vouchers also will be made from these samples. Meiofauna (64 µm portion) will be stored for future work.

Analysis

Wet weight and, where possible, individual counts, will be determined for all macroflora and macrofauna. From this, various parameters can be analyzed, including species richness, evenness, dominance and rare species, as well as diversity indices calculated, such as the Shannon Weaver index and the Hurlbert biodiversity index. All data resulting from NaGISA sampling will be entered into the fully georeferenced database OBIS (Ocean Biogeographic Information System) where these indices can be calculated, or large-scale comparisons can be made.

Recommendations

The above protocol constitutes the minimum standardized sampling requirement for the proposed biodiversity determination, comparison, and monitoring study. The following recommendations represent actions that are considered useful optional additions to the program: (1) Sampling to take place more than once a year, e.g., during separate periods of highest diversity for macrophytes and associated fauna; (2) Sampling of additional habitats that occur at study site, e.g., mangrove, coral reef, unvegetated sediment, sandy beaches; (3) Creation of a macrophyte and macrofauna reference collection for the study site; (4) Taking of additional samples for future molecular studies (fixed and preserved in 100% ethanol); (5) Compilation of a site species inventory from existing information; (6) Construction of site history, e.g., adjacent terrestrial land use, potential anthropogenic impacts; (7) The addition of other surveys (fish, larger mobile invertebrates, etc.); and (8) Measurement of other abiotic factors at each study site, e.g., light, current, salinity, chlorophyll a, suspended sediments, water chemistry, etc.

Sampling kit

The following is a basic sampling kit needed to perform NaGISA transect sampling.

a. Underwater digital camera

b. Sorting sieves (0.5 mm and 64 µm)

c. 64 µm mesh collecting bags

d. Laptop computer capable of storing images and data handling

e. A floating, waterproof Global Position System

f. Data logger (temperature, etc.) to provide environmental context

g. Sediment cores

h. Quadrats and transect tapes

i. Collecting vials for invertebrates

j. Pressing paper and press for algal vouchers

k. Drying oven

l. Toploading balance (1 g-1,000 g range recommended)

m. Formalin for voucher preservation

Quality insurance of data

Taxonomic identification of species is guaranteed through the involvement of taxonomic specialists. Taxonomists are a vital part of any NaGISA project; samples that cannot be positively identified in the field, have to be identified by a specialist for that particular taxonomic group. It is encouraged that different groups working on NaGISA build a network and share their information and access to taxonomic specialists since taxonomic expertise for rare groups may not always be locally available. Enumeration of taxonomists should be considered in the funding requirements. Data with uncertain taxonomic identification should be clearly marked before data entry into the common database OBIS.

Scientists also insure quality of data through the planning and organization of sampling, and the supervision of students and public (see below) involved. The close interaction between taxonomic experts and students is a valuable tool in capacity building.

Outreach

Outreach is an important component in NaGISA. The part of NaGISA working in the intertidal allows the involvement of local communities, youth groups, and students of many age groups. Participation in a real science project in their "front yard" will raise people's awareness about the diversity of marine communities, about the problems of overexploitation, habitat fragmentation, global warming, and the need for protection. Many other means of outreach are available within NaGISA, such as local presentations, Web pages (http://www.westnurc.uaf.edu/anagisa.html), and participation in OBIS which is publicly accessible.

Funding of NaGISA transects

Funding for sampling NaGISA transects should be raised locally. The nearshore character of NaGISA is ideally suited to meet local needs for coastal management, monitoring, or conservation issues. The basic character of NaGISA allows tailoring of proposals toward local questions, and to build on the NaGISA baseline data for further applied or scientific questions. Being a nearshore project with a large intertidal component, NaGISA can also be linked with a strong local community involvement or with student involvement during field classes (see above). This can reduce the cost of transect sampling considerably.

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Biodiversity of the Arctic Ocean

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The history of Arctic faunal studies in Russia began more than 200 years ago. As early as the end of the eighteenth century the Zoological Museum acquired its first collections from the Barents, Kara, and White seas. Since then Russian scientists have obtained samples from more than 14,000 stations in Arctic seas, most of which were from the Barents and White seas. The number of samples collected from these stations is several times higher than the number of stations. A large part of the material obtained has been deposited in the scientific collections of the Zoological Institute. There are more than 90,000 samples of different animal taxa collected from the Arctic seas in the collections.

There are several institutions that participated in the study of the Arctic marine flora and fauna in Russia, including four institutions at the Russian Academy of Sciences: Zoological Institute in St. Petersburg, Institute of Oceanography in Moscow, Murmansk Marine Biological Institute in Murmansk, and Botanical Institute in St. Petersburg. Colleagues from the Institute of Oceanography studied materials collected in the Barents and Kara seas before the Second World War and materials of several Russian drift ice stations in the Canada Basin, *North Pole 22* (1976-1978, 1978-1979, 1980), and in the Makarov Basin, *North Pole 23* (1977). Moreover, in 1993 the Institute of Oceanography carried out an expedition into the Kara Sea; 68 samples were collected. During 1988-2000 the Murmansk Marine Biological Institute carried out 26 expeditions into the Barents, White, and Kara seas. About 2,000 samples at 630 stations were collected during these expeditions. Between 1967-1989, the Zoological Institute carried out 12 expeditions into different Arctic seas from the Barents to the Chukchi Sea where more than 1,000 samples were collected. In shallow waters to a depth of 40 m, quantitative investigations were performed using scuba. This method allows for more precise results to be obtained on the predominantly hard substrate in the upper parts of the shelf and among algae than the quantitative analysis of abundance and distribution using grabs or trawls from a research vessel.

In the beginning of the 1990s, a freedom enveloped Russia and a possibility of closer cooperation of Russian scientists with foreign colleagues appeared. The fall of the Iron Curtain allowed organizing several expeditions, which were financed mainly by Western countries (Germany, Norway, United States, and others). Scientists from the Zoological Institute took part in 14 expeditions aboard Russian, German, and U.S. vessels. About 1,000 samples at 470 stations were collected during these expeditions.

The study of the rich material collected during the last nine years has allowed us to considerably increase our knowledge about species diversity of the insufficiently studied Siberian seas, such as the East Siberian, Chukchi, and Laptev seas. As a result of seven expeditions on board the German icebreaker *Polarstern* (1993, 1995, 1998) and the Russian research vessels *Ivan Kireev* (1993), *Prof. Multanovsky* (1994), *Capitan Dranitzin* (1995), and *Jakov Smirnitsky* (1995) almost 400 more species were discovered in the Laptev Sea alone. Some of the above-mentioned and several other expeditions also worked in other Arctic seas besides the Laptev Sea and in the adjacent deep waters of the Arctic Basin, which resulted in the addition of many more species to their species lists.

The book *List of Species of Free-Living Invertebrates of Eurasian Arctic Seas and Adjacent Deep Waters* is a result of our investigations during the last ten years. It includes about 4,800 species of invertebrates. The area covered extends from Svalbard, Bjørnøya, and Nordkapp (25°47'E) in the western Arctic to Point Barrow (157°W) in the east and includes the White, Barents, Kara, Laptev, East Siberian, and Chukchi seas and the deep-water part of the central Arctic Basin adjacent to these seas. The lists of species were prepared mainly by the most skilled taxonomists in Russia (Zoological Institute of the Russian Academy of Sciences [RAS], P.P. Shirshov Institute of Oceanography of the RAS, Institute of Marine Biology, Far Eastern Branch of RAS, St. Petersburg State University, Moscow State University) and the Ukraine (Institute of Biology of Southern Seas of the Ukrainian Academy of Sciences, Kharkov State University). Fifty-nine taxonomists took part in compiling the lists. Lists of only six small invertebrate taxa were compiled by non-specialists including Acari, Tanaidacea, Cladocera, Phoronida, Enteropneusta, and Appendicularia. Most species lists were prepared using collections, published and unpublished catalogues, and literature data. The lists cannot be considered a complete listing of all species inhabiting Eurasian seas of the Arctic because non-described species in collections of the Zoological Institute were usually not included. In the future, these lists should be updated regularly. The present version was completed in May-September 2001 for different invertebrate taxa. The present up-to-date checklist is the first step in producing "Illustrated Keys for the Identification of Free Living Invertebrates of Eurasian Seas of the Arctic," which the Zoological Institute intends to publish in the near future.

The most species rich Eurasian sea of the Arctic is the Barents Sea, inhabited by 3,245 invertebrate species. The White Sea fauna is an impoverished Barents Sea fauna comprising 1,817 species. The number of species steadily declines eastward from the North Atlantic: 1,671 species are known for the Kara Sea, 1,472 for the Laptev Sea, 1,011 species for the East Siberian Sea, and 1,168 species for the Chukchi Sea. These figures suggest a notable influence of the Atlantic Ocean on the faunal composition. Pacific species play a minor role; their importance shows in the Chukchi Sea (mainly), the Beaufort Sea, the east Siberian Sea, and in the eastern part of the Laptev Sea. There are 837 known species in the deep-water part of the central Arctic Basin adjacent to Eurasian seas.

Species composition of the Barents and White seas is best compared to other Arctic seas. Species composition of some groups (Ciliophora, Turbellaria, Harpacticoida, Nemertini, and Nemathelminthes) in the White Sea is better studied than in other Arctic seas owing to several biological stations permanently maintained in the White Sea. Fauna of the Kara, Laptev, and Chukchi seas is less known, and the species composition of the east Siberian Sea is the least known.

The fauna of Arctic marine invertebrates comprises three large groups: macrobenthos, comprising 60% of the species, meiobenthos—34%, and plankton—approximately 6%. Our knowledge of planktonic organisms, which have a lower species diversity and a wider distribution range compared to benthic animals, is more complete. Different benthic groups have been studied to varying degrees. The study of species diversity started with large organisms. Therefore, macrobenthos is better studied than meiobenthos. Meiobenthic groups such as nematodes, turbellarians, harpacticoids, and ostracods are particularly poorly studied. Several groups of invertebrates are variable in the study areas: Sarcomastigophora, Ciliophora, Annelida, Crustacea, and Mollusca.

Analysis of the distribution of different benthic biocenoses in the Eurasian seas has allowed us to establish some regularities. It turns out that belts with dominant groups of animals are typical for these seas. The estuarine Arctic complex with species such as *Portlandia aestuariorum* and *Cyrtodaria curriana* inhabits areas close to large rivers. There is a very broad belt of the biocenosis dominated by different species of bivalves in the more open waters. More than ten species of bivalves, such as *Astarte borealis*, *Macoma calcarea*, *Portlandia arctica*, *Leionucula tenuis*, *Nuculana pernula*, *Nuculana radiata,* and others inhabit the belt. At a depth of 60-540 m there is also a broad belt of the biocenosis dominated by brittle stars (*Ophiocten sericeum*, *Ophiopleura borealis*, *Ophiocantha bidentata*) and different species of polychaetes.

At depth greater than 540 m ophiuroids disappear as the dominant group in grab samples. At most stations polychaetes keep the dominant position or share it with sponges, coelenterates, bivalves, sipunculids, holothurians, or rarely with other groups of invertebrates.

Between the depths of 1,580 m to 3,310 m the members of the deepwater complex are met with groups of typical species. These are holothurians (*Kolga hyalina*, *Elpidia heckeri*), sea urchins (*Pourtalesia jeffreysi*) and bivalves (*Cyclopecten frigidus*). However, so far we have not been able to distinguish a special community where the above-mentioned species are dominant because the species composition of these areas differs little from adjacent areas and, moreover, the main dominants in these areas often turn out to be polychaetes.

In the northern part of the Laptev Sea in the region where Gakkel Ridge meets the continental slope, the subfossil shells of mollusks of the genus *Archivesica* were found in two samples on station 50 (*Polarstern*, 1993, 77º41.43 to 77º41.10'N; 125º55.68-125º54.16'E, depth 1,993-1,992 m) and station 3 (*Polarstern*, 1995, 77º46.1'N; 126º07.3'E, depth 2,054 m). These mollusks are the characteristic member of homotrophic communities. Morphological analysis of these shells showed that they are very closely related to the Californian species *Archivesica* but are rather a new species. The composition of fauna and some other features of station 50 deserve special attention. The total number of dead and live species of benthic animals in the trawl was 37. Three shallow water bivalves (*Astarte montague*, *Serripes groenlandicus*, *Hiatella arctica*) occurred only as empty shells, and presumably were transported in ice rafts from the Laptev Sea shelf. The rest of the 34 species were either deep water or ubiquitous. Among them polychaetes (*Nicomache* aff. *trispinata* and *Capitella capitata*), isopods (*Saduria sabini megaluroides*), gastropods (*Mohnia danielsseni*) and sea cucumbers (*Kolga hyalina*) were the dominants. The species number of the trawl station 50 (34 species) was poorer than that from the neighboring stations 32 (36 species) and 54 (38 species), although these stations were deeper (3,012-3,028 and 3,039-3,042 m, respectively).

During the last ten years we cooperated mainly with German colleagues from the Alfred Wegener Institute for Polar and Marine Research and from the Institute of Polar Ecology. The product of our collaborations with the Alfred Wegener Institute is a set of articles on the fauna of the Laptev Sea and the book *Biodiversity of the Weddell Sea: Macrozoobenthic Species* (demersal fish included) sampled during the expedition ANT XIII/3 (EASIZI) with RV *Polarstern*. Our institute also maintains an active collaboration with the University of Alaska Fairbanks and Norwegian Akvaplan-niva in the study of biodiversity in the Barents and Chukchi seas.

Biodiversity of Free-Living Invertebrates in the Far Eastern Seas and the Proposition of NaGISA Transects around the Bering Sea

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The Vitus Bering Expedition started Russian investigations of the Far Eastern seas in the first half of the eighteenth century. Since then about 150 expeditions have been organized in those regions. A rapid increase in the investigation of marine fauna occurred in the 1960s when Russian scientists began using scuba equipment. Aqualung permitted studies of previously inaccessible shallow water areas with predominantly rocky and gravel substrate. Valuable material on invertebrate fauna has been obtained since the early 1980s as a result of using the submarine vehicles *TINRO-2, Sever-2, Pisces*, and *Mir* in deeper waters.

During the entire study period of Far Eastern seas approximately 15,000 stations were sampled and a large number of samples were taken. Unfortunately, taxonomists examined only part of the material; some of it was lost. Most of the preserved material has been deposited in scientific collections at the Zoological Institute in St. Petersburg. The remaining material was deposited in the Institute of Oceanography at the Russian Academy of Sciences, the Zoological Museum at Moscow State University in Moscow, the Institute of Marine Biology at the Russian Academy of Sciences in Vladivostok, and in the Kamchatka Institute of Ecology and Nature Management at the Russian Academy of Sciences in Petropavlovsk-Kamchatski.

Here, I am reporting results on the analysis of biodiversity of invertebrate fauna inhabiting the Russian part of the Far Eastern seas. The American fauna of the eastern part of the Bering Sea and fauna of the southern part of the Sea of Japan are not taken into account. The entire study region is divided into five areas: Bering Sea,

Sea of Okhotsk, Sea of Japan, Pacific coast of Kamchatka including the Commander Islands and the north and middle Kurile Islands and, separately, the south Kurile Islands.

Information obtained from leading scientists in Russia and published data have permitted me to characterize the diversity of marine invertebrates in each of the above-mentioned areas and also to show the degree of knowledge available about them. It appears that the fauna of free-living marine invertebrates in the Far Eastern seas of Russia includes 5,940 species. This does not include species of several groups: Cyclopoida, Rotatoria, and Appendicularia. Apart from free-living species, about 900 parasitic invertebrate species are known from the Far Eastern seas. Species distribution of different taxonomic groups suggests that the most numerous invertebrates are the arthropods, consisting primarily of about 1,700 species of crustaceans. Next to them in diversity are the mollusks (more than 600 species), protozoans (approximately 500 species), tentaculates (more than 400 species), and echinoderms (around 400 species). Analysis of species distribution in ecological groups shows the greatest diversity for macrobenthos (around 4,500 species), and less for meiobenthos (882 species) and plankton (592 species).

Comparison of the invertebrate fauna within areas of the Far Eastern seas reveals a regular decline in the number of species from south to north (from 2,900 species in the Sea of Japan to 2,000 species in the Bering Sea). Therefore, the Sea of Japan appears to be the most species rich within the five regions that were separated. Following the Sea of Japan is the Sea of Okhotsk, the region from the middle Kurile Islands to the Commander Islands, the south Kurile Islands, and lastly the Bering Sea.

Over the past 40 years the pace of studying biodiversity has increased considerably. Comparison of recent data with the data published by P. Ushakov (1953) and L. Zenkewitsh (1963) shows that the number of species of known invertebrate organisms nearly doubled during that period. Around 200 new species have been described for mollusks over the past 15 years. Scientists studying ostracods, bryozoans, ascidians, and polychaetes have described tens of new species.

Questioning of leading specialists allowed me to obtain approximate data on the possible number of all invertebrate species inhabiting the Far Eastern seas. It appears that in this area, one can expect to find more than 9,000 invertebrate species. More than 3,000 species of marine organisms or 34% of the entire fauna of the Far Eastern seas remain unknown. A part of these species, no doubt, will be new to science. Different groups have been studied to varying extents; 80 to 90% of some groups of invertebrates have been studied; these include sponges, hydroids, mollusks, decapods, echinoderms, etc. Only 8-10% of nematodes, 30% of turbellarians, and 40% of scyphozoa have been studied.

I would like to note that, considering the great diversity of fauna in the North Pacific, close cooperation is needed in this field among Russian institutions and on the international level, in particular with scientists from North America. Only joint efforts will attain considerable progress in studying patterns of biodiversity.

