



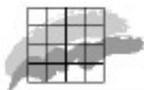
**National Environmental Research Institute**  
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# Physical and biological oceanography in West Greenland waters with emphasis on shrimp and fish larvae distribution

*NERI Technical Report, No. 581*



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National Environmental Research Institute  
Ministry of the Environment

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# Physical and biological oceanography in West Greenland waters with emphasis on shrimp and fish larvae distribution

*NERI Technical Report, No. 581*  
2006

*Johan Söderkoist*  
*Torkel Gissel Nielsen*  
*Martin Jespersen*

# Data sheet

Title: Physical and biological oceanography in West Greenland waters with emphasis on shrimp and fish larvae distribution

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Abstract: The report provides an overview of the hydrography and plankton dynamics and shrimp and fish larvae distribution in Disko Bay, and the waters along south west Greenland. Observations of hydrography and the plankton community in Disko Bay and on the banks along the Greenland south west coast show that marine life is mainly concentrated in transition zones between water masses, on the steep bottom slopes of the banks, and at the shallow parts of the entrance to Disko Bay. High production of the plankton community is also expected in the marginal ice zone west of the Greenland west coast, but due to insufficient amount of observations it cannot be confirmed in this study. The plankton bloom in Disko Bay is triggered by upwelling of saline and warmer water at the end of April. Onset of the plankton bloom, magnitude, and the distribution of the plankton community are highly affected by the large inter-annual variations of the ice extent in spring. Onset of the plankton bloom at the banks south of Disko Bay is also expected to take place in April. The zooplankton community, including fish and shrimp larvae, increases in abundance and are abundant in the surface layer during early summer. Later in the season the plankton community is more scattered, and mostly beneath the surface layer. The aim of the report is – based on an analysis of physical and biological oceanography with emphasis on shrimp and fish larvae distribution – to support the identification of potential hot spots in time and space where an oil spill will have the largest consequences on the marine ecosystem. The most sensitive season – i.e. when an oil spill can be expected to have the most severe ecological consequences – is April to June when high biological activity of the pelagic food web from phytoplankton to fish larvae are concentrated in the surface layers. On a horizontal scale the most important area is the fronts in association with the transition zone between different water masses.

Keywords: West Greenland, hydrography, biological oceanography, impact of oil spill, pollution

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## Summary

A hydrographic and plankton community description of the Disko Bay region has been made. The aim was to identify sensitive regions and time periods to oil spill. Analysis of historical observations of hydrography during the period April 1996 to August 1998 and spring 2005 showed that there was only polar water in Disko Bay, originating from the Arctic Ocean. In summer, the surface salinity is lower than in the polar water, which is an effect of ice melt from glaciers and sea ice. The observed hydrography at the Arctic Station, located 1 nautical mile south of Qeqertarsuaq, showed that the warming of the surface water in Disko Bay started in May and continued to late August. Ice melt during summer increased the strength of the stratification and intensified the heating rate in the upper layers. The summer mixed layer thickness was typically 10-20 m. Convection together with advection of water from outside the bay from early September 1996 to late January 1997 increased the sea surface salinity from 30.7 to 33.4. Satellite observations showed that the ice growth season exhibited large interannual variations. The ice growth season in 1996 and 1997 started in January, but in 2005 Disko Bay was nearly ice free throughout the winter season.

In contrast to the general believe that decreased surface density due to warming or decreased surface salinity triggers the spring bloom, the present study suggests that increased salinity below the surface layer initiated the spring blooms in Disko Bay in 1997 and 2005. The increase in vertical stratification might have been generated by upwelling or inflow of dense water in the deeper parts of Disko Bay. The spring bloom started around the 20th of April for both 1997 and 2005.

The horizontal mapping performed in June 1996 and 1997 in Disko Bay suggests that there was a clockwise circulation in the upper 100 m during early summer. The coastal current in the bay received warm and saline water from the West Greenland Current. A fraction of the water left the bay along the southern coast of Disko Island. Analysis of the easternmost area in June 1997 suggests that there was an inflow in the surface layer through the northern entrance of Disko Bay, the Vaigat.

The aim of the report is – based on an analysis of physical and biological oceanography with emphasis on shrimp and fish larvae distribution – to support the identification of potential hot spots in time and space where an oil spill will have the largest consequences on the marine ecosystem. The present report provides an overview of the hydrography and plankton dynamics and shrimp and fish larvae distribution in Disko Bay, and the waters along south west Greenland.

In this context, knowledge about the interaction between hydrography and the pelagic food web is essential. Therefore attention is drawn to the identification of hydrodynamic discontinuities, i.e. sites where water masses with different properties meet and enhanced biological

activity can be expected. These sites are particularly sensitive and areas where pronounced ecological effects of a potential oil spill can be expected.

# Sammenfatning

Rapporten indeholder en beskrivelse af Disko Bugtens hydrografi og planktonsamfund. Formålet er at identificere områder/perioder, som er specielt udsatte i forhold til et eventuelt olieudslip.

En analyse af tidligere indsamlede hydrografiske data fra Disko Bugten viste, at vandmassen primært er polarvand. Denne vandmasse stammer fra det Arktiske Ocean. Om sommeren er overfladevandets saltholdighed lavere end polarvandet pga. ferskvandstilførsel fra havis og gletschere. Den observerede hydrografi på en permanent station 1 sømil syd for Qeqertarsuaq viste, at opvarmningen af overfladevandet startede i maj og fortsatte indtil august. Ferskvandstilførsel i løbet af sommeren forstærkede yderligere lagdelingen og opvarmningen af overfladelaget. Det opblandede overfladelag var typisk 10 til 20 m tykt. Konvektion og advektion af vand ude fra bugten øgede overfladelagets saltholdighed fra 30,7 til 33,4 fra september til januar. Satellitobservationer viste, at der var store år til år variationer i varigheden af isdækket. Havisen blev etableret i januar i 1996 og 1997, mens der stort set ikke var noget sammenhængende havisdække i 2005.

I modsætning til den generelle antagelse at en reduktion i overfladelagets massefylde, pga. opvarmning eller reduceret saltholdighed, udløser forårsopblomstringen, viser nærværende analyse, at øget saltholdighed af vandmassen under den fotiske zone initierer forårsopblomstringen i Disko Bugten i 1997 og 2005. Opblomstringen startede i de to år ca. 20. april. Lagdelingen skyldes formodentlig opstrømning eller indstrømning af vand med høj densitet til de dybere områder i Disko Bugten. Tykkelsen af overfladelaget blev efterfølgende reduceret, da overfladelaget strømmede ud af Disko Bugten.

Undersøgelsen af Disko Bugten i juni 1997 og 2005 viste, at de øverste 100 m af vandsøjlen strømmede med uret rundt i Disko Bugten. Kyststrømmen i bugten modtog varmt og salt vand fra Den Vestgrønlandske Strøm. En del af vandet forlod bugten i den sydlige del af Disko Bugten. Analyser af den østlige del i juni 1997 viste, at vandet også forlod bugten igennem Vaigat.

Hensigten med denne rapport er – ud fra en analyse af områdets hydrografi – at understøtte identifikationen af potentielle biologiske produktionsmæssige "hot spots" i tid og rum, hvor et eventuelt olieudslip må forventes at have de største konsekvenser for det marine økosystem. Rapporten bidrager med et overblik over hydrografi, planktondynamik og udbredelse af reje- og fiskelarver i Disko Bugten og havområderne langs med Sydvestgrønland. I denne sammenhæng er kendskabet til samspillet imellem hydrografi og det pelagiske fødenet centralt. Specielt skal man være opmærksom på hydrografisk diskontinuitet, dvs. områder hvor forskellige vandmasser mødes og forhøjet biologisk aktivitet kan forventes. Sådanne områder er specielt følsomme og er områder, hvor den økologiske påvirkning af et eventuelt olieudslip kan forventes at være mest udtalt.

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# Eqikkaaneq

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# 1 Introduction

The interest for oil exploration in the Arctic areas is increasing due to increased oil prices, new technology and last but not least the reduced extensions of ice cover. This will open previously ice covered areas and make the logistic to drill less complicated and reduce the exploration expenses. Recently, interests in the potential oil resources of West Greenland have been made and oil prospecting on the shelf outside the Greenland west coast is under consideration.

The Greenland community and economy are strongly dependent on exploitation of marine resources. The major export income originates from fishery of fish and crustaceans. Disko Bay and the fishing banks along West Greenland are in this connection very important nursery and feeding grounds for most of the exploited fish, birds and mammal stocks. Consequently an oil spill in these sensitive areas potentially may impact the marine productivity and economy of the Greenlandic community. Investigations of the environmental impact of an oil spill on the structure and function of the Arctic marine ecosystem are limited.

Disko Bay is situated about 300 km north of the polar circle (69°15'N, 53°33'W). Disko Bay is located at the southern border of the arctic sea ice, and is thus likely to be affected by changing temperatures. The break-up of sea ice in Disko Bay normally takes place between April and May but oscillates considerably between years thereby influencing the timing of the phytoplankton spring bloom and the initiation of the pelagic production. The temporal and spatial patterns of production are very heterogeneous – in general blooms are triggered in the spring when the stratification keeps the plankton in the illuminated part of the water columns. Most nutrients in the surface layer are depleted after the main bloom and the phytoplankton have to rely on nutrients regenerated in the surface layers. Hot spots in relation to production are observed in frontal systems where mixed and stratified water masses meet, e.g. at the edge of the freshwater plume leaving Disko Bay. Other important hot spots are shallow areas, e.g. the fishing banks or islands where deep nutrient rich water upwells to the surface (*Møller & Nielsen 2000*).

These highly productive areas are very important for the production of the succeeding links in the pelagic food web, and often enhanced concentrations of fish, birds and mammals are also located here. In this report we will try to pinpoint the temporal and spatial productivity hot spots, since these areas will be particularly sensitive to an oil spill.

The upper 500 m of the ocean along the Greenland west coast are formed in the Arctic Ocean, in the Greenland Sea, Irminger Sea and the North Atlantic west of Cape Farewell (*Buch 1990*). The East Greenland Current (EGC) transports the water along the Greenland east coast to the southern part, Cape Farewell. The EGC changes then name to the West Greenland Current (WGC), and continues to flow north-westward along the Greenland west coast. The current mainly

follows the steep bottom slope westward of the Greenland west coast but complex topography, such as the fishing banks, deflects the current, and clockwise circulation around the banks is sometimes present (*Ribergaard 2004*). Along the path, ice melts from glaciers and sea ice which decreases the surface salinity. One fraction of the WGC deflects to the west at about  $64^{\circ}\text{N}$  (*Buch 1990*), towards the Canadian West Coast, making the WGC weaker. At about  $69^{\circ}\text{N}$  one branch of the WGC enters Disko Bay. CTD casts from the summer period shows that the deeper part of Disko Bay has similar T/S-characteristics as the water observed in Fylla Bank at depths of about 100-200 m, located upstream in the WGC (*Sloth 1983*). The intermediate water in Disko Bay is cold polar water, and the surface layer is polar water mixed with ice-melted water from glaciers and sea ice (*Buch 1990*).

Here we present historical observations and analyses of hydrography, nutrients, plankton, and shrimp and fish larvae from Disko Bay and the banks along the Greenland west coast, south of Disko. We also present some model results from a three dimensional hydrodynamic model. We focus on periods where we have the most extensive data sets; these are the years 1996, 1997, and the first ice free year observed in Disko Bay 2005. We also present results from a hydrodynamic model, describing hydrography and ocean currents in the region. Of special interest are highly productive areas and regions where possible oil spills may have the greatest impact. We combine model results and analyses of observations to identify upwelling and frontal zones. These regions are highly productive areas with large biological activity. Oil spill in these regions will have potentially large negative impact on the marine life.

## 2 Materials and methods

### 2.1 Disko Bay

The report summarises data on temporal and spatial patterns in the water column structure collected in the Disko Bay area during the last decade. Disko Bay is a 10,000 km<sup>2</sup> large bay on the western part of Greenland. It is located about 300 km north of the polar circle (69°15'N, 53°33'W). The Baffin Bay and the Banks of Disko border the bay. There are two entrances into Disko Bay. The southern entrance is about 60 km wide, and has a narrow channel that is about 500 m deep. Islands and shallow depths dominate, however, the topography at the entrance. The northern entrance, Vaigat, is a 100 km long channel with a sill depth of about 250 m.

The data are composed of time series data collected at a permanent station of Qeqertarsuaq and data collected over the entire bay during cruises with R/V Adolf Jensen, Greenland Institute of Natural Resources.

Ice conditions were determined through satellite observations, and the model results from a three dimensional hydrodynamic model were performed by the Danish Meteorological Institute (DMI).

### 2.2 The permanent station

Time series studies were conducted at the Arctic Station, which is located approximately 1 nautical mile off Qeqertarsuaq (69°15'N, 53°33'W) in Disko Bay, West Greenland. The depth at the Arctic Station is about 250 m.

#### 2.2.1 Annual study

The site was visited 52 times from April 1996 to June 1997. Sampling was conducted in regular intervals except in may 1996 where the boat was docked for three weeks. During the open water period, the station was visited with the research vessel Porsild (Arctic Station, Copenhagen University), while dog sledges were used during the ice covered season. When the bay was ice covered, sampling was conducted using a tripod trough a hole in the sea ice. Sampling was conducted around local noon. Vertical profiles of temperature, salinity and fluorescence were recorded from the surface to the bottom using a Seabird CTD. The *in situ* fluorometer was calibrated against spectrophotometrically measured chl-content in the water samples taken at the routine depths and a linear regression was conducted. The salinity probe was calibrated against a Guildline Portasal salinometer using samples from the monthly high resolution stations. The *in situ* fluorometer was calibrated against the spectrophotometrically determined chlorophyll concentrations in the water samples.

## 2.3 Cruises: Adolf Jensen

Three cruises were made during the summer period with Adolf Jensen (Greenland Institute of Natural Resources); see *Table 2.1*. Salinity, temperature and fluorescence were sampled on stations along transects from 65°N to 69°15'N on the Greenland west coast and in Disko Bay.

### 2.3.1 Nutrients

Samples for the determination of nutrient concentration ( $\text{NO}_2^-$ ,  $\text{NO}_3^-$ ,  $\text{PO}_4^{3-}$ ,  $\text{SiO}_4^{3-}$ ) were frozen on board the ship. Measurements were carried out at the National Environmental Research Institute (NERI) on an automatic nutrient analyzer (Dansk Havteknik) following *Grasshoff (1976)*. All nutrient samples were analysed in duplicate with a precision of 0.06, 0.09 and 0.12  $\mu\text{M}$  for nitrate, phosphorus and silicate, respectively.

### 2.3.2 Chlorophyll-a and phytoplankton

Samples (1-2 litres) intended for chlorophyll-a measurements were placed in the dark and within 3 hours after collection filtered at the land-based laboratory onto GF/F filters, extracted in 96% ethanol (*Jespersen & Christoffersen 1987*) and measured spectrophotometrically (*Strickland & Parsons 1972*).

### 2.3.3 Zooplankton

Mesozooplankton were collected at four depth intervals: 0-50, 50-100, 100-150 and 150-200 m using a plankton pump (900 l  $\text{min}^{-1}$ , mouth opening 25 cm) equipped with a 50  $\mu\text{m}$  mesh size net with a non-filtering cod-end or a modified WP-2 net (mesh size 50  $\mu\text{m}$ ). The pump was retrieved slowly through the water column to obtain depth-integrated samples. A flowmeter at the entrance measured the volume filtered. The samples were concentrated on a 45  $\mu\text{m}$  filter, preserved in 2-4% formalin, and stored for later enumeration and biomass estimation. The samples were split by a plankton splitter to obtain sample sizes of approximately 500 individuals, and all identifiable zooplankton were identified to either species or genus and developmental stage. Prosome lengths were measured on 10 individuals from each copepodite stage and total body length was measured on 25 to 50 nauplii. Carbon content was estimated from length-weight regressions (*from the literature*).

### 2.3.4 Fish and shrimp larvae abundance

For ichthyoplankton and larger zooplankton sampling we used a ring net with a diameter of 2 m, equipped with a black net of 16 m length and 1 mm mesh size. Oblique hauls were carried out to 10 m above sea bottom (maximal depth 90 m) at a ship's speed of 3 knots. The net was deployed and retrieved at speeds of  $\sim 20$  and 10  $\text{m min}^{-1}$ , respectively. A calibrated flowmeter in the opening of the net was used to estimate filtered volume of water. The fish larvae were immediately sorted from the sample and preserved in 96% ethanol. In the labora-

tory, the larvae were identified to species, and up to 50 individuals per species and station were length measured to standard length.

