Carbon cycling and climate change: Predictions for a High Arctic marine ecosystem (Young Sound, NE Greenland)

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Abstract

This chapter reviews current predictions of future changes in the High Arctic marine ecosystem Young Sound, NE Greenland. A high-resolution regional atmosphere-ocean model predicts an increase in atmospheric temperature of 6–8°C and in precipitation of 20–30% by the end of this century (2071–2100), leading to increased freshwater runoff, thinning of sea ice, and an increase in open-water period from 2.5 months to 4.7–5.3 months. Evaluation of the consequences of enhanced freshwater runoff to the fjord revealed that the mixed layer thickness of the water column will change only marginally, whereas the transport of saltwater from the Greenland Sea to Young Sound below the halocline is predicted to increase considerably due to stimulated estuarine circulation. The thinning of sea ice and the increase in the open-water period is expected to enhance primary productivity in the area due to a c. 50% increase in light availability. The phytoplankton bloom will continue to occur in a sub-surface layer, but as the exchange between the fjord and the Greenland Sea increases, production will benefit from increased import of nutrients. We estimate that primary productivity in the area will have tripled by the end of the century compared with present-day levels. The longer ice-free period will induce a shift in the pelagic food web structure, from a copepod-dominated grazer community to a situation with growing influence of protozooplankton. The increased pelagic production will enhance sedimentation and thus intensify bacterial mineralization at the sea floor along with carbon burial. This will reduce oxygen availability in the sediment and the relative importance of anaerobic degradation will increase. The rise in sedimentation will also improve food availability for the benthic animals and thus stimulate growth and production until a certain threshold, where sulphide released from anaerobic sulphate reduction may become inhibitory. Finally, an increase in the ice-free period will prolong the period in which birds and marine mammals – e.g. walruses – have access to the food-rich coastal area, and thus improve their foraging conditions. All in all, conditions in Young Sound in 2071–2100 are predicted to resemble present-day conditions c. 450 km further south, e.g. Scoresby Sound.

12.1 Introduction

In the previous chapters, details have been provided on various aspects of the High Arctic marine ecosystem in Young Sound, NE Greenland. This has formed the basis for establishing a carbon budget in the outer part of the fjord under present-day conditions with low temperatures and thick sea-ice cover most of the year (Chapter 11). The question is how this system will develop in response to rising temperatures. Evidence of global climate change is increasing (IPCC 2001) and the changes are expected to be amplified in Arctic and subarctic regions (ACIA 2005). Surface air temperature observations reveal that the largest increase in recent decades has occurred over the Northern Hemisphere land areas from about 40 to 70°N (Serrenze et al., 2000). Due to warming of the world oceans (Levitus et al., 2000) the sea ice cover in the Arctic has decreased by c. 14% since the 1970s (Johannessen et al., 1999). This decrease has led to prolongation of the ice-free period off the north coast of Russia, in the Greenland Sea, the Barents Sea, and in the Sea of Okhotsk (Parkinson, 1992, 2000). In addition, a general increase in precipitation in the 55–85°N latitude band was observed during the last century (Serreze et al., 2000). In the present chapter, we attempt to forecast the response of a High Arctic ecosystem to the climate changes taking place during this century. The forecast will be based on previously published material and on a synthesis of the knowledge presented in the preceding chapters of this book.