In this connection I consider a series of short nearshore NaGISA transects around the Bering Sea to be very important. This region of the junction of Asian and American fauna is needed to understand the origin and distribution patterns of fauna in the whole north Pacific Ocean. Preliminary investigations of species composition and distribution of the rather small and mainly shallow water group Polyplacophora, or chitons, shows an interesting peculiarity. There are 31 species of chitons in the shelf fauna of the Aleutian Islands and the eastern Bering Sea, while only 18 species occur in the shelf fauna of the Commander Islands and eastern Kamchatka. Moreover, 16 species are common for the both regions. We can say that the chiton fauna of the Commander Islands and eastern Kamchatka is impoverished compared to the Aleutian Islands and eastern Bering Sea. However, chitons are principally warm water animals. It would be interesting to compare the fauna of other non-warm water groups of plants and animals.

According to the data collected by an expedition of the Zoological Institute in 1975 to eastern Kamchatka and the expeditions of the Kamchatka Institute of Ecology and Natural Management in 1986 and 1987 to the Bering Islands, the dominant species in both areas are rather similar. About half of the dominant algal and animal species are common for both regions. They consist of the algal genera *Laminaria, Alaria, Thalassiophyllum, Agarum, Neoptilota*, and *Lithothamnion*, barnacles of the genus *Semibalanus*, and sea urchins of genus *Strongylocentrotus*.

My own underwater observations in 1973, 1977, and 1990 from east Kamchatka and the Commander Islands and in 1988, 1999, and 2000 from the eastern Aleutian Islands near Dutch Harbor showed much similarity in species composition of the dominant species. These observations showed that the Aleutian fauna is more diverse than the fauna of east Kamchatka and the Commander Islands. It would be interesting to compare present day data with the historical data obtained in 1975 (near east Kamchatka and in 1972, 1973, 1986, 1991, and 1992 near the Commander Islands).

Biodiversity of the Commander Islands and Bering Sea Coast of the Kamchatka Peninsula by Russian Scientists

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Since the eighteenth century naturalists have rather accurately studied the terrestrial fauna and flora of the Commander Islands and Kamchatka Peninsula. However, hydrobiological studies have only been carried out periodically since the 1930s in the southern part of the Pacific coast (Gur'yanova 1930, Tarakanova 1964, Spasskii 1964, etc.). Unfortunately, a portion of these collections was lost. Another portion was worked up and deposited in the collections of the Zoological Institute and Botanical Institute of the Russian Academy of Sciences. Taxonomists have used these samples for systematic reviews but from a biocenological point of view, these samples were discussed only in one popular paper (Gur'yanova 1935).

Detailed research of the intertidal and sublittoral zones around the Commander Islands and some areas of the Bering Sea coast of Kamchatka began in the 1970s-1980s. Modern hydrobiological methods and scuba were used for studying benthic intertidal and subtidal communities. Different areas of the Mednyi and Bering islands, and the gulfs of Karaginskiy and Olutorskiy of the Bering Sea coast have examined sampling areas of between 100 cm^2 and 1 m^2. A number of standard hydrobiological sections have been performed; hundreds of qualitative and quantitative macrobenthos samples and some thousands of herbarium sheets of various groups of algae were collected (Fig. 1). Samples were sorted into taxonomic groups, organisms counted and weight (blotted on filter paper) determined within 10 mg. Samples were preserved in 75% alcohol or 4% seawater formalin solution. Species lists of intertidal algae and animals summarized from different collections were published in 1978. A total of 121 species of algae and 308 species of animals were reported for

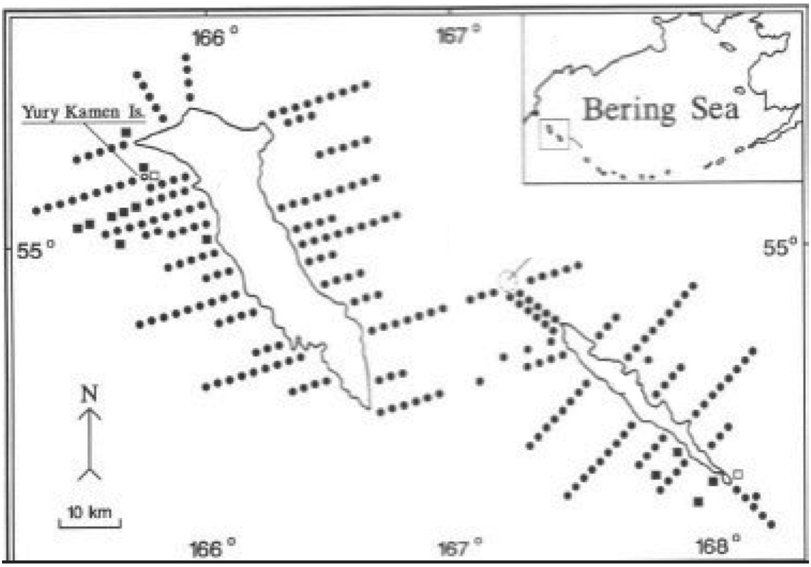

Figure 1. Schematized map of Commander Islands. Intertidal points, subtidal transects, and scuba diving stations are designated.

the Commander Islands and the gulfs of Olutorskiy and Karaginskiy (Kusakin 1978, Vinogradova et al. 1978).

The intertidal of the Commander Islands has been investigated in reasonable detail. There is a description of the intertidal zonation and composition of belt-forming communities of the Mednyi and Bering islands. The population density, biomass, species diversity, and trophic structure of various low-, mid-, and high-intertidal communities have been described. In general, a high species richness of macrophytes and zoobenthos in the littoral zone has been established: 263 species for the Kamchatka coast, 163 species for Mednyi Island, and 145 species for Bering Island (Tarakanova 1978, Kusakin and Ivanova 1995).

Between 11 and up to 29 belt-forming communities were described for different areas of the Bering Sea coast of Kamchatka and the Commander Islands, all of which are distinguished by different dominant species of macrophytes and invertebrates. Within the kelp zone of Mednyi Island, 47 species of macroalgae and 116 species of macrobenthic animals were found; this does not include some species of actinians, nemerteans, and ascidians that are still unidentified. With respect to species richness and diversity, polychaetes (35 species), red algae (24), brown algae (17), gastropods (20), amphipods (19), and bivalve mollusks (12 species) ranked highest (Fig. 2). The biomass of the belt-forming algae amounted to 36 kg per m^2 for *Laminaria longipes*, 22 kg per m^2 for *L. yezoensis*, 15.9 kg per m^2 for *L. bongardiana*, 26 kg per m^2 for *Alaria angusta,* 12.6 kg per m^2 for *A. fistulosa,* and 15.9 kg per m^2 for *Cymathere triplicata*. Among invertebrates the greatest biomass was recorded for the sponge *Halichondria panicea* (4.8 g per m^2, Kusakin and Ivanova 1995) (Fig. 3).

A similar picture of intertidal species richness and diversity was observed on Bering Island. The dominant macrophytes were *Laminaria bongardiana, Fucus evanescens,* and, among invertebrates, the barnacle *Balanus cariosus* and the hermit crab *Pagurus hirsutiusculus*. In some places, the biomass of the sea urchin *Strongylocentrotus polyacanthus* exceeded six times the biomass of seaweed in the community zone of *Ulva fenestrata* and *Bossiella cretacea* (Tarakanova 1978).

More than 20 community types were described from 14 study sites along the intertidal of the Bering Sea coast of the Kamchatka Peninsula. They were characterized by the dominance of the brown algae *Laminaria bongardiana, Fucus evanescens* and other associated algal and animal species similar to those on the Commander Islands (Kusakin, Ivanova 2002).

Some floral and faunal groups in the shallow subtidal of the Commander Islands have been investigated (Fig. 4). A total of 648 species were recorded, almost 25% of them being macroalgae (Sheiko and Stepanjans 1997). Detailed data on species composition, ecology, and distribution have been given for macrophytes (150 species), sponges (47), hydrozoans (52), nemerteans (17), polychaetes (125), bryozoans (141), chitons (18), bivalves (20), gastropods (29), and decapods (25 species).

The collections from three hydrobiological expeditions (1972, 1973, 1993) to the Commander Islands shelf were specifically analyzed for bivalve mollusks. Sixty-three species, 30 of which were new records for this region, have been found. Bivalve species composition was analyzed by depth strata: intertidal zone—20 m, 40-80 m, and 100-300 m—and species composition was found to be determined by the substrate type specific to these depths. A comparative similarity analysis of the bivalve fauna of the Commander Islands shelf with the bivalve fauna of other North Pacific regions shows that the Commander Islands bivalve composition is most similar to Kamchatka (Fig. 5) and the least similar to the Aleutian Islands and Alaska (Kamenev 1995). At the same time, there is one species of prickleback, *Alectridium aurantiacum,* which is common in the intertidal for both the Commander and Aleutian islands (Balanov et al. 1999).

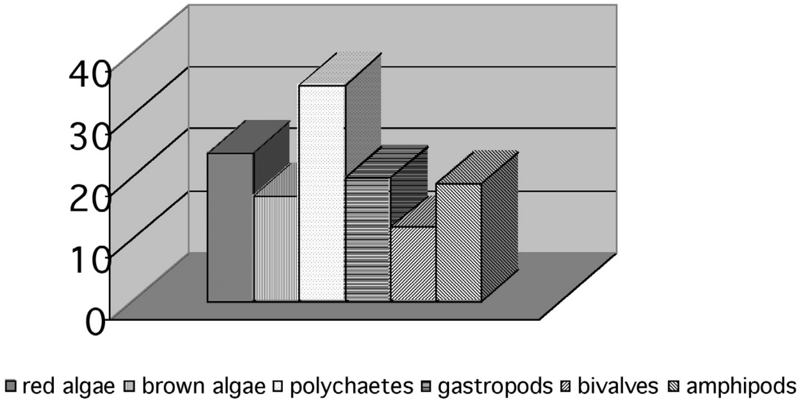

Figure 2. Community of laminarian algae. Species richness of the Mednyi Island intertidal.

Figure 3. Community of laminarian algae. Algal biomass at Mednyi Island.

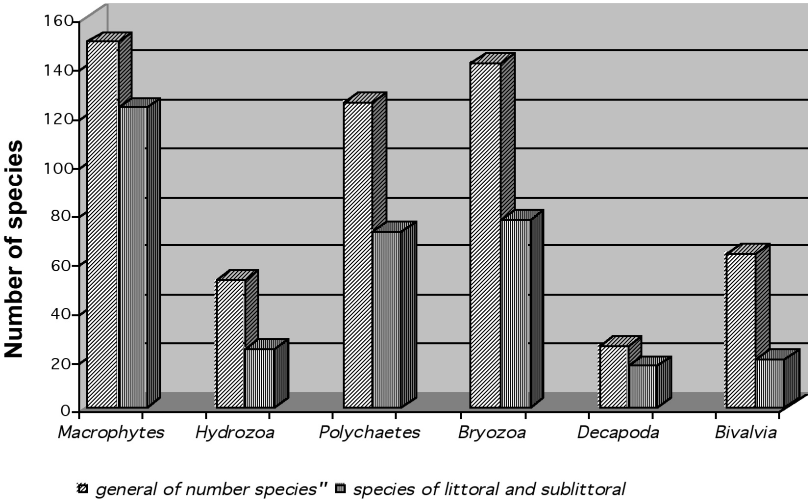

Figure 4. Species richness of shallow waters of the Commander Islands.

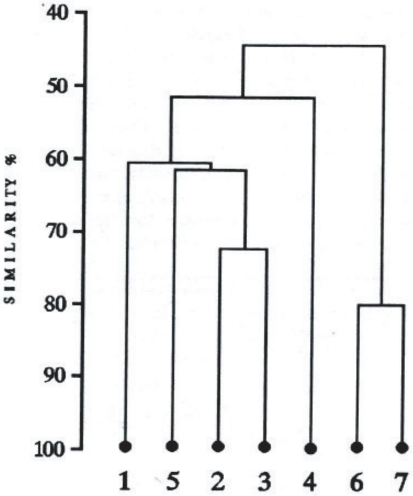

Figure 5. Dendrogram of similarity of bivalve species composition for the seven North Pacific shelf zone regions. 1 = Kurile Islands; 2 = Pacific coast of Kamchatka; 3 = southwestern Bering Sea; 4 = Anadyr Bay; 5 = Commander Islands; 6 = Aleutian Islands; 7 = Bering coast of Alaska (by Kamenev 1995).

At present it is impossible to perform a detailed comparison of the composition and structure of the intertidal communities of the Commander Islands and the Aleutian Islands due to the lack of detailed description of the intertidal biota of the latter. However, judging from the species lists of common algae of the subtidal fringe, many belt-forming species seem to be common for both the Mednyi Islands and the Aleutian Islands. These are *Laminaria longipes, L. yezoensis, Thalassiophyllum clathrus, Odonthalia floccosa,* and others (Estes et al. 1978, Dethier and Diggins 1988, Simenstad et al. 1978, Kusakin and Ivanova 1995). Among the most abundant species of invertebrates mentioned by these authors for the lower intertidal zone and subtidal fringe of the Aleutian Islands are *Strongylocentrotus polyacanthus, Cryptochiton stelleri, Collisella pelta, Leptasterias alaskensis,* and some others that are also typical for the Commander Islands. However, the chiton *Katharina tunicata* that is common in the coastal waters of the Aleutian Islands, including the western ones, is not found on the Commander Islands.

The scientists who worked on the Commander Islands during the last century mentioned the occurrence of the large laminarian algae *Nereocystis luetkeana* and *Hedophyllum sessile* among the common species. The former one was so abundant in the upper subtidal zone and in the infra-littoral fringe that, according to Grebnitskii, it was very difficult for a boat to move through the thickets of this alga (Zinova 1940). Kardakova-Prezhentsova (1938), who worked on the Commander Islands (including Mednyi Island), mentioned that this species often washed ashore during winter, and that the local inhabitants made ropes and lines for halibut fishing out of its trunk-like stipe and used the floats of the alga for some small odd jobs. According to their data, *Hedophyllum sessile,* together with *Alaria angusta* and *Fucus evanescens,* formed dense mats on stones and dried during low tides, and these algae were used to feed cattle and polar fox. However, neither Tarakanova in 1964 nor the authors of this paper in 1972 and 1993 encountered these algae on the coast of the Commander Islands. Only single dried floats of *N. luetkeana* were occasionally found on the beach. As another testimony of change in species ranges, the American isopod species *Idotea* (*Pentidotea*) *wosnesenskii* was found in the rocky mid-intertidal zone of Mednyi and Toporkova islands in great abundance in 1993. This species had never been found on the Commander Islands before, at least not before 1972 (Kusakin and Ivanova 1995).

Long-term studies, which have continued for at least a century in the coastal waters of the Commander Islands by naturalists and later, hydrobiologists, have shown the existence of a continuous exchange of some floristic and faunistic elements between the Commander and Aleutian islands. In such an exchange, the role of the Mednyi Islands, which are closest to the Aleutian ridge, is especially significant. It is interesting that, despite insignificant differences between the hydrological regimes of the Commander Islands and the western Aleutian Islands, the existing exchange of species seems to be limited and undergoing considerable fluctuations.

At the same time, the data on the collections of many invertebrate groups (soft and gorgonian corals, gastropods, ostracods, polychaetes, etc.) remain unpublished and also sorted only into larger taxonomic groups. The biodiversity of the Kamchatka coast remains poorly investigated. The information on these regions sometimes has fragmentary character and is scattered among various reviews on oceanographic regions or taxonomic groups.

The Institute of Marine Biology has highly skilled marine biologists and taxonomists with experience working in various areas of the world's oceans. The institute also provides a diving service with professional divers. Marine operations of the Far East Branch of the Russian Academy of Science has various research vessels without restriction of areas of navigation with laboratories for 25-38 scientists. Employees of the institute perform sampling and processing of intertidal and sublittoral samples. They can provide taxonomic identification of the following groups: Amphipoda, Decapoda, Isopoda, Echiurida, Foraminifera, Gastropoda, fishes, Hydroidea, Mollusca, Ostracoda, Polychaeta, Priapulida, and Sipuncula. Meiobenthos can be sorted into major groups.

It is evident that it could be of considerable interest to execute a detailed comparative hydrobiological survey of the intertidal and sublittoral zones of the Commander-Aleutian arch at the present conditions. Areas of special interest for such a comparison would be Gladkovskaya Bay and Korabelnaya Bay (Mednyi Island), Buyan Bay and Cape Tolstyi (Bering Island), and the area of Cape Africa (coast of Kamchatka).

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Arctic Benthic Diversity: Deep-Sea Meiofauna and Shelf Macrofauna

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Summary

Biological diversity can be examined at different spatial scales: within community (α diversity), between communities (β diversity), and regional (γ diversity) (Whittaker 1975). Most studies compare within community diversity or diversity between communities along an environmental gradient (e.g., depth, productivity), though regional diversity gives greater insight into evolutionary and biogeographic patterns. Biodiversity research examines patterns of biological diversity revealed by these measures of diversity to ask three main questions (Lambshead 1993): (1) what species are present in an area and where are they found? (2) what are the processes causing extinctions and speciation over evolutionary time scales? and (3) what processes control diversity over ecological time scales? My contribution largely compares within community diversity of meiofauna and macrofauna from along a transect in the central Arctic Ocean and among areas on the northeast Greenland Shelf in the Northeast Water Polynya.

The abundance of the meiobenthos and the biomass and community structure of the nematodes in the central Arctic Ocean along two transects, sampled in 1991 and 1992, were investigated by Vanreusel et al. (2000). Meiobenthic densities were on the same order as other oligotrophic areas of the world's deep oceans (<100-600 individuals per 10 cm^2) and nematodes were the numerical dominant meiofaunal group (94%) of the 19 different taxa collected. Water depth and latitude explained 67% and 55% respectively of the variability in nematode biomass, suggesting that both vertical and advective fluxes of organic material are important sources of food to the meiobenthos. In the paper, we used multivariate analyses of nematode genera to reveal differences among stations in the Eurasian and Amerasian basins.

We did not, however, examine patterns of diversity in nematode genera beyond reporting the number of genera found (50 in 1991, and 111 in 1994 of which 41 were also found in 1991). A genus accumulation curve across all samples shows no indication of reaching an asymptote, indicating that the diversity of nematode genera from the central Arctic Basin is in excess of 120 genera.

