Ocean temperature oscillations causing the reappearance of blue mussels in Svalbard after 1,000 years of absence

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Running head: Reappearance of *Mytilus* in the high Arctic

Key words: *Mytilus,* Arctic, Atlantic Water transport, remote sensing, SST, temperature oscillations, Holocene.

ABSTRACT: During the last 120,000 years world ocean temperatures have varied significantly (Rahmstorf 2002). Since the last glaciation, a maximum in sea surface temperatures (SST) peaking at around 9,000 years BP affected also the Arctic through an enhanced northward heat transportation by the Gulf Stream system (Rahmstorf 2002, Sarnthein et al. 2003). Distribution patterns of blue mussels in the high Arctic indicate that this thermophilous mollusc was abundant along the west coast of Svalbard during warm intervals (Salvigsen et al. 1992, Salvigsen 2002, Lønne & Nemec 2004) of the Holocene (Fig. 1A). Here we report and demonstrate the linkage between the reappearance of living blue mussels in Svalbard after 1,000 years of absence and oscillations in ocean climate.

INTRODUCTION

Blue mussels (*Mytilus edulis* L.) have not been present at Svalbard for the last 1,000 years (Salvigsen 2002, Lønne & Nemec 2004), and not in great abundance since 7,000 years BP (Fig 1A). The period between 10,700 and 7,700 years BP has been identified as a Holocene thermal optimum (Rahmstorf 2002, Duplessy et al. 2001, Andreev 2004) with summer SST of 8°C in addition to an enhancement (Sarnthein et al. 2003) of the West Spitsbergen Current (Fig. 1B). Related to this well documented distribution pattern of blue mussels during the Holocene, the discovery of a viable population in Svalbard raises important questions regarding effects of short term ocean climate oscillations in the high Arctic. Due to the blue mussels' sensitivity to short-term marine temperature fluctuations (Peacock 1989, Honkoop & van der Meer 1998), these findings suggest that recent water temperatures approach those of the Medieval Warm Period when Viking settlements were founded on Iceland, Greenland and Newfoundland.

However, although the world ocean heat inventory has increased during the last 50 years (Levitus et al. 2000, Fukasawa et al. 2004), fluctuations on inter-annual scales are pronounced (Levitus et al. 2000, Johannessen et al. 2004). We discuss how recent inter-annual variations in ocean temperatures and northward transport of Atlantic water have caused a northward extension to the distribution range of blue mussels.

MATERIAL AND METHODS

Currents

Transport effects in the eastern branch of the NwAC, the NwASC (Orvik & Niiler 2002, Orvik & Skagseth 2003), and further north in the WSC are studied (Fig. 1B). These current systems transport AW, as an extension of the Gulf Stream system, with salinity >34.90 psu and temperature >3°C when it enters the Arctic Ocean (Swift & Aagaard 1981). Here it meets the fresher and colder ArW with salinity between 34.3-34.8 psu and temperatures below 0°C. The transport time of water masses from Northern Norway (Lofoten / Vesterålen area at ~69°N, see Fig 1) to the shelf areas outside Isfjorden in Svalbard (a distance of approx. 1000 km) is estimated to be between 32-38 days for an average current speed between 0.30-0.35 ms^{-1} (Fig 1B-C). These estimates are based on time series observations of the NwASC (Orvik & Niiler 2002) and WSC (Schauer et al. 2004). In terms of inter-annual variability, the annual mean volume transport of AW in the Svinøy section (a site at 62°N used for estimation of water transport by the NwAC) was at an absolute minimum in 2001 and increased to an absolute maximum in 2002 (Orvik & Skagseth 2003).

