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# Oceanographic regime shift during 1997 in Disko Bay, Western Greenland

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## Abstract:

Data from a long time series of temperature, salinity, and nutrient measurements in Disko Bay (West Greenland) reveal a marked change in the water characteristics during recent years. Seasonal dynamics in the upper 150 m of the water column were highly affected by the seasonality in meteorological conditions, while the deeper water strata were more stable and were primarily influenced by large-scale circulation patterns. There was a marked increase in the average water temperatures at 200-m depth in spring 1997, with the long-term average increasing from 1.30°C to 2.25°C. Weekly data from 1996 to 1997 show that the sudden change in bottom water occurred in April 1997, due to the inflow of a larger proportion of North Atlantic water, which propagated north along the coast before entering the bay. Further support for this inflow was found when tracing the relative proportion of Atlantic water in the bay, using inorganic nutrients. These changes in the oceanography of the bay will not only lead to further glacial retreat but will also affect the local marine ecosystem by changing the relative dominance of major copepod species that overwinter in bottom waters of the bay.

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## INTRODUCTION

In Greenland coastal ecosystems and society are experiencing the effect of recent climate change. The major changes in physical forcing factors are: Increased melting and calving of the Greenland Ice Sheet; changed coastal circulation and subsequent ocean to shelf heat exchange; and reduced sea ice coverage (Comiso et al. 2008; Holland et al. 2008; Straneo et al. 2011). These oceanographic factors have a considerable effect on the composition and productivity of the marine ecosystem, to which Greenlandic society is intrinsically linked. Changes in the composition of key species at the base of marine food web will have great implications for both Greenlandic society (cultural hunting) and industry (fisheries and tourism).

Recently, a series of studies have documented the effect of warm Atlantic waters (AW) in Greenlandic fjords have on increasing submarine glacial melting and the subsequent acceleration of past (Andresen et al. 2011) and recent glacial retreat (Holland et al. 2008; Rignot et al. 2010; Lloyd et al. 2011). These warm waters originate from the Irminger Current. During the 1990s a shift in atmospheric forcing (North Atlantic Oscillation) resulted in the greater penetration of warm AW northwards along the Greenlandic west shelf (Buch et al. 2004; Myers et al. 2007; Holland et al. 2008). Although these altered circulation patterns have implications for the hydrography of Greenland fjords and the subsequent melting of deep bed glaciers, we can also expect considerable effects on the marine ecology of these productive coastal waters (Buch et al. 2004; Drinkwater 2006; Slagstad et al. 2011).

Disko Bay, located on the Western coast of Greenland (Fig. 1), is the recipient of the Jakobshavn isbræ, the most productive glacier in the Northern Hemisphere, draining ca. 5.4% of the Greenland Ice Sheet (Motyka et al. 2011).  The effect of both ice melt and direct sub-glacial freshwater flow is apparent from the surface water salinities in the bay which decrease from approximately 33 outside the bay to below 30 near Jakobshavn (Buch 1990). The general circulation pattern in the bay is cyclonic, with coastal shelf water from the south entering the bay and leaving again both to the north and south of Disko Island. Glacier ice production and sea ice coverage greatly influence the productivity and seasonal succession of the plankton community in Disko Bay. The presence of sea ice reduces underwater light levels leading to light limitation for phytoplankton. The combination of the breakup of the sea ice and enhanced stratification of the water column from sea ice and glacier melt results in a very productive spring phytoplankton bloom which supports a substantial secondary production in the bay. This ultimately provides the basis for much of the recreational, cultural and commercial fishing and hunting activities in the region.

The early measurements of hydrography and productivity in Disko Bay near Copenhagen University's Arctic Station in Qeqertarsuaq were conducted in 1959-1960 by Petersen (1964) and followed up in 1974-1976 by Andersen (1981). Since 1992 the seasonal plankton community structure, succession and production at a 300 m deep station off Qeqertarsuaq have been studied frequently (Nielsen and Hansen 1995; Levinsen et al. 2000; Madsen et al. 2001). During the last decades marked hydrographic changes have occurred. The period of ice cover has decreased by approximately 50% and the date of ice break (Hansen et al. 2006), and the subsequent spring bloom, now occurs earlier. In addition there has been an acceleration in the meltwater input from the Jakobshavn isbræ to the bay due to increased submarine melting as a result of an increased presence of warmer oceanic waters from the Atlantic in the bay (Holland et al. 2008; Motyka et al. 2011).

The changes in the physical forcing factors of Disko Bay impair the phenology and potentially the productivity of the pelagic food web. The spring phytoplankton bloom starts when the sea ice breaks allowing light to enter the water column and as the bloom progresses the nitrate concentrations in surface waters become limiting (Dünweber at al. 2010). This spring phytoplankton production is the major source of nutrition for secondary producers (i.e., copepods of the genus *Calanus*) and therefore a linchpin of the marine food web in the bay. *Calanus* spp. time their release from hibernation in bottom waters and ascend to forage upon the emerging phytoplankton (Hansen et al. 2003), representing a perfect trophic match (Swalethorp et al. 2011). The trigger for this ascent is currently unknown and three *Calanus* species with different nutritional value and phenology are present in bottom waters awaiting the spring phytoplankton bloom (Swalethorp et al. 2011). Changes in the hydrography of the region such as the timing of the ice break and the composition of bottom waters will alter plankton phenology and have consequences for the rest of the food web in the bay and may result in a trophic mismatch. The origin of the ‘new’ bottom water and its higher temperature may favor the smallest, less nutritious, *Calanus* species *C. finmarchicus* at the expense of the larger much more lipid rich true arctic species, *C. glacialis* and *C. hyperboreus* (Swalethorp et al. 2011). A trophic mismatch at this bottleneck of the lipid transfer at the base of the food web will result in lower food quality and less reproduction success for the copepods (Madsen et al. 2001; Hansen et al. 2003; Madsen et al. 2008*a*) and influence the feeding conditions and breeding success at higher trophic levels (Laidre et al. 2007; Karnovsky et al. 2010).

The aim of this study was to gather the available data for the hydrographic and nutrient conditions in the Disko Bay area, collected from the last 100 years of research associated with Arctic Station, and to document the changes in hydrographic conditions that have occurred during the period. Changes are apparent during the years 1996-1997, and based on the high temporal resolution sampling in the years 1996-1997 we investigate whether the system past a hydrographic threshold with subsequent general change in hydrography. We hypothesize that passage of such a hydrographic threshold might also have changed the ecosystem of the bay partly due to a linkage between zooplankton phenology and the water circulation.