I used three measures of within community diversity to compare the diversity of meiobenthos among locations across the Arctic Basin. Rarefaction curves revealed large differences in the diversity of nematode genera among stations, $EG_{(125)}$ varied between 11 and 31, but there were no clear patterns. The Amerasian Basin had a greater number of meiofauna taxa (6.4) and nematode genera (29) compared to the Lomonosov Ridge (5.0 and 24.4) and the Eurasian Basin (4.5 and 23.5), but the differences were not significant. Rarefaction curves and K-dominance curves of nematode genera also revealed no differences in diversity among these areas. The Shannon diversity index was also not different between the basins and the Lomonosov Ridge and was not related to water depth or latitude.

Nematode diversity in the central Arctic Ocean appears to be greater than in the Laptev Sea (Vanaverbeke et al. 1997), the one other study of Arctic meiobenthos that identified nematodes (but see Pfannkuche and Thiel 1987). This pattern agrees with the pattern of greater diversity of nematodes from abyssal and bathyl depths in temperate and tropical areas compared to sublittoral and estuarine habitats (Boucher and Lambshead 1995). The diversity of nematodes at similar depths in Antarctica (Weddell Sea) is much greater than we found in the Arctic Ocean. The estimated number of nematode genera from 100 individuals was 1.5 to 2 times greater in the Weddell Sea than in the Arctic Basin and the highest Shannon Index was 3.4 in the Arctic compared to 5.6 in the Antarctic (Vanhove et al. 1999).

Macrofauna (collected on a 250 µm sieve) were collected at the same stations as meiofauna on the 1994 transect. Except for polychaetes, which were identified to family, other taxa were only identified to phylum (nemerteans, sipunculids), class (mollusks), or order (crustacean). Density was low compared to other deep-sea areas, ranging from 141 to 6,878 individuals per m^2 for metazoans with as many as an additional 5,456 Foraminifera per m^2. Biomass ranged from 1.7 to 522 mg C/m^2 with up to 96% accounted for by the Foraminifera. The number of taxa collected exceeded 40 and there was no indication that number of new taxa collected was declining with increasing sampling. The number of taxa collected was similar to the number collected by Kröncke (1998) in the Amundsen Basin and Yermak Plateau and Deubel (2000) in the Eurasian Basin and along the Lomonosov Ridge, but fewer by 50% than the number Kröncke

(1994) collected along a transect from Svalbard to the Makarov Basin. The mean number of taxa per station was significantly greater in the Amerasian Basin (11.3) compared to the Eurasian Basin (5.0) with the number of taxa per station on the Lomonosov Ridge intermediate (7.3). There was no significant difference in the Shannon diversity index among these areas. There was a significant relationship between the number of taxa and both water depth and latitude suggesting that differences between the Amerasian Basin and the Eurasian Basin are due to the deeper depths of the Eurasian Basin stations and its covariate greater distance from the shelf break.

It is difficult to draw any conclusions about the diversity of meiofauna and macrofauna in the central Arctic Basin because so few studies have been conducted in this area. Density and biomass are low as is to be expected for the oligotrophic deep sea. There are differences in community composition and species diversity across the Arctic Basin and the limited data on these communities suggest that organic input, controlled by water depth, distance from shore, and topography, is the most significant factor in explaining patterns (Kröncke 1994, Vanreusel et al. 2000, Deubel 2000).

The Northeast Water Polynya (NEW) is a recurrent annual feature of variable size on the northeast Greenland Shelf. The area is characterized by complex bathymetry: very shallow banks (water depth <40-150 m), separated by a trough system (Belgica Trough in the South and West Wind Trough in the north with water depths of 250 to >500 m). Total abundances of nematodes, polychaetes, and peracarid crustaceans are primarily related to parameters characterizing organic input to the benthos (water column and benthic pigments) while abundances of Foraminifera and megabenthos are largely associated with sediment grain size and bottom water temperature (Piepenburg et al. 1997). Multivariate analysis of polychaete families clearly distinguishes two areas of the northern trough (east and west) and the southern trough as having distinct community composition, with stations from the shallower banks less differentiated. Patterns of benthic diversity in the NEW polynya have not been previously examined.

Over 150 polychaete species were identified from replicate (4-5) cores (0.005 m^2) from 28 stations with no indication that the sampling effort had been sufficient to collect all the species present. The southern trough had significantly fewer polychaete species per sample (14.7) compared to stations from the northern trough (23.4) or central bank (25.7). But infaunal densities are also significantly lower in the southern trough compared to other areas in the polynya (Ambrose and Renaud 1995), biasing any comparison of just species richness. The Shannon diversity index and rarefaction curves confirmed the lower diversity in the southern trough compared to the bank and northern trough. The southern trough has greater ice cover than the central bank and northern trough which open earlier in the season, so it is tempting to explain the lower polychaete diversity in the south compared to the north by differences in water column productivity between these areas. Both polychaete species richness and the Shannon diversity index are negatively correlated with grain size (Φ), however, and stations in the southern trough have a finer sediment (greater Φ) and greater depth than other areas sampled.

A comparison of β diversity between the trough stations and stations on the bank indicates that northern and southern troughs are more similar to each other than to the bank. But the Bray-Curtis similarity index shows only a 33% similarity in the polychaete fauna between troughs, which are only 17% similar to bank stations. The lack of similarity, particularly between troughs with similar water depths and sediment grain size, indicates the need to sample across habitats and at large spatial scales if we hope to examine regional diversity across the Arctic.

More studies of benthic diversity have been conducted on Arctic shelves than in the Arctic Basin. As early as 40 years ago, Zenkevich (1963) estimated there were 1,600 species in the Barents Sea and over 2,000 in the Western Bering Sea (of which 80% are probably benthic taxa, Curtis 1975) while he records only 363 benthic species from the Laptev Sea. While species richness appears to be low in the Laptev and Beaufort seas relative to other shelf areas (Curtis 1975), there appears to be remarkable similarity in diversity on Arctic shelves from the Chukchi Sea to the Barents Sea (Stewart et al. 1985, Grebmeier et al. 1989, Kendall and Aschan 1993, Kendall 1996, Sejr et al. 2000). The estimated number of species for 201 individuals collected ranges from 28 in a Svalbard fjord to 52 in a Greenland fjord with both the lowest (1.0) and highest (5.9) Shannon index recorded from stations in Davis Strait. Most shelf areas, however, have an $ES_{(201)}$ of 35-40 and a Shannon index of 2-3.

Arctic benthic communities do not appear to be impoverished compared to communities on shelves at lower latitudes. A comparison of diversity from the Svalbard Shelf and a fjord on the west coast of Svalbard with lower latitude locations of similar depth and grain size indicates these assemblages are equal in diversity to samples collected from the North Sea and Java (Kendall and Aschan 1993, Kendall 1996). There appears to be no latitudinal gradient in the diversity of infauna on continental shelves.

Most studies of benthic diversity concentrate on the infauna and there have been few studies examining the distribution, abundance, and diversity of epifaunal organisms and all of these studies have been conducted on shelves. Megabenthos in general and epifaunal organisms in particular are not sampled quantitatively with the grabs and cores typically used to sample benthic communities. Photography, either still or video, have proven more successful than core or grab sampling at quantifying the abundance and diversity of epibenthic communities. The epibenthos on Arctic shelves is dominated by echinoderms (see Piepenburg 2000 for review, Ambrose et al. 2001) where densities and biomass of ophiuroids alone can reach 250 individuals per m^2 and 5,000 mg C/m^2 (Ambrose et al. 2001). Piepenburg has conducted photographic surveys of epibenthic fauna around Svalbard (Piepenburg et al. 1996), on the east Greenland Shelf (Piepenburg and Schmid 1996a), in the Laptev Sea (Piepenburg and Schmid 1997), in the Barents Sea (Piepenburg and Schmid 1996b) and north of Iceland (Piepenburg and Juterzenka 1994). These studies and Ambrose et al. (2001) indicate that bottom topography, grain size and hydrography are the most important factors controlling the structure of megabenthic communities on Arctic shelves. A systematic comparison of the epibenthos from Arctic shelves has not been made, but the abundance of echinoderms alone in the Chukchi Sea is the highest recorded on any shelf (Ambrose et al. 2001). In addition, ROV footage from the head of Barrow Canyon suggests that areas with high flux of organic material and diverse bed forms promise to support high epibenthic biomass and diversity.

Clearly more systematic studies of benthic diversity in the Arctic need to be conducted. Our knowledge of the distribution, abundance, and diversity of benthic communities in the central Arctic Basin is particularly inadequate. But even the more numerous studies on Arctic shelves have been concentrated in very few areas. In these areas polychaetes dominate the macrofauna and have received the most attention. Foraminifera often dominate macrofaunal samples from the deep sea, and are common in shelf samples but their patterns of diversity have not been adequately explored (Ahrens et al. 1997, Wollenburg and Kuhnt 2000). There have been only three studies (Vanaverbeke et al. 1997, Pfannkuche and Thiel 1987, Vanreusel et al. 2000) of meiofauna from the Arctic Basin with few samples taken from Arctic shelves (Pfannkuche and Thiel 1987). Furthermore, only one study (Piepenburg et al. 1997) has quantified distribution and abundance patterns of different fractions of the benthos ranging in size over 6 orders of magnitude (from 100 µm for meiofauna to 10 cm for epibenthos). These limited data suggest that the diversity on Arctic shelves is similar to shelves in temperate and even tropical areas, while deep-sea communities in the Arctic are impoverished even when compared to Antarctic communities.

Many of the studies examining biodiversity of the benthos were conducted as part of projects designed to address questions other than biodiversity. Consequently, sampling strategies were not optimized to quantify the diversity of habitats or regions. It is critical to design sampling programs specifically to investigate diversity and not expect to collect useful diversity data as an afterthought to a sampling program designed for other purposes. In order to obtain the spatial coverage necessary to address patterns of regional diversity, it may be necessary to sacrifice finer scale patterns of diversity and some replication. Samples should be collected at a variety of spatial scales along gradients in depth, organic input, and bottom topography using methods to sample the full range of benthic taxa if we are to document and understand local and regional patterns of species diversity in the Arctic.

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Biodiversity in the American Arctic

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What is biodiversity?

Biodiversity is a product of the interactions of life on scales ranging from the smallest, at the chromosome level, to organisms, and ecosystems. There are three general kinds of biodiversity: genetic diversity, species diversity, and habitat diversity. The survival of each is linked to the health of the other two, and together they comprise ecosystems.

Species biodiversity

Species biodiversity is what most people refer to when they discuss biodiversity. Species biodiversity is defined by the kinds and numbers of organisms within a particular region and their pattern of distribution. This discussion will focus on what is known about species biodiversity of the marine habitats of the Alaskan Arctic coastal waters.

History of marine research in the American Arctic

OCSEAP

Prior to 1970, studies of the Arctic coast were limited primarily due to the remoteness of the area and extreme weather conditions. Discovery of oil on the North Slope in 1968 and the subsequent leasing of Beaufort Sea offshore tracts for oil exploration and drilling prompted the U.S. government to sponsor intense baseline studies of the continental shelf surrounding Alaska. The Outer Continental Shelf Environmental Assessment Program (OCSEAP) was established by basic agreement between the U.S. Department of Commerce via the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Department of the Interior, via the Bureau of Land Management (BLM) and Minerals Management Service (MMS), to conduct environmental research on Alaskan Outer Continental Shelf (OCS) areas identified by the BLM for potential oil and gas development. Teams of scientists from many universities and agencies collected data on physical regimes (ice, currents, salinity, temperature, etc.) and biological ecosystems (phytoplankton, zooplankton, benthos, etc.) for a decade starting in 1975. Participating scientists were required to submit reports that were bound into numerous volumes. A bibliography volume listing all submitted reports was printed in 1990. The most complete set is housed at the University of Alaska Fairbanks.

Other research

Several other programs collected data on Alaskan marine species but all focused on the Bering and Chukchi seas with only a few stations sampling the far western portion of the Beaufort Sea. NSF's Inner Shelf Transfer and Recycling (ISHTAR) cruises took place in the summers of 1985 and 1986 and sampled both the northern Bering and Chukchi seas. A Science of Opportunity (SOO) cruise aboard the USCGC *Polar Sea* sampled the Chukchi and western Beaufort seas during June 1998. The Third (1988) and Fourth (1993) Joint U.S.-USSR Bering and Chukchi Seas Expeditions (BERPAC) sampled the western Chukchi and then traveled into waters adjacent to Russia which were previously inaccessible to U.S. scientists. The Western Arctic Shelf Basin Interactions (SBI) program will collect data in the Chukchi and western Beaufort seas in summer 2002 and 2004. Smaller cruises on the R/Vs *Alpha Helix, Northwind, Glacier, Burton Island,* and *Acona* have taken place over the past 25 years in the Bering and Chukchi seas.

Benthic biomass data

The continental shelf of the Arctic Ocean has proven to be a highly productive zone despite low temperatures and only seasonal pulses of particulate organic matter. In 2000 all known Bering, Chukchi, and Beaufort sea biomass data from 62° north latitude and above were compiled and gathered into a Microsoft Access database. Ken Dunton and Jackie Grebmeier were co-PIs on this project working under Phase I of The Western Arctic Shelf Basin Interactions (SBI) program. The data sources used for this project are listed below.

Benthic biomass data sources

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Summary of northern continental shelf research compiled for OCSEAP

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The purpose of the project was to retrieve benthic biological data from NODC and other published and unpublished data. Geographic Information Systems (GIS) software was used to examine and graphically display the spatial and temporal trends of the benthic data. A bathymetric map was built of the study area and data from six researchers' work on 14 cruises made over a 25 year period (1970-1995). The mean biomass data from 1,093 sites were mapped and examined (Fig. 1). An extension of ArcInfo 8.2, Geospatial Analyst, was used to perform geostatistical methods to determine the spatial and temporal trends of the benthic community. Interpolation of the data (by kriging) was used to predict a surface area between data points because it had the smallest mean error and root-mean-square prediction error and most accurately modeled the data. Application of geostatistical techniques revealed areas of high biomass (>250 gm^{-2}) in the southern Chukchi Sea and in the northwestern Bering Sea, compared to less than 30 gm^{-2} on the Beaufort Sea shelf (Fig. 2). The high benthic biomass in the Bering-Chukchi is coincident with the abundance of benthic feeding marine mammals (e.g., gray whales, walrus) in this region.

Shannon-Wiener Diversity Index

A.C. Broad calculated Shannon-Wiener Index values for each of his benthic sampling stations. The Shannon-Wiener function assumes a random sample is taken from an infinitely large population

$$H' = -\sum_{i=1}^{s} \ln(p_i)$$

p_i = proportion of individuals that belong to species i.
s = number of species in the sample

Higher H' values are associated with greater diversity and a community that is not generally dominated by a few species. Comparison of Figs. 1 and 3 reveals that high biomass and high diversity were not necessarily linked (Fig. 4). On the left (Fig. 4) is a photo of the catch from a trawl in the Chukchi Sea. The biomass is very high but the number of species is low. The right panel shows a photo from the Beaufort Sea Boulder Patch kelp community. The biomass is not extremely high but there are many different species.

Beaufort Sea Boulder Patch

The Boulder Patch deserves special mention because it is a unique area of the Alaskan nearshore with the richest and most diverse biological community known in the American Beaufort Sea (Fig. 5). It is also conveniently located over potentially rich oil and gas reserves. The Alaskan Beaufort Sea shelf is predominantly blanketed by silty sands and mud with faunal assemblages of polychaetes, tiny crustaceans and mollusks. Conversely, the Boulder Patch is characterized by boulders and cobbles which provide a solid substratum for colonization of a large variety of algae and epilithic invertebrates. The

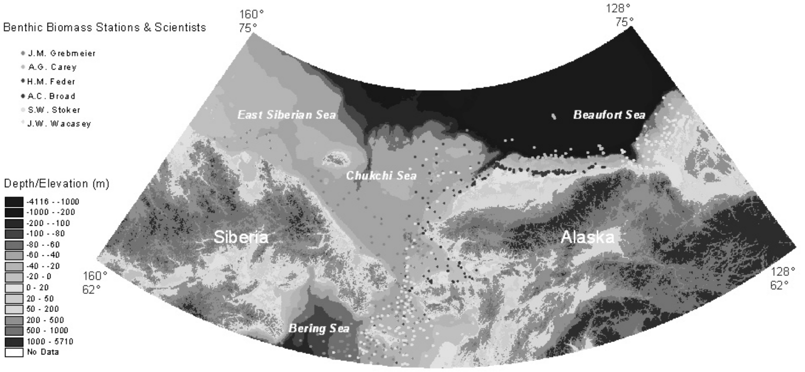

Figure 1. Research station locations on a bathymetric map of the Bering, Chukchi, and Beaufort seas.

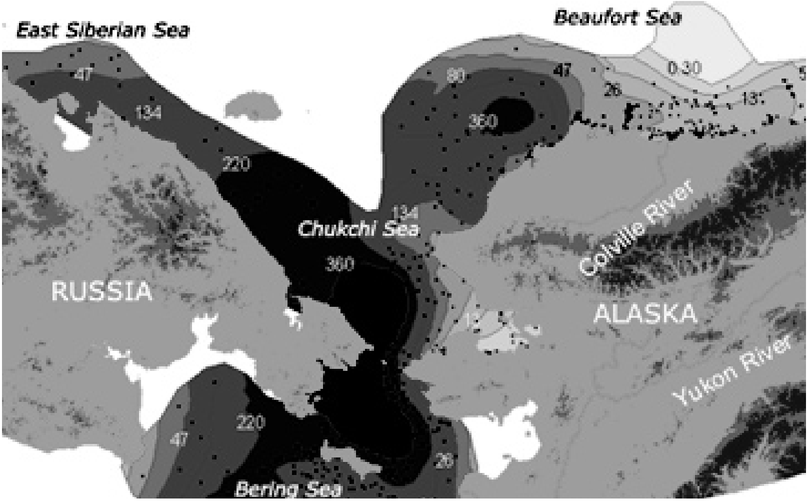

Figure 2. Benthic biomass in the Bering, Chukchi, and Beaufort seas.

