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Norwegian Sea intermediate water in the Faroe–Shetland Channel

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During the 1980s the presence of a salinity minimum was noted in the water column of the Faroe–Shetland Channel at temperatures close to 0°C between Arctic intermediate (AI) water, formed along the Faroe–Iceland Ridge, and the Norwegian Sea deep (NSD) water occupying the lowest levels of the channel. The minimum was most marked in the north-east entrance to the channel, indicating a Norwegian Sea origin. Analysis of the long series of Nolsø–Flugga hydrographic sections shows a relatively large salinity variability which coincides with the depth of this minimum, suggesting that this water could have been present but undetected over many years. Similar water has been recently noted throughout the southern Norwegian Sea by Blindheim (1990. Deep-Sea Research, 37: 1474–1489), although his name for it, Arctic intermediate water, conflicts with the established use of this term for the warmer AI water found at lesser depths between northern Iceland and the Faroe–Shetland Channel. Hence the term Norwegian Sea intermediate (NSI) water is used here. Although modern CTD profiles greatly aid identification of this water, careful scrutiny of past water bottle sampling reveals evidence of its presence over the past three decades, the period for which high-quality salinity determinations have been available, showing that its presence is not solely a phenomenon of the 1980s. An additional indicator appears to be a dissolved silica minimum, which suggests a relatively recent connection with the upper waters. The minimum salinity of water between 0 and 1°C was therefore compared with the mean salinity of the upper north Atlantic (NA) water of the Faroe–Shetland Channel. A peak correlation at the 0.1 probability level was found to occur with a time-lag of 7 years between the salinity fluctuations of NA water passing into the Norwegian Sea and those appearing in the NSI water in the depths of the same channel.

Key words: salinity, water mass, dissolved silica.

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Introduction

The Faroe–Shetland Channel is the meeting place for a number of water masses. It is the principal route for warm water from the north Atlantic entering the northern seas, and below this inflow it is also a route by which Arctic-type water masses flow southward into the north Atlantic. It has a complex hydrography and a high variability (Dooley and Meincke, 1981). The area has been sampled with varying degrees of intensity since 1902. This sampling has been largely along two main hydrographic sections, namely the Nolsø, Faroe–Flugga, Shetland section, and the Munken, Faroe–Fair Isle section (Fig. 1). Over the period 1902 until the early 1980s only four principal water masses were distinguished. (a) Warm saline north Atlantic water (NA) with a salinity that can fluctuate between 35.25 and 35.45 psu is consistently found along the edge of the Scottish continental shelf (Dooley and Martin, 1969). (b) The surface layers of the remainder of the Channel are normally occupied by modified north Atlantic water (MNA) (Dooley and Meincke, 1981) of similar origin to the NA water but whose track to the Faroe–Shetland Channel is more northerly. The temperature and salinity of MNA water fluctuates in phase with NA water but, because of its northerly track, it is both colder and less saline. (c) Immediately below MNA water, at depths varying from 300–600 m, Arctic intermediate water (AI) is found. On occasions, this water can extend upwards into the near surface layers. AI water is formed on the Faroe–Iceland Ridge (Meincke, 1972) from an admixture of north Iceland winter water (NI) (Jacobsen, 1943) and NA water (Stefansson, 1962), and its passage can be traced into the Faroe–Shetland Channel from north of Faroe (Meincke, 1978). Its temperature and salinity range is relatively large, 2.0–4.5°C and 34.76–34.99, respectively, with the result that the temperature/salinity profile within the Faroe–Shetland Channel is very variable (Fig. 2). (d) Occupying the depths of the Faroe–Shetland Channel is Norwegian Sea deep water (NSD), sometimes referred to as Norwegian Sea bottom water. Its temperature and

