Impacts of Global Warming on Polar Ecosystems

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4. IMPACTS OF GLOBAL WARMING ON ARCTIC PELAGIC ECOSYSTEMS AND PROCESSES

by

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THE ARCTIC has an important, but so far inadequately known role on the climate of the globe. Recent observational studies have revealed significant reductions in Arctic sea-ice cover and thickness and increased air and ocean temperatures, indicating that we may already be seeing the early warning signs of an ecosystem on the verge of dramatic changes. Warming in the north is several times greater than in central Europe and the pronounced changes in the Arctic can be used as bellwethers for the general state of the northern hemisphere. The current changes in the Arctic Ocean have consequences for fisheries, animal abundance and diversity, the formation of deep water (which influences atmospheric CO_2 concentration), storm patterns and the living conditions of northern people. The Arctic is an integrated part of our lives, and we cannot ignore it just because it is far away and few people live there. By the middle of the century, most of the ice cover may have disappeared from the pan-Arctic shelves in late summer, leaving just a core of ice over the pole. The basin-wide band of the marginal ice zone and flaw polynyas, which in today's Arctic is situated on the shelves but will shortly move from there into the deep Arctic Ocean, is the most visible indication of our era of climate change.

In this chapter, we describe some of the variability, dynamics and reduction of sea ice and how the production of biogenic matter in open Arctic waters and the marginal ice zone varies as a function of ice cover and the physical structure of the water column. We show that a warmer climate with less ice cover will result in greater primary production, a reduction of the stratified water masses in the south, changes in the relationship between biological water column processes and sediments, a reduction in niches for higher trophic levels and a displacement of Arctic by boreal species. In addition, increased runoff from the large Siberian rivers and the reduction of permafrost will result in

◀ Photo 4.1: Frozen landscape typical of the Arctic Ocean near the island of Spitsbergen (Svalbard Archipelago, Norway)

higher turbidity, decreased primary production and an increased supply of old biogenic matter to the Arctic Ocean. The changes ahead of us stand to radically change the productivity, functional relationships and biodiversity of the Arctic Ocean.

4.1. INTRODUCTION

The sub-Arctic has played an important role for the development of Europe, as stockfish and whale oil (lamps) were essential for European living conditions in earlier times. While the sub-Arctic still represents the most important fishing ground in Europe, sea-based extraction of gas and mineral oil is moving steadily northwards due to climate warming and ice reduction. Soon vital economic activities will enter the Eurasian Arctic with the development of the largest ever marine gas field, the Shtokman Field in the central-eastern Barents Sea. And similar plans exist for other regions, given that 25% of the world's gas and oil reserves are assumed to be located in the Arctic. The Arctic is thus no longer the remote, ice-covered, inhospitable place of past eras, but a well-integrated part of our contemporary global economy, playing a significant role for the Northern Hemisphere population.

Climate defines the prime forcing of Arctic ecosystems, and both observations and models suggest that climate is changing (see Sorteberg et al. 2005). Arctic shelf ecosystems are likely to be more sensitive to climatic perturbations than those of temperate shelf areas, firstly because disproportionate warming is expected (see Hassol 2004), and, secondly, because these ecosystems are characterised by comparatively few trophic links and low biodiversity (see Sakshaug et al. 1994). Indeed, recent studies have revealed significant reductions in Arctic ice cover at both pan-Arctic (Johannessen et al. 2004) and regional (Shimada et al. 2006) scales, and we may already be witnessing the early stages of ecosystems on the verge of dramatic change (see Grebmeier et al. 2006). Reductions in ice cover thickness, extent and duration, and changes in current patterns and fronts will likely have both gradual (predictable) and catastrophic (surprise) consequences. Hence bottom-up controls (e.g., stratification, mixing, upwelling) will certainly change; keystone predators within a given region may be recruited, relocated or made extinct; and ecosystems may shift from tight to weak pelagic-benthic coupling. Changes in the cryosphere will have cascading effects throughout the ecosystem, from altered patterns of primary production (Wassmann et al. 2006a) to changes in trophic structure and elemental cycling pathways (see Grebmeier et al. 2006), the introduction of boreal and the displacement of Arctic species (see Berge et al. 2005) and modifications in oceanic and atmospheric transport mechanisms (see Olsen, Johannessen and Rey, 2003). System perturbations brought on by climate change will interact with human activities such as fishing, mineral extraction, oil and gas exploitation and shipping, which will grow significantly in the near future. Because change may be rapid and sweeping, extraordinary and novel measures of conservation will be required to ensure marine animals have the resilience to relocate as existing biomes are altered by climate forcing, be it natural, anthropogenic or both.

In contrast to the poorly productive deep Arctic Ocean basin, the surrounding marginal seas of the European Arctic contain some of the most dynamic and productive ecosystems in the world, supporting food webs that culminate in large populations of seabirds, mammals and species targeted by regional fisheries whose harvesting has important consequences for system sustainability and northern populations (see Wassmann et al. 2006b). The structure and functioning of these ecosystems are intimately linked with ocean and sea ice dynamics and biogeochemical exchange processes. These highly productive regions appear to be more sensitive to climatic perturbations than temperate areas, due to expected disproportionate warming of these areas and ecosystems characterised by comparatively few trophic links (Carrol and Carroll 2003; Hassol 2004).

Recent observational studies have revealed significant reductions in Arctic sea-ice cover and thickness as well as increased air and ocean temperatures (Lindsay and Zhang 2005). What is now needed is to develop a predictive understanding of the effects and long-term ecosystem responses of the Arctic and its marginal seas to changes in climate and human activities. However, the state of our environmental knowledge of the Arctic Ocean is fairly limited, and time series are particularly scarce. We are faced with a number of questions that we cannot yet answer and have an immense amount of work in front of us to investigate and understand the basic function of the Arctic Ocean. And matters are further complicated by the fact that rapid environmental change is already taking place.

In the first part of this article, we explain something of the geographical setting and basic physical and marine ecological dynamics of the pelagic zone of the Arctic Ocean for the less familiar reader. We describe annual ecosystems dynamics, with particular regard to primary production, in general terms and with a more detailed example from one of the best known Arctic shelves, the Barents Sea. We also discuss the role of pelagic-benthic coupling in the Arctic Ocean and speculate how global warming might alter biogeochemical cycling in decades to come. In the next section, we examine these changes in the light of ecosystem variability over geological time scales, before concluding with a call for international cooperation to address the scientific challenges involved in studying a remote and ice-covered region.