Boulder Patch was discovered by marine geologists during summers of 1971 and 1972. Ken Dunton started biological investigations on the diversity and abundance of biota in 1978. Over 160 species representing a variety of invertebrate phyla have been collected from rocks and sediments within the Boulder Patch (Table 1).

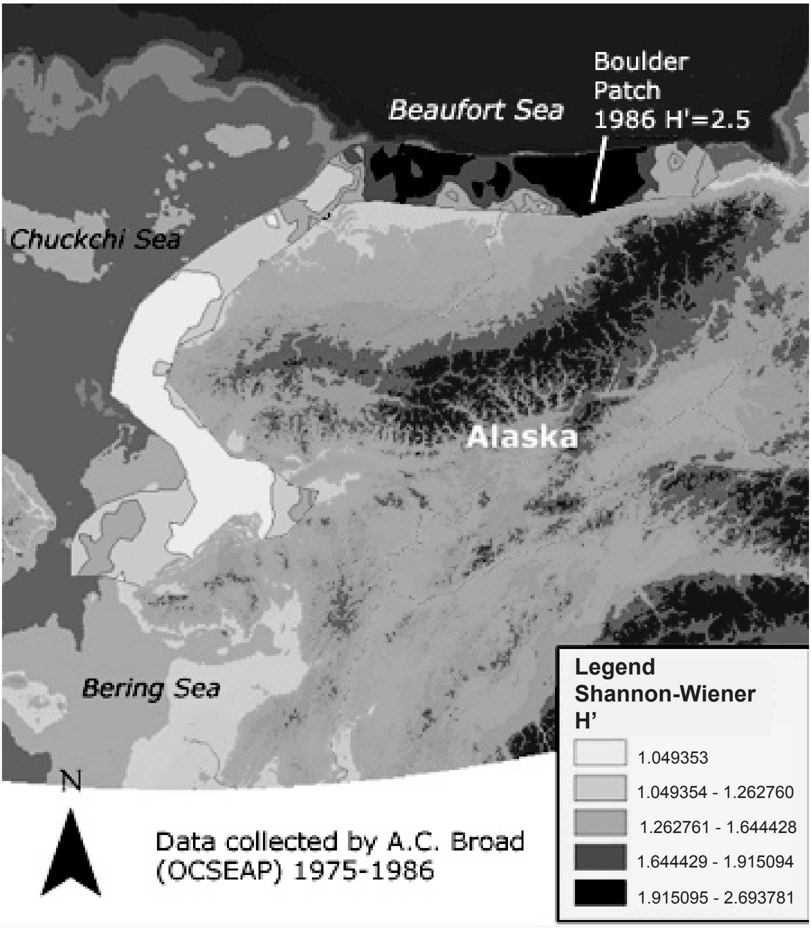

Figure 3. **Plot of Shannon-Wiener Diversity Index H' of benthic biomass data.**

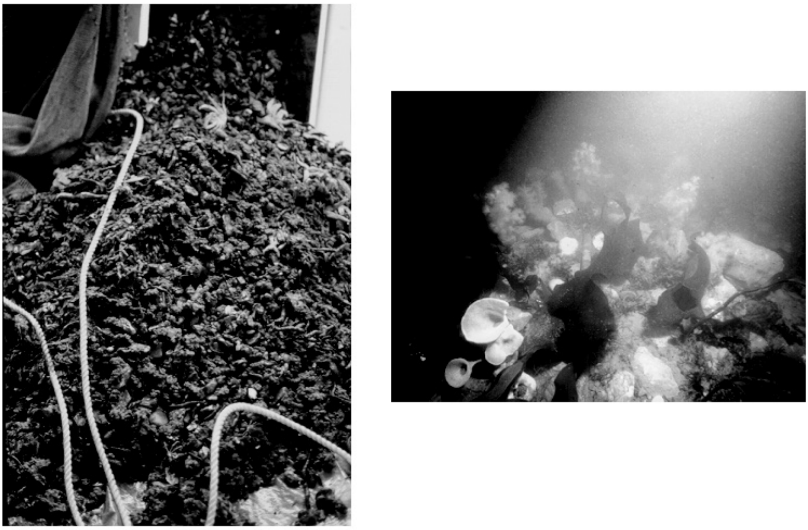

Figure 4. The left photo is the contents of a trawl made in the Chukchi Sea showing high biomass and relatively low diversity. The right photo is of the Beaufort Sea Boulder Patch community with lower biomass but a large number of species.

Table 1. Percentage biomass of biological groups of epilithic and non-epilithic organisms collected between and under rocks in the Boulder Patch.

	Epilithic fauna	Between-rock fauna	Under-rock infauna
Phaeophyta	20%		
Rhodophyta	39%		
Fish	9%		
Porifera	9%	8%	
Polychaeta	3%	15%	7%
Mollusca	7%	34%	6%
Crustacea	1%	7%	6%
Cnidaria	4%	9%	1%
Bryozoa	5%	22%	6%
Ascidacea	2%		
Asteroidea		1%	8%
Foraminifera		2%	1%
Miscellaneous		2%	2%

Figure 5. Location and configuration of the Beaufort Sea Boulder Patch.

Figure 5. (Continued.) Location and configuration of the Beaufort Sea Boulder Patch.

The Hidden Ocean: Explorations under the Ice of the Western Arctic. A Multidisciplinary Project Funded by the NOAA Ocean Exploration Program

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Life in the crystal palace of sea-ice communities

Sea ice is an important habitat for a wide range of Arctic marine organisms, from bacteria to polar bears. Distinct communities have been observed at the various sub-habitats. The ice surface can be dominated by snow algal communities similar to those from terrestrial annual snowfields; the ice interior is characterized by heterotrophic bacteria and flagellate associations. Diatoms, flagellates, ciliates, nematodes, turbellarians and nauplii dominate the bottom decimeters, and amphipods and copepods frequent the ice-water interface. Bacterial abundances show the lowest vertical variability of all taxa studied so far. Although previous studies demonstrated regional differences of faunal and floral composition in Arctic seas, due to local ice regimes, no attempt has been made so far to assess biodiversity of sea ice biota on a Pan-Arctic transect. Such an undertaking is crucial for the understanding of future changes in the Arctic with observed decreases in ice extent and thickness.

Arctic sea ice exhibits strong regional variability: fast ice differs in its characteristics from the pack ice on the shelves and the deep basins. Algal biomass is varying by about three orders of magnitude with highest values in the coastal and shelf locations. While the shelves have been studied intensively over the last 20 years as part of, e.g., SHEBA, ProMare, SFB 313 and the Laptev Sea project, little progress has been made in the Canada Basin since the Transarctic Transect in 1994. Two recently launched major interdisciplinary research projects (SBI, CASES) contain sea ice components, but the work largely focuses on energy flux on the American/Canadian shelves and the interaction with the deep basins, biomass accumulation and sedimentation patterns. The recent NOAA Ocean Exploration investigation offered the opportunity to collect sea ice samples of offshore Beaufort Sea sea ice. However, the enormous retreat of the pack ice during summer 2002 allowed for only four ice-coring stations, forbidding any basin-wide extrapolations. The combination of ice coring with scuba diving (8 stations) provided the following insights: (a) The pack ice of the Beaufort Gyre is inhabited by sea ice meiofauna, which is comparable with studies from the transpolar drift in terms of abundance and diversity; (b) diver observations and video recordings demonstrated the significance of spatial niches for ice-associated amphipods and *Boreogadus saida*; (c) faunal and floral abundance and biomass on shelf stations in the Chukchi and Beaufort seas were considerably higher than in the Beaufort Gyre, most likely due to the inflow of nutrient rich waters through Bering Strait; (d) some ice meiofaunal taxa might be undescribed species; and (e) the loss of typical ice fauna, as proposed by Melnikov and co-workers based on SHEBA observations, was not observed. These observations lead us to the following recommendations for future ice studies in the High Arctic: (1) A transarctic transect should include shelf regions of the Chukchi and Beaufort seas, extend through the Beaufort Gyre across the transpolar drift, and end (or start) on the Eurasian shelves; (2) such a transect should be augmented by investigations on fast ice systems in various locations (e.g., Amundsen Gulf, Barrow, Franz-Josef-Land); (3) the work should include both ice coring and under-ice diving as tools. The study would benefit from additional sampling of the seasonally ice covered regions of the White Sea, the Sea of Okhotsk and the Baltic Sea, to help identify biogeographical ranges and boundaries.

The pelagic fauna

Knowledge of marine life, especially in the deeper parts of the water, is rudimentary principally because the environment is enormous and alien. Plankton nets, the most universal tool used to obtain samples for over l00 years, capture only a small fraction of the pelagic fauna, primarily the smaller, slower, more robust species. When compared to the more numerous crustaceans like copepods and euphausiids, relatively little is known about ctenophores, siphonophores, hydromedusae, scyphomedusae, pelagic mollusks, and pelagic tunicates in all oceans, but especially in polar seas. The most obvious explanation for this disparity is their extreme fragility. Collection with nets destroys most soft-bodied species or reduces them to fragments. As a result the remaining parts are usually ignored, discarded, misidentified, or simply recorded as "jelly." Not as apparent is the fact that nets commonly used to sample copepods are often too small (≤ 1 m diameter) and fitted with mesh that's too fine (≤ 0.5 mm). Consequently, the volumes of water filtered are inadequate to provide reliable estimates of a more dispersed fauna like the gelatinous zooplankton. Furthermore, conventional preservatives typically dissolve the natural rich iridescent colors of live animals and often liquefy ctenophores. It is, therefore, not surprising that the basic biodiversity as well as the biomass and abundance of gelatinous animals are grossly underestimated.

Descriptions of gelatinous zooplankton from the Arctic Ocean are widely scattered in the published literature. Investigations began in the late 1800s and have continued, sporadically, with much of the work conducted in the European and Russian seas. Presently, the number of species recognized for each group varies depending on the source. The known diversity of the gelatinous groups is as follows: ctenophores (6 species), medusae (45 species), siphonophores (12 species), pteropods (4 species) and larvaceans (5 species). In contrast to the fragile gelatinous zooplankton, knowledge of Arctic cephalopods suffers due to their ability to avoid nets and trawls (only 7 species are known), however, there is a long history of successful observation of this group by ROVs and submersibles. Based on our ROV/submersible experience in other oceans, we expected that at least twice as many species actually exist in each group, probably more. Their ecological importance in the Arctic is poorly known.

Understanding the dynamics of any biological community requires knowledge of diversity, abundance and biomass. We needed to see if a medium-sized "portable ROV," the *Global Explorer*, was up to the task. As a first step, we began to develop an in situ photographic inventory of gelatinous zooplankton in the entire water column, as well as shipboard photography of all live material collected by fine-meshed plankton nets equipped with large-volume cod-ends. The patterns of distribution and density were observed throughout the water column down to 2900 m on 5 dives accruing over 30 hrs of observations. Logistical and mechanical problems greatly limited the number of dives performed and prevented detailed observation or collection. Ten stations were sampled with plankton nets to 500 m depth, with unexpected success. Plankton net collections, videotape, and still images are still being processed, with molecular bar-coding under way for select groups.

Deep-sea benthos diversity and food web structure

Benthic communities in general depend on food supplied from the water column. In high latitudes, the amount of sedimenting food particles rather than the low water temperature per se is restraining growth and survival of Arctic benthic organisms (Clarke 1983, Hebbeln and Wefer 1991). On the shallow North American shelves, particle transport to the benthos from the pelagic realm to the benthos is relatively large over the ice-free period. An impressively high faunal biomass is supported in the areas of the very nutrient-rich and productive Bering Sea–Anadyr water in the northern Bering and Chukchi seas (Grebmeier et al. 1995). However, few of the accessible benthic data in the North American Arctic are from stations deeper than 200 m. Information about slope and deep-sea benthos in the Canada Basin are based on collections from early Arctic drifting stations (summarized by Mohr and Geiger 1968). The drift station data from the Alpha Cordillera area (1,000-2,500 m) and more recent studies in the deep Eurasian Basins and on the ridges (Kröncke 1994, 1998, Deubel 2000) and the deep Greenland Sea (Piepenburg et al. 2000) indicate comparatively low biomass from these Arctic deep-sea areas. According to the few available reports, dominant benthic taxa in the Canada Basin in terms of abundance were polychaetes, bivalves, crustaceans and sponges (Paul and Menzies 1974, Oceanol. 1978).

Our objectives in studying the Canada Basin benthos were (1) to identify habitats, species composition, abundance and biomass of major faunal components using ROV (Global Explorer, Deep-Sea Systems) in situ imaging in conjunction with box core samples; (2) to investigate the food web structure of the benthic community using stable isotope analysis; and (3) to investigate trophic links between the benthic, pelagic and ice-associated food webs of the deep Arctic Ocean, based on stable isotope analysis.

Due to various constraints, only eleven individual box cores were collected at six stations ranging from 625 m to 3,250 m along the cruise track (Aug.-Sept. 2002), from Amundsen Gulf to Northwind Ridge. Along with 853 still images, 9.2 hours of video were recorded. All quantitative materials are currently being analyzed. Preliminary data from photographic materials indicate that the most abundant epifauna taxa were polychaetes, fish (Liparidae, Zoarcidae), crustaceans (amphipods, isopods, decapods), ophiuroids and anemones. Whenever hard bottom was present (western basin), it was occupied by cnidarians, tube building polychaetes, ascidians and crinoids (both stalked and unstalked). So far, noteworthy differences between stations include the following: higher energy environment on the western slope of the basin (Northwind Ridge: more rocks, less lebensspuren, coarser sediment) with numerous suspension feeders; eastern deep basin: finer sediment, persisting lebensspuren, relatively more deposit/opportunistic feeders. Preliminary analysis of the box core samples indicated low macro-infauna abundances and biomass compared to lower latitudes. In terms of abundance, the dominant macro-infauna taxa were polychaetes, crustaceans (tanaids, cumaceans, ostracods, amphipods, isopods), and mollusks (bivalves, scaphopods). Among less frequent taxa were sponges, cnidarian tubes and ascidians. While not quantified, dominant meiofaunal groups were nematodes and harpacticoid copepods.

The $d^{15}N$ ratios are indicative of relative trophic relationships with a stepwise enrichment between trophic levels (TL) of 3-4‰. Mean $d^{15}N$ isotopic values for POM (particulate organic matter) from water samples across the Canada Basin at various depths was 5.1‰. Benthic animals ranged from 10.2‰ to 17.7‰ in their $d^{15}N$ isotopic values with most of the organisms falling into the second and third trophic level with respect to the POM values. This observation points toward little fresh phytodetritus reaching the seafloor resulting in organism associations that largely deposit feed on refractory material (e.g., many polychaetes) or are scavengers, predators or omnivores (e.g., amphipods). In contrast to the benthic system, distinctive herbivores (TL1) were present at the sea ice and the upper water column, as to be expected. Few pelagic/ice organisms fell within the third TL. The data suggest that the link between the pelagic/sea ice and the benthic system in late summer was through sinking of grazers and their products (e.g., fecal pellets, molts, dead animals) to the seafloor rather than through direct input of algal material to the benthos.

With regard to future recommendations for the Canada Basin project, better spatial coverage with adequate replicate sampling is recommended, both for biodiversity and food web diversity studies. Net tows should be added to collect macro-epifauna. The ROV capabilities need to be improved to obtain better camera settings and more ship independent operations. In terms of CoML, we recommend a high-resolution transarctic transect from the Eurasian to the American Arctic, covering all depth ranges but focusing on great depths. Methods should be uniform and should include traditional gear such as box cores and nets in combination with underwater imagery. Several selected small-scale assessments should be embedded in the large-scale survey. Several U.S. and Canadian coast guard/research icebreakers as well as coastal research facilities would potentially be available for the North American portion of a transarctic biodiversity study.

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Canada and Arctic Marine Biodiversity Research

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History of data collection

Canada's Arctic marine coast embraces the Beaufort Sea to the west, dominated by the effects of the Mackenzie River and to the east, the vast island network of the Canadian Arctic Archipelago. Southward is Hudson's Bay, Hudson Strait, and Ungava Bay. South of 60º, Newfoundland and Labrador are bathed by the cold Labrador Current and receive icebergs from Greenland. Canadian records of its Arctic marine biodiversity date back 250 years to the early explorers and whalers in the North (Martin 2002, http://www.marinebiodiversity.ca/mbw/index.html). Expeditions searching for the Northwest Passage in 1818 through to 1833 carried naturalists on board and later expeditions in 1875 through to 1902 did as well. Currently, these data are being collated into the Science Data Inventory Database, for which the 247 Arctic records covering 1910 to 2000 are housed at Fisheries and Oceans Canada in Winnipeg, Manitoba (http://www.dfo-mpo.gc.ca/regions/central/index_e.htm). During the 20th century, much of the Arctic research was conducted at the Arctic Biological Station in Ste. Anne de Bellevue, Québec. Their products, which spanned 46 years of Arctic research, covered oceanography, phytoplankton, zooplankton, zoobenthos, fish, and marine mammals. Many of their research findings appeared in Fisheries Research Board Data Reports, and these can be obtained through interlibrary loan (http://inter01.dfo-mpo.gc.ca/wavesdocs/waves_mainmenu.html). Many of the Arctic specimens from this research are housed at the Canadian Museum of Nature (http://www.nature.ca). Arctic bird data are collected by the Canadian Wildlife Service (http://www.cws-scf.ec.gc.ca/index_e.cfm).

Additionally, Arctic marine biodiversity data for the western Arctic may be obtained at the Aurora Research Institute (http://www.nwtresearch.com/default.cfm) and in the eastern Arctic at the Nunavut Research Institute (http://pooka.nunanet.com/~research/). Universities also support northern research, and scientists who obtain logistical support through Canada's Polar Continental Shelf Project will have their projects listed on its Web site: http://polar.nrcan.gc.ca/home_e.html. Arctic marine information can also be found at the Arctic Institute of North America (http://www.ucalgary.ca/aina/) and the Canadian Polar Commission (http://polar.nrcan.gc.ca/home_e.htm). Other federal departments with responsibilities in the Canadian Arctic are Indian and Northern Affairs Canada (http://www.ainc-inac.gc.ca/), Natural Resources Canada (http://www.nrcan-rncan.gc.ca/inter/index.html) and Environment Canada (http://www.ec.gc.ca/).