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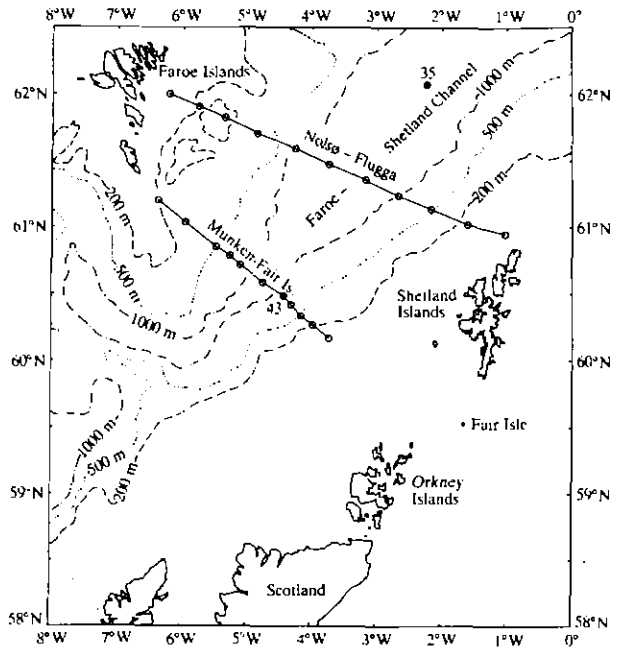

Figure 1. The Faroe–Shetland Channel sections. Positions of Stations 35 and 43 of Figure 4 also marked.

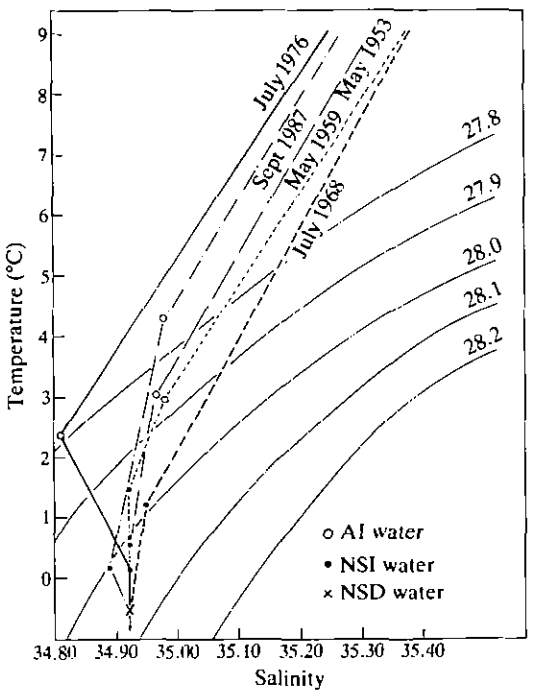

Figure 2. Temperature/salinity profiles in the Faroe Shetland Channel.

salinity characteristics are close to −0.5°C and 34.92 (Dooley *et al.*, 1984). Swift and Kolterman (1988) show that NSD appears to be composed of approximately equal parts of Greenland Sea deep water (GSD) and Eurasian basin deep water (EBD) from the Arctic Ocean. GSD arises from deep convective mixing with upper water which Peterson and Rooth (1976) estimate to take place upon a time scale of about 30 years. Subsequent exchange of deep waters between the Greenland and Norwegian Seas has a time scale in excess of 100 years, and is essentially isolated from other water mass formation which occurs above the permanent pycnocline of the Norwegian Sea. Any changes in the temperature and salinity (TS) characteristics of the NSD water would therefore be expected to occur extremely slowly. This fact has been extremely useful as it has enabled the less reliable early salinity determinations to be revalued by comparing the apparent salinity of the NSD water with its known value.