*Table 2.1* Table summarising the origin of the CTD data. See *Figure 2.1* for location of the stations.

Time period	Station no.	Type of data
1996-04-22 - 1997-06-19	Arctic Station	salinity, temperature, fluorescence
2005-02-22 - 2005-05-30	Arctic Station	salinity, temperature, fluorescence
1996-06-25 - 1996-06-28	1-14	salinity, temperature, fluorescence
1996-06-30 - 1996-07-02	15-29	salinity, temperature, fluorescence
1996-07-02 - 1996-07-03	30-39	salinity, temperature, fluorescence
1996-07-04 - 1996-07-05	40-52	salinity, temperature, fluorescence
1997-06-10 - 1997-06-11	5-10	salinity, temperature, fluorescence
1997-06-12 - 1997-06-13	13-18	salinity, temperature, fluorescence
1997-06-13 - 1997-06-14	22-31	salinity, temperature, fluorescence
1997-06-14 - 1997-06-16	32-40	salinity, temperature, fluorescence
1997-06-11 - 1997-06-16	11-36*	salinity, temperature, fluorescence
1998-08-20 - 1998-08-21	1-11	salinity, temperature, fluorescence

\* Not all stations between 11 and 36. Only stations 11, 12, 16, 20, 24, and 36 are used.

## 2.4 Ice conditions

The ice concentration in this study is monthly mean values from the period 1996-1998. The data are satellite observations from SSM/I and SSMR data, derived from the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) and the Defense Meteorological Satellite Program's (DMSP) DMSP-F8, -F11 and -F13. Special Sensor Microwave/Imager (SSM/I) has been generated using the Bootstrap Algorithm with revised sets of tie-points (*Comiso 2003*).

## 2.5 Model description

The hydrodynamic simulations were performed by the Danish Meteorological Institute (DMI), using the Hybrid Coordinate Ocean Model (HYCOM). The model is described in detail by *Bleck (2002)*. It is a primitive equation ocean general circulation model which solves the three-dimensional prognostic equations for horizontal velocity, salt and temperature. The vertical coordinate is generalized. In the hybrid configuration, the vertical coordinate is isopycnal in the open, stratified ocean, but smoothly reverts to a terrain-following coordinate in shallow coastal regions, and to z-level coordinates in the mixed layer and/or unstratified seas. The model includes a thermodynamic representation of sea ice, but lack sea ice dynamics (ice drift).

The present model set up is described in detail in *Ribergaard et al. (2006)*. The model domain is divided into two regions, one large scale region covering the entire Arctic Ocean and North Atlantic north of approximately 20°S. It has a horizontal resolution of approximate 50 km

and with 29 layers in the vertical. This coarser model is nested with a more high-resolution model, with a horizontal resolution of approximately 10 km, and with 26 layers in the vertical. The model domain for the smaller region covers the entire shelf around Greenland, most of the Canadian Archipelago, the Baffin Bay, the Labrador Sea, the Irminger Basin, Denmark Strait, and half the Iceland and Greenland Sea including the Fram Strait. The nesting procedure between the two model domains is a one-way. This means that the simulations are performed sequential and that output from the larger domain is used as boundary condition for the smaller domain, but there is no feedback of information from the smaller domain to the larger.

The model is initialized with high resolution ( $1/4^\circ$ ) climatological temperature and salinity fields by *Boyer et al. (2005)*. These fields are also used for the relaxation procedure of the model surface temperature and salinity. The atmospheric forcing fields are taken from the DMI numerical weather prediction model DMI-HIRLAM-T (*Yang et al. 2005*) covering a large part of the northern hemisphere with a 0.15 degree resolution.

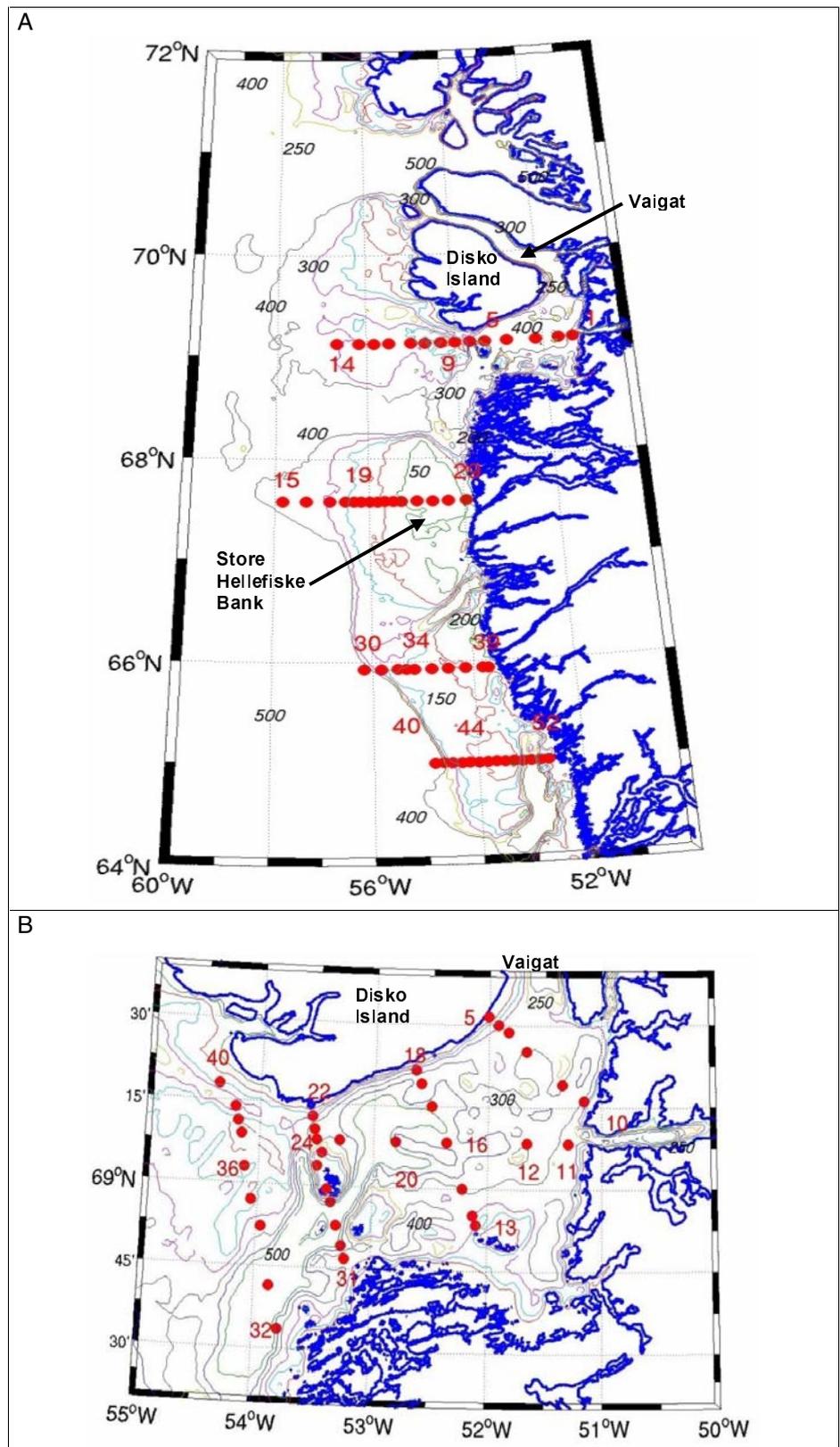


Figure 2.1 A) Overview of the Greenland west coast and station map for transects performed in June 1996. B) Bathymetry in Disko Bay and station map for transects performed in June 1997. The Arctic Station is located close to station 22, just south of Disko Bay.

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### 3 Monthly mean ice conditions from 1996 to 1998 and 2005

The duration and extension of the ice cover in Disko Bay showed large interannual variability. Since ice reflects more than 50% of incoming solar radiation, it has a large impact on the pelagic primary production. When other factors favour plankton bloom, e.g. shallow mixed layer depth, net primary production in the water column starts when the ice disappears. Here we present ice concentrations based on SSM/I and SSMR satellite data during 1996, 1997 and 1998, with a special focus on the spring (*Comiso 2003*).

In April 1996, Disko Bay was fully ice covered, and the ice concentration just outside the bay was about 80-90% (*Figure 3.1A*). The ice break up in Disko Bay started in May, with an ice concentration of about 80-90% (*Figure 3.1B*). In June the southern entrance to Disko Bay was ice free, and the ice concentration in the inner parts of the bay was typically 30%, and in the Vaigat 70%. During fall and early winter the ice concentration changed back and forth with periods of ice growth and periods of ice melt. Ice concentration was generally higher in the inner parts of the bay than at the entrance and in the central parts of Disko Bay. The minimum ice concentration for this particular winter season occurred in January 1997. The ice concentration in Disko Bay was then typically 20%, and 60-70% in the Vaigat. The ice growth season started in February, and the ice concentration quickly reached 80-90%, and remained at high values during March and April (*Figure 3.1C*).

Ice melt in May reduced the ice cover down to about 30-40% in Disko Bay, but was as high as 80-90% in the Vaigat (*Figure 3.1D*). Along the Greenland east coast south of Disko Bay, the ice concentration was less than 10% in May. In June and July the southern entrance to Disko Bay was ice free, the inner parts had an ice concentration of about 30%, and in Vaigat the concentration was about 70-80%. Some ice remained in the bay throughout the summer, mostly along the inner part and in the Vaigat. The minimum ice concentration for the winter season 1997/1998 occurred in November.

In 1998 there was much less ice in the area than in 1996-1997. In April the ice concentration in Disko Bay and south of the Bay was typically 50% (*Figure 3.1E*). In May the southern entrance was ice free, and the concentration of ice in the inner parts of Disko Bay was 30-40% (*Figure 3.1F*). In June the concentration was 20-30% in the bay, and in July the bay was ice free. The first year with no ice observed in Disko Bay was 2005 (O.M. Tervo, personal observations).

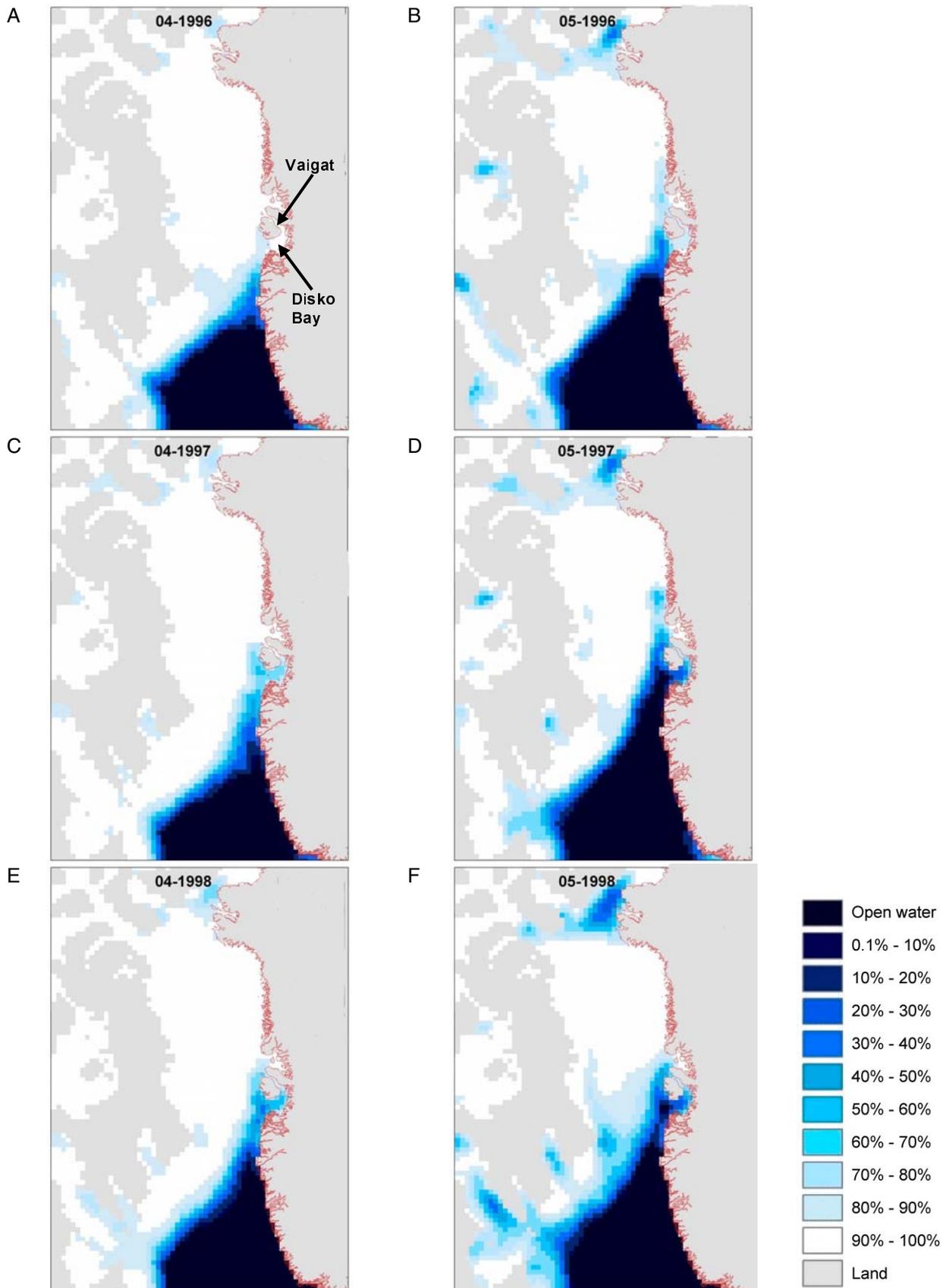


Figure 3.1 Maps showing ice concentration from SSM/I and SSMR data (Comiso 2003) during A) April 1996, B) May 1996, C) April 1997, D) May 1997, E) April 1998 and F) May 1998. The data are derived from the Nimbus-7 Scanning Multichannel Microwave Radiometer (SSMR) and the Defense Meteorological Satellite Program's (DMSP) DMSP-F8, -F11 and -F13, Special Sensor Microwave/Imager (SSM/I) has been generated using the Bootstrap Algorithm with revised sets of tie-points.

## 4 Observations of hydrography, chlorophyll, plankton and larvae in the Disko Bay region

In this chapter we present time and horizontal variability of hydrography, chlorophyll, plankton and larvae in the Disko Bay region. Observed time variability of hydrography and chlorophyll during the periods April 1996 to June 1997 and spring 2005 are from the permanent station 1 nautical mile south of Qeqertarsuaq, Arctic Station. The analyses of the horizontal variability in temperature and fluorescence are based on measurements concluded in Disko Bay and the Greenland west coast south of Disko Bay during June 1996, June 1997 and August 1998.

In this study we used the water mass definitions from *Buch (1990)*, but broadening the salinity interval for polar water mass according to *Rudels et al. (1999)*. The polar water mass originates from the upper layers of the Arctic Ocean, and has salinity (S) below 34.5 (*Figure 4.1*). Atlantic water that has a salinity interval of:  $34.5 < S < 34.85$  and temperature (T) around 4.5° C. In the Irminger Sea between Iceland and Greenland, Irminger water is formed, and has the following properties:  $34.95 < S < 35.1$ ;  $4^{\circ} \text{ C} < T < 6^{\circ} \text{ C}$ .

The observed T-S characteristics in June 1996 along the Greenland west coast showed that in the upper 150 m there was polar water mass and that there was a gradual cooling and decrease in the salinity of the water in the northern direction (*Figure 4.1B*). Warm Atlantic water was observed in the deeper parts of the zonal transects along 65°N and 66°N (see *Figure 2.1A* for location). The minimum temperature at these two transects was about 1° C. In the two northern transects, the minimum temperature was close to the freezing temperature, and the salinity was below the lower limit for Atlantic water, that is 34.5. The T-S properties observed from April 1996 to June 1997 in Disko Bay at Arctic Station, 69°15'N, 53°33'W, and in the transects sampled in Disko Bay early summer in 1997 (see *Figure 2.1A* for location) showed that there was only polar water mass in Disko Bay (*Figure 4.1*). Ice melt from glaciers and sea ice in Disko Bay decreased the surface salinity below the lower limit of salinity for polar water (*Figure 4.1A*).