Canadian Arctic marine biodiversity and biogeography

Surveying 18 publications and reports, Martin (2002) tallied 1,098 invertebrate species, 199 fish species, and 8 marine mammals that live in Canadian Arctic marine waters. Lee (1980) documented 382 species of macroalgae in the Canadian Arctic. Viruses, bacteria and protists would add a much higher number. The number of marine bacteria in the eastern Arctic is consistently in the range of 0.1-1.0 million cells/ml (Longhurst et al. 1989). Viruses are about 10 times this abundant (C. Suttle, University of British Columbia, pers. comm.). Diatoms and other large celled protists have been found at densities of 925,000 cells/l, with about 10-25% of primary production due to picoplankton and about 10% of enzyme activity deriving from ultramicroplankton cells <0.2 µm (Longhurst et al. 1989).

According to Wares (2002), the opening of the Bering Strait 3.5 million years ago resulted in a large interchange of marine life between Pacific and Atlantic coasts via the Arctic. The low salinity Pacific water is a conduit for propagules from the Bering Sea, transporting them eastward through the Beaufort Sea to the Canadian Arctic Archipelago, and thence to the North Atlantic through the Labrador Sea (Carmack and Macdonald 2002). Wares (2002) estimates that up to 80% of New England rocky shore fauna have a Pacific origin.

The western and eastern Arctic regions differ both in geography and in glacial history. The western Arctic, encompassing the Beaufort Sea and the Amundsen Gulf, has been controlled by the Mackenzie River for 60 million years. The Mackenzie is the fourth largest Arctic river and discharges an average of 333 km^3/yr (AMAP 1997). It is the only large river on the North American coast of the Arctic Ocean and its effects are felt deep into the Canada and Makarov basins (Guay and Falkner 1997). The freshwater plays a key role in the formation of sea ice (Aagard and Carmack 1989) which, in turn, determines the exchange of heat and moisture between the air and the sea (Maykut 1978). This constrains the strongly pulsed annual cycle of biological productivity (Legendre et al. 1992). The Mackenzie brings in not only large volumes of freshwater but also about 130 million metric tons of sediment/yr (Carson et al. 1998), a quantity greater than any other Arctic river (Carmack and Macdonald 2002). According to S. Blasco, Geological Survey of Canada (pers. comm.), the Mackenzie has deposited a 12,000 m thick layer of sediment on the coastal Beaufort seabed over this time. By comparison, the coast of the eastern Arctic is sediment starved as there are no large rivers feeding into it. During glaciation, ice was never on the western Arctic's Beaufort shelf as the climate was too dry. Only the Mackenzie Canyon was filled with an ice tongue. In the eastern Arctic, ice was grounded in the channel areas. The eastern Arctic is still rebounding about 30 cm/century whereas the Beaufort is actually sinking due to the weight of sediment deposited by the Mackenzie River. Even the climates of the eastern and western Canadian Arctic differ but they flip between heavy and light ice years in part due to changes in the Arctic Oscillation (Thompson and Wallace 1998). Climate warming will have marine effects such as longer ice-free periods, more wind-mixing, upwelling and wintertime brine rejection, thus increasing the availability of nutrients to phytoplankton, longer periods of light availability to phytoplankton and the benthos, increased export of organic terrestrial material to the coastal zone due to increased rainfall, rising sea level, more coastal erosion, and shifting water mass fronts and currents (Carmack and McLaughlin 2001).

The Canadian Arctic provides a diversity of habitat types for benthic marine life. The western Arctic is largely dominated by fine grained sediments but there are boulder beds off Herschel Island and sand beds farther east which may provide refugia for course-sediment inhabitants. Sea ice and icebergs scour long furrows to about 50 m water depth, creating a mosaic of recolonizing communities. Gas vents and submarine pingos provide unique habitats and drilling platforms alter the seabed, generating pits, islands, and hard substrates. Off the Mackenzie River are two canyons which funnel and exchange shelf water (Carmack and Macdonald 2002). The Mackenzie River itself pools into a 12,000 km^2 lake when it is dammed by the offshore stamukhi (pressure ridge) zone in the winter. This lake ranks 20th in the world by area and 30th by volume (Carmack and Macdonald 2002). A flaw polynya opens offshore of the stamukhi zone in late winter, leading eastward to the Cape Bathurst polynya. The fauna on the coast of the western Arctic are dominated in number and diversity by burrowing polychaetes. Large isopods, *Mesidotea* spp. are common near the Mackenzie inflow. Small bivalves, brittle stars, and a variety of tanaids, cumaceans and amphipods also inhabit the benthos. In the eastern Arctic, strong currents between the islands winnow the glacial sediment, leaving gravel and cobble for hard substrate attachment by macroalgae, sea anemones, and sea urchins. The coastal benthos is dominated in biomass by large clams, sea stars, sea cucumbers, sea anemones, soft corals, and sea urchins. Bedrock is exposed on the coasts of Ellesmere, Devon and Baffin Islands for soft corals, crinoids, and sponges to colonize. Such organisms also coat sunken ships, such as the *Bredalbane* off Beechey Island, which is in 100 m of water. These islands provide abundant fjord communities. Frobisher Bay on Baffin Island has extremely high tidal ranges, reaching up to 15 m. Under the polar pack ice above 130 m depth off Ellesmere Island, large siliceous sponges support a diverse benthic community and form reef mounds up to 10 m high (Van Wagoner et al. 1989). The North Water Polynya enhances productivity in northern Baffin Bay (http://www.fsg.ulaval.ca/giroq/now/). Numerous smaller polynyas occur in the eastern Arctic as well (http://www.fsg.ulaval.ca/giroq/now/polyb.jpg). Potential commercial fisheries are being evaluated for turbot, shrimp and clams and whales, walruses, seals and bears are hunted by the Inuit and Inuvialuit.

Pelagic organisms are influenced by stratification caused by the Mackenzie River inflow in the western Arctic. Different water masses from the Pacific and Atlantic may affect dispersal and isolation. Either phosphate or light (or both) limit primary production in the inner Canadian Shelf, while farther offshore, nitrate and light availability are the limiting factors (Carmack and Macdonald 2002). Under-ice organisms are limited by light penetration and nutrient supply and contribute only about 10-15% of the annual primary production in the western Arctic (Carmack and Macdonald 2002) and 5% in the eastern High Arctic (Longhurst et al. 1989). However, epontic algae extend the growth season for some Arctic zooplankton and, for the copepod *Pseudocalanus*, enables it to complete its life cycle in one year (Longhurst et al. 1989). Among the zooplankton, about 70% of the biomass in the top 250 m of the Canadian Arctic Ocean is composed of copepods, with about another 11% being pteropods and about 10% amphipods, with ostracods, coelenterates and appendicularians comprising most of the remaining biomass (Longhurst et al. 1989). Migratory birds depend on open water and a food supply available at the time of arrival. The eastern end of the Beaufort Shelf around Cape Bathurst is heavily used by eiders and long-tailed ducks for diving for benthic molluscan and crustacean prey (Dickson and Gilchrist 2002). Walrus prey on the large clams *Mya truncata* and

Serripes groenlandicus which are abundant in the eastern Arctic. The dynamics of polar bear populations are intertwined with those of their seal prey and sea ice thickness (Stirling et al. 1999, Stirling 2002). Separate populations of beluga whales congregate at the mouth of the Mackenzie River in the western Arctic and off Devon Island in the eastern Arctic. Bowhead whales are more abundant in the western Arctic than in the eastern but still suffer the population decimation of past European whaling. The Arctic cod, *Boreogadus saida*, is a key species transferring carbon from plankton to other fish (char and plaice), birds (murres, guillemots and kittiwakes), seals (harp and bearded), and whales (narwhal and beluga) (Longhurst et al. 1989). Anadromous fish such as cisco and char are seasonal components of Arctic marine biodiversity and their movements into the Arctic Ocean are tied to the hydrological cycle and its timing (Carmack and Macdonald 2002). In turn, the hydrological cycle is partly controlled by the ice, a feature affected by climate change. The diversity and stability of Arctic marine life is intimately linked to the dynamics of sea ice, and the potential effects of climate change on sea ice can be rapid and formidable. The consequences of climate warming for Arctic marine biodiversity will be huge.

Recent marine research programs in the Canadian Arctic

Beaufort Seabed Mapping Program (contact: Mr. Steve Blasco, blasco@agc.bio.ns.ca)

A joint geological and biological study of coastal features of the Beaufort Sea and associated biological diversity.

CASES: Canadian Arctic Shelf Exchange Study (http://www.giroq.ulaval.ca/cases/)

Based on the general hypothesis that the atmospheric, oceanic and hydrologic forcing of sea ice variability dictates the nature and magnitude of biogeochemical carbon fluxes on and at the edge of the Mackenzie Shelf, the major objectives of CASES are to assess:

1. The role of hydrologic, oceanographic and meteorological processes in ice growth, decay and transport on the shelf and beyond.

2. The hydrodynamic (including ice and snow cover dynamics) control of Arctic shelf photosynthetic production and its export to the benthos and the pelagic food web.

3. The potential impact of increased UV radiation on biological productivity.
4. The role of microheterotrophs and mesozooplankton in transforming particulate and dissolved matter on the shelf.
5. The fluxes of particulate matter and carbon across the shelf to the deep basins.
6. The distribution of riverine and airborne contaminants in the trophic web.
7. The potential impact of a reduction in ice habitat on birds and marine mammals.
8. The decadal and millennial variations in ice cover and their impact on ecosystem productivity.

NOW: International North Water Polynya Study (http://www.fsg.ulaval.ca/giroq/now/)

1. Physical mechanisms responsible for the opening, maintenance and closure of polynyas.
2. Effects of these mechanisms and the environmental characteristics of polynyas on ecosystems and carbon cycling.
3. Intercomparisons of the physics, chemistry, biology and carbon cycling in polynyas.
4. Interannual variability in the time of opening, extent, biological productivity and carbon sequestration in sediments of polynyas, based on remote sensing (sea ice, ocean color, etc.) and sediment records.

JWACS: Joint Western Arctic Climate Study (contact: Dr. Eddy Carmack, CarmackE@pac.dfo-mpo.gc.ca)

The study area focuses on the shelf-slope area of the Beaufort Sea and Central Arctic from the Northwind Ridge to Banks Island. The primary focus is on physical, biochemical and paleoceanography, but some biodiversity research is being conducted as well.

SBI: Western Arctic Shelf-Basin Interactions Project (http://nsidc.org/arcss/projects/sbi.html)

The Western Arctic Shelf-Basin Interactions (SBI) program is aimed at improving our understanding of shelf-basin exchange and should lead to improved predictions of global change impacts in the Arctic. The SBI program will include field and modeling studies directed at elucidating the physical and biological shelf and slope processes that influence the structure and functioning of the Arctic Ocean.

The SBI program is proceeding in three phases:

1. Phase 1 involves analysis of regional historical data, opportunistic field investigations, and modeling.
2. Phase 2 comprises core regional field investigations in the Chukchi and Beaufort seas, along with continued regional modeling efforts.
3. Phase 3 will investigate global change ramifications on the ecosystems of the Arctic shelves and basin. This phase will involve development of a pan-Arctic model (including embedded regional submodels) suitable for exploring hypothesized global change scenarios.

SHEBA: Surface Heat Budget of the Arctic Ocean (http://sheba.apl.washington.edu/)

SHEBA is a coordinated project to investigate the role of Arctic climate in global change. The primary goals of SHEBA are:

1. To determine the ocean-ice-atmosphere processes that control the surface albedo and cloud-radiation feedback mechanisms over Arctic pack ice, and to use this information to demonstrably improve models of Arctic ocean–atmosphere–ice interactive processes,
2. To develop and implement models that improve the simulation of the present day Arctic climate, including its variability, utilizing coupled global climate models.

Although primarily non-biological, some plankton research was conducted.

Facilities for research in the Canadian Arctic

Accommodation, equipment and transportation

Aurora Research Institute (http://www.aurresint.nt.ca/index.htm)
Nunavut Research Institute http://pooka.nunanet.com/~research/)
Polar Continental Shelf Project (http://polar.nrcan.gc.ca/home_e.html)

Ships

Canadian Coast Guard (http://www.ccg-gcc.gc.ca/)

Catalogues and guides to the identification of Canadian Arctic marine life

Phytoplankton

Tomas, C.R. (ed.). 1997. Identifying marine phytoplankton. Academic Press. 858 pp.

Macroalgae

Lee, R.K.S. 1980. A catalogue of the marine algae of the Canadian Arctic. National Museums of Canada, National Museum of Natural Sciences, Publications in Botany 9. 82 pp.

Polychaetes

Pocklington, P. 1989. Polychaetes of Eastern Canada. An illustrated key to polychaetes of Eastern Canada including the Eastern Arctic. Ocean Dumping Control Act Research Fund, National Museums of Canada, and Department of Fisheries and Oceans, Mont Joli. 233 pp.

Mollusks

La Rocque, A. 1953. Catalogue of the recent Mollusca of Canada. Canada Department of Resources and Development, National Parks Branch, and National Museum of Canada. Bulletin No. 129, Biological Series No. 44. Queen's Printer, Ottawa. 406 pp.

Lubinsky, I. 1980. Marine bivalve mollusks of the Canadian Central and Eastern Arctic: Faunal composition and zoogeography. Canadian Bulletin of Fisheries and Aquatic Sciences 207. 111 pp.

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Arctic Deep-Sea Biodiversity Research: The U.K. Perspective

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Arctic marine deep-sea biodiversity research: The known

Current knowledge of the deep-sea fauna of the deep European Arctic (Arctic, Norwegian, and Greenland seas) consists of both diversity studies and older faunistic studies (e.g., Sars 1885; Hansen 1916; Gurjanova 1930, 1933; Dahl et al. 1976; Svarvasson et al 1990, 1993; Brandt 1997) in addition to extensive faunistic works on the Greenland and Iceland continental shelves (e.g., Thorson 1933; 1936; Madsen 1936; Heegard 1941; Stephensen 1944; Piepenburg 1988; Brandt 1993; Brandt and Piepenburg 1994; Brandt et al. 1996, 1997). Many of the recent works (e.g., Brandt 1993, 1997; Brandt and Piepenburg 1994; Brandt et al. 1996) have focused on abundance and diversity patterns and, in many cases, highlighted the need for improved taxonomy in their species lists. For example, of 110 amphipod entities collected between 200 and 2,200 m on the Greenland continental shelf (Brandt 1997), 54 (~50%) were not identified to species level (i.e., were labeled either "cf." or "*Genus* sp." indicating problems in identification).

The most recent review of deep-sea biodiversity issues, Snelgrove and Smith (2002), summarizes the many processes that have been proposed to regulate biodiversity in deep-sea environments. The authors conclude that no single process is responsible for the high diversity of deep-sea ecosystems and that it is likely that a variety of non-equilibrium processes (such as disturbance, and spatial, and temporal patchiness in food supply), operating in a relatively stable, low productivity environment, will combine to enhance species diversity over a range of scales.

Snelgrove and Smith (2002) also discuss deep-sea species richness and the various estimates of global species number, (between

10^5 and 10^8 species) that have been calculated using reported examples of high local diversity in deep-sea environments. The debate as to whether or not the deep sea harbors greater species richness than shallow seas continues to this day with an entire literature being devoted to the subject. It is important to note that few large scale studies have been carried out in the deep-sea environment and therefore most researchers are comparing local diversities based on samples collected at single sites. The only genuine study of deep-sea biodiversity at a regional scale is that of Grassle and Maciolek (1992) who analyzed box cores collected along a 176 km transect of the Northwest Atlantic continental slope. The continuing debate clearly indicates the need for more such studies.

Especially relevant to Arctic biodiversity issues is the existence or otherwise of latitudinal diversity gradients in the deep sea. This has been another area of disagreement (Rex et al. 1993, 1997, 2000, 2001; Gray 1997, 2002; Culver and Buzas 2000; Lambshead et al. 2000, 2001a, 2002). Once again, claims that these gradients exist have been largely based on comparisons of local diversities based on samples collected at individual sites. It is also likely that historical factors exert a strong influence in some areas such as the Greenland-Norwegian Sea, which due to ice-cover during the last glaciation the fauna is likely to be evolutionarily younger and therefore possibly less diverse. The relationship between diversity and latitude is stronger in the North Atlantic but the relationship is significantly weakened when data from the Norwegian Sea is removed.

Arctic marine deep-sea biodiversity research: The unknown

The crucial "unknowns" that require work are as follows:

1. The apparent rarity of most species, and the fact that many are undescribed, hold progress back. Improvements to taxonomy are crucial to any census of marine life.

2. In order to have any confidence in deep-sea species richness assessments we need to scale up from local studies and studies on single taxa to larger and more comprehensive research programs.

3. Sampling programs need to study a wide variety of taxa, size classes, and functional groups at spatial scales of one kilometer, tens of kilometers (landscape scale), hundreds of kilometers (regional scale) and thousands of kilometers (basin and global scales). Without such knowledge, it is impossible to tackle the question of whether diversity in deep-sea environments is really

higher than diversity on the continental shelf (Gray 2002). The research effort required to address these aims is considerable and therefore best approached through international cooperation.

4. Issues relating to how the samples are collected are paramount. We must ensure that data sets are comparable (equipment and survey design) as is being recommended by NAGISA. In recent years, many studies in the Arctic have made use of epibenthic nets and/or box cores to carry out deep-sea diversity studies in the Arctic. However, during a recent environmental survey of the deep-water oil province off Angola, a comparative trial of macrobenthos samplers was carried out, which has shown that box corers lose about 50% of specimens and change the composition of the fauna (Bett et al., unpubl. data).

