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Hydrographic conditions in Icelandic waters, 1990–1999

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The main results of the hydrographic conditions in Icelandic waters in the 1990s reveal the same variability from year to year observed since the 1950s, including Atlantic, Polar, and Arctic periods in North Icelandic waters. Attention is paid to the hydrographic conditions in the warm water from the south (Irminger Current) which developed at the end of the 1990s into high saline conditions comparable with the period prior to the 1960s. This includes the northern component flowing into North Icelandic waters. The conditions in the East Icelandic Current also improved at the end of the 1990s with relatively high salinities. Thus the hydrobiological conditions in Icelandic waters were favourable at the end of the 1990s with regard to the various fish stocks.

Keywords: East-Icelandic Current, hydrographic conditions, Icelandic waters, Irminger Current, NAO.

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Introduction

Icelandic waters are located at the boundary between warm Atlantic Water from the south and cold water from the north, i.e. the oceanic Polar Front in the northern North Atlantic and Nordic Seas (Figure 1). The warm Irminger Current flows northwards and splits into two branches west of Iceland. The western branch meets the cold East Greenland Current and flows southwards into the Irminger Sea. The eastern branch flows north and eastwards off Northwest Iceland into North Icelandic waters (The Iceland Sea) and disperses off the eastern coast of Iceland (Stefánsson, 1962). The cold low saline water masses are those of the East Greenland (Polar) Current, flowing southwards through the Denmark Strait, and the East Icelandic Current flowing southwards north and east of Iceland (Malmberg, 1984, 1985). This circulation is complicated by north–south fluctuations of the boundary zone from year to year, mainly expressed by the presence of Atlantic, Polar, or Arctic Water in North and East Icelandic waters. These shifts in the location of the oceanic Polar Front deeply affect the climate and ecology in Iceland as well as the surrounding waters.

Materials

Since 1970, hydrobiological investigations have been carried out in Icelandic waters on standard sections on a seasonal basis (Figure 1). Similar investigations were started on a more or less annual basis in the spring of 1948 in connection with herring surveys in North Icelandic waters (Stefánsson, 1962; Jakobsson, 1980; Stefánsson and Jakobsson, 1989; Jakobsson and Östvedt, 1999).

The current study mainly presents a follow-up, for the years 1990–1999/2000, of the hydrographic data series published previously in *Annales Biologiques* (e.g. Malmberg, 1980, 1983) and elsewhere by Malmberg (1984, 1985, 1986, 1988), Malmberg and Kristmannsson (1992), and Malmberg *et al.* (1996).

Water masses

The main water masses in Icelandic waters are given in Table 1. These water masses are of importance for the ecology of Icelandic waters. In addition, the deep and bottom water and fresh water flux of the Polar Currents play a very significant role in the

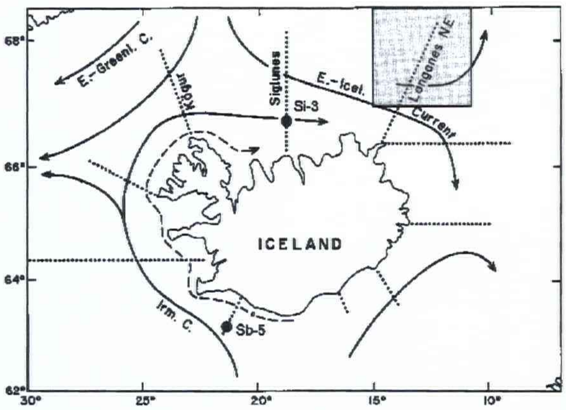

Figure 1. Main ocean currents and sections of hydrobiological standard sections in Icelandic waters. Selected areas and stations dealt with in the article are indicated.

Table 1.

Water mass	t	s	Water-mass origin/regime
Atlantic Water (AW)	3–8°	>34.9	North Atlantic and Irminger Current
Polar Water (PW)	<0°	<34.4	East Greenland Current
Arctic/Polar Water (ASW/PW)	<0–2°	34.3–34.9	East Icelandic Current
North Icelandic Winter Water (NIWW)	2–3°	34.8–34.9	North Icelandic Shelf
Bottom/Deep Water (DW)	<0°	3489–3492	Deeper layers north and east of Iceland
Arctic Intermediate Water (AIW)	0–2°	~34.95	Below the PW in the East Greenland Current
Coastal Water (CW)	Var.	<34.0	Shelves around Iceland diluted by run-off

water mass budget and climatic aspects of the northern North Atlantic and even globally (e.g. Swift, 1984; Hansen and Østerhus, 2000; Hansen *et al.*, 2001).

