Chapter 2
Volume and Heat Transports to the Arctic Ocean Via the Norwegian and Barents Seas

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2.1 Introduction

The first comprehensive description of physical conditions in the Norwegian – and the Barents Seas was provided by Helland-Hansen and Nansen (1909), who described both the two areas individually and the relationships between them. They indicated a 2-year delay in the temperature signal from Sognesjøen (west coast of Norway at about 61° N) to the Russian Kola section, and suggested that this time lag could be used to predict temperature conditions in the Barents Sea on the basis of upstream observations. Helland-Hansen and Nansen also pointed out that variations in physical conditions had great influence on the biological conditions of various fish species, and that ocean temperature variations "are the primary cause of the great and hitherto unaccountable fluctuations in the fisheries". The importance of climate impact on marine organisms at high latitudes has recently been well documented in the Arctic Climate Impact Assessment report (ACIA 2005).

The Norwegian Sea, the Greenland Sea and the Iceland Sea comprise the Nordic Seas, which are separated from the rest of the North Atlantic by the Greenland–Scotland Ridge (Fig. 2.1). The Norwegian Sea consists of two deep basins, the Norwegian Basin and the Lofoten Basin, and is separated from the Greenland Sea to the north by the Mohn Ridge. To the west, the basin slope forms the transition to the somewhat shallower Iceland Sea. The upper ocean of the Nordic Seas consists of warm and saline Atlantic water to the east, and cold and fresh Polar water from the Arctic to the west. The Barents Sea, with an average depth of 230 m, is one of the shallow shelf seas that constitute the Arctic continental shelf. Its boundaries are defined by Norway and Russia in the south, Novaya Zemlya in the east, and the continental shelf breaks

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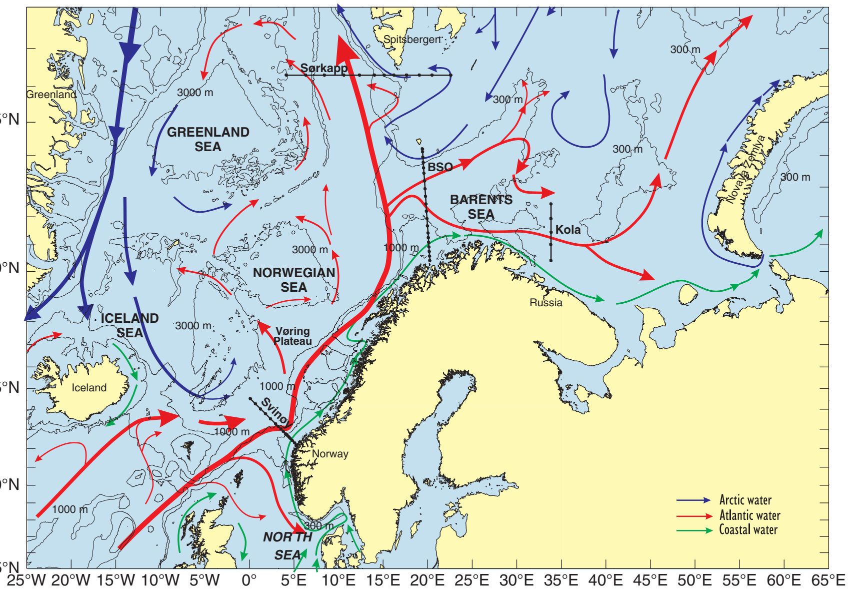

Fig. 2.1 Schematic map of the study area showing the major upper ocean currents and the repeated hydrographic sections used in this chapter; the Svinøy Section, the Barents Sea Opening, the Kola section and the Sørkapp section

towards the Norwegian and Greenland Seas and the Svalbard Acrhipelago in the west and northwest and the Arctic Ocean in the north (Fig. 2.1).

The Norwegian and Barents seas are transition zones for warm and saline waters on their way from the Atlantic to the Arctic Ocean. The major current, the Norwegian Atlantic Current (NwAC), is a poleward extension of the Gulf Stream and the North Atlantic Current, that acts as a conduit for warm and saline Atlantic Water from the North Atlantic to the Barents Sea and Arctic Ocean (Polyakov et al. 2005). As Fig. 2.1 shows, the North Atlantic Current splits into two branches in the eastern North Atlantic before entering the Norwegian Sea over the Iceland–Faeroe Ridge close to the eastern coast of Iceland, and through the Faeroe–Shetland Channel close to Shetland (Fratantoni 2001; Orvik and Niiler 2002). The water then continues in two branches through the entire Norwegian Sea toward the Arctic Ocean (Poulain et al. 1996; Orvik and Niiler 2002). The western branch is a jet associated with the Arctic Front. It tends to feed the interior of the Norwegian Sea via several recirculation branches. The eastern branch, known as the Norwegian Atlantic Slope Current (NwASC), is an approximately 3,500 km long, nearly barotropic shelf edge current flowing along the Norwegian shelf break, that tends to flow into the Barents Sea and Arctic Ocean. The NwASC is thus the major link between the North Atlantic, and the Barents Sea and Arctic Ocean.

In the Barents Sea, the relatively warm Coastal and Atlantic waters that enter between Bear Island and northern Norway, hereafter called the Barents Sea Opening, dominate the southern regions. As they transit the Barents Sea, the Atlantic water masses are modified through mixing, atmospheric cooling, net precipitation, ice freezing and melting, before exiting primarily to the north of Novaya Zemlya (Loeng et al. 1993). This transformation is important for the ventilation of the Arctic Ocean (Schauer et al. 2002; Rudels et al. 2004). The Norwegian Coastal Current mixes with river water to form low-salinity shelf waters (Rudels et al. 2004). Atlantic water has a typical temperature range between 4.5 °C and 6.5 °C but varies seasonally and interannually (Midttun and Loeng 1987). Arctic waters ($T < 0$ °C, $34.3 < S < 34.7$) dominate the northern Barents Sea, entering between Franz Josef Land and Novaya Zemlya and to a lesser degree between Franz Josef Land and Spitzbergen.