Overview of other Arctic biodiversity activities in the U.K., and collaborations with other national/international research groups

The **DEEPSEAS** benthic biology group at Southampton Oceanography Centre (SOC) is jointly funded by the Natural Environment Research Council through the George Deacon Division for Ocean Processes and the University of Southampton through the School of Ocean and Earth Science. The group consists of five prime movers, five post docs and fifteen Ph.D. students all working on aspects of deep-sea biodiversity and ecology. We have expertise in the taxonomy of deep-sea echinoderms, megafaunal and macrofaunal Crustacea, and meiofaunal Foraminifera and Nematoda. The group has been studying the deep-sea fauna for over 30 years and collectively has experience that totals more than 100 man-years in the ecology of the oceans. Our work covers a variety of habitats, from continental margins to abyssal plains and hydrothermal vents. In recent times, work has extended beyond taxonomy and ecology to molecular approaches.

The DEEPSEAS group has applied its research to the needs of government departments, industry (offshore oil and gas) and non-governmental bodies such as the World Wildlife Fund for Nature. DEEPSEAS has in recent years conducted six major field programs to map deep-sea habitats in areas of interest to deep-water hydrocarbon exploitation, resulting in the discovery of the coral-topped Darwin Mounds, areas that are now designated as the first U.K. offshore special area of conservation. DEEPSEAS is working closely with the Oil and Gas Producers Forum to establish good sampling protocols by the industry worldwide and making the samples taken in monitoring programs accessible to the scientific community. DEEPSEAS has a major program studying long-term change in the Northeast Atlantic (1989-2003), funded in part by European projects in Framework Programmes II, III, and IV, and has participated in three Framework V Programmes (ACES [Atlantic Coral Ecosystem Study], ECOMOUND [Environmental Controls on Coral Mounds], and OASIS [OceAnic Seamounts, an Integrated Study]). Other programs of interest at SOC include a study of soft-shelled foraminiferans from the fjords around Svalbard where they are very abundant. The project, led by Andy Gooday at SOC, is ongoing and aims to study the foraminiferans for genetic phylogenetic studies. A number of Ph.D. students and staff are involved in ANDEEP, a program to study the Antarctic benthos, and have experience of polar sampling.

Currently DEEPSEAS is involved with organization of the Census of Marine Life initiative, including hosting the office for the COML project on Chemosynthetic Environments (ChEss), and has recently been funded to organize a similar workshop to this to discuss the "Known, Unknown and Unknowable of the Biodiversity of Deep-Sea Sediments" on a global scale. This will be held in Oregon in August 2003 just prior to the Deep Sea Biology Symposium.

As the **BP Deep-Sea Biodiversity Research fellow** based at Southampton Oceanography Centre in the U.K., I am focusing my research on the Northeast Atlantic, in particular the regions to the west and north of the Shetland Isles where BP exploration is taking place. I am currently studying amphipod specimens collected during the AFEN (Atlantic Frontier Environmental Network) 1996 and 1998 and DTI 2000 and 2002 large-scale surveys to characterize the deep-water areas of the U.K. EEZ (Exclusive Economic Zone). My work is primarily taxonomic, aiming to improve problems of identification in the deep-sea amphipod fauna by describing new species and revising problem taxa. Many of the specimens I am studying are from the cold, deep waters north of the Wyville-Thomson Ridge and up into the Norwegian Basin.

As part of the BP Deep-Sea Biodiversity Research Fellowship, a collaboration has been initiated to make use of BP ROV downtime for scientific purposes. The first trials of this industry collaboration were last summer. During a two-week trip on board MSV *Regalia*, a number of successful deployments of holothurian traps were made to study feeding ecology, and observations of the megafauna led to improved understanding of the behavior of some common animals. The collaboration is set to continue with closer links and new projects.

SAMS–Northern Seas Programme

(See Burrows 2003, this volume)

British Antarctic Survey (BAS)

British Antarctic Survey carries out Arctic research, as a part of their program of polar research. The Natural Environment Research Council, the parent body of the British Antarctic Survey, supports environmental research in the Arctic at U.K. universities and research institutes. BAS is in the process of writing its science plans for 2005-2010, in the form of large grant proposals. BAS does have a small but strong biodiversity program, but at present work is concentrated in Antarctica. BAS would be interested in comparative data from the Arctic (for example specimens of the bivalve genus *Limopsis* to compare with Southern Ocean species), but at present has no formal Arctic program. The marine ecologists at BAS do have a bipolar interest, and it is possible that some themes may emerge as they shape their new round of science programs.

In 1991 the NERC International Arctic Environmental Research Station was established at Ny-Ålesund (79ºN 11ºE), on the High Arctic island of Spitsbergen, part of the Svalbard archipelago. The station, which supports mainly earth and life scientists is part of an international research community including stations owned by Norway, Germany, Japan, Italy, France, and the U.K. Ny-Ålesund is situated on the south side of the deep and sheltered Kongsfjord on the west coast of Spitsbergen. The southern shore alone provides 50 km of tundra and alluvial plain. Access to other shores and islands is possible by a NERC owned boat. Opportunities exist for researchers to carry out environmental research at Ny-Ålesund. This location is particularly suitable for ecological research, glacial/periglacial geomorphology, hydrology and atmospheric chemistry. The station provides laboratory space with limited equipment: glacier and boating equipment, radios, firearms (training provided), computers, telephone, fax, and email. There are seven bedrooms and those who cannot be accommodated by NERC use bedrooms owned by Kings Bay Company (the owners of Ny-Ålesund) who charge a daily board and lodging fee. Access is by light aircraft from Longyearbyen 100 km to the south. Longyearbyen receives scheduled flights daily from Norway.

Technological resources available to perform biodiversity work in your countries (icebreakers, ROVs, AUVs, etc.)

The Ocean Engineering Department at SOC comprises the Underwater Systems laboratory (USL) and U.K. Ocean Research Services (UKORS). USL tackles research and development projects in the broad area of platforms and sensors for ocean science. An organizational goal of USL is to benefit from interaction between ocean engineers at SOC and researchers. UKORS provide the scientific technical support in terms of equipment and staff to the U.K. marine science community principally in conjunction with the NERC Research Ships Programme. The National Marine Equipment Pool is managed by UKORS, which allows access to many pieces of sampling equipment (e.g., laboratory containers, winches, generators, corers, millipore system, moorings, dredges and trawls, computing, geophysics equipment, water sampling, and monitoring equipment).

Autosub

Autosub is an Autonomous Underwater Vehicle (AUV). AUVs are unmanned and untethered submersibles that are programmed to carry out missions without communication to the surface. One advantage of AUVs is that they can survey remote environments that are inaccessible to ROVs and other submersibles. Autosub can collect physical, chemical, biological and geophysical data from the ocean surface to the seabed using a suite of sensors and sampling devices tailored to individual mission requirements. Autosub technology has also been licensed to Haliburton Subsea for use in the oil, gas and subsea cable markets. Between 2001 and 2006, Autosub will return to the Polar Regions under the auspices of the **Autosub Under Ice Thematic Programme** in order to investigate (among other things) water circulation, how ice forms, and how the air, ice and ocean interact. The environment under ice shelves is one of the last great, unexplored regions of the planet. In July/August 2004, Autosub will be going under ice in North East Greenland. Nioghalvfjerdsfjorden Glacier (also known as NFG or 79ºN Glacier) drains 8.4% of the Greenland ice sheet area. The glacier enters Nioghalvfjerdsfjorden from the west and forms a floating ice tongue 60 kilometers long and 20 kilometers wide. One of the projects that will begin during this expedition is a study of “Controls on marine benthic biodiversity and standing stock in ice covered environments” led by Prof. Paul Tyler et al. For this project, a digital still camera system will be integrated with the Autosub vehicle and used to study the standing stock of benthos in Arctic and Antarctic regions. Seabed photography will be used to assess the megabenthos in three types of environment: (1) open water areas, (2) areas of seasonal ice cover and (3) areas of permanent ice cover. By contrasting the ecology of these three environment types, the project will address the question: "What are the dominant controls on the diversity and standing stock of the benthos in Polar Regions?"

ISIS

ISIS is the new U.K. Remote Operated Vehicle, based at the Southampton Oceanography Centre, U.K. *ISIS* has been developed in parallel with the ROV *Jason II* at the Woods Hole Oceanographic Institution, U.S.A., and can operate as deep as 6,500 m. She is equipped with a digital video camera, digital still photography camera, a number of sensors and two articulated arms for grabs and manipulations. The ROV is remotely operated from a control van on board the ship, where pilots and scientists can obtain data in real time. Sea trials of *ISIS* were completed in March 2003, during which *ISIS* was successfully deployed from RV *Atlantis* and tested on a series of dives to depths between 800 m and 4,300 m.

Ships

The NERC ship the RRS *James Clarke Ross* is normally found working in the Antarctic but has recently been taken to 81ºN with the Scottish Association of Marine Science, as part of the Northern Seas Programme.

The vessel is a Lloyds+100A1 Ice 1AS and is 99.04 m in length with a beam of 18.85 m. It has a double bottom ice strengthened hull. It has a maximum endurance of 57 days at sea. It can carry a maximum of 31 scientists and has a large amount of scientific deck space (650 m^2) consisting of a wet lab, main lab, rough workshop, scientific workshop, water bottle annex, chemistry lab, preparation lab, biochemistry lab, microbiology/radioactive lab, underway instrument and control room, electronics workshop, data preparation room, computer room and a darkroom.

The NERC ship the RRS *Ernest Shackleton* is an Antarctic logistics and marine science vessel. The vessel is a Det Norske Veritas *1A1 ICEBREAKER ICE 05 E0 HELDK ICS DYNPOS-AUTR W and is 80.00 m in length with a beam of 17.00 m. It has a double bottom ice strengthened hull. It can carry a maximum of 59 scientists and has a small wet lab and dry lab.

The NERC Research ship the RRS *Discovery* is currently being refitted and is a DTp VII, Lloyds 100A1 class vessel with a double bottom hull, capable of worldwide marine biology and oceanography research. It is 90.25 m in length with a beam of 14.00 m and has a maximum endurance of 55 days at sea. It can carry a maximum of 28 scientists and has a large amount of scientific deck space (460 m^2) consisting of an oceanographic wet lab, a multipurpose dry lab, chemistry lab, computer room, darkroom, plot and a constant environment lab.

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Arctic Nearshore Biodiversity Research: The U.K. and Scottish View

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Arctic research on nearshore and intertidal benthos

Ice as the dominant structuring agent in shallow water and intertidal communities

Limits to species distributions

Latitudinal gradients in species diversity

Phylogeography and the development of the post-ice-age coastline in the North Atlantic

Nearshore shallow water and intertidal areas have the most studied biodiversity of marine habitats in temperate regions. Ease of access to these shallow areas and proximity to centers of human population have ensured that the biodiversity of the fauna and flora, and the processes that shape coastal communities are well known (Rafaelli and Hawkins 1996). Yet in the Arctic shallow water and intertidal areas are among the most physically stressful of all marine habitats and as a result are relatively species-poor in comparison with Arctic deep-water benthic communities. The principal stressor in these areas is ice scour. Episodic ice-scour in subpolar regions demonstrates the catastrophic effects on intertidal and shallow water benthic communities (McCook and Chapman 1991, 1993, 1997; Minchinton and Schiebling 1997). In the Arctic intertidal, the upper part of the shore may be completely ice-covered, while the lower shore may be kept ice-free by the rise and fall of the tides (Barnes, M. 1999). Intertidal species such as barnacles are restricted to crevices where physical abrasion may be less. The seasonal effects of appearance and disappearance of ice can result in ephemeral communities developing on open rock surfaces (Pugh and Davenport 1997), with the effect that intertidal communities are primarily structured by the balance between disturbance and colonization at large and small scales (Conlan et al. 1998; Barnes, D. 1999).

In deeper waters (5-100 m), the effects of ice may be insignificant or confined to the occasional grounding of large icebergs (Peck et al. 1999). Such events may be similarly catastrophic for the benthos, but, if spatially limited, may be followed by reasonable rapid recolonization.

While physical disturbance by ice remains the primary driver of Arctic intertidal and nearshore biodiversity, the intensity of species interactions may increase at higher latitudes. Asymmetry in outcome of competitive interactions between species of bryozoans increases with latitude (Barnes 2002), primarily because the interaction webs are simpler because of the reduced number of species. This may further reduce species richness in the Arctic.

Hop et al. (2002) provide an excellent review of the well-studied Arctic nearshore ecosystem in Kongsfjord, Svalbard.

Links to biodiversity patterns in northern temperate regions

Rapid assessment of intertidal community structure using categorical abundance scales (Crisp and Southward 1954)

Examples from recent W Scotland work and potential for comparisons with Arctic work

Understanding the biodiversity of nearshore and intertidal habitats in temperate regions has progressed through a number of recognizable phases. Taxonomic work on species descriptions of the large conspicuous species was largely complete by the early to mid-20th century. This was followed by an intensive period of description of the small and large-scale distributions of the communities (Stephenson and Stephenson 1948, Lewis 1964). A desire to understand the processes structuring the communities inspired several subsequent decades of experimental studies, particularly on rocky shores, of community development, the role of key species such as grazers and predators (e.g., Paine 1966), and the influence of larval supply and recruitment. These experiments continue to this day, with a shift in emphasis from almost exclusively rocky habitats towards experiments on soft sediment communities.

The recognition that shore communities could be badly affected by coastal pollution, particularly by wrecks of large oil tankers (Southward and Southward 1978), led to the development of methods for rapid and large-scale assessments of abundance of rocky intertidal species based on categorical abundance estimates (Crisp and Southward 1958). Combined with modern statistical methods for analysis of multivariate data (such as PRIMER; Clarke 1999) and novel methods for measurement of species diversity (Clarke and Warwick 1999) such methods can give considerable insights into spatial and temporal trends in coastal biodiversity (Burrows et al. 2002).

Future issues

The latest projections from recent trends in sea ice cover in the Arctic suggest that most of the coast will be ice-free in the summer by 2050 (Comiso 2002). Summer minimum ice cover has declined in the area by up to 20% since the 1950s, while winter maximum cover has also declined at an accelerating rate since the mid-1970s. This retreat will produce huge stretches of new coast suitable for colonization by rocky and sandy shore species. As the icecap retreats from the coast of the Arctic Ocean, so the summer open areas in the Kara Sea, Laptev Sea, Siberian Sea etc. become increasingly connected and the interchange of species by advection of planktonic larvae will increase. Reduced ice cover could also increase biological productivity. These changes will likely increase genetic exchange between isolated populations of the same species, while the opening of summer northern sea routes between the Pacific and the Atlantic will increase likelihood of trans-Arctic invasions of alien species.

Given that surface ice is the primary structuring agent of shallow water and intertidal biodiversity, nowhere else in the marine Arctic is as likely to see such a dramatic change in species diversity and species composition. The first decade of the 21st century may be the last chance to see the Arctic coasts in their present species-poor state.

Arctic biodiversity-related research at SAMS and links with other Arctic polar stations

The Scottish Association for Marine Science: Northern Seas Programme

The Northern Seas Programme (NSP) at SAMS has a strong emphasis on latitudinal comparisons of patterns and processes in the oceans from the temperate North Atlantic to the Arctic. Two primary geographical foci delineate the research program: ocean margins and fjords. The science spans the major disciplines from physics, through geochemistry and geology, to the biological sciences, including whole organism physiology and behavior, and the ecology and genetics of microbial and multicellular species.

Since the beginning of the NSP in 2001, several projects have had a significant Arctic component. Two cruises on RS *Discovery* (2001) and RS *James Clarke Ross* (JCR2002) have gone into the Arctic, hosting projects on the geochemistry and ecology of both deep-water and nearshore benthos. JCR2002 traversed the Norwegian coast and across to Kongsfjord in Svalbard, then up to Greenland. The objective of this work was to link functional diversity and infaunal biomass to processes responsible for biogeochemical cycling. Sediment communities were sampled for their diversity at functional level to determine their capacity for sediment transport and mixing. Biological parameters were related to sediment oxygen uptake, metal distributions and nutrient fluxes. Longer-term work in Kongsfjord, using land-based fieldwork at the European Large Scale Facility at Ny-Ålesund on Svalbard, is designed to determine the seasonality and magnitude of organic input to the system.

A recent expansion of SAMS' polar capabilities has resulted from the relocation of the Sea-Ice Group from the Scott Polar Institute in Cambridge. This group has its own field program, largely based at sea or in ice camps.

Taxonomic expertise at SAMS covers the macrofauna of intertidal and nearshore sediment and rock, including nearshore fish species. The laboratory also has a long established expertise in the identification of deep-water fishes and benthic organisms.

ENVINET. European Network for Arctic-Alpine Environmental Research

SAMS is a founder member of ENVINET, an "Infrastructure Co-operation Network" focusing on multidisciplinary environmental research in Northern Europe. The network involves 17 research stations from the European Alps to the Arctic (see Appendix Table 1). ENVINET also has representatives from relevant international organizations and networks. The participating stations cover a broad range of environmental sciences, primarily within atmospheric physics and chemistry, and marine and terrestrial biology. ENVINET is funded from May 2000 to April 2003 under the EU 5th framework program. The Norwegian Polar Institute is the responsible coordinator of the network and hosts the secretariat. Four General Meetings and an International Conference have identified fields of collaboration between the stations in marine, terrestrial and atmospheric sciences.

New laboratory at Ny-Ålesund, Svalbard

A new marine laboratory at Ny-Ålesund, Svalbard is planned for construction in 2003-2004 for operations from 2005. The laboratory will be built and owned by Kings Bay AS and rented out to a consortium of rental shareholders, and others as space allows. This will be an international laboratory with researchers from many nations conducting experiments on marine organisms. Currently, the participating institutions are represented by the Marine Lab Project Group (chaired by the Norwegian Polar Institute). Present members include the Italian National Research Council (CNR); National Polar Institute (NIPR), Japan; Alfred Wegener Institute (AWI), Germany; National Science Foundation (NSF), USA; Scottish Association for Marine Science (SAMS), Dunstaffnage Marine Laboratory; University Courses on Svalbard (UNIS); and the Norwegian Polar Institute (NP). SAMS has committed funding to the construction and running costs of the laboratory, and will have full access to new facilities.

