

# 20 The Arctic

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## 1 Introduction

Global climate change in the Arctic is a growing concern. Research has already documented pronounced changes, and models predict that increases in temperature from anthropogenic influences could be considerably higher than the global average (e.g. AMAP, 1998).

The impacts of climate change on Arctic ecosystems are complex and difficult to predict because of the many interactions within ecosystem, and between many concurrently changing environmental variables (Callaghan and Jonasson, 1995; Heide-Jørgensen and Johnsen 1998). Despite the global consequences of change in the Arctic climate the monitoring of basic abiotic as well as biotic parameters are not adequate to assess the impact of global climate change.

The uneven geographical location of present monitoring stations in the Arctic limits the ability to understand the climate system. The impact of previous variations and potential future changes to ecosystems is not well understood and need to be addressed. At this point, there is no consensus of scientific opinion on how much of the current changes that are due to anthropogenic influences or to natural variation. Regardless of the cause, there is a need to investigate and assess current observations and their effects to the Arctic.

In this chapter examples from both terrestrial and marine ecosystems from ongoing monitoring and research projects are given.

### 1.1 Global influence

The Arctic is important to global-scale processes in several ways:

1. The thermohaline circulation driven by interaction between the Arctic Ocean and the North Atlantic is responsible for a considerable part of the Earth's poleward heat transport and may also serve as a sink for CO<sub>2</sub> (Buch et al., Chapter 4). Alterations of this circulation, as have been observed during climatic changes of the past, can affect global climate and in particular the climate of Europe and North America (e.g. Broecker et al., 1985a, 1985b, 1990; and Andersen et al., Chapter 3).

2. The melting of the Arctic land ice sheets will cause sea level rise around the world. Glaciers and ice caps are projected to continue their widespread retreat during the 21st century. Global mean sea level is projected to rise by 0.09 to 0.88 metres between 1990 and 2100. This is due primarily to thermal expansion and loss of mass from glaciers and ice caps (IPCC, 2001).
3. Arctic soils can act as either sinks or sources of greenhouse gases depending on temperature and moisture changes within the Arctic. Moisture has opposing effects on the concentrations of the two major trace gases: CH<sub>4</sub> flux declines with soil drying while CO<sub>2</sub> flux initially increases (Oechel et al., 1993, 1995, 1997). These changes can influence greenhouse gas warming globally.
4. Our current understanding of the Arctic climate system suggests that positive feedbacks in high-latitude systems, including the snow and ice albedo effect, amplify anthropogenically-induced atmospheric changes and that disturbances in the circumpolar Arctic climate may substantially influence global climate (IPCC, 1992, 1996).

### 1.2 The models

General circulation models (GCMs) predict that the effect of greenhouse warming will be amplified in the northern high latitudes due to feedbacks in which variations in snow and sea ice, the stability of the lower troposphere and thawing of permafrost play key roles. The Arctic warming is somewhat diminished when anthropogenic change simulation models include sulphate aerosol effects and coupling to a deep ocean and regional patterns of warming. There are differences among simulations, but still the amplification in the Arctic remains (Serreze et al., 2000; Giorgi et al., 2001).

The simulations of future climate with the AOGCM used in this book (Stendel et al., Chapter 9) confirm the previous simulations showing maximum warming in the Arctic with larger warming in winter over land than over oceans. During summer the warming is less pronounced but still areas as Greenland and North America show warming. The simulation also shows that warming goes along with a melting of sea ice, estimating a reduction in sea ice cover of about 40% particularly in summer. Also the thickness of the ice decreases.

It is important to realise that there still are difficulties and uncertainties in the simulation models. This is particularly the case for the Arctic where regional models are very sparse or non-existing. In October 2000 it was decided by the Arctic Council to initiate an Arctic Climate Impact Assessment (ACIA). This also includes an effort to make better regional models for the Arctic.

In this chapter assessing the likely changes on the ecosystems in the Arctic, the scenario mentioned above is used.

### 1.3 Real observation in the Arctic

Research has repeatedly documented climatic changes that are more pronounced in the Arctic region than in other regions of the world. Pronounced winter and spring warming over northern continents since 1970 is partly compensated by cooling over the northern North Atlantic. Warming is also found over the central Arctic Ocean. There is a downward tendency in sea ice extent, attended by warming and increased area extension of the Arctic Ocean's Atlantic layer (Serreze et al., 2000).

Most inland Arctic areas have warmed in winter by 2.0°C per decade during the last 30 years, while more coastal regions have shown less severe warming and some records, e.g. in the West Greenland/Davis Strait area, have even shown cooling in winter

(Rigor et al. 2000; Serreze et al., 2000). Furthermore, it seems to be confirmed that Arctic cyclones are becoming both more common and intense, implying increased poleward heat transport (Serreze et al., 2000).

Sea ice extent in the Arctic has decreased Arctic-wide by 0.35% per year since 1979. During the summer of 1998, record reduction of sea ice coverage was observed in the Beaufort and Chukchi seas (e.g. Johannessen et al., 1999; Vinnikov et al., 1999).

Sea ice thickness has apparently been reduced by 1-2 meters in most parts of the Arctic Ocean and the sub-Arctic seas (Rothrock et al., 1999).

An increased warming of the Arctic Ocean's Atlantic layer and an approximately 20% greater coverage of Atlantic water types have occurred, as summarised in Serreze et al. (2000). A general warming of soils in regions with permafrost, derived primarily from Alaskan data, has also been observed over recent years (Serreze et al., 2000).

Regarding recent changes in climate, it is important to note that different trends have been observed in different parts of the Arctic. Over the last 30 years, average temperatures in the western parts of North America and in Siberia have been increasing, while temperatures in Hudson Bay and Greenland have decreased. These signals illustrate the complex nature of the response of the Arctic region to climate change. In addition to spatial differentiation, there are variable response times and differences in the magnitude of reactions. These result from the distinctive distribution of land and ocean and from couplings to regions outside the Arctic (Chapman and Walsh, 1993).

## **2 Terrestrial impacts**

### **2.1 The ZERO programme**

The relative influences of climatic processes on biological processes are difficult to detect, but are essential to climate change ecology. In some species, biological interactions may be important, whereas others may be more influenced by climate. Furthermore, climate may only be important under specific biological conditions, such as high densities. In other words, ecological responses to climatic and biotic variability are complex and neither process should be studied in isolation.

So far, the integration of climatic and biotic environmental variables into climate change ecology studies has been constrained by the lack of detailed and contemporary long-term data. However, the long-term, multidisciplinary monitoring and research programme, Zackenberg Ecological Research Operations (ZERO), in central Northeast Greenland, provides a foundation for such complex studies of the interface between climate and ecology. Very few long-term studies on the dynamics of Arctic ecosystems exist, and no such studies took place in Greenland before ZERO started at the Zackenberg Research Station (74°28'N, 20°33'W) in high Arctic Greenland in 1995. ZERO encompasses three monitoring programmes, a wide range of research projects (see below) and the logistics involved. Besides the terrestrial facility at Zackenberg, a marine division is situated at nearby Daneborg. At this place in Young Sund, a project concerning responses of production, consumption and degradation in Arctic coastal marine ecosystems to future changes in temperature and sea ice-cover is carried out (see also below).

*Figure 1 The Zackenberg Research Station seen from south-west in late August 1996.  
(Photo: Hans Meltofte)*



The Zackenberg Research Station is situated in the middle of a 3-5 km wide valley, Zackenbergdalen, surrounded by 1000-1400 m high mountains (Figure 1). The habitats range from extensive lush fens to barren gravely and stony expanses and mountain slopes. The investigated area constitutes the drainage basin of the river Zackenbergelven (c. 500 km<sup>2</sup>). A large variety of ponds and lakes are found within the study area.

The three monitoring programmes comprise a climate programme, ClimateBasis, a geomorphological/hydrological programme, GeoBasis, and a biological programme, BioBasis. Together, the programmes encompass the physical nature as well as the majority of plant communities and animals living at Zackenberg. Standardised sampling year after year gain insight into the annual variation and long-term changes of the whole ecosystem. By correlating the annual variability in the ecosystem with climate parameters such as temperature, incoming radiation, extent of snow cover and progress of snowmelt together with summer precipitation, data are obtained on the importance of these factors and combinations of them. This can provide data for modelling of expected changes on longer time-scales. At the same time, data-series that will make it possible to document the effects of natural as well as man-induced climate changes are built up. Such data can only be obtained at an undisturbed place like Zackenberg, where fixed plots can be checked at a regular schedule, and where local human influences can be controlled.

#### *ClimateBasis and GeoBasis*

ClimateBasis is operated by ASIAQ (Greenland Field Investigations), and GeoBasis by the Institute of Geography, University of Copenhagen (in co-operation with the Danish Polar Centre). The variety of data collected by ClimateBasis and GeoBasis are summarised in Table 1.