Variations in the properties and volume transport of Atlantic water have a major impact on the oceanographic conditions of the Barents Sea over a broad range of timescales (Loeng et al. 1992), and both in the Barents and the Norwegian Seas large-scale atmospheric circulation changes influence the currents and hydrographic conditions. Since the 1960s, changes in the large-scale wind pattern, principally the North Atlantic Oscillation (NAO), have resulted in a gradual change of the water mass distribution in the Nordic Seas. In particular, this is manifested by the development of a layer of Arctic intermediate waters, deriving from the Greenland and Iceland Seas and spreading over the entire Norwegian Sea (Blindheim et al. 2000). In the Norwegian Basin it has resulted in an eastward shift of the Arctic front and, accordingly, an upper layer cooling in wide areas due to increased Arctic influence. Blindheim et al. (2000) also found that the westward extent of Atlantic water in the Norwegian Sea was less during the high phase of the North Atlantic Oscillation than during the low phase, with the difference between its broadest recorded extent in 1968 and its narrowest extent in 1993 exceeding 300 km. This implies that a stronger cyclonic atmospheric circulation pattern would move the surface waters to the east. This would decrease the area of Atlantic water and thus reduce ocean-to-air heat losses, and could contribute to a warmer Atlantic inflow to the Barents Sea in positive NAO years. In the Barents Sea, higher temperatures are found during positive phases of the NAO index (Dickson et al. 2000). The fluctuations in the strength of the inflow, as measured at the western entrance between northern Norway and Bear Island, depend mainly on the atmospheric circulation (Ingvaldsen et al. 2004a, b).

The present paper offers an overview of the transport of Atlantic water and its properties along the Norwegian Coast and into the Barents Sea. Section 2.2 presents the mean state of currents and hydrography in the Norwegian Sea and in the Barents Sea Opening, followed by an overview of variability at various scales in Section 2.3. Suggested forcing mechanisms for the variability are discussed in Section 2.4 before the paper is summarized and concluded in Section 2.5.

2.2 The Mean State

2.2.1 The Mean Hydrography and Current Structure in the Svinøy Section

The Svinøy section runs northwestward from the Norwegian coast at 62° N and cuts through the entire Atlantic inflow to the Norwegian Sea just to the north of the Iceland–Scotland Ridge. It is thus a key location for comprehensive monitoring of the Atlantic inflow to be used as an upstream reference for the Barents Sea and the Arctic Ocean. Monitoring of the Svinøy section started in the mid-1950s with repeated hydrographic sections, and current measurements commenced in 1995.

We define the Atlantic inflow in the Svinøy section to be water with salinity above 35.0 (Fig. 2.2). This corresponds to a temperature of about 5 °C, and is the definition used by Helland-Hansen and Nansen (1909). By using high-resolution SeaSoar-CTD methodology, the hydrographic field reveals a nearly slab-like extension of warm saline Atlantic water (Orvik et al. 2001). The slab extends about 250 km northwestwards from the shelf break where the interface outcrops the surface and forms a sharp front (the Arctic front) between the Atlantic and Arctic waters. Toward the coast it leans on the shelf slope above the 600 m isobath. This is in contrast to the historical view of the Atlantic water as a wide wedge-shape westward extension. In summer a surface layer of fresh coastal water can be observed in the section. In summers with stronger northerly winds the coastal water tends to extend further westward in the Norwegian Sea than in summers with no or weaker northerly winds (Nilsen and Falck 2006). During the winter this layer disappears as it mixes with the Atlantic water. Arctic intermediate water, situated between the Atlantic and deep-water masses, can also be observed in Fig. 2.2 as a water mass with salinity below 34.9.

The slab-like average hydrographic feature mirrors the baroclinic flow as a frontal jet in accordance with the western branch of the NwAC. By using Vessel Mounted-ADCP transects the western branch of the NwAC has been identified as an unstable and meandering jet in the Arctic Front. In average, the jet is about 400 m deep and 30–50 km wide, located above the 2,000 m isobath. Observations show a maximum speed of 60 cm s^{-1} in the core at a depth of about 100 m.

Over the shelf-slope our moored array has captured the eastern branch of the NwAC as an approximately 30–50 km wide nearly barotropic current, trapped along the topography between 200 and 800 m depth. The annual mean appears as a stable flow, 40 km wide and with a mean velocity of about 30 cm s^{-1} (Fig. 2.2). Accordingly, the volume flux of the slope current can be estimated based on one single current meter in the core of the flow (Orvik and Skagseth 2003a, b), resulting in an average of 4.3 Sv (1 Sv = 10^6 m^3s^{-1}) for the period 1995–2006.

2.2.2 Mean Structure of the Hydrography and Currents in the Barents Sea Opening

In the Barents Sea Opening repeated hydrographic sampling has been performed since the mid-1960s, and current measurements since 1997. Atlantic water, defined as water with salinity above 35.0 and temperature above 3 °C,