4.2. A FEW FACTS ABOUT THE WORLDS LAST *TERRA INCOGNITA:* THE ARCTIC OCEAN

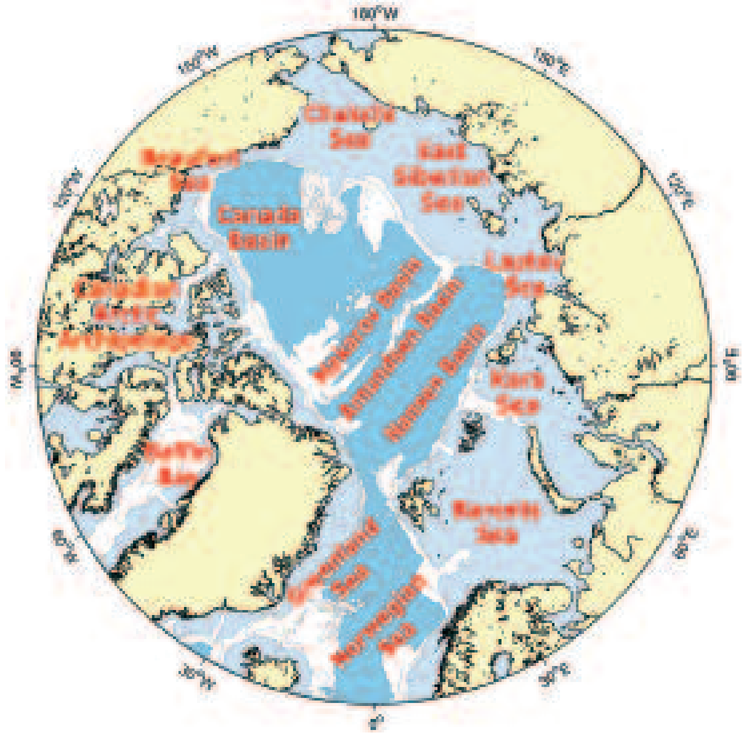
After the early exploration of the Arctic Ocean (see Nansen 1906) and scientific expeditions into the marginal ice zone (MIZ) of the Greenland Sea (see Gran 1902), a few local marine biological investigations were conducted before World War I off Spitsbergen, Franz Josef Land and in the Barents and White seas (see Zenkievich 1963; Vetrov and Romankevich 2004). Russian scientists were active in the inter-war years in the Barents Sea and along the Siberian shelves (see Zenkievich 1963), as well as in the central Arctic Ocean (see Ugryumov and Koronin 2005). The Soviet Union's closure of the North-East Passage after World War II ruled out international and pan-Arctic research activities in the Arctic Ocean. On the Siberian shelf, the Soviet Union gave precedence to studies of ice dynamics and physical oceanography, lending scant attention to the benthos, let alone plankton or ecosystem dynamics (but see Codispoti and Richards 1968, for an investigation carried out by intruding US naval vessels). The geopolitical climate of the Cold War awakened greater interest for the southern polar oceans, and International Geophysical Year 1958 was devoted to Antarctica. This has been a dominant trend in polar research until recently.

Thanks to a recent suite of research programmes (SHEBA, PRO MARE, SBI, CASES and CABANERA, to mention just a few), we have gained a basic understanding of certain sections of the pan-Arctic shelf expanse (for two recent summaries, see Stein and Macdonald 2004; Wassman 2006). However, some shelf regions have never been investigated and the majority only for limited periods of time (mainly summer to early autumn). Beyond the pan-Arctic shelf and the shelf break, information on the deep Arctic Ocean is decidedly scarce, save for the likes of the SBI and CASES projects. The regions of the shelf edge and slopes are among the main targets of International Polar Year 2007-2008, and significant advances can be expected in the near future.

The shelves of the Arctic Ocean are strikingly different from those of the world's other oceans. Approximately 50% of its surface is made up of shelves (map 4.1), engirdling four basins, more then 3,000 metres deep and separated by deep ridges such as the Lomonosov and Gakkel ridges. The Nansen and Amundsen basins are closely connected to the Atlantic, while the Canadian Basin, the most isolated of all, is fairly weakly connected to the Pacific. The Makarov Basin occupies an intermediate position. There are also significant differences among the pan-Arctic shelves. The shelves off North America are typically narrow, while those of Eurasia are wide with very steep slopes. The shallowest shelves are those of the Chukchi, East Siberian and Laptev seas (often only a few tens of metres deep), while those of the Barents Sea and the Canadian Archipelago are relatively deep.

The Arctic Ocean is a Mediterranean ocean in the strict sense of the Latin term *media terra.* Its shelves are connected to the hinterland by some of the

Map 4.1: Topography of the Arctic Ocean and pan-Arctic shelves



The image evidences the width of the shelves, shown in light blue, the circular structure of the Arctic Ocean and the separation of the deep basins, shown in darker blue, by a series of ridges.

world's major rivers (e.g. the Lena, Ob and Mackenzie rivers), which drain enormous territories as far south as central Asia and North America. Around 10% of the world's freshwater discharge enters the Arctic Ocean. This highly seasonal freshwater supply supports the formation of sea ice, as stratified waters freeze quickly. Most of the Arctic Ocean is ice covered during winter and spring with a reduction during summer and early autumn (photo 4.2). Ice cover is one of the prime factors driving ecological processes such as primary production in the Arctic Ocean, and this in and out "breathing" determines the seasonal and interannual pace of productivity. The Arctic shelves are also characterised by polynyas; open areas in ice-covered regions that are important sites for the production of new ice and biogenic matter. They can be persistent or transient, and the most prominent of all are the flaw polynyas that, later in the season, unite with the permanent MIZs in the Barents and Greenland seas. Together they form a continuous MIZ rim that moves northwards towards the permanently ice-covered region over the North Pole.

The oceanographic dynamics of the Arctic Ocean are heavily influenced by the import and export of water. Most imported water is brought in by the

Photo 4.2: A view of the seasonal ice zone with around 10% of open water

Norwegian Atlantic Current either through the Barents Sea or along western Spitsbergen (Wassmann et al. 2006b). Pacific water enters the Arctic Ocean through the Bering Strait (Woodgate and Aagaard 2005). The Atlantic inflow is more then six times greater than that of the Pacific, and much of the fauna in the Arctic Ocean suggest an Atlantic origin (Zenkievic 1964; Wassmann et al. 2006b). Arctic water and ice flows out over the export shelves (see Carmack et al. 2006) of the western Fram Strait and through the Canadian Archipelago.

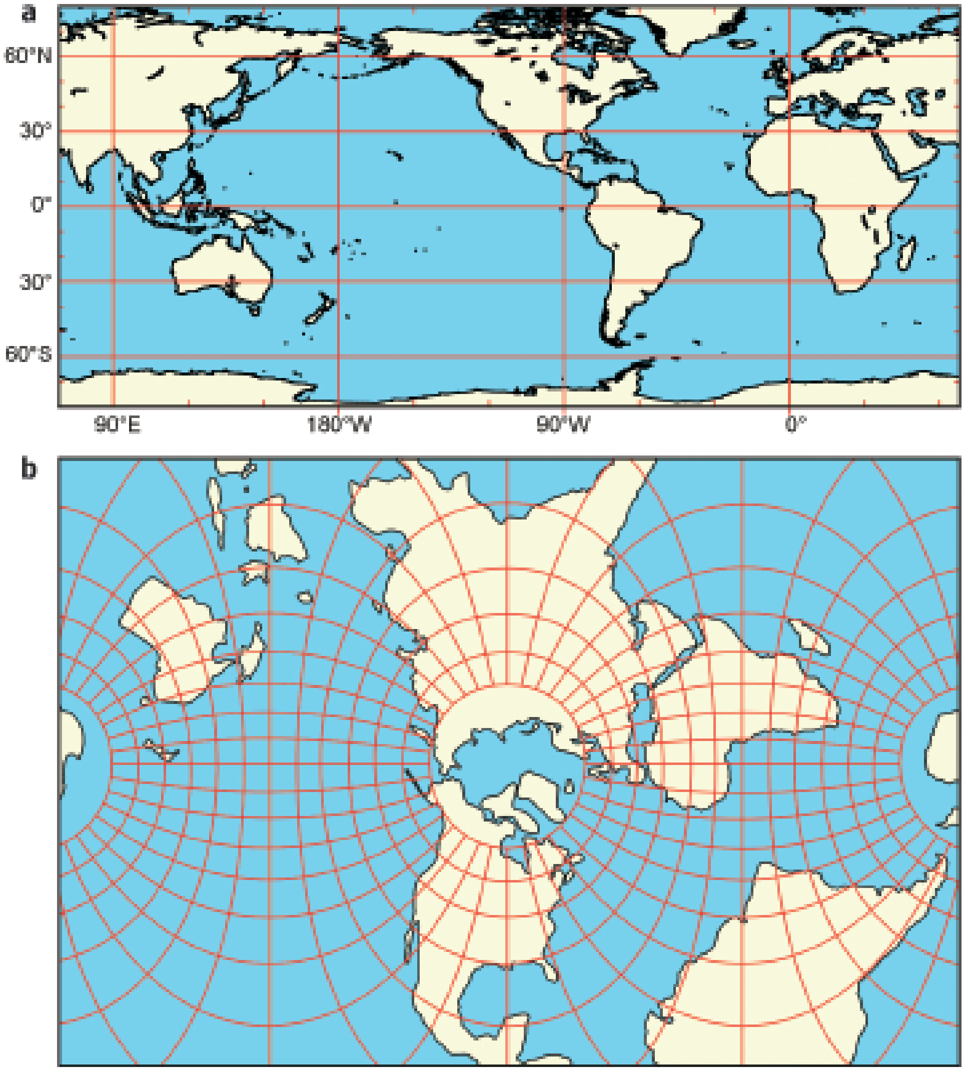
People's general perception of the Arctic has been strongly influenced by the projection chosen for maps. The most widely used is the Mercator projection (map 4.2a), which presents the distance and proportions of regions between 60° south latitude and 60° north latitude to considerable advantage, but simultaneously depicts high-latitude regions like the Arctic as remote, vast and "linear", and the Atlantic and Pacific oceans as separate and far apart. In reality, the Arctic Ocean is small and circular, the distance between the Atlantic and Pacific is relatively short and the two are directly connected (map 4.2b). This kind of projection allows us to get a true grasp of Northern Hemisphere oceanography. And the comparison shows us that progress can be made by determining the most appropriate perspective, even before any science is carried out.