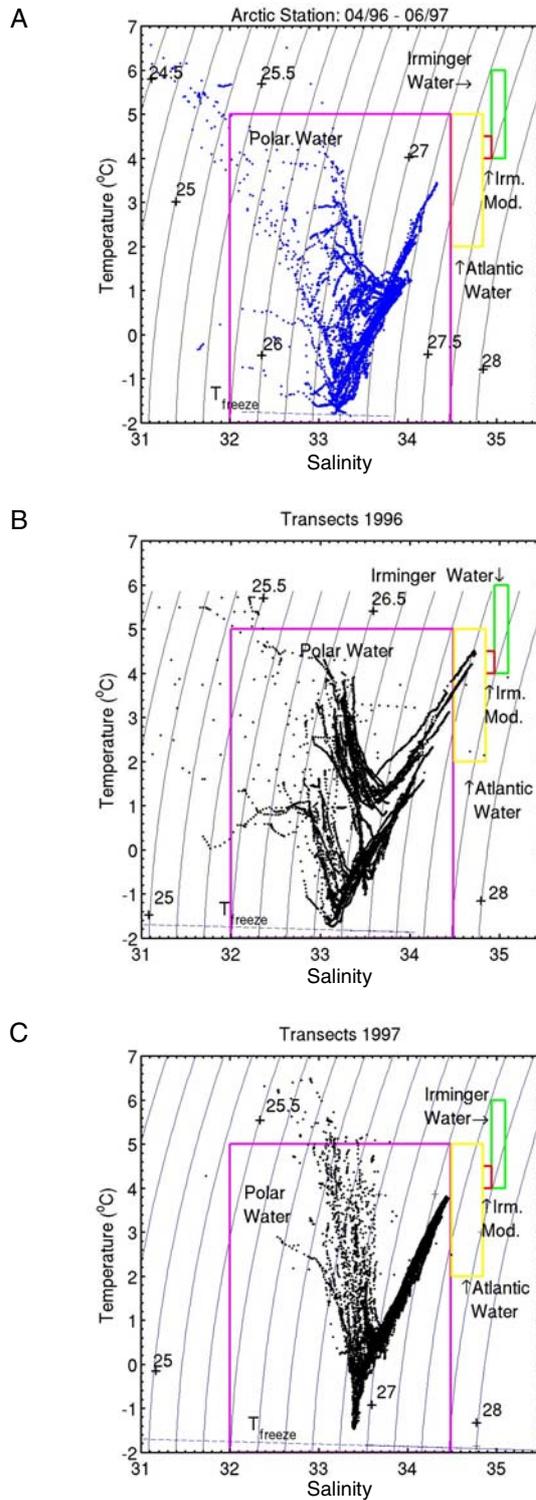


Figure 4.1 CTD casts obtained during cruises with R/V Adolf Jensen showing TS-scatter plots at **A**) Arctic Station 22 April 1996 – 19 June 1997, **B**) during transects in Disko Bay and along the Greenland west coast, 65°N – 69°15'N in June 1996, and **C**) during transects in Disko Bay in June 1997. The squares show the different water masses present along the Greenland east coast (see chapter 4 for definition of the water masses).

## 4.1 Annual cycle of temperature, salinity, and density

Observations at the 250 m deep station located 1 nautical mile south of Qeqertarsuaq (the Arctic Station) showed that the surface mixed layer was 50 m deep at the end of April 1996. The mixed layer temperature was close to freezing point (*Figure 4.2A*) and the mixed layer salinity was about 33.4 (*Figure 4.2B*). In May runoff from melting glaciers decreased the sea surface salinity down to about 32, and the mixed layer thickness to about 10 m. Intensified solar radiation in summer together with a thinner mixed layer increased the temperature and consequently also the ice melt rate. At the end of August the sea surface temperature was about 7° C and the sea surface salinity had decreased down to about 30.5. Wind mixing increased the depth of the mixed layer from 10 m in June to 25 m in late August. In late summer, the stronger stratification inhibited vertical mixing of warm surface water with water from deeper layers. During September advection from regions outside the bay increased the surface salinity from 30.5 to above 33. Convection could not have generated the increase in surface salinity. Vertical mixing would then decrease the salinity below the surface layer, which was not the case. Weak stratification in salinity together with continued cooling during fall strengthened the convection deeper down in the water column. In January the succeeding year, the mixed layer thickness had increased to 200 m and the temperature had reached the freezing point. Freezing temperature at the surface in January indicates the start of the ice growth season. In *chapter 3* it was shown that the ice growth season was between January and April. During this period, the sea surface salinity was rather constant, meaning that brine rejection and advection had insignificant effect on the surface salinity during the ice growth season. From February 1997 to May 1997 warm and saline water was advected from the sea, increasing the temperature and salinity in the deeper layers (below 100 m depth) (*Figure 4.2*). The stratification in spring was generated by a larger increase in salinity at the deeper layers than at the surface (see also *section 4.2*). Compared to 1996, the warming period, as determined from temperature and salinity, started about one week earlier in 1997, and two weeks earlier in 2005 (data not shown). Ice concentration in spring thus had to some extent an effect on the warming period. The monthly mean of observed ice concentration in Disko Bay in April 1996 was almost 100% in 1996, 70% in April 1997 and in 2005 Disko Bay was ice free the whole season (*chapter 3*). In May observed ice concentrations were 70-80% in 1996 and about 40% in 1997 (see *chapter 3*).

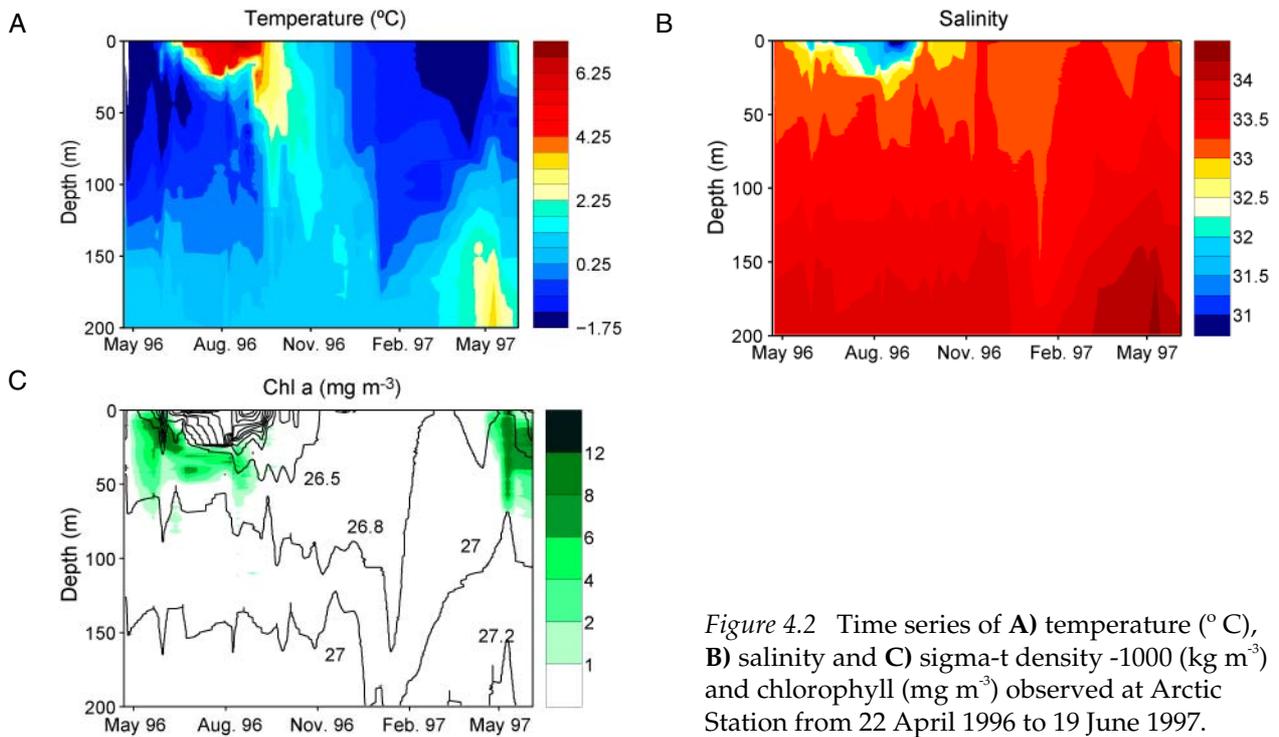


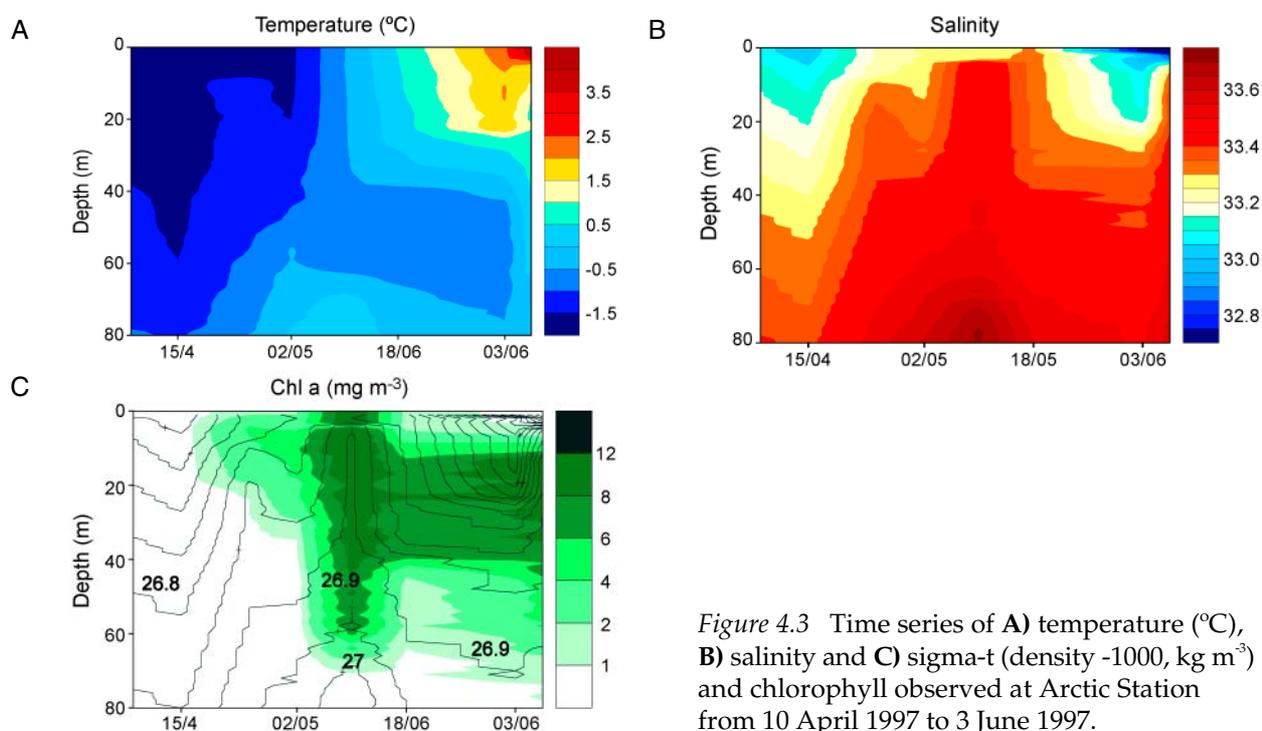
Figure 4.2 Time series of **A)** temperature ( $^{\circ}\text{C}$ ), **B)** salinity and **C)** sigma-t density  $-1000$  ( $\text{kg m}^{-3}$ ) and chlorophyll ( $\text{mg m}^{-3}$ ) observed at Arctic Station from 22 April 1996 to 19 June 1997.

## 4.2 The spring phytoplankton bloom

The initiation of the pelagic productive season is very much dependent on a shallow mixed layer combined with sufficient solar radiation. Under these circumstances, plankton is able to use sunlight for net growth and a bloom can develop. Presence of sea ice delays the initiation of the primary production. In 1996 the plankton bloom started sometime between 25th April and 21st May (*Figure 4.2C*). The temporal resolution in the observations was too coarse to resolve the bloom in details this year. Consequently, we focus on the spring blooms in 1997 and 2005, where the sampling frequency was higher.

The spring bloom in 1997 started in the upper 20 m somewhere between 15th and 25th April, with a maximal chlorophyll concentration of  $2\text{--}4 \text{ mg m}^{-3}$  at about 10 m (*Figure 4.3C*). The density difference between the surface and 20 m was only  $0.13 \text{ kg m}^{-3}$  (*Figure 4.3C*). The bloom was triggered by a stronger stratification in the upper 50 m. Since the increase in sigma-t ( $\text{kg m}^{-3}$ ) with depth during spring is rather linear (*Figure 4.3C*), it is difficult to identify a mixed layer depth. Here we instead used the rate of change in sigma-t with depth as a measure of the strength in stratification. The observations showed that the vertical distance between the isopycnals (lines for constant density) decreased during spring, thus a stronger stratification. On 15th April, before the plankton bloom, the vertical distance between the  $26.7 \text{ kg m}^{-3}$  and  $26.8 \text{ kg m}^{-3}$  isopycnal was 25 m. The bloom started about five days later. At the end of April the distance between these two isopycnals had decreased to 15 m, and at the peak of the plankton bloom (10th May) the sigma-t increased  $0.15 \text{ kg m}^{-3}$  in the upper 10 m (*Figure 4.3C*).

Since the changes in salinity and temperature at greater depths occur at an earlier time than at the surface (*Figure 4.3A & B*), we suggest that the increased stratification discussed above was primarily generated by upwelling or advection of water; not by changes at the surface due to heating or freshwater outflow. During the second half of May, melt water outflow from glaciers reduced the sea surface salinity with about 0.3 and the upper 5 m became highly stratified. The heat was trapped in the shallow mixed layer and the temperature increased rapidly from  $-0.5^{\circ}\text{C}$  to  $1.5^{\circ}\text{C}$  (*Figure 4.3A*). The concentration of nutrients (not shown) and chlorophyll (*Figure 4.3C*) decreased rapidly. The decrease in plankton concentration may be due to rapid consumption of nutrients in the shallow surface layer or due to freshwater outflow from glaciers that contains extremely low concentrations of nutrients. The highest phytoplankton biomass observed in late May and early June was found from 20 to 60 m depth (*Figure 4.3C*).



*Figure 4.3* Time series of **A**) temperature ( $^{\circ}\text{C}$ ), **B**) salinity and **C**) sigma-t (density -1000,  $\text{kg m}^{-3}$ ) and chlorophyll observed at Arctic Station from 10 April 1997 to 3 June 1997.

In early April 2005, the temperature in the upper 80 m was close to freezing point (*Figure 4.4A*), and the salinity increased by about 0.1 from the surface to 80 m (*Figure 4.4B*). The plankton bloom started around 20th of April (*Fig. 4.4C*). At this point the increase in salinity below the surface layer had generated a stratification (*Figure 4.4B*) that made it possible for plankton to stay in the upper layers. Note that only a density difference between the surface and 50 m of about  $0.1 \text{ kg m}^{-3}$  was needed to trigger the bloom (*Figure 4.4C*). A rather constant surface salinity together with continued increase in salinity below the surface layer in the beginning of May boosted the plankton bloom (*Figure 4.4C*). Freshwater outflow in the middle of May decreased the mixed layer salinity and mixed layer depth down to 33.1 and five meters, respectively (*Figure 4.4B*). The nutrients rapidly con-

sumed by plankton in the surface layer (not shown) and the bloom descended below the surface layer below 10 m. As for the case in 1997, the decrease in surface chlorophyll in late May was due to decreased concentration of nutrients, generated by increased consumption or outflow of nutrient poor glacial melt water to the surface layer. At the end of May, the chlorophyll concentration was rather low in the depth interval 10-40 m (about  $2 \text{ mg m}^{-3}$ ), while it was above  $6 \text{ mg m}^{-3}$  below 40 m. Lack of salinity and temperature data for this date complicate interpretation of the mechanism for changed vertical distribution of plankton. Extrapolation of the isolines for constant density (isopycnals) suggests that downwelling of surface water decreased the plankton concentration in the upper 40 m.