Results and discussion

East Icelandic Current

The water system in the Iceland and Norwegian Seas north and east of Iceland is mainly fed by the East Greenland Current and the Irminger Current, and known as the East Icelandic Current (Knudsen, 1899; Kiilerich, 1945; Stefánsson, 1962; and Swift and Aagaard, 1981). The East Icelandic Current, an ice-free so-called Arctic current in the period 1948–1963 (salinities above 34.7 and even 34.8 in spring) developed into a Polar Current from 1964–1971 (salinities below 34.7 and even 34.4), transporting and preserving drift-ice due to suppressed convective overturning in the upper layers (Malmberg, 1969, 1972; Dickson *et al.*, 1988). The "cold tongue" (< 0°C) of the current also advanced further south and east off Iceland into the Norwegian Sea than before (e.g. Vilhjalmsson, 1994; Blindheim *et al.*, 1999). These changes in the 1960s, along with a negative impact in North Icelandic waters on nutrient supply (Stefánsson and Olafsson, 1991), primary production (Thordardottir, 1977), and zooplankton concentrations (Astthorsson *et al.*, 1983; Astthorsson and Gislason, 1995), changed the feeding migration of the Atlanto-Scandian herring stock in the Iceland and Norwegian Seas (Malmberg, 1967; Jakobsson, 1980; Stefánsson and Jakobsson, 1989; Jakobsson and Östvedt, 1999). The herring disappeared from the traditional feeding grounds in North Icelandic waters and migrated into the Norwegian Sea along the eastern boundary of the "cold tongue" of the East Icelandic (Polar) Current. The Polar period in the East Icelandic Current in the 1960s occurred during the most negative NAO Index in the 20th century (Hurrell, 1995; Dickson *et al.*, 1996) and was the driving force for the "Great Salinity Anomaly" in the northern North Atlantic in the 1970s (Dickson *et al.*, 1988). More recently, Polar conditions ($S < 34.7$) were found in the East Icelandic Current in 1976–1979, 1982, 1988, and 1996–1998 (Figures 2A and 3B), but not so extreme as in the 1960s (Malmberg and Kristmannsson, 1992; Malmberg *et al.*, 1996; Malmberg *et al.*, 2001), and Arctic conditions ($S > 34.7$) during other years.

These results can be used to estimate variations in the volume transport and the fresh water flux in the East Icelandic Current from year to year. The current velocities are presumably relatively weak (Poulain *et al.*, 1996), except over the continental slope northeast of Iceland, where velocities in the order of 10 cm s^{-1} were obtained in the near-surface layer by direct current measurements and geostrophy in 1997–1998 (Valdimarsson and Jonsson, 2000). However, in 1995–1996, satellite-tracked drifters drogued at 15 m gave three times as high mean velocities (Valdimarsson and Malmberg, 1999). The width of the main branch of the current above the slope can be taken as 50 km and the depth of the current used for proxy volume estimates as 100 m. This results in an overall estimated transport of the East Icelandic Current above 100 m of 0.5×10^6 m^3 s^{-1} (0.5 Sv). For freshwater estimates, a reference salinity of 34.85 was used, which is based on repeated hydrographic observations (Malmberg and Kristmannsson, 1992). Thus, according to these estimates, during the ice-free Arctic period in the 1950s and early 1960s the freshwater thickness was

