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RECENT UPPER LAYER COOLING AND FRESHENING IN THE NORWEGIAN SEA

by

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ABSTRACT. Several time series of temperature and salinity in the Norwegian Sea indicate a general upper layer decrease in both variables. The observations indicate that this change began in about the middle of the 1960s. Time series at Ocean Weather Station “M” (OWS“M”), from Russian surveys in the southern Norwegian Sea as well as Scottish and Faroese observations in the Faroe-Shetland Channel and around the Faroes, all have similar trends and show that this is a phenomenon which affects wide areas in the Norwegian Sea. The reason for this trend is an increased supply of freshwater in the East Icelandic Current. As a result, both temperature and salinity is now at a lower level than during the “Great Salinity Anomaly” (“GSA”) in the 1970s both at 400 m depth at OWS “M” and in the 200-500 m layer in the southern Norwegian Sea as observed in the Russian time series. The forcing may be increased production of Arctic surface water in the Greenland Sea when the deep convection is reduced, or more probably, increased export of freshwater from the Arctic Ocean. There is fairly good correlation between the wind stress curl over the Greenland Sea and the Russian time series of temperature and salinity, averaged between 200 and 500 m depth and between 0 and 3.5°E along 63°N in the Norwegian Sea.

Considerably increased supply of Arctic Water from the East Icelandic Current during a period around 1978, clearly reinforced the “GSA” in the Nordic Seas. This also explains the coinciding variation in Atlantic and Arctic waters in the Faroe-Shetland Channel during the “GSA”.

Introduction

The large scale circulation in the Nordic Seas (Greenland, Iceland and Norwegian Seas) is dominated by a northward flow of warm water on the eastern side and a cold, southward flowing current on the western side, with the Arctic Front in the border zone between the cold and the warm water masses. The Norwegian Atlantic current with its branches, which forms the northward flow, is the most northern limb of the North Atlantic current system. Besides its crucial importance for the regional climate, it keeps the entire Norwegian Sea and large areas of the Barents Sea ice free and open for biological production. Fluctuations in properties and fluxes in this current system are also of large ecological importance. Hence, the condition of the fish stocks indigenous to the region is normally best when the temperature is relatively high as both recruitment success and growth is best during warm periods.

The East Greenland Current (EGC) forms the cold, southward flow in the west. In its upper layers it carries surface water of low salinity, including ice, from the Arctic Ocean while in its deeper strata there is also a transport from the Arctic Ocean consisting of Eurasian Basin Deep Water. This is an important component of the deep water in the Nordic Seas. A warmer intermediate layer carries water of Atlantic origin which recirculates from the West Spitsbergen Current. The main branches of the EGC are, firstly, the Jan Mayen Current which brings all the three water masses into the cyclonic circulation in the Greenland Basin, and secondly and further south, the East Icelandic Current (EIC) which carries a somewhat varying combination of the same water masses from the EGC into the Iceland and Norwegian Seas (Buch et al., 1996). Along the North Icelandic shelf these waters also mix with Atlantic Water carried by the North Icelandic Branch of the Irminger Current. The remaining water in the EGC leaves the Nordic Seas through the Denmark Strait to supply fresh water to the Subpolar Gyre in the North Atlantic as well as dense overflow water which contributes to North Atlantic Deep Water.

Fluctuations in fluxes and water mass properties in these two major current systems are of decisive importance for the structure and distribution of the water masses both in the Nordic Seas and at least to some extent, in the Subpolar Gyre in the North Atlantic. Hence, the supply of Arctic water carried by the EGC into the Subpolar Gyre and its mixing with North Atlantic water may be an important, but not the only mechanism to create fluctuations in the Atlantic inflow to the Nordic Seas. However, the present analysis indicates that the Arctic water carried directly into the Norwegian Sea by the EIC also plays a large and important role for the distribution of water masses and their properties in the Nordic Seas, particularly in the southern Norwegian Sea and the area along the Greenland-Scotland Ridge.

The Scottish standard section across the Faroe-Shetland Channel and the Russian Kola section in the Barents Sea which both have been observed since the beginning of the century (e.g. Dooley et al., 1984; Bochkov, 1982), reveal rather irregular variability. While a broad spectrum of time scales, ranging from seasonal and interannual to inter decadal is observed (Loeng et. al. 1992), both these time series are also suggestive of a more long-term fluctuation, possibly with a time scale of about the length of the observational period. Hence, the salinity trend in the Faroe-Shetland Channel which is shown in Fig. 1, indicates a general increase from about 1910 to the 1940s or 1950s. Since then the trend has in general been decreasing. Similar fluctuations occurred in the Kola Section, and also over wide areas in the northern North Atlantic, in about the area of the Subpolar Gyre. Hence, based on observations of sea surface temperature from ships of opportunity, Smed (1965) worked out mean surface temperature anomalies in sub areas in the north Atlantic (50°-67°N, 0°-58°W) for the periods 1876-1900, 1901-1925, 1926-1950 and 1951-1961, using the period 1876 - 1915 as normal. Generally, he found the highest temperatures in the period 1951-1961 and compared with the coldest period, 1901-1925, he found a temperature rise of about 0.5°C in the south, ranging to about 1°C in the north. Although Smed's analysis of surface temperatures were terminated in 1979, there are indications that the Subpolar Gyre has been cooling again since about 1950-1960. The Nordic Seas have open connection with the Subpolar Gyre and indeed, exhibits similar fluctuations. The present paper focuses on a long term cooling and freshening trend in the Norwegian Sea. Although interrupted by decadal variability, there has clearly been a considerable decrease in both temperature and salinity in the upper layers of the area since the 1960s.