4.3. PRIMARY PRODUCTION AND CARBON BUDGETS IN THE ARCTIC OCEAN

Over the last 30 years, our view of the Arctic Ocean has changed considerably: from the early days when it was considered an ocean with little variability to the more recent conclusion that it is the most variable of all, both in space and over time (Wassmann et al. 2004). Simultaneously, primary production estimates for the Arctic Ocean proper have increased from about 10 to 30 g of carbon per m^2 ($g\ C\ m^{-2}$) (Sakshaug 2004). Primary production estimates on the shelves and from polynyas range from about 10 – 20 $g\ C\ m^{-2}$ in the Laptev Sea to > 300 $g\ C\ m^{-2}$ in the North Water Polynya (Deming et al. 2002). The general increase in primary production estimates is primarily the result of an increased number of measurements, and not of a lesser extension of thinner ice due to global warming.

A complete overview on primary production in the Arctic Ocean is not possible for the moment (but see Sakshaug 2004). We accordingly start our account with a summary of the general principles of primary production in

Map 4.2: Two differing geographical projections of the terrestrial globe; that of Mercator (a) and a Northern Hemisphere perspective with the North Pole at its centre (b)

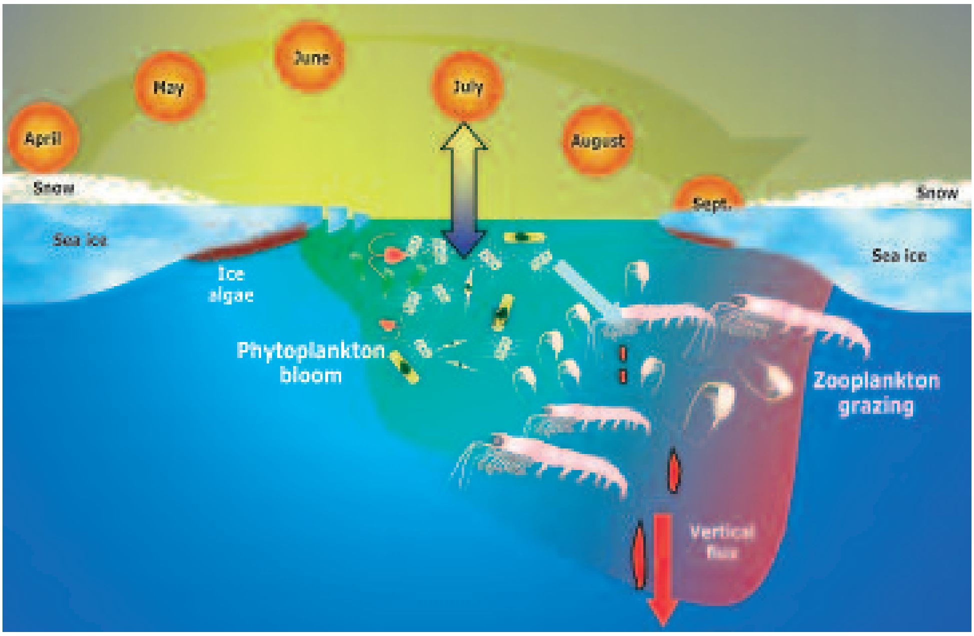


These two maps illustrate how geographic perspectives determine our vision of the Arctic.

Source: Maps redrawn from Carmack and Wassmann 2006.

ice-covered Arctic waters (figure 4.1), followed by a more detailed description of the primary production in the Barents Sea (map 4.3). Primary production in the Arctic Ocean is primarily determined by light availability, which is a function of light penetration (ice thickness, ice cover, snow cover, light attenuation), the abundance of both ice algae and phytoplankton, nutrient availability and surface water stratification. In winter and early spring, the sun is either under or low over the horizon (figure 4.1), and this, along with the snow and ice cover, prevents algae growth. The first signs of spring are already apparent in March (Reigstad et al. 2002), but it is not until the ice thins out and the snow has disappeared that the algae begin to proliferate on the underside of the ice (figure 4.1). Nutrients are abundant. The break-up of the ice and formation of an MIZ are followed by a major bloom of a few weeks duration made up basically of phytoplankton (Sakshaug and Skjoldal 1989) (figure 4.1). Larger mesozooplankton in the Arctic Ocean, having adapted their life cycle to unpredictable food supply by means of overwintering strategies, move from their hibernation to their potential feeding grounds before the spring bloom (Falk-Petersen et al. 1999; Kosobokova 1999; Arashkevich et al. 2002). Grazing thus occupies the entire length of the productive season (figure 4.1) and is only partly phased as in boreal and temperate waters. The bloom is able to take place despite heavy zooplankton grazing pressure (reducing the bio-

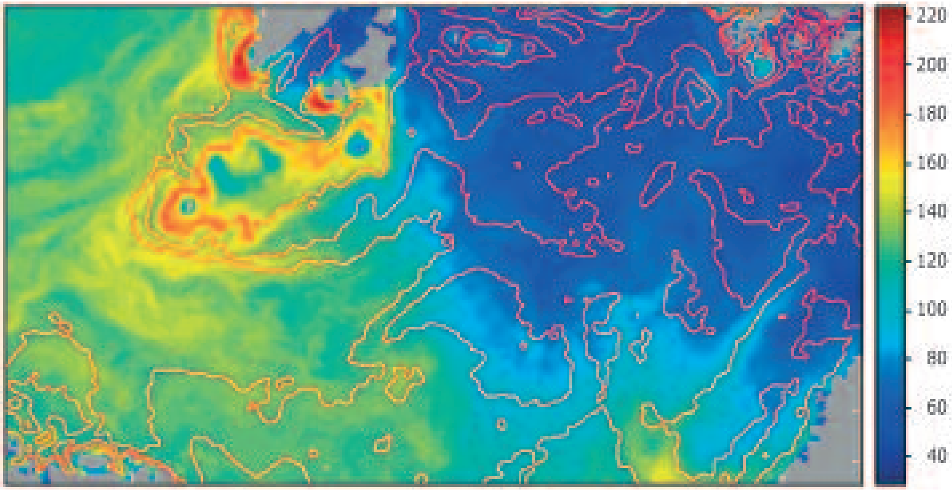
Figure 4.1 The annual cycle of physical forcing and biological response in the Arctic



The figure shows the variation in depth of the euphotic zone, the predominance of autotrophy and the shift with time into heterotrophy (green to red). The vertical arrow symbolises the exchange of CO_2 from and to the atmosphere, illustrating the important role played by the Arctic Ocean in atmospheric CO_2 dynamics.