Norwegian Sea intermediate water

Since 1981, temperature and salinity values have occurred in the Faroe–Shetland Channel which indicate the presence of a hitherto unknown water mass. Salinity values between 34.89 and 34.90 occurred in water of 0–2°C, producing a salinity minimum in the TS profiles between the AI and NSD water masses. This became particularly clear during hydrographic work in the Faroe–Shetland Channel in September 1987 when the TS profile (Fig. 3) indicated the presence of a water mass with TS characteristics 0.25°C and 34.89. The salinity minimum of this water mass was more marked on the northern hydrographic section between Nolsø, Faroes, and Flugga, Shetland (Fig. 1) than on the more southern section between Munken,

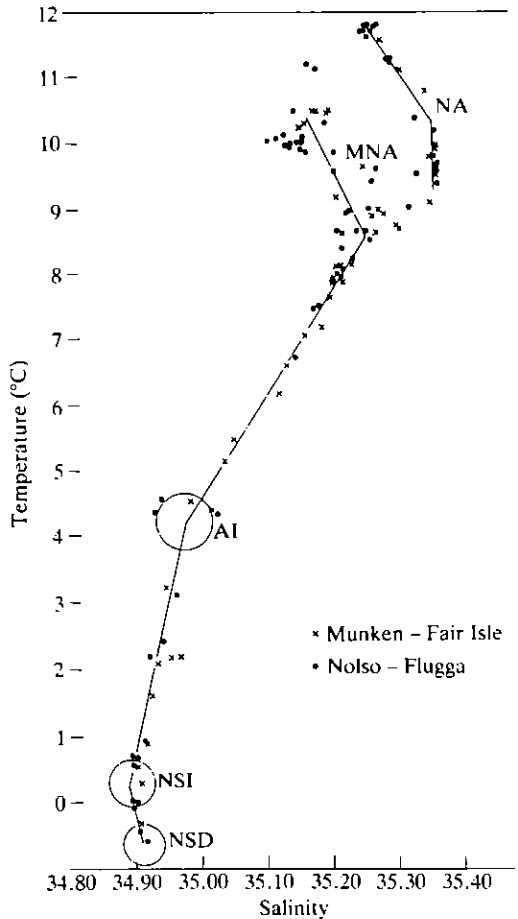

Figure 3. TS plot in the Faroe–Shetland Channel, FRV "Scotia" September 1987.

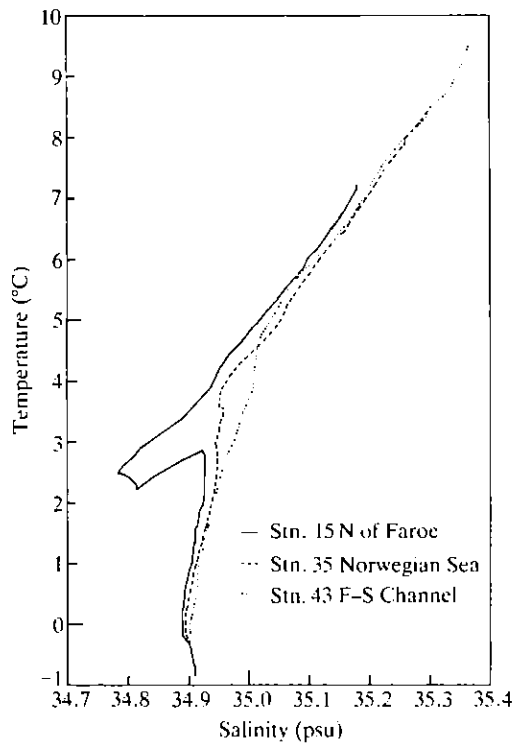

Figure 4. TS plots around the Faroe Islands, RRS Challenger May 1987. Stn 15 63°13'N 6°21'W, 13 May. Stn 35 62°06'N 2°14'W, 24 May. Stn 43 60°28'N 4°27'W, 25 May.