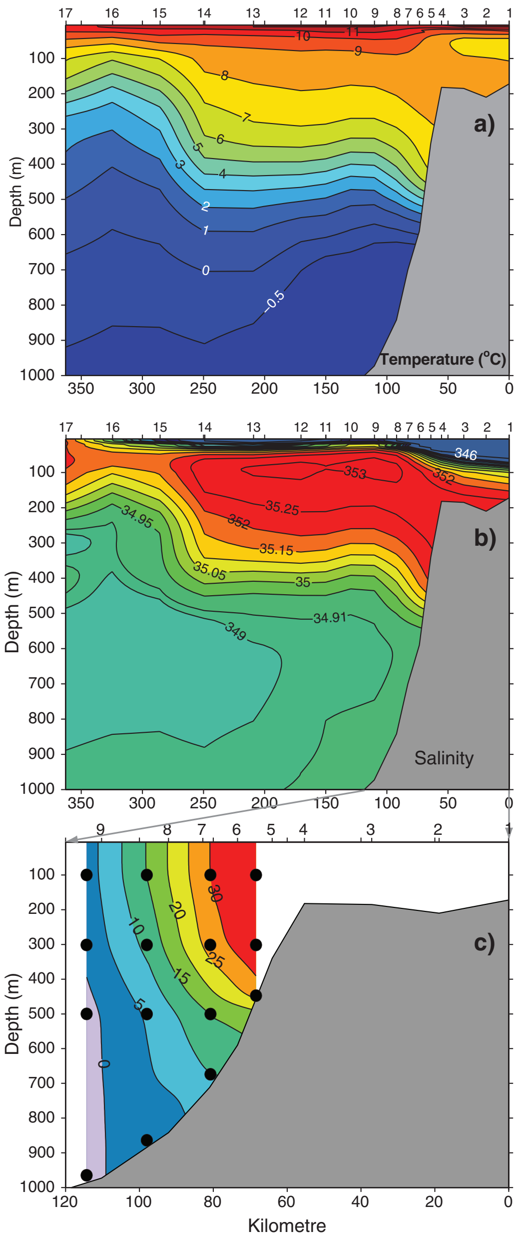

Fig. 2.2 Temperature (upper) and salinity (middle) in July 1998, and mean velocity (lower) in the Svinøy section

occupies most of the section (Fig. 2.3). Above the Atlantic water there is a surface layer of warmer and fresher water. During the winter the surface layer breaks down and Atlantic water extends to the surface. Between the Atlantic

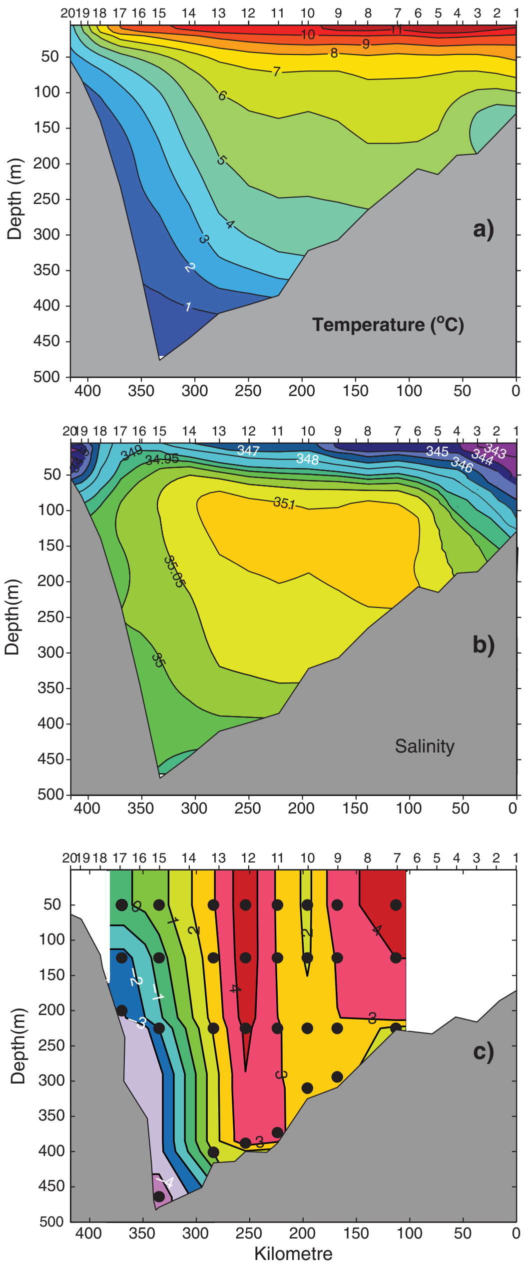

Fig. 2.3 Temperature (upper) and salinity (middle) in August 1998, and mean velocity (lower) in the Barents Sea Opening

inflow and the Norwegian Coast, the Norwegian Coastal Current flows north-eastwards into the Barents Sea. The temperature of the Coastal water is about the same as in the Atlantic water, but the salinities are lower ($S < 34.7$). During winter the Norwegian Coastal Current is deep and narrow, while during summer it is wide and shallow and spreads northwards as a wedge overlying the more saline Atlantic water (Sætre and Ljøen 1971). The northward extent of the upper layer is subject to large inter-annual variations, but in years with favourable wind directions it may reach the middle of the section (Olsen et al. 2003). The shelf slope south of Bear Island is occupied by a mixture of Arctic and modified Atlantic water masses.

Compared to the mean velocities in the Svinøy section of about 30 cm s^{-1} (Fig. 2.2) the mean currents in the Barents Sea Opening are weak (Fig. 2.3). The Atlantic water entering the Barents Sea have a more unstable core and the inflow can form a wide branch, centred close to 72° 30′ N, a relatively narrow inflow in the south accompanied by a wide outflow in the north, or an inflow comprising several branches with return flows or weaker inflows between them (Ingvaldsen et al. 2004a). Daily mean velocities in the Atlantic water core may reach 20 cm s^{-1}, but the long-term means are generally much weaker. In the Norwegian Coastal Current, that is, shoreward of the present mooring array, Blindheim (1989) found mean velocities of about 15 cm s^{-1} based on a 1-month measuring period. The dense current that leaves the Barents Sea in the deepest part of the Barents Sea Opening has mean velocities of 5 cm s^{-1}.

2.3 Variations

2.3.1 Long-Term Hydrographic Changes in the NwAC and the Propagation of Anomalies

The longest instrumental record of the Barents Sea climate is from the Kola section (Bochkov 1982; Tereshchenko 1997, 1999). Focusing on the multidecadal scales, the series shows substantial variations; cold at the beginning of the 20th century, a warm period in the 1930–1940s, followed by a cold period in the 1960–1970s and finally, a still ongoing warming (Fig. 2.4). In order to illustrate the spatial scale of this variation a comparison with the Atlantic Multidecadal Oscillation (AMO) index of Sutton and Hodson (2005), representing the large-scale sea surface temperature variation in the Atlantic, is shown. This record, extending back to the 1870s, shows a remarkable similarity with that of the Kola section, demonstrating that the climatic variation found in the Kola section is a local manifestation of a larger-scale climate fluctuation covering at least the entire North Atlantic Ocean.