Temperature data and biological samples

Seawater temperature and salinity measurements along West Spitsbergen were collected by use of a SeaBird Electronics SBE911-plus CTD (Conductivity Temperature Depth) on UNIS cruises with R/V *Håkon Mosby* in 2002 and 2004, and R/V *Sarsen* in 2003. The CTD instruments were calibrated with bottle samples, and the uncertainty of the CTD salinities after calibration is typically 0.001. Remotely sensed images of SST was made by the Moderate Resolution Imaging Spectroradiometer (MODIS) deployed on the Aqua satellite (EOS PM, MODIS Land Rapid Response Team, NASA/GSFC) with a resolution of 4 km $pixel^{-1}$. Revisit time of MODIS is 1-2 days. All biological samples were collected by SCUBA-divers in August and September 2004. The tidal amplitude in Isfjorden is ~1.3m.

Abbreviations used in the text: Atlantic Water (AW), Arctic Water (ArW), North Cape Current (NCC), Norwegian Atlantic Current (NwAC), Norwegian Atlantic Slope Current (NwASC), Sea Surface Temperature (SST), West Spitsbergen Current (WSC).

RESULTS AND DISCUSSION

Blue mussel population

The population of blue mussels was discovered in August 2004 south east of the rocky islet Sagaskjæret, Isfjorden (Fig. 1C) at 4 – 7 m depth. Our data indicates that a seeding stock of blue mussel larvae, originating from the Norwegian coast, has been transported by the WSC, settled down at the mouth of Isfjorden and eventually established a viable population (Fig. 1B-C). The site is close to a locality where remains of Holocene blue mussels, radiocarbon dated to ~7,200 years BP, are in abundance (Fig. 2), and was characterised by an uneven distribution of mussels with about 0,5 individuals pr. m^2. Eleven specimens were haphazardly collected ranging from 2.7 - 5.5 cm in length. Most specimens were 2.7 - 3.4 cm, whereas the largest was 5.5 cm in length.

Transportation of larvae

The NwASC has its shortest distance (Orvik & Niiler 2002, Orvik & Skagseth 2003) to the Norwegian coastline in the Lofoten / Vesterålen area (69°N). North of this site the NwASC is dividing (Fig 1B) into the NCC and the WSC, leading into the Barents Sea and to west Spitsbergen, respectively. A seeding stock area of larvae in coastal waters of the Norwegian coast at 69°N yields the fastest and hence the most logical transport route for blue mussel larvae in order to reach Svalbard. The total longevity of the pelagic larvae-stages (trochophora-, veliger- and pediveliger larvae) is usually up to 4 weeks, but may be extended in suboptimal (e.g. low temperatures) conditions (Bayne 1965, 1976). Based on an average current speed of 0.30-0.35 m s^{-2} (Orvik & Niiler 2002, Schauer et al. 2004) the longevity of larvae matches our estimated transport time of 32-38 days (Fig. 1C). The transport time for larvae originating further south in the North Atlantic and sub-Arctic region would significantly exceed the longevity of blue mussel larvae, whereas larvae originating further north are transported into the Barents Sea and not northwards to Svalbard (Fig. 1C). Transportation of blue mussel larvae by the NwAC is considered the most logical route of dispersal, as ballast water arriving to either of the two ports (Barentsburg and Svea) consists strictly of off-shore waters (at latitudes of approximately 70°N). In addition, ballast water is emptied while loading cargo-ships in the port (*pers com.* and local environmental guidelines), hence at a long distance from the site in question here; Sagaskjæret at the mouth of Isfjorden.