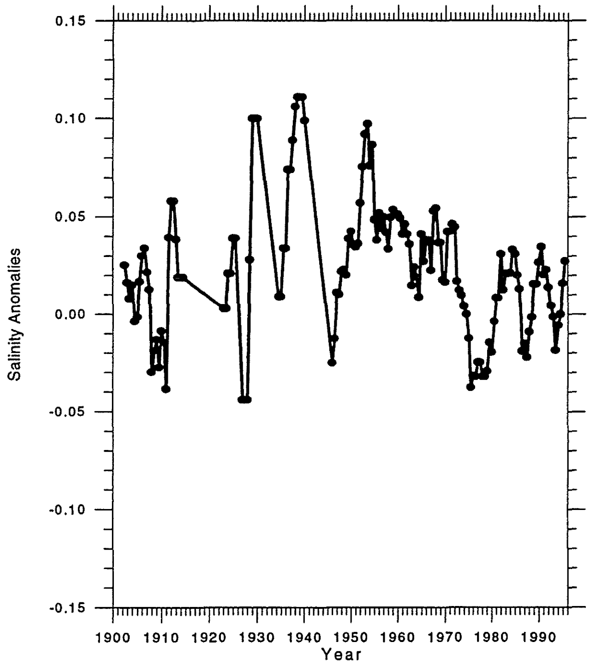

Figure 1. Time series of salinity in Atlantic water on the upper Scottish shelf in the Faroe-Shetland Channel from 1902 to 1995.

Data

Positions of sections and observational stations which are used here, are shown in Fig. 2. These include time series of T and S at a station on the Siglunes section north of Iceland (e.g. Malmberg and Kristmannsson, 1992), a section across the Faroe-Shetland Channel (Turrell et al., 1993), the Svinøy Section running NW from about 62N on the Norwegian coast (e.g. Blindheim and Loeng, 1981), a section along 63° N in the Norwegian Sea occupied during Russian surveys in June/July every year since 1959 (Borovkov and Krysov, 1995), and a time series of temperature and salinity observed since 1948 on the Ocean Weather Station "M" at 66°N,02°E in the Norwegian Sea (e.g. Gammelsrød et al. 1992).

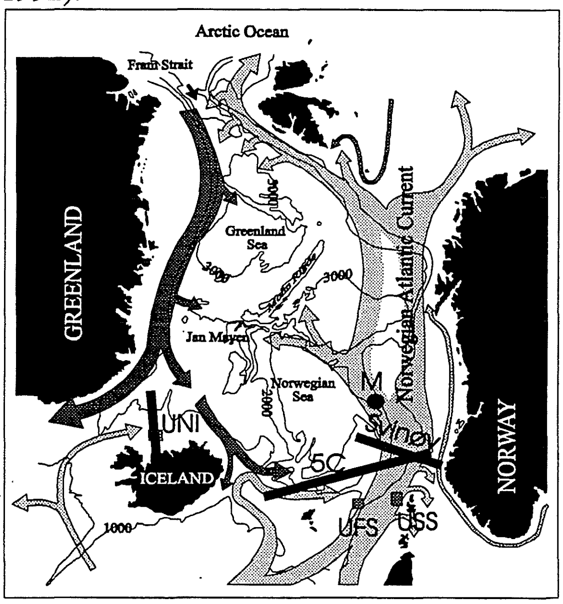

Figure 2. Positions of time series .

Results

Fig. 3 shows a time series of temperature and salinity , observed in May/June at 50 m depth off Siglunes on the North Icelandic coast. (Anon 1995, Malmberg and Kristmannsson, 1992). The figure shows that there was a rather abrupt change in both temperature and salinity during the later half of the 1960s. During this relatively short period the shelf waters which earlier were of Atlantic character with salinities on average about 35 and temperatures mostly in excess of 5°C, were replaced by colder, Arctic and Polar waters. This resulted in an average decrease of more than 2°C and 0.4 salinity units, although conditions have been much more variable during the following years than before 1965. These changed conditions in the North Icelandic shelf area in the late 1960s were due to changes in the supply of Polar water to the EIC further offshore. Hence, the EIC changed from an ice-free Arctic current to a polar current preserving drift ice and even performing ice formation (Malmberg, 1969).