Source: Wassmann et al. 2004.

Map 4.3: Average annual primary production in the Barents Sea, based on a physically-biologically coupled 3D model driven by a meteorological, hind-cast database



Average annual primary production, expressed as g of carbon per m^2 (see scale), is based on results from four different years. Also shown is the 100-300 metre bathymetry (isobaths in red). On the lower left is the northern part of Norway; centre top, the island of Spitsbergen; in the top right corner, Franz Josef Land; and on the lower right, the archipelago of Novaja Zemlja.

Source: Wassmann et al. 2006.

genic matter that can sink while producing faecal pellets with a high sinking rate), because phytoplankton growth outstrips feeding activities in biological spring (Wassmann et al. 1999). Under Arctic conditions the ecosystem spring bloom is net-autotrophic, but turns into a net-heterotrophic system over time (signalled by the change from green to red in figure 4.1) as the euphotic zone deepens. Ice formation resumes with the pronounced decline of sunlight in early autumn, accompanied by ice algae growth and a drastic reduction in water column light availability. The overwintering zooplankton then descend to depths. The winter in the Arctic Ocean remains largely an enigma.

Among the best known Arctic shelves is the highly productive Barents Sea, which supports one of the largest fisheries in the world (see Falk-Petersen et al. 2000; Wassmann et al. 2006b). Some of the typical dynamics of Arctic primary production can be exemplified by modelling results from this shelf (map 4.3) (for more details, see Slagstad and McClimans 2005; Wassmann et al. 2006a). What we find are compelling annual differences in primary production between the southwestern and northeastern Barents Sea, ranging from below 30 to over 200 g C m^{-2} a year. This is basically a result of ice cover. The regions where annual primary production fails to reach 80 g C m^{-2} are all ice covered in spring, and a highly stratified surface layer is left behind in the wake of the receding ice, limiting phytoplankton growth. In the ice-free, Atlantic-water-influenced regions to the southwest, annual primary production is approximately in the range of 120-160 g C m^{-2}, but certain high-production structures are clearly visible (map 4.3). This is especially true of the area around the Svalbard Bank and Bear Island. This region is characterised by a band of very high production, caused firstly by the shear currents of the Polar Front (between Atlantic and Arctic waters) at around 100 m depth, and, secondly, by extensive tidal currents sweeping over the Bank. This generates high productivity along the rim of the Bank throughout the productive season and nutrient depletion in the centre, resulting in a crosswise gradient of about 100 g C m^{-2} a year. The model also points to upwelling close to the Spitsbergen coast, but that has so far not been verified. On average, annual primary production is 93, 130, 68 and 132 g C m^{-2} for the entire Barents Sea, its Atlantic and Arctic sectors and the Svalbard Bank respectively (Wassmann et al. 2006a). However, interannual variability is on a significant scale, due mainly to climate-induced changes in ice cover, particularly in the Arctic sector where it is estimated at ± 26 %.

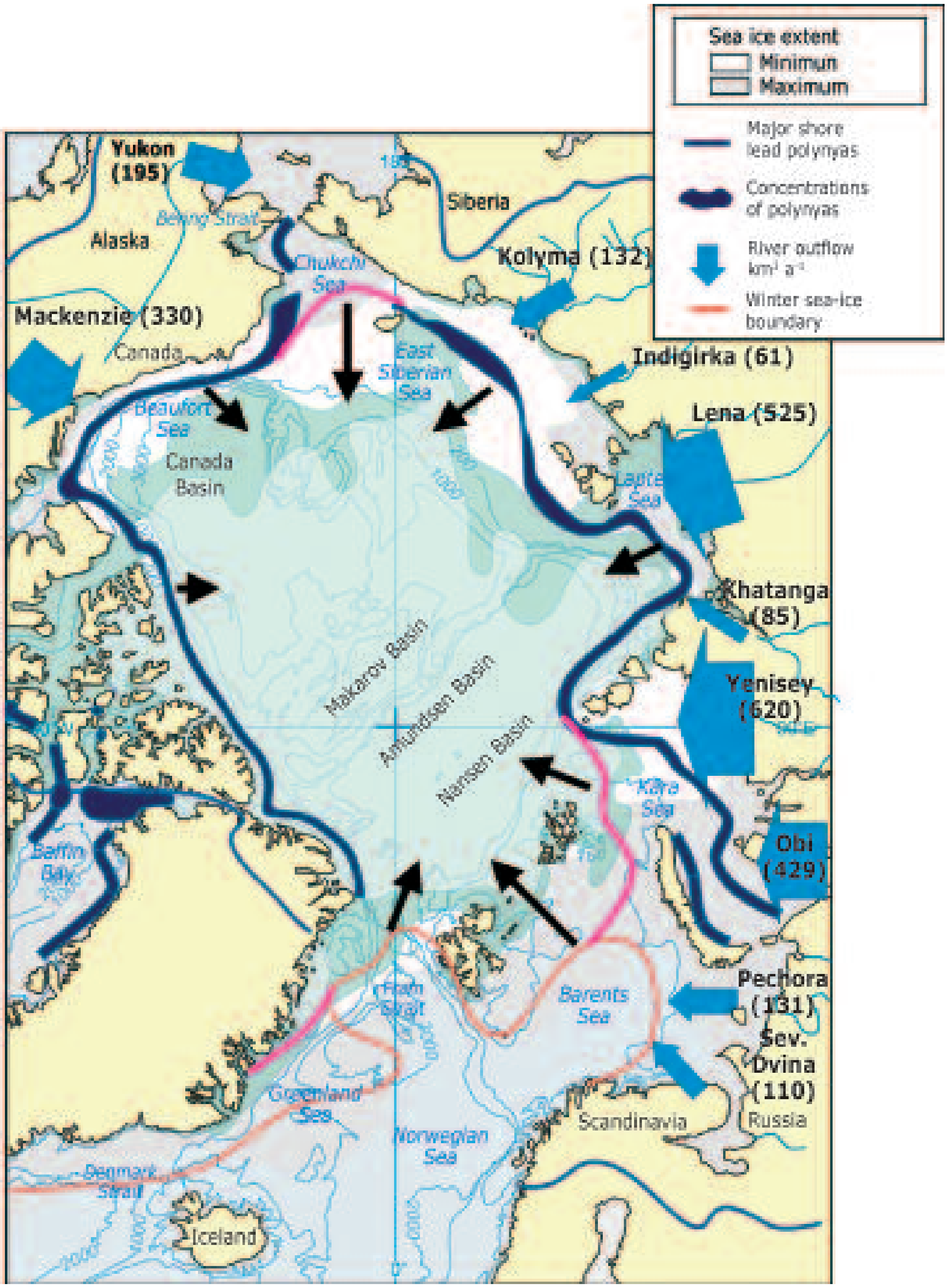
The Barents Sea/European Arctic Ocean corridor is an area of bi-directional horizontal exchange and a critical zone for the physical transition of freshwater—in the form of low-salinity water and ice—and carbon from the Arctic to the North Atlantic (Aagaard and Carmack 1998). Changes in the volume of freshwater input to the North Atlantic influence the properties of the world's oceans via impacts on thermohaline circulation and deep water formation. Water exiting the Arctic basin is also characterised by significantly higher dissolved organic carbon (DOC) levels than the receiving North Atlantic, due to inputs from Siberian rivers entering the Arctic Ocean (Anderson et al. 1998). In the other direction, highly productive Atlantic water flows around and through the Barents Sea as a boundary current into the Arctic basin, carrying large amounts of newly fixed organic carbon in the form of living plankton and organic detritus (Wassmann 2001)