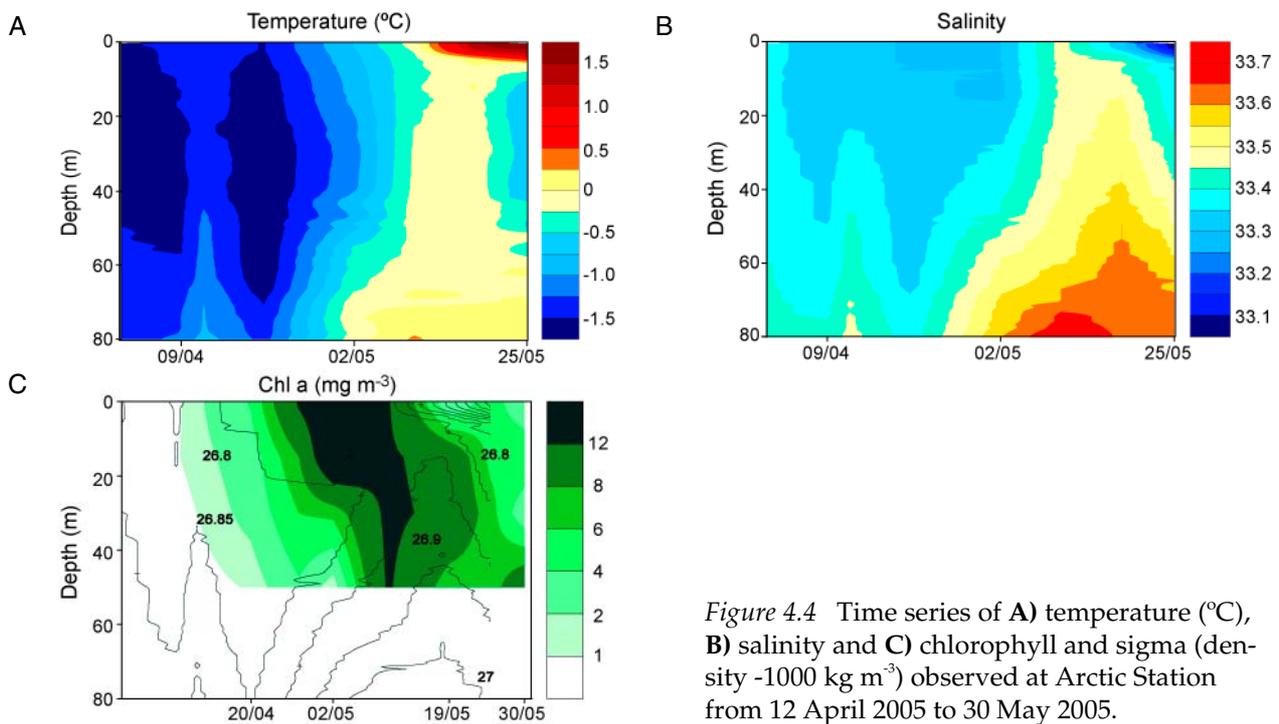


Figure 4.4 Time series of A) temperature (°C), B) salinity and C) chlorophyll and sigma (density -1000 kg m<sup>-3</sup>) observed at Arctic Station from 12 April 2005 to 30 May 2005.

### 4.3 Transects of hydrography in Disko Bay and along the Greenland west coast, south of Disko Bay

Large-scale current patterns tend to follow the bathymetry along the Greenland west coast (*Ribergaard et al. 2004*). In this region, including Disko Bay, the topography is complex and there are several shallow banks that deflect the coastal currents and generate instabilities in the current field. Store Hellefiske Bank, located just south of the entrance to Disko Bay (*Figure 2.1A*), has thus a large impact on the current pattern at the southern entrance of the bay. The inflow at the southern entrance of Disko Bay is also to a large extent affected by the topography of the entrance area, with shallow regions and islands. Here we present CTD casts performed in Disko Bay region during June 1996,

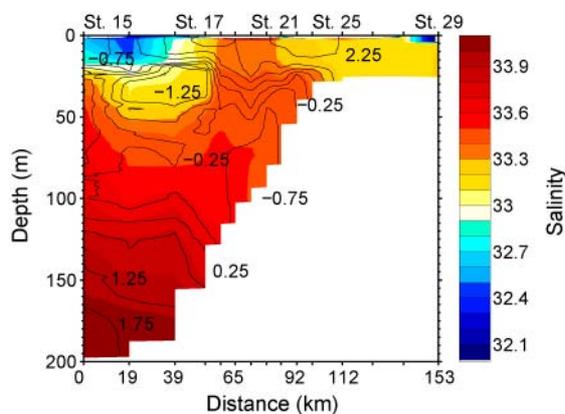
June 1997 (*Figure 2.1*), and briefly discuss the observations made in August 1998. Analyses of the CTD casts give information of the horizontal distribution of salinity, temperature, and fluorescence after the spring bloom. The analyses may also give some ideas of possible internal wave activity and the baroclinic currents, which are currents generated by horizontal density differences and earth rotation. In steady state, the current is directed perpendicular, and to the right of the pressure gradient. For example, less dense water concentrated along the Greenland west coast generates a northward flowing coastal current. The analyses of the currents in sections 4.3.1 - 4.3.2 are based on the measurements at that particular time and may be more or less persistent.

#### 4.3.1 June 1996

The West Greenland Current (WGC) originates from the Arctic Ocean and flows southward through the Fram Strait and along the Greenland east coast, turning northward again to the Greenland west coast. The WGC is located further offshore than the transect along 66°N (*Figure 2.1*), and at the transect along 65°N only the westernmost station (station no. 40) gives some information about the WGC (not shown). The distribution of salinity and temperature are therefore only briefly discussed below. The density variation in the transects was mainly determined by the distribution of the salinity and thus to a lesser extent by temperature. There was a 40 km wide low saline, warm core along the coast suggesting a northward surface current. Both transects (along 65°N and 66°N) crossed a shallow bank. West of the banks, at 50-140 m depth, there were cold cores along the bottom slope. From 50 to 150 m the salinity and density increased from the bottom slope towards the west, suggesting a southward baroclinic current. The transect along 65°N had deeper layers, where salinity below 150 m was above 34.5, and the isopycnals were sloping upwards towards the bank. This suggests that there was a northward flowing current of Atlantic water. This water was about 2° C warmer than the layers above. Fluorescence was also measured along the transects south of 68°N, but the concentration was very low and therefore not discussed.

The transect along 67°30'N (*Figure 2.1*) is located just south of Disko Bay and crosses Store Hellefiske Bank. Along this transect, Store Hellefiske Bank is located about 50-100 km from the coast. The WGC is located at about 100 km to 150 km away from the coast, trapped along the steep bottom slope westward of Store Hellefiske Bank (*Figure 4.5*). The upper 25 m of the WGC had been diluted with freshwater from melting glaciers and sea ice. The solar heating during spring was trapped within this shallow layer, resulting in a relatively warm low saline layer with a temperature close to 0.5° C and a salinity of about 32.2-33.2. At greater depths, there was polar water present originating from the Arctic Ocean that had been in contact with the sea surface during the previous winter, which explains the cold and more saline water. Below 100 m the salinity and temperature increased with depth, but not high enough to be characterized as Atlantic water. Between the transects along 67°30' N and 69°N, the WGC splits into three branches. One part continued northward, a second branch entered Disko Bay and the third continued to follow the bottom

slope clockwise around Store Hellefiske Bank (*Figure 4.5*). The southward current close to the coast east of Store Hellefiske Bank was about 40 km wide and had a somewhat higher salinity than the northward flowing surface current on the western side of the bank. The temperature in the well-mixed coastal current was about 2.5° C. Lack of stratification suggests large tidal mixing.



*Figure 4.5* Zonal transect along 67°30'N starting at the Greenland east coast (station 29). Black lines show temperature (°C), and the colour map shows salinity in June 1996. See *Figure 2.1A* for location of transect. The lower x-axis show the distance from the westernmost station (station 15) and the upper x-axis show station number.

At station 7 in the northernmost transect in June 1996 shown in *Figure 2.1* at about 69°N, there was a sharp front in temperature and salinity (*Figure 4.6*). The sea surface temperature and sea surface salinity in Disko Bay was about 5° C and below 32, respectively. Outside the bay the sea surface temperature and salinity are typically 2° C and 33, respectively. Transects performed in June 1997 and August 1998 showed that water in this region flowed out of Disko Bay along the southern coast of Disko Island (see below). Below the warm surface layer, there is a 100 m thick cold layer (about -1° C). This water was in contact with the surface during the previous winter season, and decoupled from the surface when solar heating increased the surface temperature and decreased the surface salinity. During the plankton bloom in spring, the nutrients were consumed in the surface layer, but at greater depths concentration of nutrients remained constant from winter to late summer (see *chapter 4.1*). The nutrients in the cold winter layer might have been available for primary production during summer in regions where there was strong upward mixing. In semi-closed basins, such as Disko Bay, the stratification below the surface layer is very much effected by the stratification outside the bay. The transect along 69°N showed east-west variations in salinity in and outside Disko Bay (*Figure 4.6*). The isohalines in the east west direction had amplitude of about 20 m, suggesting internal wave activity in the area. The vertical variations of the isohalines might have generated large water exchange below the surface layer. For example, the dominating mechanism for water exchange in the semi-closed basin Gullmarsfjord, located on the Swedish west coast, is vertical variations of isopycnals at the entrance of the fjord (*Arneborg 2004*). When the depth of the halocline in Gullmarsfjord changes, for example from 60 m to 40 m, it forces an outflow of a volume corresponding to the

mean area around 50 m depth, times the depth interval of the vertical variation of the halocline, here 20 m. This volume is in the Gullmarsfjord far much greater than the water exchange generated by winds and sea level variations. Vertical variation of isopycnals at the entrance of a semi-closed basin, such as Disko Bay, may be generated by upstream variations of the stratification of the coastal current or tidal currents that disturbs the stratification at the sill. Time variability of the salinity observed at the Arctic Station showed that isohalines varied with typically 20 m within a period of about one month (Figure 4.2). There might also have been baroclinic motions at higher frequencies (e.g. tidal frequencies) than the observed sampling frequency (1 week).

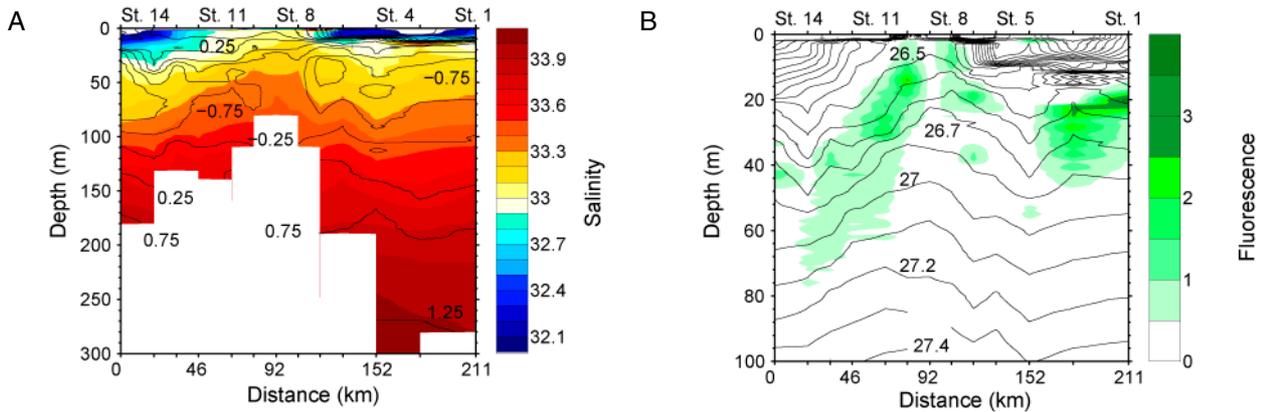


Figure 4.6 **A)** Zonal transect along  $69^{\circ}15'N$  starting inside Disko Bay (station 1). Black lines show temperature ( $^{\circ}C$ ), and colour map shows salinity in June 1996. See Figure 2.1A for location of transect. The lower x-axis shows the distance from the westernmost station and the upper x-axis show station numbers. **B)** Fluorescence along the transect (colour map) and sigma (black lines).

### 4.3.2 June 1997

Here we present results from four transects (Figure 2.1B): 1) zonal transect where the end stations are station 37 and station 11, 2) transect parallel to the southern entrance outside the bay (stations 32-40), 3) transect at the southern entrance (stations 22-31) and 4) transect in the eastern part of Disko Bay (stations 5-10). The transect consisting of the stations 13 to 18 is only discussed briefly below.

In the zonal transect from outside the bay, station 37, to the eastern part of the bay, station 11 (Figure 2.1B), CTD casts showed that there were internal waves below 75 m depth (Figure 4.7). The tidal currents generated large mixing along the bottom, and in turn weaker stratification at the shallow stations, station numbers 23 and 37. As observed in June 1996, there was a cold layer below the warm surface layer. The thickness of the cold winter water was about 50-75 m at the entrance and in the eastern part of the transect. In the central part the thickness of the cold winter layer was 100 m, thus a similar pattern as observed in 1996. As for 1996, the maximum fluorescence along the zonal transect in 1997 was observed at the entrance and close to the east coast of the bay (Figure 4.7C). Internal wave activity and large tidal mixing in these regions might have transported nutrients up to layers where there was sufficient sunlight to generate primary production.

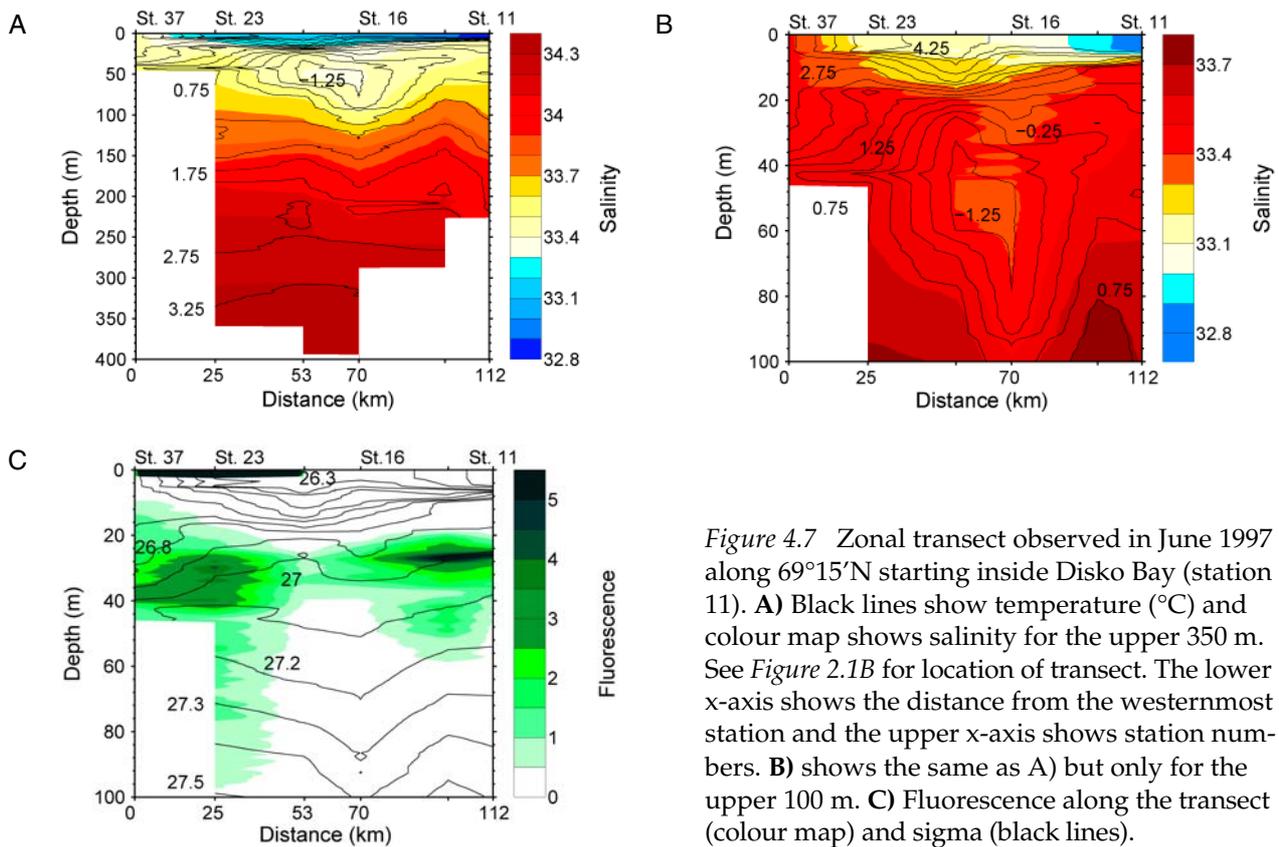


Figure 4.7 Zonal transect observed in June 1997 along 69°15'N starting inside Disko Bay (station 11). **A)** Black lines show temperature ( $^{\circ}$ C) and colour map shows salinity for the upper 350 m. See Figure 2.1B for location of transect. The lower x-axis shows the distance from the westernmost station and the upper x-axis shows station numbers. **B)** shows the same as A) but only for the upper 100 m. **C)** Fluorescence along the transect (colour map) and sigma (black lines).