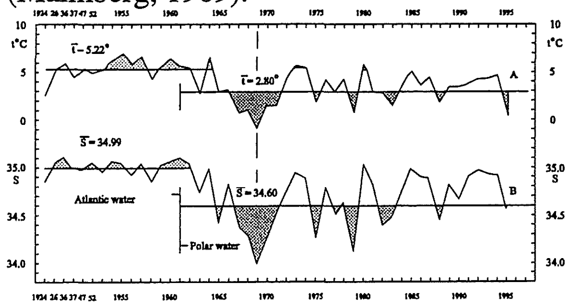

Figure 3. Temperature and salinity variations at 50 m depth in North Icelandic waters off Siglunes.

The observations at OWS "M" show cooling and freshening in the upper layers to about 800 m depth (Østerhus et al., 1996) and for example at 400 m depth both temperature and salinity were in 1995 at the lowest level since the station was established in 1948 (Fig. 4).

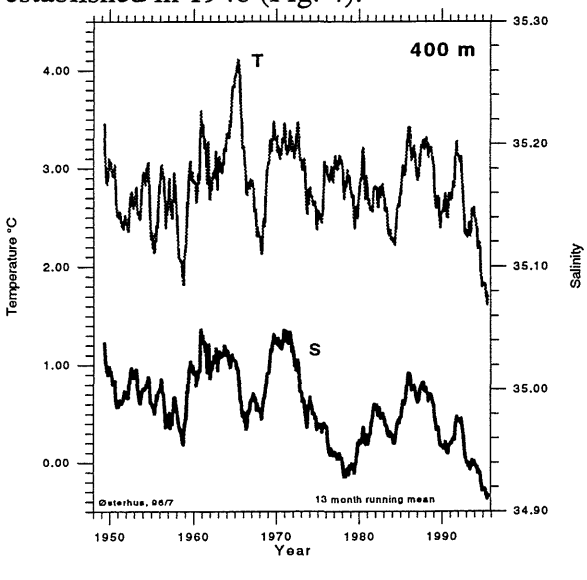

Figure 4. Time series of temperature and salinity at 400 m depth at Ocean Weather Station "M", 66°N, 2°E, from 1948 to 1995.

Similar trends appear in a Russian section (5C) along 63°N (Borovkov and Krysov, 1995) as shown by time series of temperature and salinity averaged over 0 - 200 m and 200 - 500 m depth and over 5 stations between 3°30'E and 0°05'E. These time series (Fig. 5) show a decrease of about the same magnitude in both depth intervals, about 1°C and 0.2 PSU over the period 1959 - 1995. The fluctuations of shorter time scales show larger amplitudes in the 0 - 200 m interval than between 200 and 500 m. As a consequence, the 200 - 500 m salinity was in 1995 at a lower level than at the minimum of the "Great Salinity Aanomaly" ("GSA") in the 1970s (Martin, 1981, Dickson et al. 1988). Further, it is noteworthy that in winter and spring 1995, cold Arctic waters in north and east Icelandic waters were found to have a more extreme extension than ever observed before since the investigations were initiated in 1949 (Anon, 1995; Malmberg and Jonsson, 1996)

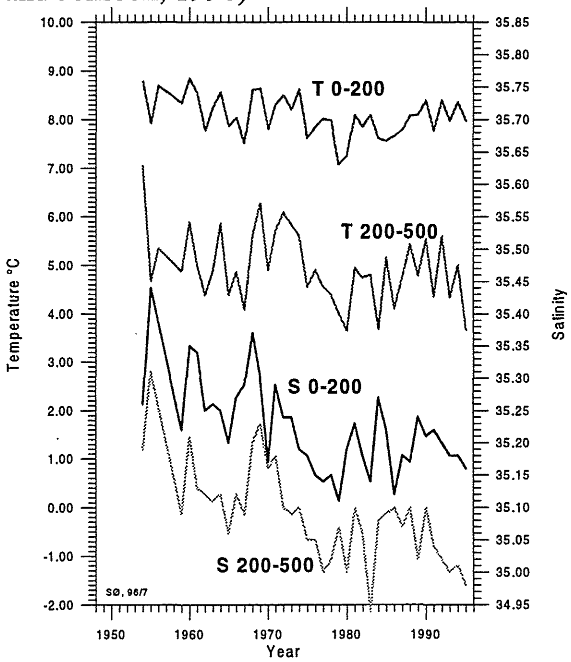

Figure 5.Time series of temperature and salinity averages in the Russian section 5C along 63°N, averaged over the depth intervals 0-200 m and 200-500 m and over 5 stations between 0.1°E and 3.5°E.