The properties of the Atlantic water that enters the Norwegian Sea change as we move northwards along the Norwegian continental slope toward the Barents Sea and the Arctic Ocean. Both temperature and salinity are reduced due to mixing with the fresher Norwegian Coastal Current, the colder, less saline Arctic water from the west, and by net precipitation and heat loss to the atmosphere.

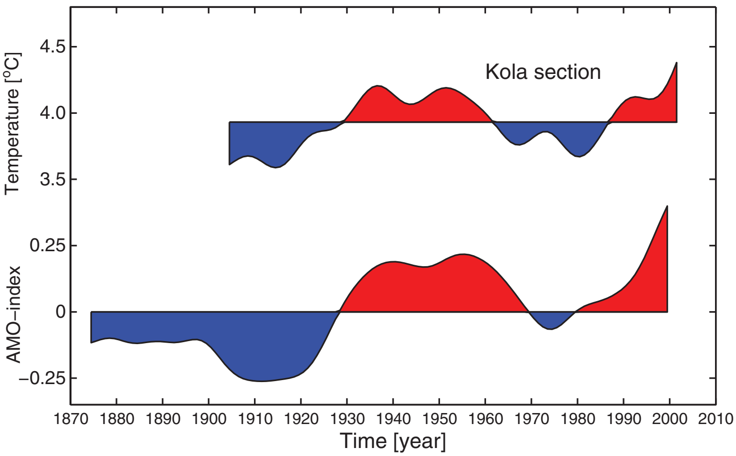

Fig. 2.4 Time series of the Kola section mean temperature (upper graph) and the Atlantic Multidecadal Oscillation (AMO) index (lower graph). The series were filtered using a two-way 14-year Hamming window. The AMO index is based on the sea surface temperature in the region 0–60° N and 7.5–75° W. The Kola section data were obtained from PINRO

In order to identify these changes, temperature and salinity variations in the core of the Atlantic water at three key sections are shown; in the Svinøy section, which represents the starting point of the northward transit, and in the Sørkapp section and the Barents Sea Opening, which represent the two major exits from the Norwegian Sea (Fig. 2.5). The temperature variation in the Barents Sea Opening has been shown to be representative of climate variability in the western Barents Sea (Ingvaldsen et al. 2003). The northward cooling of the Atlantic water is clearly seen in the temperature series, with long-term means of 7.9, 5.3 and 4 °C, respectively for the Svinøy section, Barents Sea Opening and Sørkapp section. Long-term mean salinities are 35.23 for the Svinøy section and about 35.07 for both the Barents Sea Opening and Sørkapp section. Since the late 1970s the temperature has increased in all three sections and all-time high values have been recorded in the past few years, except for a relative cooling in the Svinøy section in 2005. However, in 1960 the temperature for the Svinøy section was at similar level as during the last years. During the period with current measurements in the Svinøy section and the Barents Sea Opening there have been increases of temperature and salinity of 1.0 °C and 0.1, respectively in all three sections. The temperature time series from the current meters in the Svinøy section and Barents Sea Opening display similar trends to those from the hydrographic sections.

The largest change in salinity was during the late 1970s, when the Great Salinity Anomaly (GSA) passed through the Norwegian Sea (Dickson et al. 1988). However, there are several low temperature and salinity anomalies in the time series: in the late 1970s, late 1980s and mid-1990s. Several authors have explained

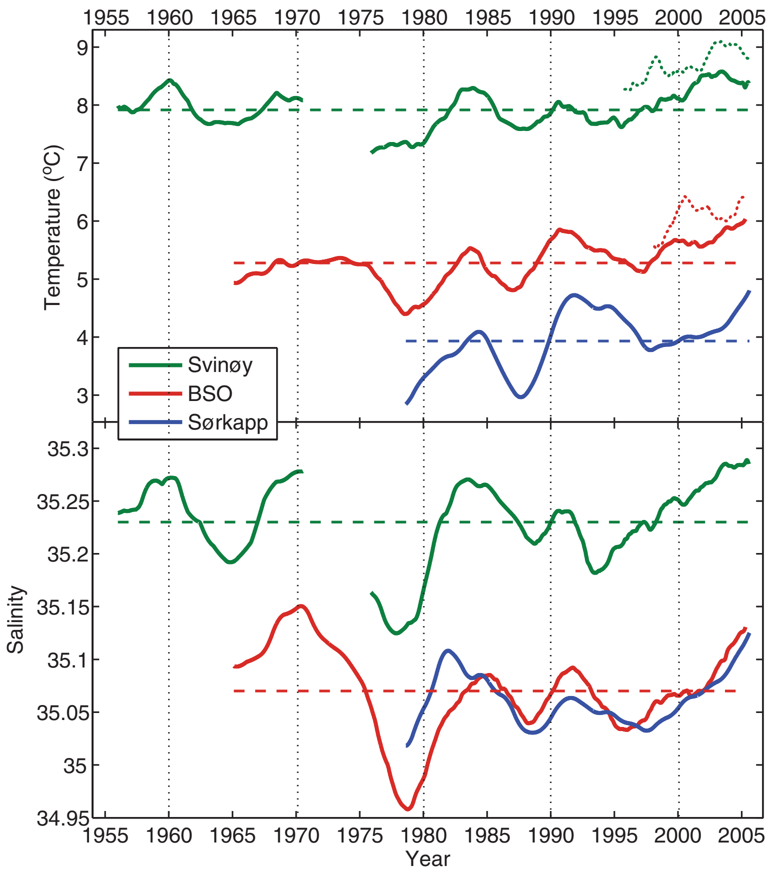

Fig. 2.5 Time series of temperature and salinity in the core of Atlantic water for the Svinøy section, Barents Sea Opening and Sørkapp section. The data from both the Svinøy section and Barents Sea Opening are de-seasoned. The Sørkapp section includes data obtained in August/September only. Before 1977, the data in the Svinøy section is from winter only and the data from the Barents Sea Opening is from August only. Three years moving averages are applied on all data for the three sections. The temperature data from the current meters in the Svinøy section and the Barents Sea Opening are also included (dotted lines). For these data a 1-year running average was applied, due to the relatively short time series