*Table 1 Main elements monitored by ClimateBasis and GeoBasis.*

Element	No. of sites	Sampling frequency	Measurement period
<b>ClimateBasis</b>			
Air temperature, 2 m above terrain	1	Every 15 minutes	Whole year
Air temperature, 7.5 m above terrain	1	Every 15 minutes	Whole year
Humidity, 2 m above terrain	1	Every 15 minutes	Whole year
Humidity, 7.5 m above terrain	1	Every 15 minutes	Whole year
Wind speed, 2 m above terrain	1	Every 15 minutes	Whole year
Wind speed, 7.5 m above terrain	1	Every 15 minutes	Whole year
Wind direction, 2 m above terrain	1	Every 15 minutes	Whole year
Wind direction, 7.5 m above terrain	1	Every 15 minutes	Whole year
Air pressure	1	Every 15 minutes	Whole year
Incoming short wave radiation	1	Every 15 minutes	Whole year
Outgoing short wave radiation	1	Every 15 minutes	Whole year
Net radiation	1	Every 15 minutes	Whole year
UV-B radiation	1	Every 15 minutes	Whole year
Precipitation	1	Every 15 minutes	Whole year
Snow depth	1	Every 15 minutes	Whole year
Ground temperature, 0 cm below surface	1	Every 15 minutes	Whole year
Ground temperature, 2.5 cm below surface	1	Every 15 minutes	Whole year
Ground temperature, 5 cm below surface	1	Every 15 minutes	Whole year
Ground temperature, 10 cm below surface	1	Every 15 minutes	Whole year
Ground temperature, 20 cm below surface	1	Every 15 minutes	Whole year
Ground temperature, 40 cm below surface	1	Every 15 minutes	Whole year
Ground temperature, 60 cm below surface	1	Every 15 minutes	Whole year
Ground temperature, 80 cm below surface	1	Every 15 minutes	Whole year
Ground temperature, 100 cm below surface	1	Every 15 minutes	Whole year
Ground temperature, 130 cm below surface	1	Every 15 minutes	Whole year
River water discharge	1	Every 15 minutes	Whole year
<b>GeoBasis</b>			
Snow cover in lower Zackenbergdalen	1	Daily	Whole year
Water temperature in Zackenbergelven	1	Daily	June-August
Conductivity in Zackenbergelven	1	Daily	June-August
pH in Zackenbergelven	1	Daily	June-August
Solute transport in Zackenbergelven	1	Daily	June-August
Suspended sediment transport in Zackenbergelven	1	Daily	June-August
Organic matter transport in Zackenbergelven	1	Daily	June-August
Air temperature near ground	9	Every 2 hours	Whole year
Active layer temperature profiles	6	Every 2 hours	Whole year
Active layer depth	2	Every 14 days	June-August
Soil water chemistry	2	Every 14 days	July-August
Shore line position (surveying)	6	Annually	August
Salt marsh accretion (surveying)	2	Every 5 years	August
Ice wedge growth (surveying)	2	Every 5 years	August
Photo monitoring of different dynamic landforms	24	Annually	August

**ClimateBasis:** The main purpose of ClimateBasis is to provide climate data from the research area. These data are mainly collected from a climate station consisting of two 7.5 m masts and two 2.0 m masts. Furthermore, the programme takes care of the automatic measurements of river water discharge in Zackenbergelven. As such, ClimateBasis collects data, which are essential for all other monitoring and research programmes and projects at Zackenberg.

**GeoBasis:** GeoBasis measures the dynamics of the abiotic nature, *i.e.* in practise the hydrology and the geomorphology.

Snow cover in the lower part of Zackenbergdalen is measured from daily images obtained with a normal digital camera standing on a rock 480 m above the valley floor. Software has been developed for transformation of oblique digital photos into ortho-photos and for identification of snow cover within ortho-photos. By this method changes in snow cover with high resolution in space can be measured on a daily basis throughout the year. Snow cover is probably among the most important parameters controlling the dynamics of the high Arctic ecosystem. The occurrence of snow on a specific site changes the surface albedo dramatically and thereby the energy balance of the site. At the same time, snow protects the habitats below from severe frost during the winter and it represents a water reservoir during melt. Changes in snow cover and timing of snowmelt will therefore have a great influence on the entire ecosystem.

Active layer depth is measured in grids at two sites using the CALM/ITEX method (Nelson et al., 1996). One site is on an almost horizontal dry heath while the other site is on a slope with a snow patch leading to a horizontal fen area. Air temperature, time of snow-cover disappearance and substrate control active layer depth.

Air temperature at ground surface and in active layer profiles are measured in different settings at different altitudes. These measurements make it possible to describe the effects of substrate and microclimate on active layer development and enables a future modelling of active layer development under different climate conditions.

Soil water chemistry (Na, K, Mg, Ca, Fe, Cl, NO<sub>3</sub>, SO<sub>4</sub>, HCO<sub>3</sub>, pH and conductivity) is measured at the same sites as the active layer depth with suction probes inserted in the soils at different depths. First of all these measurements are used to characterise the soils at Zackenberg under present climatic conditions, and to quantify their contribution of solutes to the rivers. Eventually, these measurements will be used to gain knowledge about soil development in the Arctic under changing climatic conditions.

The water chemistry (same elements as above) and the suspended sediment concentration (organic and inorganic) in Zackenbergelven are measured once every day. Together with the discharge measurements from Zackenbergelven these measurements are used to quantify the fluxes of sediment and ions out of the drainage basin and thereby to quantify the weathering rate in the drainage basin. Preliminary results indicate that major rain events are the most important factor controlling fluxes of sediments and nutrients.

Finally, a large variety of different geomorphological elements (like e.g. coastal cliffs and spits, salt marshes, alluvial fans, talus cones, rock glaciers and ice wedges) are monitored either by surveying or by regular photo-documentation.

### *BioBasis*

BioBasis is run by the National Environmental Research Institute. The goal of the programme is to monitor the dynamics of a large variety of organisms and biological processes in the local ecosystem. An overview of the main monitoring elements is presented in Table 2, and at <http://biobasis.dmu.dk> an introduction to the programme, a complete manual of sampling procedures and current data are given.

**Vegetation:** Plant production is monitored both from satellite images and by field measurements in different plant communities. Both methods use greening as an indication of annual production. Greening in 25 study plots is measured on a weekly basis during the entire summer season, and satellite images are analysed at the peak of an-

nual growth around 1 August. Furthermore, CO<sub>2</sub> fluxes from tundra heathland are measured at an automatic micro-climatic station. Annual production is regulated both by timing of snowmelt, microclimate and in dry habitats also by availability of water.

Table 2 Main elements monitored by BioBasis.

Element	No. of species	No. of plots	Frequency of sampling	No. of variables per plot
<b>Vegetation</b>				
Reproductive phenology	6	25	Weekly	4
Relative vegetation index	-	25	Weekly	2
Amount of flowering	7	29	Annually	1
Berry production	3	3	Annually	1
Plant zonation along 8.8 km transect	100	128	Every 5th year	15
Plant communities	100	9	Every 5th year	75
Cryptogam communities	50	41	Every 5th year	45
NDVI (from satellite images)	-	13	Annually	13
Plant community dist. (from satellite images)	9	1	Every 5th year	9
CO <sub>2</sub> and water vapour from mesic tundra	-	1	21 times/sec.	2
<b>Arthropods</b>				
Arthropod occurrence and phenology	40 <sup>1</sup>	6	Weekly	80
Insect predation	3	12	Weekly	2
<b>Birds</b>				
Population density	16	5	Annually	16
Reproductive phenology	5	1	Annually	10
Hatching success	5	1	Annually	5
Fledging success	5	1	15 times/year	5
General species occurrence	30	1	Daily	50
<b>Mammals</b>				
Lemming winter and summer population	1	1	Annually	8
Musk ox occurrence and demography	1	20	Daily/weekly	9
Musk ox carcasses	1	3	Annually	3
Arctic fox occurrence and reproduction	1	1	Every 2nd week	15
Seal occurrence on fjord ice	1	1	Daily	1
General species occurrence	6	1	Daily	12
<b>Lake flora and fauna</b>				
Water chemistry	-	2	3 times/year	8
Phytoplankton	9	2	3 times/year	9
Zooplankton	7	2	Annually	10
Fish stocks	1	2	Every 5th year	
<b>Abiotic parameters</b>				
Microclimate temperatures in study plots	-	21	12 times/day	2
Snow cover and melt in study plots	-	35	Weekly	1
Spring snow cover (from satellite images)	-	13	Annually	1
Ice melt on ponds etc.	-	10	Daily	1
<b>Disturbance etc.</b>				
Man days etc. in study sections	-	4	Daily	3
Aircraft operations in and over study area	-	1	Daily	6
Manipulative research and take of organisms	-	-	Annually	-
Discharges	-	-	Annually	-

1) Arthropod samples are generally only sorted to family level.

On a weekly basis, the ratio between buds, flowers, senescent flowers and open seed capsules in six plant species are measured in the same 25 plots. In this way, data are obtained on timing of flowering and seed production, which are governed by the progress of snowmelt and by microclimate. Also the total number of flowers (and berries in three species) produced in each plot is recorded. In Arctic plants, flower buds are developed during the preceding summer. Important factors for bud development are

nutrient cycling, microclimate temperatures and availability of water together with depredation by e.g. lemmings.

More long-term changes in plant community composition and distribution are monitored along a 8.8 km transect running from the seashore to the top of a 1040 m mountain as well as in nine study plots. Along the transect, 129 numbered pegs denote pronounced plant community borders. Within each community, the species composition and frequency are monitored at five-year intervals at 10-20 permanent pegs – in total 1560 stations. In the nine study plots, detailed changes in the species composition and dominance can be detected, since species etc. are recorded at 500 positions at each station. Hence, both along the transect and in the plots, changes over time within each plant community can be detected and relation to e.g. long-term changes in snow cover and melt, microclimate, summer precipitation, elevation and exposure.

**Arthropods:** Insects, spiders, mites and springtails are common in high Arctic ecosystems. The invertebrate fauna is monitored with 50 traps distributed on six stations in different habitats. Two window traps monitor flying insects over a pond, while the remaining traps are yellow pit-fall traps that catch surface active arthropods and pollinating insects.

The traps are emptied on a weekly basis, and each year c. 30,000 to 70,000 specimens are caught. Generally, specimens are sorted to family level (c. 50 different families). Springtails and mites are most common, followed by flies, midges and hunting spiders. The activity of invertebrates on the tundra is highly sensitive to weather conditions, and numbers caught vary by a factor ten due to weather conditions. This means that both taxon richness and total numbers of invertebrates are sensitive indicators of climate variability and long-term change. It is too time consuming for the time being to identify the specimens to species level, which is necessary for the study of more sophisticated relations between climate and invertebrate occurrence.