Spawning of blue mussels is highly temperature dependent and occurs typically at temperatures around 8-10°C (Bayne 1965, 1976, Hovgaard et al. 2001). Based on remotely sensed monthly average SST data (MODIS-Aqua), the western and northern coastline of Norway typically reaches an SST of 10°C in June. Thus, combining estimated transport time and temperature data from the seeding stock area, larvae will not reach the shelf region outside Isfjorden before July-August. Based on both the size of the observed mussels, and the absence of spats and fully developed specimens in exposed areas of Sagaskjæret, all observed mussels must be older than one year and thus also have survived at least one winter. The absence of spats in August-September 2004, during two site examinations by means of SCUBA diving, indicates a lack of both local reproduction and transport of larvae in 2004. Furthermore, all mussels found were partly covered with coarse sediments, well protected from ice scouring in leads or cracks in the bedrock. The lack of blue mussel spats and fully developed specimens in exposed areas or in the intertidal zone, is primarily related to ice scouring at 0-4 m depth (no perennial kelp forest found < 4 m depth). The largest mussel (5.5 cm) had well-developed gonads, and both sides were overgrown with bryozoans and cirripeds, indicating that it is at least one year older than the other specimens which had only very little epifauna. The development of gonads is shown to be either delayed or totally impeded in water temperatures below 7°C (Honkoop & van der Meer 1998). A recent study from Iceland (Thorarinsdóttir & Gunnarson 2003), however, reported a continuous, although strongly delayed gonad development at temperatures approaching 0°C. The developed gonads and epifauna on the largest (oldest) specimen suggest that settlement of mussels have occurred at least in two different time-periods at Sagaskjæret.

The heat transport and its variation in the Barents Sea-Svalbard area is mainly determined by the influx (Bower et al. 2002, Loeng 1991) of AW, Fig.1B), and affect the Svalbard Archipelago mostly along the western coast (Fig 1B). Based on inter-annual variations in remotely sensed SST (Fig. 3A-C) and *in situ* measurements (Fig. 3D-E) west of Spitsbergen in 2002 - 2004, we hypothesise that the majority of blue mussels were transported as larvae in unusual warm water by the WSC from the mainland of Norway up to Spitsbergen during the summer of 2002 (Fig. 3). The settlement and growth of larvae to adult mussels at Sagaskjæret in Isfjorden was made possible due to an increased autumn SST in 2002 that also was evident in 2003 (Fig. 3A-C). This flux of AW into Isfjorden in August and September 2002 is confirmed by the anomalous appearance of the temperate planktonic diatom *Skeletonema costatum*, in addition to mass appearance (*pers obs*.) of Atlantic cod (*Gadus morhua*) and Atlantic salmon (*Salmo salar*). Isfjorden is a broad fjord with no distinct sill at the mouth, and it is therefore directly linked to the shelf and slope area along West Spitsbergen where AW is guided from the WSC in towards the mouth of the fjord. The WSC has been considered as the major pathway both for heat and water volume export to the Arctic Ocean (Aagaard & Greisman 1975), and it is especially the part of the WSC confined over the upper part of the continental slope of Spitsbergen (i.e. the warm core of the WSC) which feeds the major input of heat into the Arctic Ocean (Schauer et al. 2004, Gammelsrød & Rubels 1983, Aagaard et al. 1987, Fig. 1B). Hydrographic measurements have been conducted every autumn along West Spitsbergen and in Isfjorden since 1999, and these show that autumn 2002 was a special year during which AW managed to enter Isfjorden (Fig. 3D and G). The same abnormal situation in 2002 was also reported from Storfjorden (south-east of Isfjorden), with AW being the dominant water mass (Skogseth et al. *in press*). The shelf areas outside Isfjorden were also flushed with AW in 2003 (Fig. 3E and H), but these water masses did not penetrate into Isfjorden and other fjords around Svalbard. The along-shore wind component was an important factor controlling this interannual variability. During summer and early autumn, when the fjords and shelf waters have a two-layered stratification (Fig. 3G-I), the normal wind direction is from south south-east. This is not a favourable direction for transporting AW onto the shelf areas, as explained by a two-layered costal upwelling model and the concept of wind impulse (Cushman-Roisin et al. 1994) (Fig. 4A). But, a northerly wind along the West Spitsbergen (Fig. 4B) coast will produce an offshore Ekman drift of cold and fresh water with a compensating onshore transport of the warm and saline in the lower layer, thereby increasing the topographically steered flow of AW towards Isfjorden (confirmed by numerical model simulations using the Bergen Ocean Model, *unpublished*). By using hindcast wind stress data (Reistad & Iden 1998) from the shelf area, the direction of the wind impulse was calculated during June and July for the six years 1999-2004. From these data, it is evident that 2002 was characterised by a wind impulse from the north. Thus, in addition to a generally augmented northward volume transport in the North Atlantic (Orvik & Skagseth 2003) in 2002, the northerly wind impulse along western Spitsbergen further provided increased opportunities for AW, and hence also blue mussel larvae, to enter Isfjorden. The offshore transport in the surface layer (Fig. 3G-I) also reduces the probability of any blue mussel larvae being transported to Svalbard by way of ballast water to eventually reach and settle at Sagaskjæret.