## METHODS

Disko Bay is located on the west coast of Greenland and the focus of this study is the region south of the Qeqertarsuaq (Godhavn) 68.8°– 69.5° N, 51.5°– 54.5° W (Fig. 1). The data originates from a combination of sources covering the period 1924–2010. The majority of the data stem from Copenhagen University's Arctic Station (AS) main sampling station, positioned at 69°15´ N, 53° 33´ W (Fig. 1). This is approximately 1.5 km offshore, and here regular sampling and monitoring have been carried out since the mid 1970s (Andersen 1981).

The presented climate data, consisting of air temperature, wind velocity and ice cover, are from the AS monitoring program. Air temperature and wind velocity are automatically registered every 30 minutes at AS and sea ice coverage is registered daily by visual inspection from the laboratory. Sea temperature and salinity from the years 1924–1971, 1980–1990, 1998–2007 and nitrate and phosphate concentrations from the years 1982–1998 are downloaded from the International Council for the Exploration of the Sea (ICES) database (http://www.ices.dk/ocean/). Temperature and salinity data 1973–1975 are partly provided by O. G. N. Andersen (data collected at AS main station) and from (Andersen 1981). Temperature, salinity, phosphate, and nitrate data from the years 1992, 1994, 1996, 1997, 1998, and 2007–2010 was sampled either from the sea ice during winter, or from R/V *Porsild*, and represent a combination of routine measurements by AS and data from a series of research projects. Conductivity, temperature, and depth (CTD) profiles at AS station were collected using a Seabird SBE25-01 CTD system. Water was sampled from 1, 10, 15, 20, 30, 40, 50, 100, 150, 200, and 250 m using a Niskin sampler. Salinity samples were collected in glass bottles and used to calibrate conductivity measurements using a 8410-Portasal salinometer (Guildline) calibrated with International Association for the Physical Sciences of the Oceans (IAPSO) standard seawater (Ocean Scientific International ltd). Nutrient samples were frozen immediately after sampling and later analyzed at the National Environmental Research

Institute (NERI) in Denmark on a flow injection autoanalyser following Hansen and Koroleff (1999). Temperature and salinity transects from June 1996 and 1997 (Fig. 1. horizontal line, Munk 2000; Munk et al. 2003) along 69.08° N were carried out using a CTD Seabird 25-01 and are presented here to provide an impression of the geographical variability of the water column conditions in the region of the AS sampling station.

With this array of different data sources it is difficult to assess the precision and accuracy of each instrument and technique used during the 86 years covered by the time series. However, for the more recent data (after 1990), originating from the AS monitoring program and the associated research projects, the comparability is good. The CTD temperature and salinity sensors were calibrated annually by Seabird, and the salinity calibration monitored using salinometer measurements on water samples. In addition nutrient analyses were performed using the same techniques in the same laboratory at NERI. As the period where we identify marked changes in oceanographic conditions is covered by these recent measurements with good quality control we are confident that the trends observed are not due to systematic error.

*Estimating the source of bottom water in Disko Bay*–In addition to characterizing the bottom waters in the bay by temperature and salinity, a technique using inorganic nutrient concentrations was applied (Jones et al. 1998). Depending on the relative contribution of waters from the south (Atlantic waters: AW) or from the north (waters from the Arctic Ocean) the relationship between nitrate and phosphate can be expected to change. Sub-surface waters from the Arctic Ocean consist of a combination of AW that has entered the Arctic Ocean via the Nordic seas, and Pacific water (PW) from the Bering Straits. Jones et al. (1998) showed that these two water masses had distinct nitrate to phosphate relationships and this could be used to derive the relative contribution of each in the sampled water. The slopes of the relationships are very similar to the expected Redfield ratio, however, PW differs notably by having an excess of phosphate (i.e., there is a notable difference in the intercepts of the relationships). Due to the circulation patterns in the Canadian Basin the contribution of PW in the water exiting the Arctic Ocean via the Canadian Archipelago is high and PW can be traced as far south as the Labrador Sea (Jones et al. 2003). Here we apply the technique to indicate if there are changes occurring in the relative composition of the bottom waters of the bay. Although it cannot be expected to be as precise as the salinity and temperature data, the evidence from the nutrient relationships may support the trends observed in the temperature and salinity data. The nutrient relationships for AW and PW were modified from those published by Jones et al. (2008). The modification was that the slight phosphate excess at zero nitrate in Atlantic water (intercept at approximately 0.2 $\mu$mol L$^{-1}$) is set to be zero as Atlantic water originating from south of Iceland, such as in this study, is known to not have this excess (Jones et al. 1998). The calculations were only applied to samples from below 50 m. The following equations were used to derive contribution of PW ($f^{PW}$).

$$PO_4^{AW}=0.0545\times NO_3 \qquad (1)$$

$$PO_4^{PW}=0.0653\times NO_3+0.94 \qquad (2)$$

$$f^{PW}=\frac{(PO_4-PO_4^{AW})}{(PO_4^{PW}-PO_4^{AW})} \qquad (3)$$

$NO_3$ and $PO_4$ correspond to the measured nitrate and phosphate concentrations. In this paper we will be focusing on the fraction of water originating from the Atlantic and therefore refer to $f^{AW}$, which is 1- $f^{PW}$. There are several assumptions associated with this approach (Jones et al. 2003). Riverine runoff and sea ice melt are assumed to have a negligible influence on nutrient concentrations at these depths and salinities. The effects of denitrification are expected to be greatest in shallow waters in contact with sediments and generally not influence regional sub surface waters (50–400 m). Finally possible nitrogen fixation in surface nitrate limited waters are assumed to not influence waters at these depths. We emphasize however that this calculation is applied here not to provide precise estimates of the fraction of AW in the bottom waters but rather to indicate any possible shifts in the composition of the bottom waters, which may support the other measurements. For the former a more detailed mapping of bottom water nutrient concentrations in the region is required to refine the estimates.

## RESULTS

*Seasonal variability*–Before presenting the data from the time series, measurements from an intensive sampling campaign in 1996 and 1997 will be presented to provide insight into local temporal and spatial variability in the region. Based on these findings we will restrict the analysis of the longer time series to periods and depths that are less influenced by short-term fluctuations due to local forcing. In addition, these data of a fine-grained temporal resolution show the magnitude of intra-annual variability and offer a framework within which inter-annual changes can be interpreted.

