OCEAN Challenge

The Challenger Society for Marine Science

Volume 6, No.1, 1995

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OCEAN Challenge

The Magazine of the Challenger Society for Marine Science

SCOPE AND AIMS

Ocean Challenge aims to keep its readers up to date with what is happening in oceanography in the UK and Europe. By covering the whole range of marine-related sciences in an accessible style it should be valuable both to specialist oceanographers who wish to broaden their knowledge of marine sciences, and to informed lay persons who are concerned about the oceanic environment.

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The cover image shows the global phytoplankton distribution. Phytoplankton concentrations are low in the central gyres (purple, deep blue), and tend to be high along coasts (yellow, orange and red). The images, which were made by processing thousands of individual scenes from the Coastal Zone Color Scanner, have been used by courtesy of Gene Feldman, NASA/ Goddard Flight Center, Space Data and Computing Division, Greenbelt, Maryland 20771, USA.

The cover was designed by Ann Aldred Associates.

GUEST EDITORIAL

A Centenary of hydrographic work in the Faroe-Shetland Channel

On 4 August 1893 Dr H.N.Dickson of the Fishery Board for Scotland on board HMS *Jackal* carried out the first hydrographic station of what has now become the standard Nolso-Flugga Faroe-Shetland Channel section. Using the Scottish designed self-locking slip bottle Dickson went on to carry out casts at stations 2, 5, 7 and 9 along this section, and also at stations 6, 9 and 11 of the Fair Isle-Munken section. Dickson repeated some of these stations in 1896 when some of his casts were to depths greater than 1000m, where he, for the first time, sampled Norwegian Sea Bottom Water. Dickson's observations in the Faroe-Shetland Channel together with some of the earlier pioneering work of Danish and Norwegian oceanographers laid the foundation for the systematic study of the climatology of the North Atlantic by I.C.E.S. In 1903 regular sampling along the Nolso-Flugga section was established, and has been maintained nearly every year since then; the breaks being the war years and a five year period in the early 1980s.

In 1993 the centenary of Dickson's observations was celebrated at a meeting hosted by the Marine Laboratory Aberdeen. Two ICES working groups were invited to participate, the Oceanic Hydrography Working Group and the Marine Data Management Group. The meeting took the form of a one-day symposium followed by four days of working group meetings, at which a broad range of topics were discussed including the general hydrography and circulation within the Faroe-Shetland Channel, the relationship between hydrography, fisheries and climate change and the importance of maintaining the continuity of long time-series of oceanographic observations.

We considered that a compilation of many of the papers presented at this meeting would be of considerably interest to a broader oceanographic audience. So we have encouraged the authors, where necessary, to update their contributions, so that they can be published in an issue of *Ocean Challenge*. What emerges is a fascinating insight into the way in which the foresight and scientific curiosity of a few enthusiastic individuals laid the foundations for the systematic study of an area of ocean, and how scientific concepts have evolved to account for the observed fluctuations. These concepts now underpin so much of the theory that we now take for granted when thinking about the role of the North Atlantic in regulating the climate of North-western Europe, and the way in which our exploitation of resources, particularly living resources, must be tuned to these fluctuations if we are to manage them sustainably.

We are sure that readers will find the individual accounts of considerable interest. But we feel that their real value is as an entity illustrating the way in which carefully planned long time series of quite simple observations can generate high quality science. Monitoring is often denigrated as being non-scientific, but given good design and continuity the results can be highly informative. Good old data, like vintage wine that has been properly laid down, can mature and become much more valuable.

Bill Turrell and Martin Angel

All the etchings are taken from volumes of The Norwegian North Atlantic Expedition 1878-1879, published by Grondahl & Sons, Bogtrykkeri, Christiania 1882-1896.

HMS *JACKAL*

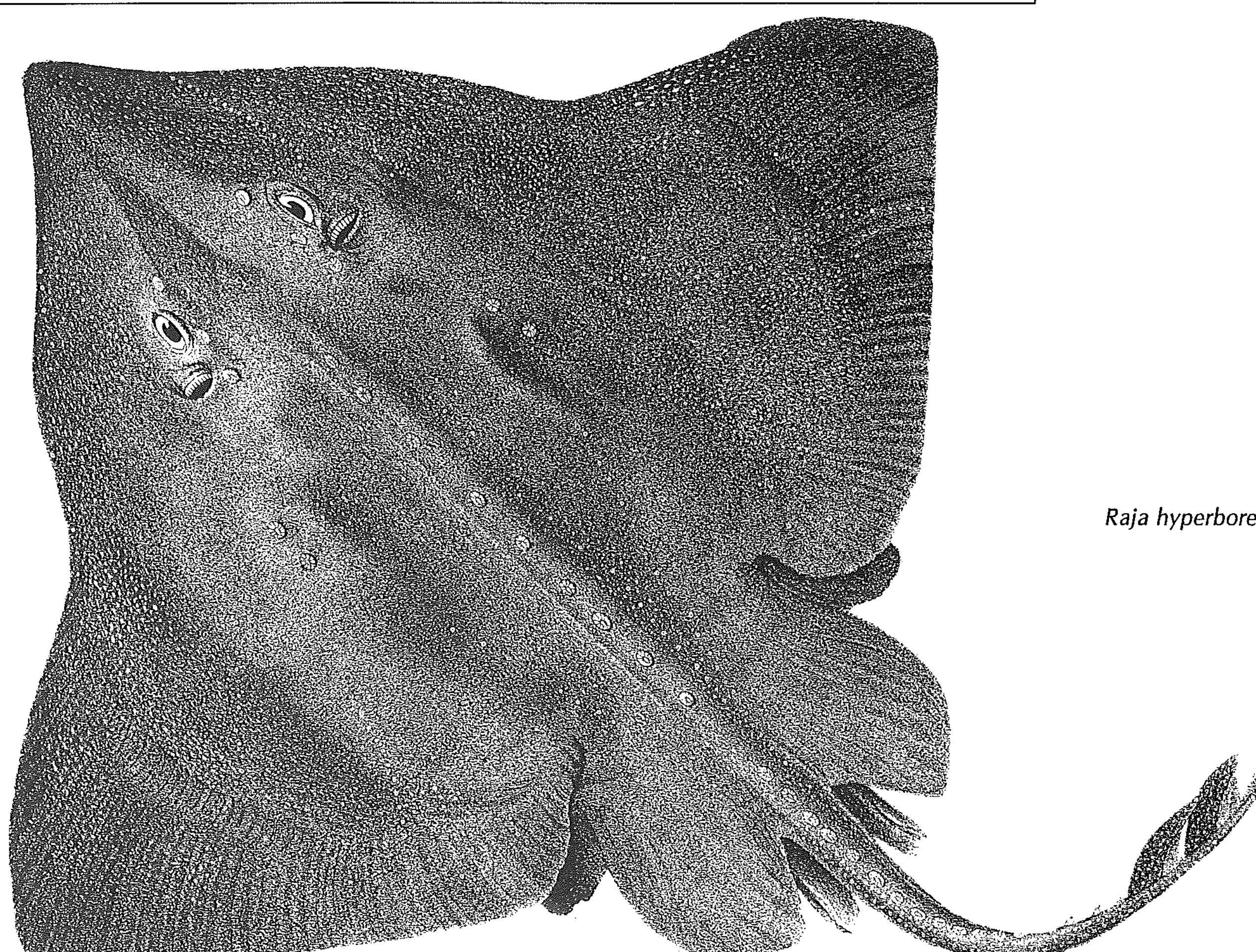
Twin screw iron fishery protection vessel, 750 tons displacement, 148' long, 26' beam, 814 i.h.p., purchased in 1885 as the tug *Woodcock* and renamed in 1886.

In 1887 the Jackall was used, under the command of Lieut A.M. Farquhar, for a physical and chemical cruise to the Hebrides for the Scottish Fisheries Board with Hugh Robert Mill as scientist. Mill was on the staff of the Scottish Marine Station, originally established on a floating laboratory, *The Ark*, at Granton in the Firth of Forth in 1884. The Marine Station was financed by the Scottish Meteorological Society and its establishment had been recommended by the Society's fisheries committee of which John Murray was chairman. Mill was given leave of absence to take part in the Fisheries Board cruise because the original choice, John Gibson, disliked working at sea. Mill suggested that the only significant result of this cruise was his coining of the term Continental Shelf!

In 1893-1894 the *Jackal* was used for a further series of similar cruises to investigate the water masses flowing through the channels connecting the North Sea with the Norwegian Sea and the Atlantic, including the Faroe-Shetland Channel, this time with H.N. Dickson as the scientist. These cruises had the twin objectives of extending the observations made by Mill and also being the British contribution to the international survey of the North Sea and North Atlantic proposed by Scandinavian scientists, particularly Otto Pettersson and Gustaf Ekman.

Like so many other survey vessels, the *Jackal* seems to have been particularly unsuitable for the work for which she was used, for she could not steam at less than about 4 knots and she could not be hove to. Nevertheless, extensive sounding, submarine temperature and salinity observations were made down to depths of about 400 fathoms (728m). The sediment samples collected on the sounding leads were examined by John Murray, while the small number of townet samples, obtained at the request of Pettersson, were examined by W.C. McIntosh and A. Scott.

Reproduced with permission from the author from 'British Oceanographic Vessels 1800-1950' by A.L. Rice, Ray Society, London, 1986.



Raja hyperborea

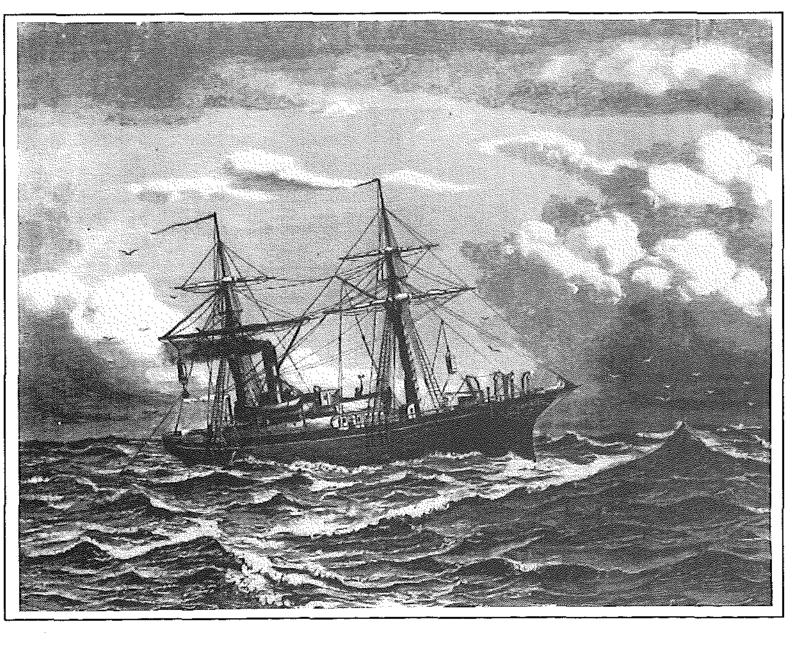
HISTORICAL STUDIES IN THE FAROE-SHETLAND CHANNEL

The NORWEGIAN PERSPECTIVE

Johan Blindheim

The earliest Norwegian oceanographic observations in the Faroe-Shetland Channel were made during the first year of the Norwegian North Atlantic Expedition in 1876-1878. The initiative for this first Norwegian oceanic expedition devoted to marine sciences, came from two professors at the University of Kristiania (Oslo) H. Mohn and G.O.Sars. Mohn who was professor of meteorology, can be considered to have been the founder of both physical oceanography and meteorology in Norway. Sars was also an influential pioneer in Norwegian research both in fisheries and biological oceanography. In their application for government funds to

Figure 1. The Vøringen, the first vessel used by H. Mohn and G.O. Sars for their research.



conduct research expeditions to the region between Norway and Greenland, they referred to the success of recent British expeditions:- "In the face of the facts set forth above, we will emphasize our previously expressed conviction, that, in order to investigate effectively the tract of ocean stretching west of the shores of Norway, a special expedition must be despatched. As models we have the *Porcupine* and *Challenger* Expeditions. The latter, which has for its object the exploration of the great Oceans of the globe, is furnished with a powerful *steam-corvette, which has been fitted out on* a scale commensurate with its importance, and is in every way worthy of the British nation. But means so extensive and costly are not required for investigating the Norwegian Sea; and an expedition similar, for instance, to that sent out with the *Porcupine*, would certainly be adequate for the attainment of the end proposed." They also argued that "a Norwegian expedition must derive additional importance from its intimate relation to British expeditions, and more especially to that despatched with the *Porcupine*, since it would furnish the very desirable opportunity of carrying on and completing *in direction* of the Arctic Ocean the work begun by the *Porcupine* Expedition". Their hope was that a new, specially-designed vessel would be provided, but in the end they had to make do with a partially converted charter vessel, the *Vøringen* (Figure 1). During this expedition some oceanographic observation were made in the Faroe-Shetland Channel.

The 1876-1878 expedition marked the beginning of an active and fruitful phase for oceanic research in Norway. Its successes encouraged the Norwegian Government to provide further grants for marine research which in 1900 became formalized by the setting-up of the Norwegian Fishery and Marine Investigations and its provision with a new custom-built and fully-equipped scientific research vessel R/V *Michael Sars*.

The *Jackal* Survey

The first international investigations organised by the International Council for the Exploration of the Sea (ICES), led to the development of collaborative links between UK and Norway. In 1902, Professor D'Arcy Thompson invited Dr B. Helland-Hansen to participate in a hydrographic survey of the Faroe-Shetland Channel and Northern North Sea. Helland-Hansen sailed on HMS *Jackal*. When in 1905, he reported on his results from that cruise in the Journal of the Fishery Board for Scotland, he used the formula he had for computing geostrophic currents that later became so well known. This formula was a development of earlier deductions based on Bjerknes' theorem of circulation published by Sandström and Helland-Hansen in 1903. Mohn had derived the general formula for computing ocean currents from the slope of the isobaric surfaces in 1885, but in doing so had not discriminated clearly between the slope resulting from the internal distribution of mass and the slope resulting from external forces. Moreover, as Sandström and Helland-Hansen pointed out Mohn's method involved very laborious calculations which, in the days before computers, was a powerful argument against its general application.

The 1900-1904 surveys

Once the new research vessel *Michael Sars* had become operational, the Norwegian Fishery and Marine Investigations embarked on an intensive period of research. Figure 2 shows the sections worked during 1900-1904, several of which crossed the Faroe-Shetland Channel. One section in particular is of considerable historical importance, the "Sognefjord Section" which extended from the Norwegian coast between about 60°45'N, 5°00'E and 64°15'N, 5°00'W,

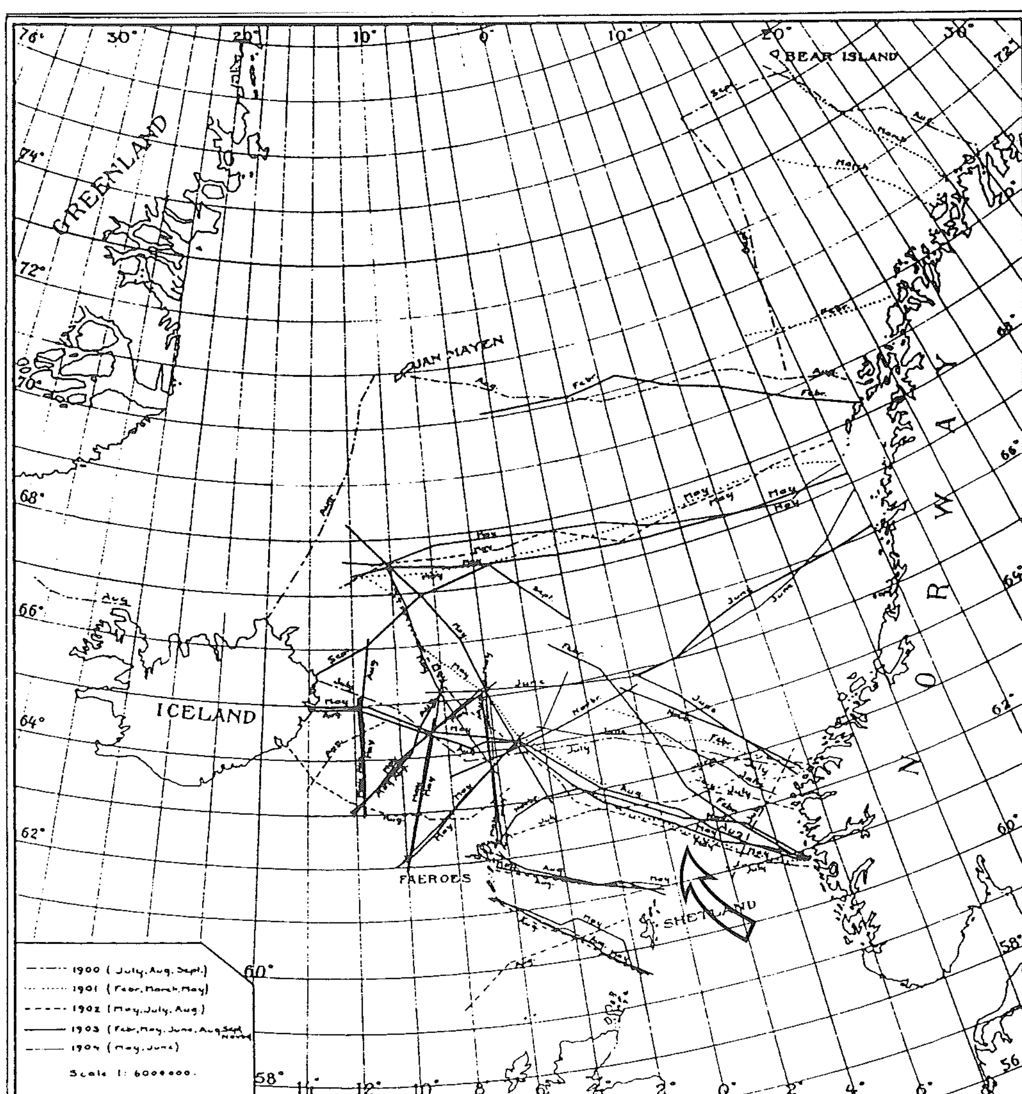


Figure 2. Sections worked by the R/V Michael Sars in 1900-1904. The Sognefjord section is indicated by the superimposed arrow. (copied from Helland-Hansen and Nansen 1909)

crossing the northeastern part of the Faroe-Shetland Channel. This section has been repeated over and over again to provide a long-time series of data. The results from the first set of surveys were published in 1909 by Helland-Hansen and F. Nansen in their famous report *The Norwegian Sea*. They described how fluctuations in Atlantic influence in the Faroe-Shetland Channel, appear off Lofoten after a one year time lag, and in the Barents Sea after two years (Figure 3). Although their time series were short, they demonstrated this northward progression fairly clearly. Helland-Hansen and Nansen also discussed the influence of the fluctuations in the quantity of heat in the Atlantic water, calculated as the product of the sectional area and the mean temperature, on mean winter temperatures in Scandinavia (Figure 4) and further, how these fluctuations affected ecological events both in marine and terrestrial environments as well as ice conditions in the Barents Sea. They found similar correlations between the temperature fluctuations and a range of indicators of the physiological condition of the stock of spawning cod, such as the amount of liver and roe. The fluctuations in Atlantic influence are now applied prognostically in the management of the fisheries.

The Depths of the Oceans

In 1910 the R/V *Michael Sars* once again visited the Faroe-Shetland Channel while returning from a cruise in the North Atlantic. The initiative (and funding) for this cruise came from Sir John Murray who had written to Dr Johan Hjort, the director of the Norwegian Fisheries and Marine Investigations offering to pay all expenses if the Norwegian Government would lend the ship and her staff for a four month cruise in the North Atlantic. This proposal was greeted with enthusiasm by both Government and staff. Some of the results from this cruise were published in 1912 in the oceanographic classic *The Depths of the Ocean* for which Murray and Hjort were the editors and main authors.

The Sognefjord Section revisited

After the World War, observations along the Sognefjord Section were repeated. Helland-Hansen in contributing a paper on analyses of the observations made in 1925, 1927 and 1929 to the James Johnstone Memorial Volume in 1934 applied his new method for dynamical computations over a bottom sloping up to depths shallower than the reference layer. He attributed the inspiration for the idea to Fridtjof Nansen. "In April 1930, some weeks before he died, Fridtjof

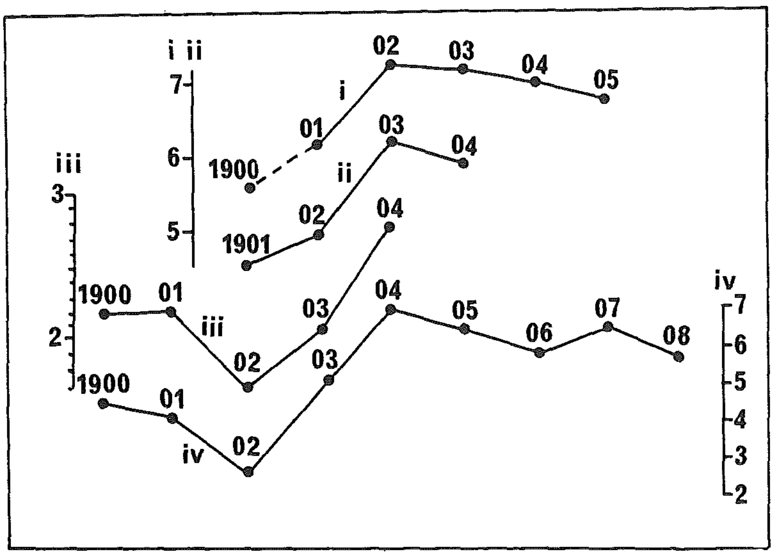


***Figure 3**. The northward progression of the effects of the fluctuations in the Atlantic Current taken from Helland-Hansen and Nansen (1909):-*
1. The mean temperature of Atlantic water along the Sognefjord section for May (1901-1905).
II. The mean temperature of Atlantic water along the Lofoten section for May (1901-1904).
III. The mean temperature of the water at between 100 to 200m at three stations along the Russian Kola section for May (1900-1904).
IV. The mean area (in 10^4km^{-2}) of open water in the Barents Sea in May 1900-1908 (scale to right).