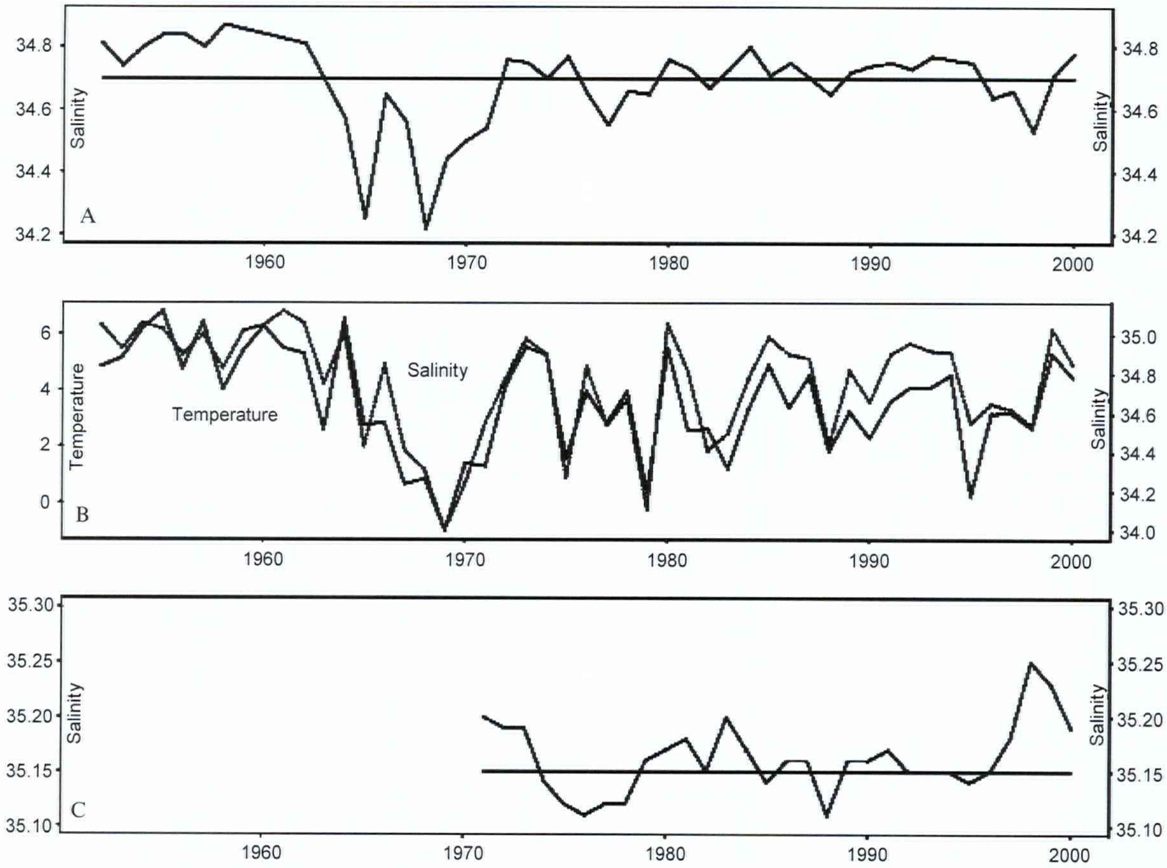

Figure 2. A. Means of salinity in spring at 25-m depth in a selected area in the East Icelandic Current northeast of Iceland 1952–2000. B. Temperatures and salinity in spring at 50-m depth on a hydrographic station in North Icelandic waters; Si-3; 1952–2000. C. Salinity in spring at 100-m depth in the Irminger Current south of Iceland; Sb-5; 1971–2000. For locations see Figure 1.

approximately 0.2 m, but 1.0–1.5 m during the Polar drift-ice period in the late 1960s, which is in good agreement with earlier results (Jonsson, 1992). These thicknesses result in different freshwater fluxes of $10^3\ m^3\ s^{-1}$ and at least $5 \times 10^3\ m^3\ s^{-1}$, i.e. 0.001 Sv during Arctic years and 0.005 Sv or more during the Polar years in the late 1960s (Figure 4). Much less variation has occurred since then, with generally less fresh water flux than in the late 1960s ($2 \times 10^3 - 4 \times 10^3\ m^3\ s^{-1}$ or 0.002–0.004 Sv).

North Icelandic waters

A selected hydrographic station on the shelf in North Icelandic waters (Si-3; 50 m; Figure 1) has been used to show seasonal and annual variability in the area since 1952 up to and including the past decade (Figures 2B and 5). The changes in the latter half of the 1960s (prior to the "Great Salinity Anomaly" (GSA) in the 1970s (Dickson *et al.*, 1988)) are notable. At this time of the extreme Polar Water period in the East Icelandic Current, the hydrographic conditions in North Icelandic waters changed from being Atlantic ($t > 4°C$; $S > 35.0$) to Polar conditions (t~0°C; S as low as 34.0; Figure 2B) after decades of Atlantic conditions ever since the 1920s (Stefánsson 1962, 1969). After the Polar period, or so-called ice-years, in the late 1960s, the conditions shifted between Atlantic (1972–1974, 1980, 1984–1987, 1991–1994, and 1999–2000) and Polar conditions (1975–1979, 1988, 1996–1998). Furthermore, a third occurrence of so-called Arctic conditions (1981–1983, 1989–1990, and extremely so in 1995) was observed. These Arctic conditions in North Icelandic waters included moderate cold temperatures of 0–3°C and rather homogeneous salinities of around 34.8 throughout the water column into the near-surface layers. Thus the conditions revealed a relatively weak stratification in North Icelandic waters in 1981–1983 and 1989–1990 (downstream conditions of the GSAs in the 1970s and 1980s) (Dickson *et al.*, 1988; Belkin *et al.*, 1998). The relatively unstratified water was observed along with poor living conditions (Malmberg, 1986; Malmberg and Blindheim, 1994). In general, the inflow of Atlantic Water into the spawning and