This trend in the 5C time series is of similar time scale as the long-term salinity trend in the Faroe-Shetland Channel although the freshening in the Atlantic water on the upper Scottish slope (U-SS water) has amounted to only about 0.05 PSU since 1950 (Fig.6). In the Faroe-Shetland Channel, however, the whole water column has been affected. The intermediate and bottom water also show a cooling and freshening trend since about 1960 (Fig. 7, Turrell, unpublished document). In contrast to the time series in the Norwegian Sea, however, there is poor or no coherence between the trends in temperature and salinity. Hence, in the U-SS waters there was a conspicuous temperature minimum in the 1960s when the salinities were rather average and to the contrary, during the "GSA" when the salinities were at the lowest on record, the temperatures were only moderately below average.

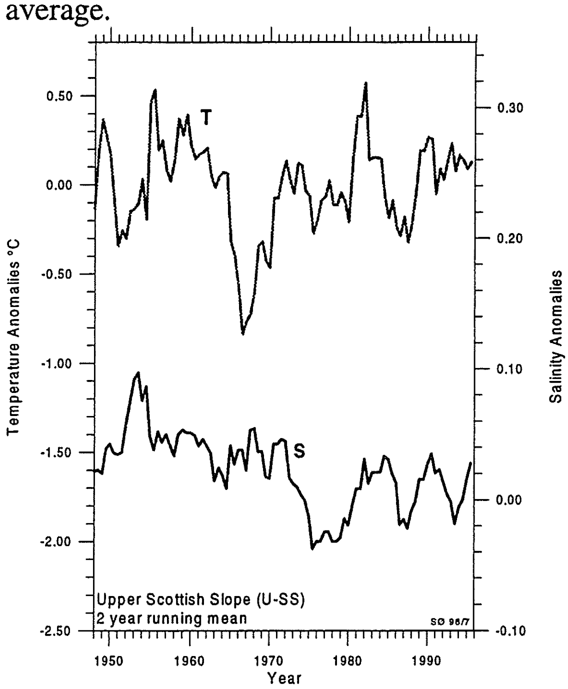

Figure 6. Time series of temperature and salinity anomalies on the upper Scottish slope (U-SS) from 1948 to 1995.

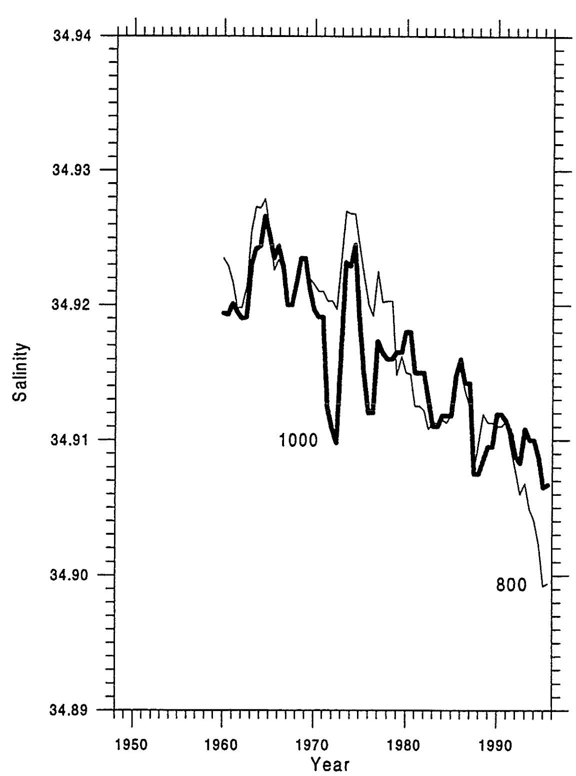

Figure 7. Salinity fluctuations at 800 m and 1000 m depth in the Faroe-Shetland Channel from 1960 to 1995.

The time series in the waters on the upper Faroe slope (U-FS), show the trend on the northern side of the Faroe-Shetland Channel, and reflect the conditions in the North Faroese Branch of the Atlantic inflow. They show similarities with the time series on the Shetland side, but also considerable dissimilarities (Fig. 8). The anomalies are larger than in the U-SS water in both salinity and temperature. The temperature maximum around 1960 as well as the minimum in the late 1960s had considerably larger amplitudes in U-FS water than in U-SS water. The large temperature maximum in the early 1980s in the U-SS water was not observed in U-FS water. It is also worth noting that the salinity anomaly during the "GSA" was larger in U-FS water than in the U-SS water.