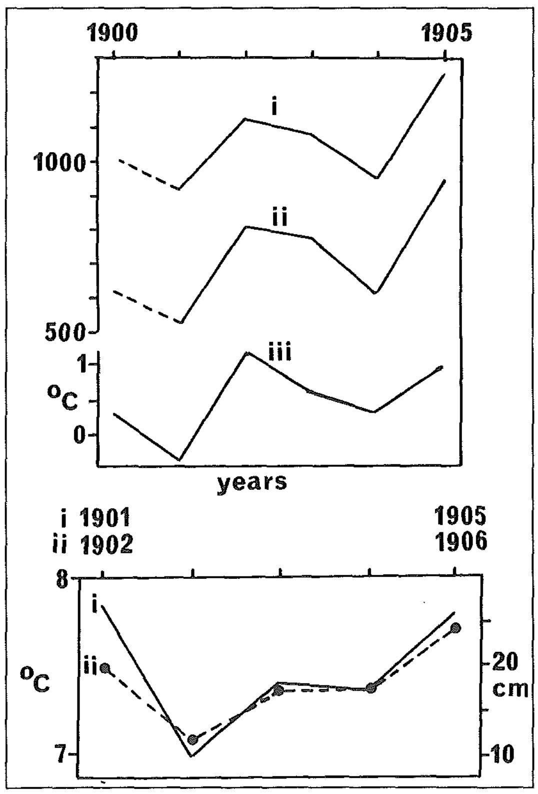


***Figure 4**. The correlation between mean surface temperature along the Sognefjord section, average winter air temperatures and the average growth of firs in eastern Norway:-*
Above 1. Quantity of heat in Atlantic Water along the whole of the Sognefjord Section expressed as the product of the sectional area and the mean temperature. II. Quantity of heat in Atlantic Water along the Sognefjord Section to the west of Station 3. III. Mean anomaly of air temperature, following Winter (November - April) for 22 Norwegian meteorological stations.
Below I. Mean surface temperature along the Sognefjord Section in May. II. Average growth (cm) of fir in eastern Norway. (from Helland-Hansen and Nansen, 1909).

Nansen suggested to the author that, for calculating the gradient currents in shallow water adjacent to a deep ocean the following view might be useful: Suppose a station A in the ocean reaching the deep "nought-level" with a uniform density in a horizontal direction, and another station B above the continental slope or shelf. A tube may be imagined, going from the surface at station A down to the "nought-level", from there horizontally it reaches the bottom of the slope, thence along this vertical to the surface. The difference in the level of the surface at A and B may then be found from the distribution of density within the two parts of the tube lying above the "nought-level", as the pressure at the bottom ends of the horizontal part of the tube is the same". Helland-Hansen incorporated this concept into his method.

The Sognefjord Section was once again repeated several times after World War II. O.H.Saelen (1959) when publishing the results for the period 1947-1953 reported very large variations in the calculated transport, even between sections observed within a few days. To try to understand these results Saelen re-examined the theory of dynamic computations with special emphasis on what happens when a section extends into shallow water. He concluded that the computed variations in transport may not be real but are partially the result of variable currents in the reference layer.

Current meter observations

In 1961, the first current meter mooring was deployed in the Faroe-Shetland Channel by the Geophysical Institute of the University of Bergen, and were repeated using Aanderaa RCMs during following years. Although these measurements examined the flow through the Channel, a major objective of the exercise was to develop mooring techniques and data handling, so only the observations spanned only short time periods.

The Geophysical Institute also participated in the North Atlantic Norwegian Sea Exchange (NANSEN) Project in the 1980s which aimed at quantifying the exchanges of Atlantic inflow over the Scotland-Iceland Ridge both to the north and to the south of the Faroes. Although much of this activity was concentrated on transport measurements in the sector of the Atlantic Current to the north and west of the Faroes, it contributed to knowledge of the oceanography of the Faroe-Shetland Channel since much of this water recirculates back into the Channel to the southeast of the Faroe Islands.

Fisheries research

The investigations of the Institute of Marine Research at Bergen have been focussed more on the assessments of pelagic fish stocks, then on problems associated directly with the physical oceanography of the Channel. While most of the populations studied – the Norwegian spring spawning and North Sea herring (*Clupea harengus*) and the blue whiting (*Micromesistius potassou*) – occur beyond the Channel, the surveys have always included parts of the Channel. In 1950 Finn Devold who was in charge of the herring investigations, established a survey system designed to follow the spawning migration of the Norwegian spring spawning herring, from their wintering grounds to the east of Iceland in to the Norwegian coast. These surveys were carried out in December and January throughout the 1950s and 1960s. These surveys resulted in maps of temperature and salinity which included the northeastern part of the Channel (Figure 5). Cruises to study herring in the Northern North Sea also covered the southern end of the Channel.

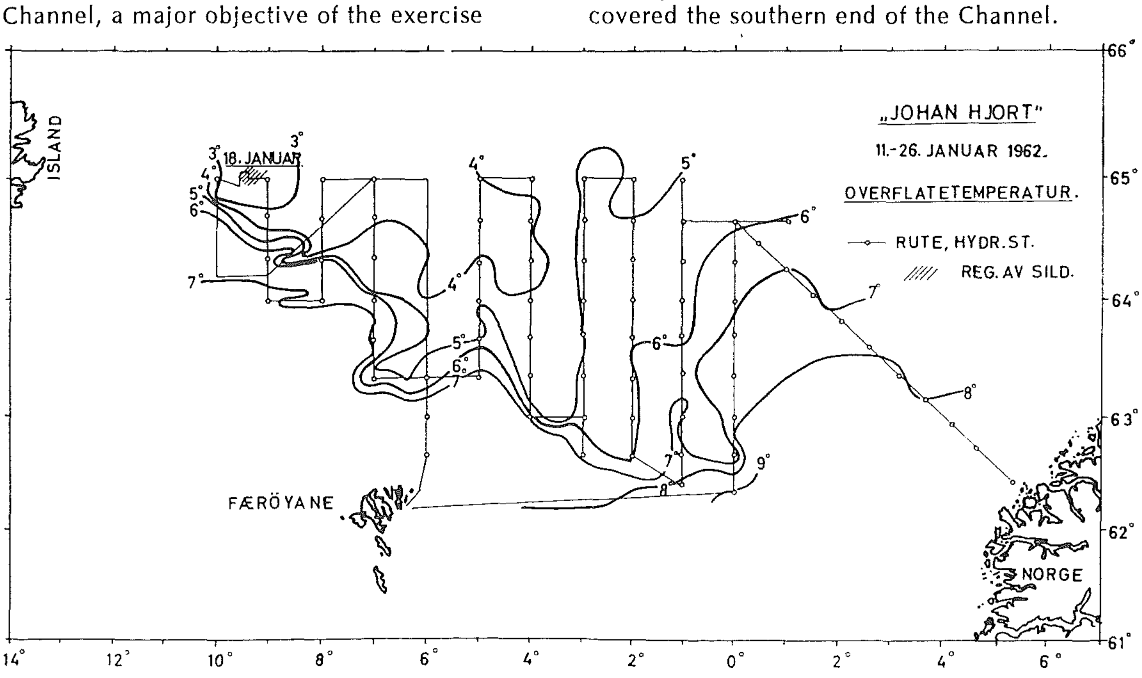


Figure 5. Survey tracks, hydrographic stations and the distribution of sea surface temperatures from the herring survey of January 1962, designed by Finn Devold. (Copied from Fisken og Havet, no 4, 1962).

In the 1970s surveys were carried to map the prevailing environmental characteristics encountered by the stocks of blue whiting migrating from their feeding grounds in the Norwegian Sea to their spawning grounds to the west of the British Isles. Some of these surveys covered the Channel, and Figure 6 illustrates the blue whiting stocks moving southwestwards through the Channel as mapped by their acoustic backscatter. Also shown are their day and night distributions in relation to the temperatures and salinity profiles.

Although this brief review of Norwegian research in the Faroe-Sheltland Channel reflects a range of activities, the key interest has probably been connected to the Channel's role as being the main pathway for the transport of heat into the Nordic Seas. A reliable quantitative assessment of this transport is still to be achieved.

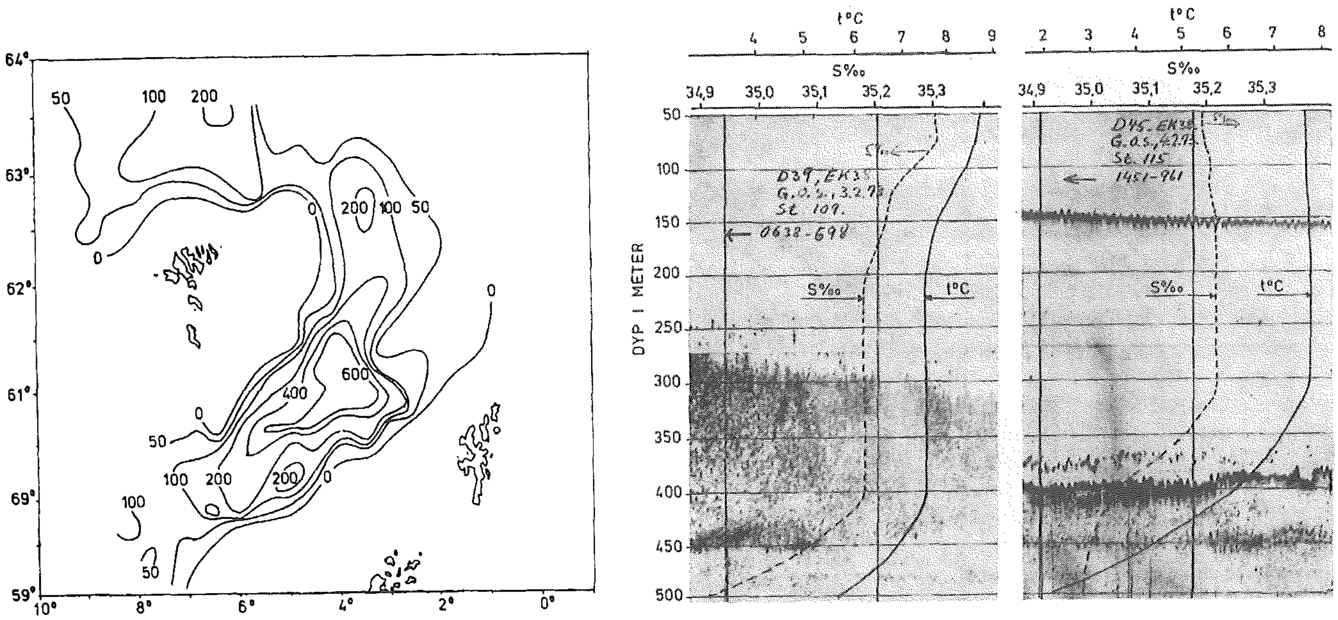


Figure 6. Blue whiting (Micromesistius potassou) migrations through the Faroe-Shetland Channel:- Left: Distribution of Blue whiting in the Channel as revealed by acoustic back-scatter, 28 January to 9 February 1973. Right: Night (left) and day (right) vertical distribution of the back-scatter from blue whiting in the Channel with the temperature and salinity profiles superimposed. (Copied from Fiskets Gang. no 16, 1973).

Further reading

The Norwegian North Atlantic Expedition 1878-1879 Volumes 1-7 Published by Grondahl & Sons, Bogtrykkeri, Christiania 1882-1896. Especially Volume 2 by H. Mohn 1887. The North Ocean, its depths, temperature and circulation. 209pp

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HISTORICAL STUDIES IN THE FAROE-SHETLAND CHANNEL

The DANISH PERSPECTIVE

Erik Buch

Until the middle of this century, Greenland, Iceland and the Faroe Islands were all linked administratively to Denmark, and so for centuries there have been regular trans-Atlantic crossings by Danish naval and merchant ships.

There were a number of intelligent and far-sighted naval officers like Irminger, Wandel and Ryder who recognised the importance of understanding the patterns of the ocean currents in the North Atlantic. By the middle of the nineteenth century they had initiated programmes of systematic observation of physical oceanographic parameters from the Danish ships crossing the North Atlantic. At first only sea surface temperatures were measured, but then the observations were extended to include surface salinities and vertical profiles of temperature and salinity, and later drift-bottle experiments.

The turn of the century saw the first truly scientific expeditions to Faroese waters being initiated and lead by some of the well-known Danish marine scientists of the time including Martin Knudsen, J.P.Jacobsen and J.N.Nielsen. These expeditions continued irregularly until World War II.

After the War until the mid-1970s observational programmes around the Faroes were carried out annually by the Danish Institute for Fisheries and Marine Research in support of fisheries research and for many years the data were analysed by Frede Hermann. However, in the mid-70s the observational programme was taken over by the Faroese Fisheries Research Institute under the direction of Bogi Hansen, and since then Danish research activity has ceased.

Introduction

In a historical sense, the discoveries of the Faroe Islands, Iceland and Greenland can be considered to be the first major results of marine research in the North Atlantic which provided information on the ocean currents. Although these discoveries did not result from Danish efforts, all three countries became closely linked with Denmark. And so for several centuries Danish merchant shipping companies monopolised trade between them and the Danish navy had the responsiblity for protecting Danish interests in the North Atlantic. Consequently, every year there were several crossings of the region by Danish shipping, both mercantile and naval. Knowledge of the surface currents in the region was gradually compiled, but even so, it was not until the middle of the nineteenth century that far-sighted naval officers initiated a programme of regular and systematic measurements of physical oceanographic parameters.

> "Ocean currents, which can rightfully be called the arteries of the globe, because flowing through different zones they heat the cold regions and cool the warm, has not, in relation to the widespread shipping, received the attention they deserve." (Author's translation)

A statement along these lines might be expected to appear in any modern science plan seeking to address the importance of the role played by ocean currents in climate variability, but it comes from a publication by Irminger written in 1853!

Irminger, one of the pioneers of Danish oceanography, took a special interest in the circulation of the North Atlantic. As a young officer he had served on naval vessels patrolling the waters around the Faroes, Iceland and Greenland, and it was during these voyages that he started to make regular observations of sea surface temperature. On one of his first voyages between 19 June and 13 July 1844, he recorded in the ship's log that around the Faroes sea surface temperatures were never lower than 7.74°C and never higher than 8.25°C (Irminger, 1853). Using his sea surface temperature data, he was the first to demonstrate how the East Greenland Current turns west at Cape Farewell (Irminger, 1853). However, no one believed him and it took another forty years before another Danish naval officer, C.F.Wandel provided the convincing proof (Wandel, 1893).

In 1846, Irminger persuaded the harbour authorities in Thorshavn to make daily observations of sea surface temperature (SST) in the harbour. Irminger used these observations to calculate the monthly mean temperature (Table 1). These data, together with the 1844 observations are some of the oldest oceanographic data from the Faroes Islands.

Month	Year	Mean SST °C
October	1846	7.27
November	1846	6.79
December	1846	4.91
January	1847	4.90
February	1847	4.05
March	1847	5.08
April	1847	5.10
May	1847	6.28
June	1847	7.39

Table 1. *Mean monthly sea surface temperatures (SSTs) in Thorshavn harbour October 1846 to June 1847. After Irminger (1853).*

Irminger's great interest in ocean currents lead him to experiment with instruments for measuring subsurface currents. He tried out the German-built instrument shown in Figure 1 which was designed to measure the direction of subsurface currents. Irminger was not very impressed with its performance since in his report he wrote:- "Under certain circumstances the current direction may be measured". Only a brief look at the way the instrument functioned is needed for a modern oceanographer to be in full agreement with Irminger. It will come as no surprise to anyone that such an intelligent and enterprising officer like Irminger was eventually promoted to the rank of admiral, which to him was probably more important than having a sea named after him!

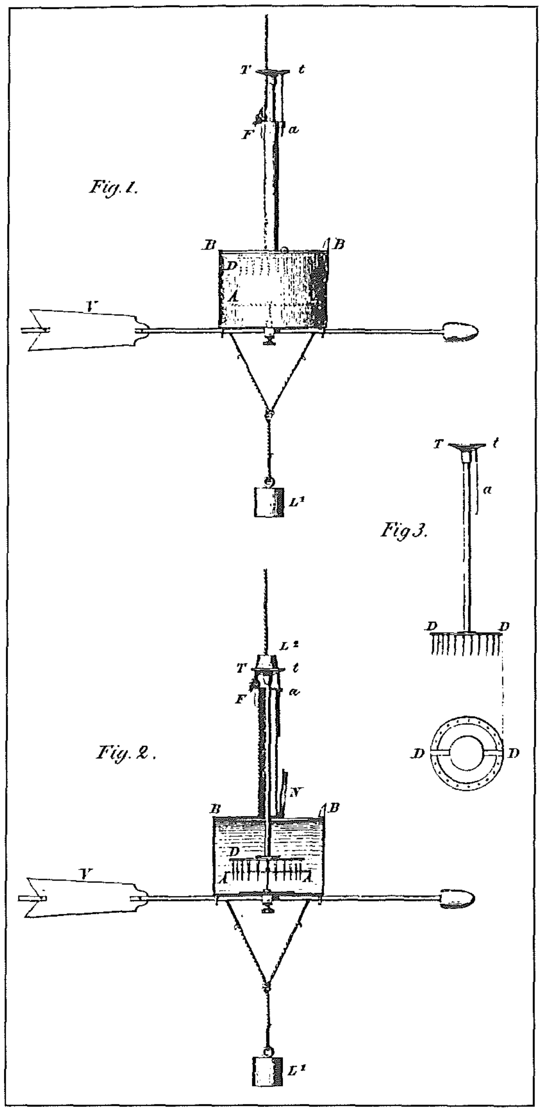


Figure 1. *Instrument used by Irminger for measuring subsurface current direction (after Irminger, 1853)*

During the 1890s, there was another increase in Danish interest in the oceanography of Faroese waters again stimulated by a naval officer C. Ryder. Like Irminger, Ryder was very interested in the currents, and it was he who initiated the drift bottle experiment which lasted from 1891 to 1902, with the maximum effort in the latter three years. Before the programme started he found out, with what must have been highly enjoyable tests, that champagne bottles were the most effective drifters; because they floated horizontally and were, therefore, not exposed to the wind as much as the other types of bottle. These experiments revealed that the waters around the Faroes are influenced not only by the warm water of the North Atlantic Current (then called the Gulf Stream) but also by cold arctic water being carried in by the East Icelandic Current (Figure 2). They also gave an indication as to just how complex the currents are in the region. Ryder's estimates for mean current speeds between the Faroes and Iceland was 5-10 cm s^{-1}, and double that speed between the Faroes and the Shetlands.

Ryder also continued to make observations of sea surface temperature and salinity, and his data were analysed and published in 1900 by our next notable Danish oceanographer Martin Knudsen.

Martin Knudsen

Knudsen was fascinated by the fact that the waters around the Faroes are influenced by two current systems with very different temperature characteristics. He was particularly interested in the role played by the East Icelandic Current in modifying the islands' climate. He was able to relate differences in air and sea surface temperatures around the Faroes to wind direction, i.e whether the winds were coming in from over the cooler East Icelandic Current waters or from over the warmer waters of the North Atlantic Current. He observed that the wind-related changes in

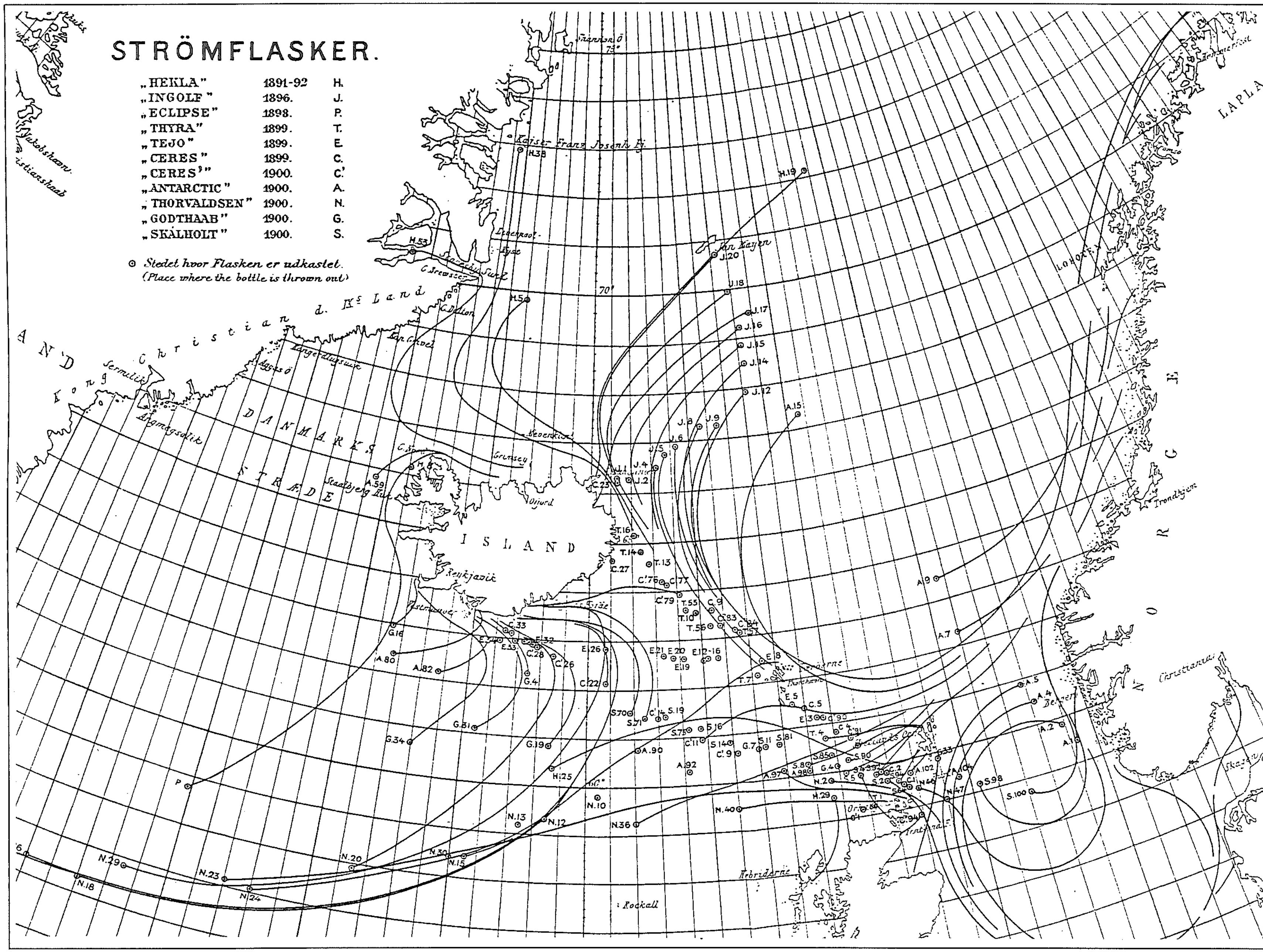
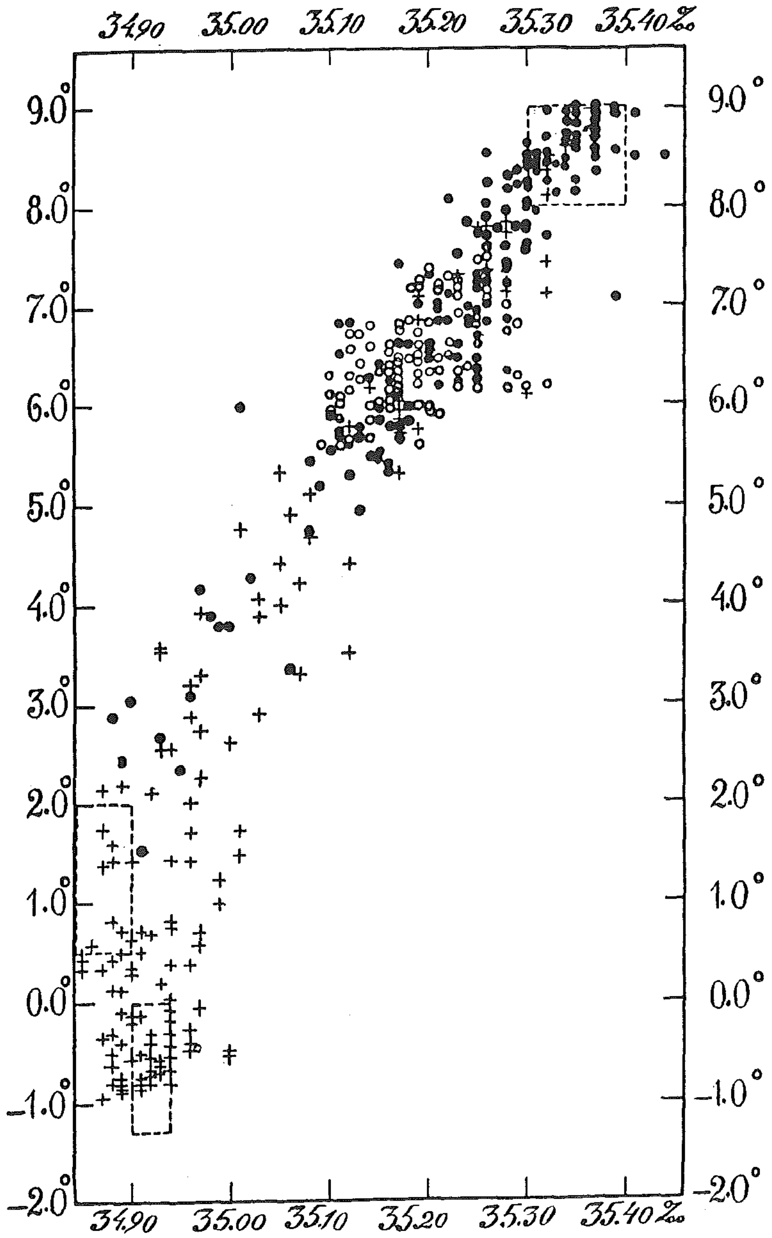


Figure 2. Tracks of the drift bottles recovered during the 1891-1900 programme. The circles indicate the start of the track where the bottles were launched. The tracks clearly show the northerly flow of North Atlantic Water on the western side and the southerly flow of cold East Icelandic Polar Water in the Norwegian Sea (From Ryder, 1901)

air temperature were greatest in March (6.7°C) and smallest in July (1.5°C). Sea surface temperatures showed similar seasonal responses but the differences were much smaller, with a maximum difference of 1°C in winter and almost no detectable difference in summer. Knudsen ascribed the smaller summertime fluctuations in both air and sea temperatures to the result of solar heating of the surface waters of the East Icelandic Current.