Faroes, and Fair Isle. A cruise of RRS "Challenger" around the Faroe Islands 4 months earlier in May 1987 (Saunders and Gould, 1988) showed the presence of this water mass to the north and east of the Faroe Islands as well as within the Faroe–Shetland Channel itself (Fig. 4). However, as this water mass penetrated into the Faroe–Shetland Channel its TS characteristics tended to be lost due to the intense mixing that takes place within the channel. The standard deviation of salinity was calculated for all standard depths at all the fixed stations on the Nolsø/Flugga and Munken–Fair Isle sections for the period 1960–1987. It was frequently necesssary to interpolate to standard depths data from non-standard depths. No attempt was made to interpolate data from non-standard positions and this unfortunately eliminated a number of sections. It was felt that the risk of error was too great. Soviet hydrographic data which fell into this category was, however, closely examined for evidence of NSI water. The standard deviations of salinity for the period 1960–1987 are shown in Figures 5 and 6 and these show interesting patterns. In Figure 5 the standard deviation of more than 40 Nolsø–Flugga sections is greater than 0.1 psu across almost the entire channel at depths of 300–400 m and this is indicative of salinity variability in the AI water. However, below the AI water, at a mean depth of 700 m and against the slope of the Faroese shelf, is an area of even greater salinity variability where the standard deviations are equal to or greater than 0.15. This is the depth and location where NSI water was found in the 1980s. A similar analysis of standard deviation of salinity for the southern section, Munken–Fair Isle (Fig. 6), shows nothing to indicate the intrusion of NSI water along this section. It follows therefore that if NSI water intrudes from the Norwegian Sea into the Faroe–Shetland Channel then it is most likely to be found in the north-eastern part of the channel before it is subject to intense mixing.

The same water mass can be recognized in CTD profiles taken in the Faroe–Shetland Channel by Van Aken and Eisma (1987) during the summer of 1983. Their figure 15 shows salinity minima occurring at ca. 0°C between AI water and NSD water.

Nomenclature of Norwegian Sea intermediate water

Blindheim (1990) has shown this water to be extensively distributed throughout the southern Norwegian Sea. He

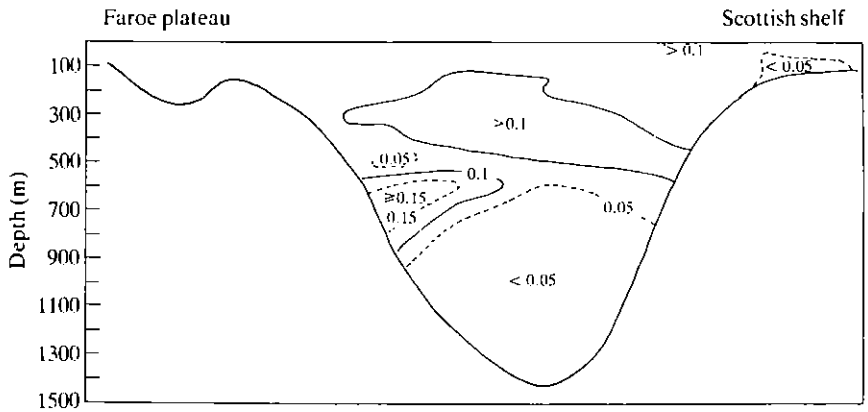

Figure 5. Nolsø–Flugga section, standard deviation of salinity (psu) 1960–1987.

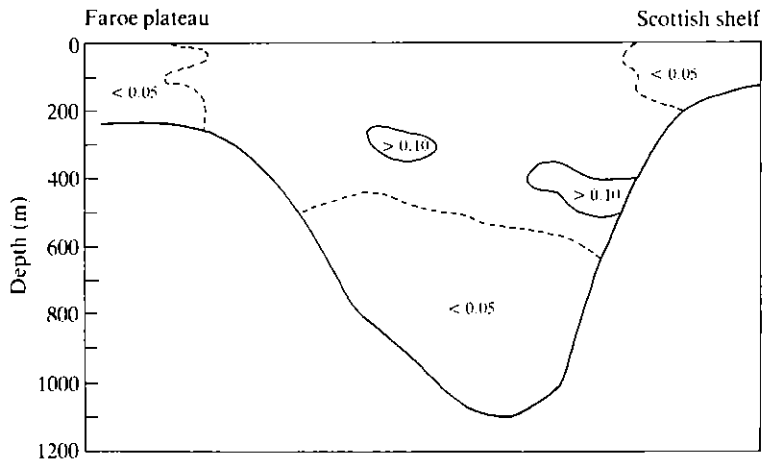

Figure 6. Munken–Fair Isle section, standard deviation of salinity (psu) 1960–1987.