12.2 Results & discussion

12.2.1 Physical conditions in Young Sound, 2071–2100

The HIRHAM regional model (Christensen & Christensen, 2003; Christensen & Kuhry, 2000; Christensen et al., 1998) has previously been used to predict changes in wind, temperature, and precipitation minus evaporation conditions in East Greenland (Kiilsholm & Christensen, 2003; Rysgaard et al., 2003). The model has a 50-km horizontal resolution and has been shown to realistically simulate present-day Arctic conditions (Christensen & Kuhry, 2000; Dethloff et al., 1996). The two emission scenarios, A2 and B2, which are in the middle of the range of the scenarios provided by the Intergovernmental Panel of Climate Change (IPCC), were used in the regional simulations. Small (<5%) changes were predicted in the average 30-year wind conditions in the Northeast Greenland region by the end of this century (2071–2100), as compared to present-day conditions (1961–1990). In contrast, the model predicted a dramatic increase in the average 30-year atmospheric temperatures of up to 6–8°C in NE Greenland by the end of this century (Fig. 12.1a). In addition, the average 30-year precipitation minus evaporation in the region is expected to increase 20–30% during the same time period (Fig. 12.1b). The effect of increased temperatures, precipitation and freshwater runoff can be expected to cause dramatic changes in future sea-ice conditions in Young Sound. Today, sea ice covers the fjord for 9–10 months of the year and grows to a thickness of c. 1.5 m (Chapter 4). Given the increase in air temperature of 9.3°C ± 1.5 during December–February; 4.7°C ± 1.3 during March–May; 0.4°C ± 0.3 during June–August, and 8.6°C ± 2.1 during September–November predicted by HIRHAM (scenario

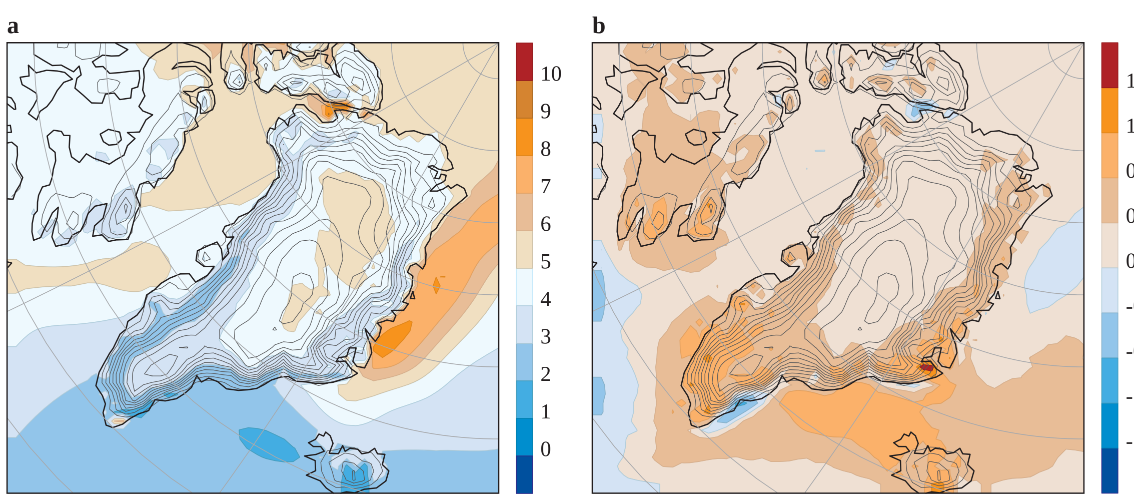

Figure 12.1 Change in **(a)** temperatures at 2 m (°C), and **(b)** precipitation-evaporation (mm d^{-1}) during 2071-2100 relative to 1961-1990, as predicted by HIRHAM4 scenario B2 simulations. Contour interval shown for every 500 m. Redrawn from Rysgaard et al. (2003).

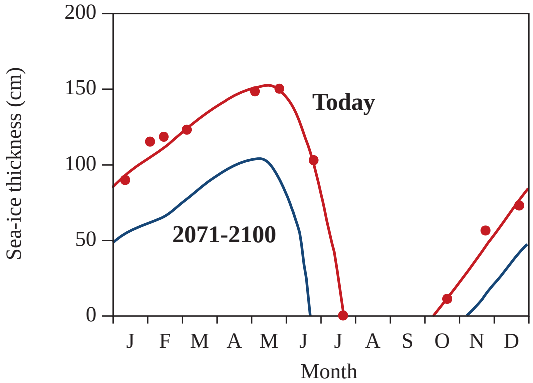

Figure 12.2 Sea ice conditions today and in 2071-2100 as predicted by HIRHAM4 scenario B2 simulations and additional sea ice modelling (see main text for details). Data points represent direct ice thickness measurements and line represents model output. Data from Rysgaard et al. (2003).