All the results described above had been based data gathered by "ships of opportunity" and the enthusiasm of a handful of individuals. The first real scientific cruise to Faroese waters was made the R/V *Thor* in 1903. Knudsen who had recently been appointed as Director of the Danish Hydrographic Research Institute planned the programme of observations, and J.N.Nielsen was responsible for carrying it out at sea. Knudsen was particularly interested in the surface fronts which form between the different waters of the two currents – the warm North Atlantic Water and the cooler East Icelandic Polar Water – and so the bulk of the observations were made between the Faroes and Iceland. The *Thor* expedition was an immediate outcome of the scientific and political agreements reached at the Stockholm and Kristinia conferences which in 1902 also lead to the establishment of ICES – the International Commission for the Exploration of the Seas.

Figure 3. *TS-diagram of waters sampled at various locations within the Faroe-Shetland Channel identifying the various water masses, as identified by the hatched boxes (from Jacobsen and Jensen, 1926)*
o observations from the Faroe's shelf (depths < 300m)
• observations from the upper 300m beyond the shelf.
+ observations at depth > 300m.



Further research cruises were carried by the R/V *Thor* in 1904, 1905 and 1910, which resulted in pioneering publications by Knudsen, Nielsen and J.P. Jakobsen on the hydrography and variability of the waters around the Faroes, fjord oceanography, and tidal currents and water mass mixing.

Research post-1910

The 1914-1918 War put a halt to Danish marine research activities in the North Atlantic. It was not until 1924 that there was another major research programme, the combined Scottish and Danish programme conducted aboard the R/V *Explorer* and the R/V *Dana I* in the Faroe-Shetland Channel. The different water masses found in the area can be identified on the TS-diagram shown in Figure 3 (Jacobsen and Jensen, 1926). These observations were used to calculate the geostrophic currents and an example of one of their vertical profiles of current velocities is illustrated in Figure 4.

After 1924, Danish oceanographic research in Faroese waters focussed on the routine observations made during fishery research cruises. These observations continued, apart from an interruption during World War II, until the middle of the 1970s when the R/V *Dana II* was taken out of service. The results were published in a series of papers by Frede Hermann, an oceanographer at the Danish Fisheries and Research Institute, who also for many years was head of the laboratory responsible for producing Standard Seawater. Hermann was also responsible for the last major Danish contribution to the oceanography of Faroese waters, the contributions to the international OVERFLOW programmes in 1960 and 1973.

Responsibility for monitoring the hydrographic conditions around the Faroes was then taken over by the Faroese Fisheries Research Institute, where Bogi Hansen is now responsible for the oceanographic studies. Danish oceanographers are currently involved in NORDIC WOCE, the collaborative Nordic contribution to the World Ocean Circulation Experiment (WOCE). During 1993-97, NORDIC WOCE will be estimating the volume transport of water across the submarine ridge that extends from Greenland via the Faroes to Scotland.

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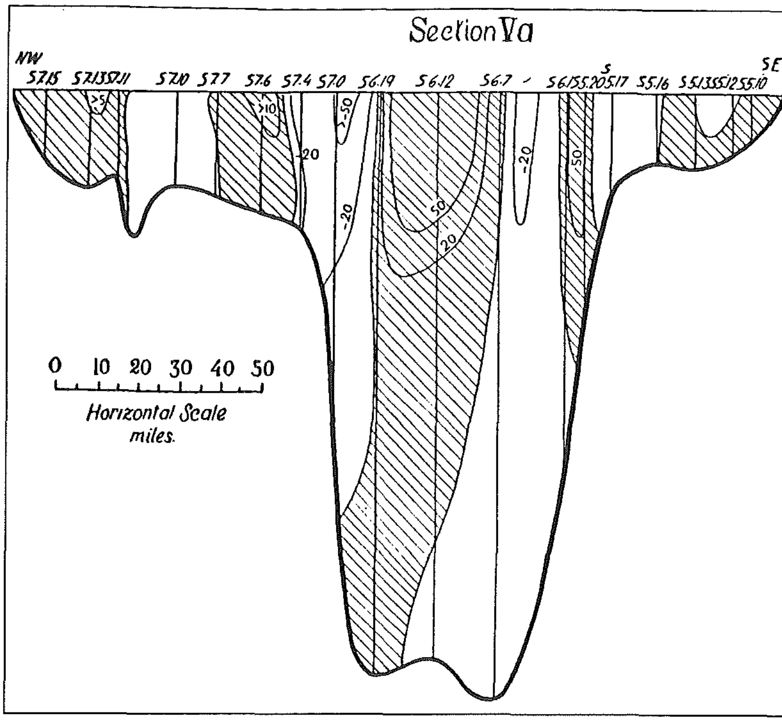
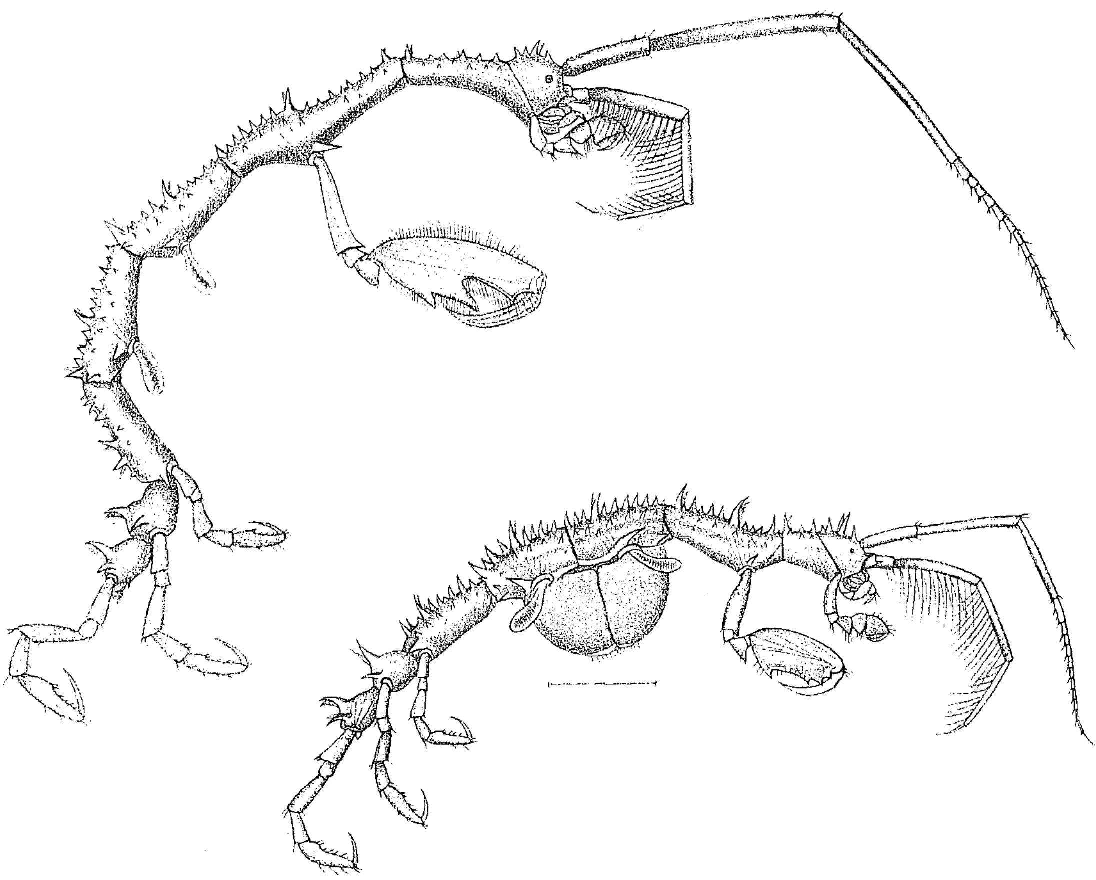


Figure 4 *Profile of geostrophic current velocities observed across the Faroe-Shetland Channel in 1924. The velocities are given in cm s^{-1}, and the hatching indicates currents flowing to the north-east and the negative currents are to the south-west (from Jacobsen and Jensen, 1926).*



HISTORICAL STUDIES IN THE FAROE-SHETLAND CHANNEL

The SCOTTISH PERSPECTIVE

Jim Adams

To appreciate fully the history of Scotland's contribution to our scientific knowledge of the Faroe-Shetland Channel, it is appropriate to start in August and September 1868. This was when Charles Wyville Thomson, a Scot then occupying the Chair of Natural History at Queen's College Belfast, and William Benjamin Carpenter of London visited the Channel aboard HMS *Lightning*. This was the cruise on which they made their classic observation that deep temperatures were 0.5°C and 1.1°C to the south of Thorshavn, but were 6.4°C at similar depths only some 100km to the south. The few trawls they were able to achieve showed that the bottom-living animals were as different as the temperatures. They returned the following year at same season, but this time onboard HMS *Porcupine* to continue dredging at depths which hitherto had generally been supposed to be devoid of life.

They considered the results of the first cruise to be disappointing, the *Lightning* performed poorly in the bad weather that was encountered. Even so, the success of the two cruises led directly to the setting up of the *Challenger* Expedition of 1872-76 with Wyville Thomson as its leader. Throughout the *Challenger* Expedition collections were dispatched back to Edinburgh where Wyville Thomson had been appointed Professor of Natural History in November 1870. As a result, the *Challenger* Office at 32 Queen Street, Edinburgh, became a major centre for marine research during the latter part of the 19th century, and it was from there that the analyses of the *Challenger* material was coordinated and the results were published.

During that period Wyville Thomson, who by then had been knighted, sought help from the British Admiralty to investigate the possibility that submarine topography was playing an important role in controlling the distribution of the warm and cold waters which had been encountered during the *Lightning* and *Porcupine* cruises to the Faroe-Shetland Channel. The outcome of these approaches was a cruise by *Knight-Errant* in July/August 1880 followed by another by HMS *Triton* in 1882. These two cruises firmly established the existence of the feature now known as the Wyville Thomson Ridge. Sadly Wyville Thomson died in March 1882, but his work of running the *Challenger* Office was successfully continued for many years by his former shipmate and colleague John (later Sir John) Murray.

Edinburgh's claim as a major centre for marine research was further strengthened by the interests of the Scottish Meteorological Society. In 1857, within two years of its foundation, the Society began to collect data on sea temperatures; its interest was stimulated by an appreciation of the importance of the influence of sea temperature on weather. By the early 1870s, this interest had extended to trying to establish possible links between sea temperatures and successes and failures in the Scottish herring fisheries. Subsequently the Society took an active interest in the possible links between weather and other important Scottish fisheries for salmon and trout. Lack of finance was a perennial problem, but in February 1883 the Society received a windfall of £1,600 – the balance left after an International Fisheries Exhibition which had been held in Edinburgh the previous April. John Murray, who was convener of the executive committee of the Exhibition and greatly interested in the work of the Society, was central in arranging the grant. The Society used £900 of this money, supplemented by further grants from Murray and his supporters to establish the Scottish Marine Station for Scientific Research, onboard *The Ark* moored at Granton on the outskirts of Edinburgh. This floating laboratory opened in the Spring of 1884, and over the years, provided the base for several research workers who made valuable contributions to marine and fisheries science. In the context of this paper, mention need only be made of the Station's chemist and physicist, Hugh Robert Mill.

In 1882 the Fishery Board for Scotland had been reconstituted. This was the first Governmental body in the United Kingdom to have a permanent organisation devoted to the scientific investigation of fishery problems. Despite the Board also being based in Edinburgh relations between it and the Granton Station were rather strained; according to Mill the Fishery Board was "too proud and stiff to co-operate with an unofficial body like the Marine Station".

The feeling appears to have been largely mutual since, when, in 1886, Mill was asked to help the Board with its studies of the Moray Firth and its associated inner firths, John Murray did not wish the Granton Station's cooperation to be official. Instead it was arranged that Mill would take a "holiday" so that he could sail on the Board's research yacht *Garland*. Mill undertook another task for the Board in 1886, when he collaborated with John Gibson of the University of Edinburgh's Chemistry Department, to advise the Board on the equipment it needed to undertake its physical observations. They recommended the use of Negretti and Zambra deep-sea thermometers (see paper by Sherwin) mounted on a frame devised by Mill (the Scottish Frame), together with water bottles, hydrometers and discs for estimating the transparency and colour of the water.

In July/August 1887, Mill had another "holiday" this time aboard the fishery cruiser HMS *Jackal*, describing, on behalf of the Board, the distribution of salinity and temperature in the waters to the west of the Outer Hebrides. Despite a series of gales which limited the number of his observations, Mill was, nevertheless, able to confirm the importance of the influence of bottom topography on the structure of the water column and circulation. This cruise proved to be of interest on two other counts. Firstly, according to Mill himself, it was his participation in this cruise, which led to him introducing the term *continental shelf* into the geographic and oceanographic vocabulary. Secondly, this was the first research cruise by the vessel which subsequently worked in the Faroe-Shetland Channel through the 1890s and early 1900s.

For many years a paddle gun vessel *Jackal* had been one of the main naval vessels assigned to fishery protection duties in Scottish waters. In 1886, when this original *Jackal* was replaced by a swift more powerful twin-screw vessel, the 148 foot-long (45m) *Woodcock*, the replacement was renamed *Jackal*. This "new" *Jackal* was fitted with a deck house containing a scientific laboratory and a cabin with three berths for scientists. As a research vessel she had some serious short-comings, not only did she roll heavily in the least of swells, but also her inability to steam at speeds slower than 4 knots further detracted from her suitability for dredging, trawling and surface netting. No photographs of her appear to have survived, but plans of the refitted vessel are held at the National Maritime Museum at Greenwich. These show that, as was typical of that era, she carried a hen coop on deck, so at least the crew had the benefit of an occasional fresh chicken, but whether or not they laid eggs is not recorded.

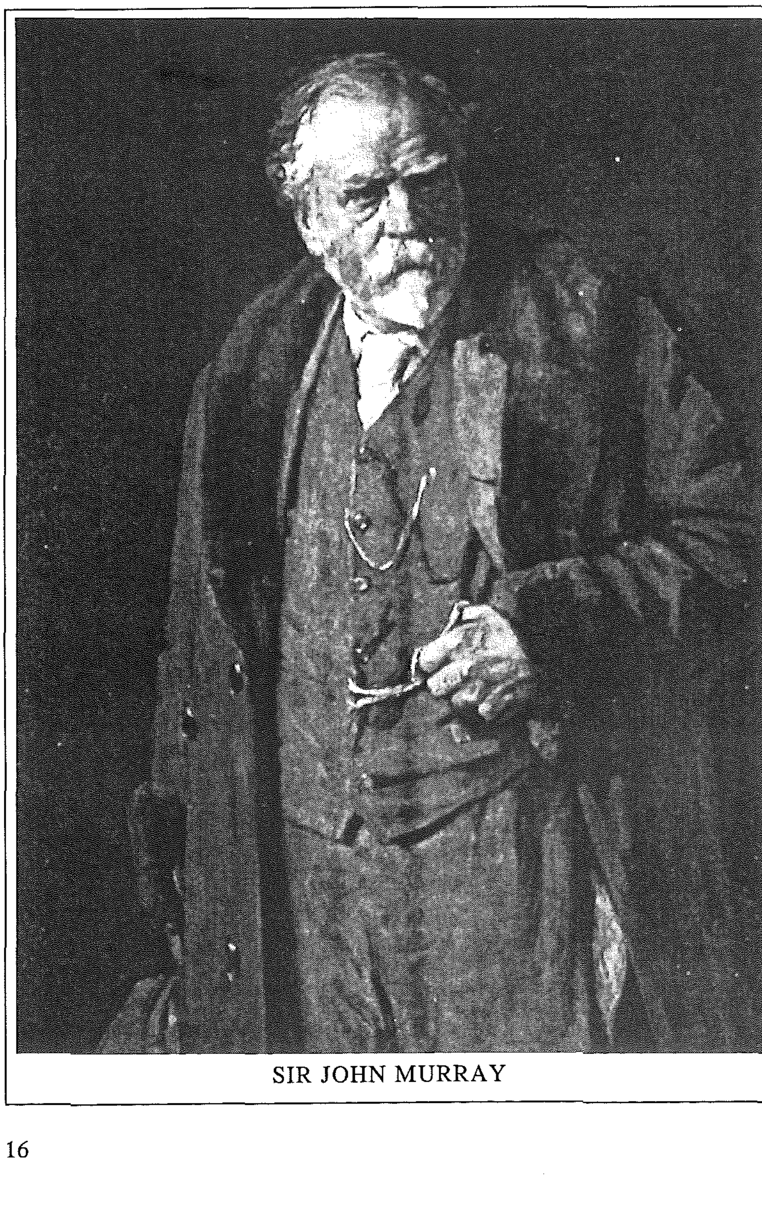
In 1892 Mill left Edinburgh to take up an appointment as Librarian at the Royal Geographical Society in London, but he still continued to undertake occasional work for the Fishery Board until at least 1896. The significance of his contributions to marine and fisheries science was still being stressed at the time of his death in 1950, although by then his main claim to fame was as a meteorologist, and expert in rainfall and geography.

Investigations into the links between sea temperature and fisheries, the focus of interest by the Scottish Meteorological Society, had made greater progress in Germany and Scandinavia. Following the success of the multi-ship surveys in the Skaggerak

Henry Newton Dickson at Oxford in 1901. In addition to being an oceanographer, Dickson was expert in meteorology and surveying. In 1899 he was appointed part-time lecturer in Physical Geography at the School of Geography, University of Oxford. In 1904 he moved to University College Reading as a lecturer in Physiography and Meteorology, but he still continued to instruct military students in Oxford in surveying. He became Professor of Geography at Reading, but resigned in 1920 when he moved to London to become involved in editorial and publishing activities. He worked in the geographical section of Naval Intelligence in 1915-1919. He died at his brother's home in Edinburgh on 2 April 1922. Further details of his life are given in The Mariner's Mirror 72 (1): 85-88, February 1986, and in Halford Mackinder by B.W.Blouet, pp. 98-107, Texas A&M University Press, 1987. This plate is a detail of a group photograph of the School of Geography, University of Oxford, and was kindly prepared by M. Barfoot.

and Kattegat conducted by the Swedish scientists Gustav Ekman and Otto Pettersson, the British Government was invited to participate in an international hydrographic survey of the North Sea and Baltic which was to take place in 1893-4. It was Mill who appears to have been instrumental in arranging for Henry Newton Dickson to take charge of the Scottish contribution to this survey.

Dickson, born in Edinburgh on 24 June 1866, the son of William Dickson, a wholesale stationer and his wife Anne, while studying at Edinburgh University, had, like many of his student contemporaries, worked as a volunteer in the *Challenger* office and at the Granton Station. He had assisted Mill in his field work both aboard the Station's vessel the *Medusa*, and also at the Ben Nevis Observatory, another of the Scottish Meteorological Society's ventures. In December 1890, he was appointed assistant to the Director of the Marine Biological Association's Laboratory in Plymouth, where he investigated temperature and salinity in the English Channel. In 1893, he moved to Oxford, where he made a living from teaching, writing and examining. It was from there that he set out to join the *Jackal* cruise, the centenary of which is being celebrated in this issue of *Ocean Challenge*.



SIR JOHN MURRAY

As late as 13 July 1893 Dickson was writing to Mill from Oxford that:-

"*Jackal* gives no sign. I hope to goodness they don't ask me to go now a month's notice or a fort-night's notice would be a perfect fool, and I have got fairly into work here."

It was nine days later that he received a letter from T. Wemyss Fulton, the Scientific Superintendent of the Fishery Board offering him £20 to take charge of making the physical observations an the cruise, and also stating that, as observations were required on the plateau off the Faroes and Shetland on 1 August, there was no time to lose in making arrangements. Dickson wrote to Mill explaining that, while he accepted Fulton's terms, he had received such short notice that he could not possibly sail until 31st August. Dickson was also concerned that he had been inadequately briefed; what exactly was expected of him, and to what extent he could organise the work in his own way? In his letter to Mill he wrote:-

"Your reference – as I understand it – is that I am to study the distribution of temperature and salinity between the Atlantic and the North Sea, at least as far north of the Shetlands, with the view of ascertaining the transition from one to the other. Could you let me have that in writing before Wednesday? I want clearly to understand whether I am to do that in my own way – as you told me – and to go where I want to, or am I to take special instructions from Fulton informed by Pettersson. I mean I want the terms of your reference - in case Fulton wants to be inconvenient, for of course I undertook the work from your explanations."