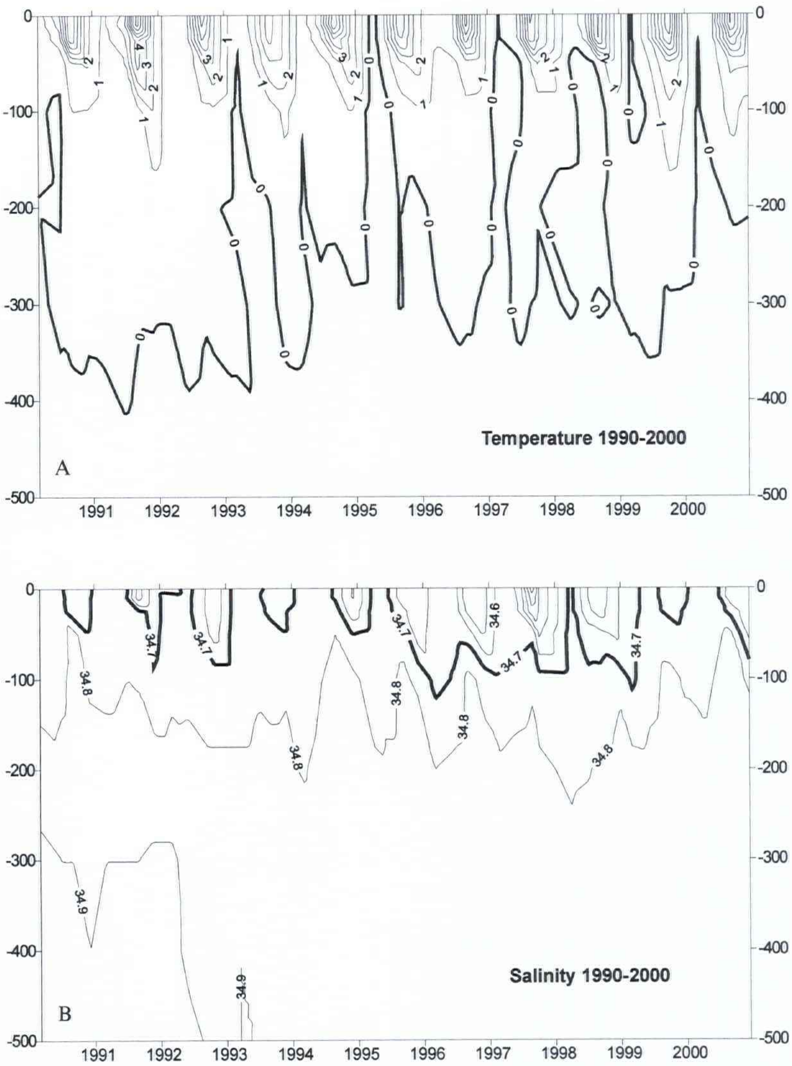

Figure 3. Temperature and salinity isopleths of monthly means for all data available in a selected area in the East Icelandic Current northeast of Iceland shown in Figure 1 during the period 1991–2000. Contours every 1°C and 0.1S.

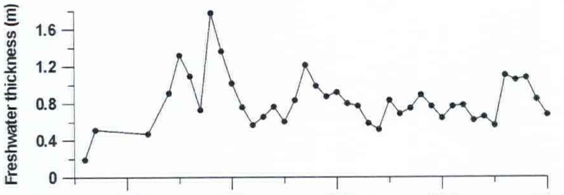

Figure 4. The freshwater thickness at a selected station of the Langanes NE section. (Station 4; Figure 1) above 150 m, relative to a salinity of 34.93, in spring 1956–2000 (Jonsson in Malmberg *et al.*, 2001).

feeding rounds in North Icelandic waters favours the recruitment and growth of commercial fish stocks such as cod (e.g. Vilhjalmsson, 1997; Astthorsson and Vilhjalmsson, 2001). Furthermore, the Icelandic capelin stock was at its lowest during the Arctic years in North Icelandic waters, presumably depending on zooplankton conditions, and growth of cod was also at its lowest, since it depends on the capelin as a food supply. Until the 1990s, the salinity of the Atlantic Water flowing into North Icelandic waters never reached the high values obtained prior to the mid-1960s ($S > 35.0$; Figure 7). This low salinity period ($S < 35.0$) may even reveal a general tendency, since the 1960s, to Arctic conditions. In 1999/2000, however, an increase in salinity towards former values was observed. The seasonal and annual variations in North Icelandic waters during the period 1974–2000 are further well established in Figure 8 with the highest temperatures