these anomalies by a strong outflow of Polar water from the Arctic Basin that propagated anti-clockwise around the North Atlantic before reaching the Norwegian Sea several years later (Dickson et al. 1988; Belkin et al. 1998; Belkin 2004). In addition to this advective view of the propagation of salinity anomalies, Sundby and Drinkwater (2006) proposed that salinity anomalies, through the greater gyre of the northern North Atlantic, are caused by changes in volume fluxes along salinity gradients. The high temperature and salinity values observed during the past few years have also been monitored in the Faeroe–Shetland Channel. These extremes are associated with a weakening of the Sub-polar Gyre circulation (Häkkinen and Rhines 2004), resulting in a larger northward flow of subtropical Atlantic water from the northeastern Atlantic to the Nordic Seas (Hátun et al. 2005). The large salinity anomalies observed the last years are not exceptional in the Barents Sea Opening, as the highest salinity value was observed in 1970.

In most cases both the temperature and salinity anomalies fluctuate in phase at the different locations, but with a certain time lag. However, the magnitude of the propagated anomalies might be damped or amplified northward and in some cases the anomalies are also generated within the Nordic Seas (Furevik 2001). While the warm anomaly in the first half of the 1980s weakened to the north, the warm anomaly in the early 1990s became stronger as it propagated northwards, due to anomalous high air temperature in the Nordic Seas associated with an extreme positive NAO index around 1990 (Furevik 2001).

2.3.2 Variations in Flux Estimates in the Svinøy Section and the Barents Sea

The NwASC in the Svinøy section and the Atlantic flow in the Barents Sea Opening show fluctuations over a wide range of time scales, from weeks to months, seasons and years (Fig. 2.6). The 12-month moving average values range from 3.7 to 5.3 Sv with a mean of 4.3 Sv for the NwASC, and from 0.8 Sv to 2.9 Sv with a mean of 1.8 Sv for the Barents Sea Opening. Thus the Barents Sea Opening has only 45% of the mean flow of the NwASC but substantially greater inter-annual variability. The volume fluxes in the two sections show some co-variability. Both fell to a minimum in the winter of 2000–2001, and both showed a major increase from mid-2004 to the end of the time series in spring/early summer 2006. However, in 2002–2003, the fluxes diverged. Both increased toward the winter of 2002, but while the NwASC reached a relatively weak local maximum and started decreasing, the flux in the Barents Sea Opening kept increasing toward a strong local maximum in winter 2002–2003. A possible link to the atmospheric forcing is discussed in the following section.

There is a pronounced seasonal signal in both time series, although its strength varies in time. The NwASC seem to have a stronger seasonal signal before 2001 than after, while the opposite is the case in the Barents Sea Opening. These concurrent shifts in the seasonal cycle coincide with large-scale changes in the atmospheric circulation. Before 2001 the NAO winter index was mostly in a positive phase, while since 2001 it has been low and irregular.

When we consider the long-term changes in the volume flux, the NwASC shows no significant trend in the course of the measurement period 1995–2006 (Table 2.1). Orvik and Skagseth (2003b, 2005) found a downward trend of 12% in the velocity field for the period prior to 2005, but due to the strong increase in 2005–2006 (Fig. 2.6), this trend broke down when 2006 was included. In the

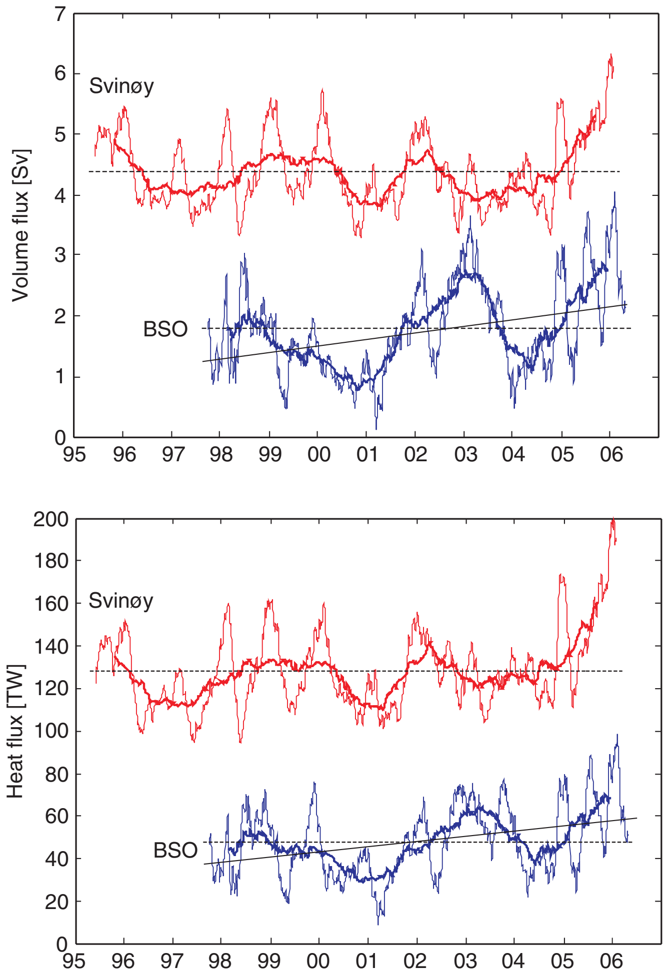

Fig. 2.6 Time series of volume (upper) and heat (lower) fluxes in the Svinøy section (red line) and the Barents Sea Opening (blue line). Lines showing the mean and, when significant, the trend, are included

Table 2.1 Mean fluxes and calculated annual trend when significant at 95% level

	NwASC (1995–2006)		BSO (1997–2006)	
	Volume flux (Sv)	Heat flux (TW)	Volume flux (Sv)	Heat flux (TW)
Mean	4.3	126	1.8	48
Trend (year^{-1})	Not significant	Not significant	0.1	2.5

Barents Sea Opening on the other hand, there is an upward trend of 0.1 Sv per year. Over the 9-year measurement period this trend suggests an increase in volume flux of 45% of the mean value. The strong trend is partly due to a strong increase in 2005–2006, but there was also a significant upward trend before 2005.