The salinity along the transect located outside Disko Bay (stations 32-40) was below 34.4. This means that there was polar water along the entire transect. Between two warm cores of about  $5^{\circ}$  C in the upper 10 m (Figure 4.8B), the temperature was lower and the salinity higher (Figure 4.8B), and thus more dense (Figure 4.8C). High values of fluorescence were also observed in this shallow part of the transect (Figure 4.8C). The dense water and large plankton concentration may be explained by vertical upward mixing of subsurface nutrient rich waters to layers with sufficient light for plankton growth. The minimum temperature along the transect ( $0.25^{\circ}$  C) was found in the southern part at a depth of 30-50 m (Figure 4.8B). The temperature and salinity increased up to about  $3^{\circ}$  C and 34.4 at a depth of 400 m. Between the stations 32 and 34, the isohalines and isotherms below 50 m were sloping upward towards north (Figure 4.8A), suggesting a baroclinic outflow of warm and saline water from Disko Bay.

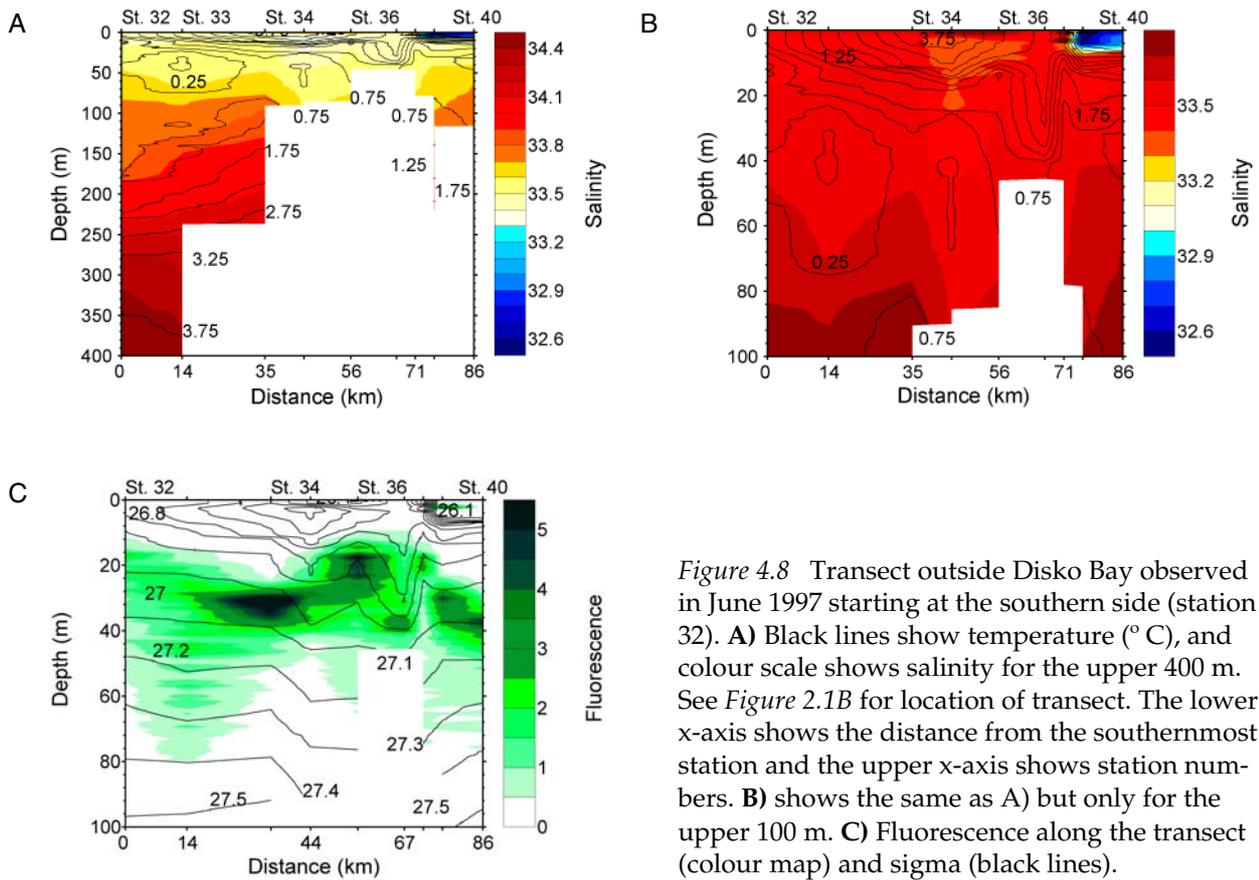


Figure 4.8 Transect outside Disko Bay observed in June 1997 starting at the southern side (station 32). **A)** Black lines show temperature ( $^{\circ}$  C), and colour scale shows salinity for the upper 400 m. See Figure 2.1B for location of transect. The lower x-axis shows the distance from the southernmost station and the upper x-axis shows station numbers. **B)** shows the same as A) but only for the upper 100 m. **C)** Fluorescence along the transect (colour map) and sigma (black lines).

At the northern boundary of the transect located at the southern entrance of Disko Bay (stations 22-31), there was a warm low saline core at the surface (Figure 4.9B). The core of less dense water was part of the coastal current that transported the surface water in Disko Bay out of the region along the southern and western coast of Disko Island (close to station 22). For the upper 80 m the isopycnals were sloping upward towards the southern part of the transect (Figure 4.9C), suggesting that there was a baroclinic outflow in the upper 80 m in the transect. Below 100 m the temperature and salinity increased towards the bottom to about  $3.75^{\circ}$  C and 34.4, respectively. The low salinity values showed that there was polar water along the transect at the southern entrance of the bay, see also Figure 4.3C. The fluorescence values were large from 10 to 40 m depths along the entire transect (Figure 4.9C). Large mixing along the steep bottom slopes and around the islands might have transported nutrient-rich water from below and fuelled the plankton production.

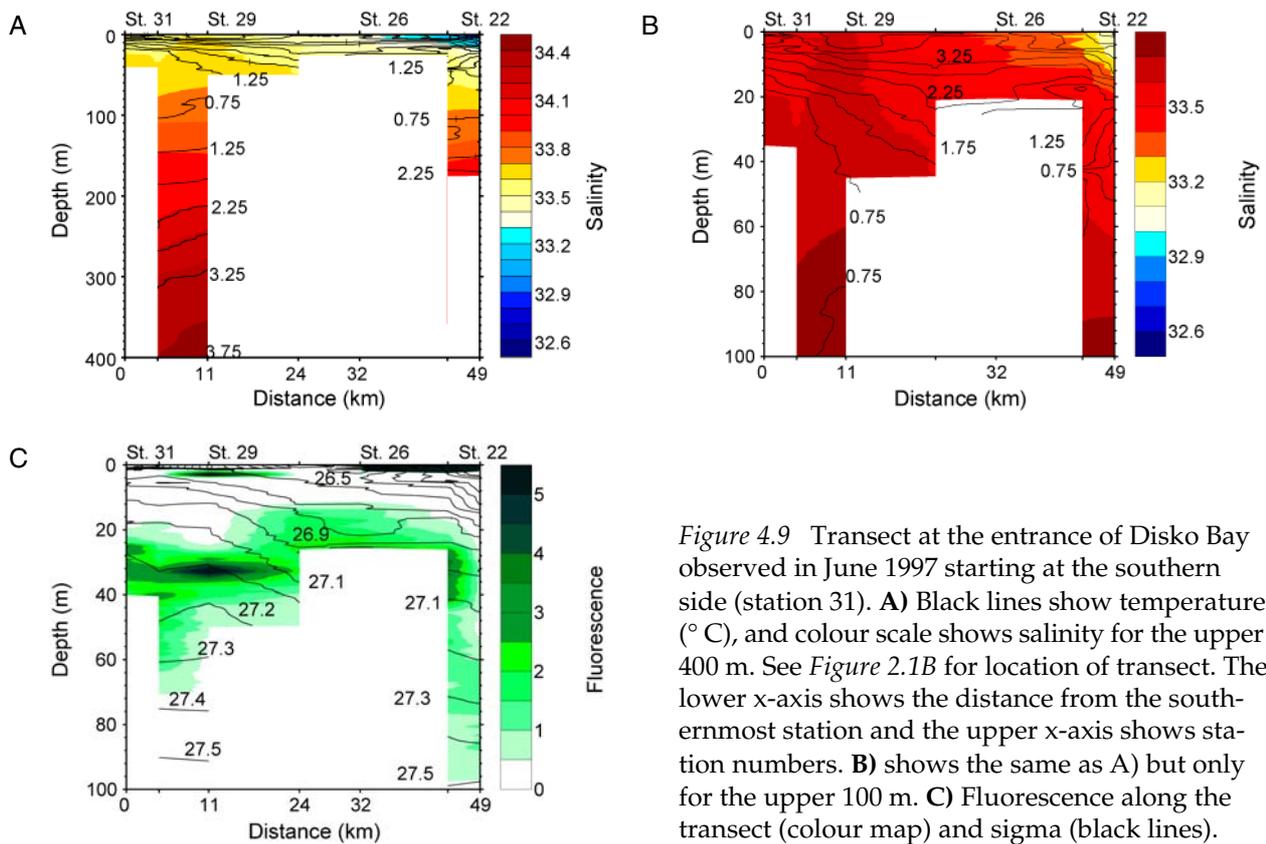


Figure 4.9 Transect at the entrance of Disko Bay observed in June 1997 starting at the southern side (station 31). **A)** Black lines show temperature ( $^{\circ}$  C), and colour scale shows salinity for the upper 400 m. See Figure 2.1B for location of transect. The lower x-axis shows the distance from the southernmost station and the upper x-axis shows station numbers. **B)** shows the same as A) but only for the upper 100 m. **C)** Fluorescence along the transect (colour map) and sigma (black lines).

In the easternmost transect (stations 5-10) the sea surface temperature was about  $4^{\circ}$  C (Figure 4.10A), thus about the same as observed at the other transects in June 1997. The sea surface salinity is typically 32.6. The temperature and salinity increase with depth. Below 300 m close to the mainland, the salinity was about 34.2 and the temperature  $2.75^{\circ}$  C, corresponding to polar water in Disko Bay. The isotherms and isohalines in the upper 50 m were sloping downward from the south side to the northern part (Figure 4.10B), i.e. towards Disko Island (Figure 2.1B). The less dense water concentrated to the coast of Disko Island suggests a surface current directed to the south-west. At intermediate depths (150-250 m) the isolines for constant temperature and salinity were rather horizontal, thus weak baroclinic currents. At station 9, however, the isolines were somewhat shallower than at the other stations, which may indicate a northward flow along the coast of Disko Island, and currents directed to the south-west closer to the mainland (Figure 4.10A).

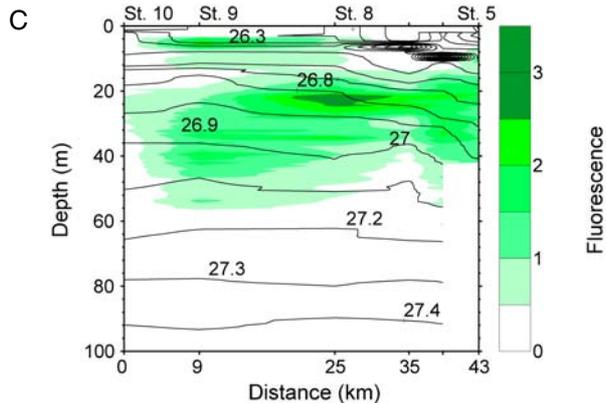
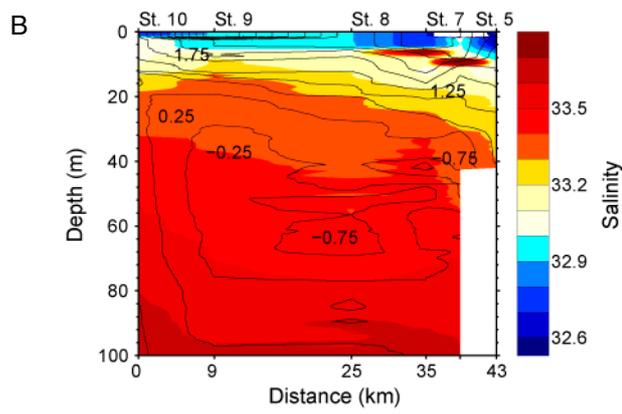
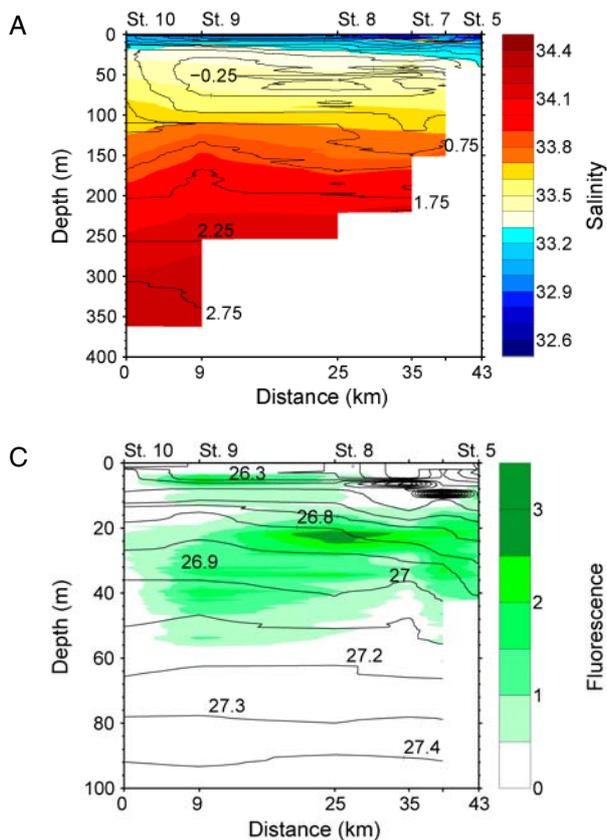


Figure 4.10 The easternmost transect at the entrance of Disko Bay observed in June 1997 starting at the southern side (station 10) to the Disko Island coastline (station 5). **A)** Black lines show temperature ( $^{\circ}\text{C}$ ), and colour scale shows salinity for the upper 400 m. See Figure 2.1B for location of transect. The lower x-axis shows the distance from the southernmost station and the upper x-axis shows station numbers. **B)** shows the same as A) but only for the upper 100 m. **C)** Fluorescence along the transect (colour map) and sigma (black lines).

Along the transect covering the stations 13 to 18, the isotherms and isohalines followed a similar pattern as in the easternmost transect (not shown). Some differences in the upper 100 m were present though, such as parallel isolines in the upper 25 m, suggesting no baroclinic currents in the surface layer at the time when the measurements were performed. In the central part of the transect at about 25-100 m, there was a cold and less saline core, similar to the zonal transect discussed above (stations 11-37). The similar patterns in the hydrography in the zonal transect (stations 11-37) and near meridional transect (stations 13-18) showed that there was a cold and low saline core in the central part of the bay, and warmer and more saline water towards the coast. The domelike structure in the central part of the bay also suggests that there was a clockwise circulation along the coast consisting of warm and salty water, and cold less saline water that was more stagnant in the central part of the bay. Inflow from the WGC fed the circulation in the bay with warm and salty water. The minimum temperature observed at the southern entrance of the bay was  $0.25^{\circ}\text{C}$  (Figure 4.9B).