It is not clear whether the clarification was forthcoming, but Station I was occupied north of Unst at 1215 GMT on 1 August. At 1230 GMT on 4 August observations started at station X, the first hydrographic station on what now become the standard the Nolso-Flugga line. The equipment used was essentially that recommended by Gibson and Mill in 1886. However, because Mill's self-locking slip water bottle sometimes closed prematurely as result of the jerking of the sounding line, Dickson eventually designed and used a bottle which was lowered closed and opened at depth.

By 6 August Dickson, obviously pleased with progress having already completed 12 stations, wrote to Mill from the *Jackal* berthed at Lerwick:-

"We have had great luck. The Commander and officers are capital chaps and quite keen, and we have had very decent weather – got rather a bucketing on the way north, but since then only a long heavy swell.....

I find everywhere on the plateau your layer of hot (sic) water – thicker and relatively hotter the further from the edge and trailing off as you go to deep water. I propose to go right off the plateau and see if it disappears. Obviously we don't need to touch bottom."

Further cruises, which were unfortunately greatly hampered by exceptionally severe weather during the winter, took place in November 1893, February 1894, April-May 1894 and, by the officers of HMS *Research*, in August 1896. Dickson's reports appeared in the 12th and 15th *Annual Reports of the Fishery Board for Scotland* and in the *The Geographical Journal* in March 1896, and Pettersson's account of the work together with a proposed scheme for a further international survey of the North Atlantic, the North Sea and the Baltic appeared in the *Scottish Geographical Magazine* in 1894. Pettersson's proposals eventually lead, via the 1895 Sixth International Geographic Congress in London and meetings in Stockholm and Oslo in 1899 and 1901 respectively, to the setting up of the International Council for the Exploration of the Sea (ICES).

Scotland, or at least representatives with strong Scottish links, were associated with all the developments leading up to the foundation of ICES. Appropriately Scotland immediately started to contribute its work, through the auspices of the Fishery Board and under the direction of Professor D'Arcy Thompson who, together with the Investigation's hydrographer, was base in University College, Dundee. It became Thompson's responsibility to procure one of the two research vessels for which the British Parliament allocated £4,000. After inspecting a number of vessels, he eventually made a bargain for a 166 foot-long (30m) steam trawler *Goldseeker*. The arrangement was that £1,200 a year would be paid for three years, and then there would be an option to purchase the trawler for £2,000. The bargain was finalised in November 1902, and on 30 March 1903 Thompson wrote to Mill:-

"I have been worried to death, or nearly so, with many things, and not least by the countless sources of delay in fitting out the *Goldseeker*. She is all but ready now. I take some comfort in this tempestuous weather, for it is better that she should be idle in the builder's yard without a crew, than idle in Aberdeen with a dozen stalwarts drawing their pay and rations 'full and plenty'."

However, *Goldseeker* was not finally ready until the spring of 1903, and this nearly lead to Scotland failing to participate in the first of the international surveys in 1902.

Otto Pettersson and Johan Hjort had offered the services of the Norwegian oceanographer B. Helland-Hansen to undertake Scotland's cruise in August 1902 (See also Blinheim's paper in this issue). Thompson accepted the offer, anticipating that *Scotia*, the vessel that William S. Bruce was fitting out for the Scottish National Antarctic Expedition of 1902-1904, would be available as a replacement for *Goldseeker*. However, when it became clear that *Scotia* would not be ready, Thompson approached the Chairman of the Fishery Board for a loan of one of its fishery cruisers for a 8-10 day research cruise. The Chairman objected to taking a vessel off routine patrol duties but suggested that once again the *Jackal* should be used. Thompson eventually at short notice got approval from the Admiralty, and *Jackal* sailed on 25 August 1902 with Helland-Hansen onboard. The cruise lasted until 1 September during which 26 stations were worked along a track from the Moray Firth to Shetland, then north-eastwards towards the Norwegian coast, westwards to the Faroes, and then finally back via the Fair Isle Channel into the North Sea and the Moray Firth. Assisting Helland-Hansen on this cruise was Frank Pearcy. He had been Wyville Thomson's assistant on the *Challenger* Expedition. Thus through Pearcy's link with the past, the fist series of Scottish investigations in the Faroe-Shetland Channel came full circle.

Acknowledgements

The various letters in this article are in the Hugh Robert Mill archives at the Royal Geographical Society, London. I am grateful to the Society for the opportunity to consult these archives and to quote from them. I am also grateful to M. Bott (Reading University Library), Professor A.J. Goudie (School of Geography, Oxford) and Professor A.J. Southwood (MBA Plymouth) who all kindly provided guidance and details about Dickson's life and work. I also thank the National Maritime Museum, Greenwich for the plans of the *Jackal*.

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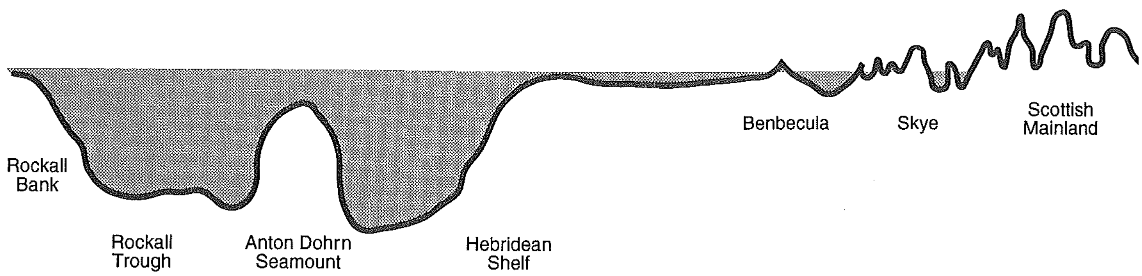


Physical Oceanography of THE ROCKALL TROUGH

Dave Ellett

Introduction

The success of the Aberdeen Marine Laboratory in maintaining a long-time series of physical observations in the Faroe-Shetland Channel, led J.B Tait (Aberdeen) and A.J. Lee (Lowestoft Fisheries Laboratory) to propose in 1960 that research was needed upstream of the Channel in the then poorly known deep water to the west of Scotland. In response the UK Hydrographic Office arranged for the surveying ship HMS *Dalrymple* to be made available to representatives from both Aberdeen and Lowestoft. G.C. Baxter and J.H.A. Martin worked water-bottles sections across the Rockall Trough from Malin Head to Rockall on ten cruises between August 1963 and November 1965. The same section was subsequently repeated several times by R/V *Ernest Holt* – one of the Lowestoft Fishery Laboratory research vessels.

In the late 1960s, the Scottish Marine Biological Association (SMBA) opened its new laboratory at Oban, a port on the west coast of Scotland that had been the point of departure for several oceanographic cruises during the previous century. SMBA proposed a programme of work in the adjacent deep waters, and the new research ship RRS *Challenger* which was being built for the laboratory by the newly-constituted Natural Environment Research Council (NERC) was lengthened on the stocks so that she could be used to undertake these studies. Once *Challenger* was ready for service, a full programme of physical oceanography was initiated, and from May 1975 a section from the shelf-edge west of South Uist to Rockall, crossing the Anton Dohrn Seamount (Figure 1), has been regularly profiled with a CTD. This section traverses the narrowest part of the Rockall Trough, so its 20 stations can usually be completed within 40 hours – an important consideration in an area traversed by depressions on a roughly 5-day cycle throughout much of the year. Up until May 1993 the section has been attempted 43 times and completed on 29 occasions.

Although these observational programmes in the Rockall Trough have spanned only three decades, compared with the century of observations available from the Faroe-Shetland Channel, they have already shown the occurrence of significant variations. The time coverage can be extended using the 45 years of observations of surface temperature and salinity made mostly by UK Ocean Weather ships on passage through the area, and since the early 1960s the Weather Ships have made regular observations of the water column while on station to the south and west of the Rockall Plateau.

Over the years the main questions that have been addressed are:-

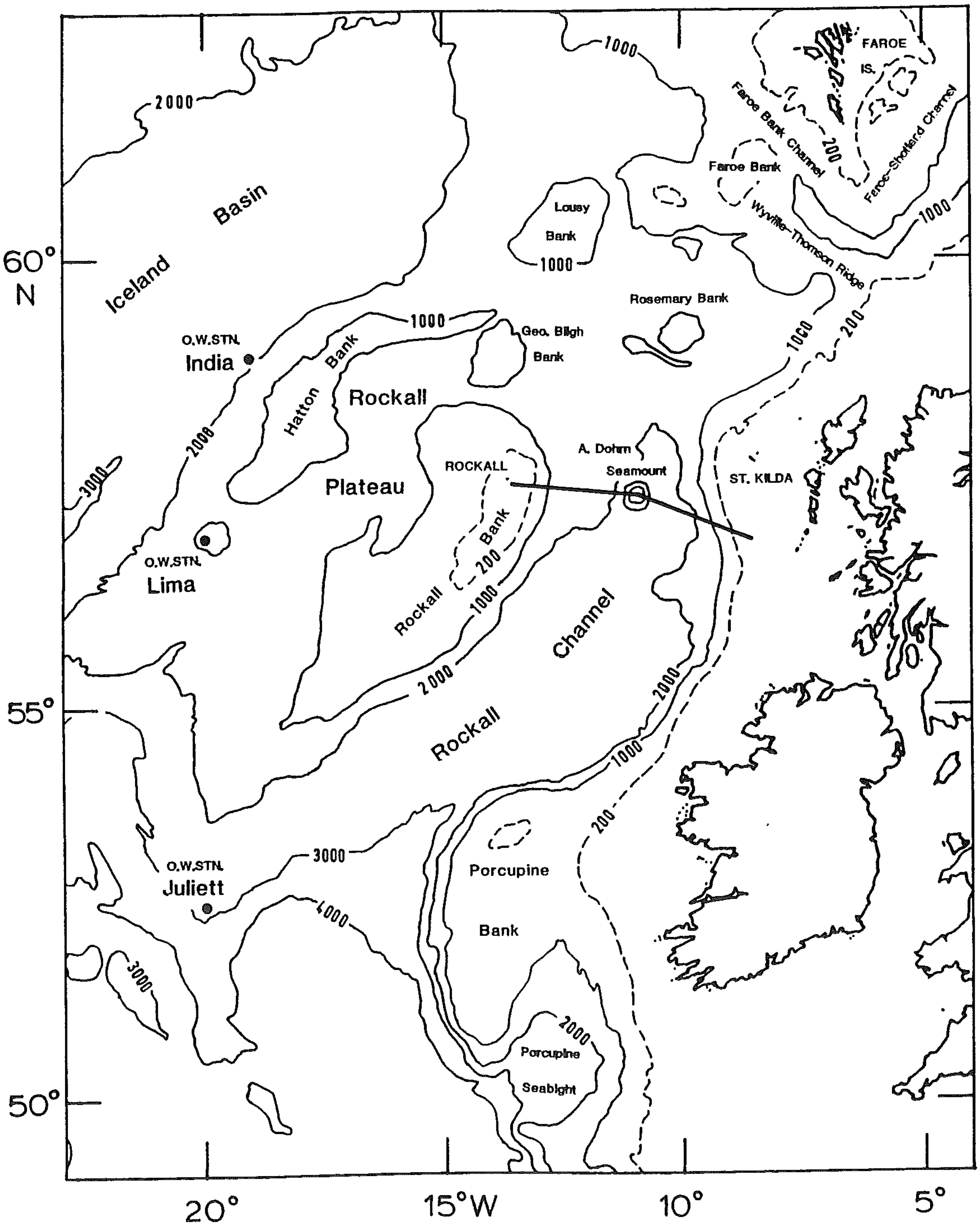
- Is the flow through the Rockall Channel a direct continuation of the Atlantic Current?
- What does the NE Atlantic contribute to the waters in the Trough?
- Is there an eastern boundary current?
- What quantities of water are in motion?
- Is there significant overflow of cold Norwegian Sea Water cross the Wyville-Thomson Ridge?
- What water mass variations do we find?
- Do processes in the Rockall Channel play any role in climate change?

Good progress has been made in answering all these questions, greatly improving our understanding of this part of the Northeastern Atlantic.

The Atlantic Current and the Rockall Channel

The early studies of the area by Nansen and Helland-Hansen are still relevant. Nansen observed that inflow into the channel in 1910 was from the south rather than from the southwest. Then later with Helland-Hansen, he suggested a pattern of subsurface circulation for the Atlantic Current in which a large part of the cross-Atlantic Current is being diverted to the west of the Rockall Plateau, and another part is being diverted southeastwards towards the Bay of Biscay. The detailed North Atlantic surveys published after the International Geophysical Year of 1958 traced the oceanic Polar Front along the northern boundary of the Atlantic Current as far east as 25° to 20°W, where it became less easy to define in the region where Helland-Hansen and Nansen proposed the divergence was occurring. The latters' streamlines curved from southwest to northwest around the position of the former Ocean Weather Station *Juliett* (OWS *J*) at the southwestern end of Rockall Bank (see Figure 1) close to the eastern extremity of the Polar Front. Water-bottle data were collected both at OWS *J* and at Ocean Weather Station *India* (OWS *I*) through 1963-75, and these support this pattern, indicating that subsurface water enters the Rockall Channel between OWS *J* and Porcupine Bank. At OWS *I*, 700km to the north, temperatures and salinities below depths of 350m are warmer and more saline than at OWS J. Within the Rockall Channel, they are yet warmer and more saline, showing that this water had passed quite close to the Porcupine Bank. Thus, it seems that the flow that crosses the Mid-Atlantic Ridge into the NE Atlantic becomes partly de-coupled from the flow through the Rockall Channel, which is influenced by input from the south.

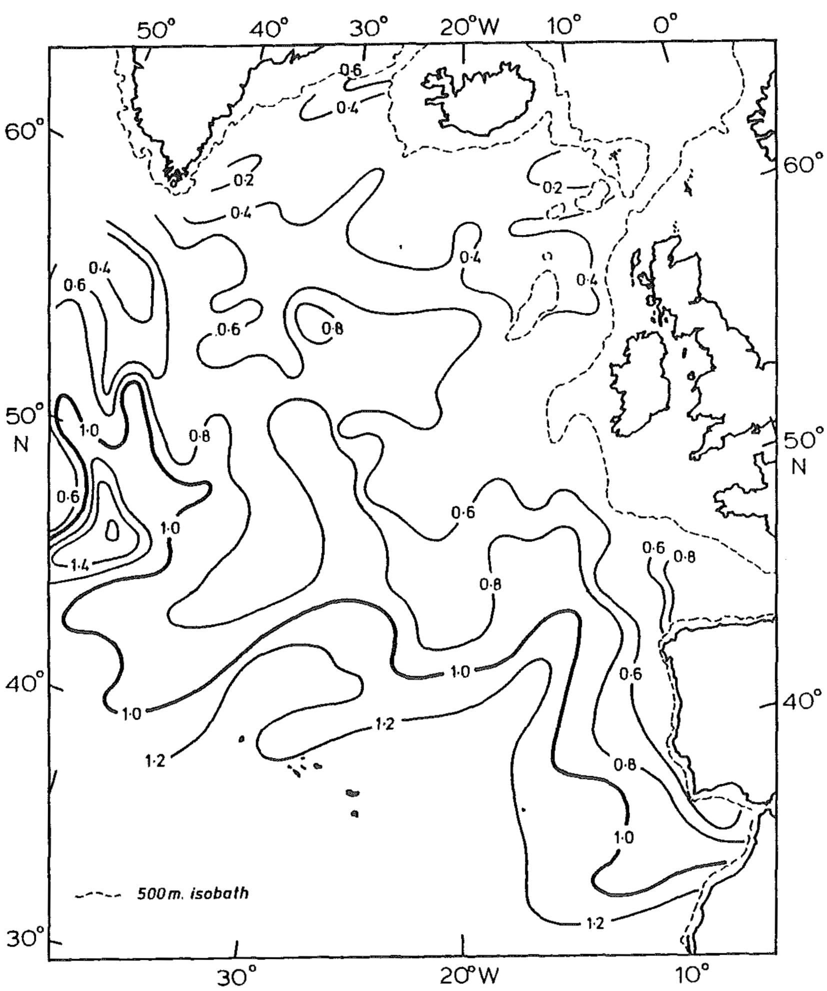
***Figure 1**. Physical features of the Rockall Channel and NE Atlantic. Isobaths in metres. The heavy line marks the Dunstaffnage Marine Laboratory's Anton Dohrn Seamount section.*



The North Atlantic contribution

The degree of this de-coupling suggests that at intermediate depths the waters may be modified before they enter the Channel from the south. At these intermediate depths (i.e 300-1200m) the structure of the Northeast Atlantic is influenced by two water masses - the shallower being water Subarctic Intermediate Water (SAIW) which forms and sinks along the Polar Front in the vicinity of the Mid-Atlantic Ridge – the deeper being formed as dense Mediterranean Water mixes with Atlantic water as it cascades from the Straits of Gibraltar to depths of around 1000m. This mixture is often referred to as Mediterranean Water but should be termed Gulf of Gibraltar Water, the name given to it by Cooper in 1952. As this high salinity Gulf of Gibraltar Water is advected northwards along the West European continental slope, its influence is spread upwards by mixing, increasing the salinity of the upper waters of the Atlantic and forming a water mass known as the Eastern North Atlantic Water (ENAW). At depths of 400-800m the densities of ENAW and SAIW are very similar, and so although in the approaches to the Rockall Channel there is a lot of detailed structure in the water column, much of this detail is lost through mixing within the Channel. This reduces the density of the near-surface waters relative to those occurring in the regions to the south and west (Figure 2), and so enables the winter gales to extract more heat from the upper waters. Consequently winter convection can penetrate to depths of 400-600m within the Channel.

Figure 2. Late-summer density difference (kg m[-3]) between the 50 and 500m levels in the NE Atlantic.



The Slope and Eastern Boundary Currents

The separation of the Atlantic Current Water which flows to the west of the Rockall Plateau and the water flowing through the Channel with its more southerly characteristics, suggests that the circulation from north of the Bay of Biscay may be some sort of eastern boundary current. The northward flow across the Anton Dohrn Seamount section is characterised by a high-salinity core against the continental slope which gradually tapers westwards (Figure 3). Our current meter moorings deployed in 1979 revealed a narrow and remarkably persistent current centred over the slope to the west of Scotland. In 1982-3 a collaborative UK investigation confirmed the existence of this Northeastern Atlantic Slope Current at sites along the slope from the Celtic Sea to the north of Shetland. Satellite-tracked drogues released into this current tracked along the slope from the Rockall Trough and either entered the North Sea around the north of Scotland or followed the Norwegian slope ending up to the west of the Lofoten Islands. This slope current appears to be driven by the contrast between the poleward decline in oceanic dynamic heights and the lesser decline in dynamic heights on the adjoining shelf. The 1982-3 investigations showed although the volumes of water being transported remained constant throughout, the current which started as being relatively broad in the Celtic Sea, became progressively narrower as it approached the Wyville-Thomson Ridge.

At greater depths, it has recently been suggested that there is a system of deep boundary currents which flow from the south along the European margins and bring Antarctic Bottom Water (AABW) into contact with the overflows from the Norwegian and Greenland Sea which hug the bottom of the slopes. The high silicate content of the deepest waters of the Rockall Channel indicates the presence of AABW.

Transport through the Trough

Water passing into the Norwegian Sea from the Rockall Channel has to cross the Wyville-Thomson Ridge which has a sill depth of about 550m. Geostrophic calculations based on twelve crossings of the Malin Head-Rockall sections during 1963-68, show the mean northeasterly transport above 500m (relative to the 1800m level) to be 2.75 Sv (1 Sverdrup = $1 \times 10^6 m^3 s^{-1}$). However, this estimate was the balance between a mean for northeasterly transports of 6.75Sv and a mean of southerly transports of 4.0Sv, so transport is strongly influenced by mesoscale eddies passing up the Channel. This became even more evident from the long-term deployment of current meters at two deep water stations to the east and west of the seamount during 1978-83, and from the tracks of satellite-tracked drogues released during the early 1980s. To this mean figure must be added the contribution of the slope current, estimated from the joint CONSLEX current meter deployments as being between 1.2 and 2.2SV inshore of the 2000m isobath. The part of this flow that is below the sill depth of the Wyville-Thomson Ridge must recirculate westwards within the channel. A general estimate, therefore, for the combined mean flow of the deep-water and slope currents entering the southwest corner of the Faroe-Shetland Channel from the direction of Rockall is about 4Sv.

Cold overflows across the Wyville-Thomson Ridge

Although by far the greatest quantities of water in the Trough are from sources to the south and southwest, there is a small but apparently steady input from the northeast. The Scotland-Greenland Ridge system forms a barrier to the southwards spread of deep-water from the Nordic Seas into the Atlantic. The water balance in maintained in part by dense cold water that escapes over the crest of the ridge and through some gaps. Nowadays there is only a small-scale overflow across the Wyville-Thomson Ridge, but in the geological past such overflow may have been responsible for laying down the drifts of sediments forming the Feni Ridge along the western bed of the Rockall Trough. Current meters deployed at sites just to the west of the Ridge for nine months in 1987-88, recorded a steady westerly flow at deepest depths throughout the observational period. This westward flow may be augmented by the lower part of the Slope Current when it becomes diverted from its northeasterly directions by the Ridge. The current meters at depths above the depth of the ridge crest recorded predominantly northeasterly flow, but in spring and early summer brief spells of strong westerly flow were recorded, perhaps related to the movement of a cyclonic dome just to the north of the ridge. During the 100 days when both current meter moorings were recording the mean westward flow descending into the Trough was estimated to be 0.3Sv, but only 25% of the water could be said to be Norwegian Sea Deep Water, the remainder being Atlantic water entrained from around and above.

At the present time the direct input to the Rockall Trough from the Norwegian Sea appears to be small, although short sharp inflows of cold dense water have been noted in the past. The influence of overflow water

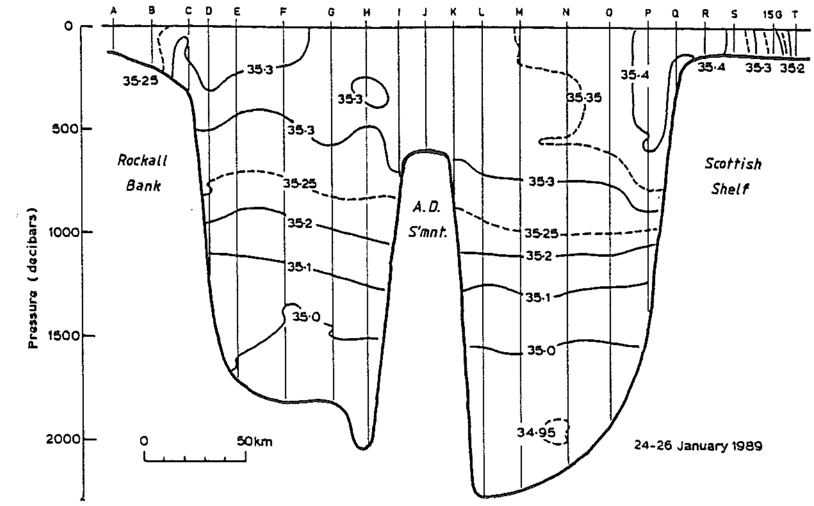


Figure 3. An example of salinity distribution in winter across the Anton Dohrn Seamount section observed from RRS Discovery, 24-26 January 1989.

has been demonstrated at the bottom of the western flank of the Trough northwards from the Anton Dohrn Seamount, but is disputed in regions to the south of this. In 1992 Mike McCartney of WHOI suggested that increasing salinity below 1800m in the southern part of the Trough originates from mid-latitudes sources carried northwards in the deep boundary current.