Reliability of *Mytilus edulis* as a temperature indicator

It has recently been argued (Feder et al. 2003) that the distributional pattern of *Mytilus edulis* and *M. trossulus* is not a reliable indicator of temperature changes, as mussels may form refugee populations in areas with highly variable salinity conditions in order to avoid predation. We argue that salinity is not a relevant factor for the distribution of blue mussels at the Norwegian coast and Svalbard, as salinity levels here are relatively higher and more constant than in Arctic Alaska. Also, most of the localities around Svalbard, where ^{14}C dated blue mussels have been found, are more comparable to those at Sagaskjæret today (Fig. 2) than any of the relict populations in Arctic Alaska. The environmental conditions at Sagaskjæret today are characterised by a strong and year-round influx of warm and saline modified AW from WSC, which provides ample conditions for the most important predators of blue mussels (Feder et al. 2003). In addition, despite intensive sampling along the western coast of Spitsbergen during the last 30 years, no evidence of settled blue mussels have been obtained. Sagaskjæret in particular has been used as a regular sampling locality by scientific divers from UNIS for the decade. These factors (key environmental variables such as temperature, salinity, influx of AW in addition to the negative observations) combined thus diminish the probability of Isfjorden holding a relict population similar to those in Arctic Alaska.

CONCLUDING REMARKS

Our analyses of the physical ocean conditions affecting the Svalbard archipelago and the newly discovered population of blue mussels discovered at Sagaskjæret, Isfjorden, support the hypotheses that the population is young, partly established during the summer/autumn of 2002, and that it is founded by larvae carried up to Spitsbergen by the WSC. However, regardless the means of transportation, SST on the west coast of

Svalbard have for the last 2-3 years been sufficiently high to sustain survival, growth and gonad production of blue mussels.

Acknowledgements. The authors are grateful for the help of S. Frantzen (HiF, Norway), C. von Quillfeldt (NP, Norway), A. Wolfe (UNIS), B. Jakobsen (UNIS), H. Christiansen (UNIS) and R. Langvatn (UNIS) for their help during the process of writing this manuscript. The first three authors contributed equally to this work throughout the process, whereas the fourth author contributed mostly during fieldwork and the initial part of planning the manuscript.

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LEGENDS TO THE FIGURES:

Fig. 1 a. Estimated SST (°C) from the western Barents shelf from 13,000 years to present (reproduced with permission from M. Sarnthein: Sarnthein et al. 2003), and the relative abundance of radiocarbon dated blue mussels in the Svalbard archipelago (data taken from Salvigsen 2002), (b) Aqua Satellite (MODIS instrument) image of cumulative SST from 1.7.2002-31.8.2004 showing warm and saline NwASC flowing along the shelf break of the Norwegian coast, separating into the NCC and the WSC. Svalbard (Sv). The yellow square indicates sampling site of the core used to estimate Holocene climate condition (Sarnthein et al. 2003), (c) Modelled transport route of NwASC-WSC water from the Lofoten / Vesterålen area (69°N) to Isfjorden (78°N).

Fig. 2. *In situ* picture August 2004 of a blue mussel from Sagaskjæret (upper, ~30 mm length) and a Holocene 7250±660 cal yr BP (AAR-9452) blue mussel from Kapp Linné (lower, ~5 cm) found by H. Christiansen, UNIS.