The 12-month running average heat flux ranges from 110 TW (1 TW = 10^{12} W) to 160 TW with a mean of 126 TW for the NwASC, and from 29 TW to 70 TW with a mean of 48 TW for the Barents Sea Opening. The variability in the heat flux closely resembles the variability in the volume flux, indicating that the heat flux variations are dominated by velocity fluctuations rather than temperature fluctuations (Fig. 2.6). In particular, this holds for the seasonal scale, where the heat flux is higher in spite of the fact that temperatures are lower during the winter than in summer. An example is during the maximum flux in the Barents Sea Opening in winter 2002–2003. The heat maximum was clearly caused by a velocity maximum (Fig. 2.6), but as the temperature was decreasing at the time (Fig. 2.5), the heat flux maximum was attenuated.

On inter-annual time scales the temperature variations become increasingly important (Orvik and Skagseth 2005). In the NwASC there are no significant trends, either for heat or for volume flux over the 11-year measurement period. Orvik and Skagseth (2005) found that a weak reduction in the velocity field was compensated for by a 1 °C increase in temperature (Fig. 2.5). In the Barents Sea Opening the annual upward trend in heat flux is 2.5 TW, suggesting an increase of 23 TW (48% of the mean value) in the course of 9 years. The trend in volume flux was significant also before 2005, although somewhat weaker. The trend in the heat flux is due to a positive trend in the volume flux combined with a 1 °C increase in temperature (Fig. 2.5).

2.4 Forcing Mechanisms

Identifying the forcing mechanisms for the NwAC into the Arctic is a major task. It will probably depend on the time scales, as we can expect different forcings to be important for mean flow than for fluctuations on for example daily or even monthly timescales. Here we will leave the question of whether the mean flow is wind- or thermohaline-driven, as these forcings are intrinsically linked. Instead we discuss observations and physical mechanisms of relevance to variations in the fluxes, with a major focus on the period of simultaneous mooring records along the Norwegian Coast.

Considering variations in the rate of Atlantic water flow through the Norwegian Sea and into the Barents Sea, there are two main questions. First, what is the driving force for the NwASC, i.e. the topographically trapped current along the Norwegian Continental Slope, and secondly, what determines which fraction of this water that will enter the Barents Sea?

The driving mechanism of the NwASC has been studied in detail on the basis of data from the Svinøy section. A major part of the variation in the Atlantic water flow in the NwASC can be linked to the passage of the atmospheric lows that typically originate southwest of Iceland and propagate northeastwards towards Scandinavia. The accompanying along-slope (coast) component of the wind is found to be a key driver of variations in the flow (Skagseth and Orvik 2002; Skagseth et al. 2004). The mechanism is through surface Ekman transports toward the coast, balanced by a deeper return flow that is transferred into an along-slope current (Adams and Buchwald 1969; Gill and Schumann 1974). On the basis of satellite altimeter sea-level anomaly (SLA) data, Skagseth et al. (2004) found coherent variations in the NwASC from west of Ireland to the entrance to the Barents Sea, forced by wind associated with variations in sea-level pressure (SLP) resembling the NAO pattern. A negligible phase lag clearly indicated barotropic transfer mechanisms.

The volume flux of Atlantic water entering the Barents Sea is highly dependent on the regional wind pattern in the Barents Sea Opening (Ingvaldsen et al. 2004a, b). They found that the variations in the inflow are due to surface Ekman transports toward the coast setting up sea-level gradients that in turn were balanced by flow into the Barents Sea, and argued that these effects were enhanced by divergent Ekman fluxes in the Barents Sea Opening. As for the NwASC, the inflow was strong when the SLP resembled a strong NAO pattern. Additionally, simple theory involving topographic steering implies that during periods of anomalous eastward/westward extent of the NwAC as observed by Blindheim et al. (2000) and Mork and Blindheim (2000), less/more water is recirculated in the Norwegian Sea and more/less water enters the Barents Sea. This has been shown in model runs with idealized (Furevik 1998) and real (Zhang et al. 1998) topography.

With these general considerations of the relevant forcing in mind, it is of interest to compare the records of the Atlantic water flow in the Svinøy Section and in the Barents Sea Opening, and their relationship with atmospheric forcing. The correlation between the monthly filtered mooring records from the Svinøy section and the Barents Sea Opening (starting in 1995 and 1997, respectively) has a maximum for velocity of r = 0.41 with zero lag, and a maximum for temperature of r = 0.65 with

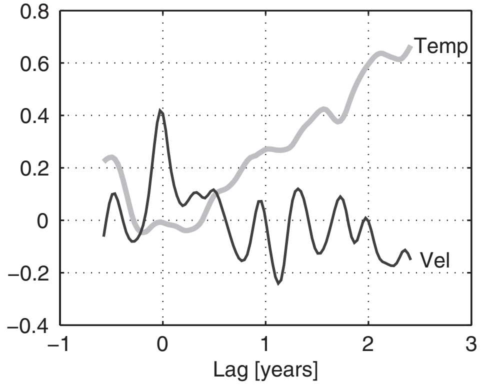

Fig. 2.7 Correlation functions based on the index series of velocity and temperature

a lag of 2 years (Fig. 2.7). The moderate correlation for the currents indicates that the local effective atmospheric forcing of the current at the two sites is different for at least part of the time.