A warmer climate will result in reduced ice cover, increased primary production and a wide band of highly stratified surface water that stretches from the shallow southern rim of the seasonal ice zone (SIZ) to the, for the moment, permanently ice-covered regions of the deep Arctic basins. Another likely consequence will be a change in the horizontal exchange of freshwater, dissolved and particulate organic material (increased river run-off, precipitation and loss of permafrost) and living organisms across the Barents Sea/European Arctic Ocean corridor. The implications for system processes such as geochemical cycling, trophic interactions and shelf-basin exchange may prove to be significant. The supply of organic matter to the benthos will increase significantly, boreal species will spread northwards, and Arctic shelf species may "run out of shelf". The advent of boreal Atlantic and Pacific species (see Berge et al. 2005) will profoundly change the ecological and biogeochemical function of the currently ice-covered regions, causing what we might call an "Atlantification" or "Pacification" of the inflow shelves and adjacent internal shelves (see Carmack et al. 2006).

4.4. ENGIRDLING THE ARCTIC OCEAN: MARGINAL ICE ZONES AND FLAW LEAD POLYNYAS

Before turning to the pelagic-benthic coupling in the Arctic Ocean, we will look more closely at its rim: the SIZs (photo 4.2), MIZs and flaw lead polynyas (map 4.4). It is inside this rim of sea ice that most of the primary production of the Arctic Ocean takes place and where global change is revealed in its fullest impact. The SIZ is the ice-covered region that melts annually; that is, the region between the maximum (April-May) and minimum (September-October) ice extent. The boundary between the ice-covered region and the open water is what we call the MIZ, a physically complicated region that may be 100 or more km wide. Beyond the SIZ we find the multi-year ice (MYI), several metres thick, that covers the central Arctic Ocean. On the Atlantic side, the SIZ is represented by a permanent MIZ, while on the Siberian and Pacific side last fast ice (LFI) connects the SIZ to dry land (map 4.4). It is in the interface between the LFI and the SIZ that flaw lead polynyas are found; permanently or periodically open leads that, together with other polynyas, form specific regions especially important for Arctic Ocean productivity and biogeochemical cycling. In the Laptev Sea, for example, flaw leads are important sites for ice formation. This new ice crosses the entire Arctic Ocean as the Transpolar Drift in the direction of the Fram Strait, where it melts releasing sediments and terrestrial matter (Bauch and Kassens 2005). The North Water Polynya is a highly productive open water site between northwestern Canada and western Greenland (Deming, Fortier and Fukuchi, 2002) that is home to the world's northernmost human settlement, the Inuit village of Thule. Intermittent polynyas around Franz Josef Land and St. Lawrence Island support rich benthos and walrus communities (see Grebmeier et al. 2006).

Map 4.4: Flaw polynyas and marginal ice zones of the Arctic Ocean



A seasonal flaw polynya-marginal ice zone continuum engirdles the pan-Arctic shelves and the deep Arctic Ocean proper. In light green: minimum ice cover during summer.

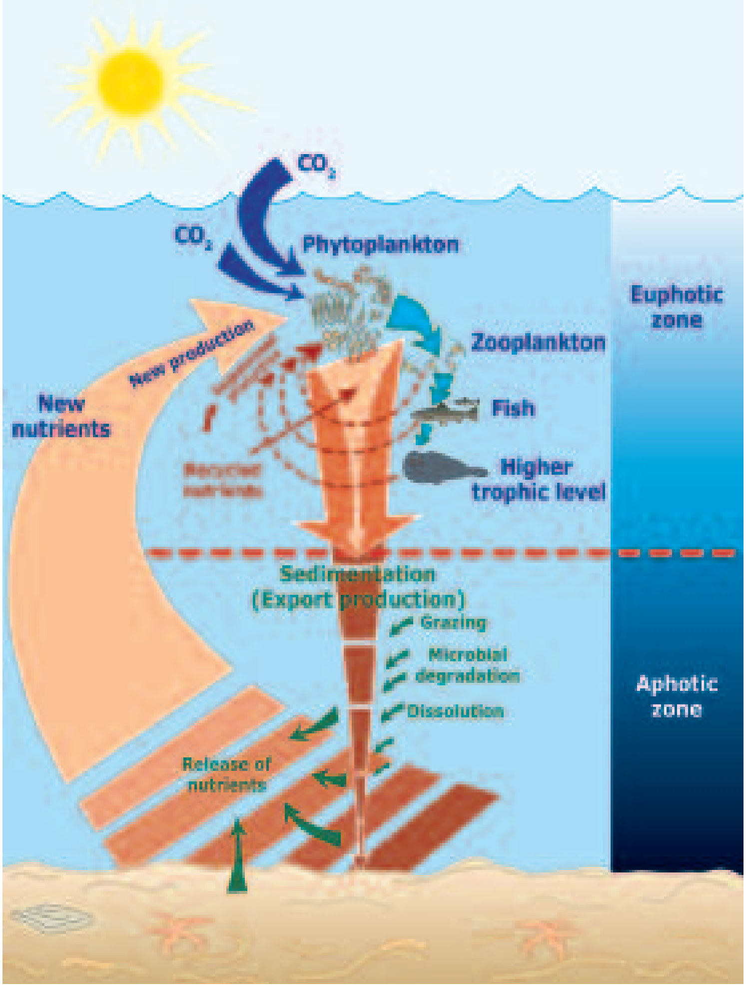
With time, the MIZs and flaw lead polynyas unite, forming a single ecosystem that engirdles the Arctic Ocean, and the central ice cap shrinks towards its minimum, dominated by MYI. In decades to come, most of the changes in the Arctic Ocean with a bearing on pelagic ecosystems and processes will take place in the SIZ-MIZ-polynya complex. As the winter ice advances less, the edge of the presently stratified outer SIZ will be modified and torn by storms, diminishing its stratification. Regions with a strong vertical mix in the water column—like, for instance, the southwestern Barents Sea—will gain in extent, adding to the general increase of primary production in the Arctic Ocean. The SIZs will also widen, supporting increases in primary production in regions still presently covered by MYI. However, stratification and thin ice cover will limit primary production to a relatively low rate.