Fig. 3 a-c. MODIS images of cumulative SST for August 2002, 2003 and 2004 (see Fig. 1 for colour scale), (d-i) CTD sections collected on the shelf and slope areas outside Isfjorden in positions indicated by green circles in Fig. 1c. Black thick marks on top of each section correspond to the green circles in Fig. 1c. Temperature (d-f) sections and salinity sections (g-i) were collected in autumn 2002 (d, g), 2003 (e, h) and 2004 (f, i). The sections start from the warm core of WSC confined to the steep slope on the hand left side, and ends up in the mouth of Isfjorden on the right hand side.

Fig. 4 a. “Normal” autumn current-system (a) and the unusual 2002 situation (b) in Isfjorden and the adjacent shelf areas. The red thick arrows depict the AW branch emanating from the WSC and flowing in the layers below the surface layer towards the mouth of Isfjorden trough topographical steering. The isobaths are contoured on data from The Norwegian Hydrographic Service and blue dots gives the positions of the eastern most stations in the CTD sections (Fig. 3d-i), (a) in “normal” years with a southerly wind (black arrow) component, AW flowing towards Isfjorden is not allowed to enter the mouth of Isfjorden as a front system is created between inflowing AW and a westwards wind induced counter flow in the sub-surface layers (e.g. Fig. 3h), (b) in 2002, this front was absent, mainly due to a week northerly wind (black arrow) component, and hence, AW were able to penetrate towards the mouth of Isfjorden and further into the fjord.