Transects in August 1998 also exhibited similar domelike patterns in hydrography (not shown). However, the temperature at the coast and in the central parts was about  $1^{\circ}\text{C}$  higher than in June 1997 and June 1996. The warmer water along the coast might also be an indication of upwelling or vertical mixing. The transects in August 1998 were located perpendicular to the south and southwest coast of Disko Island. The hydrography from these transects showed that the surface mixed layer was 20 m, thus 10 m thicker than in June 1996 and June

1997. The sea surface temperature and salinity in the bay were about 6° C and 32, respectively. The transect at the southern entrance of the bay followed a similar structure as in June 1997, with weak stratification in the upper 50 m in the shallow parts and close to the islands, and downward sloping isohalines from the central part of the transect towards the southern side. The warmer and less saline water in the surface layer made the pycnocline stronger than in June the two previous years. The stronger pycnocline in late summer made it more difficult to mix nutrient-rich water from below and to generate primary production.

#### **4.4 The fate of the primary production, i.e. coupling to the higher trophic levels**

The fishing banks along south western Greenland and the Disko Bay area are important spawning, nursery and fishing ground, especially for the northern shrimp (*Pandalus borealis*) and Greenland halibut (*Reinhardtius hippoglossoides*) (Buch *et al.* 2004, Simonsen *et al.* 2006). Through their early life, the larvae are spread by the currents from the spawning grounds. During their early life they are dependent of the plankton food until they settle to the bottom and feed on benthic invertebrates. In this chapter we summarize the knowledge about the pelagic food web with emphasis on the key processes responsible for the temporal and spatial distribution of shrimp and fish larvae.

##### **4.4.1 Disko Bay**

The development of the spring bloom is the single most important event determining the production capacity of the arctic marine food webs. The onset of the bloom varies between years depending on duration of ice cover, hydrography and meteorological conditions as documented above (see 4.2). But when the water column is stabilized, the spring diatom bloom develops exponentially and quickly depletes the surface layer for nutrients after which it settles out of the euphotic zone (Figures 4.2, 4.3. 4.4).

Disko Bay off Qeqertarsuaq is the only locality along western Greenland where the annual dynamics of the plankton community have been investigated at high temporal resolution. During 1996 to 1997 a very intense sampling programme (Figure 4.11) was conducted from the Arctic Station (Levinsen *et al.* 2000, Madsen *et al.* 2001). The knowledge gained from this station will in the following be used as background for the evaluation of implications of oil spills in areas where the sampling effort is less intensive.

Copepods of the genus *Calanus* are key players in high latitude marine ecosystems. They dominate the mesozooplankton communities, are significant grazers on the primary production (Nielsen & Hansen 1995 and Levinsen & Nielsen 2002) and constitute an important prey item for numerous fish, birds and whale populations. At the same time *Calanus* have a key role in the supply of high quality food to the benthic communities by acceleration of the vertical flux through production of large fast sinking faecal pellets (Pedersen *et al.* 2006). In Greenland waters three species of *Calanus* totally dominate the meso-

zooplankton community during spring and early summer (Møller *et al.* 2006, Madsen *et al.* 2001). *Calanus hyperboreus* and *Calanus glacialis* are true arctic species inhabiting polar waters, while *Calanus finmarchicus* is a temperate species associated with Atlantic waters (Hirche *et al.* 1991, Conover 1988). In Disko Bay the three species meet and co-exist in the same biomass (Madsen *et al.* 2001) being the northern border for *C. finmarchicus* and the southern for *C. glacialis*.

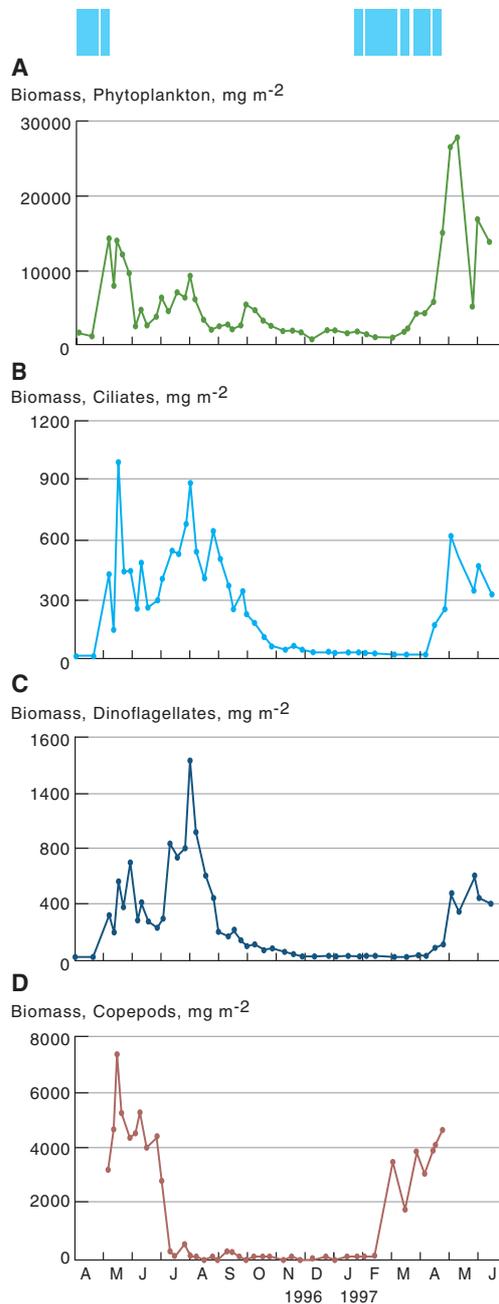


Figure 4.11 Annual cycle integrated biomass ( $\text{mg C m}^{-2}$ ) of the pelagic community in Disko Bay off Qeqertarsuaq. **A)** integrated phytoplankton biomass, **B)** ciliates, **C)** heterotrophic dinoflagellates, and **D)** copepods. The blue bars indicate the ice cover. From Nielsen 2005.

The *Calanus* have developed life strategies involving hibernation in deep cold waters during winter followed by ascend to the productive layers in early spring when the spring bloom develops, where spawning, feeding and refuelling of lipid stores are initiated after which

the adults leave the surface layers in the late summer (Figure 4.12). Later in the season, the *Calanus* can be brought to the surface layers in connection with upwelling along the fishing banks or islands (Møller & Nielsen 2002) or in association with fronts, e.g. the freshwater influenced plume of the Jakobshavn ice glacier (Munk et al. 2003).

The main grazers in the surface layer after the larger zooplankters have left are developmental stages of copepods and microprotozooplankton (Figure 4.11).

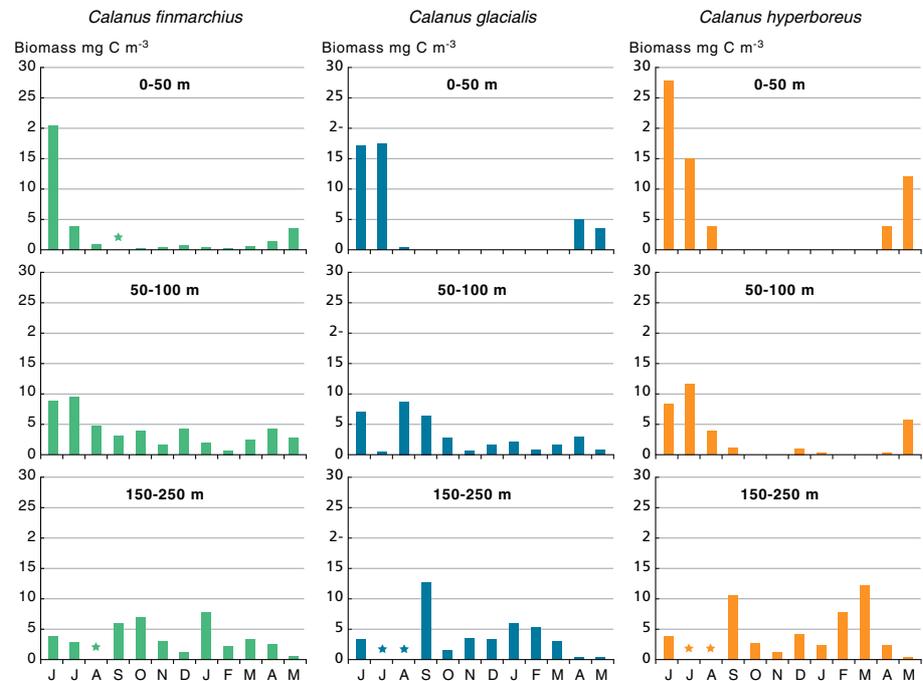


Figure 4.12 The mesozooplankton, i.e. the zooplankton > 200  $\mu\text{m}$ , are totally dominated by three *Calanus* species. The three *Calanus* species primarily occur in the surface layers from April to June when they exploit their lipid stores after the spawning period. Later in the season they migrate to deeper water to their hibernation depths (Nielsen 2005).

High-resolution knowledge about the seasonal distribution of the larger non-copepod zooplankton, e.g. amphipods, krill and shrimp and fish larvae in arctic waters is very limited. During the intensive investigations of the pelagic ecosystem off Qeqertarsuaq, the larger zooplankton and fish larvae were collected along with the other pelagic parameters (Figure 4.13).

It is obvious that the peak abundance of the larger zooplankton, e.g. the amphipods *Parathemisto*, the chaetoganths, the pelagic gastropods, are very closely coupled to the spring bloom and the population of the *Calanus* in the surface water. After mid summer most of the larger zooplankters and fish larvae are more scattered and not present in the surface layer in high concentration.

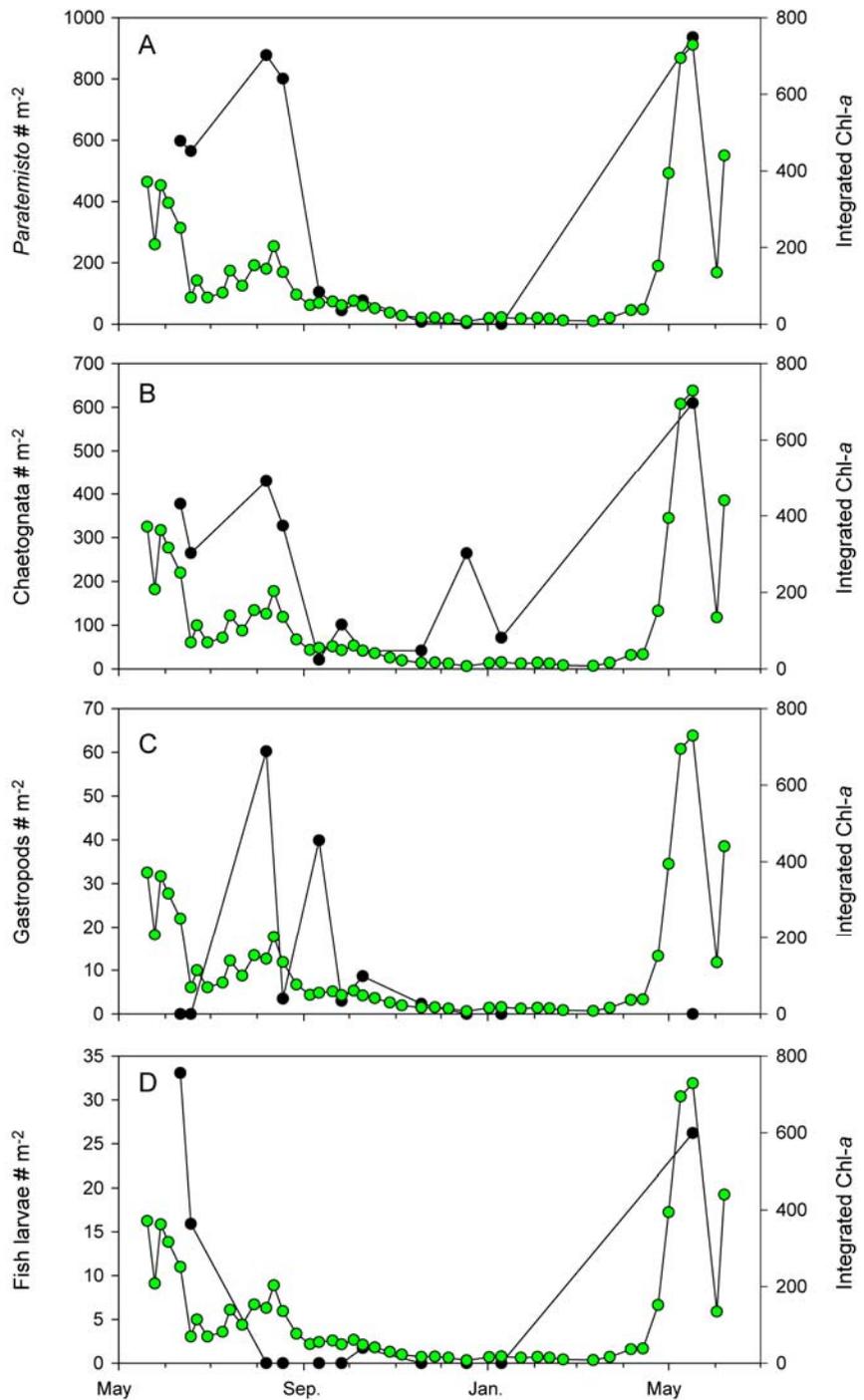


Figure 4.13 Abundance of the larger plankton species and fish larvae of Qeqertarsuaq, the green graph superimposed on all graphs illustrates the seasonal distribution of phytoplankton (integrated. Chl-*a* in the upper 50 m). A) The amphipod *Paratemisto*, B) Chaetognata, C) Pelagic gastropods, and D) Fish larvae (Munk et al. unpublished).

#### 4.4.2 The banks off western Greenland

Information about the plankton dynamics and the marine ecosystem outside Disko Bay is based on a much lower temporal resolution than the investigation in the bay. Due to logistic constraints, most of the surveys outside the bay have been conducted during the open water period. However, the overall succession patterns resemble those described for Disko Bay.

In the past the investigations along the coast off south western Greenland were associated with fisheries research and exploitation of the marine resources. The main focus has been primary production (*Smidt 1979*) and the distribution of mesozooplankton, i.e. the direct link to the fish stock (*Jespersen 1934, Ussing 1938, Smidt 1979, Digby 1953, Pedersen & Smidt 2000*). These investigations have all demonstrated the prominent role of the large copepod genus *Calanus* in the marine ecosystem around Greenland.

*Pedersen & Smidt (2000)* analyzed 34 years of zooplankton and shrimp and fish larvae samples taken along three transects during summer along the Greenland west coast. *Figure 4.14* summarizes some of the key spp. from the paper. From the distribution maps the importance of the bank areas along the west coast is clearly illustrated since these areas host the highest abundances.

Recently, several surveys have investigated the horizontal distribution of shrimp larvae (*Pedersen et al. 2002, Storm & Pedersen 2003*) and fish (*Munk 2002, Simonsen et al. 2006*) in relation to hydrography and their potential prey along West Greenland. An integrated part of these investigations were the establishment of a particle tracking model. To simulate larval drift, particles (larvae) were released in four areas along south-western Greenland assuming a pelagic life of 100 days duration (*Ribergaard et al. 2004*). The model illustrates how the fish larvae are concentrated above the fishing banks. The retention times were significantly longer along the banks indicating that they act as retention areas. Despite pronounce difference in the year class strength, the simulations of shrimp larval drift for 1999 and 2000 were almost identical. The suggested model is a good first attempt to couple oceanographic models with dispersion of shrimp or fish larvae.

The model results are clearly corroborated by the results of the sampling programmes conducted along the coast. The cruises cover the main part of the productive season (May to July). They document that the important sites for the development of shrimp (*Figure 4.15*) and fish larvae are the slopes of the banks along the coast and the shelf break where the highest biomass of their copepod prey is also located (*Simonsen et al. 2006*). The banks are also very important feeding grounds for benthic feeding diving ducks (*Mosbech & Johnson 1999, Mosbech et al. in press*) and the banks and their slopes are important for pelagic feeding seabirds (*Barret et al. in press*) and marine mammals exploiting the enhanced biomass of invertebrates and fish.