Research initiatives

In Europe: BIOMARE, MARBENA, MABREF

Nearshore and intertidal research on marine biodiversity is presently coordinated at the European scale via the BIOMARE initiative. This project has identified primary sites for inventories of marine biodiversity across Europe, extending as far north as Svalbard and northern Norway (Tromso). The present partners with some additional members (including SAMS) are preparing a bid for a European Network of Excellence under Framework 6.

Trans-Atlantic comparisons: The CORONA network

CORONA is an NSF-funded multidisciplinary research network to study the marine biota of the North Atlantic. The network includes 118 scientists from 13 countries across the North Atlantic. The invasion of marine organisms from the Pacific after the Bering Strait opened in the late Pliocene put closely related organisms on both coasts of the North Atlantic. The major goals of this network are to encourage trans-Atlantic ecological research when closely related taxa are found in the NW and the NE Atlantic, and to link these studies with molecular phylogeographic and systematic studies of taxa found on both coasts. The network holds an annual meeting devoted to a coordinated synthesis of the historical ecology of the temperate North Atlantic Ocean. In the U.K., the BIOMICS project will contribute to these research goals. The proposal for BIOMICS is presently being prepared for submission to the U.K. Natural Environment Research Council in summer 2003.

Other relevant work on polar marine biodiversity in the U.K.

The British Antarctic Survey has the largest group of researchers in polar biodiversity in the U.K. SAMS has close links with BAS, particularly with its ecosystem research group. I jointly supervise a Ph.D. student at BAS who is presently modeling interactions between macaroni penguins and their krill prey.

Overview of the technological resources available to do biodiversity work in your countries

Ships and AUVs

The U.K. shipborne and AUV capability for Arctic research has been well summarized in Dr. Tammy Horton's paper (this volume).

Autonomous benthic landers

SAMS and the University of Aberdeen have a long history of the development and deployment of autonomous benthic landers. While these have often been used as platforms for physical instruments, the addition of video and still cameras has produced much information on the diversity of epibenthic species and their behavior and physiology. The use of baited traps (Professor Monty Priede's group in Aberdeen) has been used to attract and capture scavenging species. Researchers at SAMS are also using these landers to assess benthic communities and physical conditions associated with colonies of the deep-water coral, *Lophelia pertusa*. Success in attracting university infrastructure funding (JIF) has led to the building of major new facilities in Oban and Aberdeen (OCEANLAB) for the building of new benthic landers.

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Appendix Table 1. ENVINET: Participants as of April 2003.

Research stations	Country	Member organizations
Sverdrup Res. Station, Ny-Ålesund LSF	Norway	Norwegian Polar Institute
Kristineberg Marine Res. Station	Sweden	Goeteborg University
Bergen Marine Food Chain Research Infrastructure	Norway	University of Bergen
Dunstaffnage Marine Laboratory	Scotland	Scottish Assoc. for Marine Sciences
Zackenberg Field Station, Greenland	Denmark	Danish Polar Center
Abisko Scientific Res. Station	Sweden	Royal Swedish Aca. of Sciences
Station Alpine du Lautaret/Chalet Lab.	France	Univ. Joseph Fourier-Grenoble
Harland Arctic Station, Ny-Ålesund LSF	England	Natural Environment Res. Council
ALOMAR Observatory	Norway	Andøya Rocket Range
High Alpine Res. Station of Jungfraujoch	Belgium	Belgian Inst. of Space Aeronomy
Kiruna Observatory	Sweden	Swedish Inst. of Space Physics
Koldewey Station, Ny-Ålesund LSF	Germany	Alfred Wegener Inst.
Sodankylae Observatory	Finland	Finnish Meteorological Inst.
Sonnblick Observatory	Austria	Vienna Univ. of Technology
Mace Head Field Station	Ireland	National Univ. of Ireland, Galway
Arctic Station Dirigibile Italia, Ny-Ålesund	Italy	Conciglio Nazionale delle Richerche
Zeppelin Air Monit. Station, Ny-Ålesund LSF	Norway	Norwegian Inst. of Air Res.
		AMAP
		IASC
		SCANNET
		Nordic Ozone and UV Group

Aspects of Biological Diversity in Benthic Communities: German Research Activities in Arctic Deep-Sea Regions

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Deep-sea research activities in Germany radiated in a variety of research interests by several institutions in the last thirty years, ranging from the effects of deep-sea mining in the South Pacific to research projects on seamounts, cold seeps, and gas hydrates.

Biological processes in deep benthic environments in the Greenland-Iceland-Norwegian (GIN) Seas had been a topic of the multidisciplinary research project SFB 313, which, after 14 years of research (1985-1998), can be considered one of the best studied subbasins of the world's ocean. Several meso-scale field studies on benthic faunal assemblages have been conducted at the East Greenland continental margin down to water depth of 3,700 m. Overall, there was no consistent latitudinal or bathymetric trend for species richness throughout the study area (summarized in Piepenburg et al. 2000).

Various aspects of the biology and ecology of the small biota, ranging from bacterial to deep-sea meiobenthos, have been investigated in the deep Fram Strait, on the Yermak Plateau, and adjacent Arctic slopes and basins (Kröncke et al. 1994; Vanaverbeke et al. 1997; Schewe and Soltwedel 1999; Soltwedel et al. 2000, 2003; Tseitlin et al. 2001). Comparably high abundances of meiofauna as well as substantial amounts of biogenic sediment compounds in the Molloy Deep (5,600 m) indicated this area as a possible natural sink for organic matter (Soltwedel et al. 2003). Some recent studies dealt with faunal elements of the deep Eurasian Arctic Basins including quantitative assessments of macro- and megafauna (Kröncke 1994, 1998; Kröncke et al. 2000; Deubel 2000; see Deubel and Klages 2003, this volume), thus affecting the actual knowledge on deep benthic communities in the central Arctic and serving as geographical steps between the Canada Basin and Russian work at Eurasian slopes and adjacent deep-sea areas (Paul and Menzies 1994; Sirenko 2003, this volume). Bipolar comparisons of megabenthic diversity are restricted to shelf ecosystems off Northeast Greenland and in the Weddell Sea (Piepenburg et al. 1997, Starmanns and Gutt 2002). There are several indications as to how the resuspension and particle transport processes in the benthic nepheloid layer may affect macrobenthic communities in continental slope and deep-sea environments of the GIN Seas and Fram Strait (Thomsen et al. 1995, Rutgers van der Loeff et al. 2002). Recent observations of planktonic organisms in near-bottom water layers such as high concentrations of the dominant herbivorous copepod *Calanus hyperboreus,* which were found 1 m above the seafloor at 2,200 m water depth in Fram Strait (Auel et al. in press), will bring future attention to the dynamics of hyperbenthos communities.

Since 2000, several Arctic deep-sea research activities at the Alfred-Wegener Institute for Polar and Marine Research (AWI) were integrated into a multidisciplinary project group "AUV payload development and gradients in the deep sea." Starting from the hypothesis that biological, biogeochemical, and physical gradients foster a postulated high biodiversity in the deep sea, the effect of such gradients on structure and functioning of deep-sea communities is the main aim of current research activities. In summer 1999, a deep-sea long-term station (AWI's "Hausgarten") was established about 150 km west of Svalbard, which consists of sampling sites along a depth transect between 1,000 and 5,500 m and additional sites along a latitudinal transect following the 2,500 m depth isobath, crossing this depth transect. The area is revisited yearly to analyze seasonal and inter-annual variations in a variety of parameters. Two sites at 2,500 m were chosen for biological long-term experiments to study cause and effects of gradients on deep-sea biodiversity. Sampling programs, mooring and free-fall lander deployments are accompanied by Remotely Operated Vehicle (ROV) operations in cooperation with IFREMER, owner of the 6,000 m depth rated ROV *VICTOR 6000.* Recently, another hotspot of research, the Håkon Mosby mud volcano, representing a cold seep environment northwest of Norway characterized by distinct biogeochemical gradients at the sediment-water interface, is also revisited regularly. Studies on Håkon Mosby communities could also contribute to a census of deep-water chemosynthetic ecosystems in ChEss (see Ramirez Llodra et al. 2003, this volume). The evaluation of "biological diversity" in terms of species richness, and spatial and temporal distribution patterns, is concentrated on bacteria, benthic meiofauna, megabenthic epifauna, as well as the description of habitat diversity in Arctic deep-sea areas. Current investigations are following classical approaches as well as analysis of genetic fingerprinting techniques in selected groups of organisms, starting with prokaryotes.

The investigation of natural gradients and their effect on benthic communities already led to manifold findings on the ecology of Arctic deep-sea communities during recent years.

Small natural food-falls and their effect on the motile macro- and megafauna have been described from the long-term observation area (Klages et al. 2001, Soltwedel et al. in press). The effects of benthic habitat heterogeneity caused by epifaunal species on the community of small sediment-inhabiting organisms are found to be rather diverse (Soltwedel and Vopel 2001). Gradients on larger spatial scales have been followed by means of imaging methods in the framework of a multidisciplinary study in a channel system in the deep Greenland Sea and are still the focus at AWI's Hausgarten. In addition to topographical features such as sediment waves, slope environments, and natural sediment traps, the availability of hard substrates in soft-sediment environments can play a significant role in structuring benthic communities. A combination of ROV sampling and video observation can be used to describe taxonomic and ecological characteristics of specific epibenthic species (e.g., the deep-sea holothurian *Irpa abyssicola*; Gebruk et al. 2003)

Several ROV-supported experimental approaches are followed to study effects of gradients in physical, chemical, and biological parameters on deep-sea diversity. Physical disturbances were created by using the ROV to elucidate their role on benthic diversity in terms of recovery potential and long-term effects, whereas the development of the small sediment-inhabiting biota protected from any kind of disturbance (predation, sediment disruption by motile megafauna) is studied by exclusion experiments. Food-fall experiments were initiated to investigate the effect of large food-falls as natural biological disturbances on the surrounding sediment community. The combination of optical and acoustical measurements allows the long-range detection of approaching scavenging amphipods to baited time-lapse cameras (Premke et al. 2003). Pandalid shrimps *Pandalus borealis*, caught in water depths down to 1,100 m around Svalbard, were used to investigate mechanoreception as a possible mechanism of food-fall detection in deep-sea scavengers in ex situ experiments (Klages et al. 2002). A description of benthic responses to particle flux patterns in deep Arctic sediment communities (Schewe and Soltwedel, in press) will be followed up by experimental approaches. The function of hard substrates in fostering benthic biodiversity is studied by means of colonization experiments. Mimics simulating sessile organisms (sponges) being anchored in 2001 will be sampled in 2003 to study the relevance of biogenic modifications of the near-bottom flow field, thereby possibly enhancing the diversity of surrounding sediment-inhabiting microorganisms.

Currently, the main platform of German research activities in ice-covered Arctic deep-sea environments is the ice-breaking research vessel *Polarstern.* In cooperation with IFREMER, the ROV system *VICTOR 6000* has been deployed several times in the deep Greenland Sea and Fram Strait and the program will continue in the future. In fall 2002 the Alfred Wegener Institute for Polar and Marine Research ordered an AUV with a maximum diving depth of 3,000 m, developed by Bluefin Robotics Corporation. The AUV will be delivered in September 2003 and will allow high-resolution seafloor mapping, the use of various payload developments, and under-ice studies in the future. Thus, multi-year research at the long-term observation area Hausgarten and a coverage of benthic communities on larger spatial scales by ROV and AUV operation are expected to give future insights in temporal and spatial variations of biodiversity in the deep sea.

National cooperations include the GEOMAR Research-Centre for Marine Geosciences (Kiel); Institute for Polar Ecology, Christian-Albrechts-University (Kiel); International University Bremen; Max-Planck-Institute for Marine Microbiology (Bremen); Marum-Centre for Marine Environmental Sciences (Bremen); and Senckenberg Research Institute (Frankfurt/Wilhelmshaven). International partners are found at the Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER, France); Nederlands Instituut voor Onderzoek der Zee/The Netherlands Institute for Sea Research (Texel, The Netherlands); University of Ghent (Belgium); Institute for Oceanology, Polish Academy of Sciences (Gdansk, Poland); Institute for Applied Physics, Russian Academy of Sciences (Nizhny Novgorod, Russia); P.P. Shirshov Institute for Oceanology, Russian Academy of Sciences (Moscow, Russia); Florida State University (Tallahassee, Florida, U.S.A); University of Alaska Fairbanks (Fairbanks, Alaska, U.S.A); and National Institute of Water and Atmospheric Research (New Zealand).

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Remarks to Macrobenthic Investigation of the Siberian Shelf Seas and Deep Arctic Basins with Special Reference to the Kara Sea, Laptev Sea, and Lomonosov Ridge Areas

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Although the Arctic Ocean covers only about 4% of the world ocean area, the Arctic contains about 25% of the continental shelves on earth where 10% of the global river runoff takes place. Strong seasonality of the light regime and the sea ice cover are special characteristics for polar oceans. Together with these factors the strong signals of fresh water, heat and matter supply originating from large rivers during spring and summer are dominating factors which influence the productivity, consumption and transformation processes in the Arctic. The annual discharge from the Eurasian land mass into the Arctic Ocean implies that a total of about 28×10^6 t organic carbon enters the shelf areas where intense transformation processes take place and a yet unknown amount reaches the external shelf areas and the adjacent deep Arctic basins. Among water depth and local environmental conditions, the import of allochthonous food affects biogeography, diversity, population densities, biomass and the activity of the seafloor community.

Since 1997, the Alfred-Wegener-Institute in Bremerhaven (Germany) is strongly involved in the joint-Russian-German project SIRRO (Siberian River Runoff). Its primary objective is the understanding of biological, geochemical and geological processes related to the freshwater and sediment input by the Siberian rivers Ob and Yenisei (Kara Sea). The interdisciplinary biological studies covered most of the ecosystem compartments, e.g., phytoplankton, zooplankton and benthos including the significance of fluvial matter for the Kara Sea macrozoobenthos. During the project, four multidisciplinary scientific expeditions were carried out with RV *Akademik Boris Petrov* in the summers of 1997, 1999, 2000 and 2001 (Matthiessen et al. 1999; Stein and Stepanets 2000, 2001, 2002). Our data basis comprises 96 stations sampled in the southern Kara Sea at water depths between 10 and 300 m. In cooperation with Russian scientists from Murmansk (Murmansk Marine Biological Institute), Moscow (Shirshov Institute of Oceanology) and St. Petersburg (Zoological Institute St. Petersburg) the investigations were carried out along transects starting at the river mouths of Ob and Yenisei up to the central Kara Sea. The geographical area represented by stations analyzed covers roughly 222,500 km^2, which is about one-fourth of the entire Kara Sea. However, for logistic reasons offshore parts of the Kara Sea, which are more difficult to reach, have been investigated insufficiently, mainly by Russian colleagues (Denisenko et al. in press).

The intense continental outflow indicates a distinct salinity-gradient on the Kara Sea shelf, since the outflow spreads out northward from the river estuaries into the central Kara Sea and significantly influences the distribution of the benthic fauna and flora as well as their productivity and consumption (Klages et al. in press). About 300 species of invertebrate macrozoobenthos were identified, with Polychaeta, Crustacea, Mollusca and Echinodermata being most abundant (Deubel et al. in press). On the Kara Sea shelf, the macrofauna shows a remarkable increase in species numbers, biomasses and diversity toward the higher salinity and hence with increasing distance from the coastline.

A main focus in future scientific programs is to extend this kind of investigation also to early spring conditions when the onset of ice melt takes place and large amounts of riverine fresh water enter the Kara Sea, to investigate the interrelationship between the pelagic system and sedimentation processes in different seasons. First investigations on the activity of benthic invertebrates during the dark winter season were carried out on 16 stations within the *Polarstern* expedition ARK XIX/1 (WARPS; 2003) in the Barents Sea and Svalbard waters.

Comparable with the Kara Sea, the Laptev Sea is influenced by large rivers leading to reduced salinity and enhanced ice formation. Benthos samples taken systematically by joint Russian-German expeditions (RV *Ivan Kireev* 1993, RV *Polarstern* 1993 and 1995, IB *Kapitan Dranitsyn* 1995); and the identifications by Russian and German scientists from St. Petersburg (ZISP), Kiel (IPOE) and Bremerhaven (AWI) increased the macrofaunal species number in the Laptev Sea (Petryashov et al. 1999). The expedition ARK XI/1 (1995) with RV *Polarstern* focused on the Laptev Sea–Arctic Deep-Basin Interrelation (LADI). Accordingly, the main objectives of the multidisciplinary program were to study the material flux and the ecological relationships between the Siberian shelf areas, particularly the northern Laptev Sea as well as the northeastern Kara Sea, and the adjacent deep Arctic basins. Altogether, the benthos work during ARK XI/1 (1995) and the Swedish expedition Arctic Ocean ‘96 (IB *Oden* 1996) is a continuation of the investigations initiated during ARK IX/4 in 1993 (Fütterer 1994). Additional macrobenthic invertebrates were sampled extensively during the expeditions with RV *Polarstern* to the continental slope of the northern Barents Sea (ARK VIII/2; Rachor 1992) and the central Arctic Ocean (ARK VIII/3; Kröncke 1991). On the Siberian marginal seas and in the central Arctic basins strong regional variabilities in macrobenthic species numbers as well as in abundances and biomass are obvious. Quantitative macrofaunal and megafaunal assessments in the central Arctic Ocean are extremely limited (Kröncke 1994, 1998; Rachor et al. 1999; Deubel 2000). These few investigations demonstrated very low species numbers and abundances. The number of species, abundance and biomass of the macrofauna showed a clear relation to the different depth. In the central Arctic Ocean on the Lomonosov Ridge, a latitudinal reduction to the north was proved. Our recent results on macrobenthic biodiversity (calculation of Shannon indices per station) for the Kara Sea and the Lomonosov Ridge area show fairly high and moderate values.