**Birds:** The high Arctic bird fauna is poor in species. Of the c. 25 species breeding in the study area, waders (shorebirds) make up the most common and diverse group. Breeding bird populations are monitored within a 19 km<sup>2</sup> census area reaching from the seashore and up to 600 m on the slopes of Zackenbergdalen. Here, a total of 250-300 pairs of waders are breeding together with many snow buntings, long-tailed skuas and small numbers of other species. In selected species, breeding phenology (timing of egg-laying, hatching and fledging), clutch size, hatching success (e.g. depredation rate) and production of fledglings are monitored as well.

Most of the species involved are long-lived with a slow population turnover. Since they are also highly site-tenacious, the populations are relatively stable from year to year. This means that the population densities reflect 'average' breeding conditions in the area, and that population changes will mirror long-term trends in these conditions.

**Mammals:** Three species dominate the mammalian fauna of Zackenbergdalen: collared lemming, Arctic fox and musk ox. Besides these, Arctic hare, Arctic wolf, and polar bear occur in the valley.

Lemming populations are well known to show pronounced fluctuations with peaks at 3-4 year intervals. The ecological factors governing these fluctuations are far from perfectly understood, but winter snow cover, food quality and depredation are probably important factors. Monitoring comprises winter nest and summer burrow density and distribution within a 2.5 km<sup>2</sup> study area. Besides, parameters such as nest size, amounts of faeces (indicating extent of occupation), signs of breeding and depredation are measured.

Seven Arctic fox dens are found in Zackenbergdalen. The dens are checked regularly for occupation and pups. Apparently, the fox population in Zackenbergdalen is influenced by winter weather conditions, lemming density and frequency of musk oxen killed by wolves.

Every year, more than one hundred musk oxen gather in Zackenbergdalen during the rut and pre-winter fattening in August-September. Their winter survival and production of calves are highly sensitive to winter snow and weather conditions. Deep snow with ice crusts in winter may kill many musk oxen.

#### *What will happen?*

With only 5-6 years of data, it is far too early to predict what the effect of Global Climate Change will be in high Arctic Greenland. But based on the prediction that winter temperatures will increase, and supposing that this will lead to reduced extent and density of drift ice along the coast, a few scenarios can be suggested.

The continental high Arctic climate of Northeast Greenland is primarily a result of a several hundred kilometre wide belt of dense pack ice drifting southward along the East Coast of Greenland. This ice belt reduces the influence of the sea on weather conditions on land and results in relatively limited amounts of snow, more or less continuous hard frost from September until May and frequent occurrence of high-pressure conditions during summer. A reduction of the ice will result in a more maritime climate with more fog, clouds and precipitation. This will heavily influence both winter and summer conditions, and we may expect deeper, more extensive and longer lasting snow cover, more frequent thaw events during winter leading to ice crust development, and more unstable summer weather. Summer air temperatures are not expected to increase much. Such changes will have pronounced effects on the local ecosystem.

#### *Soil ecology*

In addition to BioBasis programme, several Nordic groups of soil ecologists are actively working in field and through laboratory experiments with the consequences of climate change in temperate and Arctic areas. Especially, temperature and humidity are important for terrestrial ectothermic species. One project aims at investigating adaptation processes in collembolans and earthworms, including the genetic background for temperature and humidity stress, the genetic regulation of tolerance to stress, and to what extent physiological adaptation preadapts to tolerance of these stress factors.

## **2.2 Arctic carbon budgets in a global change perspective**

Although Arctic terrestrial ecosystems only cover about 5-6% of the Earth's land surface, they contain about 14% of the total terrestrial stock of soil carbon (C) that has accumulated over the last millennia (Post et al., 1982). This accumulation has occurred in spite of low primary productivity, indicating constrained decomposition of the soil organic matter (SOM). Hence, the Arctic has been an important area for C sequestration from the atmosphere. This implies that the Arctic also is a potential source area for C release to the atmosphere, if the conditions change so that the carbon balance of the ecosystems turns from being a sink to a source.

Both the sequestration and the release of C are controlled by biological processes, with rates controlled proximately by environmental conditions such as, e.g. temperature and moisture and indirectly by the coupling of the C cycle to the nutrient cycles (Jonasson et al., in press). Hence, there is a possibility that the projected, future changes in the climate systems may affect the functioning of Arctic ecosystems, including the nutrient cycling and carbon balance. If this happens, it is likely to have consequences at a

regional scale with e.g. displacement of the distribution of species and rearrangement of community types. In addition, the consequences can also go beyond the Arctic and be noticeable even on a global scale, if the changes are profound enough to markedly alter the balance between sequestration of C in the Arctic and the loss of C from the Arctic soils.

Denmark has contributed with research on terrestrial C fluxes and their control in the Arctic with studies located principally at the high Arctic Zackenberg and at the sub-arctic Abisko in northernmost Sweden. Further investigations of fluxes of "greenhouse gases" were also done along the entire coast of the Russian Arctic during the Swedish-Russian tundra expedition in 1994, with Danish participation (see summary and further references in Christensen et al., 1999).

The studies in Greenland have focused on controls of the exchange of "greenhouse" gases (water vapour, CO<sub>2</sub> and CH<sub>4</sub>) between the atmosphere and the soil/plant system (e.g. Christensen et al., 1998, 2000; Friborg et al., 2000; Soegaard and Nordstroem, 1999; Soegaard et al., 2000). Gas flux studies have also been done at Abisko. For instance CO<sub>2</sub> and CH<sub>4</sub> exchange have been measured during the period of snowmelt (Friborg et al., 1997) and a study of annual exchange of greenhouse gases has recently been initiated in collaboration with Swedish research institutes. However, the research in northern Sweden has mainly consisted of measurements and functional interpretation of biological responses to experimentally imposed changes in the environment, including enhanced temperature and increased nutrient availability (e.g. Christensen et al., 1997; Graglia et al., 1997, in press; Jonasson et al., 1999; Michelsen et al., 1996; Schmidt et al., 1999). These results have served as a basis for various inter-site comparisons through data syntheses together with researchers working within similar projects in other Arctic and non-Arctic regions. By this approach, it is possible to pinpoint generalities in the control of ecosystem carbon balance and nutrient cycling across regions, as well as distinguishing general responses from specific responses at the different sites (Jonasson et al., 1996, in press; Shaver and Jonasson, 1999; Shaver et al., 2000). Below, follows a short summary of results from these studies, from which we draw conclusions of likely factors that affect the C cycle in the Arctic.

#### *Controls of ecosystem functioning*

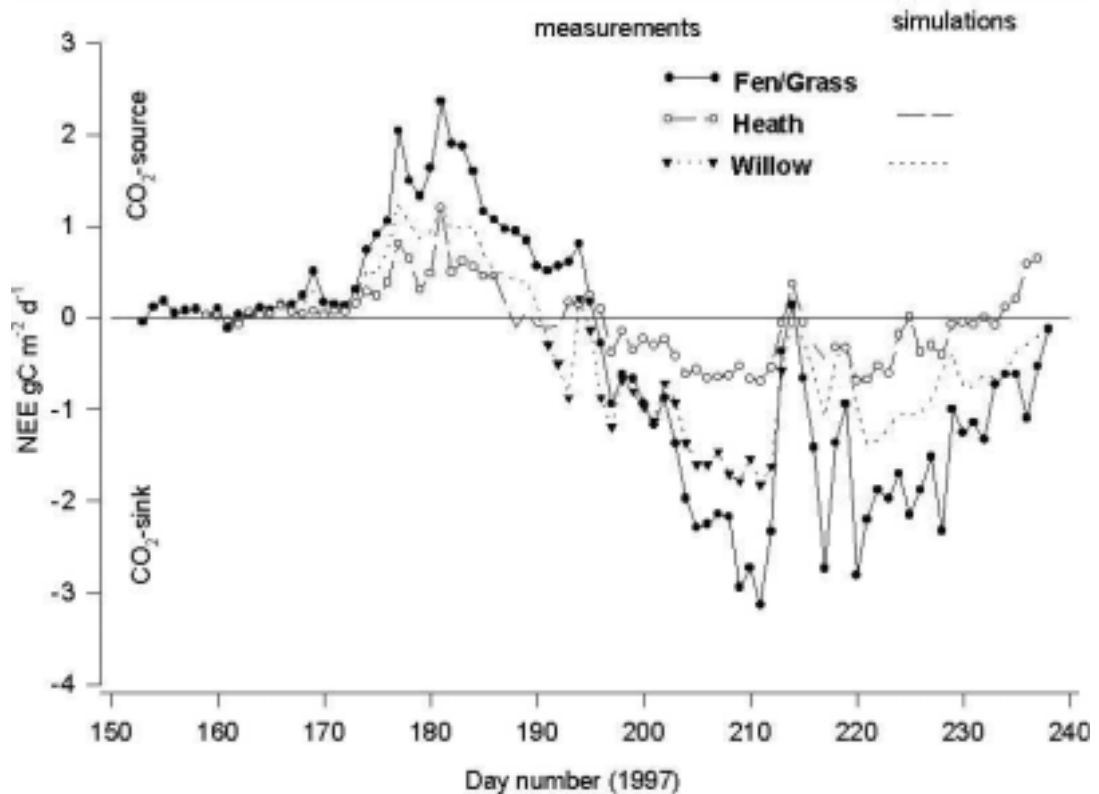
The low rate of primary production in almost all Arctic ecosystem types has been ascribed to low release rate of nutrients, mostly nitrogen (N) or phosphorus (P) or both, due to low decomposition rate of SOM (Nadelhoffer et al., 1992). The nutrient control of the rate of primary production has been shown in a large variety of arctic ecosystem types as a rapid increase of net primary production after application of inorganic fertilisers (e.g. Jonasson, 1992; Jonasson et al., 1999; Parsons et al., 1994). In some cases, fertiliser application has also resulted in a pronounced change in species composition (Chapin et al. 1995). Because of the nutrient limitation, it appears that the productivity is relatively insensitive to changes in atmospheric CO<sub>2</sub> concentration (Tissue and Oechel, 1987). However, viewed across the landscape, it is evident that hydrological conditions rather than nutrient supply rates are the proximate reason for the diversity of ecosystem types and the uneven distribution of plant biomass and SOM, in spite of the nutrient limitation (Jonasson et al., in press). For instance, although the mean ratio of SOM to plant biomass integrated over the entire Arctic is, roughly, 17:1, there is a huge local variation. The driest ecosystem types, such as tundra heaths, generally have a ratio of less than 10:1, while wet ecosystem types (e.g. wet sedge meadows) generally have a ratio far above 40:1. The different ratios are generally a function of differences in the amount of accumulated SOM rather than in the amount of plant biomass, suggesting that the mosaics of ecosystem types is affected more by variations in decomposition

rate than by differences in plant productivity. Hence, although plant productivity is limited by low nutrient supply rate, it appears that the long-term development of Arctic ecosystem types and their biogeochemical characteristics is regulated mostly by differences in decomposition rate. These differences are related to the hydrology, which in turn generally is coupled to topographic features.