B2) in 2071-2100, Rysgaard et al. (2003) estimated that the winter fast-ice thickness in Young Sound would decline from c. 1.5 m to c. 0.8 m, and the open-water season increase from 2.5 months today to 4.7 months by the end of the century (Fig. 12.2). Application of the scenario A2 data would lead to a further decrease in sea-ice thickness and an increase in the sea-ice-free season to 5.3 month.

12.2.2 Primary production in 2071-2100

The reduced sea ice thickness and increased open-water period will alter the light regime in the fjord in the course of this century. By applying the attenuation coefficients for snow and sea ice (Chapter 4), the future sea ice thickness and 20% increase in snow cover (Fig. 12.2), and assuming unchanged downwelling irradiance, future sea ice conditions can be estimated to lead to a c. 50% increase in light availability for primary producers (Fig. 12.3). During the sea-ice-cover period the interception of light by sea ice and snow cover would still limit primary production. However, following the break-up of sea ice the immediate increase in light availability would increase pelagic and benthic primary production (Chapter 5; Chapter 9). Thus, the earlier break-up of sea ice in the future will stimulate both pelagic and benthic primary producers, which are severely light-limited today (See former chapters). The annual pelagic primary production versus the productive open-water period from various Arctic areas has been compiled previously (Rysgaard et al., 1999) and is presented in Fig. 12.4. The increasing trend is presumably a combined effect of increasing light and intensified upwelling during open-water periods enhancing nutrient supply to the photic zone. The scatter around the curve most likely reflects different hydrographical regimes with respect to wind, temperature, salinity and current conditions induced by local upwelling and downwelling. Areas with intense upwelling such as the Bering Strait and Nares Strait (Sambrotto et al., 1984; Springer et al., 1996; Tremblay et al., 2006) are obviously out of range and therefore not included. Based on the relationship in

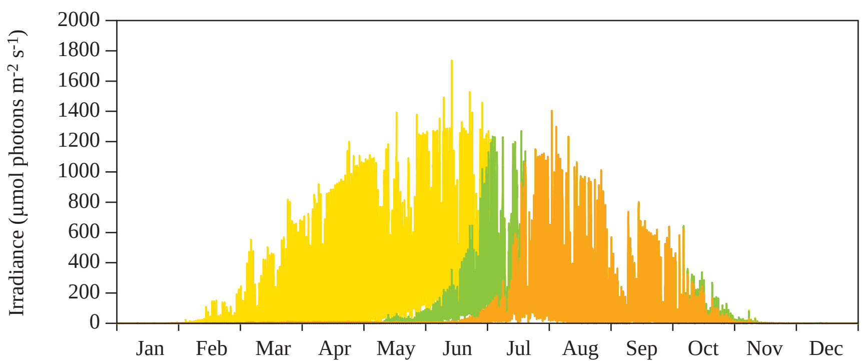

Figure 12.3 Incoming irradiance (PAR) to the surface of Young Sound (yellow + green + orange), below sea ice and during the open-water period under present conditions (orange), and in 2071-2100 (green + orange). PAR data from present time (1999) are from the Zackenberg Basic monitoring programme. PAR data in 2071-2100 are predicted from Fig. 12.2 by applying the attenuation coefficients for snow and sea ice (Chapter 4).

Fig. 12.4, predictions of the sea ice (Fig. 12.2) and light conditions in 2071–2100 (Fig. 12.3), we estimate that primary productivity in the area will have increased from present-day values of c. 10 to c. 35 g C m^{-2} yr^{-1} by the end of the century. Furthermore, the increase in precipitation and melting of the Greenland Ice Sheet will increase freshwater runoff, and model evaluations (Rysgaard et al., 2003; Chapter 3) predict that the transport of saltwater from the Greenland Sea to Young Sound below the halocline will increase considerably due to increased estuarine circulation (Fig. 12.5). Because the mixed layer thickness will change only marginally in the course of this century, the phytoplankton bloom will continue to occur in a subsurface layer, but as net transport increases, production will benefit from increased import of nutrients from the Greenland Sea.