Long-term temperature and salinity variations

Surface temperature and salinity data have been collected by UK weather ships in the central Rockall Trough for the Lowestoft Fisheries Laboratory since 1948. These data supplemented with research ship observations continue to build up a valuable time series. In particular, because of the deep convection which occurs in winter, surface data from this season may be seen as representing the upper waters of the Trough. In Figure 4 the January to March values for each year are shown as anomalies from the monthly mean values for 1961-70. Temperature rose during the 1950s towards a maximum in 1960, subsequently remaining within 0.5°C of the mean values, though with alternating cooler and warmer periods lasting 4-6 years. Salinity on the other hand rose from 1950 to a maximum in 1968, and then fell dramatically to a minimum in 1976. It then recovered between 1977 and 1984 before falling back a little. In 1990-2 winter salinity values again approached those of the late 1960s, but have since declined again.

The temperature series offers useful confirmation of changes seen in adjacent areas. Temperatures around the Atlantic rose during the first half of the century, maxima occurring earlier in the Western Atlantic and later off Greenland. The Rockall Channel peak in 1960 appears to fit the pattern of this maximum spreading through the Atlantic gyre system from west to east and then on to subpolar regions. Salinity series are much rarer than temperature data, and so the Rockall Channel series has proved extremely valuable in monitoring NE Atlantic changes. The fall here in the 1970s first drew attention to what has since become known as the "Great salinity Anomaly", when low salinity water circulated from off east Greenland in 1968, passing Scotland in 1975-6 and returning back to its region of origin by 1981-82. Across the Atlantic progress of this anomaly gives a mean advective speed of 4-5km/day. Similarly the data are being used to investigate the causes and the history of high salinity values in the European seas during 1990-92. These would now seem to have been relatively short-lived events, since in late 1992 and early 1993 Rockall Channel salinities have dropped back again to their lowest values since the Great Salinity Anomaly.

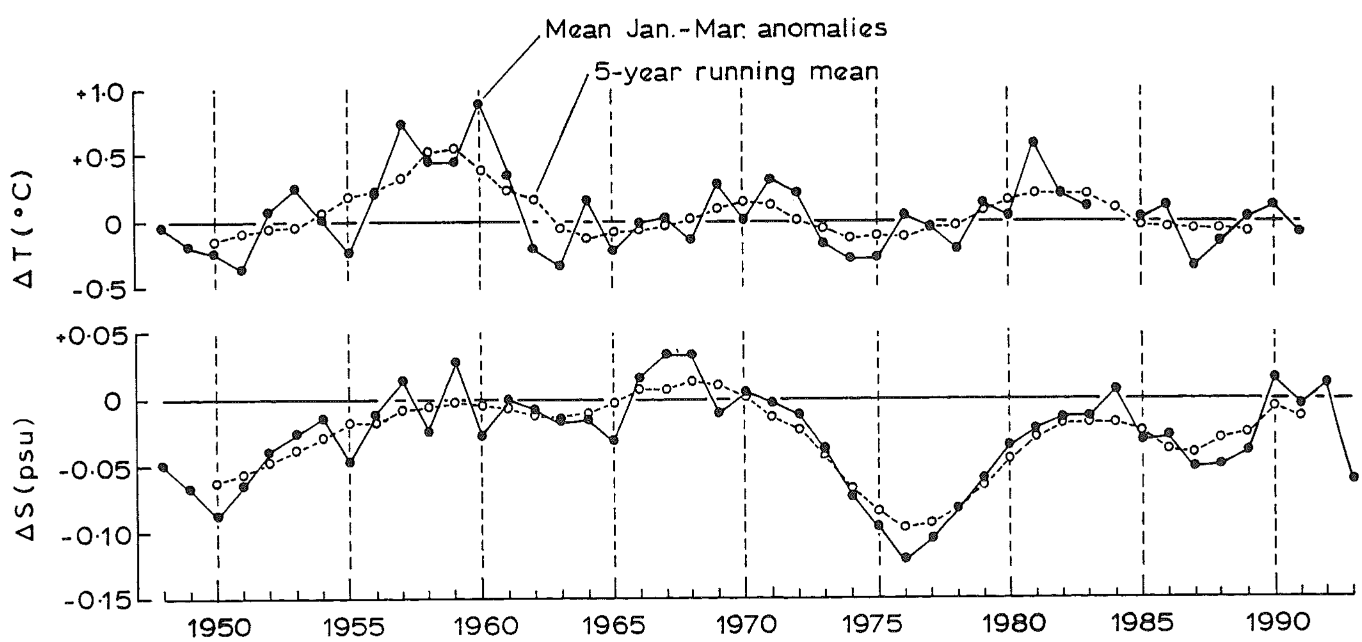
By enabling time-scales to be set upon circulation features, long-term data have a more than local use. Where the surface series have helped to time Atlantic-wide surface phenomena, the subsurface section data have recently allowed the time-scale for a deeper water mass to be deduced. Below about 1200m in the Rockall Channel, the influence of Gulf of Gibraltar Water gives way to that of the Labrador Sea Water (LSW), a low salinity water mass from the NW Atlantic. When the surface salinity was lowered in the Labrador Sea during the passage of the Great Salinity Anomaly, the normally deep convection was greatly inhibited, and so the salinity of the LSW where it is generated gradually rose. In 1971-2, after the Great Salinity Anomaly had moved on, the deep mixing resumed and new fresher LSW began to form. West of Scotland salinity at 1600-1800m fell slightly after 1984 relative to the values observed during the previous decade, but in 1990 there was a sudden fall (Figure 5). This appears to be the signal of the resumption of LSW formation in winter 1971-72, which had thus taken 18 years to reach our waters, a mean velocity of 0.4km d^{-1}. This gives us the first estimate of the time scale for the advection of this water mass across the Atlantic.

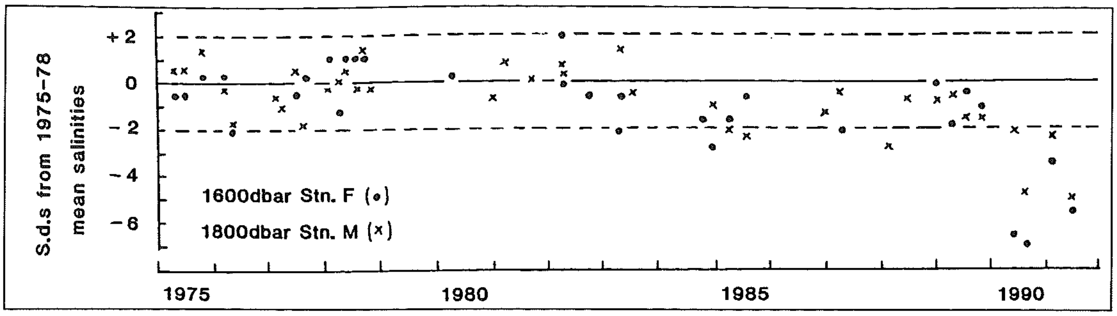
The NE Atlantic and climate change

In the region of their origin, these surface and deep changes in salinity were accompanied by changes in temperature. Even on the shorter time-scales of the surface variations, comparison of the upper and lower parts of figure 4 shows that events of the intervening years had greatly reduced the correlation between temperature and salinities changes. Nevertheless, on a comparatively local scale the residual heat anomalies must affect conditions to the west of Britain to some degree, and winter salinity changes by modifying density, affect the extraction of heat by convective processes. However, there is great interest in speculating whether the hydrography of the area could be responsible for major climate changes, and one aspect in particular suggests itself.

We have seen earlier that warm and saline subsurface water passing northwards from both the eastern Atlantic and the Atlantic Current have to do so in the region to the west of Porcupine Bank. Here there is in effect a gap of some 600km between the easternmost extremity of the Polar Front and the northern European shelf, and this is the location where the Atlantic Current divides into branches subsequently heading by various routes into the Nordic, Irminger and Labrador Seas. It is thus an important gateway for heat input to a large part of the Northern Hemisphere. The question arises as to whether this gateway has been, or can become, constricted as a result of fluctuations

Figure 4. Winter (January-March) anomalies of surface temperature and salinity (from 1961-70 means) in the central Rockall Channel.





in atmospheric or oceanic circulation, with far-reaching consequences for northern regions. To date, there are no instances since oceanographic records began of major changes in this area, but there have been a number of cases which suggests that some switching between westerly- and southerly-derived waters may occur. Some of the evidence comes from the alteration of high and low salinity periods in European waters, particularly during the period of the Great Salinity Anomaly, when Subarctic Intermediate Water originating from the northwest of the Polar Front strongly influenced the water column at OWS *Juliett*, 300km from Porcupine Bank, but it is evident that such influences can penetrate even further to the east from a cold-core eddy of SAIW which was observed within 30km of the bank's shelf edge in February 1989. The consequences of more sustained input of this sort to the Rockall Channel upon circulation and water mass formation in northern regions could prove an interesting aim for future modelling effort.

Conclusion

Although detailed investigations in the Rockall Channel have spanned less than half the period of the Faroe-Shetland Channel programmes, a comprehensive outline of the prevailing hydrography has been established. Work is continuing at the Dunstaffnage Marine Laboratory at Oban, and time series aspects are currently of especial value in order to place the present WOCE decade into a longer-term context. In the immediate future eastern boundary current work will be

Figure 5. Deep salinity variations during 1975-91 at stations F and M of the Anton Dohrn Seamount section expressed in terms of standard deviations from the 1975-91 means.

to the fore with the Land-Ocean Interaction Study (LOIS) – a multidisciplinary research programme run by NERC – providing an intensive examination of slope and shelf-edge processes west of Scotland, and linking with the Ocean Margin Exchange programme (OMEX) – a MAST project funded by the European Union – which is studying regions at the shelf edge to the south of Britain.

Further Reading

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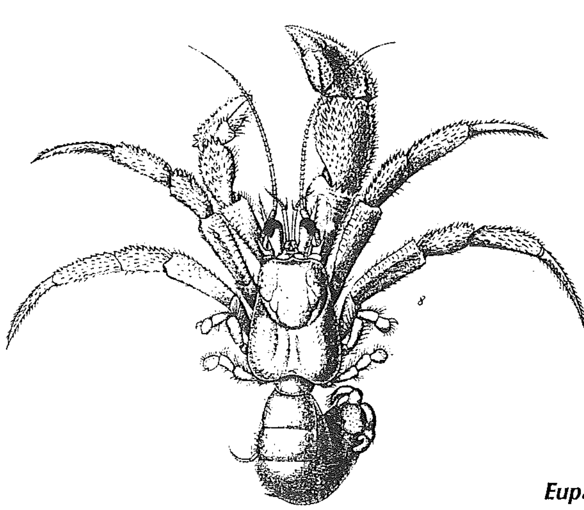


Eupagurus tricarinatus

Hydrographic conditions in the Faroe-Shetland Channel

July 1988 and 1989

Pawel Schlitholtz

In 1987 the Polish research vessel *Oceania* began a series of multidisciplinary experiments in the Norwegian Sea. In July 1988 and 1989 a transect of observations (Figure 1) was repeated at fifteen hydrographic stations at a spacing of 18km from the Faroes to Shetland (from 61.7°N, 6°W to 60.2°N, 2.5°W). Here I summarise the information in the context of current ideas about the basic hydrography of the northern North Atlantic.

Figure 2 shows the profiles for potential temperature (θ), salinity (S) and potential density along the transect for both years (note that here and elsewhere in this paper density values are plotted after subtraction of 100 kg m^{-3}). This figure shows both similarities and differences in the hydrographic conditions observed on the same day, 8-9 July, in the two successive years. Such differences were not unexpected because the Channel is at the boundary between the contrasting regimes of the subpolar North Atlantic and the Nordic Seas (i.e Norwegian, Iceland and Greenland Seas). These distinct hydrographic regimes, their mutual interactions and air/sea interactions result in a range of different water masses being formed at the surface. The typical distribution of these water masses is illustrated in Figure 3. Water masses are large volumes of water with sufficiently characteristic (and restricted) ranges of physical, chemical and biological properties to be identified (and named). They are generally defined by segments of the θ-S curves, and in the real ocean they are separated by fronts - *narrow zones across which there are steep gradients in the properties, where currents tend to be strong and mesoscale activity high.*

Over low and mid-latitudes in the North Atlantic, the distribution of wind stress curl, generated by the north-east trade winds in the subtropics and by the westerlies at mid-latitudes, and the effects of the Earth's rotation (or planetary vorticity), requires there to be a southward transport of water in the ocean's interior. The conservation of mass and the presence of the continental barriers results in a strong boundary current, the Gulf Stream, emerging form the Western side of the North Atlantic. This current transports very warm and salty water, the product of the strong solar heating and high evaporation in the tropics. To the east and north of the Grand Banks off Newfoundland (52°N), the Gulf Stream extends into the North Atlantic Current and so carries its warm and salty water to high latitudes in the north Atlantic. This creates the right conditions for air-sea interactions to generate a range of intermediate and deep water masses, since if the waters are at the surface become denser (e.g by being cooled), they sink (i.e the net buoyancy flux becomes negative) and this is the process which triggers the thermohaline circulation of the ocean. Along its path the warm surface water of the North Atlantic Current is cooled and also its salinity increases because, in winter, evaporation from the surface of the ocean exceeds the freshwater input from rainfall. As the density of the water column becomes progressively more uniform, convective mixing begins to homogenize the upper layers of the water column creating a new water mass. These new water masses are called *mode* waters and appear as *pycnostads* (i.e thick layers of water with uniform density). In hydrographic sections pycnostads can be identified by a wide separation between the lines of constant density (i.e the isopycnals).

Warm pycnostads (10°C < θ < 15°C) recirculate clockwise within the subtropical gyre, and serve to maintain a large volume water mass known as North Atlantic Central Water (NACW). Another branch of the North Atlantic Current carries a heavier, cooler pycnostad (8°C < θ < 10°C) northwards past Ireland. This water follows two main paths, one closes the cyclonic subpolar gyre and the other enters the Nordic Seas, along both of these paths the surface water becomes both cooler and saltier through evaporation. Around the subpolar gyre the water is cooled to 3.5-4°C and contributes to the Subarctic Waters in the Labrador Sea. The other flow is a branch from the subpolar gyre which enters the Nordic Seas via either the Denmark Strait between Iceland and Greenland or the Faroe-Shetland Channel. The flow through the Denmark Strait produces a variety of pycnostads > 6°C, which are termed Modified North Atlantic Waters (MNAW) and are of minor climatic significance. The larger flow, the main branch of the North Atlantic Current carries water from further south than that contributing to the Modified North Atlantic Waters, and so over the Shetland slope even warmer pycnostads at 8-9°C are to be found.

The flow of North Atlantic Water feeds into the Norwegian Current resulting in comparatively mild climatic conditions extending far

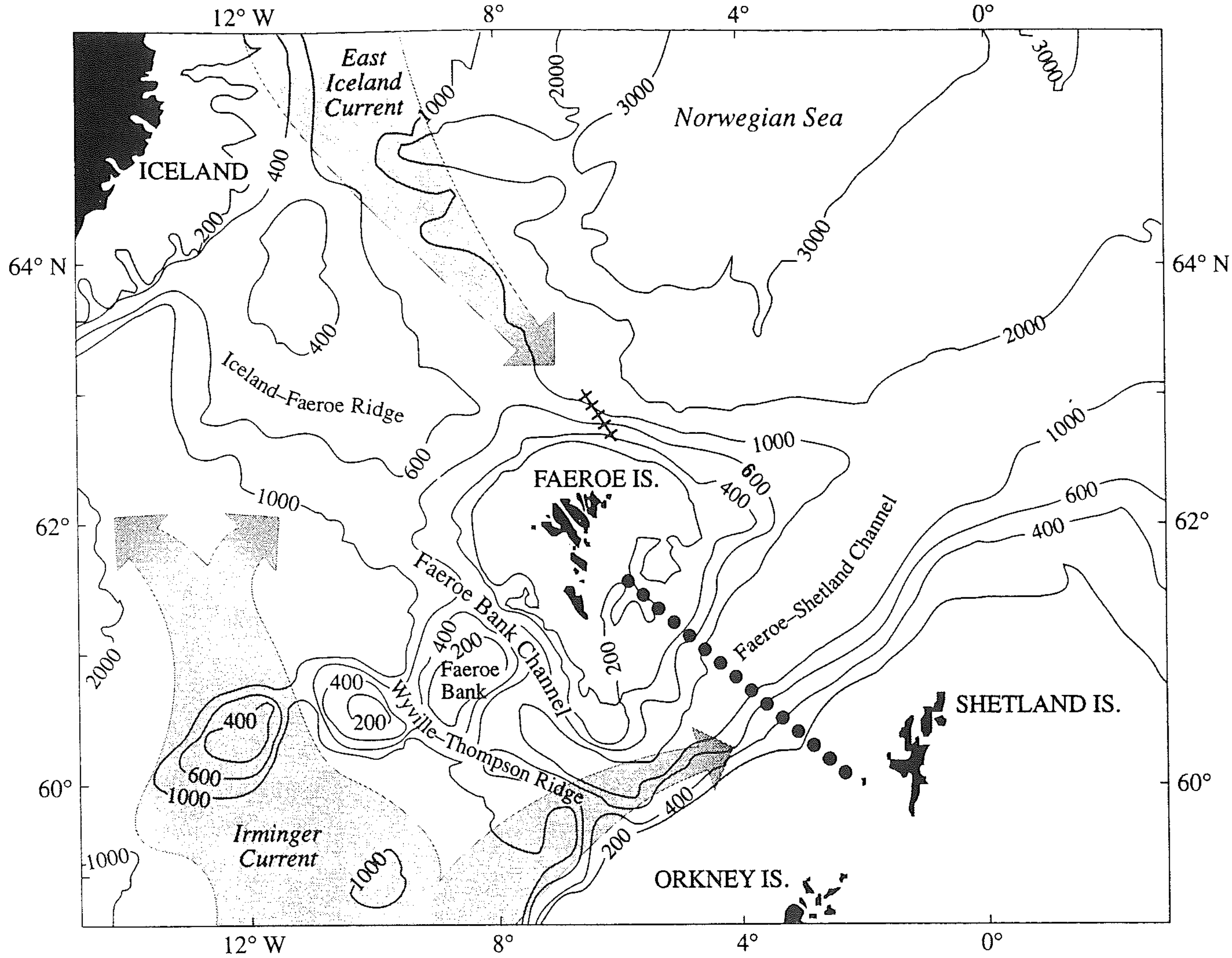


Figure 1. Bottom topography of the Faroes region showing the location of the transect of stations (dots) occupied in July 1988 and July 1989. The crosses to the north of the Faroe Islands indicate the positions of five station occupied by Poseidon in 1977. The arrows depict the location and direction of the main currents in the area: NAC - North Atlantic Current; EIC - East Icelandic Current; IC - Irminger Current.

to the north along the Norwegian coast. The positive temperature anomaly generated by this current (i.e the increase in temperatures above the mean for a given latitude) at times reaches as far north as 68°N off the Lofotens so that in summer air temperatures occasionally reach 27°C. In summer, surface waters in the West Spitsbergen Current (an extension of the Norwegian Current) to the south-east of Spitsbergen can reach 5-6°C, and ice-free conditions are maintained as far north as 80-82°N. North Atlantic Waters entering the Polar Ocean through the Fram Strait and around northern Norway into the Barents Sea are an important source of heat and salt. They form a layer of warm, salty pycnostad water ($\theta > 2$°C) in the Polar Ocean which underlies the very cold low-salinity surface waters which have been diluted by the freshwater outflow of the major Siberian rivers.