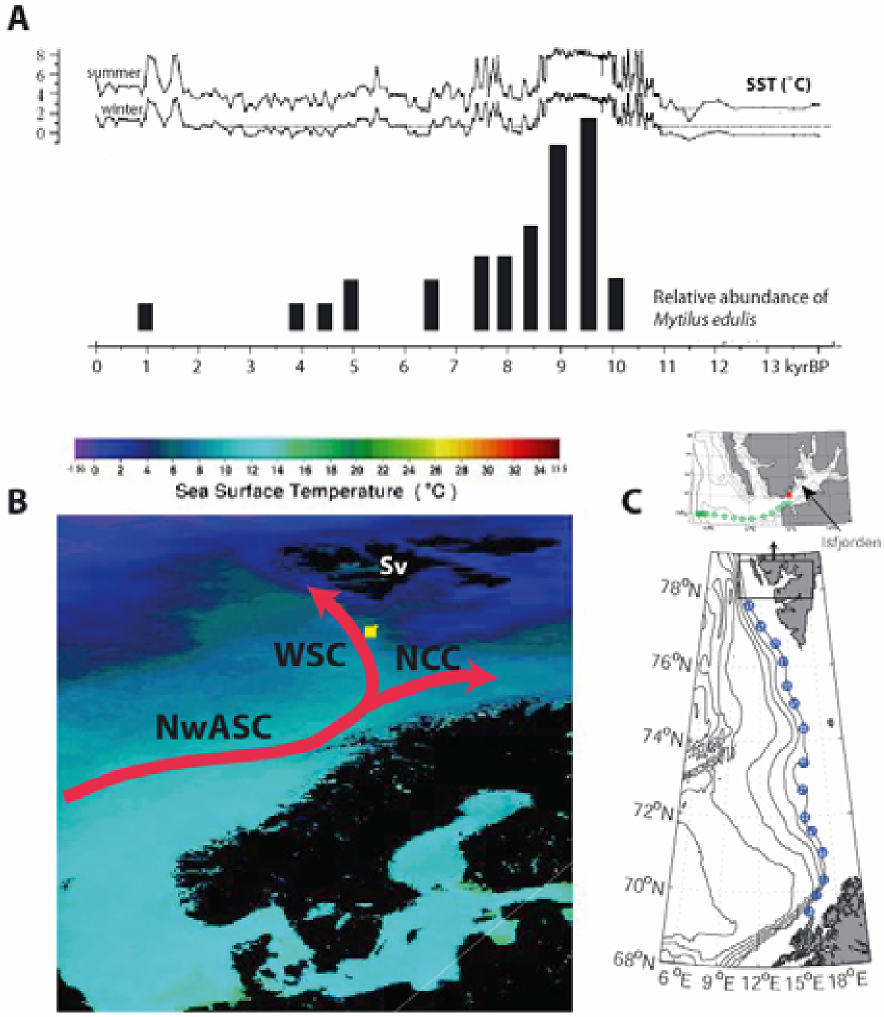

A
summer
winter
SST (°C)
Relative abundance of
Mytilus edulis
0 1 2 3 4 5 6 7 8 9 10 11 12 13 kyrBP
Sea Surface Temperature (°C)
B
Sv
WSC
NCC
NwASC
C
Isfjorden
78°N
76°N
74°N
72°N
70°N
68°N
6°E 9°E 12°E 15°E 18°E