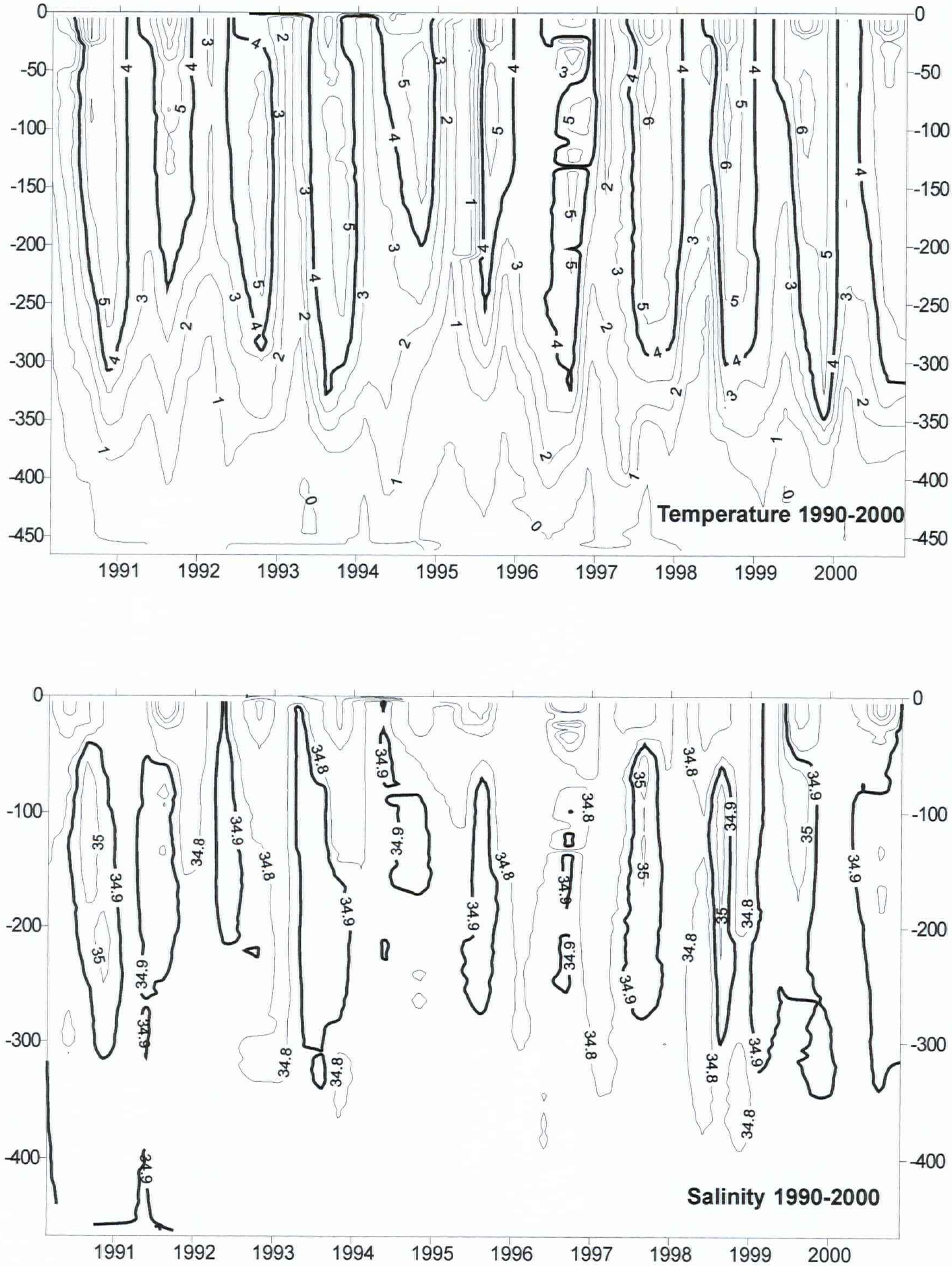

Figure 5. Temperature and salinity isopleths at station Si-3 in the Siglunes section, 1990–2000. For location, see Figure 1. Temperature contours every 1°C; salinity contours 34.0, 34.2, 34.5, 34.8, 34.9, 35.0.

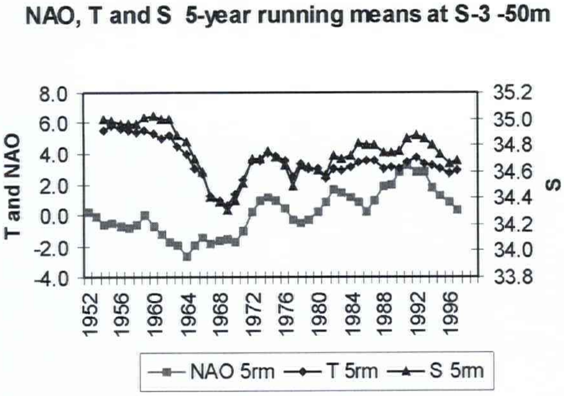

Figure 6. Five-year running means of the winter NAO Index and temperature and salinity in spring at 50-m depth at station Si-3 in the Siglunes section, 1950/1952–1999. For location, see Figure 1 (Malmberg and Desert, 1999).

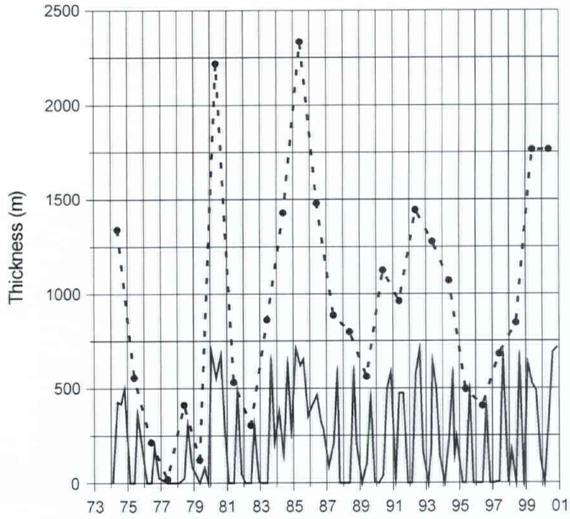

Figure 8. Atlantic layer thickness (t > 3°C; S > 34.9) at Stations 2, 3, and 4 in the Siglunes section, 1974–2000, seasonally and accumulated annually (Mortensen in Malmberg *et al.*, 2001).

and salinities during the years and periods 1972–1974, 1980, 1984–1986, 1991–1994, and 1999–2000. Sometimes these outstanding conditions are just seen during single years, as in 1980, and at other times they may last for a few years, as in the 1980s and early 1990s. This is important and renders forecasting difficult.