The inflow of North Atlantic Waters into the Polar Ocean is balanced by an outflow of low salinity, cold Polar Water in the East Greenland Current along with heavy pack ice which makes the eastern coastline of Greenland inaccessible to shipping throughout most of the year. In winter, the ice is transported as far south as 45°N in western North Atlantic. Between the "Atlantic" domain of the Nordic Seas and the "Polar" domain of the western regions of the Greenland and Iceland Seas there is another distinctive hydrographic regime, the "Arctic" domain. The water mass found there in the upper layers - the Arctic Water, is not a simple product of mixing between the Atlantic and Polar Waters. When warm, saline water mixes with cold, fresher water of similar density, the resulting water mass becomes denser than both the source waters (because the equation of the state of sea water in non-linear). Winter cooling at the surface of the already dense waters in the Arctic domain adds negative buoyancy (i.e makes them heavier), and so in local areas a series of very dense intermediate and deep waters are produced, with pycnostads which occasionally even reach the bottom. The coldest ($\theta < -1$°C) deep product of the convective overturning of the water column in the Arctic domain, is Greenland Sea Deep Water, which is amongst the densest water masses in the World's Oceans. In the upper layers of the Nordic Seas, the Arctic Waters are separated from the Polar

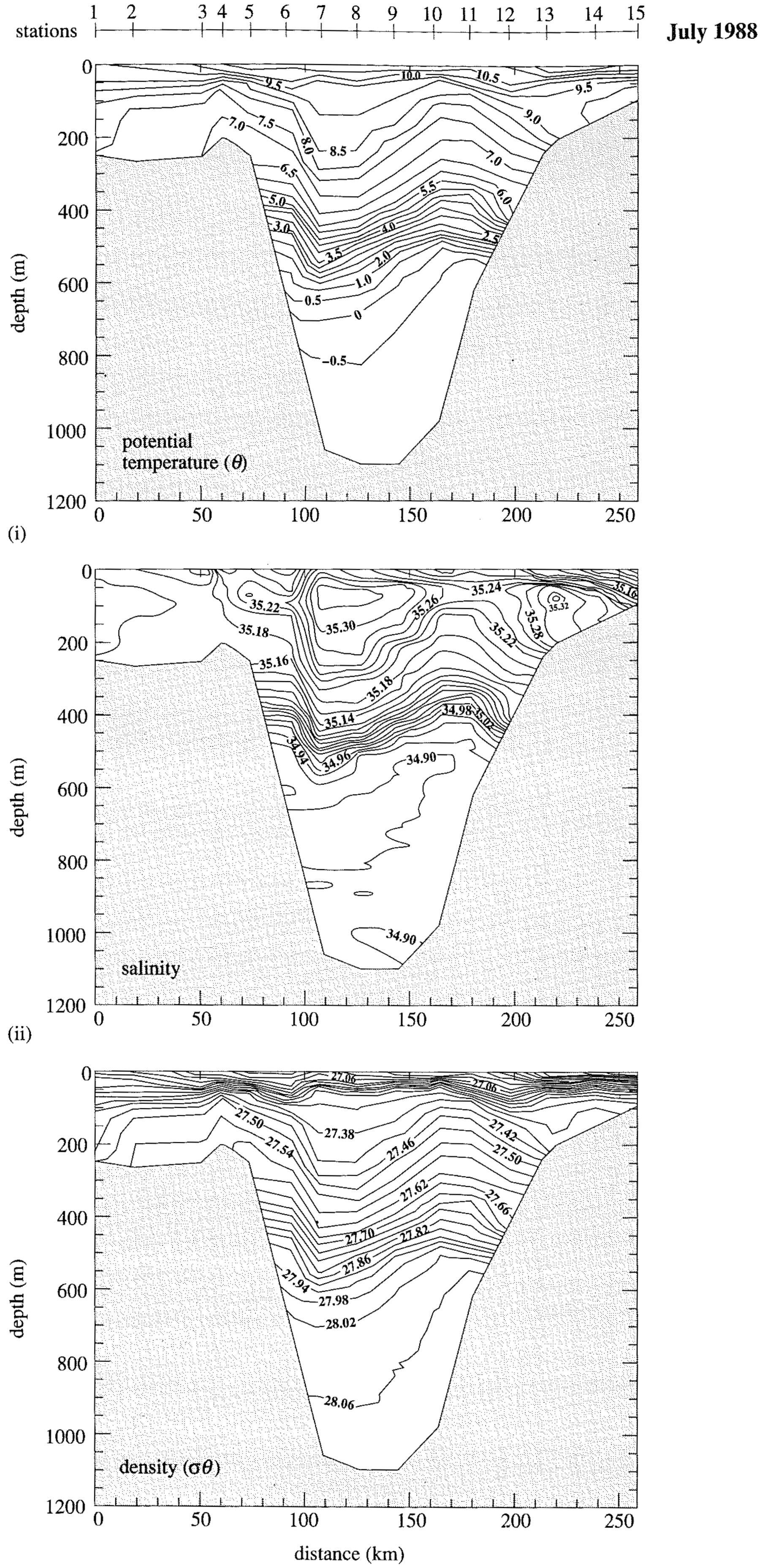
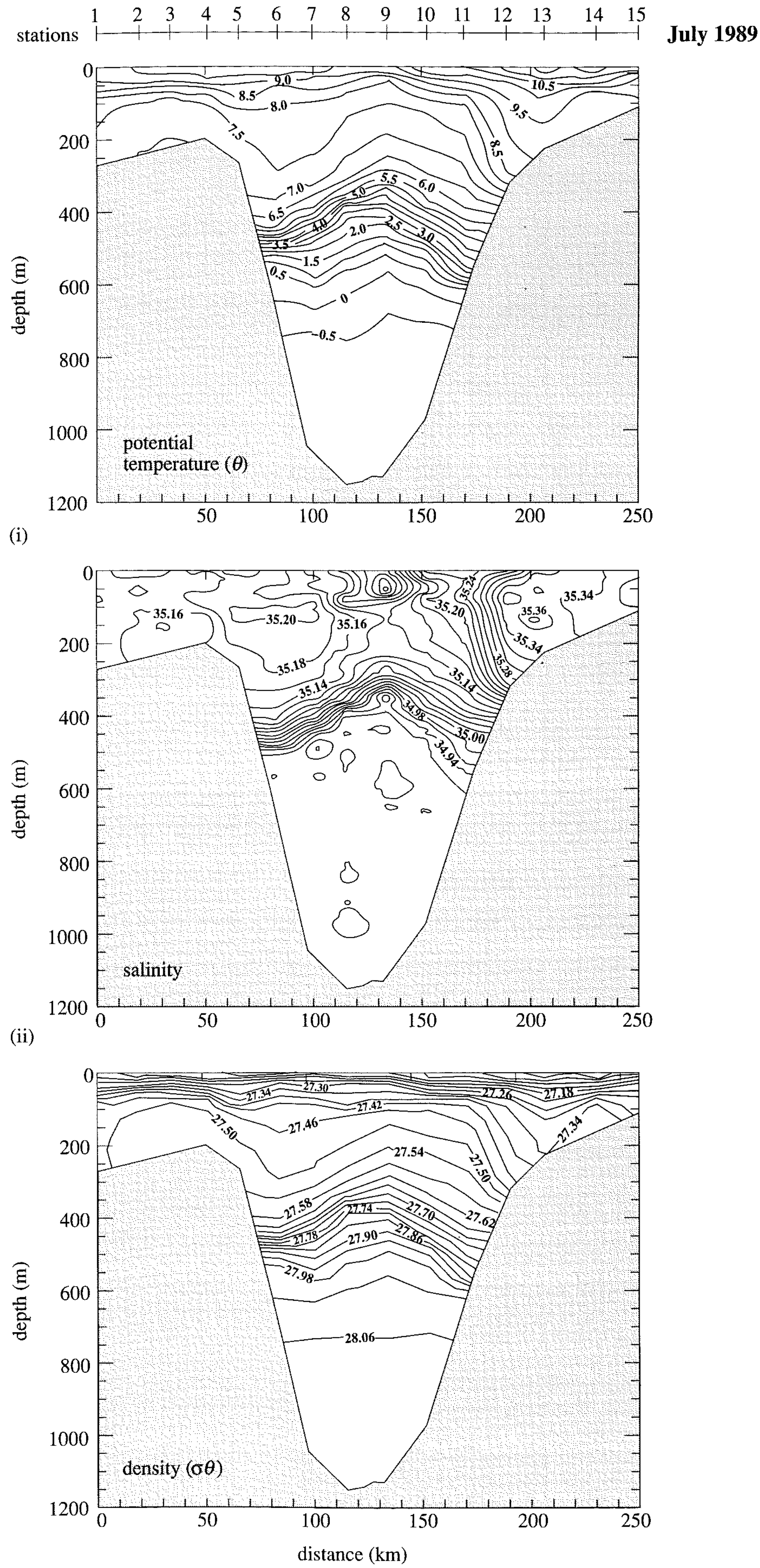


Figure 2. Sections of potential temperature, salinity and density across the Faroe-Shetland Channel in a. July 1988 and b. July 1989.



stations
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
July 1989
depth (m)
potential temperature (θ)
salinity
density (σθ)
distance (km)
(i)
(ii)

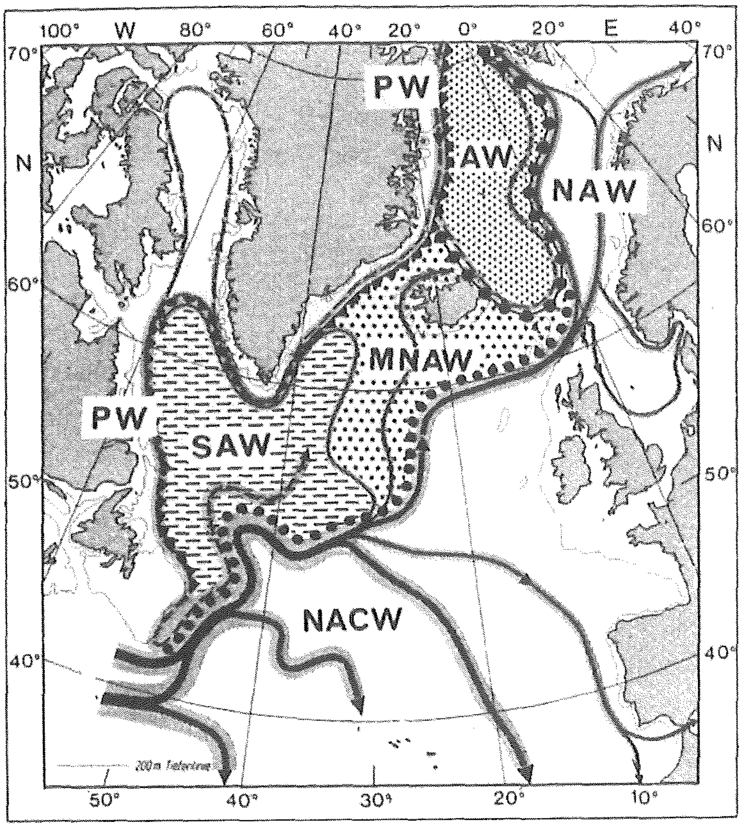


Figure 3. Normal distribution of water masses and fronts in the northern North Atlantic:- NACW - North Atlantic Central Water; NAW - North Atlantic Waters; MNAW - Modified North Atlantic Waters; SAW - Subarctic Waters; AW - Arctic Waters, and PW - Polar Waters. (Redrawn from Dickson et al. 1989).

Waters by the Polar Front, and from the North Atlantic and Modified Atlantic Waters by the Arctic Front. Another front shown in Figure 4, is the Subarctic Front between the warmer and colder North Atlantic Waters

The cold (< 0°C) dense waters produced in the Arctic domain are important to climate. They overflow the relatively shallow Greenland-Scotland Ridge at intermediate depths with a maximum depth of 830m in the Faroe Bank Channel (FBC), and renew the deep and bottom waters in the North Atlantic. These overflows follow two main routes, one via the Faroese Channels (FSC and FBC), the other via the Denmark Strait. On the Atlantic side both cascade down slope mixing with the subpolar circulation system to the south of Greenland. This deep flow then turns southwards and combines with the coldest pycnostads of the subpolar gyre, the Labrador Sea Water, to form the North Atlantic Deep and Bottom Waters. These then flow equatorwards via the Western Boundary Current into tropical latitudes. These overflow waters are continually entraining warmer waters so between leaving the Nordic Seas their temperature had risen from 0°C to around 2°C by the time they reached 50°N.

This is a very simple outline of some elements of the dynamic and thermodynamic system of the North Atlantic, and some of the other complications should be mentioned, for example the linking of the North Atlantic to the other oceans via the so-called "conveyer belt", and the outflow of Gulf of Gibraltar Outflow Water. This complex system has developed over geological time in response to long-term variations in external forcing, such as the variations in the Earth's orbit and the effects of continental drift. There are also variations and cyclic phenomena which are significant even on human time-scales such as interannual and decadal fluctuations in climatic factors, such as the incoming solar radiation, which result in fluctuations in the system resulting from interannual variability in the extent of ice coverage, the position of fronts, the intensity of currents and the formation of deep water masses and so on. The seasonal cycle alters the behaviour of the system still further, and even when the circulation and water mass distribution has been determined by the interannual and seasonal trends, there are still stochastic effects from transients such as mesoscale eddies. These eddies which have dimensions ranging from a few to hundreds of kilometres and time spans of weeks to months, are generated either by atmospheric interactions or by instabilities in the circulation patterns especially along fronts and associated with bathymetric features. In shallow water regions like the Faroe shelf, there are also important local phenomena generated by the tides. Several of small-scale processes can have an impact on larger-scale water mass composition, for example, when more saline waters overlie fresher in a thermally stabilized water column, double diffusion processes can develop and vertically transport significant quantities of heat and salt. Such conditions are common along the track of the North Atlantic Current in subpolar and arctic regions. Finally human activities may now be beginning to influence the system.

One of the best known examples of a large-scale, long-term fluctuation in the thermohaline structure of the northern North Atlantic is the "Great Salinity Anomaly". This was a 200-800m thick wedge of low salinity water which took 14 years to tour around the northern gyre. The source of this fresher water has been attributed to a period of very strong northerly winds which were associated with a persistent atmospheric high over Greenland and resulted in an abnormally high southerly transport of polar water by the East Greenland and East Iceland Currents during the 1960s. The anomaly arrived in the Faroe-Shetland Channel in 1976. Its signal can be identified in the salinity time series for 1902-82 (Figure 4). A decrease in salinity of about 0.1 is seen in FSC in both the Atlantic waters in the surface 300m (Figure 5a) and in Arctic waters at depths of 300-500m (Figure 5b).

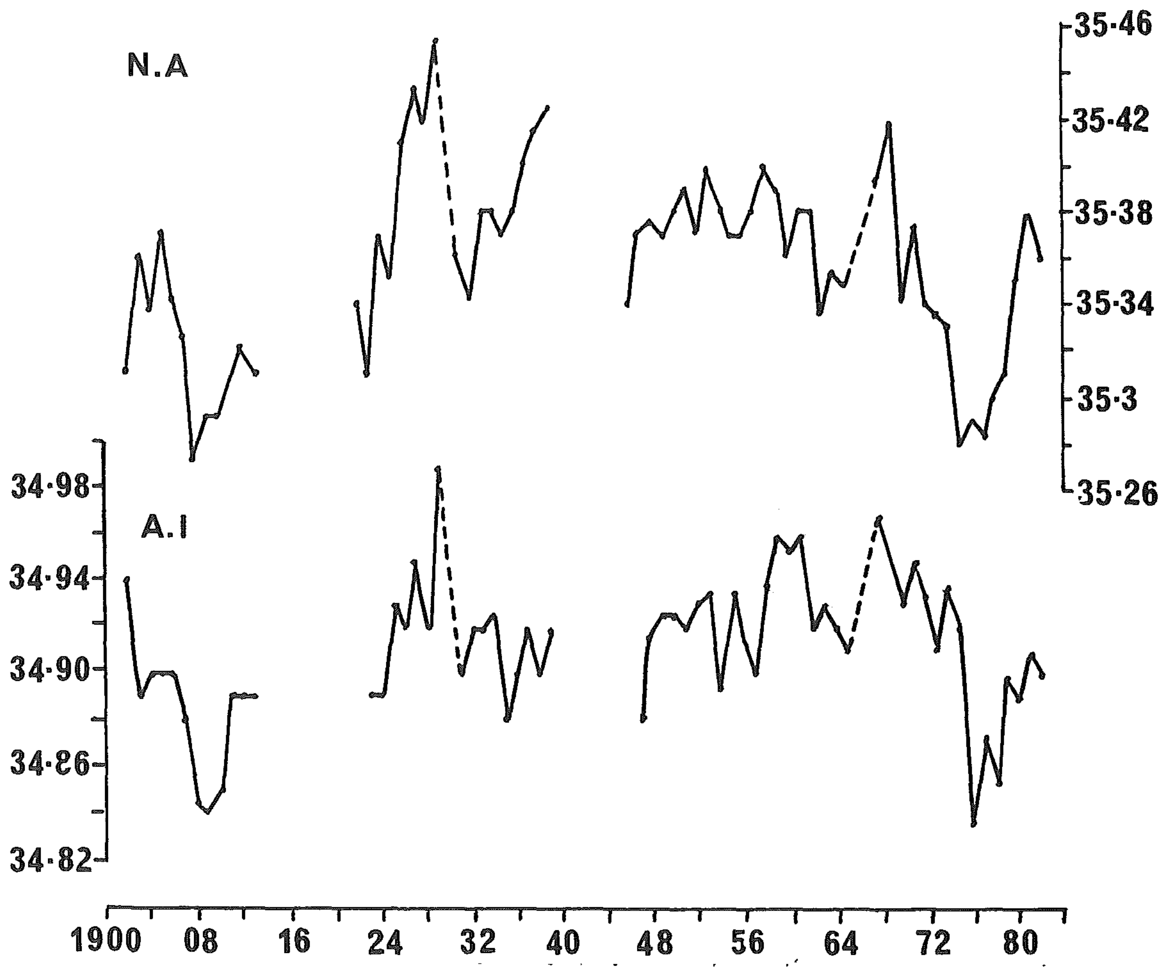
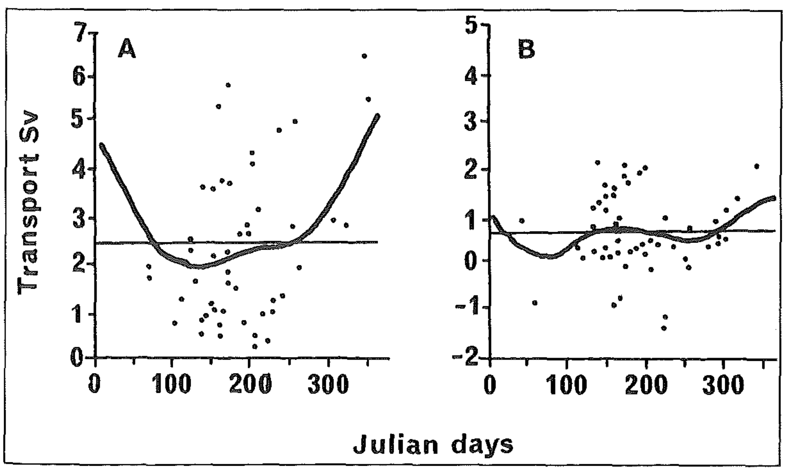


Figure 4. A time series of salinities in the Faroe-Shetland Channel from 1902-1982 for a. North Atlantic Waters, and b. Arctic Intermediate Waters (from Dooley et al. 1984).

The inflow of Atlantic Waters into the Norwegian Sea through the Faroe-Shetland Channel is another example of an oceanographic process which varies in time. Estimates of the inflow range from 2-8 sverdrups (1 Sv = $10^6 m^3.s^{-1}$). This wide range of the estimates not only reflects a real interannual variability in the strength of the northerly flow, but also results from the different methods of estimating the volume transport and the seasonal signal in the hydrographic data. Figure 5 illustrates how seasonal estimates of the inflow of Atlantic Water and the outflow of Norwegian deep water fluctuates throughout the year. The estimates of the Atlantic inflow, calculated from hydrographic data from 1927-58, show a strong winter maximum, whereas the deep outflow based on data from 1927-64 shows a slight minimum in winter. The 35 isohaline often provides the best demarcation between these two waters, and so in estimating the flows this isohaline has been taken to be the classical level of "no motion". More recent attempts to calculate the velocity field from hydrographic data, and hence the volume transport through the Channel, have abandoned this concept of a zero-velocity level. The flow has been constrained either by using current meter data or by imposing mass conservation in boxes constructed from the hydrographic stations and selected isopycnals. The dynamic calculations for our data were set with a level of "no motion" at σ = 27.8 kg.m^{-3} in

Figure 5. Estimates of transport through the Faroe-Shetland Channel for a. the inflow of North Atlantic Waters from 1927-58; and b. the outflow of deep and intermediate waters for 1927-64. The solid line represents a fit with an 8th order polynomial, and the light line indicates mean flows of 2.6 and 0.75 sverdrups respectively (Redrawn from Hopkins 1991).



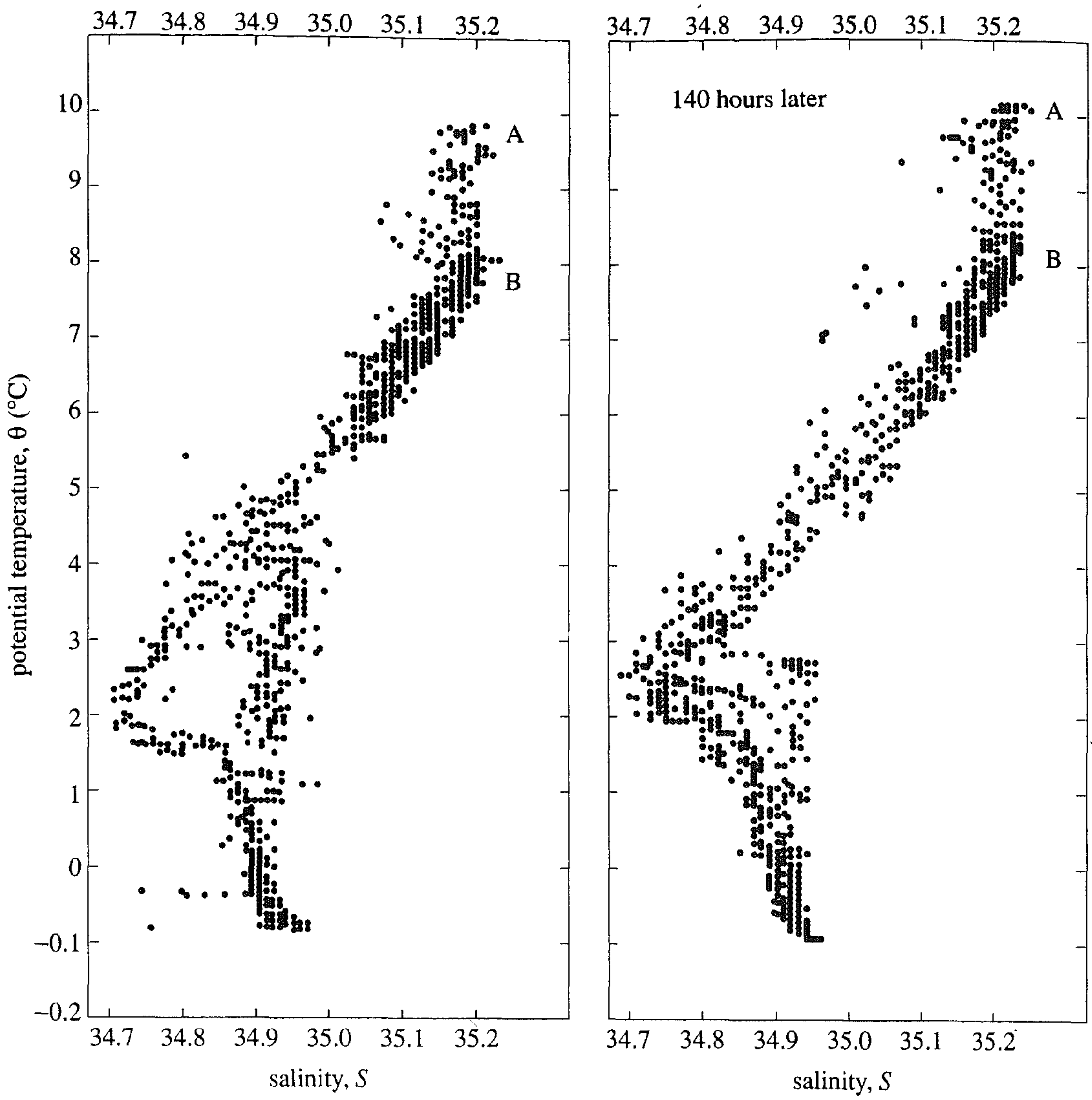


Figure 6. *Plots of all θ-S data for the five Poseidon stations occupied to the north of the Faroe Islands in July 1977 (stations 100-104 were occupied 140 hours later than stations 19-23). (redrawn from Meincke, 1978).*

1988 and at σ = 27.5 kg.m^{-3} in 1989. For the 1988 data this gave a larger (ca. 2Sv) net transport of warm water ($\theta > 3\,°C$) than in 1989 (ca. 1 Sv). There were marked differences between the estimated outflow into the Atlantic in the deep water, in 1989 it was ca. 0.5 Sv, compared with ca. -0.5 Sv (i.e flow back into the Norwegian Sea) in 1988. However, this apparent reversal in estimated deep water flow may have resulted from a mesoscale eddy temporarily disturbing the normal patterns at the time of the 1988 observations (see below).