#### *CO<sub>2</sub> fluxes in the high Arctic at Zackenberg*

Ecosystem exchange of trace gases, including CO<sub>2</sub> and CH<sub>4</sub>, has been measured at Zackenberg by using a so-called eddy correlation technique with continuous measurements over large areas from spring to autumn. These landscape-scale measurements have been supplemented by interval measurements at a smaller scale (<1 m<sup>2</sup>) in closed chambers. Figure 2 shows the pattern of CO<sub>2</sub> exchange between the atmosphere and biosphere for the summer of 1997 in three ecosystem types of different soil water regimes, with measurements starting just before snowmelt and ending at freeze up in early autumn (Soegaard et al., 2000). In early spring, there was a low flux out of the system lasting until snowmelt in mid June, followed by about 10 days of increasing net loss of CO<sub>2</sub> from the ecosystem. From around 1 July, the losses decreased continuously during a period of one to two weeks, when the vegetation developed rapidly. This was followed by a period of net uptake of C from mid July until mid or late August, occasionally interrupted by low C accumulation during periods of adverse weather conditions. The entire period with positive C balance lasted only about seven to eight weeks.

*Figure 2 Net ecosystem exchange (NEE) of carbon in three ecosystem types in Zackenbergdalen, Northeast Greenland, estimated by eddy correlation and modelling. Negative values indicate net increase of ecosystem carbon, positive values indicate loss of carbon to the atmosphere. (Data are from Soegaard et al., 2000.)*



The daytime net fluxes computed from the eddy correlation measurements across all vegetation types reached a growing season mean of about  $26 \text{ mg C m}^{-2} \text{ hr}^{-1}$  and was close to the flux of about  $22 \text{ mg C m}^{-2} \text{ hr}^{-1}$  measured independently with a closed chamber technique (Christensen et al., 2000). However, there was a strong variation between years. For instance, the C gain in the wet sedge ecosystem was estimated at  $49 \text{ g C m}^{-2}$  in the growing season of 1997 but reached  $96 \text{ g C m}^{-2}$  in the growing season of 1996. The difference was mainly due to about two weeks later onset of net C sequestration in 1997 than in 1996, combined with the period of low C sequestration in mid-summer, when the C balance even turned negative on a single day (Figure 2). This illustrates that relatively small changes in growing season length and stochastic fluctuations in weather conditions can have profound effects on the C balance in these northern ecosystems with an extremely short growing season.

#### *Variation of gas fluxes among ecosystem types*

The flux data from Zackenberg (Figure 2) show pronounced differences between ecosystem types. The amplitude of the fluxes decreased from a wet fen, through a moist willow area to the lowest values in a dry heath. Moreover, the breaking point between negative and positive C balance in spring and between positive and negative C balance in autumn differed. Peak net ecosystem C sequestration was reached earlier in the heath than in the other ecosystem types, because of earlier display of near annual maximum leaf area in this ecosystem type with a high proportion of evergreen shrubs with overwintering leaves. However, the effect of higher photosynthesis in the other vegetation types was greater than the effect of the earlier peak photosynthesis in the heath and resulted in higher growing season C accumulation in the wetter ecosystems. Over the entire growing season the wet fen, willow and heath ecosystems accumulated about 49, 23 and  $7 \text{ g C m}^{-2}$ , respectively. Estimates of the annual fluxes during 1997 showed a net influx of about  $19 \text{ g C m}^{-2}$  to the fen, near zero net flux in the willow ecosystem and a loss of about  $5 \text{ g C m}^{-2}$  in the heath.

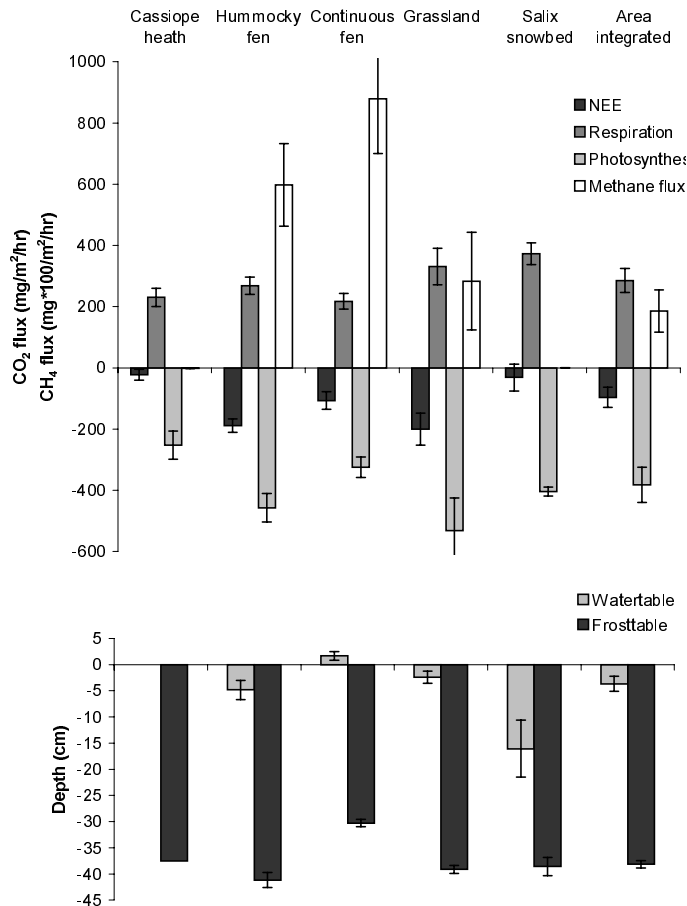
The ecosystem types also had a pronounced effect on methane ( $\text{CH}_4$ ) fluxes (Christensen et al. 2000). Only wet ecosystem types with a water table close to, or above, the soil surface showed appreciable  $\text{CH}_4$  fluxes of up to  $9 \text{ g m}^{-2} \text{ hr}^{-1}$  in the wettest ecosystem type as compared to no flux, or even a small  $\text{CH}_4$  consumption in dry *Cassiope* heath and *Salix* snowbeds (Figure 3). Integrated over the period from 1 June to 1 September and across the entire landscape with a mosaic of different vegetation types, the flux reached  $3.7 \text{ g m}^{-2}$  (Friborg et al., 2000).

The radiative forcing of  $\text{CH}_4$  is about 21 times higher than that of  $\text{CO}_2$  calculated on a mass basis and a 100-year time horizon (Houghton et al., 1996). Hence, although the  $\text{CH}_4$  flux was 25 times smaller than the respiratory  $\text{CO}_2$  flux, the potential contribution to the radiative forcing (i.e. the "greenhouse warming") was similar for the two gases in the wettest ecosystem type.

#### *Environmental controls on productivity and cycling nutrient*

While the measurements at Zackenberg have been focused on trace gas fluxes in different ecosystem types over the entire landscape, the research at Abisko has focused on responses to environmental perturbations within ecosystem types (Jonasson et al., 1999). Among these are measurements of responses in plant productivity and nutrient cycling to increased temperature and fertiliser application to a climatically relatively benign tree-line heath and a much colder high altitude fell-field.

**Figure 3** Seasonal daytime  $CO_2$  and  $CH_4$  fluxes from five major vegetation types in Zackenbergdalen, Northeast Greenland, the area integrated mean flux across the valley and the depth of the water- and frost table in the vegetation types. Values are averages \* SE of measurements at 15 occasions during the growing season. (Data are from Christensen et al. 2000.)



After five years of nutrient applications at a rate of 10 g nitrogen (N), 2.6 g phosphorus (P) and 9 g potassium (K) per  $m^2$ , the plant biomass had increased by more than 50% at the heath and more than doubled at the fell-field. Temperature enhancement of 2.5 – 4.0 °C had a slightly lower effect on the biomass in both ecosystem types (Jonasson et al. 1999). Plant tissue N and P concentrations in warmed plots were close to the concentrations in unwarmed control plots and, hence, the biomass had sequestered more nutrients per unit ground area. This indicates that the effect of the warming mostly was indirect through higher plant nutrient uptake resulting from stimulation of microbial nutrient mineralization in the warmed soils, rather than a direct effect of plant growth from the increased temperature.

#### *Global change and tundra carbon balance*

From these investigations, we are able to make the following predictions of how the Arctic may respond to changes in climate.