South Icelandic waters

The Selvogsbanki section crosses the South Icelandic shelf on the main spawning grounds of cod in Icelandic waters (Figure 1). The section includes the coastal water with its dilution of run-off as well as the Atlantic Water of the Irminger Current. The local variations in the coastal water are important for the spawning of cod (Jonsson, 1982; Olafsson, 1984; Thordardottir, 1988). The slight variations observed in the Atlantic Water are connected with large-scale features in the open ocean (Neumann, 1940; Smed, 1975; Rodewald, 1967, 1972; Dickson *et al.*, 1988; Belkin *et al.*, 1998). Thus the low

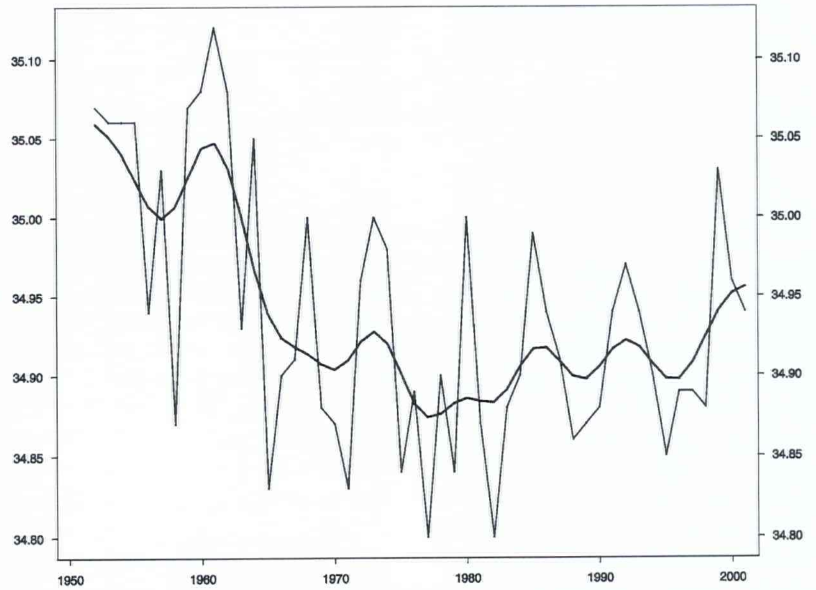

Figure 7. Maximum salinity in spring 1952–2000 in the upper 300 m at station Si-3 in the Siglunes section together with a 5-year smoothed running mean (Gaussian filter). For location, see Figure 1.

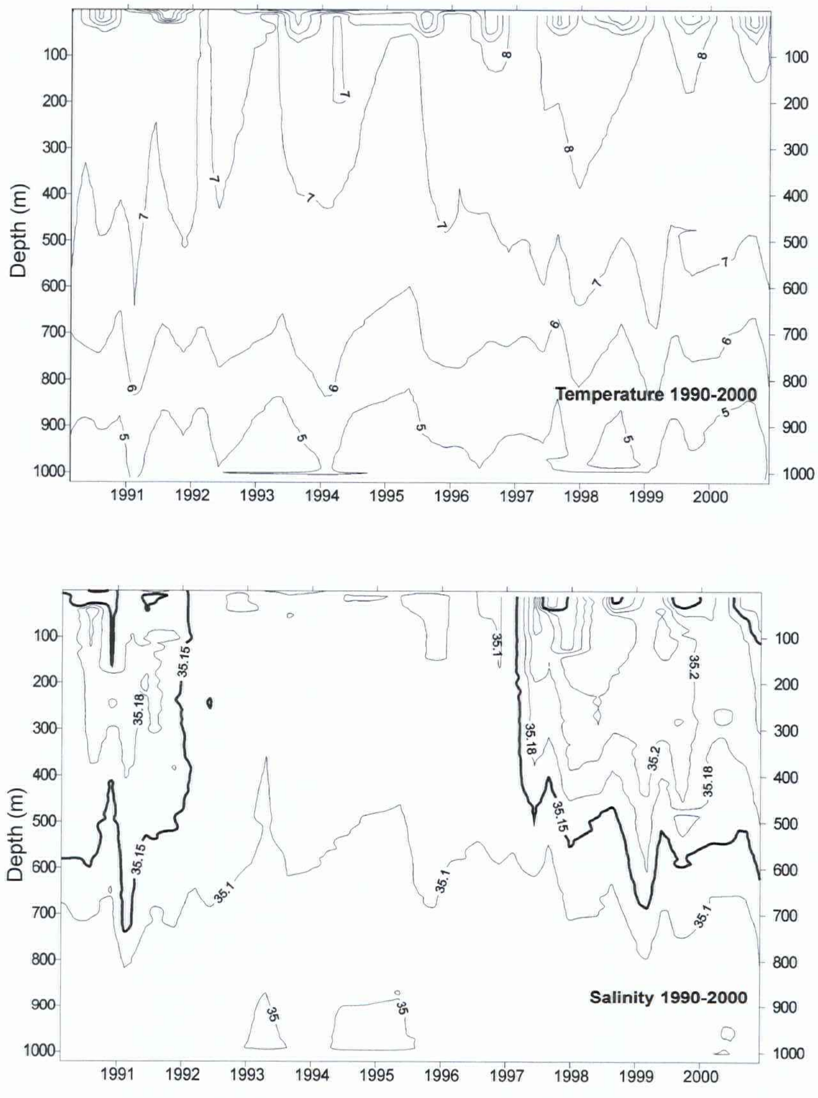

Figure 9. Temperature and salinity isopleths at station Sb-5 in the Selvogsbanki Section, 1990–2000. For location, see Figure 1. Temperature contours every 1°C; salinity contours 35.1, 35.15, 35.18, 35.20, 35.22.