In order to identify the atmospheric variations corresponding to different co-variations of the currents in Svinøy section and the Barents Sea Opening we considered SLP composite fields. The most frequently observed situations occurred when the anomalous currents were simultaneously either strong or weak. The case of anomalous

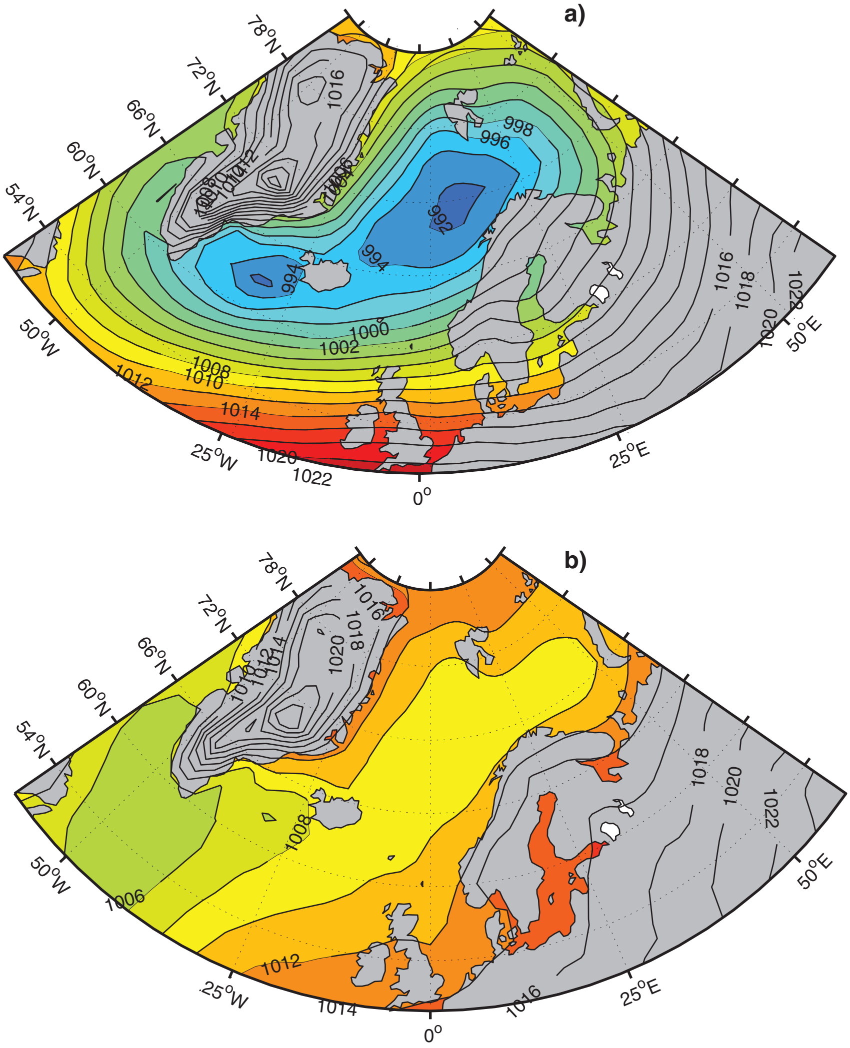

Fig. 2.8 Composite plots of sea-level pressure for periods during which the NwASC in the Svinøy section and the Atlantic inflow to the Barents Sea are either anomalously high (upper panel) or anomalously low (lower panel)

strong currents at both sites was characterized by an atmospheric low extending from southwest of Iceland, seawards along the coast of Norway, and partially into the Barents Sea (Fig. 2.8). This is the most common pathway of Icelandic lows as they propagate into the Norwegian Sea. The case of anomalously negative currents at both sites was characterized by highs over Scandinavia, and generally very weak SLP gradients and hence also weak winds (Fig. 2.8).

The associated changes in sea level were identified by similar sea-level anomaly (SLA) composites (Fig. 2.9). These composite plots reveal marked differences for the two cases. In the case of anomalous strong currents at both sites a strong SLA gradient along the Norwegian continental slope extended into the Barents Sea. As SLA gradients represent geostrophic flow anomalies, this indicates anomalous strong surface currents. Since a significant part of the current is barotropic in the continental slope region (Skagseth and Orvik 2002) this will probably also reflect the deep currents. On the other hand, in the case of anomalous weak surface currents, the SLA gradient along the Norwegian Continental slope and into the Barents Sea was much smaller (possibly in the opposite direction), indicating weaker and a tendency for anomalous negative surface currents.

Currents with opposite phases in the Svinøy section and in the Barents Sea Opening occur less frequently, and the results should be therefore interpreted with some care. The case in which the current was anomalously high in the Svinøy section and anomalously low in the Barents Sea Opening was characterized by strong southwesterly winds towards southern Norway and a local atmospheric low in the Barents Sea (not shown). The effective forcing would be along-slope winds in Svinøy section and northerly winds in the Barents Sea Opening. A high-pressure "blocking" event over Scandinavia characterized the opposite case, with anomalous low currents in the Svinøy section and strong currents in the Barents Sea Opening. In this case the atmospheric low was forced into a more westerly route through the Norwegian Sea, before turning eastward into the Barents Sea, providing winds favourable for Atlantic inflow. The maximum flow in the Barents Sea Opening and weak flow in the Svinøy section in winter 2002–2003 (Fig. 2.6) can be related to the greater influence of such an atmospheric pattern.

The above discussion concerns relatively short time scales (<1 year), but these must be considered as fluctuations in longer timescale variations of various origin. The long-term hydrography series (Fig. 2.5) show that anomalies are a prominent part of the variability. Since these are usually generated to the south of the Greenland–Scotland Ridge they can be regarded as remote forcing in the flux budgets. Prominent examples of upstream forcing are the "Great Salinity Anomaly" (Dickson et al. 1988) and the recently reported circulation changes in the Sub-polar Gyre (Häkkinen and Rhines 2004) with associated water characteristics changes (Hátun et al. 2005). Orvik and Skagseth (2003a) also found a significant relationship on an inter-annual time scale between the wind stress curl in the northern North Atlantic and the volume flux of the NwASC 15 months later between 1995 and 2003.