12.2.3 Grazing, vertical flux and mineralization in 2071–2100

It has been shown that zooplankton normally becomes food limited in stratified water columns following a phytoplankton bloom (Kiørboe & Nielsen, 1994; Chapter 5). Thus, a prolonged open-water period is expected to increase primary production and thus zooplankton growth and production in Young Sound. Today, a single phytoplankton bloom is restricted to the short ice-free period and far exceeds that of sea-ice algal production on an annual basis (Chapter 4; Chapter 5). The classical food web dominates the

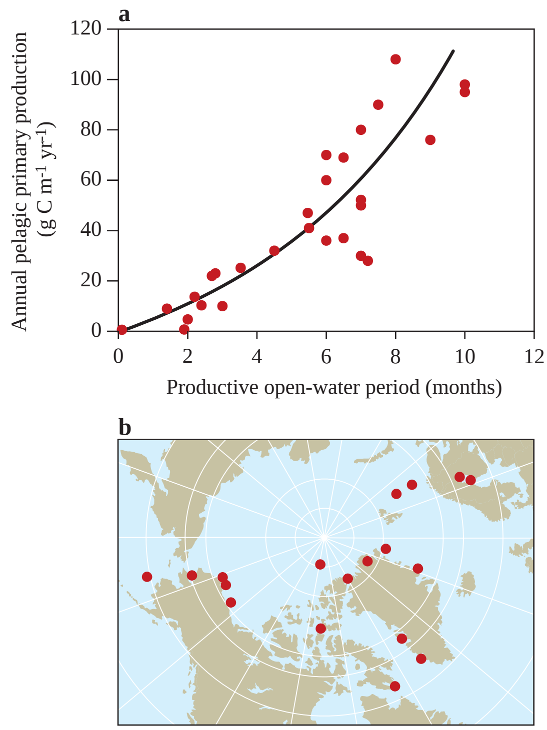

Figure 12.4 (a) Annual pelagic primary production versus the length of the productive open-water period. **(b)** Data compiled from various Arctic regions. The figure is redrawn from Rysgaard et al. (1999) with addition of a dataset from Hegseth (1999).

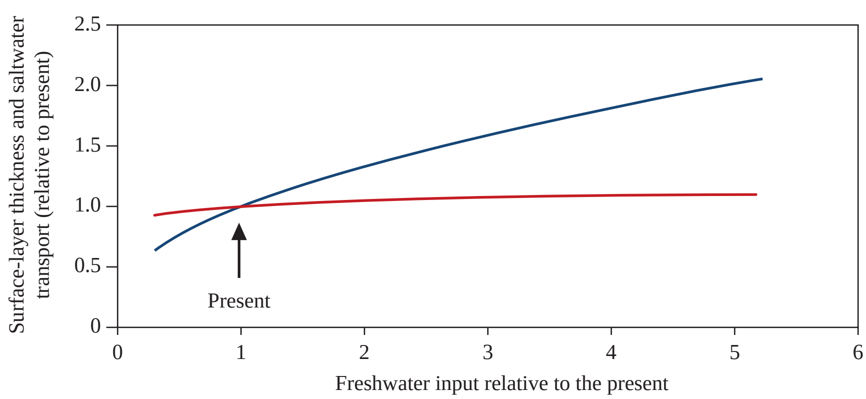

Figure 12.5 Expected changes relative to present conditions in the surface layer thickness (low salinity layer in the upper water layers; red curve) and saltwater transport (blue curve) in the outer parts of Young Sound as a function of freshwater input.