Another example of short-term variability in FSC is illustrated in Figure 6. Over 6 days in June/July 1977, there was a change in the θ-S structure of the water column at 5 stations to the north of the Faroe Islands. An interesting phenomenon is the evidence of direct mixing between the surface and the deep water, normally these are transient events but they appear as an almost constant feature in the Channel.

Looking back at the data illustrated in Figures 2, the distribution of isopycnals in July 1988 and 1989 closely resembles that of the isotherms. So salinity was making a very minor contribution to the stratification of the water column. There were also cores of high and low salinity present in the Channel. One persistent feature is the main pycnocline at depths around 400m. It is a 200m thick layer with tightly packed isopycnals which separates the warm surface waters from the cold deep waters. In summer solar heating of the surfaces layers leads to the formation of a surface pycnocline in the upper 100m. If the strength of the pycnocline was gauged by the maximum on the Vaisala-Brunt frequency mean profile, the strength of the seasonal pycnocline shown in the density sections in Figure 2 would be over one and a half times that of the permanent deep one. In 1989, the maximum, attained at the depths of the greatest vertical density gradient, was one cycle per hundred seconds in the seasonal pycnocline, corresponding to an oscillatory frequency of ten minutes. Any internal waves that develop in the pycnocline periodicities longer than this will break and so give rise to turbulence.

The layer between the two pycnoclines is occupied by the pycnostad, $\sigma \approx 27.35$ kg.m^{-3} and $\sigma \approx 27.5$ kg.m^{-3} respectively. The former corresponds to the North Atlantic Water while the latter to the Modified North Atlantic Water. From now on the names of the water masses will be given in the singular to stress their tighter regional θ-S characteristics. The origins of both Atlantic Waters as discussed above are as mode waters formed by the cooling and freshening of upper layers. The North Atlantic Water is the saltiest and warmest water mass in the FSC, with a temperature >9°C and a salinity of 35; it is always found along the Shetland slope and shelf. It maximum flow is rarely located over isobaths deeper than 500m and its cores of highest salinity and temperature occur at or to the east of the flow maximum. The vertical extent of the North Atlantic Water is limited by the sill depth of the Wyville-Thomson Ridge which intersects the northward path of the North Atlantic Current. Along the West European continental slope, the upper 1000m of the North Atlantic Current consists of East North Atlantic Water which ranges in temperature from 5 to 12°C and in salinity from 35.0 to 35.6. The sill depth of the Wyville-Thomson Ridge at 550m divides the flow into two parts. The upper warmer water flows northwards along the Shetland self into the Norwegian Sea. The deeper colder layer follows the deeper isobaths westwards to join up with the Irminger Current. The salinity maximum of the core of the North Atlantic Water over the Shetland slope was 35.34 in 1988 and 35.38 in 1989 (Figures 2, salinity sections). The North Atlantic Current occasionally becomes unstable over the slope, and starts to meander and spawn eddies. The core of North Atlantic Water seen in the central part of the Channel in the 1988 salinity section was probably such an eddy. It is 40 km wide with a salinity as high as the water occurring over the slope. Associated with this eddy there was a deepening of the isopycnals associated with this eddy throughout the whole water column. This may explain why the estimate of net transport of the cold deep water based on this section was apparently in the wrong direction.

Most of the upper layers in the FSC are occupied by Modified North Atlantic Water ($\theta > 7$°C; $S > 35.1$) which flows in from over the Iceland Faroe Ridge via an extension of the East Icelandic Current. This Modified water is derived from secondary circulations from the westward flowing Irminger Current; it is found from the edge of the Icelandic continental shelf along the southern boundary of the Iceland-Faroes Front, to the edge of the North Atlantic Current to the west and north of the Shetland Islands. It is separated from the North Atlantic Water by the northernmost sector of the Subarctic Front (Figure 3), where the 35.3 isohaline indicates the boundary between the two water masses.

Therefore in the Faroe-Shetland Channel, Modified Atlantic Water is always present to the east of the islands circulating anticyclonically. Part of its flow in the FSC recirculates back into the Norwegian Sea. The rest of it, together with intermediate and deep waters, continues to flow westwards and enters the North Atlantic. The winter mode waters occupy a broad geographical area within the polar gyre, and so their θ-S characteristics show only small interannual variability, even so the temperature of most of the MNAW in FSC in 1988 was 7°C compared with 7.5°C in 1989 (see the thermostads in the temperature sections in Figure 2). In 1988 (but not in 1989) a core of MNAW with a salinity of around 35.24 was present in the eastern part of the Channel entrained between two branches of North Atlantic Water. In both years, another core of MNAW with salinity around 35.18 occurred over the Faroe shelf and slope.

The low salinity feature seen in the upper layers in both years had a different origin. In 1988 at the easternmost station, salinity was as low as 34.95 probably as a result of run-off from the islands. In 1989, a salinity minimum of 35 occurred in the central part of the Channel where it overlay an eddy which was drawing water from the main pycnocline and above into shallow water. The hydrographic properties of the water in this eddy indicate that it had been generated at the Iceland-Faroe Front and then advected into the Channel. The position of the Iceland-Faroe Front varies from year to year, and the surface temperature change across it can be as much as 6°C. Such a strong front is likely to spawn warm-core salty eddies on its cold fresher side, and cold-core, fresher eddies on its other side. Eddies with scales of 20-50km have been described propagating along the Iceland-Faroe Front and entering the FSC, both in hydrographic sections and through using remote-sensing and satellite tracked buoys.

The presence of Arctic features in the intermediate waters was more pronounced in 1989 than in 1988. For example, in 1989 there was evidence of the lightest of these waters derived from the Arctic ($\sigma \approx 27.8$ kg.m^{-3}; $S < 34.9$; $\theta \approx 2$-3°C) in the salinity minimum at the base of the main halocline at depths of 400-500m. In 1988, this salinity minimum was less marked. The water in the minimum is called North Icelandic Winter Water. This water mass forms as a result of convective mixing during winter to the north of Iceland, and then sinks along the Iceland-Faroe Front and spreads at intermediate depths in the East Iceland Current over the north Faroe slope and into the FSC. It may well contain a component from the polar domain fed into the East Iceland Current from the East Greenland Current.

At all deep stations in 1989 and at two in 1988, the North Icelandic Winter Water was underlain by Norwegian North Atlantic Water (NNAW), the winter mode water that forms and circulates cyclonically around the southern Norwegian Sea. In FSC it appears at the base of the main pycnocline as a salinity maximum (S ≈ 34.92), with a temperature of ca. 1-2°C and densities of ≈ 27.9-28.0 $kg.m^{-3}$. In the Norwegian Sea to the north of the Channel the NNAW is at shallower depths and is both warmer (θ ≈ 3°C) and saltier (S ≈ 34.98).

Underlying both the North Icelandic Winter Water and the NNAW there is always Arctic Intermediate Water (AIW), which is characterised by a salinity minimum at a depth of ca.650m (θ ≈ 0°C; S ≈ 34.9; σ ≈ 28.02 $kg.m^{-3}$). A similar salinity minimum occurs over wide areas of the Norwegian Sea at depths of 500-1000m. AIW is a mode water formed by cooling of surface waters in the arctic domain in the Greenland and Iceland Seas. It enters FSC from the north via the deeper part of the East Iceland Current.

This band of intermediate water is thicker on the Faroes side of the Channel, more emphatically in 1988. Its volume depends mainly on input from the East Iceland Current which influenced the hydrography of the Channel more in 1989 than in 1988 (as was shown by Hansen in studying blue whiting). Towards the south the feature with its extremes of salinity, deepens and broadens and tends to loose its identity. Over the Faroe-Bank Channel it disappears completely, so unlike the Denmark Strait, it seems that the Faroe Channels export only a small portion of their intermediate waters into the Atlantic.

The water mass that is transported through the Faroe Channels in more significant amounts is the upper Norwegian Sea Deep Water (NSDW). This is the heaviest water mass in the FSC (σ ≈ 28.02 kg.m-3; θ ≈ -0.5°C; S ≈ 24.92). It fills the Channel below the salinity minimum of Arctic Intermediate Water. It is advected into the Channel from the Norwegian Sea, and is generated either by convective cooling in the Iceland Sea, or by mixing of intermediate waters with "pure" Norwegian Sea Deep Water, which forms a homogeneous layer below 2500m in the Norwegian Sea. "Pure" Norwegian Sea Deep Water (θ = -1.05°C; S = 34.91) is a mix of Greenland Sea Deep Water (θ = -1.3°C; S = 34.89) and Eurasian Basin Deep Water (θ= -0.8°C; S = 34.93) advected from the Arctic in the East Greenland Current. It is constrained to remain circulating in the Arctic Mediterranean (Nordic and Polar Sea) by the Greenland-Scotland Ridge.

Conclusion

There are six major water masses that can be identified in the FSC, which vary interannually in their volumes and distributions. At the surface is North Atlantic Water (NAW) and Modified North Atlantic Water (MNAW), both are mode waters formed during wintertime cooling of warm salty Atlantic water; MNAW forms in the subpolar gyre, NAW further to the south. The intermediate waters are also mode waters which form in different regions of the Nordic Sea and then become modified during their advection into the Channel; these are East Icelandic Water formed in the East Iceland Current, Norwegian North Atlantic Water formed in the Norwegian Sea, and Arctic Intermediate Water formed in the Iceland and Greenland Seas. The only deep water in the Channel is upper Norwegian Sea Deep Water which is probably a product of intermediate water cooled in the Iceland Sea. Waters of Atlantic and Arctic origin are always competing in the Channel. Their volumes depend on the position and strengths of the Arctic and Subarctic Fronts. In 1988 the Atlantic regime was dominant, but in 1989 it had been displaced by an Arctic regime. In 1988 the Atlantic waters were warmer and saltier, and the 35 isohaline was about 50m shallower. In 1989 there was a distinct wedge of intermediate waters across the Channel, but in 1988 the wedge was blurred, probably as a result of the eddy in mid-channel which had a surface core of North Atlantic Water and extended its influence right to the bottom.

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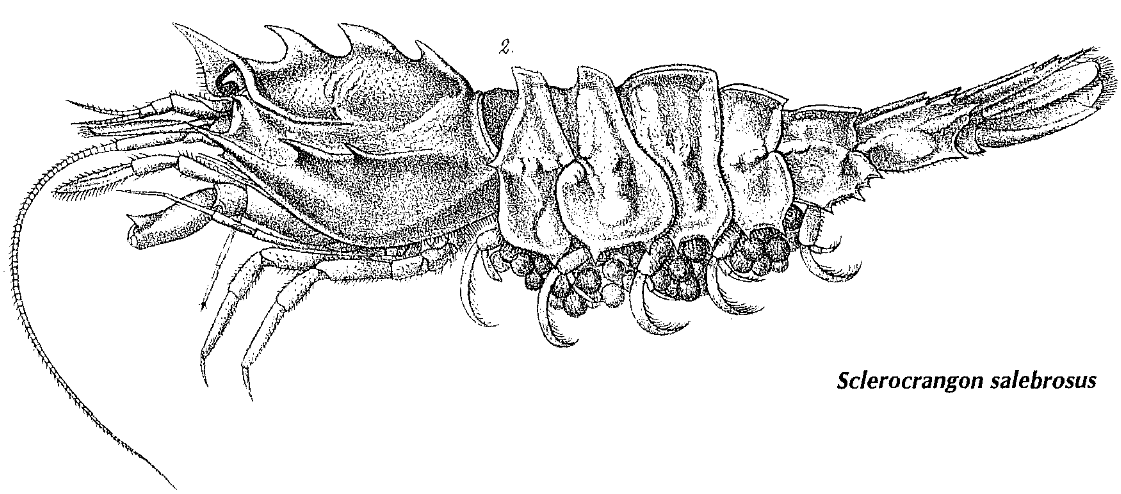


Sclerocrangon salebrosus

Tidal oscillations of the thermocline in the Faroe-Shetland Channel

Toby Sherwin

Physical oceanography was a fairly inexact science until the development of the Negretti and Zambra reversing thermometer at the end of the 19th century (Figure 1). When oceanographers started using it in the Norwegian Sea and surrounding basins, they discovered that there were short scale variations in the depths of isotherms which, they postulated, were the result of internal waves (they called them 'boundary waves'). In 1909 the Norwegians Bjorn Helland-Hansen and Fridtjof Nansen, two early fathers of modern oceanography (see the paper in this issue by Blindheim), wrote

> "we consider it probable, for instance, that tidal waves passing into a basin across a sub-oceanic ridge, like that between Scotland and Greenland, may give irregular pulses such as these" .

Today we call such pulses or boundary waves 'internal tides' because they cause wave-like oscillations of isotherms within the body of the ocean with a tidal period. The many reported observations of internal tides have shown them to be ubiquitous features of the world ocean.

Oceanographers at that time were concerned that internal waves might prejudice their estimates of advective exchange between ocean basins, and so in 1910 scientists from three countries made observations of the internal tide in the channel using repeated bottle casts over periods of one to two days. The locations of these stations, which were along a line joining Shetland with the Faroes, are shown in Figure 2 - Station 115 was observed by Helland-Hansen; Station Da by the Dane, Martin Knudsen; and Station Sc by a team from Scotland. Helland-Hansen made his observations from the famous Norwegian research ship *Michael Sars* (Figure 3), which had been purpose built in 1900 to specifications that were comparable to many modern research ships. The achievements of those early oceanographers were remarkable; it is amazing that only a year later Knudsen reported the results of a tidal analysis of the internal elevations of the temperature surfaces that he had observed - the apparent ease with which he used the technique marks him as man well ahead of his time. However, in his final analysis in 1930, Helland-Hansen decided that the oscillations (which were generally small, but occasionally reached a range of 80 m) mainly resulted from tidal advection of temperature fronts. Nevertheless he thought that further research was called for and advocated a major international investigation of internal tides in the channel, an idea which was never taken up.

Nearly 80 years were to pass from the time of the original experiments before the next serious investigation of internal tides in the Channel. In the meantime, an extraordinary incident provided clear evidence of the existence of significant internal tidal waves in the Channel. Between 21st and 26th October 1976, US Navy mini-submarine operators were working at the sea-bed on the southern side of the Channel near the ridge (position F14 in Figure 2) recovering sensitive equipment from an F14 fighter which had fallen from an aircraft carrier. During the operation they reported periodic "swirls of sand and dust (mud)" after which:-

> "the current rapidly increased to about 2.5 knots maximum with about a 20° shift in direction and a sharp temperature drop"

(at that depth they were close to the deep water thermocline). The phenomenon was so regular and intense that it earned a nickname - the *Nolter Maelstrom*. The 'On Scene Log Extraction' quite clearly indicates that the *Maelstrom* (which seems to behave like an internal bore) occurs every 12.5 hours and must be forced by the tide. Analysis of their report indicated that the disturbance was propagating northeastwards, away from the ridge and parallel to the bottom contours, with a speed of about 0.6 m s^{-1}.

This report stimulated me to reconsider the Wyville-Thomson ridge as a source of internal tidal generation. Its particular significance is that it lies at right angles to the relatively strong tidal currents that in this region oscillate parallel to the shelf edge, making it a good candidate for internal tide generation. In 1987 I had the opportunity to take the *Frederick*

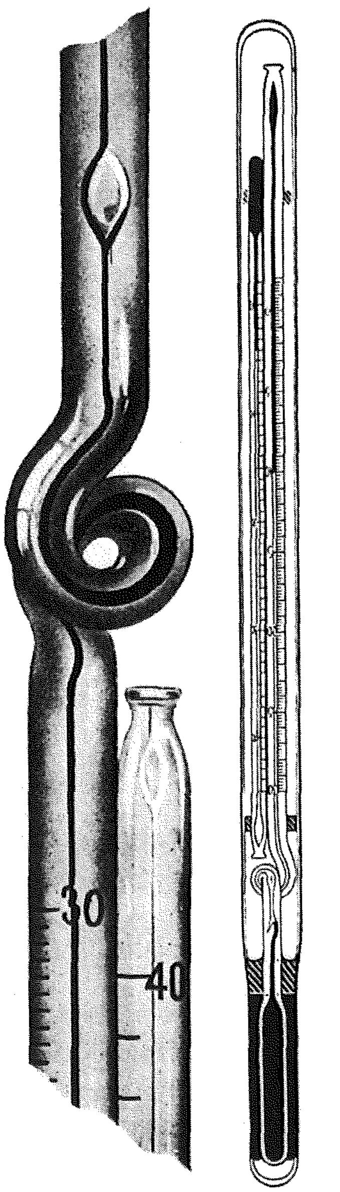


Figure 1. *Illustration of the Negretti and Zambra reversing thermometer taken from the second edition of The Science of the Sea: An elementary handbook of paractical oceanography. Edited by G.H.Fowler and E.J.Allen for the Challenger Society in 1928.*

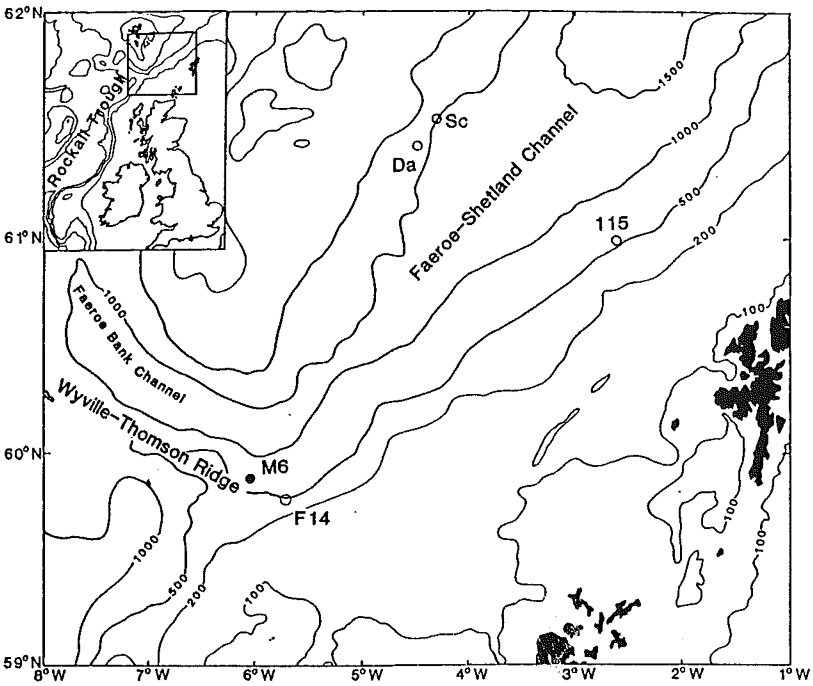
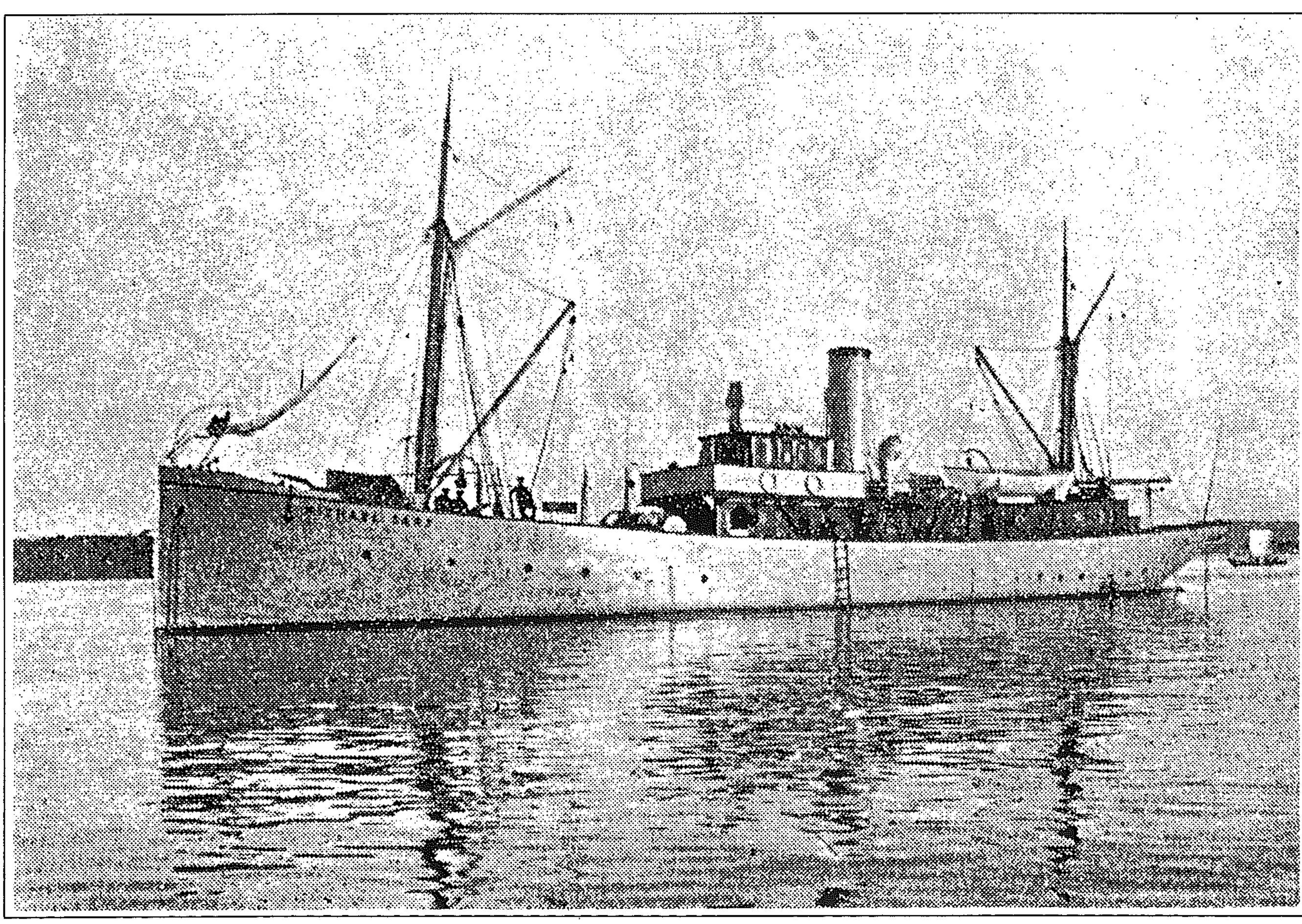


Figure 2. The Wyville-Thomson ridge and Færoe-Shetland Channel showing the locations of the various stations referred to in the text. The depth contours are in metres.

Russell, on her penultimate cruise for the Natural Environment Research Council, into the Channel to investigate the internal tide. We occupied a number of stations near the ridge and near station 115, originally occupied by the *Michael Sars*. The technique that we used in deep water was to deploy a dhan buoy and then hold the ship on station for up to 36 hours while continually yo-yoing the CTD through the water column. We also had a portable acoustic doppler current profiler (ADCP) attached to the side of the ship with which we measured currents down to 400 m. At the time I thought that my use of the dhan buoy was original, until later I read that Helland-Hansen and Knudsen had used exactly the same technique in 1910!