Figure 2 summarizes the seasonal progression in the meteorological and oceanographic conditions off Arctic Station. Besides the expected seasonal changes in wind speeds and air temperatures there are also temperature shifts, most pronounced between November and May, associated with high winds from the east and southeast (80–165°). For example between the 17 and 19 March 1997 air temperatures suddenly shifted from below -20°C to over 0°C in conjunction with the highest observed wind velocity (Fig. 2A). The presence and persistence of ice cover is largely controlled by a combination of low temperatures and wind speeds. Periods of warmer temperatures in late spring combined with increased winds can drastically reduce ice cover (Fig. 2A).

The structure and properties of the surface waters (0–50 m) are highly affected by the seasonal atmospheric warming and cooling, and the limited vertical mixing during periods of ice cover and low wind speeds (Fig. 2C). Across the year, surface water (0–50 m) temperatures varied from -1.8°C to 6.7°C with highest temperatures in late August. Surface water salinities ranged between 30.6 and 33.7 with lowest values in August and September associated with sea ice melt and increased glacial discharge during summer. The water column below 150 m was less variable across the sampling period and less affected by changing surface conditions. Temperatures remained within -0.5°C and 3.4°C and salinities between 33.3 and 34.3. During November and December there were slightly elevated temperatures at depth (>150 m) associated with the gradual entrainment of warm surface waters (Fig. 2C). In addition, between April and June warmer waters (>1ºC) were seen below 150 m; this was apparently due to a lateral exchange of water rather than vertical mixing (Fig. 2C). Salinity changes for both these events were less pronounced (Fig. 2D).

Phosphate and nitrate concentrations in the surface waters were to a great extent controlled by phytoplankton production. Concentrations were low in the ice-free summer months when incident irradiance was high (Fig. 3). Phosphate concentrations in the surface 50 m ranged between 0–0.92 $\mu$mol $L^{-1}$ and nitrate concentrations between 0–10.7 $\mu$mol $L^{-1}$. During winter, surface water concentrations increased again in conjunction with vertical mixing (Fig. 3) while maximum concentrations were reached just before ice-break. As with temperature and salinity, the nutrient concentrations were much less variable at depth (>150 m) values are between 0.52–1.32 $\mu$mol $L^{-1}$ and 4.57–15.28 $\mu$mol $L^{-1}$ for phosphate and nitrate respectively (Fig. 3).

*Spatial variability*–Temperature and salinity were measured along two transects across the study region, one in 1996 and a parallel but shorter transect in 1997 (Fig. 4). This transect sampling passed the AS monitoring station, and the information is used here to relate the observations from the AS monitoring to conditions across the study region. In the surface 100 m there were clear differences across the region. The extent of a cold-water layer between approximately 30 and 130 m varied markedly across the bay (Fig. 4). In addition, the upper 30 m of the water column on the east side of the sill in the inner basin, had the highest temperature and lowest salinity. Below 150 m temperature and salinity were relatively homogeneous along the transects (Fig. 4), corroborating that the AS monitoring station in general represents these deeper water masses of the bay.

*Trends in hydrographic conditions (1924-2010)*–Due to the large seasonality in the surface 150 m, it is important that the time series analysis is carried out using data from a relatively stable period. The most appropriate period was the summer months (June–August). Periods influenced by the formation and melting of sea ice are much more variable due to year-to-year climatic fluctuations and hinder an analysis of the longer term changes. As the summer months additionally had good coverage in the historical series, we subsequently focused on this period for the trend analysis of hydrographic conditions (Figs. 2, 4).

Summer water temperatures in the surface 50m ranged between -1.5°C and 10.3°C and salinities ranged between 30.44 and 34.20. For the deeper waters (50–400 m) water temperatures and salinities were less variable, ranging between -1.53 and 4.04, and 33.10 and 34.49, respectively. The development in the annual summer averages for two depths, surface (10m) and deep (200 m), are shown in Fig. 5. In surface waters there were no clear systematic trends in average temperatures (Fig. 5A). There was, however, an indication of generally lower surface salinities since the mid 1990s  (Fig. 5A). In deeper waters there was a clear increase in the average summer temperatures since the mid 1990s (Fig. 5B). The average temperature from the period before 1996 was 1.30°C, whilst the average from 1997 onwards is 2.25°C. In contrast to the 1980s where average temperatures were relatively constant, average values from 1997 onwards are notably higher and more variable (Fig. 5B). Bottom water salinities were comparatively constant across the whole time series, although there was a tendency for average salinities since 2000 to be equal to or higher than the long-term average.

Sub surface (50–400 m) phosphate and nitrate concentrations for the period 1982–2009 are plotted in Fig. 6 between two lines representing AW and PW relationships (Jones et al. 1998). Data between these two lines represent a mixture of these two dominant water masses. A trend in increasing proportion of AW is apparent, as the nutrient concentrations move closer to the AW relationship across the period from mid 1980s to present. The calculated $f^{AW}$ in bottom waters varied considerably across the study period (Fig. 7). Although the data coverage is much less than for the salinity and temperature data, the results indicate that the average composition of the bottom waters has changed. Before 2000 approximately 60% of the bottom waters consisted of AW, while in recent years this has increased to 80%. These calculations are solely based on the nutrient concentrations, but concurrent with the observation of a marked increase in the temperature of the deeper water masses of the bay they point to an extensive intrusion of water originating from the Irminger Current. From the data from the intensive study from 1996 into 1997, the timing of the intrusion of warmer bottom water into the bay can be delimited to April 1997 (Fig. 8). Here we see a dramatic increase in the temperature and salinity of the bottom water. The peak is in early May 1997 and there is a slight decline during the subsequent months (Fig. 8), however, temperature remains at a higher level than apparent for the period before 1997 (Fig. 5).

## DISCUSSION

*Surface water characteristics*–The extent and duration of sea ice coverage is an important forcing factor for the marine ecosystem along the coast of Greenland (Sejr et al. 2007; 2009). Disko Bay is at the southern boundary for sea ice coverage, and as a result the conditions are highly variable from year to year depending on local meteorological conditions (Heide-

Jørgensen et al. 2007). Periods with sea ice cover vary between approximately 90 to 174 days (Hansen et al. 2006). The seasonal series 1996–1997 illustrates the coupling of sea ice to local conditions (Fig. 2). During the winter of 1996–1997 ice was formed after two months with sub-zero air temperatures, causing surface water temperatures to fall below -1°C. The ice-breakup occurred in March 1997 as a result of a combination of sudden strong winds and air temperatures above zero. During ice-breakup underwater light conditions greatly improved while the water column still remained stratified. Subsequently a spring diatom bloom was initiated and this rapidly depleted surface layer nutrients while water temperatures remained below 0°C. During summer the surface waters to approximately 20–30 m depth were influenced both by melting of sea ice and by freshwater run-off from land, creating a thin layer with lower salinity. Stratification was further enhanced by radiative heating (Buch 1990).