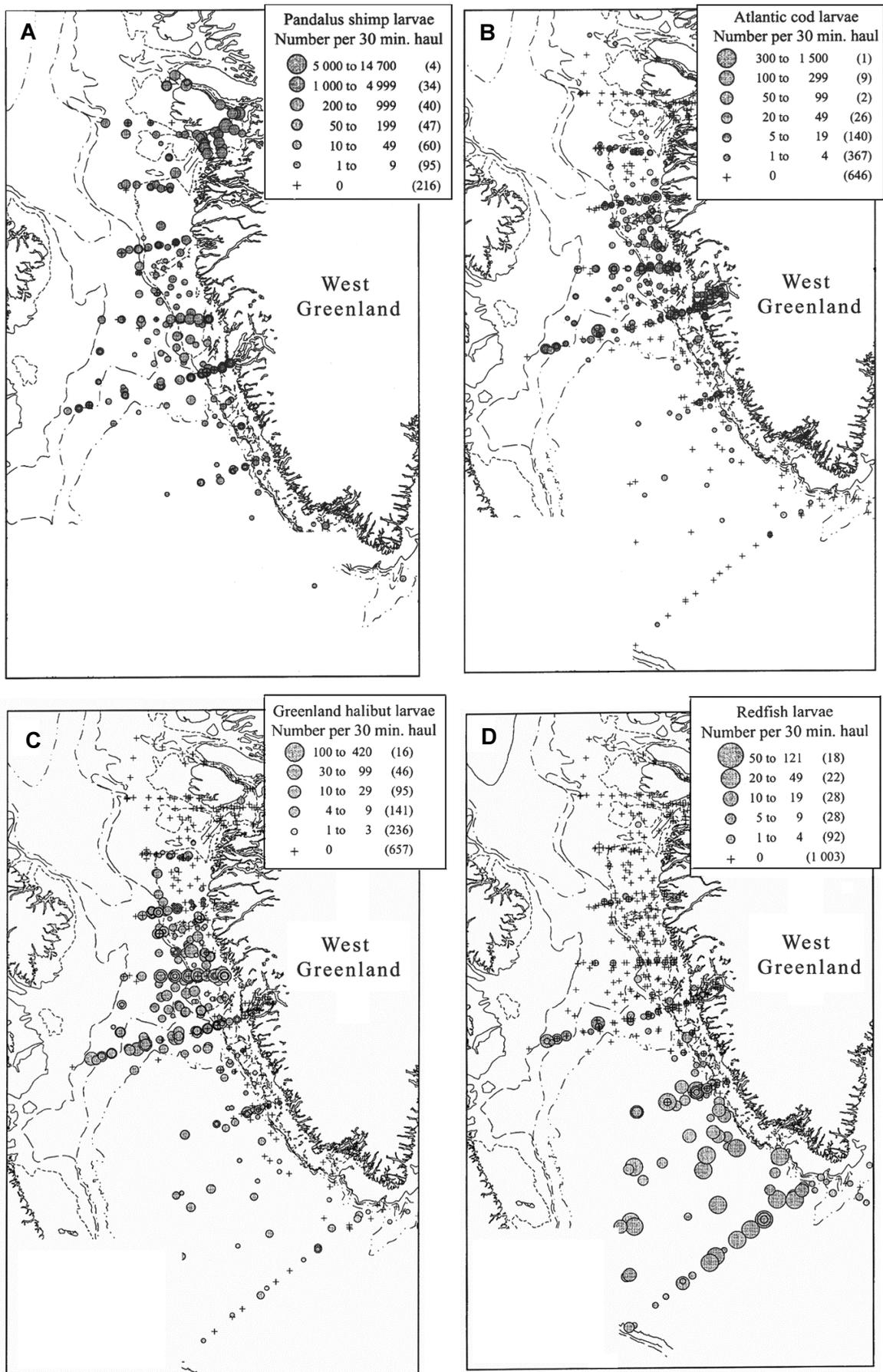


Figure 4.14 Abundance of key species along West Greenland. A) *Pandalus* shrimp larvae, B) Atlantic cod larvae, C) Greenland halibut and D) Redfish larvae (from Pedersen & Smith 2000).

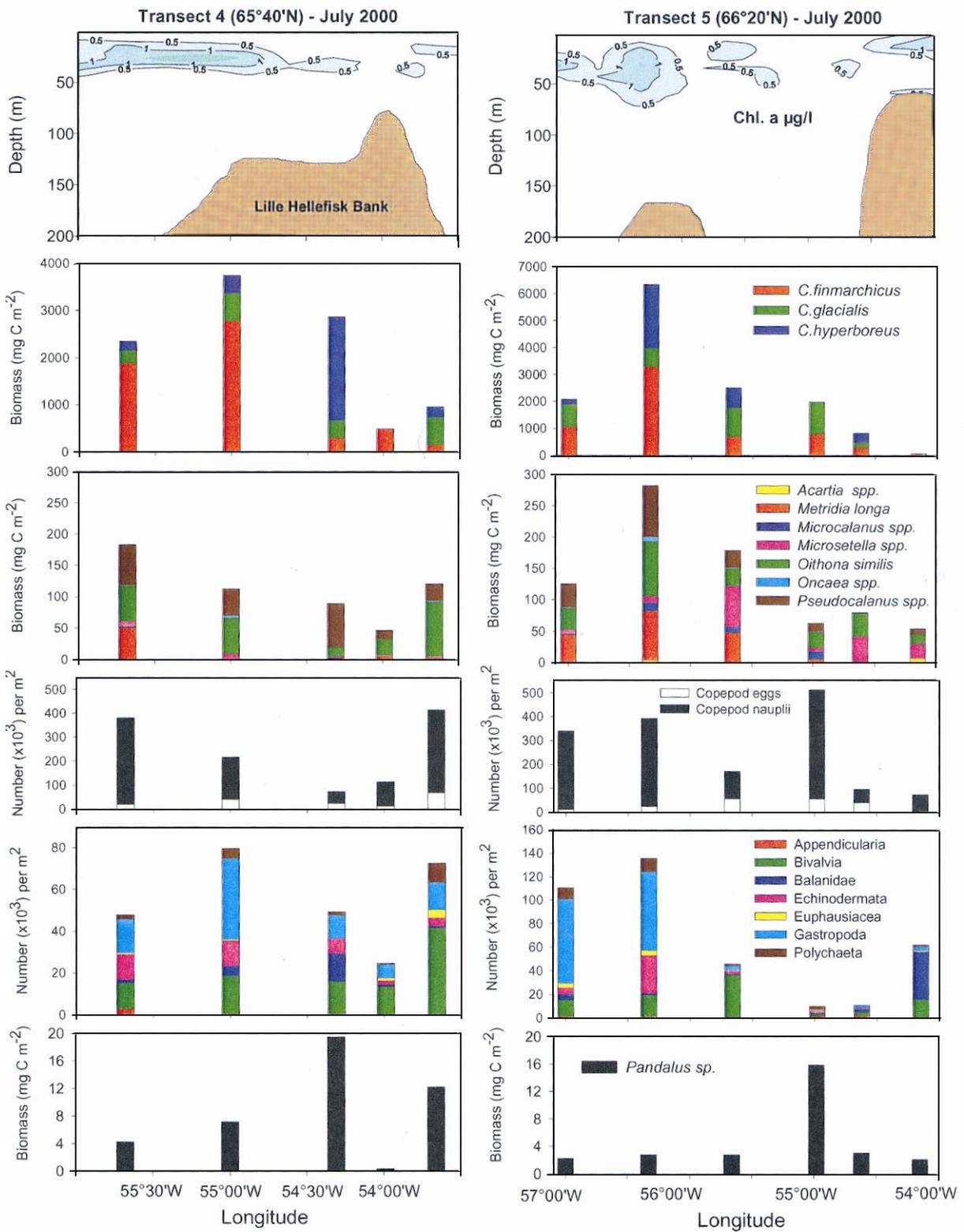
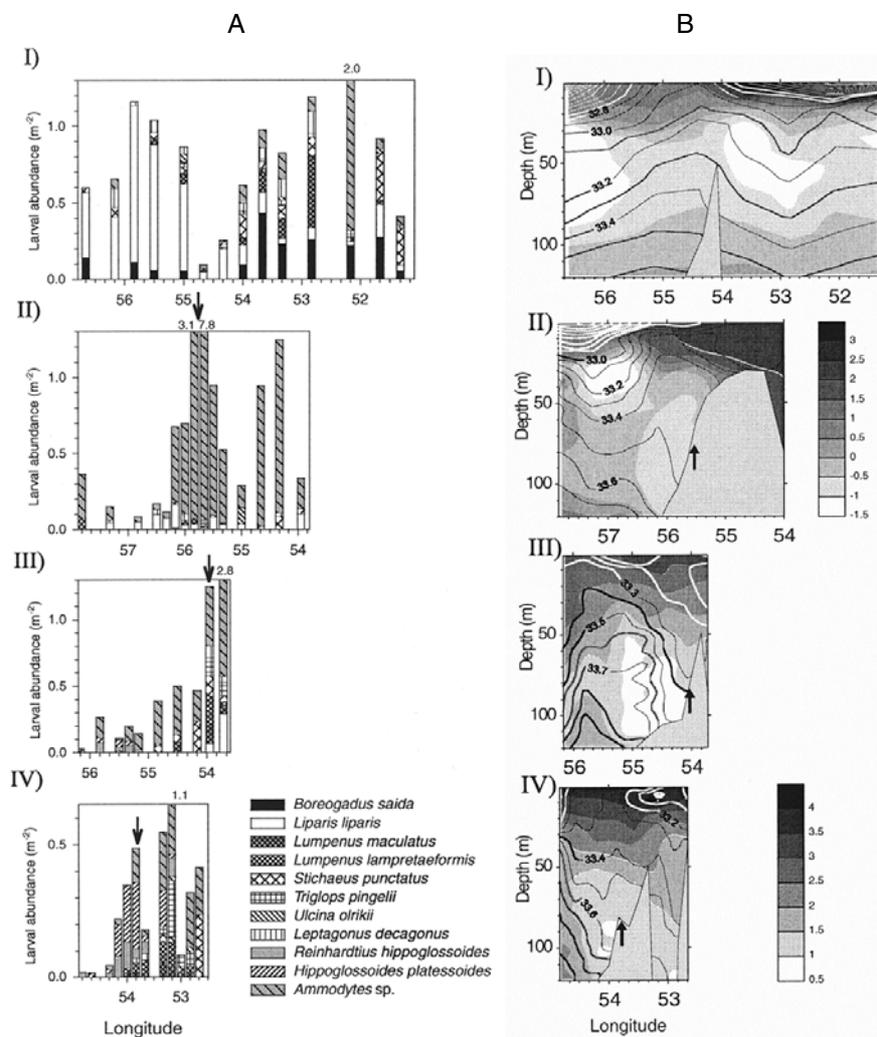


Figure 4.15 Distribution of *Pandalus* larvae biomass in relation to zooplankton and phytoplankton biomass June 2000. From Pedersen et al. 2002.

In June-July 1997 the fish larvae abundance was investigated in relation to hydrography and plankton distribution along four transects perpendicular to the coast from Sukkertop Bank in the south to Disko Bank in the north (*Munk et al. 2003*). In general the highest larval abundance was found in connection with the high productive zones between different water masses (*Figure 4.16*).



*Figure 4.16* A) Abundance of fish larvae along the transects. The arrows indicate the position of the front at the shelf slope and B) Contouring of temperature (shading) and salinity (lines) along transect I-IV (from *Munk et al. 2003*).

To fully resolve the dynamics of the marine food web along the important banks, intensive time series studies of coupled oceanographic and pelagic biology should be established. Special attention should be given to the early spring to improve our understanding of the food web dynamics along the banks.

#### 4.4.3 Marginal ice zone (MIZ) in association with the west ice

A major hydrographic discontinuity off West Greenland that has not received much attention is the marginal ice zone (MIZ). The term marginal ice zone (MIZ) is not a very well-defined term. Probably the most accepted definition is that of *Wadhams (1986)* who describes it as

“that part of the ice cover, which is close enough to the open ocean boundary to be affected by its presence”. The sea ice in Davis Strait near the west coast of Greenland, “the west ice”, clearly falls within the above definition.

Investigations of the distribution, production and the pelagic dynamics of the lower trophic levels along the “west ice” off the Greenland west coast are very limited. From other arctic areas, e.g. the Barents Sea, it is, however, well known that the marginal ice zones (MIZ) are areas of intense biological production, which are considered among the most dynamic areas in the world’s oceans (Falk-Petersen *et al.* 2000). This complex hydrodynamic at the ice edge plays an important role for production and distribution of pelagic organisms from bacteria to whales (Figure 4.17). A large number of birds winter along the MIZ in the West Greenland open water area also indicating that a high production must take place (Boertmann *et al.* 2004). Future investigations have to consider the MIZ at the west ice, if the productivity of the important West Greenland ecosystem should be understood and managed in a sustainable manner.

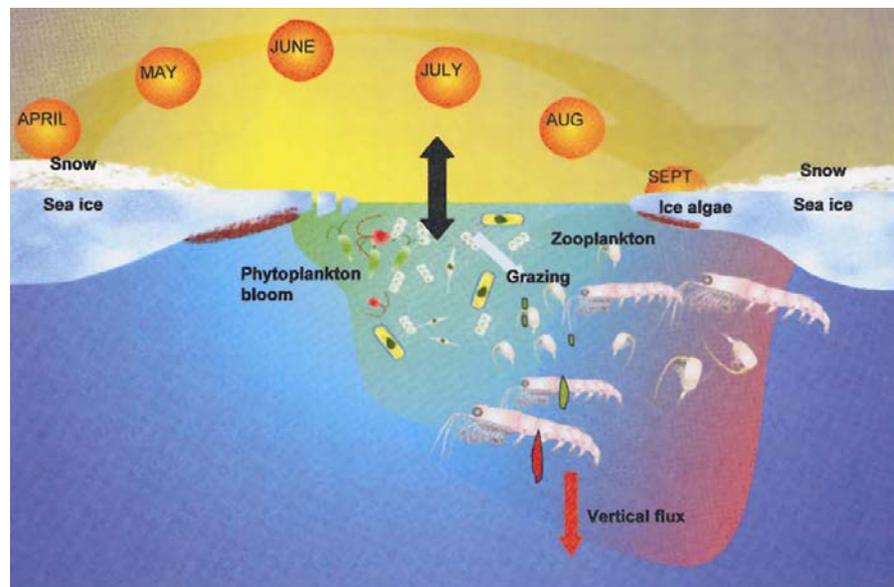
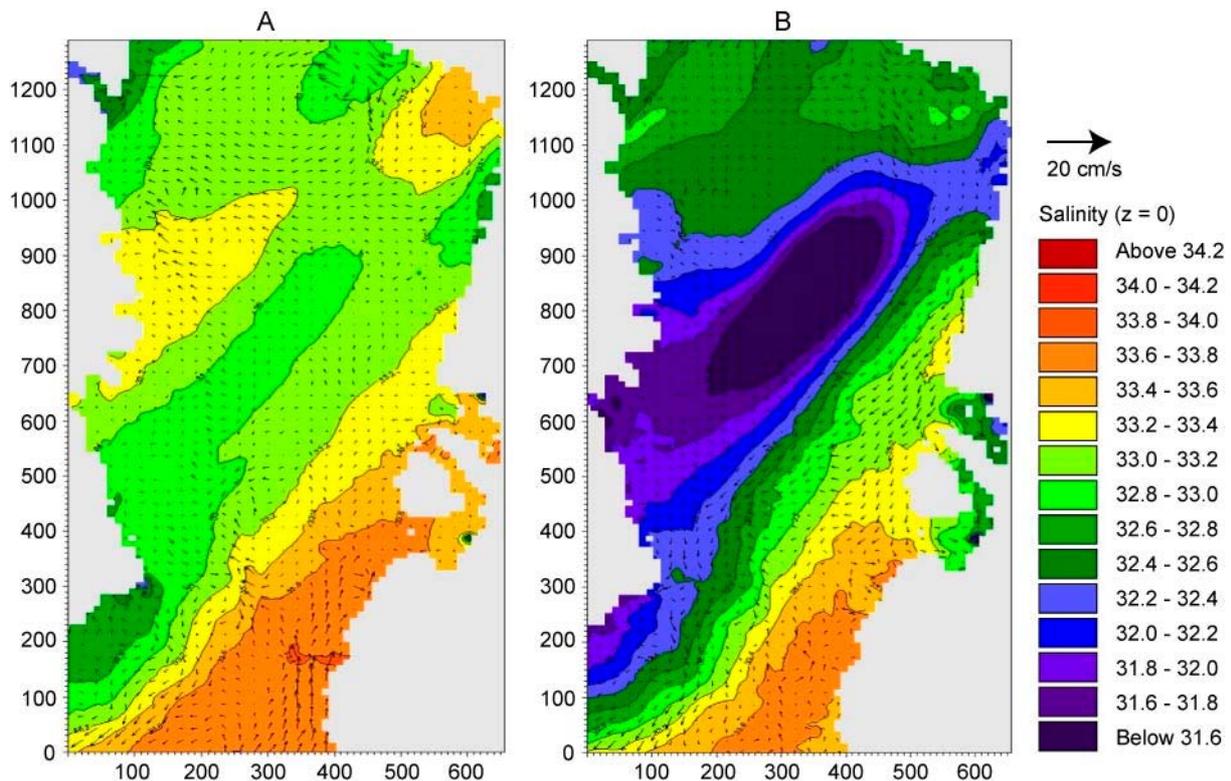


Figure 4.17 Cartoon illustrating the pelagic dynamic at the MIZ. From Wassmann *et al.* 2003.