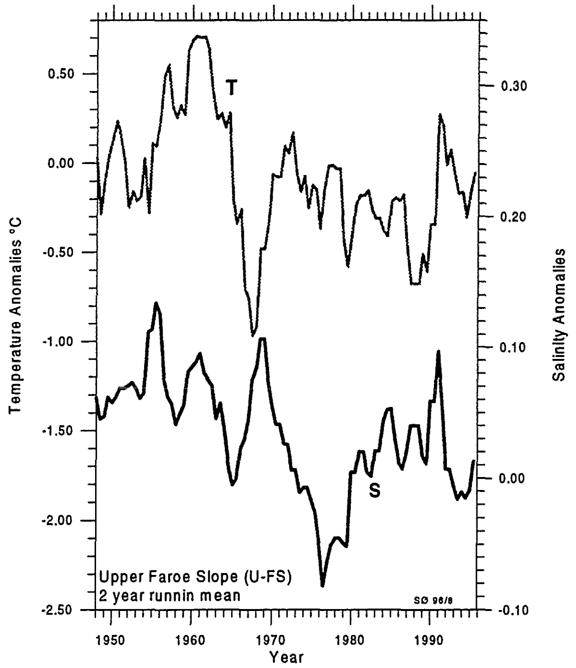

Figure 8. Time series of temperature and salinity anomalies on the upper Faroe slope (U-FS) in the Faroe-Shetland Channel from 1948 to 1995.

Further to the north east, observations have been repeated on the Svinøy Section (between 62°N on the Norwegian Coast and 64°44′ on the prime meridian) which was observed to 1000 m depth or deeper in 1958, 1968 and every year since 1978 . Averages covering the core of Atlantic inflow off the shelf break over the upper Norwegian slope (U-NS) show a very marked increase in both temperature and salinity from 1979 to 1980. During the following years there has been a general decreasing trend, similar to the trend which is better shown by the Russian observations. Fig. 9 shows temperature/salinity relationships and the vertical salinity distribution in the stations off the slope in repetitions of the Svinøy Section in 1958, 1968, 1978, 1988 and 1996. The conditions in 1958 and 1968 show a gradual salinity decrease from the relatively high salinity in the inflowing Atlantic water in the upper layers to the properties of the Norwegian Sea Deep Water (NSDW) at 1000 m depth. Although these sections were observed with reversing water bottles at standard depths, there were several temperature observations around 0° C which in the sections from later years coincided with a salinity minimum. This salinity minimum which has been observed over most of the Norwegian Sea and in the Faroe-Shetland Channel, is associated with the Norwegian Sea Arctic Intermediate Water (NSAIW; Blindheim, 1990; Hopkins, 1991; Martin, 1993). In the sections from 1958 and 1968 there were no indications of such a salinity minimum.

The section from 1978 shows a drastic change from the previous decade with considerably lower salinities between about 100 and 600 m depth. The minimum salinities occurred at 200 - 400 m depth and were associated with temperatures of 2-4°C. This is a type of intermediate water which is restricted to the upper layers and in characteristics it agrees with the water type which Stefansson (1962) defined as North Icelandic Winter Water (NIWW). As suggested by Stefansson and later confirmed by Malmberg (1969) and Meincke (1978), there may be considerable variations in this water from year to year, and the present data show that there may also be variations in its volume. In 1978 there was a gradual salinity increase between the intermediate water and the deep water and it was difficult to separate NIWW from NSAIW. The T/S relationship from 1988 shows the presence of both NIWW, which is indicated by a salinity minimum around 3°C with salinities less than 34.95, and NSAIW which is clearly shown by salinities below 34.9 at around 0°C. The range of temperatures exhibited by water with salinities < 34.9 increased from 1988 to 1996 and the salinity minimum deepened. NIWW was, however, less pronounced than in 1988.