Surface waters in summer largely consist of a combination of melt water and water from the West Greenland Current that enters the southern part of the bay and after a cyclonic circulation leaves the area through Vaigat and the northern part of the bay just off Qeqertarsuaq (Kiilerich 1939, Andersen 1981). The data from AS presented here show a tendency for lower surface water salinities during summer months for the past decade in particular (Fig. 5A). This suggests an increased freshwater supply and agrees with the findings of Motyka et al. (2010) in waters further east, closer to the Jakobshavn glacier. At intermediate depths in the bay a cold (sub-zero) water layer is present between 30 and 130 m (Fig. 4) and persists for much of the year (Fig. 2C). This layer has been reported earlier and is believed to originate from the winter cooling and vertical convection of surface waters (Buch 1990, Pedersen et al. 2006), which is also apparent in the time series of measurements in 1996–1997 (Fig. 2C).

*Changing source composition of bottom waters*–The two major sources of subsurface waters (below 150 m) in the region are AW, transported northwards in the West Greenland Current and Arctic waters transported southwards as part of the Baffin Bay Current. The conditions in the bottom waters are relatively stable across the year and early measurements suggest that bottom water in the bay is replenished episodically during winter (Buch 1990). The temperature of the two sources differ, the waters from the south containing AW being warmer. Although warm waters at depths between 100–300 m are found outside the bay, Buch (1990) found that the bottom waters of the bay normally do not exceed 2°C which indicates a limited intrusion of the warmer AW. The data presented here indicate that the situation has changed and that the relative proportion of warmer waters from the south has increased since the mid 1990s. This is further supported by the additional information based on nutrient relationships (Figs. 6, 7). There is a tendency that bottom waters in Disko Bay have increased in contribution of water from the Atlantic (Fig. 6). Conditions have changed to a much less variable composition of the bottom waters and an increase in the realtive proportion of AW (Fig. 7). An especially abrupt change in water masses is apparent for 1996 to 1997, and based on the intensive sampling during these years we trace the shift to start in April 1997 with the warmest and most saline water present in May 1997. The temperature and salinity characteristics of deep water from this period are shown in Fig. 9. Water warmer than 2 degrees and with a salinity greater than 34 enter the bay indicate an inflow of water which we interpret as AW originating from the Irminger Current and carried northwards as part of the West Greenland Current (Modified Irminger Water 3.5-5°C and $34.88 \leq S < 34.95$) (Myers et al. 2009). This evidence for warmer waters entering Disko Bay in the late 1990s is in accordance with recent findings from studies on region oceanography (Holland et al. 2008), sedimentary record of the bay (Lloyd et al. 2011) and glacial dynamics (Motyka et al. 2011).

Hydrographic conditions in the bay are the product of both regional and local processes. The relative amounts of warm and saline AW entrained into the west Greenland current and transported northwards is known to be linked to large-scale phenomena influencing ocean circulation in the North Atlantic. For example links have been made to the North Atlantic Oscillation (NAO) index (Buch et al. 2004; Zweng and Münchow 2006; Holland et al. 2008), which relates to the relative intensities of the Icelandic low and Azores high air pressure systems, which in turn influence circulation conditions in the North Atlantic. However, it is clear that the relationship is more complex, as previous large changes in the NAO index in the late 1960s are not reflected in sediment derived bottom water temperature record from Disko Bay (Lloyd et al. 2011). It is likely that other more local feedback mechanisms are also influencing conditions and the herein the relationship to the North Atlantic circulation and the NAO index. From the high temporal resolution sampling carried out in 1996– 1997 it is clear that in late autumn and early winter the water column is mixed and warm surface waters are entrained to below 100 m (Fig. 2C). An increase in the summer surface water temperatures in the bay as a result of warming local climate conditions (Hansen et al. 2006) could therefore also increase the annual vertical transport of heat to sub surface waters moving eastwards into the bay and interacting with the glacier.

It is generally believed that the recent acceleration of Greenlandic glaciers is largely due to the erosion of submarine ice buttresses due to melting from contact to warmer oceanic water (Rignot et al. 2010). The independent results from the AS time series presented here support the findings from other recent studies indicating that the temperature of sub-surface waters of the bay have increased due to the presence of a greater proportion of warm Atlantic water. The questions that remain are: how long will these warmer oceanographic conditions along the Greenlandic coast prevail and what will be the subsequent effect of a greater input of freshwater from ice melt?

Altered circulation patterns have implications for the hydrography of Greenlandic fjords and the subsequent melting of deep bed glaciers, as seen during the last 10,000 yr (Andresen et al. 2011), and one can also expect considerable ecological effects in these productive coastal waters. Changes in key species at the base of marine food web will have implications for Greenlandic society (cultural hunting) and industry (fisheries and tourism). The hydrographic changes documented here: The enhanced AW influence in bottom waters, the increased temperature in general and the reduced sea ice coverage, might impair the composition and productivity of the pelagic food web. The spring phytoplankton bloom is the major source of nutrition for secondary producers such as the copepods of the genus *Calanu*s and therefore a linchpin of the Greenlandic marine food web. *Calanus* spp. hibernate in bottom waters and synchronize their ascent to match the spring phytoplankton bloom (Hansen et al. 2003), representing a perfect trophic match. The trigger for this ascent is, however, unknown. Increased bottom water temperatures as a result of circulation changes will increase the metabolic rates of overwintering copepods and potentially reduce the energy store available for reproduction the following spring. Additionally increased use of stored lipids will affect their buoyancy (Visser and Jonasdottir 1999) and thereby disturb the diapause of the neutral buoyant copepods (Pond and Tarling 2011).

The three *Calanus* species differ in their phenology and in their nutritional value to larger consumers (Swalethorp et al. 2011). Changes in their relative proportions will alter the efficiency of energy transfer through the marine food web. The greater supply of Atlantic water and its higher temperature will likely favor the smaller fast growing and less nutritious species (*C. finmarchicus*) at the expense of the larger much more lipid rich native Arctic species (*C. glacialis* and *C. hyperboreus*) (Swalethorp et al. 2011). Such a community shift in the zooplankton is actually already apparent when comparing the zooplankton community structure before and after the observed change in bottom water characteristics (Nielsen and Hansen 1995, Madsen et al. 2001; Swalethorp et al. 2011).