1. Changes in the length of the growing season will affect C sequestering strongly with high increase of ecosystem C sequestration if the snow melts a few days earlier than at present, with increasing effects with latitude. In contrast, C sequestering will probably decline in regions with increased snowfall and a later snowmelt. With a scenario of earlier snowmelt, the proportional increase of C sequestration

will probably be larger than the proportional change in growing season length. This is because the plants will reach peak biomass at an earlier date and photosynthesise for a longer period of time at high mid-summer light before inwintering and senescence. The effect of an increase of growing season length in autumn will probably be less than in spring because of reduced light and declining leaf biomass. However, there may be a longer period of high respiratory losses from the soil if the onset of freeze-up is delayed. In a longer time-perspective, the potential increased release of CO<sub>2</sub> from stored SOM may be constrained by decreased lability of the old organic fractions.

2. Higher summer temperature is also likely to increase growing season C sequestration, as the net ecosystem exchange of CO<sub>2</sub> is closely coupled with weather conditions (see above). Lower frequencies of cold spells will add further to the C sequestration. On the other hand, increased cloudiness may reduce C sequestration. However, a model for the gas exchange at Zackenberg (Soegaard and Nordstroem, 1999) suggests that ecosystem C sequestration increases to a peak only at about 2°C higher temperature than at present. At a further increase of the temperature, the effect on respiratory CO<sub>2</sub> losses overrides the effect on photosynthesis and the C sequestration decreases with particularly strong increase of C losses from winter respiration.
3. There are large differences in C fluxes among different vegetation types. Vegetation with high leaf area index as, e.g. graminoid-rich communities, both gain more C through the photosynthesis and lose more C by respiration than vegetation types with low leaf area index and with species of slower photosynthesis rates as e.g. heaths. In wet, graminoid dominated ecosystems, anaerobic soil conditions promotes CH<sub>4</sub> production, a trace gas that have much stronger radiative forcing than CO<sub>2</sub>. A climate change towards wetter conditions, hence, is likely to increase CH<sub>4</sub> emission in presently medium wet areas while drier conditions will increase CO<sub>2</sub> emission from presently wet areas. On the contrary, in presently dry ecosystems, the activity of decomposing microorganisms apparently is drought limited (Illeris and Jonasson, 1999). Hence, contrary to in wet ecosystems, increased precipitation is likely to increase and not decrease the respiratory losses.
4. Increased turnover rate of the soil organic matter will lead to release of presently growth-limiting nutrients (N and/or P), which will increase productivity at a rate set by the changes in supply rate of the limiting nutrients (Shaver et al., 2000). Increased biomass will, hence, compensate for the enhanced C losses from ecosystem respiration and lead to a decrease of the presently high soil to plant C ratios.
5. The coupling of increased C fluxes from warmer soil, the enhanced release rate of growth limiting nutrients and the increase of plant production will eventually lead to a reduced heat input to the soil because of increased shading from the denser vegetation. This is an example of a likely transient change, which can occur in the ecosystems. Many of the changes probably will be transient and different feedback systems probably will operate to restore the C balance between the atmosphere and the ecosystems. The net result of C fluxes out of and into the ecosystem during such transient periods is probably widely different between ecosystem types and forms a crucial factor for predictions of how the Arctic ecosystems will change, and to which extent the effects of the changes will go beyond the Arctic.

### 3 Marine Impacts

The Arctic region is characterised by large inter-seasonal variations in pelagic primary production. Typically, a distinct bloom is associated with the melting of the ice cover and is followed by smaller summer blooms, depending on hydrographic conditions

and nutrient balance (e.g. Wassman and Slagstad, 1993). In addition, annual pelagic primary production is determined by the length of the growing season which, in turn, is governed by the disappearance of snow cover and breaking up of sea ice (Rao and Platt, 1984; Rysgaard et al., 1999). It is estimated that for coastal environments 25 to 50% of the carbon fixed by pelagic primary production reaches the sediment surface (Berger et al., 1989). A significant fraction of this material undergoes oxidation through a complex web of degradation processes while the remainder is permanently buried (Berner, 1980; Rysgaard et al., 1998). The sediment thereby acts as a source of nutrients and inorganic carbon for the continued water-column production, as well as a sink in regional and global nutrient and carbon cycles (Buch et al., Chapter 4).

Studies of detailed satellite records have indicated a shortening of the sea-ice season, especially in the Sea of Okhotsk, the Eastern Arctic Ocean, the Barents Sea and off the north coast of Russia and the east coast of Greenland (Gloersen and Campbell, 1991; Gloersen et al., 1992; Parkinson, 1992; Parkinson et al., 1999). Furthermore, a decrease in sea ice thickness have been observed in the Eurasian Basin and Greenland Sea since 1958 (Rothrock et al., 1999). However, it has been suggested that an increase of global temperature and a resultant increase in ice-melt may serve to freshen the surface waters of the convective gyres of the Greenland and Iceland seas, to a degree that cooling even to the freezing-point is insufficient to initiate convection (Aagaard and Carmack, 1989). This may cause the global thermohaline transport to alter, and reduce the transport of warm water to the North Atlantic region, resulting in a local cooling of the area and a subsequent increase in ice-cover (Häkkinen, 1993; Rahmstorf, 1997). Furthermore, analyses of two ice cores drilled in central Greenland (Johnsen et al., 1992; Dansgaard et al., 1993; Taylor et al., 1993) and of deep-sea cores (Bond et al., 1993) have revealed large, abrupt climatic changes of at least regional extent during the last glaciation, suggesting that the climate in the North Atlantic region can alter rapidly, perhaps even within few decades.

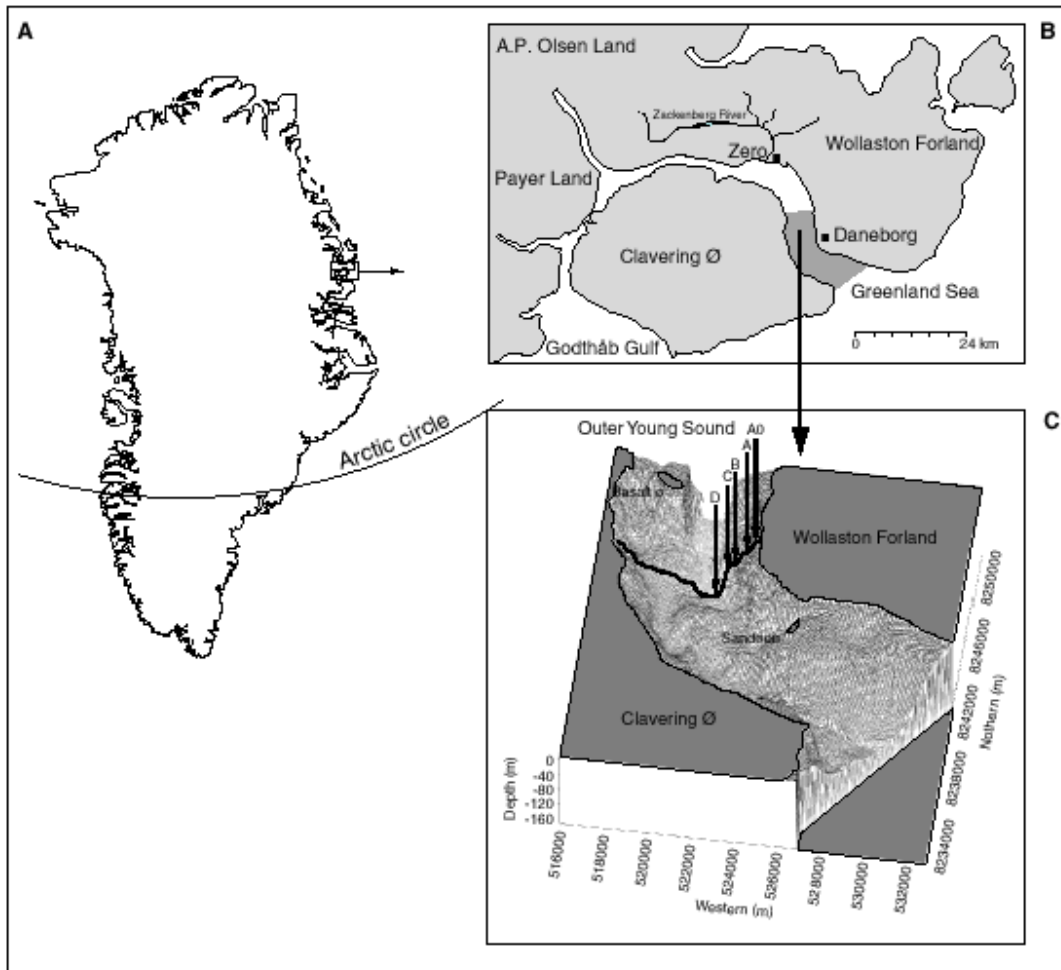
Through the above-mentioned effects on ice-cover, current patterns, and vertical mixing, global temperature changes are expected to induce ecosystem alterations affecting primary production and thus higher trophic levels.

### 3.1 The CAMP project

Since 1994 there have been an extensive research activity in the high Arctic fjord Young Sund (74°N) on the northeast coast of Greenland (Figure 4). The research has been joined in the project "Changes in Arctic Marine Production" (CAMP), which is co-ordinated by the National Environmental Research Institute (NERI) and is being effected as a collaboration between several scientific institutions: University of Aarhus, Max Planck Institute for Marine Microbiology, University of Copenhagen, University of Virginia, University of Southern Denmark, Roskilde University, Greenland Institute of Natural Resources, Cawtron Institute New Zealand and NERI.