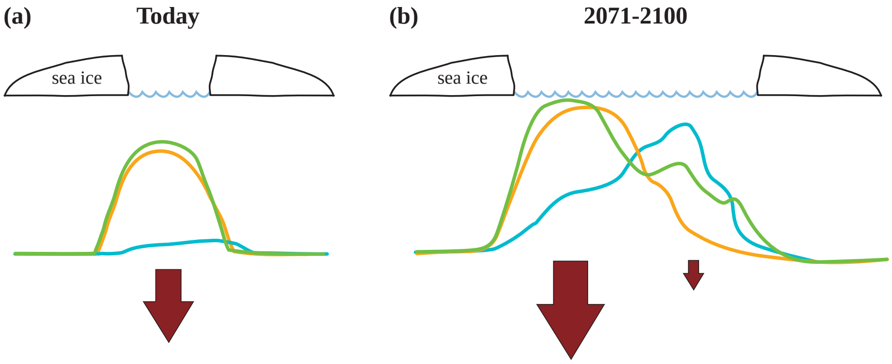

Figure 12.6 Conceptual model of **(a)** present and **(b)** future conditions in sea ice cover, primary production (green curve), copepod grazing (orange curve), protozooplankton (blue curve) as well as vertical export to the sea floor (arrows).

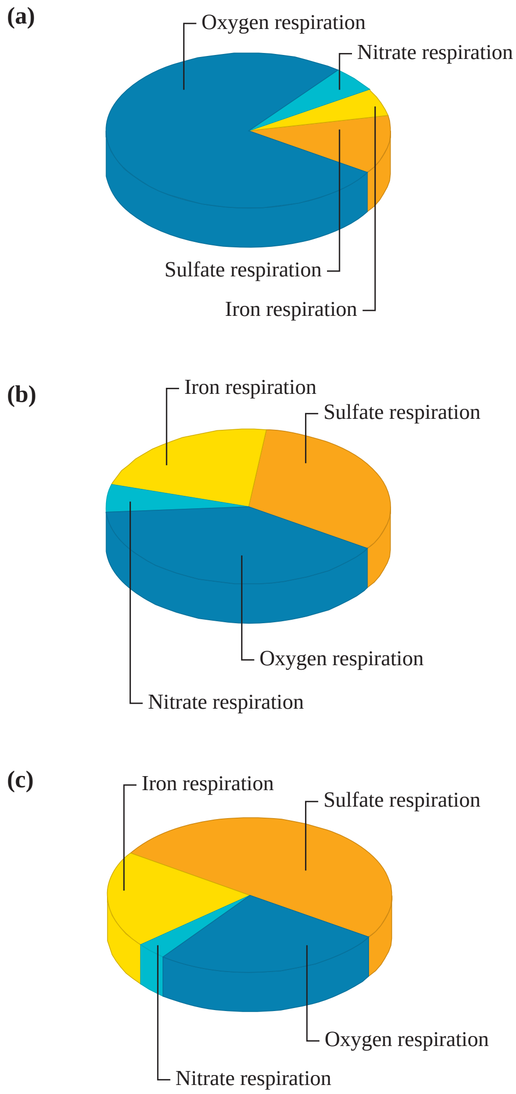

Figure 12.7 Importance of different carbon oxidation pathways in the sediment of Young Sound. **(a)** if the organic matter input is reduced by 50% of present conditions, **(b)** present conditions, and **(c)** if the organic matter input is increased by 100%. Predictions are based on model simulations (Berg et al. 2003).

fjord, i.e. copepods are responsible for >80% of the grazing pressure upon phytoplankton, and >90% of the annual vertical export of organic matter occurs around the short open-water period (Fig 12.6a). In the future, the longer open-water period is expected to induce a shift in the pelagic food web structure from a copepod-dominated grazer community to a situation where smaller protozooplankton play a greater role as observed in subarctic Greenlandic waters at present-day conditions (Levinsen et al., 2000; Levinsen & Nielsen, 2002). Furthermore, a more extensive bloom is likely to occur in the future as observed further south today (Smidt, 1979; Nielsen, 2005). This will affect the vertical flux of organic matter, and result in a high vertical export of organic matter during the spring bloom due to copepod grazing and fecal pellet export, and a second, smaller, vertical export event in autumn. The rising temperature will presumably affect the fraction of assimilated carbon respired by the microbial community, as a larger fraction is respired at low than at high latitudes under present-day conditions (Rivkin & Legendre, 2000). During mid-summer, more nutrients (and organic material) will be recycled in the photic zone, as more of this matter will be retained in the water column due to protozooplankton grazing and bacterial mineralization (Fig. 12.6b) as observed in subarctic ecosystems today (Levinsen et al., 2000; Madsen et al., 2001). An increase in vertical export to the sediment is expected, to the benefit of the food-limited benthos (Sejr et al., 2004; Chapter 7). Furthermore, an increase in the open-water period will prolong the period in which birds and marine mammals such as walruses have access to the plentiful inshore bivalve banks and thus improve their foraging conditions (Chapter 10; Born et al., 2003).