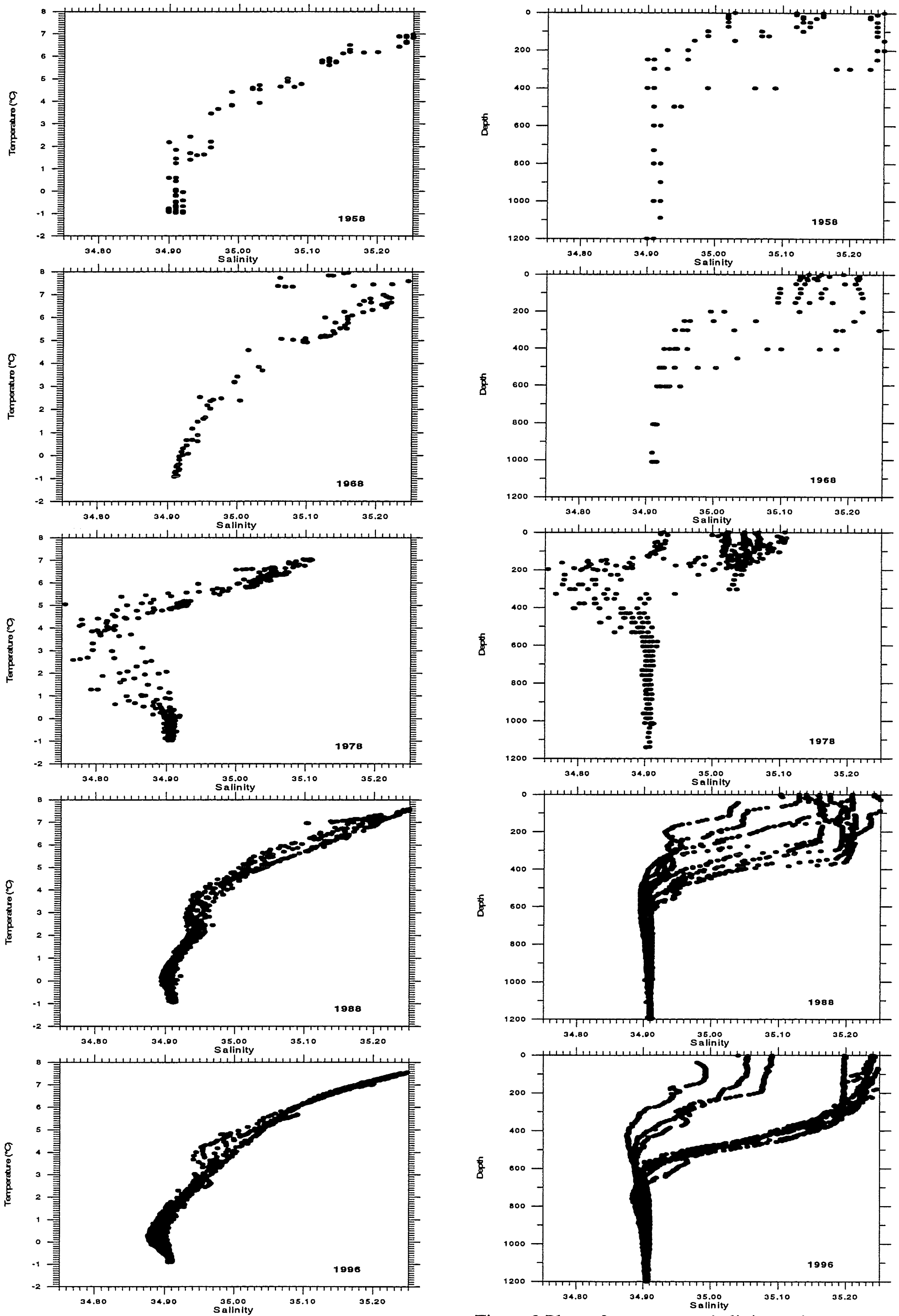

Figure 9.Plots of temperature/salinity and salinity/depth relationships in the stations off the shelf (depth > 900 m) in Svinoy sections from the years 1958, 1968, 1978, 1988 and 1996.

Discussion

The evidence from all the time series of observations presented here, spread over a wide area, show that this is a major ocean climate phenomenon with a large impact on the oceanographic structure of the Nordic Seas, their salinity and heat balance and the ocean-atmosphere interactions in the area.

The Arctic water which is transported by the EGC may affect the oceanographic structure in the Atlantic regime of the Nordic Seas in at least two ways. Firstly by direct mixing between the water masses in the Nordic Seas and those imported by the various branches of the EGC. These are composed of mainly Arctic water which flows into the Norwegian Sea from the EIC, but to some extent also some water which mixes across the frontal zone north east of Jan Mayen, between the Greenland and Lofoten Basins. Secondly, upper layer Arctic water which flows out of the Nordic Seas through the Denmark Strait enters the circulation of the Subpolar Gyre where it mixes to a varying extent with the waters of the North Atlantic Current and thereby creates variability in the properties of the Atlantic inflow to the Nordic Seas. The "GSA" which has been described to be the result of such mixing in the Subpolar Gyre (Dickson et al. 1988), peaked in the Rockall Channel in 1975 (Ellett, 1978) and in the Faroe-Shetland Channel in 1976 (Martin, 1981).

The time series both in the Norwegian Sea and in the Faroe-Shetland area show some similarities since the 1960s, with a gradual cooling and freshening. This is different from the conditions north of Iceland where there was an abrupt decrease in temperature and salinity during 1964 -1969. Since then conditions have been more variable than earlier, and on average, both temperature and salinity have remained lower than before 1965, but without any long-term trend toward lower values. As seen in Fig. 2, there is rather a tendency toward warmer and saltier conditions since 1970 than the opposite. A possible explanation for this may be that most of the Arctic waters carried by the EIC have a much shorter residence time in the Iceland Sea than in the Norwegian Sea where they accumulate in the upper and intermediate layers mainly in the Norwegian Basin. Consequently, this may lead to a long-term decrease in temperature and salinity as the proportion of Arctic water increases. As a result, in the Norwegian Sea the depth interval influenced by this Arctic water has increased. This signal is also seen in the upper bottom water in the Norwegian Basin where the transition layer between the NSAIW and the true adiabatically isothermal NSDW is increasing (Østerhus et al. 1996, b). This indicates that the top of the NSDW is gradually eroded by the increased intermixing of the Arctic water from above. Also in the Faroe-Shetland Channel temperature and salinity have decreased both in the intermediate and bottom waters since about 1960, most probably as a consequence of increased Arctic influence (Turrell et al.,1996).