The aim of the CAMP project is to investigate the responses of production, consumption, and degradation in an Arctic coastal ecosystem to changes in temperature and sea ice-cover. The main focus is the study of mechanisms controlling primary production and the subsequent regulation of secondary production and bacterial recycling of nutrients. This is accomplished through detailed field and laboratory studies of water and sediment processes in Young Sund. Additional details are found at [www.dmu.dk/LakeandEstuarineEcology/camp](http://www.dmu.dk/LakeandEstuarineEcology/camp).

Figure 4 Location of study site, Daneborg, NE Greenland. Topographic mapping of outer Young Sund. ZERO: Zackenberg Ecological Research Operations. A0, A, B, C & D intensive sampling stations used for the CAMP project.



#### *The ecology of a high Arctic fjord today*

**Hydrography and nutrients.** Typically sea ice covers Young Sund from early October to mid July. The hydrography within Young Sund is thus strongly influenced by sea ice and input of freshwater. Large amounts of melt water enter the fjord during the summer thaw from the surrounding land and from the sea ice itself. A freshwater lens just below the sea ice persists from mid-late June to sea ice breaks, after which it is mixed into the surface layers of the water column. Saline polar water enters the fjord mainly from the Greenland Sea between Wollaston Forland and Clavering Island due to the East Greenland current and tidal exchange. The combined effect of freshwater input to the surface layers of the water column and higher salinity polar water entering the fjord from the Greenland Sea creates a stable pycnocline at 15-20 m water depth. Thus, the strong stratification during the summer period effectively seals the nutrients in the deeper water layer. The nutrient concentration levels in the water column of Young Sund are similar to the observations from the adjacent Greenland Sea. Temperature in surface waters may reach 3-4°C during the open water summer period, whereas the temperature in the bottom water of the fjord is <-1°C throughout the year.

**Sea ice algae.** Sea ice algae, primarily diatoms, are heterogeneously distributed in the sea ice both vertically and horizontally. A maximum concentration is observed at the

sea ice interface in a few mm-concentrated algal layers. However, algae is also present throughout the ~1.5 m thick sea ice matrix. *In situ* investigation on different horizontal metric scales shows that the algal activity followed the light regime below the sea ice (radius of patches is 20-100 m). Annual ice algal production at the sea ice-water interface in Young Sund may be highly variable and regulated by the thickness of snow cover. Primary production was  $<0.01 \text{ g C m}^{-2}$  during 1998-1999. Compared to other coastal fast ice areas in the literature this rate seems low but comparable to measurements further out in the Greenland Sea. The low biomass and productivity in Young Sund was caused by a combination of poor light conditions due to snow cover and freshwater drainage from melt ponds and river discharge removing and/or inhibiting the algae at the sea ice-water interface through physical disturbance and exposure to freshwater. Thus, seen on an annual scale, the primary production of sea ice algae in Young Sund is  $<1\%$  of the pelagic primary production (Rysgaard et al., in press).

**Phytoplankton.** The phytoplankton community is dominated by diatoms in the surface samples as well as in the subsurface bloom succeeding the spring bloom. Pelagic primary production is limited by light during sea ice cover. After break-up of the sea ice, silicate initially limits primary production in the surface water due to a well-established pycnocline, and maximum photosynthesis occurs in a subsurface layer at 15-20 m depth. In August, production is displaced to deeper water layers presumably due to nitrogen limitation. The carbon budget describing the fate of the annual pelagic primary production in Young Sund, reveals that the pelagic production of  $\sim 10 \text{ g C m}^{-2} \text{ yr}^{-1}$  is tightly coupled to the grazer community since total consumption by the grazer community amounts to  $10\text{-}11 \text{ g C m}^{-2} \text{ yr}^{-1}$ . The classical food web dominates this north-eastern Greenlandic fjord and it is estimated that copepods account for  $>80\%$  of the grazing pressure upon phytoplankton (Rysgaard et al., 1999).

**Benthic microphytes.** Benthic microalgae, primarily pennate diatoms, live on and among sand grains on the seafloor and bloom in Young Sund during summer, when light reaches the sediment surface. The algae are distributed from ~2 to 40 m water depth with maximum biomass at depths of 20 m. Net oxygen production of benthic microalgae *in situ* starts at low irradiance of  $\sim 4\text{-}15 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$ , showing that their production is not only restricted to the open water period but also occurs in sediments below 1.5 m sea ice cover. However, they have the capability of adapting to increased irradiance over a very short time period and hence most of the annual primary production is restricted to the open water period. They also function as an efficient filter assimilating nutrients diffusing up from the sediment below and thus preventing nutrients to reach the overlying water column. Based on seasonal measurements on benthic algae from different water depths and extrapolating to the outer Young Sund with maximum water depths of 200 m net primary production of benthic microphytes is  $\sim 5 \text{ g C m}^{-2} \text{ yr}^{-1}$  (Rysgaard et al., in press).

**Benthic macrophytes.** Benthic macrophytes occur from 2 to 25 m depth in Young Sund. More dense vegetated areas are confined to 2-15 m, where the perennial brown algae *Fucus evanesceus*, *Laminaria saccharina* and *Desmarestia aculeata* are the dominant species. Maximum biomass is  $>100 \text{ g C m}^{-2}$  in the mouth facing the open water, where feeding activities of walrus, and hence disturbance of the sediment, are less violent than further inside the fjord. These macroalgae have low light requirements at the beginning of the growth season in June, when the locality is covered by snow and sea ice. The light compensation point of *L. saccharina* is around  $2 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$ , corresponding to 1-2% of the surface irradiance. Photosynthesis of *L. saccharina* saturates around  $50\text{-}100 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$ , and during the open water summer period light intensities are often above this level and therefore not available for photosynthesis. The strategy of growth in kelp; i.e. accumulation of nutrients in the tissue during win-

ter, when nutrient concentrations are high, and accumulation of carbohydrates during summer, when nutrient concentrations are low, enables these macroalgae to sustain a relatively long growth season. About 40% of the annual growth occur during the open water period and the remaining 60% during the ice covered period. Based on seasonal measurements from different water depths and extrapolating to the outer Young Sund with maximum water depths of 200 m, net primary production of benthic macrophytes is  $\sim 4 \text{ g C m}^{-2} \text{ yr}^{-1}$  (Krause-Jensen et al., in press).

**Benthic mineralization.** When sea ice breaks up typically in mid July, benthic mineralization is immediately stimulated by a significant peak in sedimentation of organic material. In response to the enhanced mineralization following sea ice break-up, sediment water fluxes of  $\text{O}_2$ , DIC,  $\text{NO}_3^- + \text{NO}_2^-$ ,  $\text{NH}_4^+$ , urea,  $\text{PO}_4^{3-}$  and Si increases and rapidly recycle nutrients to the water column, indicating an efficient benthic-pelagic coupling in Young Sund. Due to rapid mineralization of the easily degradable fraction of the settling organic material, respiration rates returns to their basic lower level within one month and remain at a lower level for the rest of the season. The mineralization rate exhibits a rapidly attenuating exponential decrease with increasing water depth and on average aerobic mineralization accounts for 30% of the total degradation. Anaerobic degradation, responsible for the remaining 70%, is dominated by sulfate and iron respiration, while denitrification and manganese respiration are of marginal importance. Benthic mineralization rates in the Young Sund sediment are comparable with rates from much warmer locations, suggesting that benthic mineralization in this high Arctic coastal sediment is regulated by the availability of organic matter and to a lesser extent by temperature. Based on seasonal measurements of mineralization rates from different water depths and extrapolating to the outer Young Sund with maximum water depths of 200 m the annual mineralization rate is  $\sim 16 \text{ g C m}^{-2}$ . The fraction of refractory carbon buried is approximately one third ( $5 \text{ g C m}^{-2} \text{ yr}^{-1}$ ) of the amount of carbon being mineralized in Young Sund. At the shallow stations, benthic infauna stimulates the benthic oxygen exchange by a factor of 1.5 to 3 relative to molecular diffusion. However, the estimated metabolic activity of the fauna itself accounts for <10% of total benthic degradation (Rysgaard et al., 1998; Glud et al., 2000; Sejr et al., 2000).

**Benthic animals.** The composition and abundance of benthic fauna has been relatively well studied in the outer parts of Young Sund. The benthic community is rich and diverse with animal abundance ranging from  $\sim 2700$  individuals  $\text{m}^{-2}$  at 20 m to  $\sim 900$  at 85 m. Like other coastal areas in the Arctic, brittle stars and bivalves are important components. Studies have focused on two species of bivalves, *Hiatella arctica* and *Mya truncata*, since they attain high biomass in shallow parts of the fjord and are the main food items of the populations of walruses in the area (Sejr et al., 2000). Compared to temporal populations, Arctic bivalves experience two types of stress; constant low temperatures and low and very variable food intake with almost no food being available during the 9 to 10 months of ice cover. Growth rates are correspondingly low with *Hiatella arctica* reaching a maximum age of 115 years and a size of 5 cm in length. Detailed physiological measurements suggest that mussels have adapted to low food availability by increasing growth efficiency and that the lack of food is what causes the extreme slow growth in these animals. Therefore, improved food conditions are expected to increase growth and production of these mussels despite the low temperatures.

**Walrus.** Within the study we determine (1) energy expenditure and requirements of individual free-ranging walruses in a high-arctic marine ecosystem, (2) the quantitative importance of predation on the infauna by walruses, and (3) the relationship between primary production, benthic animals and walruses. The project is still in its initial phase and fieldwork continues until 2002. However, preliminary data show large variations in the number of walruses between years with extensive sea ice and years

with open water at the haul-out site on Sandøen. Satellite telemetry revealed that walrus not only utilise Young Sund but also the coastal areas between Lille Pendulum and southern Clavering Island (i.e. between 74° and 74°45'N), and that they intensively feed on shallow water depths (<20 m) containing the highest biomass of bivalves. Feeding requirements of walrus will be assessed by two methods. First, measurements by an isotope-dilution method ("doubly-labelled water") will provide an integrated assessment of individual energy expenditure. Such data will be related to information on individual activity obtained from satellite-transmitters and dive recorders. Secondly, a quantification of walrus predation on the infauna obtained by direct under-water observation will be used for an assessment of the intensity of grazing on the bivalve beds (Born et al., 2000; Acquarone et al., in press).