The increase in sedimentation will stimulate organic matter degradation and carbon preservation in the sea bottom. Today, oxygen respiration in sediments at 35 m water depth accounts for 38% of the total oxidation of organic carbon, denitrification 4%, iron reduction 25%, and sulfate reduction 33% (Fig. 12.7; Rysgaard et al., 1998; Chapter 8). To evaluate potential impacts of changes in organic carbon sedimentation, dynamic modeling of organic carbon degradation in the sea bottom was performed (Berg et al., 2003). It was predicted that a 50% reduction in organic material input to the sediment would increase the proportion of organic matter being mineralized through oxygen consumption to 77%, whereas a 100% increase in organic input would reduce the importance of oxygen respiration to 26% (Rysgaard & Berg, unpub.). In the latter scenario, sulfate reduction will be responsible for half of the degradation when the input of organic matter is doubled (Fig. 12.7). Furthermore, a doubling of the organic matter input will reduce the oxygen zone in the sediment with 45% compared with present conditions. One consequence of increasing organic loading is reduction of oxygen availability, less oxidized iron and thus increasing sulfide concentrations in the sediment. This will potentially affect the distribution and composition of the benthic fauna, as sulfide is toxic to most animals.

12.2.4 Monitoring activities and future research

A long-term marine monitoring program (MarineBasic) was initiated in 2002 in order to follow and evaluate the system changes in Young Sound. MarineBasic will provide long-term data:

- Necessary for modeling the coupling between physical oceanography and biological production and consumption
- For use in modeling the regulation of pelagic-benthic coupling (vertical flux)
- To quantify and improve understanding of the lateral coupling (land/fjord/sea)
- To quantify the effect of changing freshwater input, sea-ice cover and hydrographical conditions on biological production and consumption
- To improve current understanding of the effects of climate on species composition and adaptation in the Arctic marine environment

The conceptual design, geographical positions and sampling procedures of the marine monitoring program can be downloaded at www.zackenberg.dk. The site also contains information on the ClimateBasic, GeoBasic and BioBasic monitoring programs, which collect data on the climate and terrestrial environment.

Despite the fact that several integrated research projects have been conducted in Young Sound (see previous chapters) information on certain aspects are still poorly resolved. More knowledge is needed about the physical forces in Young Sound, including brine drainage during sea ice formation and its effect on the circulation in the fjord and the water exchange with the Greenland Sea. Furthermore, model simulations are required on the extent and duration of upwelling events inside the fjord and to quantify the physical coupling to the biological production on an annual scale.

The pelagic microbial and viral loops also need further attention, as these evidently can turn over a large fraction of the organic matter in the water column (Chapter 11). Except for the walruses in the fjord, higher trophic levels have not been studied in any detail. Further work will address the impact of the fish, seals, whales and birds present in the region. A well-established population of the anadromous Arctic charr (*Salvelinus alpinus*) is present in the area, where it feeds in the fjord during summer and winters in the lakes in the valley Zackenbergdalen inside the fjord (Kunnerup, 2001). Furthermore, recent years' trial fishery has revealed occasional large populations of polar cod (*Boreogadus saida*) in the fjord. Seals such as harp seal (*Phoca groenlandica*), ringed seal (*Phoca hispida*), bearded seal (*Erignathus babatus*) and hooded seal (*Cystophora cristata*) have frequently been observed within the area. Occasionally, whales such as bowhead whale (*Balaena mysticetus*), narwhale (*Monodon monoceros*) and killer whale (*Orcinus orca*) enter the fjord. In the outer part of the fjord a small island "Sandøen" houses various birds, for example common eider (*Somateria mollissima*), Arctic tern (*Sterna paradisaea*) and Sabine gull (*Larus sabibi*). They feed in the area, and their impact needs further attention. Finally, we have no information on the quantitative importance of ctenophores and euphausiids that occasionally exhibit mass-occurrence in the fjord and in periods thus represent an important grazing potential.