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Microalgae and Biodiversity in Polar Regions

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Preface

Much of what is presented is based on von Quillfeldt (1996). The outline of the talk is as follows: some definitions, historical background, what do the diversity of microalgae reflect (habitat, season, environmental conditions, distribution), large-scale variability and small scale variability, potential problems (snapshot, patchiness, sampling methods, identification), some recommendations for how to perform a study of these organisms and, finally, microalgae as indicators of the ecosystem. During the meeting, I will also inform about other relevant activities in the Norwegian region, as well as possibilities for future cooperation.

General background

Diversity

Groombridge and Jenkins (2000) stated that the diversity of organisms may be addressed at two levels, these representing the lowest and the higher levels of taxonomic hierarchy, "First, species diversity, or the number and variety of individual species, and second, the taxonomic diversity, or the number or variety of major groups into which species may be placed."

Succession

Changes in the species composition in an area can be a result of what Gran and Braarud (1935) called succession (changing of species composition within water masses) or what they regarded as a sequence (changing as a result of changing water masses). The content of these two notions are often confused in the literature when reports on species from different areas are given and discussed. Succession is regularly used as a common term on changed species composition in an area. According to Smayda (1980), true succession involves autochthonous species, while sequential changes involve allochthonous species.

Ice algae and phytoplankton

Ice algae occur in distinct communities defined to the surface, the interior, and the bottom or the underside of the ice (Horner et al. 1992). Characteristics of ice—age, construction, thickness, degree of motions, and distance from shore—are all important regulating factors, as is the snow on top of it. Monti et al. (1996) showed that a large part of the variation in species abundances could be explained by environmental variables, especially salinity, in southeastern Hudson Bay. Also Gradinger (1999) discussed different biological regimes in Arctic sea ice. Furthermore, based on changes in sea ice chemical and biological parameters, Melnikov et al. (2002) suggested that in the Canada Basin of the Arctic Ocean, the water-ice system above the pycnocline has shifted toward a more brackish condition, compared to more typical marine conditions found in previous studies.

It is likely that pennate benthic species may be brought from the bottom by vertical mixing during autumn when the stratification of the water column is reduced, assuming the water column is not too deep. Melt pools caused by thawing consist of freshwater and contain many of the same species found in freshwater environments on land (von Quillfeldt 1996, 1997). The importance of the different communities is seasonally dependent (Horner 1985). In addition, a community often experiences a succession of species (Syvertsen 1991). Therefore, some of the differences in species composition observed are probably caused by the age of the ice. Gradinger et al. (1992) was able to characterize four different succession stages of an Arctic sea ice community. Furthermore, the two most abundant meiofauna groups showed different preferences according to algal distribution. Some areas also experience huge patchiness of distribution of sympagic algae over small scales (von Quillfeldt 1996, 1997) while in other areas this can be omitted to comparison of large areas (Wiktor and Szymelfenig 2002). In addition, a south-north gradient similar to the seasonally dependent gradient in the species composition can often be traced. The oldest ice and the most specialized community occurs farthest north (Syvertsen 1991). Thus both age and latitude affect the species composition observed in an area. Even though it is not known to what extent grazing occurs in the ice communities, the huge amount of *M. arctica* (or sometimes other species) indicates a considerable food source in some areas. The importance, the origin, the survival as well as the fate of the ice algae is much debated.

The phytoplankton composition also varies as the seasons advance. Many of the species can be characterized as typical winter, spring, summer, and autumn species, while a few are seasonally independent (von Quillfeldt 1996). A typical species succession of a spring phytoplankton bloom in the Arctic starts with dominating pennate diatoms being gradually replaced by centric ones (Grøntved and Seidenfaden 1938, Bursa 1961b, Michel et al. 1993, von Quillfeldt 2000a). A succession exists within different algal classes and between algal classes, and sometimes it is possible to trace a pattern of succession within genera. Succession is controlled by various factors such as stability, light, nutrients, and herbivores specific to the area in question (Margalef 1978, Levasseur et al. 1984, Perry et al. 1989). It is therefore important to study what species initiate blooms and if these species appear year-round. Several spring species form resting spores which may hibernate on the sea bottom, and it is possible that resuspended spores may initiate a spring bloom. In some areas, if ice is present resting cells or spores may be released from the ice and thus contribute to the spring bloom, as suggested for the southwestern Kara Sea (Druzhkov et al. 2001). In particular, some areas influenced by drifting sea ice have a species composition that indicates a possible innoculum for the spring bloom in the water column (von Quillfeldt 1996). However, for many areas this “seeding” has been equivocal (Garrison et al. 1987). The ice algal bloom and spring phytoplankton bloom can be clearly separated in time (Apolonio 1965, Clasby et al. 1973, Grainger 1977, Booth 1984) and sometimes by the species present (Horner and Alexander 1972, Horner 1977).

Different environmental conditions may be more important in determining the timing and progress of the phytoplankton spring bloom in some areas than in others. The central part of the Barents Sea is somewhat special because this is where Atlantic water meets water from the Arctic (the Polar Front), and the timing of the phytoplankton spring bloom is very much dependent on how far south the sea ice extends during winter, i.e., whether the ice comes in contact with warmer Atlantic water (Rey and Loeng 1985).

In northern areas, the species composition after a spring bloom is often composed of both allochthonous (introduced) and autochthonous (indigenous) species. However, the possibility of succeeding in an area depends on the autecology of the species. Thus, high concentrations of a particular species sometimes do not last for long if they are caused by transport to an area with unfavorable conditions for that particular species. Furthermore, this can result in large fluctuations of the species composition in an area.

Few investigations have been performed in Arctic areas during winter, but flagellates have been reported as important during winter in the Barents Sea (Rey 1986), the Bering Sea (Schandelmeier and Alexander 1981), and the Beaufort Sea (Horner and Schrader 1982).

Species living as benthos or periphyton may be important in the phytoplankton during parts of the year, as will the amount of brackish/freshwater species in some areas. For the latter, few are able to survive such huge change of environmental conditions introduced to the marine environment.

Production

As the ice melts a stable surface layer develops, revealing winter concentrations of nutrient salts. Unimpeded by deep vertical mixing, the spring algae bloom starts 6-8 weeks earlier than in open sea farther south. These favorable production conditions lead to great concentrations of krill and other crustaceans and commensurate numbers of seabirds and marine mammals that feed on them and follow the ice edge as it retreats northwards. In the Barents Sea, the blooms in Arctic water are, however, often short-lasting compared to those in Atlantic water (and constricted to a 20-50 km wide zone), which are therefore more productive overall. The highest annual primary production in Arctic and sub-Arctic seas is found on the Bering Shelf, >230 g C m^{-2}, followed by the Atlantic Barents Sea and the Chukchi Sea with 90 and 70 g C m^{-2} respectively (Sakshaug 2003). The other Siberian Shelf seas produce 35 g C m^{-2} and the deep Central Arctic Ocean, only 11 g C m^{-2}. The latter is considerably higher than earlier estimates because the multiyear ice has proved not to be the "dead zone" it once was thought to be. According to Sakshaug (2003), the deep Central Arctic Ocean water column suffers from light limitation by multiyear ice, making ice-algae the most important contributor.

Historical background

Arctic

The study of phytoplankton and ice algae of the Arctic seas dates back to the middle of the nineteenth century. At first, species lists were often the only form of results given from different areas. Ehrenberg (1841) reported on diatoms from Arctic sea ice and Cleve studied samples (mostly from the water column) collected near Spitsbergen (Cleve 1864, 1873), Greenland, and the Davis Strait (Cleve 1873). He also studied bottom, water, and ice samples from the expedition of *Vega* to the North Siberian Sea and the Bering Sea (Cleve 1883). Grunow (1884) analyzed both bottom samples and ice samples collected in the vicinity of Franz Josef Land. Both Cleve and Grunow identified a considerable number of diatom species from the plankton as well as from the sea ice. In order to give an idea of the diatoms occurring in the Arctic Ocean, Cleve (1883) gave an overview of diatoms recorded by Grunow and himself, in samples from several cruises to the Arctic Ocean and the Siberian seas. Østrup analyzed phytoplankton and ice algal samples from the Danish East Greenland Expedition in 1891-1992 (Østrup 1895) and from the west and east coast of Greenland (Østrup 1897).

Some investigations have included studies of seasonal and interannual variations. Cleve (1896) studied plankton samples from Baffin Bay and Davis Strait collected from the beginning of May to the middle of October. Gran (1897a) studied the annual phytoplankton cycle and ice algae in Karajakfjord, Greenland. Nansen (1906) and Gran (1904) studied seasonal variations of ice algae during the Norwegian North Polar Expedition of 1893-1896.

Some authors have classified plankton algae according to the water masses where they have been found (Gran 1897a,b; Cleve 1899, 1900; Gran 1902, 1908). Furthermore, Gran (1904) described the algae according to their habitat as true ice species, true plankton forms, etc.

No research on the dynamics of phytoplankton growth as a function of the Arctic environment was made until the 1930s. From then on and until today, several important investigations in Arctic areas have been performed (e.g., Heimdal 1989), including discussions of species occurrence versus Arctic environmental characteristics: Braarud (1935) from the Denmark Strait, the east coast of Greenland, Spitsbergen, and Franz Josef Land; Ramsfjell (1954) from the west coast of Spitsbergen; Bursa (1961a,b) from Hudson Bay and Igloolik; Cross (1982) from the Pond Inlet; Spies (1987) from the ice edge region of the Greenland Sea; Gradinger and Baumann (1991) from the Fram Strait; and several studies from the Russian Arctic (Usachev 1949, Melnikov and Bonderchuk 1987, Okolodkov 1993).

Some authors have concentrated on ice algae dynamics in particular, like Hsiao (1980) who studied the quantitative composition, distribution, community structure, and standing stock of sea ice microalgae in the Canadian Arctic during the years 1971 to 1978; Syvertsen (1991) who described different types of ice algal communities found in the Barents Sea from 1984-1989 and how these communities experience a succession terminated by the dominance of ice specialists; and Abelmann (1992) who investigated particle-laden sea ice collected from the western Barents Shelf and the Arctic Ocean between Svalbard (81ºN) and the Nansen-Gakkel Ridge (86ºN), and used the diatom composition to explain the pattern of ice drift. Others have investigated the fate of primary producers inside the sea ice and suggested grazing as a control of biomass accumulation (Gradinger et al. 1999).

Northern Norway

Marine phytoplankton in northern Norway has also been studied from the turn of the century (Cleve 1898, 1899; Gran 1897c, 1900, 1902; Hjort and Gran 1899; Jørgensen 1905). The diatoms in water and bottom samples from the Lofoton area up to Vardø in Finnmark, northern Norway, were thoroughly studied by Jørgensen (1905). Also Føyn (1929) and Gran (1930) investigated the Lofoton area. Braarud and Nygaard (1978) studied the Norwegian coastal waters north to 69ºN, while Rey (1981a,b) made primary production estimates and studied the development of the spring phytoplankton in the Norwegian Coastal Current as far north as 72ºN. Studies in selected fjords have also been conducted: Balsfjord (Gaarder 1938, Eilertsen et al. 1981a,b); Malangen (Gaarder 1938); the Ullsfjord area (Heimdal 1974); and Skjomen (Schei 1974, Eilertsen 1983).

Identifying species

Correct identification of species is often difficult, particularly for scientists not specialized in identification. This has notably resulted in several misidentifications in the literature. Furthermore, the species are often identified as similar species from other areas or only referred to by their genus name, or just as groups of species. It is also striking that for example *Thalassiosira constricta* which was described by Gaarder (1938) from the Tromsø area in northern Norway, was not reported again until Heimdal (1971) studied the species in material from the Kiel Bight (Germany), Oslofjord, and Trondheimsfjord (Norway). Moreover, some species are impossible to separate unless resting spores are present, for example *Chaetoceros socialis* Lauder and *C. socialis* var. *radians* Proschkina-Lavrenko, or at least difficult to separate, i.e., *Thalassiosira antarctica* var. *borealis* Fryxell, Douchette and Hubbard and *T. gravida* Cleve (von Quillfeldt 2001).

Many diatoms have also been described as a number of different species because polymorphic stages of a single organism have not been recognized. It is for example possible that *Thalassiosira gravida* and *T. rotula* Meunier are two varieties of one species, since *T. rotula* has *T. gravida* structure in cultures at low temperature (Syvertsen 1977). Life histories are also little known for most species.

Furthermore, some species have not yet been described or just been described recently even though some of these may be quite common or even among the dominant ones in certain habitats (Hasle et al. 1996; Quillfeldt 2000b, 2001).

The taxonomic systems set up by light microscopists were based on relatively few morphologic characters. The introduction of electron microscope techniques has greatly increased the number of characters available and this has led to a much improved understanding of many groups. An understanding that is further improved when protoplast characters, auxospore formation, auxospore structure, and ecology are taken into account.

Not only do morphological characteristics vary, but also physiological characteristics may vary within a species. A better understanding of the species composition may therefore improve the knowledge also about ecology and physiology of the species as well as interactions and processes in the ecosystem.

Biogeography

Several factors influence the distribution of marine phytoplankton species, e.g., the size of the cells (0.2-2,000 μm), passive transportation, living in the euphotic zone, and the rapid vegetative growth (0.2-2 divisions per 24 hours) are predominant.

Sea areas have been divided into plankton regions (Gran 1902); vegetation areas (Braarud 1935, Paasche 1960); or floral zones (McIntyre and Bé 1967) based on the occurrence of characteristic species. Species coexisting have been characterized as plankton elements (Gran 1902).

The large scale distribution pattern varies, often dependent on the temperature of the water masses. Some species are cosmopolitan, i.e., have a worldwide distribution (sometimes absent from polar regions), some are cold water species (either southern, northern or both), some are cold water to temperate species, some are temperate, some are temperate to warm water species, and some are warm water species only (Hasle and Syvertsen 1996). Others prefer the terms cold/warm temperate and tropical (Steidinger and Tangen 1996). Temperature may therefore explain why some species appear during certain seasons only or certain species are absent from an area altogether, and was probably an important factor influencing the occurrence of many of the species in the present investigation (von Quillfeldt 1996).

According to Lawrence (1989) some species are oceanic (inhabiting the open ocean), while others are neritic (living in coastal waters) or littoral (living near the seashore). There is no satisfactory explanation why some species are neritic and others oceanic, but one possibility may be that many neritic species are meroplanktonic (dependent on the bottom for a stage of their life cycle) or have the possibility to assimilate organic molecules, such as urea, introduced to the area from land or resuspension of decaying matter (Round 1985).

In spite of some mixing of different water masses, it is reasonable to believe that different water masses can to some extent be inhabited by different species. The ocean current system is important in the distribution of species and may help to explain the distribution pattern. Cleve (1896) found similarities in species composition in ice at Cape Vankarem, Franz Josef Land, Novaja Semlja, on the east coast of Greenland, and in the Labrador Current. He concluded that this was a result of ice floes drifting from the Bering Strait toward the north of Greenland, where some continued along the east coast of Greenland while others drifted with the Labrador Current. Abelmann (1992) also argued that diatoms were incorporated in the ice in shallower areas and transported by the Transpolar Drift. Likewise, Druzhkov and Makarevich (1999) explained the similarity in the phytoplankton assemblages between the southeastern Barents Sea and southwestern Kara Sea by stable water exchange between the areas and named it the Novaya Zemlya Phytogeographical Province.

According to Lawrence (1989), the distribution of phytoplankton can be circumpolar (continuous in northerly parts of the Northern Hemisphere extending through Asia, Europe, and North America or continuous around the Antarctic continent in the Southern Hemisphere), bipolar (present in both polar regions), or disjunct (potentially interbreeding populations are separated by sufficient distance to preclude gene flow). Thus, a bipolar species is also disjunct.

Moreover, scattered sampling does not illustrate the uneven dispersal across stretches of ocean (Round 1985), or the fact that different species have different vertical distribution in the water column. This also applies for ice algae. Thus, Gradinger (1999) concluded that all layers of the sea ice, and not only the bottom few centimeters, must be studied to avoid underestimation of algal biomass and production.

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Implementing the Microbial Food Web in the Arctic Pelagic Ecosystem: A Case Study from Disko Bay, Western Greenland

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Historically most research in Arctic pelagic ecology has focused on the larger components of the food web, e.g., the diatoms and the large conspicuous calanoid copepods. Research during the last century have documented the annual cycle and population dynamics of copepods of the genus *Calanus,* and stressed the key role of these organisms in high latitude ecosystems. This part of the food web is the direct link to the fish stock since most fish larvae rely on copepods during their early life. Several of the other key species of birds and mammals also to a large extent rely on *Calanus*.

Research in the microbial food web in the Arctic have been limited because the microbial loop in cold water ecosystems has been considered less important than at lower latitudes. However, our investigations in the Disko Bay, Young Sund, and the banks off West Greenland have documented that bacterioplankton and unicellular zooplankton also play a prominent role in the food web of Arctic ecosystems.

Because of the late recognition of the potential role of bacteria and unicellular grazers in high latitude ecosystems, investigations covering all major components of the pelagic food web are rare. Judged from the relative biomass distribution a large part of the annual primary production potentially is canalized through protozooplankton which, due to small size, has specific grazing and growth capacities an order of magnitude greater than copepods.

When considering the fate of primary production and coupling to the fish stock in high latitude ecosystems the small grazers are notable; they build up high biomasses and have growth rates that makes it possible for them to follow the growth of their phytoplankton prey.

From a sedimentation point of view the composition of the grazer community is also essential. The presence of the large copepods accelerates the carbon flux through production of fecal pellets, while the excretion products of the smaller grazers to a much larger extent are recycled within the surface water.

Based on high-resolution annual investigation it is suggested to establish models that integrate meteorological, oceanographic, and biological processes at stations representative for the ecosystems in consideration.

Important gaps in our knowledge about the pelagic ecosystem that should be addressed in a future Arctic research program are

- The trophic diversity of the pelagic food webs
- What happens during the winter?
- What drives the vertical export of organic matter?

A better insight in these processes is essential to understand the coupling between the productive surface layers and the benthic ecosystem.

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