Figure 1

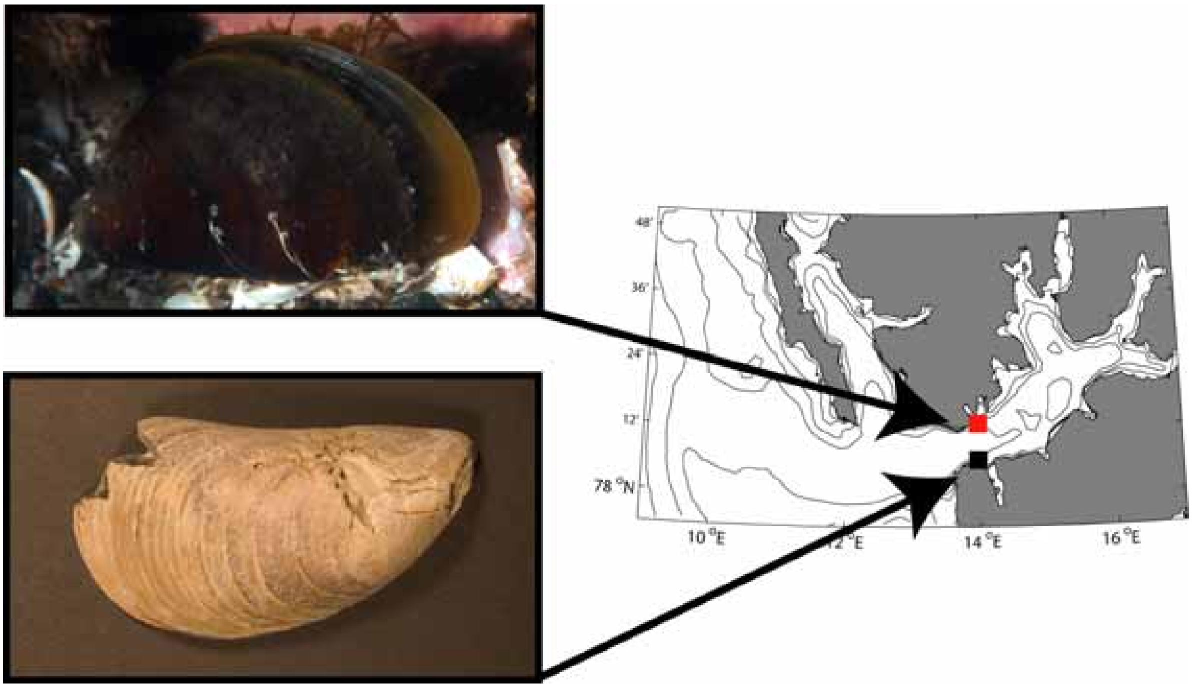
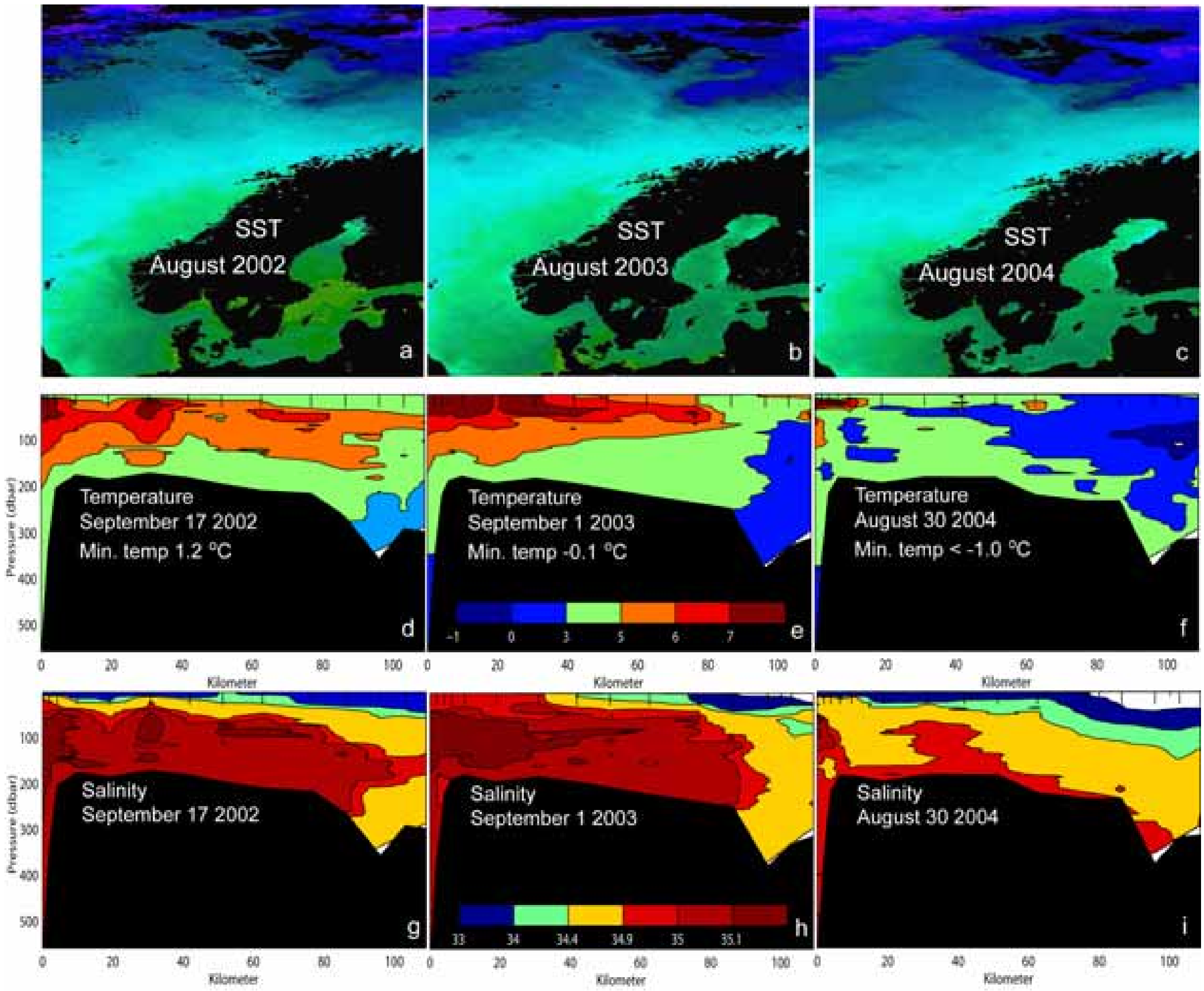


Figure 2



SST
August 2002
a
SST
August 2003
b
SST
August 2004
c
Temperature
September 17 2002
Min. temp 1.2 °C
d
Temperature
September 1 2003
Min. temp -0.1 °C
e
Temperature
August 30 2004
Min. temp < -1.0 °C
f
-1 0 3 5 6 7
Pressure (dbar)
Kilometer
Salinity
September 17 2002
g
Salinity
September 1 2003
h
Salinity
August 30 2004
i
33 34 34.4 34.9 35 35.1