12.2.5 New perspectives and recommendations

The predicted changes in temperature, ice-free conditions, and precipitation in the area during the course of this century suggest that the physical conditions in Young Sound will develop gradually towards present-day conditions c. 450 km further south, e.g. at Scoresby Sound (Fig. 12.8). Thus, the distance extending from Young Sound and a few hundred km south represents the expected temporal changes that will occur in Young Sound. Furthermore, similar climatic gradients exist on the west coast of Greenland, including subarctic and High Arctic areas. We suggest that evaluation of north-to-south transects in this region would be a highly valuable tool for evaluating shifts in ecosystem structure and element cycling due to climate change.

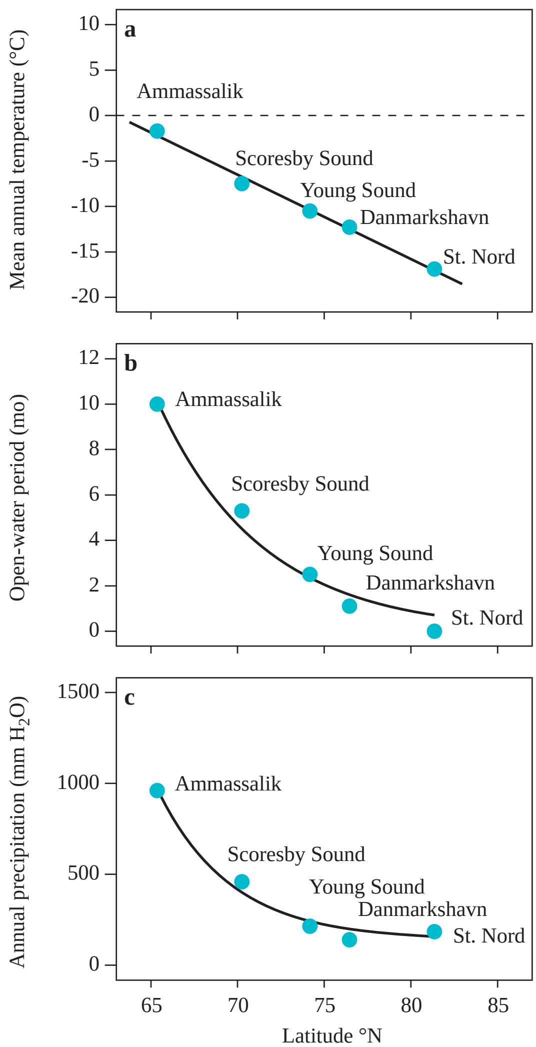

Figure 12.8 (a) Mean annual temperature in East Greenland versus latitude. **(b)** Annual open-water period versus latitude. **(c)** Mean annual precipitation versus latitude. Redrawn from Rysgaard et al. (2003).

If sea ice conditions in the future decrease as predicted, humans will have easier access to this remote region. Today, the fishing and hunting taking place in the area belonging to the Northeast Greenland National Park is limited to a few hunters from Scoresby Sound. Due to the heavy sea ice conditions off East Greenland, no trawling has occurred and, hence, undisturbed and very old benthic communities have developed. Bivalves more than 100 years old are common here. In contrast, trawling is very intense and widespread on the west coast of Greenland and one may speculate that the well-developed and undisturbed benthic communities existing in East Greenland act as a spawning site and thus seed the heavily disturbed sea floor in West Greenland through larval drift via the East Greenland Current and the Irminger Current. Furthermore, hunting of walrus, narwhales, other marine mammals and birds in the area may increase in the future due to easier access, and it is important, therefore, that plans for exploitation of the area off the coast are implemented to preserve this unique area, which, at present, has impacts well beyond the borders of the National Park.

12.3 Acknowledgements

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