4.5. PELAGIC-BENTHIC COUPLING AND PHASING IN THE OPEN WATER-SIZ-MYI COMPLEX: SOME BASIC CONSIDERATIONS

CO_2 is transferred via the atmosphere-ocean interface and taken up by phytoplankton with the aid of light and nutrients (figure 4.2). A part of primary production is defined as new production because it is based on winter-accumulated or lately supplied, i.e., new nutrients. The phytoplankton biomass is at the base of the connection between the pelagic and benthic realm (Wassmann 1998) (figure 4.2). Phytoplankton or ice algae (photo 4.3) can sink direct to the bottom or be grazed by organisms such as copepods (photo 4.4). The copepods are, in turn, grazed by fish and mammals (Wassmann et al. 2006b) (figure 4.2). Collectively they recycle some of the resulting biogenic matter back to nutrients, the so-called recycled nutrients, which can again be taken up by phytoplankton, supporting regenerated production. These upper layer retention processes together determine the flux of biogenic matter to the benthic boundary layer and sea floor. To investigate the connection between the pelagic and benthic realm, we have to analyse the production and retention processes taking place in the upper layers. A close connection between the pelagic and benthos realm may be caused by a high biomass accumulation in the upper layers, low vertical flux attenuation efficiency, i.e. low retention, or else a combination of the two (figure 4.2). If the connection is tight and immediate, we talk about “pelagic-benthic coupling”. If retention is significant, and delays between primary production and biogenic matter deposition are considerable, we talk about “pelagic-benthic phasing”. The nutrients generated by the benthos are released into the water column. These are the new nutrients that ultimately become the winter-accumulated nutrients fuelling the MIZ vernal bloom (figure 4.2).

Pelagic-benthic coupling and phasing are regulated by physical forcing and by the composition, function and efficiency of the pelagic food web (figure 4.2). It was previously assumed that the grazing food chain running from large phytoplankton such as diatoms (photo 4.3) to copepods (photo 4.4) was dominant in the Arctic Ocean and adjacent shelves, justifying the strong emphasis given to these organisms. Larger copepods, rich in lipids, are key organisms for many pelagic fish and birds in the region (see Falk-Petersen et

Figure 4.2: Carbon flux, nutrient cycle and pelagic-benthic coupling



al. 1998). However, many of these copepods, specialised herbivores that grow well during phytoplankton blooms, can also adopt an omnivorous feeding strategy. In periods with low phytoplankton abundance—for example after the spring bloom—they may depend for food on microzooplankton and faecal pellets. It would therefore be necessary to revise the traditional planktonic food web with results also including the microbial loop (figure 4.3). In effect, a whole range of autotrophic organisms supply energy to a wide variety of heterotrophic organisms that ultimately support the growth of fish larvae and larger organisms (Buch 2002). The Arctic Ocean is not that different from other oceans, except that it is characterised by an extreme seasonality and some specific adaptations to a demanding and unpredictable environment.

Specific studies on the vertical export of biogenic matter suggest features that may also be true for other Arctic Ocean areas (see Wassmann et al. 2003; Olli et al. 2006; Wexels Riser et al. 2006). Based on 24-hour measurements of 6-10 drifting sediment traps in the upper 200 m, we can identify some characteristic vertical flux profiles (figure 4.4). Vertical flux attenuation is basically a function of new production, suspended biomass accumulation, zooplankton grazing and microbial degradation. While the first two determine export production, i.e., the amount of biogenic matter that enters the aphotic zone, the last two determine the relative efficiency of vertical flux attenuation. The southern region of the SIZ, characterised by prominent ice-edge blooms and a plethora of zooplankton organisms, stands out for its high export production and vertical flux attenuation. Consequently, vertical export exhibits a marked curvature, especially above 60 m depth (figure 4.4-*A*). In the northern SIZ, ice-edge blooms and zooplankton abundance are lower, while vertical flux attenuation is on a smaller scale and occurs mainly in the uppermost part of the aphotic zone (figure 4.4-*B*). Close to the North Pole (Olli et al. 2006), there is extensive grazing and also extensive retention of the low quantities of freshly produced biogenic matter, presumably taking place above the uppermost sediment trap (30 m), which is why no vertical flux attenuation is observed (figure 4.4-*C*). In the open waters of the Barents Sea with its high primary production and weak vertical stratification, vertical mixing is considerable. The rich amounts of vertical export are not only grazed, but also mixed deeper into the water column. As a consequence, vertical export from the upper layers is lower compared to the southern SIZ, but higher at depth (figure 4.1-*D*). Pelagic-benthic coupling and phasing is thus likely to be fairly dynamic in time and space, albeit with its variability in the Arctic Ocean only rudimentarily understood.

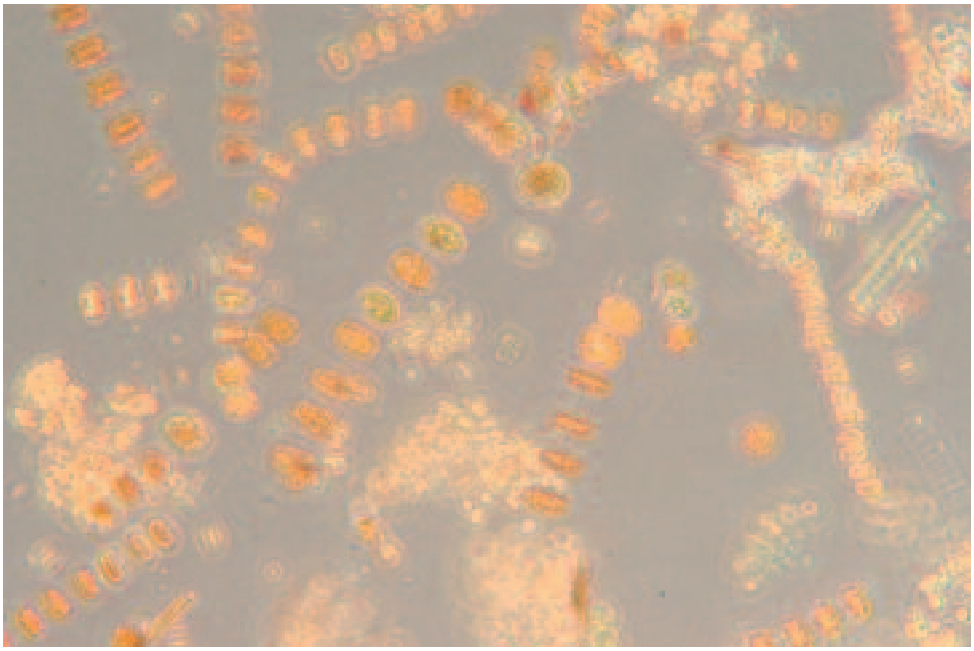
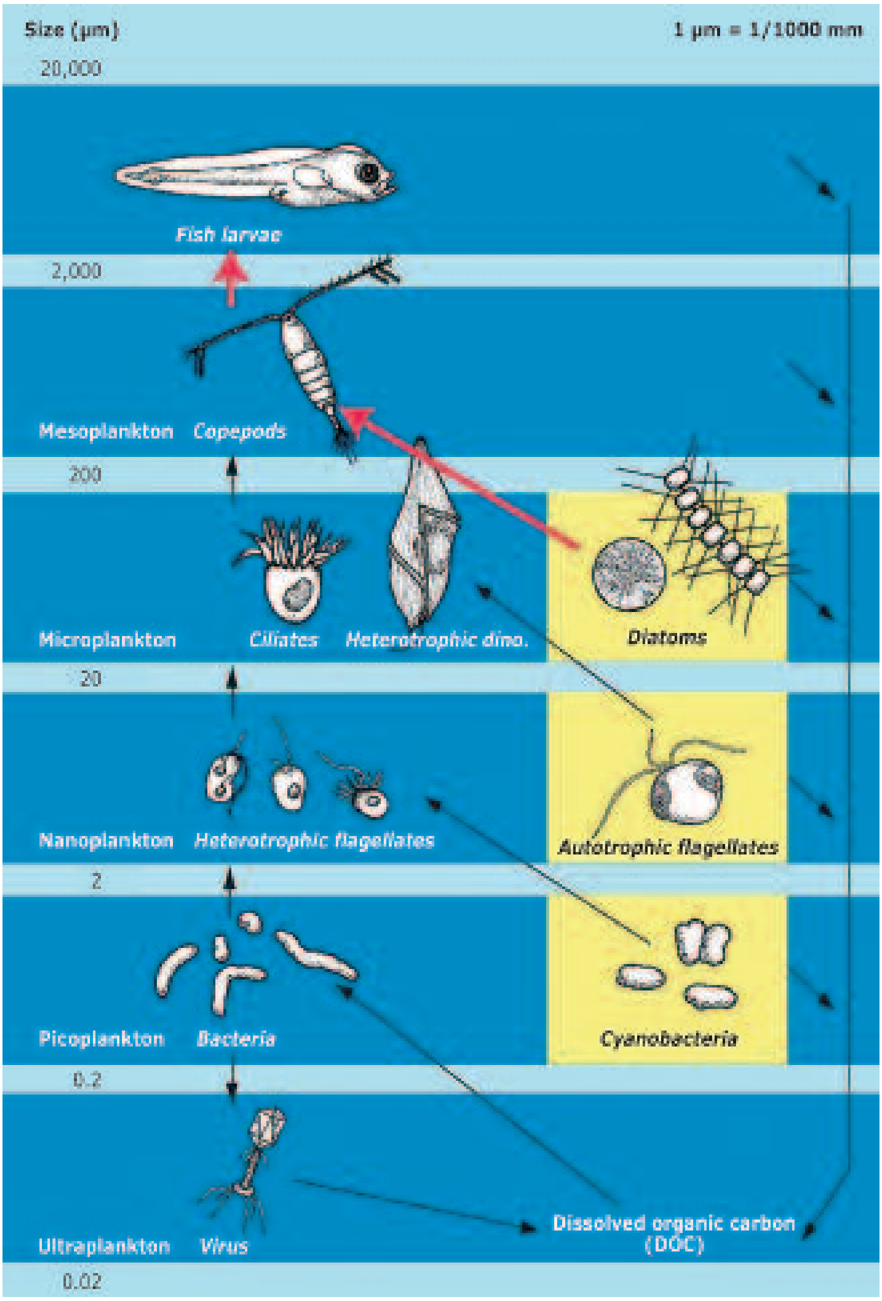