has, however, named it Arctic intermediate water, which to this author seems an inappropriate name as it is likely to confuse rather than clarify or make distinct the nature of this particular water mass. Swift and Aagaard (1981) defined three intermediate water masses in the Iceland Sea area, all labelled Arctic intermediate water; this particular water mass falls within the broad characteristics of the upper AI water of these authors but can be more precisely specified. There would also be an unfortunate confusion of nomenclature as the AI water already referred to in the description of the water masses within the Faroe–Shetland Channel (Fig. 2) is a warmer layer of variable salinity (Martin, 1976) which is also referred to as north Icelandic winter water/Arctic intermediate water (NA/AI) (Meincke, 1978) in recognition of its mixed origin along the flanks of the Iceland–Faroe Ridge. It is therefore felt that the clearly definable name Norwegian Sea intermediate water should be attached to the water mass occurring between the AI water and NSD water indicating its association with the Norwegian Sea.

Use of historical Faroe–Shetland Channel data

Blindheim (1990) in his paper asks the very pertinent question as to why this water mass was not detected before the last 10 to 15 years if it was not a new phenomenon. His answer pointed to the recognized inadequacy of reversing water bottle sections with bottles often at 200 m intervals added to the suspicion that any unusual salinity value was probably due to errors either of collection or calibration. It was not until continuous profiling CTD systems were used that the first observations of this water were made in the Norwegian Sea. However, this was not true in the Faroe–Shetland Channel where NSI water was first discovered using traditional reversing water bottle casts and subsequently identified on several occasions by the same method. Analysis of water bottle data collected in 1987 showed that water of low salinity (34.89) occurred at ca. 0°C. This water could not have been formed by a direct mixture of AI and NSD water, both of which had higher

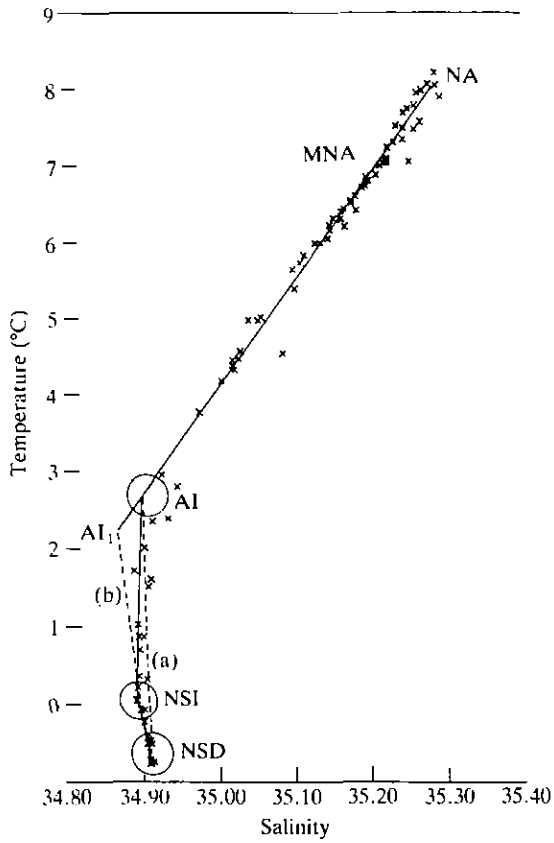

Figure 7. TS plots in the Faroe–Shetland Channel, FRV "Scotia" April 1983.