In the U-SS time series there has been poor coherence between the temperature and salinity variability (Fig. 6). An explanation for this may be that the long residence time of the source waters in the Subpolar Gyre results in the anomaly undergoing several seasonal temperature cycles, particularly in the north western North Atlantic where it probably occurred more as a surface water mass than in the north eastern Atlantic where it must have been modified by the relatively deep winter convection.

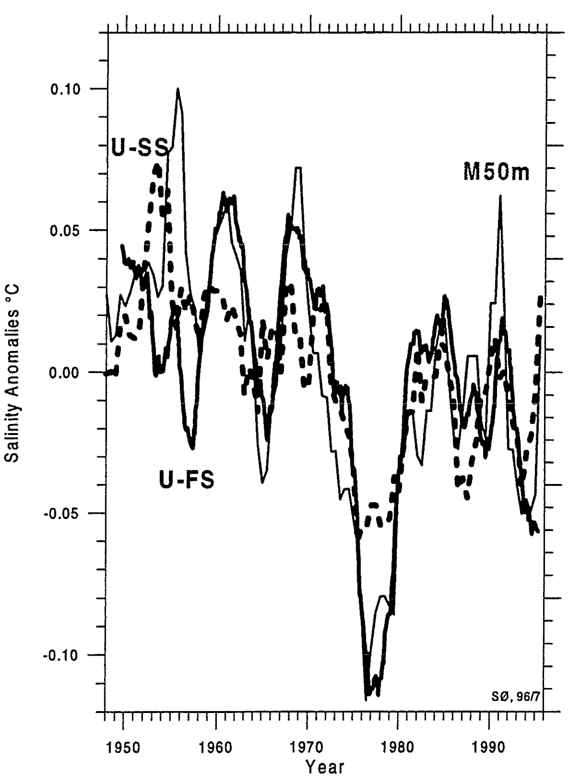

Figure 10. Time series of salinity anomalies on the upper Scottish slope (U.SS) and the upper Faroe slope (U-FS) in the Faroe-Shetland Channel and at Ocean Weather Station "M" from 1948 to 1995 (2-year running means).

Northeast of the Faroe Shetland Channel there is again better coincidence between the variation in temperature and salinity (Fig. 4, Fig. 5) and further more, the salinity anomaly has a larger magnitude than in the U-SS water. This is demonstrated in Fig. 10 which shows 2-year running means of salinity in U-SS, U-FS and at 50 m depth at OWS "M". The figure clearly shows that the amplitudes of the variability are larger in the U-FS water and at OWS "M" than in the U-SS water. And further, There is less difference between OWS "M", 5C and U-FS water than between the latter and U-SS water. On the other hand however, the general similarities in the salinity variation in the open Norwegian Sea and in the two Atlantic time series U-SS and U-FB (Figs 5 and 10) indicate that part of the salinity deficit in the Norwegian Sea derives from a deficit in the inflowing Atlantic water. This applies both to the long-term salinity decrease and to the "GSA".

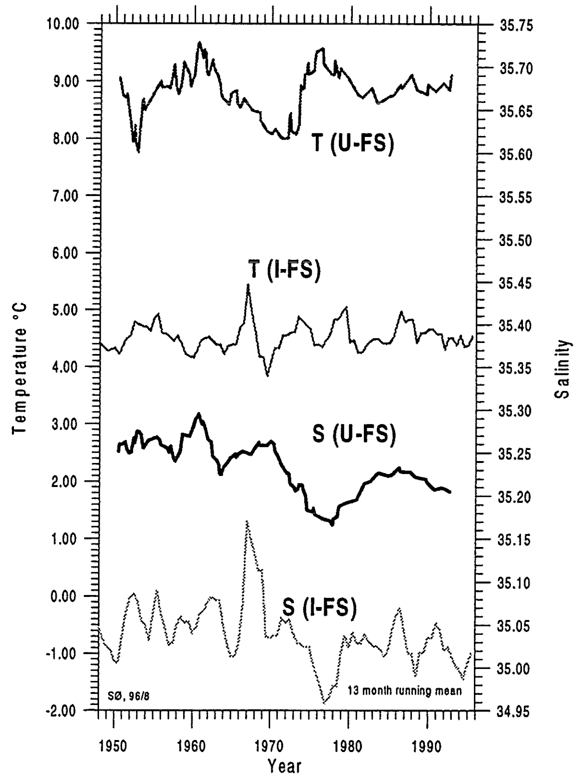

Figure 11. Time series of temperature and salinity in upper and intermediate water on the Faroe slope in the Faroe-Shetland Channel from 1948 to 1995.