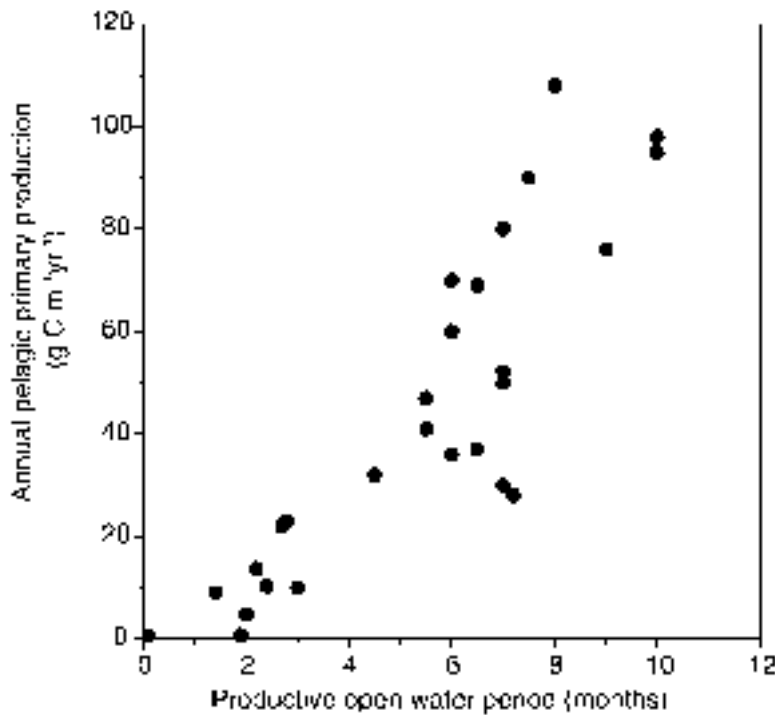
#### *The ecology of the high Arctic fjord in the future*

The future plan of the CAMP work is to link all measurements into a mathematical model describing the ecosystem of Young Sund and making predictive scenario calculations of alterations in present rates and processes due to changes in sea ice and snow conditions. However, this work has not yet been completed, and in the following, predictions of how Young Sund will respond to changes in climate will be presented based on our most recent results. Quantitative predictions will have to wait until all data analysis has been completed.

The observations that both sea ice distribution and thickness have decreased during the past decades, and that a further reduction is to take place in the future (Wadhams, 2000), makes it important to establish a relationship between sea ice and primary production in order to predict changes in Arctic marine ecosystems. A compilation from the literature on annual pelagic primary production in Arctic waters plotted against the productive open water period shows that annual primary production increases with decreasing sea ice conditions or increased open water period (Figure 5). Although, this compilation only covers phytoplankton production, our investigations in Young Sund show that also benthic micro- and macrophyte annual primary production will increase with an increasing open water period. However, sea ice algal primary production is expected to decrease due to decreasing sea ice conditions and increasing snow conditions. Since sea ice algal production is minor in comparison to the other primary producers it will be expected that total primary production will increase as sea ice retreats (see also Stendel et al., Chapter 9).

Any alteration in the amount of annual primary production will markedly affect secondary production. Grazing experiments from Young Sund shows that the grazer community in the water column is food limited and responds immediately upon addition of algal material. Furthermore, a very tight coupling between primary production and grazing by copepods was observed in the seasonal studies. This is in accordance with earlier findings that following a phytoplankton bloom associated with stratification of the water column, the growth rates of pelagic and benthic secondary producers normally become food limited (Kjørboe and Nielsen, 1994; Kannevorff and Christensen, 1986). Thus, a prolonged ice-free period and ensuing high rates of primary production will be expected to lengthen the growth season of secondary producers.

Figure 5 Annual pelagic primary production versus length of productive open water period.



The increased primary production and grazing by copepods will increase the vertical transport of organic material to the sediment. Assuming that the growth season of primary producers is extended due to reduced ice-cover and thereby increased light availability during summer, continued primary production will most likely become dependent on the availability of nutrients. An important source of nutrients for primary producers is provided by bacterial degradation of dead organic matter. Part of this remineralization takes place in the water column, whereas in shelf areas (0-200 m depth), a large fraction of the primary production is deposited on the sediment surface and degraded by microbes within the sediment. Further increase in primary production will therefore ultimately be controlled by the efficiency with which nutrients are returned to the photic zone. Thus, bacterial degradation of dead organic matter and recycling of nutrients will set an upper limit for production in the ecosystems.

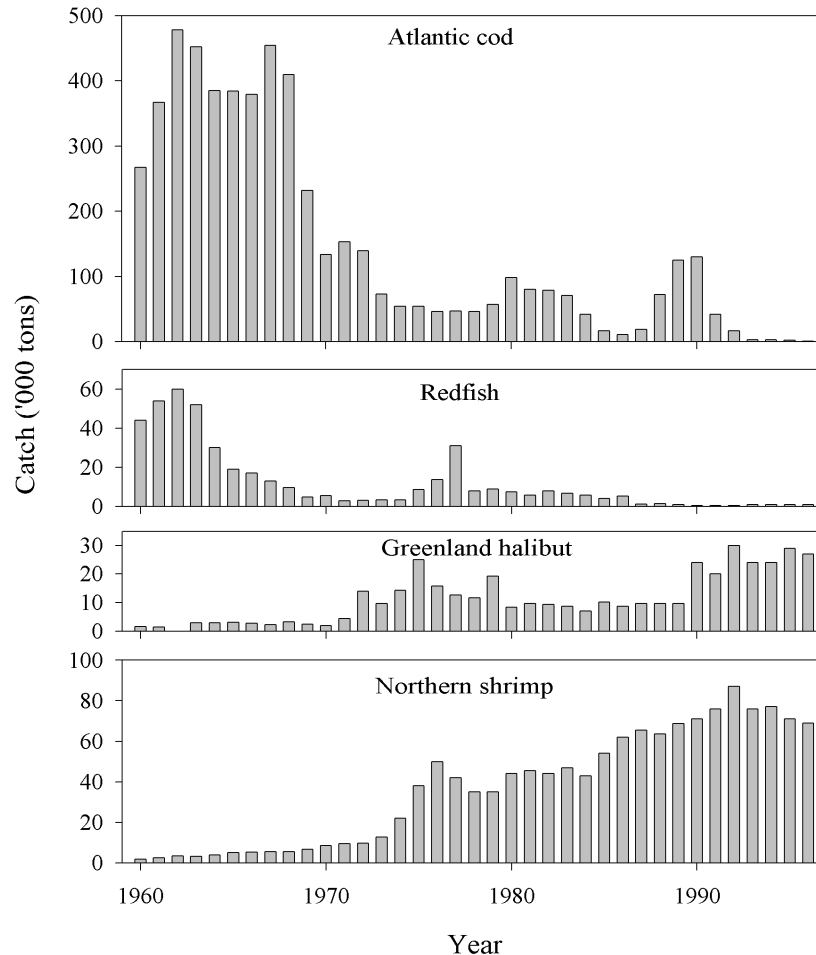
An increased flux of organic matter to the benthic animal community will increase the food available for growth and reproduction. Thus, it will be expected that the density of benthic animal will increase as a response of an increase in open water conditions. This will increase the food availability of the resident walrus. Estimates of walrus grazing combined with biomass and production measurements for bivalves in Young Sund show that the size of the walrus population is not limited by food in the area during the summer period. The increase in the length of the open water period will therefore increase the potential feeding period and thus increase the walrus population. This illustrates the tight link between changes at the physical level (ice cover and hydrography) and effects on higher trophic levels.

### 3.2 Changes in the West Greenland fisheries

The marine shelf ecosystems off East and West Greenland are intermediate between the deep Arctic water masses in the Polar Sea and temperate water masses of the Atlantic. They are important fishing grounds and are characterised by relative few dominant species, which interact strongly (Pedersen, 1994; Pedersen and Kanneworff, 1995, Rätz, 1999). Currents that exchange water between the polar and temperate regions af-

fects the marine productivity in the shelf areas, and changes in the global circulation system have major impacts on species distributions and fisheries yield (Pedersen and Smidt, 2000; Pedersen and Rice, in press; see also Buch et al., Chapters 4, and MacKenzie and Wisser, Chapter 19).

**Figure 6** Nominal catches of the most important commercial fish species in West Greenland waters, 1960-1996.



In the twentieth century there have been major changes in the international annual landings of commercially important fish species in West Greenland waters. A rich Atlantic cod (*Gadus morhua*) fishery started in the 1920s after a general warming of the Arctic (Jensen, 1939, Buch et al., 1994). Historically, Atlantic cod has been the most important commercial fish species, with annual catches peaking at levels between 400,000 and 500,000 tons in the 1960s. During the late 1960s, the annual catches of cod declined drastically as did the catches of other commercially important fish species - redfish (*Sebastes marinus* and *S. mentella*), Atlantic halibut (*Hippoglossus hippoglossus*) and wolffish (Atlantic wolffish, *Anarhichas lupus*, and spotted wolffish, *A. minor*) - mainly taken as by-catch in the fishery for cod. After 1969, catches of Atlantic cod and redfish fluctuated around a much lower mean than prior to the 1960s (Figure 6). Except for a temporary improvement of the cod fishery during 1988-1990 the catches of cod, redfish, Atlantic halibut and wolffish showed marked decreasing trends from 1980 onwards. The decline in amount caught does not tell the entire story, however, as the fisheries for cod also moved much further south in the 1980s, and the sizes of fish at age dropped greatly as well (Hovgård and Buch 1990; Riget and Engelstoft 1998). During the same period, however, the catches of two other commercially important species, Greenland halibut (*Reinhardtius hippoglossoides*) and northern shrimp (*Pandalus borealis*) increased (Figure 6).