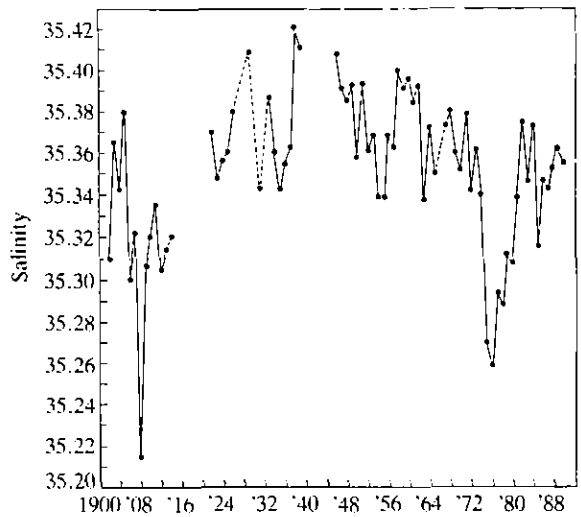

Figure 8. Annual mean salinity of NA water (0–200 m) in the Faroe–Shetland Channel.

salinity (Fig. 3). This therefore had to be a new water mass.

Historical hydrographic data from the Faroe–Shetland Channel were therefore reanalysed to seek answers to two distinct questions. First, was NSI water a new water mass or was it simply that during the 1980s it had a lower salinity value that allowed it to be more easily identified? And, if the latter, the second question follows on from the first, what caused it to have a minimum long-term salinity value in the 1980s?

An analysis of the Faroe–Shetland Channel data, most of which had been obtained by reversing water bottle casts, had not only the disadvantage of inadequate sampling around 0–1°C to identify NSI water, but also the difficulty of discerning the TS characteristics of AI water at any given time. Figure 7 is an illustration of such a difficulty; the TS characteristics of the AI water appear to approximate to 2.7°C, 34.90 which gives rise to a minimum at ca. 0°C for NSI water characteristics. However, if the core of AI water, say at AI_1, had been missed, then the minimum disappears and if NSI water is present it is not easily identified. The data was analysed with these kind of difficulties in mind and evidence of the occurrence of inflections in the TS envelope between AI and NSD water was convincing, some examples being given in Figure 2. Prior to 1953 the salinity data are inadequate for this kind of analysis, and indeed all salinity data prior to 1960, obtained by titration, have to be treated with caution.

The historical data do indicate that NSI water is not a new phenomenon but existed at least as early as the 1950s and probably is a permanent feature of the area.

This data also suggested that NSI water had a further distinguishing characteristic, namely a minimum silicate content. The Marine Laboratory has collected samples for silicate analysis on many of the Faroe–Shetland cruises but not at all stations and usually at fairly large depth intervals. Nevertheless, analysis showed that a silicate minimum could be found in 12 of the years between 1965 and 1987 in water between 0 and 1.5°C at a mean depth of 520 m. Low silicate values are also associated with AI water (Martin, 1976) but this water mass is higher in the water column (Fig. 2) and does not obscure the silicate minimum associated with NSI water. The fact that NSI water is associated with low silicate values suggests that, like AI water, recent surface water has been an ingredient. Changes in the salinity of AI water corresponded to changes in the salinity of NA water with a time delay of less than 1 year (Dooley *et al.*, 1984). This led to further research of the historical data to answer two further questions; does NSI water have a similar relationship, as with AI water, to NA water, and if so what time lag is involved? Second, was the minimum salinity of NSI water in the 1980s associated with the anomalous salinity values of NA water in the mid-1970s (Dooley *et al.*, 1984; Martin *et al.*, 1984) when NA water passing through the Faroe–Shetland Channel reached its lowest recorded salinity for over 60 years (Fig. 8)?

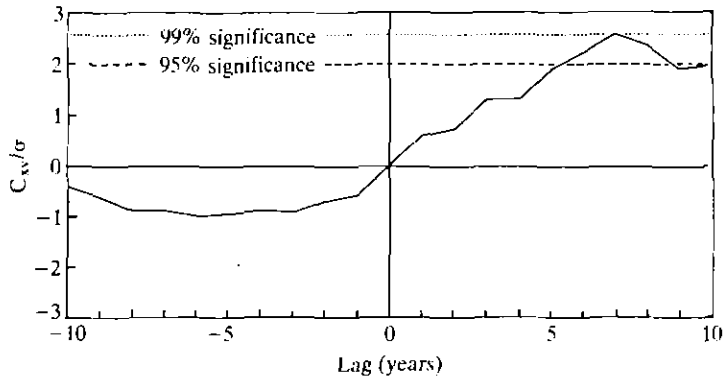

Figure 9. Lagged normalized cross-correlation coefficients (C_{xy}) of NSI and NA salinities.