A shift in the amount of lipids at the base of the food web will result in lower food quality, which potentially will affect the feeding conditions and breeding success of higher trophic levels (Laidre et al. 2007; Karnovsky et al. 2010). The Greenlandic ecosystem has shown marked changes during the last century, changes that are related to the overall changes in environmental conditions (Buch 2004). However, our understanding of underlying mechanisms lag behind, and there is a need for further details on the linkages between physical and biological processes. The present study illustrates how regional changes in major currents have local effect in a relatively small bay area, and points to the importance of linking large scale and small scale processes for understanding ecosystem responses to changing climatic conditions.

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Figure Legends

Fig. 1. Map showing south west Greenland (inset) and a more detailed map showing the location of Disko Bay with depth contours in meters and the dominating current pattern (modified after Buch 1990). Copenhagen University's Arctic Station is located on Disko Island at the town of Qeqertarsuaq (Godhavn). Disko Bay is the sampling area 68.8°– 69.5° N, 51.5°– 54.5° W. The star shows the position of the main station (69°15´ N, 53° 33´ W) and the solid horizontal line shows the transect plotted in Fig. 4. The diamond shows position of the Jakobshavn Isbræ.

Fig. 2. Seasonal trend in (A) wind speed (black), ice cover (grey) and (B) air temperature (black) shown as daily mean values. Dashed horizontal line indicates 0ºC. Depth profiles of (C) temperature (°C) and (D) salinity at the main station between 22 April 1996 – 07 June 1997. (C, D) Dots illustrates the sampling depths.

Fig. 3. Seasonal trend in nutrient concentrations at the main station. Depth profiles of (A) phosphate ($\mu$mol $L^{-1}$) with isopycnals overlain and (B) nitrate ($\mu$mol $L^{-1}$) across the same time period as Fig. 2. (22 April 1996- 07 June 1997). Dots illustrate the sampling depths.

Fig. 4. Cross section of temperature (°C) and salinity along latitude 69.08° N. Transect shown in Fig. 1. (A) temperature and (B) salinity July 1996, (C) temperature, and (D) salinity July 1997. The star shows the approximate position of the main station (69°15 N, 53° 33 W).

Fig. 5. Average summer (June to August) temperature and salinity data for the period 1924–2010: (A) Surface 10 m and (B) bottom 200 m. Error bars show the standard deviation. Solid lines

represent the average calculated across the whole period, except for the temperature data from 200 m, where two averages are shown: 1924–1996 and 1997–2009, and the dashed lines represent extrapolations across the whole period, plotted for reference.

Fig. 6. Nitrate vs. phosphate concentrations for data below 50 m for the period June 1982–May 2009. The two lines represent the relationships for Atlantic and Pacific water in the region (defined by Jones et al. 2003). The color bar indicates the year the samples were taken.

Fig. 7. Fraction Atlantic Water ($f^{AW}$) in water samples from 50–400 m from 1982–2009. Open circles represent measured data and the larger black dots are the annual averages.

Fig. 8. Temperature and salinity of water at 200 m at the main station during the study period from 1996–1997.

Fig. 9. Vertical profiles of (A) temperature (°C) and (B) salinity from depths between 100–200 m. (C) Temperature/salinity plot of the same data. Data plotted are from 22 April 1996 – 07 June 1997. Open grey are data from 1996 and black from 1997.

Fig. 1

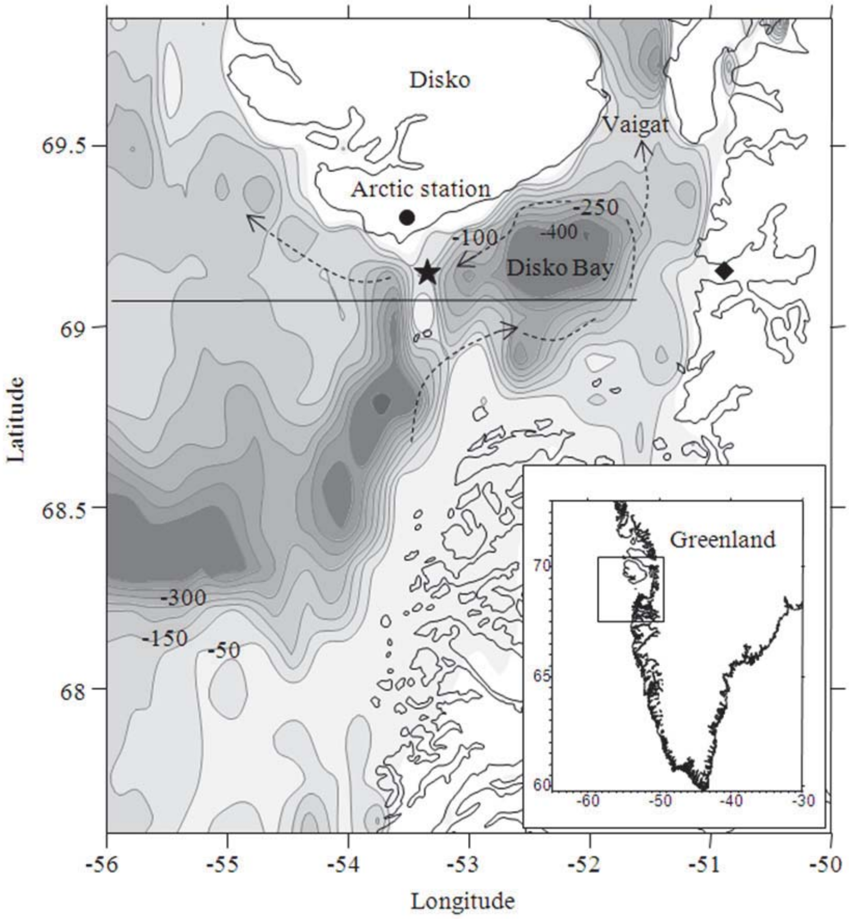

Disko
Vaigat
Arctic station
-250
-100
-400
Disko Bay
-300
-150
-50
Greenland
70
65
60
-60
-50
-40
-30
69.5
69
68.5
68
Latitude
-56
-55
-54
-53
-52
-51
-50
Longitude