Finally, a positive internal feedback mechanism has been proposed for the Barents Sea (Ikeda 1990; Aadlandsvik and Loeng 1991). The mechanism is as follows: increased Atlantic inflow to Barents Sea leads to warmer water, more sea ice melting and more open waters in the region, while increased oceanic heat loss and

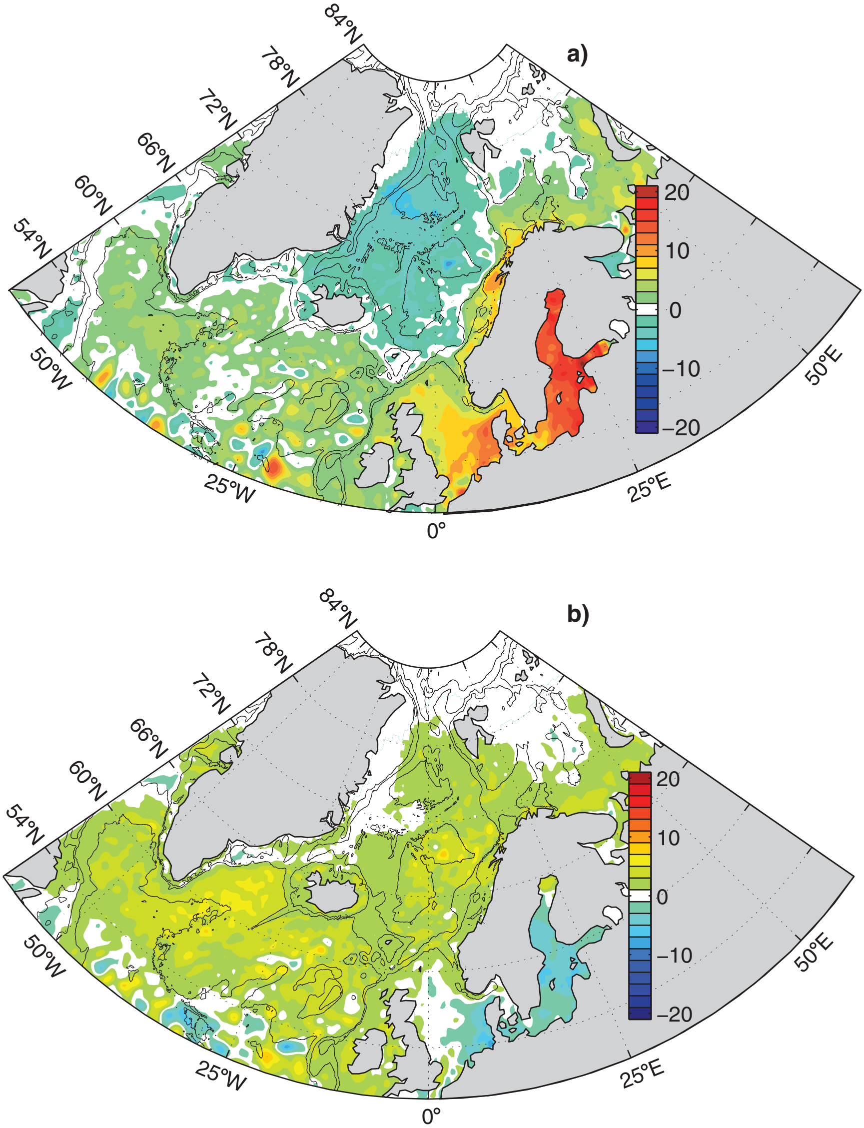

Fig. 2.9 Composite plots similar to those illustrated in Fig. 2.8, but for sea-level anomalies for periods when the NwASC in the Svinøy section and the Atlantic inflow to the Barents Sea were either anomalously high (upper panel) or anomalously low (lower panel)

evaporation create a local atmospheric low, and the associated anomalous cyclonic winds in turn amplifies the Atlantic inflow, thus closing the loop. Based on simulations with a coupled atmosphere-ocean general circulation model, Bengtsson et al. (2004) proposed that a similar feedback mechanism could explain the "early warming" in the 1930s–1940s.

2.5 Summary

The main aim of this paper has been to present a holistic view of the Atlantic water flow along the Norwegian Coast and into the Barents Sea. It has focused on the period starting in the mid-1990s, with simultaneous arrays of moored current meters in the Svinøy section and the Barents Sea Opening. These detailed measurements have provided the bases for improved estimates of means and variations in fluxes, and their forcing mechanisms.

Mean volume and heat fluxes associated with the Atlantic water are 4.3 Sv and 126 TW, respectively for the Svinøy section, showing no significant trends, and 1.8 Sv and 48 TW for the Barents Sea Opening, where positive trends have been found in both measures. The transport series show a prominent, but irregular, seasonal cycle at both sites, mainly determined by variations in the volume flux. The inter-annual changes are both substantial, but are relatively larger in the Barents Sea Opening.

In terms of prediction the data confirm the approximately 2-year lag in anomalies from the Svinøy section to the Barents Sea Opening. This strongly suggests that the recent relative cooling of the Svinøy section will be seen in the Barents Sea Opening in the next few years. However, as the heat loss becomes relatively more important in determining the climate in the eastern part of the Barents Sea, this region is probably less predictable, since atmospheric forcing is basically unpredictable beyond timescales of 1 week.

Hydrographic data along the Norwegian Coast show that the periods of direct current measurements, after 1995 for the Svinøy section and 1997 for the Barents Sea Opening, are the prolongations of a period that started in the late 1970s, since when Atlantic water has become warmer and saltier. This means that, given the assumption of constant volume fluxes, the estimated heat fluxes are higher than the long-term mean.

The close resemblance, throughout the record, between temperature variations in the Kola section and the AMO-index back to the early 20th century illustrates the importance of large-scale long-term variations in the Barents Sea system. Although the magnitudes of these variations are relatively small in comparison with inter-annual variations, other studies have shown them to be of major importance for ecosystem changes (ACIA 2005).

Forcing mechanisms, relating primarily to the wind, of the NwASC and the Atlantic water flow into the Barents Sea, were reviewed. The different forcing effects of the NwASC and the Atlantic inflow to the Barents Sea to similar atmospheric systems are noted. The results strongly suggest that the relative distribution of the NwAC entering the Barents Sea and passing through the Fram Strait is very sensitive to storm tracks. Thus, in a climate change perspective, changes in the predominant storm tracks may trigger major changes, including feedback mechanisms, for the Barents Sea climate and the heat budget of the Arctic Ocean.

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