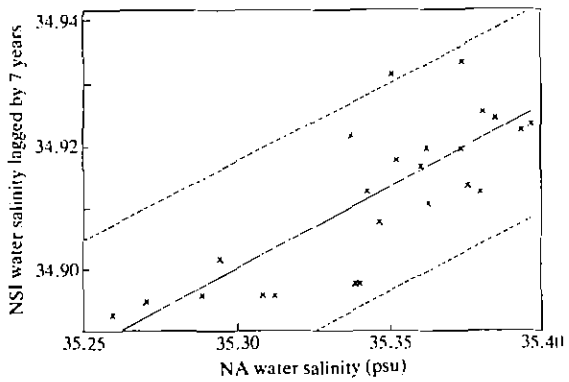

Figure 10. NA water salinity (psu) plotted against NSI water salinity (psu) lagged by 7 years.

In pursuing these questions it was assumed that NSI water was always present and that the minimum salinity of water between 0 and 1°C represented the core salinity of this water mass in any given year. This salinity value was correlated with the mean salinity of the core of the NA water as it passed through the Faroe–Shetland Channel into the Norwegian Sea. By mean salinity is meant the average value of the salinity for depths 0, 25, 50, 75, 100, 150, and 200 m where the core of the NA water was located, usually at the Continental Shelf break.

Time series data

The serial correlation between the time series of NA salinities and those of the NSI water was dealt with by normalizing the raw data by the method suggested by Sciremammano (1979). This method attempts to overcome the problems arising from the interrelation between inherent time-scales within environmental data and fixed record lengths. The method normalizes the raw cross-correlation coefficient C_{xy} with the Bartlett large-lag standard error σ, where:

$$\sigma^2 = 1/N\, C_{xx}C_{yy},$$

where C_{xx} and C_{yy} are the individual autocorrelation coefficients. The large-lag error is related to the degrees of freedom (n) of the cross-correlation by:

$$\sigma^2 = 1/n$$

and to the integral time scale τ by:

$$\sigma^2 = \tau/N\,\delta t,$$

where N is the number of observations separated by time interval δt.

The significance of the normalized cross-correlation coefficients may be directly assessed. Approximate values of $C^{xy}/\sigma = 2.6$, 2.0, and 1.7 reflect probability levels of 0.01, 0.05, and 0.10, respectively. The normalized cross-correlation coefficients are shown in Figure 9. The peak correlation occurs with a time lag of 7 years between NA water passing through the Faroe–Shetland Channel and the appearance of NSI water in the depths of the same channel, with a probability level of 0.1.

As will be seen from Figure 10, however, this statistical relationship is very dependent on half a dozen low salinity values of the NA water associated with the 1970s salinity anomaly. Historical hydrographic data shows no similar salinity event for the previous 60 years (Fig. 8) with the consequence that had it been possible to extend the period of statistical relationship prior to 1962 the level of statistical significance would have inevitably fallen. It will need another major salinity anomaly in the NA water totally to confirm the relationship between NA water and NSI water.

Conclusion

CTD casts in the future will disclose more about the nature and behaviour of NSI water but the historical hydrographic data do strongly suggest that it is a permanent feature of the northern seas. Its origins must still be

a matter of speculation. Blindheim (1990) suggests that it occurs as far north as the Iceland and Greenland Seas. Swift and Aagaard's (1981) work suggested an origin from a mixture of Arctic and Polar intermediate waters with Norwegian Sea deep water. However, cognizance must be made of its north Atlantic component and its relatively short exchange time.

Acknowledgements

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