Fig. 2

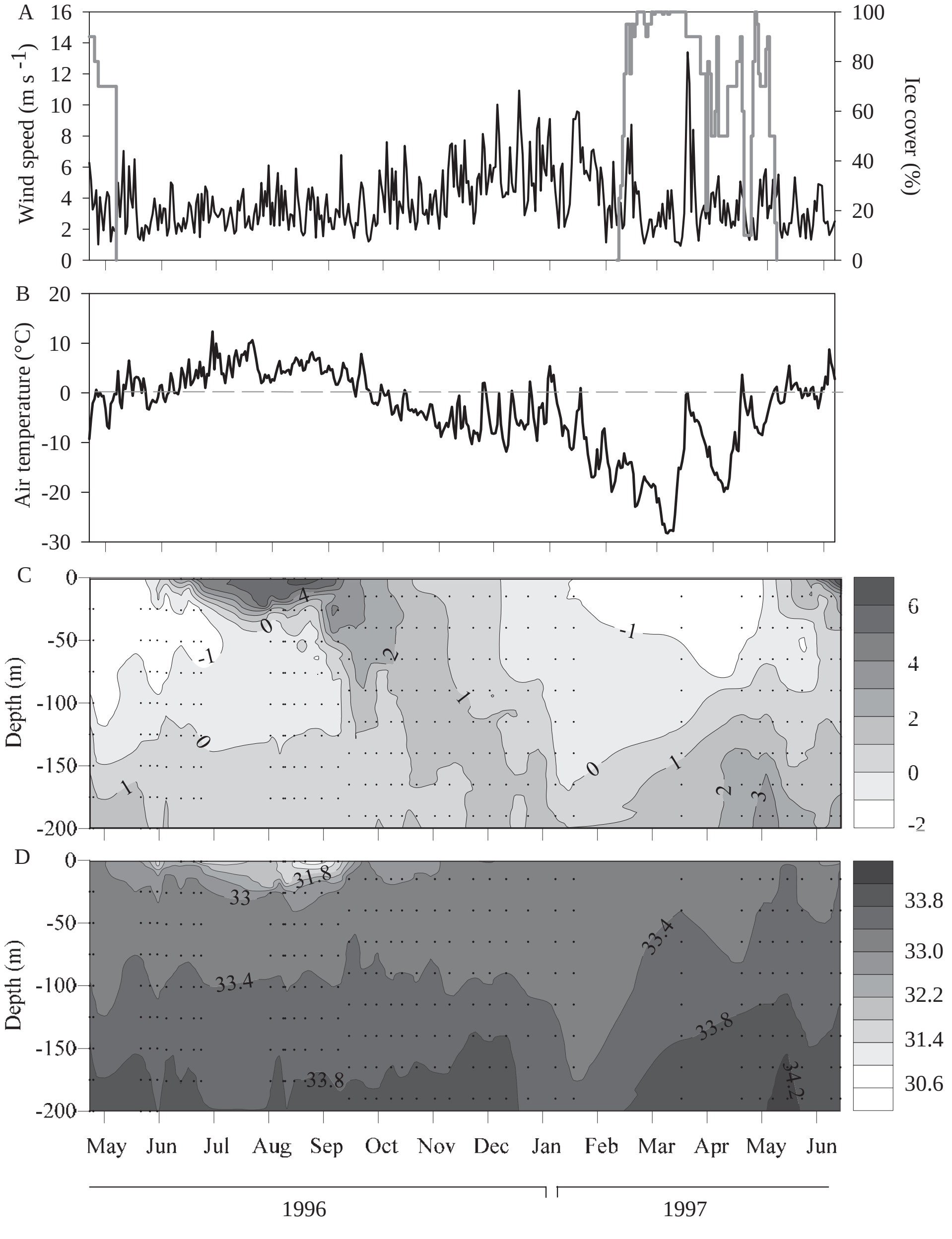

A
Wind speed (m s -1)
Ice cover (%)
0
2
4
6
8
10
12
14
16
0
20
40
60
80
100
B
Air temperature (°C)
20
10
0
-10
-20
-30
C
Depth (m)
0
-50
-100
-150
-200
4
0
-1
2
1
0
-1
0
1
2
3
6
4
2
0
-2
D
Depth (m)
31.8
33
33.4
33.8
33.4
33.8
34.2
33.8
33.0
32.2
31.4
30.6
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
1996
1997

Fig. 3

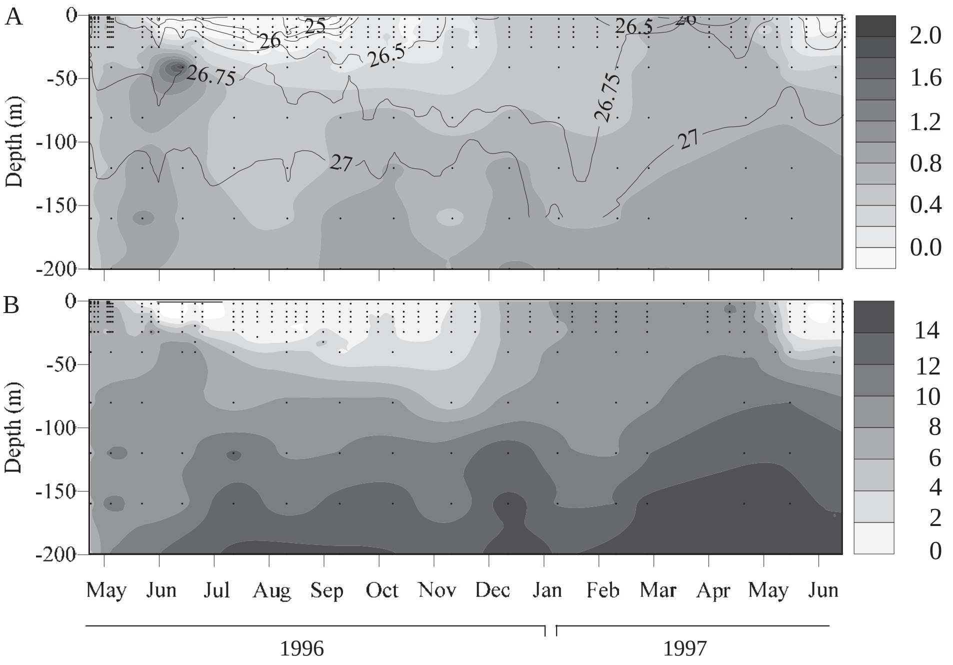

A
B
0
-50
-100
-150
-200
Depth (m)
25
26
26.5
26.75
27
26.5
26
26.75
27
2.0
1.6
1.2
0.8
0.4
0.0
14
12
10
8
6
4
2
0
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
1996
1997