salinity periods (S < 35.15) revealed at Sb-5 on the Selvogsbanki Section in the 1970s and 1980s (Figure 2C) were connected to the two GSAs. Furthermore, the relatively low salinity values found at Station Sb-5 during the years 1992–1996 (Figures 2C and 9), as well as those observed farther to the west in the Irminger Sea (Mortensen and Valdimarsson, 1999, 2000), may coincide with variations of hydrographic conditions in even the Labrador Sea (Reverdin *et al.*, 1999; Bersch *et al.*, 1999). This reflects the complex conditions in Icelandic waters and nearby waters, being located at the boundaries of northern, southern, and western ocean-atmospheric regimes. Looking further into the regime of the warm Irminger Current in the 1990s in South and West Icelandic waters, a distinct increase in salinity since 1997 is striking (Figures 2C and 8). These findings are similar to those found further downstream (West Greenland) and upstream in the North Atlantic Current System (ICES, 2001). Also North Icelandic waters benefited from this in 1999–2000, as already stated (Figures 2B, 5, and 7).

The NAO Index and hydrographic variability

The variable forcing of atmospheric conditions on the westerlies has an impact on oceanic circulation through different exchanges between atmosphere and ocean. Positive North Atlantic Oscillations indices (NAO; Hurrell, 1995) are thus generally followed by relatively strong warm humid westerlies in the eastern North Atlantic, but by cold and dry winds in the western North Atlantic. On the other hand, negative NAO indices are followed by cold and dry northerly winds in the eastern part and warm and southerly winds in the western part of the North Atlantic (McCartney, 1996).

In the 1960s, during the period of the most extreme negative NAO indices in the 20th century (Figure 6), much attention was paid to atmospheric conditions and their reflection in hydrographic conditions. This was expressed, for example, by the so-called ice-years in North Icelandic waters in 1965–1971 or the Polar years in the East Icelandic Current. Positive versus negative conditions in the atmosphere were reported (Rodewald, 1967; Bjerknes, 1972; Dickson and Lee, 1972; Cushing, 1978) across the North Atlantic from the Labrador to the Barents Seas (Sundby, 1995).

Investigating hydrographic conditions in Icelandic waters, located between the western and eastern areas of the North Atlantic and also nearby the Polar and Arctic Fronts, more complex and sensitive conditions must be expected regarding variability both in the sea and the air. The question that arises is: Is there a significant relationship between the NAO and conditions in Icelandic waters, particularly in areas along the variable Arctic and Polar Fronts in North Icelandic waters? As before, the hydrographic conditions in spring on the Siglunes section (see Figures 1 and 2B) are used as an indicator for North Icelandic waters. According to Olafsson (1999), no relationship is found between the NAO and hydrographic conditions in North Icelandic waters. This is true for single years and means of temperature and salinity from 0–200 m at 5 stations on the Siglunes section. Both low saline near-surface water from the north and higher saline Atlantic Water from the south are included in these means. Also, it should be noted that both for temperature and salinity the spring observations from 50 m at Si-3 on the Siglunes section (Figure 2B) show a positive correlation ($r^2 = 0.90$) to those presented by Olafsson (1999) from 5 stations (Malmberg and Desert, 1999). The data from 50 m at Si-3 are also occasionally influenced by near-surface fluctuations of low saline water from the north, including advection and melting of ice. As seen from 5 years running means of the winter NAO and temperature and salinity at 50 m at station Si-3 m, there may be some coherence between the NAO and hydrography in North Icelandic waters in the 1970s and 1990s, but not in the 1980s (Figure 6). The maximum salinity in spring in the upper 0–300 m at station Si-3 (Figure 7) may correspond more closely to the NAO Index, as it reveals the variations in the Atlantic influx into North Icelandic waters from the south. The maxima and minima still coincide more or less in the 1960s, 1970s, and 1990s, but not in the 1980s. The discrepancy in the 1980s may be due to the effects of the GSAs during these years, as suggested by Curry and McCartney (1996). Certainly, an absolute linearity between the data series is not present, as the NAO Index generally increases during the period 1965 to 2000, whereas the maximum salinity decreases slightly. Indeed, when dealing with the NAO Index in waters like the Icelandic ones, one must bear in mind that the tracks of the Iceland Low expressed in the NAO Index are variable in time. Sometimes they run west of Iceland, other times south and east of Iceland.

Thus, when looking further into the relationship between 5-year running means of the winter NAO and the salinity maximum in the upper 300 m at Si-3 (Figure 10), three groups appear: one for the years prior to the ice-years in the 1960s; one for the ice-years 1965–1971; and finally one for the years after the ice-years or 1972–1996. This may reflect different tracks of the Iceland Low during the three different time periods. All three periods may indicate a slight positive relationship between the 5-year running means of the NAO winter index and maximum salinity in the upper 300 m at station Si-3. Figure 10 also reveals the high salinities found prior to the ice-years, but lower ones both during the ice-years and combined with extreme positive NAO indices since the ice-years. These three periods or phases of the hydrographic and atmospheric conditions may reflect the observed climatological periods referred to above, i.e. warm Atlantic, cold Polar and moderate Arctic conditions, related to different amplitudes of the NAO and the tracks of the Iceland Low. Generally, the flow of the westerlies over the northern North Atlantic changed in the 1960s after decades of being relatively northward bounded and zonal (Rossby waves of "small" amplitudes) to a shifting more meridional flow with different phases (Rossby waves of "large amplitudes" and shifting phases; Cushing, 1978). This is also well demonstrated in the winter NAO Index of the second half of the 20th century (Hurrell, 1995; Figure 6). Thus the three periods once more express the different conditions found in North Icelandic waters.