## 5 Model results

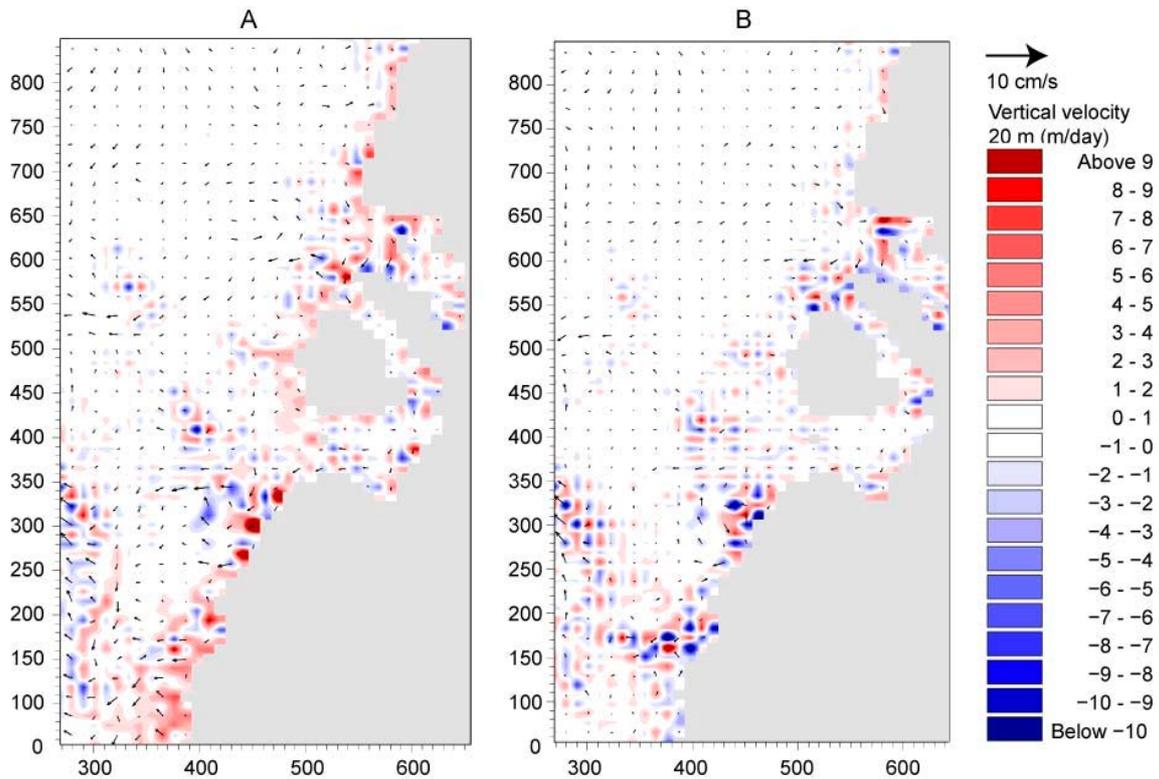
The model results analysed below are based on results from the model presented in section 2.5. The model sea surface salinity in Disko Bay was about 33 during winter 2004/2005. Freshwater run off from glacial ice melt into Disko Bay decreased the sea surface salinity in June (*Figure 5.1A and B*). The model sea surface salinity in the bay decreased down to 32 in early September. This agrees to some extent with the observed surface hydrography during the period April 1996 to June 1997, the period from where there are observations. The observed minimum salinity was about one lower than in the model, and the sea surface salinity started to increase again one month earlier than the observed time series at Arctic Station. Some differences between the model and the observations are explained by the fact that 1996 was a year with severe ice conditions, while the winter 2004/2005 was a season with no ice. The model resolution was too coarse to produce any sharp frontal zones, but there were horizontal gradients in the model sea surface salinity (*Figure 5.1*) and sea surface temperature (not shown) at the entrance of the bay from May to December.



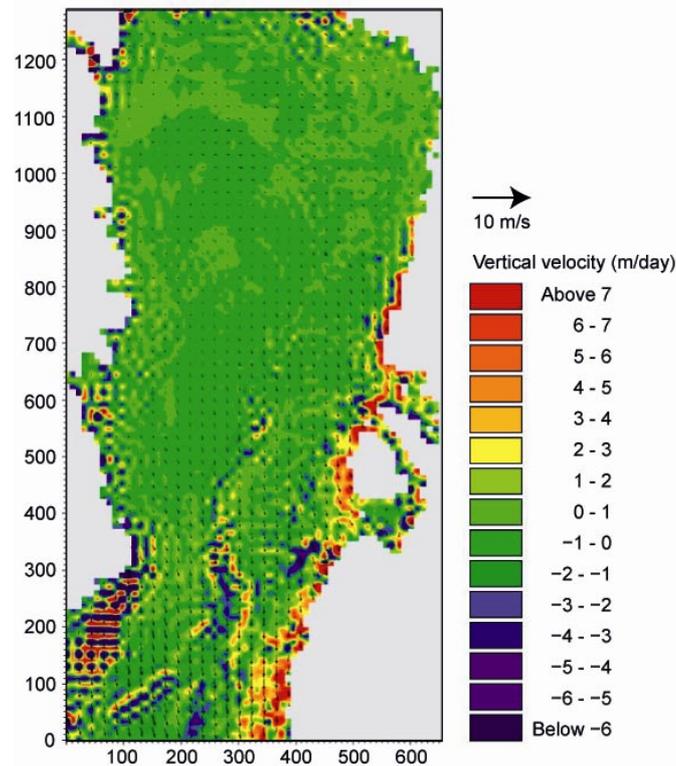
*Figure 5.1* Model results showing two dimensional fields at a depth of 0 m. **A)** colours show the salinity and arrows the surface currents daily mean for 30 May 2005. **B)** is the same as A) but for 27 June 2005.

The most frequent upwelling areas during the spring were located along the Greenland west coast both north and south of the Disko Bay entrances, and at the slopes of Store Hellefiske Bank (*Figure 5.2A and B*). In April, there was also some upwelling in Disko Bay and at the west coast of Disko Island (*Figure 5.2A*). The upwelling events in the area were mainly wind driven and occurred during northerly and north-westerly winds (*Figure 5.3*). It should be noted that large values

of vertical velocity at Store Hellefiske Bank shown in *Figure 5.3* were not caused by wind driven upwelling. The large vertical velocity was instead generated by up- and downward motion due to strong tidal currents across a shallow sloping bottom.



*Figure 5.2* **A)** The colours show monthly mean of upwelling at a depth of 20 m in April 2005 where positive is directed upward, and the arrows show wind velocity for the same period. **B)** is the same as A) but for May.



*Figure 5.3* Daily mean values of model two dimensional fields at a depth of 20 m on 24 April 2005. The colour scale shows daily mean of upwelling velocity ( $\text{m day}^{-1}$ ), and the arrows show wind speed.

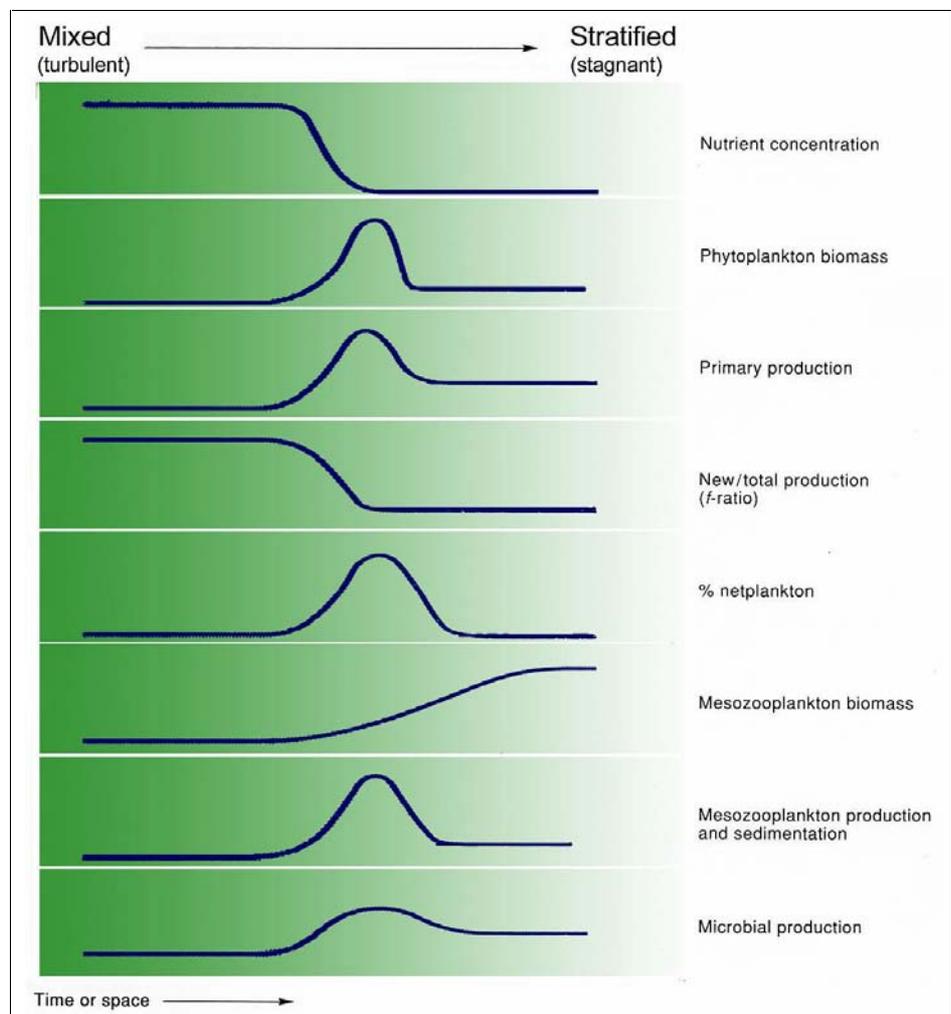


tion was observed at Arctic Station in spring in 1997 and 2005. This shows that there is a general pattern of the hydrographic conditions that tend to increase the salinity in the bay by upwelling processes, starting in the inner parts of the bay. The horizontal distribution of the density difference between the surface and 20 m showed no frontal structure as observed in the CTD-transects in the Disko Bay region 1996, 1997 and 1998. This means that the model resolution is too coarse to resolve the regions with large vertical mixing and large primary production.

## 6 Conclusions

The aim of this report is to support the identification of potential hot spots in time and space where an oil spill may have the worst consequences on the marine ecosystem. The present report provides an overview of the hydrography and plankton dynamics and shrimp and fish larvae distribution in Disko Bay, and the waters along south west Greenland.

In this context, knowledge about the interaction between hydrography and the pelagic food web is essential. Therefore attention is drawn to the identification of hydrodynamic discontinuities, i.e. sites where enhanced biological activity can be expected in the surface layers (*Figure 6.1*). These sites are particularly sensitive and areas where pronounced ecological effects of a potential oil spill can be expected.



*Figure 6.1* Hydrographic discontinuities are often sites of enhanced biological activities. These can be defined in time, e.g. the shift from mixed water in the winter to stratified water in the spring or in space when two water masses meet or at the MIZ where the frontal zone will provide better growth conditions for plankton and the succeeding links in the food web (modified from Legendre & Demers 1984).

The triggering of the plankton blooms in 1997 and 2005 is a decrease in the mixed layer depth that is generated by upwelling of warm and saline water, while the surface salinity remains rather constant; thus not warming or freshening of the surface layer. In this respect, freshwater outflow from glaciers or solar heating does not trigger the bloom. In fact, generation of a thin warm low saline layer concentrates the plankton to a smaller depth interval, resulting in a faster depletion of nutrients in the surface layer. This process forces the plankton to descend to the layer below the mixed layer. The model also captures a similar pattern of the time variability. Severe ice conditions may delay or decrease the extent of the plankton bloom. When ice reflects most solar radiation, primary production in the surface layer starts in the open water areas. The year with severe ice (1996) had weaker bloom and started about one week later in spring than years with less or no ice (the years 1997 and 2005). The observations in 1996 were, however, too sparse to be more specific about magnitude and timing of the bloom.

Freshwater outflow from glaciers in May-June generated a shallow surface layer, resulting in increased heating rate and sea ice melting rate. The warm low saline layer spread out in Disko Bay and in the end flowed out of Disko Bay along the south-southwest coast of Disko Island. In the shallow surface layer nutrients were depleted and the plankton descended to deeper nutrient-rich layer. During upwelling events, plankton blooms in the surface layer may temporally occur. The primary producers are, however, not uniformly distributed in the cold layer below the surface layer. The hydrography transects in June showed that the high productive regions were concentrated to shallow regions and along steep bottom slopes. Upwelling or upward mixing of nutrient-rich water from below probably fed the plankton bloom in early summer. According to model results, upwelling occurred during northerly and north-easterly winds in regions along the Greenland west coast, at both entrances to Disko Bay, and on the steep slopes on the shallow banks south of Disko Bay.

As illustrated here, a characteristic feature of arctic marine ecosystems is that the productive cycle is very pulsed (*Figure 4.11*). Most of the higher trophic levels in the arctic ecosystem rely on the lipid that is accumulated in the *Calanus*. Consequently, a lot of the biological activity – e.g. spawning and growth of fish – is synchronised with the life cycle of *Calanus*. The investigation in Disko Bay clearly corroborates the hypothesis that most of the biological activity in the surface layer is present in the spring and early summer in association with the spring bloom and the appearance of the *Calanus* populations (*Figures 4.11, 4.12 and 4.13*). The peak abundance of shrimp and fish larvae is also observed in the early summer in association with the peak abundance of their plankton prey.

The review of the existing data and literature clearly illustrates that the surface distribution of phytoplankton and the key player in the arctic marine food web *Calanus* can be used as proxy for high biological activity of the higher trophic levels as well.

Special attention should therefore be given to implication of oil spills in connection with hydrodynamic discontinuities, i.e. the spring

bloom, fronts, upwelling areas and at the marginal ice zone where high surface concentrations of phytoplankton, zooplankton and shrimp and fish larvae can be expected.

In conclusion, the most sensitive season – i.e. where an oil spill can be expected to have the most severe ecological consequences – is April to June where high biological activity of the pelagic food web from phytoplankton to fish larvae are concentrated in the surface layers. On a horizontal scale the most important areas are the fronts in association with the transition zone between different water masses. Later in the season, when the biological activity is more scattered or concentrated at the pycnocline, ecological damage from an oil spill is assumed to be less severe.

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## 7 References

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The report provides an overview of the hydrography and plankton dynamics and shrimp and fish larvae distribution in Disko Bay, and the waters along south west Greenland.

Observations of hydrography and the plankton community in Disko Bay and on the banks along the Greenland south west coast show that marine life is mainly concentrated in transition zones between water masses, on the steep bottom slopes of the banks, and at the shallow parts of the entrance to Disko Bay. High production of the plankton community is also expected in the marginal ice zone west of the Greenland west coast, but due to insufficient amount of observations it cannot be confirmed in this study.

The plankton bloom in Disko Bay is triggered by upwelling of saline and warmer water at the end of April. Onset of the plankton bloom, magnitude, and the distribution of the plankton community are highly affected by the large inter-annual variations of the ice extent in spring. Onset of the plankton bloom at the banks south of Disko Bay is also expected to take place in April. The zooplankton community, including fish and shrimp larvae, increases in abundance and are abundant in the surface layer during early summer. Later in the season the plankton community is more scattered, and mostly beneath the surface layer.

The aim of the report is – based on an analysis of physical and biological oceanography with emphasis on shrimp and fish larvae distribution – to support the identification of potential hot spots in time and space where an oil spill will have the largest consequences on the marine ecosystem. The most sensitive season – i.e. when an oil spill can be expected to have the most severe ecological consequences – is April to June when high biological activity of the pelagic food web from phytoplankton to fish larvae are concentrated in the surface layers. On a horizontal scale the most important area is the fronts in association with the transition zone between different water masses.

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