Fig. 4

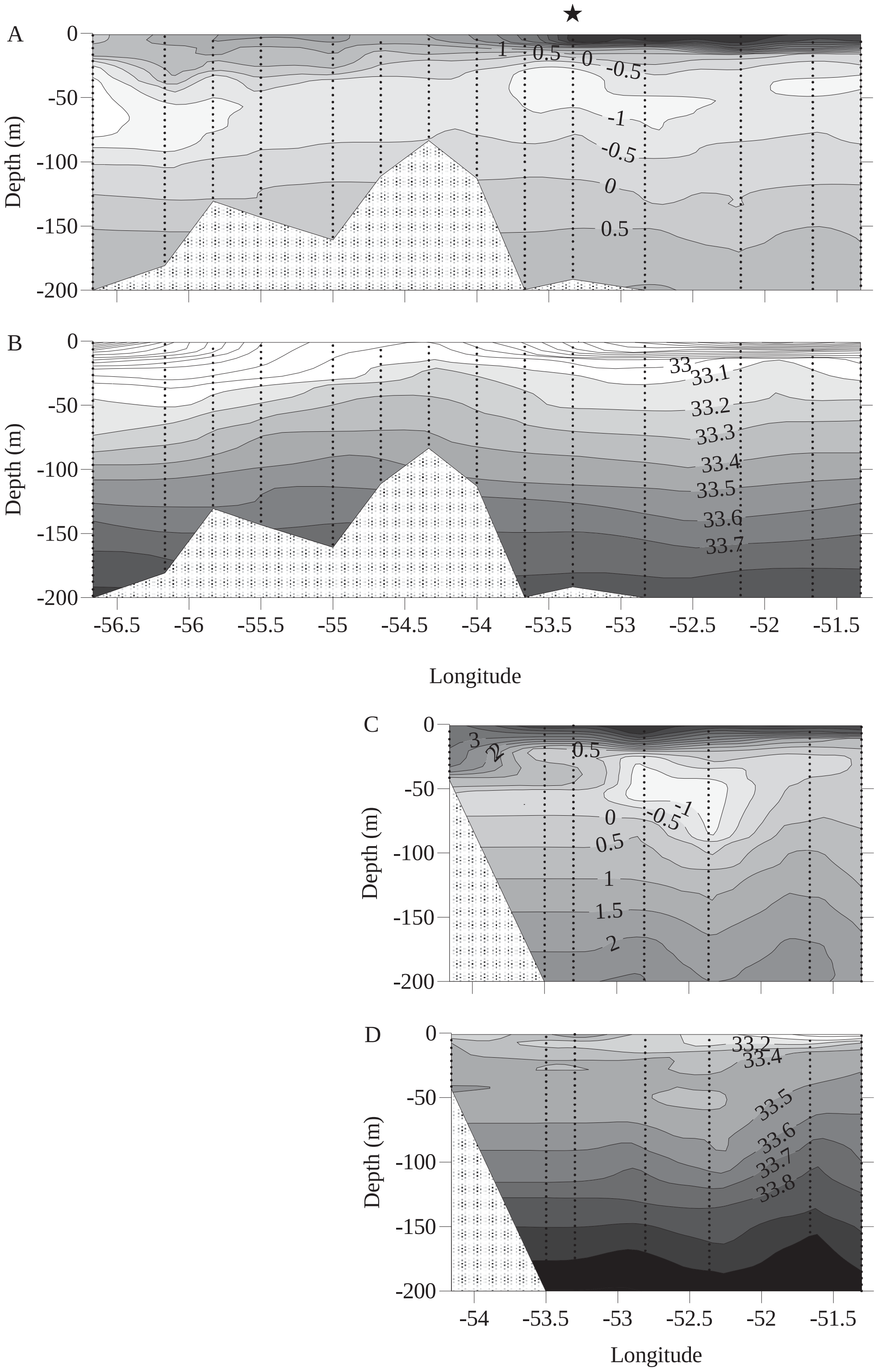

★
A
B
C
D
Depth (m)
0
-50
-100
-150
-200
1
0.5
0
-0.5
-1
33
33.1
33.2
33.3
33.4
33.5
33.6
33.7
33.8
3
2
1.5
-56.5
-56
-55.5
-55
-54.5
-54
-53.5
-53
-52.5
-52
-51.5
Longitude

Fig. 5

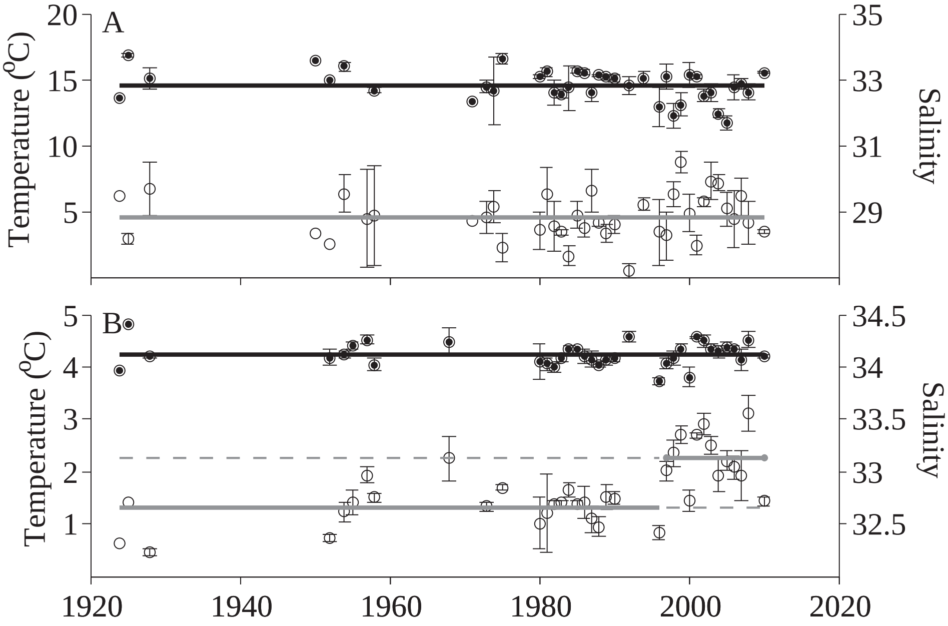
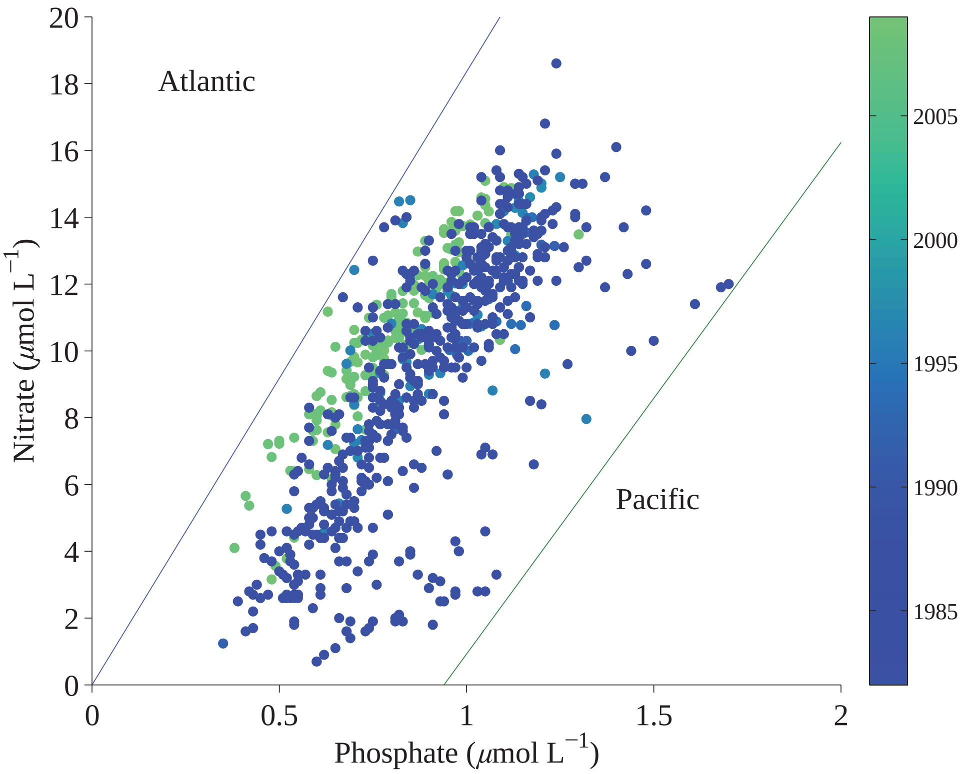