A decreased Atlantic water salinity can explain only part of the observations in the Norwegian Sea. It cannot by itself explain the correlation between the variability of surface water salinity (U-FS, Fig. 11) and variability in the intermediate water in the Faroe-Shetland Channel (I-FS on Fig.11) and neither can it explain the fact that the salinity deficits are larger in the open Norwegian Sea than in the Atlantic inflow water (Fig.10).

Apparently, the salinity variation in the open Norwegian Sea may be the result of a combination of two effects: Salinity and/or flux variations of the inflowing Atlantic water and varying influence of Arctic water in the Norwegian Sea. Strong support for this is seen in Fig. 9 where the T/S relationship for 1978 in the Svinøy Section shows particularly low salinities in the intermediate water due to increased Arctic influence. In the Norwegian Sea this coincided with the occurrence of the"GSA", while in Icelandic waters this period was characterised by much polar surface water along the north and east coasts and relatively severe ice conditions during the years 1976-1979 (Malmberg and Kristmannsson, 1992). Most likely, these conditions have also affected the Svinøy Section through a well developed EIC. A pertinent question in connection with this is then: Why was the most severe period with Arctic and Polar water in North Icelandic waters around 1968 not reflected in the T/S relationship for 1968 in the Svinøy Section. A likely reason may be the wind forcing which may have favoured a strong EIC during 1976-1979, in contrast to the late 1960s when wind conditions possibly led to reduced transport in the EIC and correspondingly increased transport through the Denmark Strait. Some support of this is given by Meincke et al., 1992, who considered wind stress curl over the Greenland Sea in relation to variability of convective conditions. They claimed that the increased freshwater transport from the Arctic Ocean during the late 1960s did not immediately affect the convective conditions in the Greenland Sea when passing en route to the Iceland Sea, in other words that little freshwater entered the circulation in the Greenland Basin. Similarly the wind forcing may have reduced the transport of Arctic water into the EIC

Generally, the wind conditions seem to be a principal forcing component in this system. Jónsson (1992) has described the importance of the wind stress curl over the Iceland Sea for the variability in the volume of fresh water in the area and its likely role in the convective conditions is already mentioned (Meincke et. al.,1992). Similarly, Malmberg and Jónsson (1996) has compared variations in wind stress curl to the timing of convection in the Iceland and Greenland Seas and conclude that leakage of freshwater from the EGC is the primary factor determining the degree of convection. Indeed there is also a fairly good correlation between the wind stress curl over the Greenland Sea and the amount of fresh water in the Norwegian Sea. The relation between the 200-500 m salinity average in the Russian 5C section and Jónssons annual values of wind stress curl over the Greenland Sea (Meincke et al. (1992) gives a correlation coefficient of 0.66. This may be taken as a clear indication of the role of prevailing winds as a forcing factor. The length of this freshening trend in the Norwegian Sea also connects associations to the North Atlantic Oscillation and the possibility that the wind forcing is not only local or regional, but may also have more far field effects.

Wind forcing may therefore also be a mechanism behind a dynamical anomaly in terms of a changed balance between the EIC and the Atlantic inflow which has been suggested by Hansen and Kristiansen (1994), for example in the way that the same structure of wind conditions which may favour increased transport in the EIC, may retard the flow which feeds the Atlantic inflow north of the Faroes. By itself an increased EIC may also have a reducing effect on the Atlantic inflow simply for continuity reasons. When much of the waters in the EGC circulates back into the Nordic Seas via the EIC in stead of flowing out through the Denmark Strait, the compensating Atlantic inflow will be reduced accordingly. Possibly, this mechanism should not be neglected as a forcing component of the "GSA" during the period 1976-1979.

Where does this Arctic water come from? One possibility is that it is formed through winter convection in the Greenland Basin. When conditions are not suitable for deep convection, the product of winter convection may be a version of upper layer Arctic water in the Greenland Sea (U-GSW). This may then flow into the Norwegian Sea via the Iceland Sea. Another possibility is that the flow of surface water from the Arctic Ocean has increased. Although the formation of U-GSW should not be ignored, it seems likely that increased outflow from the Arctic Ocean may be a more important source. It has for example been believed that the "GSA" originated from increased outflow of surface water from the Arctic Ocean which Aagaard and Carmack (1989) estimated to represent a 30% increase in freshwater flux. There are also other indications of increased export of surface water from the Arctic Ocean. Hence, Carmack et al., 1995, have found an increasing volume of the intermediate layer with water of Atlantic origin in the Arctic Ocean and Macdonald (1996) poses the question where the displaced Pacific water has gone and suggests increased transport out through the Fram Strait. The decreasing upper layer salinities in the Norwegian Sea may support this suggestion.

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