Photo 4.3: Microscopic view of Arctic marine diatom *Thalassiosira nordenskioeldii*

Photo 4.4: The calanoid copepod *Calanus hyperboreus*, one of the most important grazers in the Greenland Sea and Arctic Ocean

Figure 4.3: The Arctic food web ordered by size and characterised by key organisms (autotrophs on the right and heterotrophs on the left)



In addition to the classical food web (large phytoplankton, copepods, fish larvae), the microbial food web also plays an important role in the Arctic Ocean, according to recent research.

Source: Buch 2002.

Vertical flux measurements and tracer studies on the Arctic Ocean shelves indicate tight linkages between pelagic and benthic ecosystem components. Climate change may influence the processes governing geochemical cycling pathways, like the migration and overwintering capabilities of zooplankton and the dynamics of the microbial food web, with cascading effects on benthic communities, including species targeted by fisheries. In this section, we speculate as to what a region currently dominated by MYI might experience in terms of pelagic-benthic coupling during global warming and ice reduction. Of the scenarios reflected in figure 4.4, we would start with scenario *C*, followed by *B* and *A*. Finally, when the ice has withdrawn for good and remaining freshwater stratification has broken down, we might even have to confront scenario *D*. Global warming and ice reduction will not only change primary production and vertical flux attenuation, they will also strongly affect pelagic-benthic coupling and phasing in the Arctic Ocean, in particular on the shallow shelves. When the vertical export of biogenic matter moves from situation *A* to *C* at depths greater than 50 m, the increase in biogenic matter supply to the benthic boundary layer and sediments is more than an order of magnitude (figure 4.4). Thus, global warming and its accompanying ice thinning and reduction will most probably entail dramatic changes for the benthic communities on the northernmost shelves. These changes, however, are hard to predict and evaluate, because we start from too little data and too limited an

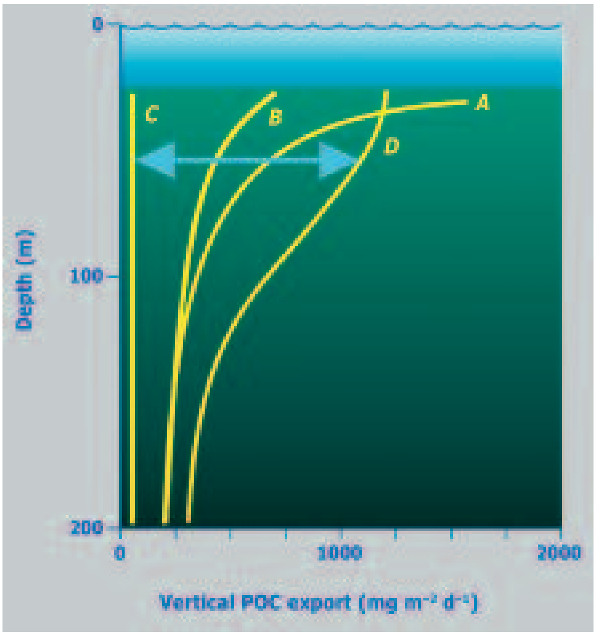


Figure 4.4: Representative and schematic vertical export profiles of particulate organic carbon (POC) in the upper 200 metres of the open Barents Sea (*D*), its marginal ice zone (*A*, *B*) and the permanently ice-covered central Arctic Ocean (*C*). The horizontal arrow suggests the potential increase in vertical export at about 50 metres depth assuming a change from permanent ice cover (*C*) to marginal ice (*D*), due to Arctic Ocean warming. The figure shows how vertical sediment flux would react to the loss of the ice cover, from curve *C* to curve *D*.

Source: Figure redrawn and changed from Carmack and Wassmann 2006.