A
B
Temperature (°C)
Salinity
20
15
10
5
35
33
31
29
5
4
3
2
1
34.5
34
33.5
33
32.5
1920
1940
1960
1980
2000
2020

Fig. 6



Atlantic
Pacific
Nitrate ($\mu$mol L$^{-1}$)
Phosphate ($\mu$mol L$^{-1}$)
0
2
4
6
8
10
12
14
16
18
20
0
0.5
1
1.5
2
2005
2000
1995
1990
1985

Fig. 7

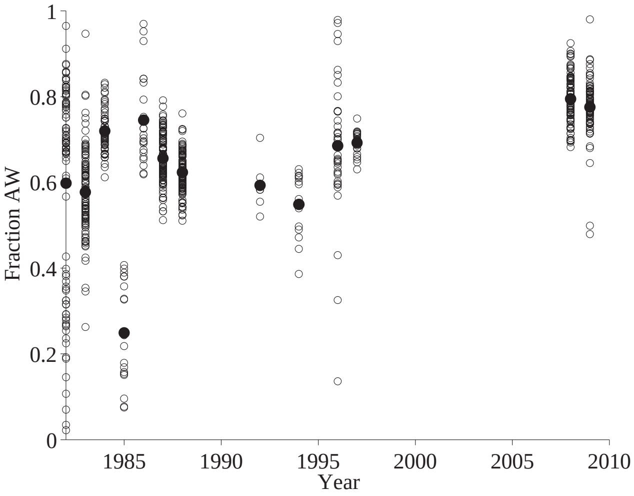


Fig. 8.

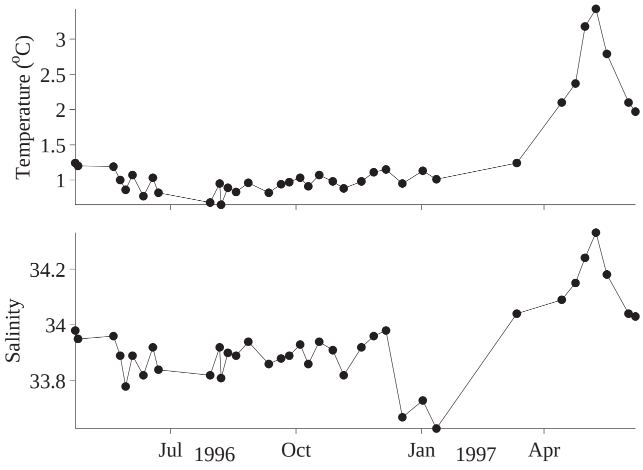
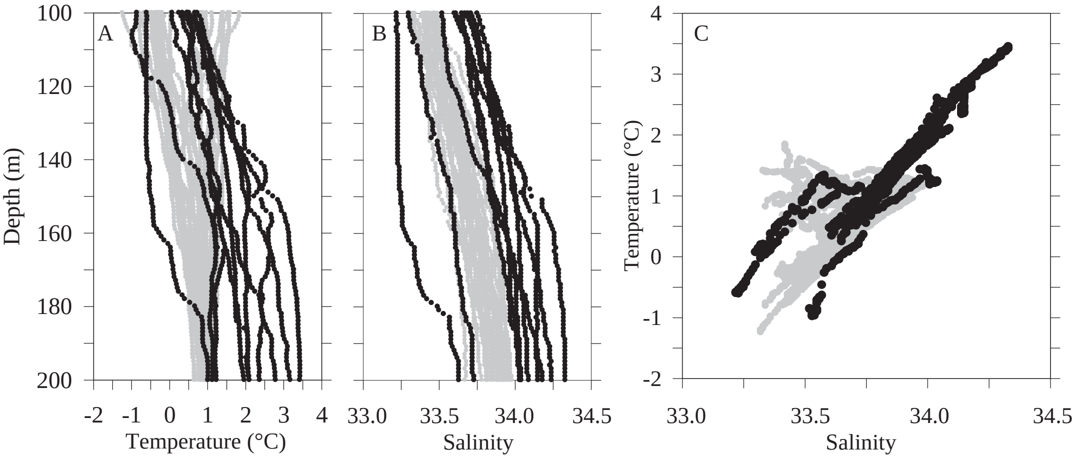

Temperature ($^{o}$C)
3
2.5
2
1.5
1
Salinity
34.2
34
33.8
Jul
1996
Oct
Jan
1997
Apr

Fig. 9.


A
B
C
Depth (m)
100
120
140
160
180
200
-2
-1
0
1
2
3
4
Temperature (°C)
33.0
33.5
34.0
34.5
Salinity
Temperature (°C)
4
3
2
1
0
-1
-2
33.0
33.5
34.0
34.5
Salinity