Figure 3

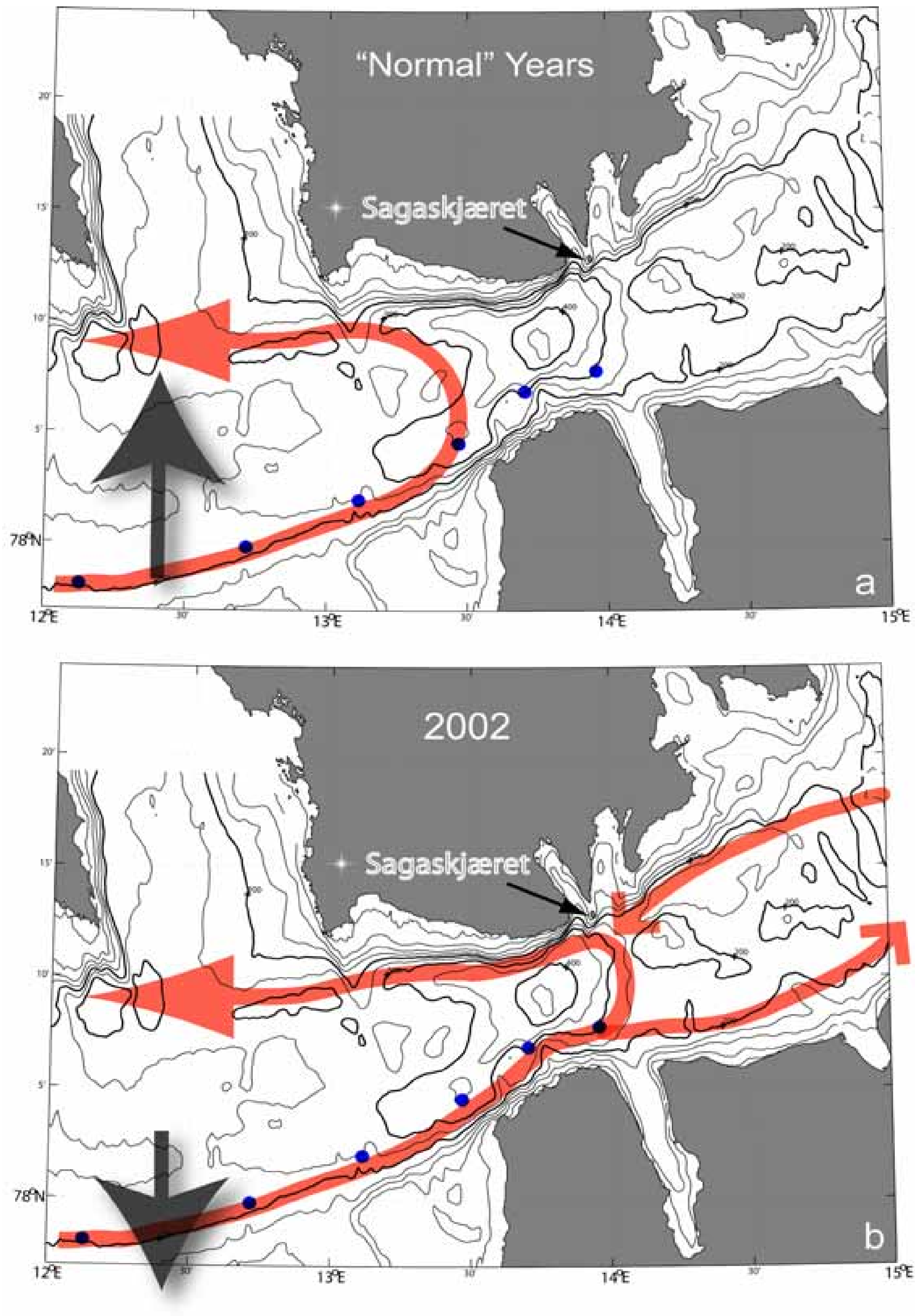

"Normal" Years
Sagaskjæret
a
2002
Sagaskjæret
b
78°N
12°E
13°E
14°E
15°E

Figure 4