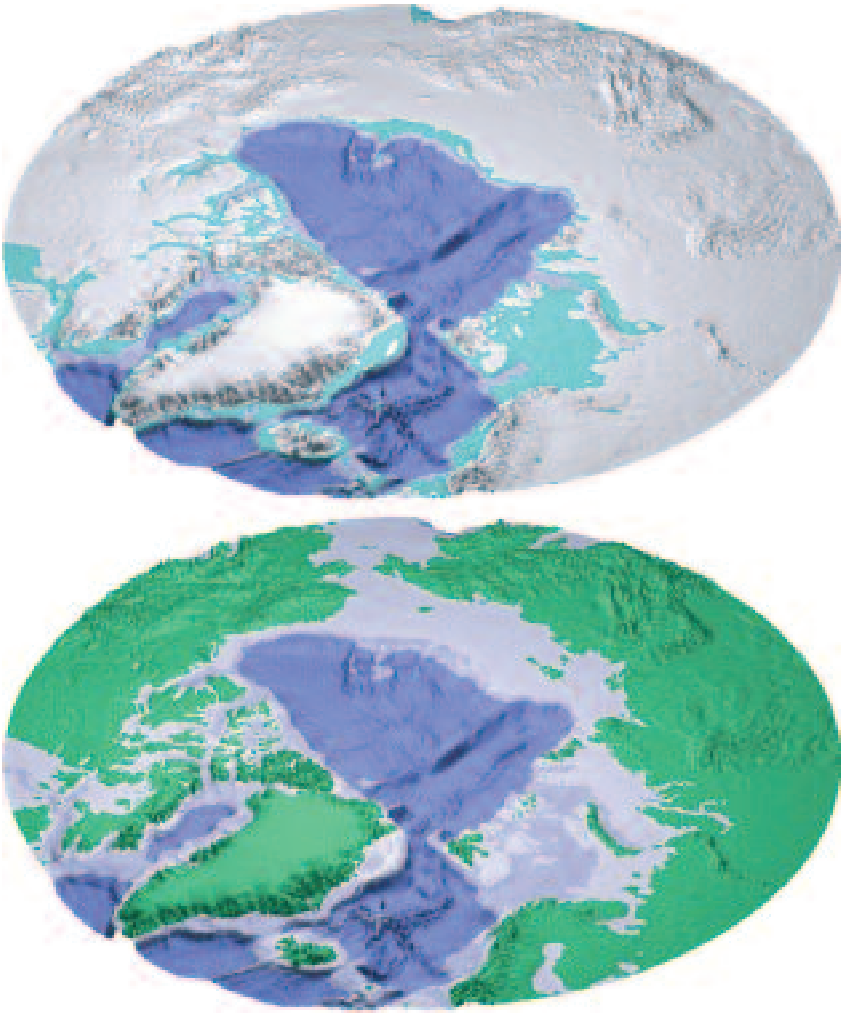
understanding. Only through a combination of focused, long-term experiments and synthetic efforts in the region will it be possible to evaluate these critical vertical exchange processes and their sensitivity to climate change.

4.6. PHYSICAL-BIOLOGICAL FORCING OF ARCTIC SHELVES: PAST, PRESENT, FUTURE

CO_2 levels are already double what they were at the peaks of glacial-interglacial fluctuations, and rising fast. With continued loading of greenhouse gasses into the atmosphere, the future Arctic Ocean is likely to have far less multi-year ice than it does at present and perhaps, eventually, none (see Johannessen et al. 2002). It is therefore worth considering how the Arctic Ocean may have functioned at various times in the past. For example, how does the present Arctic Ocean differ in structure and function compared to the end of the last glacial period? Did it have completely different environmental conditions or has it evolved gradually to its present state? To answer these questions, it is useful to start with the freshwater budget and stratification. In the modern Arctic Ocean, the freshwater budget is dominated by river inflows, Pacific inflows through the Bering Strait and water mass transformations on the broad pan-Arctic shelves (map 4.5). However, only 10,000 years ago, sea level was more than 100 metres lower, massive glaciers may have blocked many of the north-draining rivers, the Bering Strait was closed and shelves were practically non existent (map 4.5). The rivers drained directly over the shelf break into the Arctic Ocean, and the water column of the outer shelves was subject to no tidal modifications (Carmack et al. 2006). There was almost no shelf, the permafrost extended to what is currently the shelf edge, and the Arctic Ocean was basically a set of basins. Going back further in time, to the early Pliocene (~5-3 million years in the past), sea level was higher than at present (~25 m), surface temperatures were considerably hotter, and the belief is that there were no glaciers in the Northern Hemisphere.

These “paleoscenarios” provide us with a spectrum of possible futures within which to consider the impact of change on northern food chains. For example, the projected 1-2 m increase in sea level over coming decades and planetary warming will result in large-scale erosion of coastal regions, and an increase in river discharge is to be expected. The combined effects will be a higher discharge of terrestrial organic matter into the Arctic Ocean, decreased primary production on the shallow shelves (induced by increased turbidity) and possible food web expansion on the interior shelves. Further,

Map 4.5: The Arctic Ocean region 12,000 years ago (above) and at present (below)



The image shows the low water level at the end of the last glacial age, when the Bering Strait was closed. *Source*: Carmack and Wassmann (2006).

Aagaard and Carmack (1994) proposed a simple conceptual model of convective renewal occurring at various sites in the Arctic Ocean and adjacent seas under varying scenarios of increased and decreased freshwater supply. If these physical systems were to undergo catastrophic (abrupt) change, so too would their ecological functions. A logical consequence is that gyres and fronts would shift along with physical habitats, triggering changes in the structure and function of the food web.

The pan-Arctic shelves have gone through radically different phases in the geologically recent past, punctuated by abrupt changes in state. Whether or not we see the Arctic Ocean as moving to a new state outside the known paleo-record is thus a question of the time interval we choose to consider. The immense changes in Arctic Ocean climate forcing over relatively short evolutionary time scales suggest that its ecosystems are capable of coping with additional fluctuations, however abrupt, but the survival of individual species is a lot less certain. Points of no return, where climate forcing irreversibly alters the state of an ecosystem, are extremely hard to assess and may simply not exist in the case of the Arctic.

In sum, we can conclude that global warming, now and even more so in the future, will cause the recession and thinning of the ice cover, an increase in primary production, and the advent of boreal and subsequent reduction of Arctic species. The supply of organic matter to the benthic boundary layer and sediment will increase, particularly in the northernmost pan-Arctic shelf regions. Collectively, this will profoundly change the biogeochemistry of the Arctic Ocean with global ramifications that are inadequately known. In addition, these changes will impact on higher trophic levels in the northern

Photo 4.5: Walruses *(Odobenus rosmarus)*. These corpulent marine mammals dive to the bottom of the shallow Arctic shelves in search of the bivalves they feed on. The retreat of the ice cover on Arctic continental shelves is causing a decline in their ideal habitat.

regions, including human beings. Marine bird colonies may suffer the loss of feeding grounds, seals may lose their resting sites, and polar bears may be deprived of their feeding habitat while facing human encroachment on their overwintering and hunting sites. These changes will also interfere with settled hunter communities, who may have problems reaching their northward-moving hunting grounds or may even lose them altogether. In both cases, this will have severe implication for their livelihoods.

4.7. ARCTIC MARINE RESEARCH: A PRESSING NEED FOR INTERNATIONAL COOPERATION

The lack of a consistent perception of the Arctic Ocean means the first challenge is to acquire a more balanced view of pan-Arctic shelves and their adjacent, deep-ocean basins. The reduction in sea ice and the establishment of commercial and industrial activities in what is commonly assumed to be among the most pristine of ecosystems obliges us to reflect on the ecological consequences of both climate change and regional human activities. Whatever scientists and policy-makers do, they must do it together. The first step should be a collaborative effort to recognise and fully understand the characteristics of the Arctic Ocean, including the social domain and its responses to changes. This will enable the development of more effective adaptation and mitigation strategies to address global warming and other anthropogenic activities affecting the Arctic.

Changes in the Arctic Ocean ecosystem and their effects on ecosystem functioning and human conditions are a significant challenge that deserves the attention of all Northern Hemisphere nations. Improved research on the Arctic is also indispensable for the strategic interests of Europe. The management of marine systems must demonstrably be based on scientific knowledge, environmentally safe resource exploitation and precautionary principles. An efficient European marine ecological research programme in the pan-Arctic region calls for actions and structures that advance and enlarge on the current strategy with the support of general scientific principles opportunely applied.

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