The shift in the composition of landings over the last decades is assumed to be due mainly to changes in recruitment patterns driven by changes in oceanographic characteristics. In terms of mechanisms linking oceanographic factors to recruitment of fish and shellfish in West Greenland, sea temperature, drift of larvae by surface currents, and stability of the water masses (oceanographic fronts) have been proposed (see Pedersen and Rice, in press). Variability in these factors is related in turn to inflow of water from other parts of the North Atlantic. The strengths of the *East Greenland Current* and the *Irminger Current* have dominating effect on the sea environment in the shelf areas around southern Greenland.

The role of climatic variation in regulating marine populations and communities in Greenland waters is largely unknown. Investigations of climatic variability off West Greenland indicate general decreasing trends in air and sea surface temperatures from the late 1960s onwards (Figure 7), which is related to an increasing trend in the North Atlantic Oscillation (NAO) winter index (Buch, 1998; Stein, 1998; Serreze et al., 2000). The relationship between the NAO winter index and mean winter air temperature is strong ( $r^2=0.44$ ), while the relationships with mean sea temperature, abundance indices of zooplankton and fisheries resources at higher trophic levels are weaker and less obvious (Figure 7).

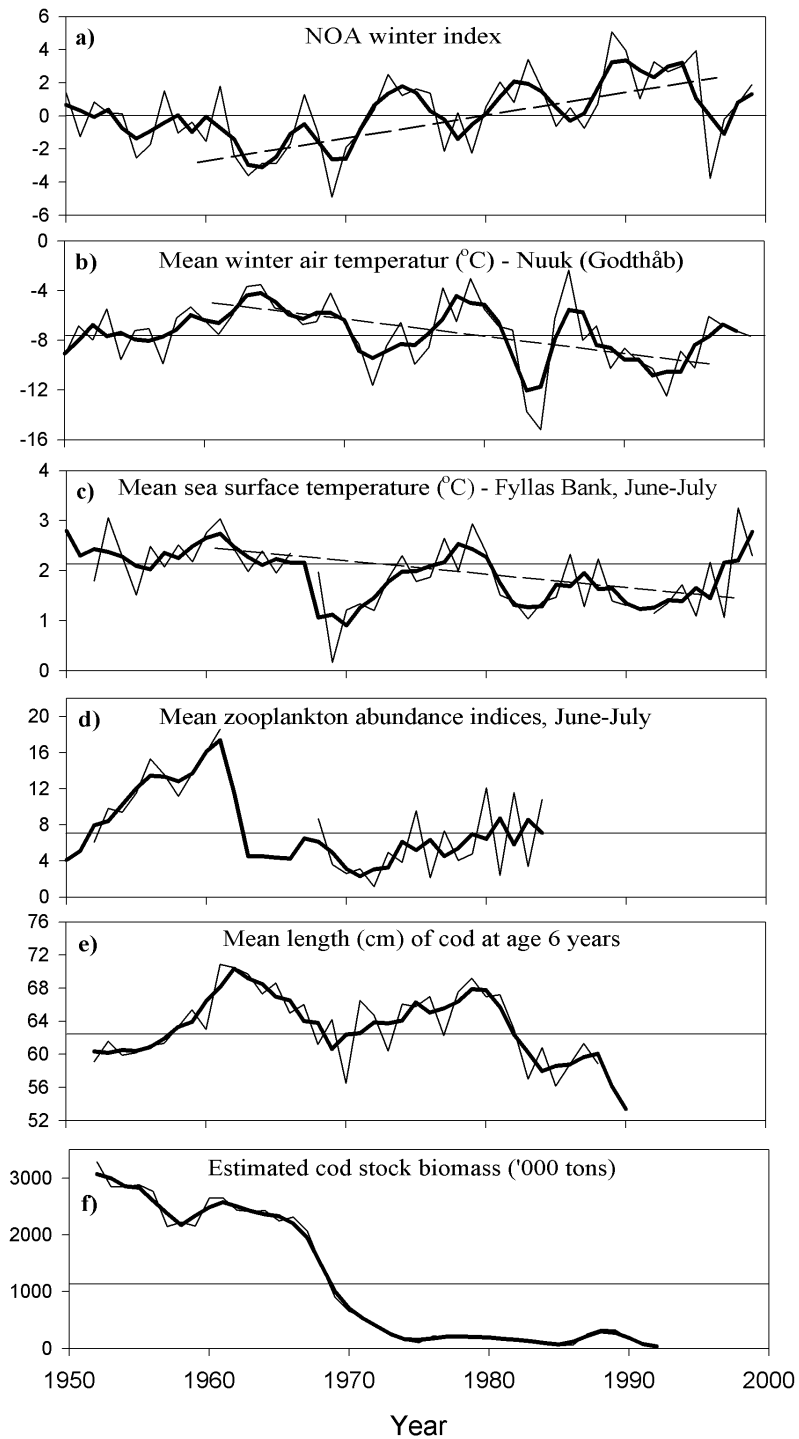
There is a need for better understanding of the dynamics between environmental conditions and variability in the West Greenland fish resources (Stein, 1998; Pedersen, 1998; Pedersen and Smidt, 2000). Progress in understanding recruitment success of fish and shellfish requires process oriented studies of zooplankton, ichthyoplankton, hydrography, and climate. Therefore, the *Greenland Institute of Natural Resources* (GINR) has initiated research on climate-ocean variability and ecosystem response.

#### *Ongoing studies of climate-ocean-fish-fishery interactions*

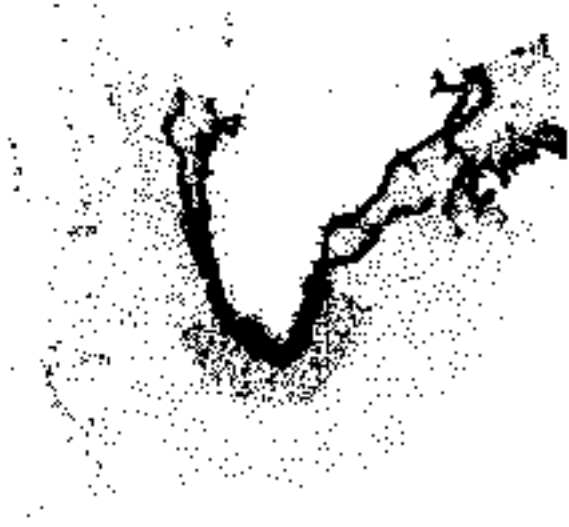
The project entitled "Hydrographic and biological processes of importance for variability in recruitment of fish and shellfish stocks in West Greenland waters" was started in 1999 with economic support from the Danish Research Councils Committee on North Atlantic Research. The project is a co-operation between scientists from GINR, the Danish Institute for Fisheries Research, the Danish National Environmental Research Institute, the University of Roskilde, and the Danish Meteorological Institute.

In 1999 and 2000 five research cruises were carried out over the West Greenland shelf area with the main purpose of investigating the distributions of fish and shellfish larvae in relation to key hydrographic processes, potential prey and predators. During these field studies the project collected data to describe the Arctic pelagic food web, its structure and dependence upon hydrographic processes (e.g. shelf break fronts) at and around the shelf banks. Understanding the dynamics of the lower trophic levels of the Arctic pelagic food web may be one of the keys to understand changes in community structure and recruitment success for fish and shellfish in West Greenland waters.

*Figure 7 Time series of the winter NAO index, winter air temperature, sea temperature, abundance indices of zooplankton, Atlantic cod length at age 6 and cod biomass calculated from virtual population analysis. Heavy solid lines are 3 year running averages. Horizontal thin line is overall long-term mean for the whole series. Short dashed lines in a), b) and c) are trends during part of the series. Data from: a) Hurrell and van Loon (1997); b) Nuuk Meteorological Station; c) Pedersen and Smidt (2000) and S.A. Pedersen and E. Buch (unpubl.); d) Pedersen and Smidt (2000); e) and f) Riget and Engelstoft. (1998).*



*Figure 8 Triangular grids used in calculations of ocean currents and particle tracking. The model has high horizontal resolution over the shelf areas (2 km) and lower resolution over deep water (57 km) (N. Kliem, unpubl.).*



Advection and aggregation at hydrographic fronts of fish and shellfish larvae, their prey and predators are important processes, which will be studied using a “state of the art” 3D-ocean current model developed at the Danish Meteorological Institute (N. Kliem, unpubl.) (Figure 8). The physical modelling is based on a hydrodynamic finite element model forced by wind, pressure and temperature field data calculated from the operational atmospheric model for Greenland. Calculated current fields will be fed into a particle-tracking model to simulate the transport of ocean drifters, mesozooplankton, shrimp and fish larvae. The advection of e.g. the shrimp larvae will be driven by the physical model component, while a biological model will describe the vertical position of shrimp larvae.

Hydrographic and biological data for modelling the processes (e.g. vertical distribution of temperature, salinity, and shrimp larvae) are obtained from the research cruises carried out by the project and from laboratory experiments (Rasmussen et al., 2000). Two satellite tracked surface drifters were deployed in the West Greenland shelf area at Fyllas Bank in May 2000. Positions and sea surface temperature obtained approximately every three hours from the two drifters are used to calibrate and validate the ocean current model.

In addition to primary studies of variable oceanographic conditions and the effects on larval fish and shellfish recruitment, the project will evaluate effects of species interactions and bycatch in the shrimp fishery for the fish community structure.

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