Conclusion

This article deals with long-term hydrographic variability in both North and South Icelandic waters. In North Icelandic waters, three phases of hydrographic conditions have been observed – Atlantic, Polar, and Arctic. In the 1990s, all these phases were observed. Polar conditions were observed in 1996–1998, although they were not as extreme as during the so-called ice-years in North Icelandic waters in

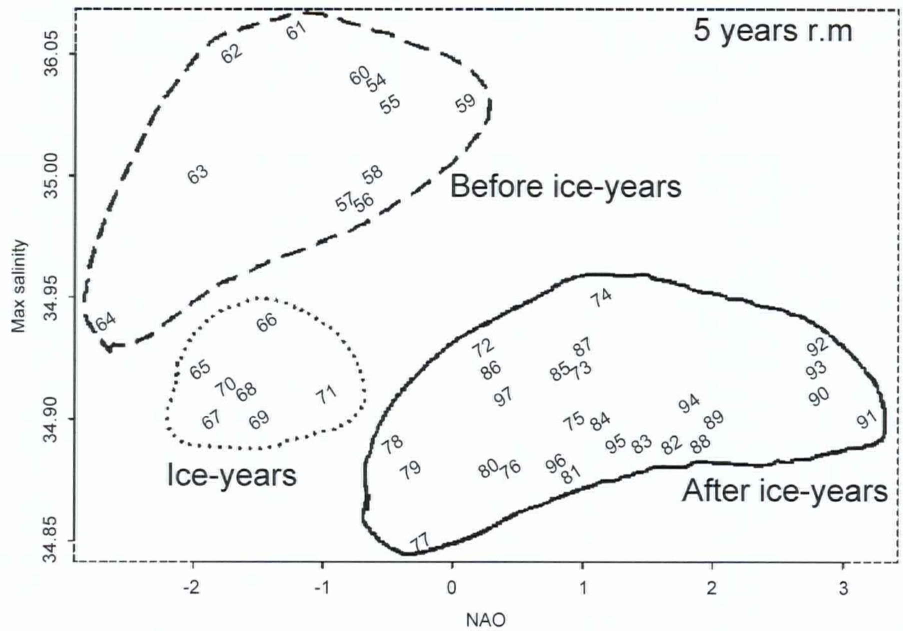

Figure 10. Relationship between 5-year running mean of maximum salinity in spring in the 0–300 m layer at station Si-3 on the Siglunes section (see Figure 7) and the 5-year running mean of the winter NAO Index (Figure 6) during the period 1950–1998.

the 1960s (Figure 2). The Arctic phase was observed in 1989–1990 and in 1995. The former two years were assumed to have been connected to the 1980s GSA (Belkin *et al.*, 1998) as the 1981–1983 Arctic phase was connected to the 1970s GSA (Dickson *et al.*, 1988). The extreme Arctic phase in 1995 has not yet been connected to any large-scale conditions in the North Atlantic and Nordic Seas, but the "low" salinity years in South Icelandic waters in 1992–1996 (Figures 2C and 8) were similar to reported variations of the Atlantic Water component in the Irminger and even Labrador Seas (Mortensen and Valdimarsson, 1999; Reverdin *et al.*, 1999; Bersch *et al.*, 1999). A striking change in salinity of the Atlantic Water influx into Icelandic waters occurred with a distinct increase at the end of the 1990s (Figures 2, 5, 9).

When considering the winter NAO Index in relation to hydrographic conditions in North Icelandic waters (Figures 6, 10) three periods also occur, one prior to the ice-years, a second one during the ice-years, and a third one after the ice-years. This occurs despite a more or less continuous increase in the NAO Index from the extreme low values in the 1960s to extreme high values in the 1990s. These three periods may reveal changes in the tracks of the air pressure fields, the track of the Iceland Low being more easterly after the ice-years than before.

Since the 1950s, three different hydrometeorological conditions or phases have occurred in the area around Iceland and in adjacent seas. These variable conditions also affected, directly or indirectly, the living marine resources in the area, as well as in wider areas throughout the North Atlantic and the Nordic Seas (e.g. Jakobsson, 1992; Malmberg and Blindheim, 1994; Vilhjalmsson, 1997).

Finally, as has been observed, the hydrographic conditions in Icelandic waters have reverted, towards the very end of the 20th century, to the "warm and saline" conditions similar to those found during the 1920s to the 1960s. The question arises, are we back to the "good old days" prior to the cold ice-years in the 1960s as regards hydrographic conditions in the northern North Atlantic and Nordic Seas with all their positive impact on climate and living marine conditions? This question is still unanswered at the start of the 21st century.

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