The most interesting station was located in 900m of water just to the north of the ridge (station M6 in Figure 2). Figure 4 shows the variation in the level of the isotherms as the CTD was plunged from the surface through the deep water thermocline which separates the North Atlantic Water from the cold Norwegian Sea Deep Water. Over a tidal cycle the depth of the contours at 550 m varied by more than 40m which, given the large density difference across the

Figure 3. The S/S Michael Sars, the research vessel built in 1900 for the Norwegian Fishery and Marine Investigations. She was based on a 'modern fishing-steamer' and had a length of 125 ft, a cruising speed of 10 knots, a 10 ton winch with a maximum winding speed of over 2 m s^{-1}, a refrigerating chamber, open deck space and a spacious laboratory. The photograph comes from the report by Hjort which gives a detailed description of the ship and how it was procured.



thermocline, implies that a lot of energy is bound up in the wave. Analysis of the motion confirmed that it could not be explained by tidal advection of a density front. Unfortunately, the ADCP was unable to measure across the thermocline where a shear in the tidal currents of about 0.1 m s-1 could be expected to exist. These observations, which are generally consistent with theoretical calculations of the magnitude of the internal tide generated over the ridge, suggest that there should be a reasonably large flux of energy into the Channel. That being so, the question arises as to why was it not also seen in the observations of those early oceanographers, or in those of my own taken further up the channel? And what role does the *Nolter Maelstrom* play in all this?

In order to investigate this further, I used a three-dimensional primitive equation numerical model to simulate internal tide generation over a ridge and into a channel with similar dimensions and density profile as the Faroe-Shetland Channel. The results showed that the energy generated by the ridge does not propagate up the channel with uniform amplitude as one might expect, but is deflected, or refracted, to the sides where it becomes trapped in the deep thermocline for a distance of up to 50 km from the ridge. This trapping of energy in the thermocline could well be the cause of the strong currents found in the *Nolter Maelstrom*.

These results have confirmed not only the original hypothesis by Helland-Hansen and Nansen that the Wyville-Thomson Ridge generates an internal tide but also have both natural and anthropogenic implications for conditions in the Channel. The focusing of tidal energy onto the southern bank will result in enhanced mixing of the water column and increased bottom friction which may slow or deflect the slope current. The *Nolter Maelstrom* not only disturbs sediments, but also has an impact on oil exploration and development because the fast currents associated with it can create problems for both divers and structures near the sea-bed. However, there is a lot more to be discovered about the magnitude and extent of the internal tide, and Helland-Hansen's sentiments that "a detailed investigation of the oscillations in question ... seems a [worthy] task" appear to be as relevant today as they were over 60 years ago.

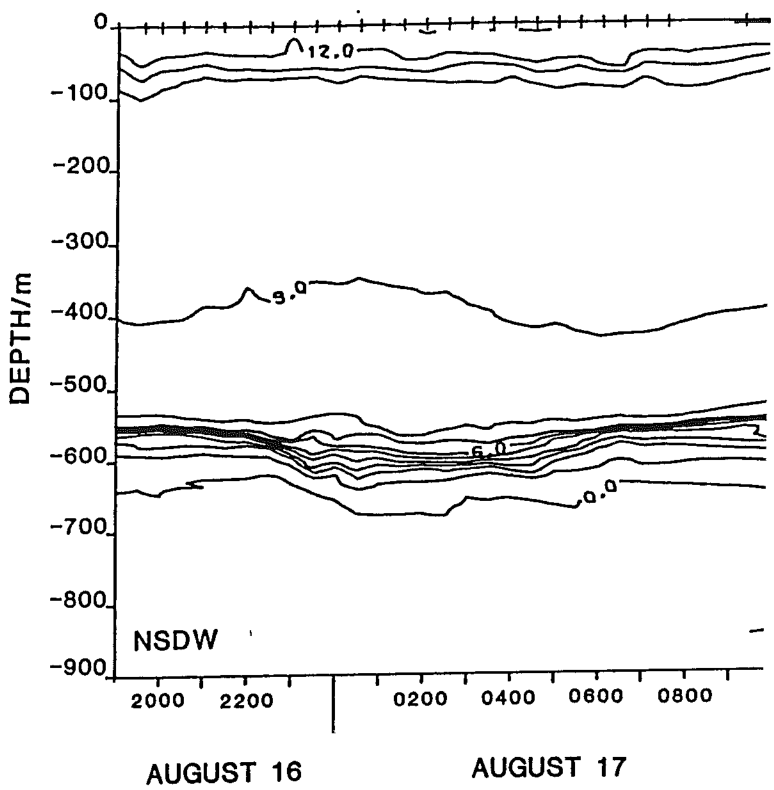


Figure 4. *Temperature contours at station M6, observed by yo-yoing a CTD, between 1900h 16th August and 1200h 17th August 1987, during the Frederick Russell cruise. The vertical oscillation of the deep thermocline was caused by an internal tide. The tick marks at the top of the figure indicate the times of individual casts.*

Further reading

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HISTORICAL SALINITY DATA OF THE NORTH ATLANTIC OCEAN

Gilles Reverdin

Our knowledge of oceanic climate over the last 100 years has been based mainly on ship-measurements of sea surface temperature, the distribution of sea ice and various atmospheric parameters. These measurements, which have been collected for the meteorological services since the early 1850s, now constitute a very valuable archive. Despite the shortcomings in the distribution of the data and precision of the instruments, and also the lack of comparable information on temperature changes at depth, these surface data have helped to define the spatial and time characteristics of oceanic climate variability during the last 100 years.

Salinity which is a measure of the concentration of dissolved salts in sea water, is also an important parameter to monitor. If there were no exchanges of water between the ocean, the atmosphere, the cryosphere and the land masses, salinity would be almost uniform. The spatial inhomogeneity of oceanic salinity results from the hydrological exchanges between these components. Most of these exchanges occur at the ocean's surface, and the resulting salinity is then advected elsewhere by the currents. Since salinity contributes to the determination of sea water density, its fluctuations modify the density stratification and hence the three-dimensional circulation wihtin the ocean. Salinity is actively involved in vertial mixing not only through its contribution to stratification, but also because it can help create the conditions leading to the process of double diffusion. Throughout large parts of the oceans at subtropical and mid-latitudes, fluctuations in surface salinity which result from variations in the balance between evaporation and rainfall, have a relatively minor influence on surface density relative to the effects of fluctuations in sea surface temperature. However, at high latitudes salinity plays the more important role. Time series of hydrographic data collected from the North Atlantic since 1948, show that wherever the winter temperature averages $<7°C$ salinity is the dominant factor controlling density variations. These series also suggest that surface salinity can often be used to monitor the changes in the upper ocean, because the salinity anomalies exhibit a large vertical coherence in winter, and late winter surface salinity anomalies often persist throughout much of the seasonal cycle. Once the average seasonal cycle is sufficiently well known, the persistence of the anomalies can be helpful in providing coherence to observations which are coarsely distributed in time. However, greater caution is needed when interpreting summertime surface salinity data, particularly where there is either seasonal drift-ice or where, like off the Grand Bank, the range in the seasonal cycle is very large so that there is no longer any correlation between surface salinity anomalies in summer and those of late winter.

Unfortunately, there is no early data set of sea surface salinity measurements comparable to that available for sea surface temperatures. The reason for this is quite simple; it was relatively straightforward to collect a sample of sea water, but estimating its salinity proved to be a more difficult task. Only during the last decade of the 19th century could salinity be estimated with sufficient accuracy to sense climate-related fluctuations in the upper ocean. Systematic sampling of the North Atlantic was initiated in 1902 by the International Council for the Exploration of the Sea (ICES) and since 1904 has relied heavily on surface samples being collected from ships of opportunity. This sampling was not started *ab nihilo*, but was founded on the efforts of a few individuals who by then had already by then collected and analysed more than 10,000 surface salinity samples during the late 19th century. At that time, surface salinity was considered to provide important information on seasonal and interannual variability. Fortunately, because the methology was still novel, most data listings in reports were accompanied by discussions of the sampling methods. The determination of salinity was yet to be standardized, so there were large methodological differences between the data collected by the various institutions. So these published accounts, together with some fortuitous overlap between some of the data sets, are very valuable for evaluating the accuracy of the data. This is important, because the large-scale signals, for which the monitoring was designed to detect, are barely larger than 0.10 (in non-dimensional salinity unit, the average salinity of the ocean is close to 35). For example, the interannual fluctuations in the hydrographic time series of upper ocean salinity in the Faroe-Shetland Channel have an amplitude of the order of 0.10, even for the major fresh water event of 1976 (the Great Salinity Anomaly). To our surprise, we find that some of the data collected during the late 19th century have accuracies better than 0.05, in particular the data measured by Danish oceanographers post-1896 and those measured by H.N.Dickson from Oxford.

Monthly maps (Figure 1) were produced and widely commented on by H.N. Dickson, J.

Hjort and H. Cleve. Although these data did not always have the spatial coverage which we would now consider synoptic, they may still be pertinent for studies of the variability of surface salinity on the time scales ranging from interannual to interdecadal over which climate is evolving. Here I give an account of why and how these early data were collected and what we can learn from them.

How was the monitoring of surface salinity started?

In Scandinavia large socio-economic consequences resulted from the failure of the Lofoten Arcto-Norwegian cod fisheries in Norway in 1860, the low cod catches between 1893 and 1899, and the failure of the Atlanto-Scandian herring winter fisheries in southwestern Norway from 1870 until 1896. The ensuing investigations of these fisheries, in particular those by G.O. Sars, revealed that the fish and their larvae undertake extensive pelagic migrations, so that their distributions are related to the hydrographic conditions. In the 1870s, H. Mohn collected surface temperature information from sealers and fishermen in the Norwegian Sea and around Spitsbergen and his results suggested an intimate link between hydrographic conditions, fisheries and the climate. Then in 1900, O. Pettersson suggested that hydrographic conditions were playing a significant role in determining the variations in the climate of Northern Europe. He believed that the distribution of surface salinity in the North Sea quantitatively indicated the inflow of North Atlantic water which was related to climate fluctuations. So investigations of surface salinities in the northern North Atlantic salinity were instigated to provide clues on two interrelated questions: what role do the oceans play in determining variations in fisheries and in the variations in the climate of Northern Europe?

In the early 1890's, new techniques were developed which allowed faster and more reliable collection of water samples from the upper ocean, so it became practical to carry out surveys that were almost synoptic. The procedure for routinely titrating chlorinity was also improved, so that salinity estimates became more reliable. The main improvement was through the use of a reference solution to provide a relative estimate of the chlorinity, although acheiving absolute measurement remained a problem until M. Knudsen began producing normal seawater standards.

Based on the experience gained during surveys in the Baltic Seas, the Skagerrak and Kattegat in 1890, a programme of regular hydrographic data collection was initiated by the Swedes in the North Sea in May 1893, involving international cooperation between the coastal countries until February 1895 (Stockholm Conference, 1892). The first year

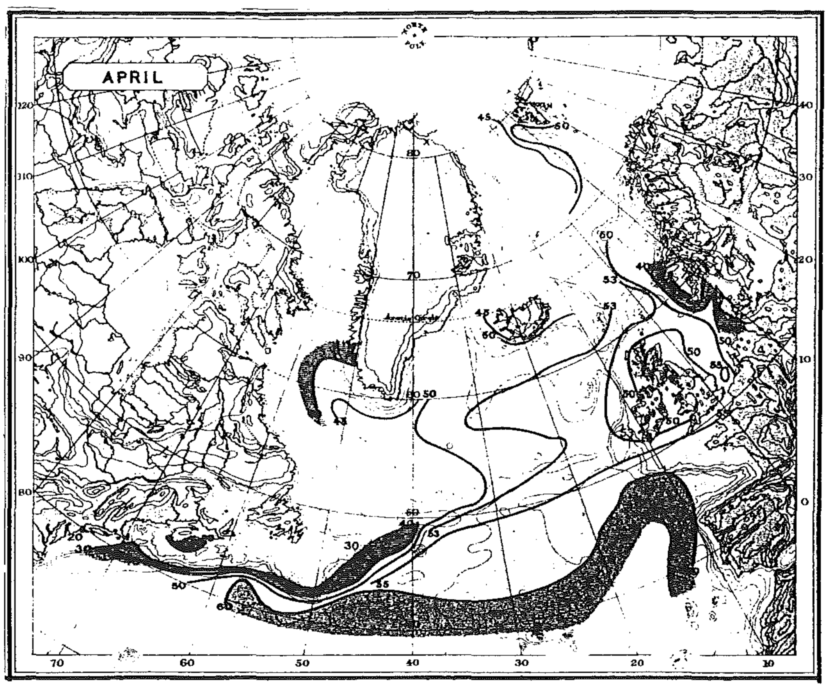

Figure 1. Salinity in April 1896 in the North Atlantic Ocean according to Dickson (1901). Contours for 33.0, 34.0, 34.5, 35.0, 35.3, 35.5 and 36.0 are indicated (labels are 30, 40, 45, 50, 53, 55 and 60 respectively).

revealed significant seasonal variations in the thermal and salinity structure which justified the need for seasonal sampling. Much of the sampling was conducted from Swedish and Norwegian steamers regularly plying across the North Sea. Initiated during February and March 1890 and 1891, this means of sampling became more regular along the route between Shields and Bergen during the winter of 1892/93, and has been operated continuously since May 1893.

These efforts were soon extended to the open North Atlantic, in particular in the subarctic gyre and northern European Seas. In 1894, regular hydrographic surveys were initiated along the Norwegian coast and in the northern North Sea. Upper ocean sections in the Norwegian Sea were then extended towards Iceland and Jan Mayen, and these routine efforts were complemented by surface sampling using various ships-of-opportunity - in 1896 in the northern North Sea and after 1897 in the Norwegian and Greenland seas. In particular, use was made of fishing and sealing vessels on their way to the Jan Mayen and other northern grounds during the May and September-October seasons. Between 1896 and 1899, Swedish scientists also collected surface waters in the [illegible]egian and Greenland Se[illegible] expeditions and fro[illegible] opportunity. Results from tw[illegible]ish Expeditions are particularly import[illegible]e 1891/92 Ryder Expedition and the *In*[illegible]xpedition during which closely-spac[illegible]rface and upper ocean sampling was [illegible]ied around Iceland in 1895-1896, tow[illegible] Greenland in 1895 and toward Jan May[illegible] 1896. Deep hydrographic stations wer[illegible] observed during these cruises (as well as during the *Fram* expedition to the Arctic Ocean); unfortunately the precision of many of the deep data from these cruises is dubious.

In 1894, O. Pettersson when presenting a few salinities from samples collected on board a merchant vessel in October 1892, advocated that regular surface sampling should be extended to the whole of the North Atlantic in order to monitor the Gulf Stream and its extension. However, it was not until 1898 that Swedish investigators were able to start such monitoring. In 1893-94 and again in 1896, H.N. Dickson conducted seasonal cruises in the Faroe-Shetland Channel onboard the *Jackal*. He soon became convinced even from his limited set of stations, that not only was the North Atlantic drift fluctuating but also it was carrying significant anomalies eastward from North America. He decided to sample regularly the surface salinity and temperature of the Atlantic, north of 35°N, relying mainly on merchant vessels and a few whalers on passage to the Davis Straits grounds. In just over 2 years, from December 1895 to January 1898, these vessels collected more than 4000 samples which Dickson analyzed at Magdalen College, Oxford (Dickson, 1901). Some of these areas were resampled in 1898 and early 1899 by a Swedish programme of monitoring plankton directed by Cleve, which relied on a different set of merchant vessels. Data for more than 1000 surface salinities collected in 1898 and early 1899 outside the North Sea are recorded in the plankton lists stored at the Museum of Natural History of Gothenburg. As a follow-up to the *Ingolf* expedition in 1895-1896, Danish scientists were also involved with surface sampling of salinity in the North Atlantic between the Shetlands, Iceland and Greenland. Since 1897, surface water samples were collected in all seasons by various merchant vessels and mailsteamers between the Shetland Islands and Iceland, and less frequently during May to October between the Pentland Firth (north of Scotland) and western Greenland. These data were listed in various reports, and later scrutinized by M. Knudsen who continued the monitoring programme and was directly involved in the analysis of the samples.

The data

These various monitoring efforts contributed 10,600 temperature-salinity records between 1895 and 1899, the majority from 1896 and 1897. We have not included the data collected during the scientific expeditions. These expeditions were often of long duration and salinities were often estimated by on-board density measurements, which were less reliable than chlorinity titrations. However, these data have proved to be useful in detecting wildly erroneous measurements from the ships-of-opportunity programmes. Particularly useful are the data from the *Valdivia* Expeditions in 1898 to the west of the British Isles and towards the south Atlantic and in April 1899 between the Gibraltar Channel and the English Channel, also stations worked by the *Princesse Alice* in the summers of 1895, 1896 and 1897 near the Canary Islands.

A quick glance at the data suggests that there are serious discrepancies between the different data sets. For example, in 1897, samples were collected by the *Laura*, alternately for H.N. Dickson and the Danish programme, the Danish salinities are higher by 0.10; a significant difference as the standard deviation between samples is only 0.11. Such discrepancies are not surprising considering the differences in the methods for collecting, storing and analyzing the samples. It is interesting to review these methods briefly, identify what were the sources of error and how they can now be partially corrected. The salinity data were associated with temperature measurements, which were also very inhomogeneous in quality (for example, temperatures were clearly too high on French vessels used in the Swedish sampling programme). The positions at which the samples were collected are only approximately known, particularly in the northern European seas, where navigational fixes could seldom be made because of difficult weather conditions.

How were the samples collected?

The form sent to observers by H.N. Dickson mentions the use of a bucket as the sampler. A bucket was filled by plunging it into the sea and then measuring the temperature of the water in the bucket. Buckets were used on most research vessels and probably on most other vessels; a possible exception being the fast steamboats used in 1898 and 1899 for the Swedish monitoring programme, on which the samples were collected from a pump. The type of the bucket used was seldom specified, but on most transatlantic crossings generally either canvas or wooden buckets were used, whereas on research vessels the buckets used were mostly of galvanized iron. Water samples collected in canvas buckets gave positive salinity errors unless the bucket had been left to soak in the ocean before being retrieved, and the sample had not been left on the deck too long before being drawn and so subject to evaporation. Positive errors could also arise if a bucket was not cleaned properly before use. These problems, already recognized by M. Knudsen at the beginning of the century, are still causing significant errors in modern data sets. Recommendations were made as to the time of day at which the salinity samples were to be collected, but even though the times differed from set to set, this is unlikely to have reulted in large systematic differences.

How were the samples stored?

Most water samples were stored in sealed glass bottles and brought ashore for analysis; an exception being the samples collected by the *Ingolf* expedition most of which were analyzed on board soon after collection. The bottles used both by H.N. Dickson and for Swedish investigations were made of regular glass (Swedish bottles contained 100mls and British bottles 187mls). They were sealed with "properly-secured cork stoppers", and for additional security, both Dickson and Knudsen soaked the corks in very hot molten paraffin wax. The errors associated with the storage certainly depend on the duration of the storage. In 1900, Helland-Hansen and Nansen commented that samples stored for a year in the small (100 cc) bottles with good corks yielded positive errors of 0.07 psu, but for samples stored in bottles sealed with poor corks the errors rose to 0.08 psu within 5 months. Even with better bottles, closed with patent stoppers, long storage resulted in an increasing scatter of the salinities with a distribution skewed toward positive errors.

For North Sea samples, storage times were only a few weeks, but on cruises to Spitsbergen and other northern areas, the ships were often at sea for more than 5 months. Nansen suggested that evaporation had happened with the corked bottles of the 1896-97 Andree Expedition on board the *Virgo* and in 1899 also on board the *Antarctic*. Dickson was usually able to analyse his samples within 2 months of the collection. However, for vessels which collected only a few samples per crossing, the bottles did not become available for analysis for quite some time. This was frequently the case on the route between the English Channel and South America, and may explain why samples collected by the steamer *Para* in 1896 and 1897 appear too saline not only when compared with samples collected nearby and analyzed areometrically on board the *Princesse Alice*, but also relative to other surface samples collected by the *California*. All the sources of error we have described would be expected to have introduced a positive bias so, we were surprised by unexpectedly low salinities collected in March-April 1898 along the line from the English Channel to New-York; while being suspicious of these data, we have no obvious explanation for such errors.

How were the samples analyzed?

After being stored in the bottle (at least long enough for the bottle to equilibriate with the laboratory temperature), two methods of analysis were used. Either the density of the sample was measured at a known temperature or its chlorinity was measured by titration. Estimating the salinity from the density requires the use of an equation of state. In the laboratory, where densities were mostly measured using Sprengel tubes (pyknometer), applying an updated equation of state is not too difficult. However, for these early data sets the method used was usually Mohr's method of titration for chlorinity. Prior to May 1901, different formulae were used to estimate salinity from the titrated chlorinity, but since these formulae were always documented, it is easily retrospectively to correct them to the recommended ratio S/Cl=1.80655 which has been used below in discussing the data. Titrations were rarely done at sea during those early years, except during the *Ingolf* Expedition, when most of the titrations were done onboard, albeit with some difficulty because of the engine vibrations. The titration was done against a standard solution of silver nitrate using potassium chromate as the indicator of the reaction end (following the procedure described by Pettersson in 1894).

Two errors can be distinguished: one associated with the uncertainties of the volume of the pipette and burette used for the titrations, the other with the precise determination of the strength of the standard silver nitrate solution. In 1894 Pettersson recommended that the problems associated with the volumes of the pipette and burette could be minimised by operating at a temperature close to 15°C, but later both Dickson and Pettersson concluded this had little effect, so long as both the sea water and the silver nitrate solution were at the same temperature. I suspect that these errors could be kept at a tolerable level in the 1890's.

Determining the precise strength of the silver nitrate solution was a more serious problem. Dickson and Petterson titrated it against pure NaCl which had to be carefully weighed (Dickson, 1901; Pettersson, 1894). Sometimes, the investigator relied on either sea water or a solution of potassium chloride for which the chlorinity had been carefully estimated: for example, Martin Knudsen during the *Ingolf* Expedition used a sample of sea water whose halogen concentration had been measured by Pettersson. Gran also comments:-

> "The chlorine titration of the solution of nitrate of silver has not been fixed by the introduction of small portions of pure chloride of sodium, but by a solution of chloride of a known strength".

The idea was that a large volume of a reference solution, comparable in concentration to that of sea water was prepared which could presumably be protected from contamination. By using it regularly as a standard, both the evolution of the silver nitrate solution could be corrected for and some of the uncertainties related to the volumes of the burette and pipette eliminated. The main question was then how well the strength of the reference solution was known, particularly if the same solution was used repeatedly over a long period of time. If this solution evolves by evaporation, as was the case during the 1901-1903 *Gauss* expedition to the South Atlantic and South Indian Oceans and its "strength" is assumed to be the initial one, the titrations underestimate the chlorinity. On the other, if the strength of the solution was estimated retrospectively, the chlorinities of the samples will have been overestimated.

The accuracy of determining the strength of the reference solution was a lingering and serious issue for many years, with Nansen concluding in 1898 that the differences between the different groups could be as much as 0.10. The idea of exchanging

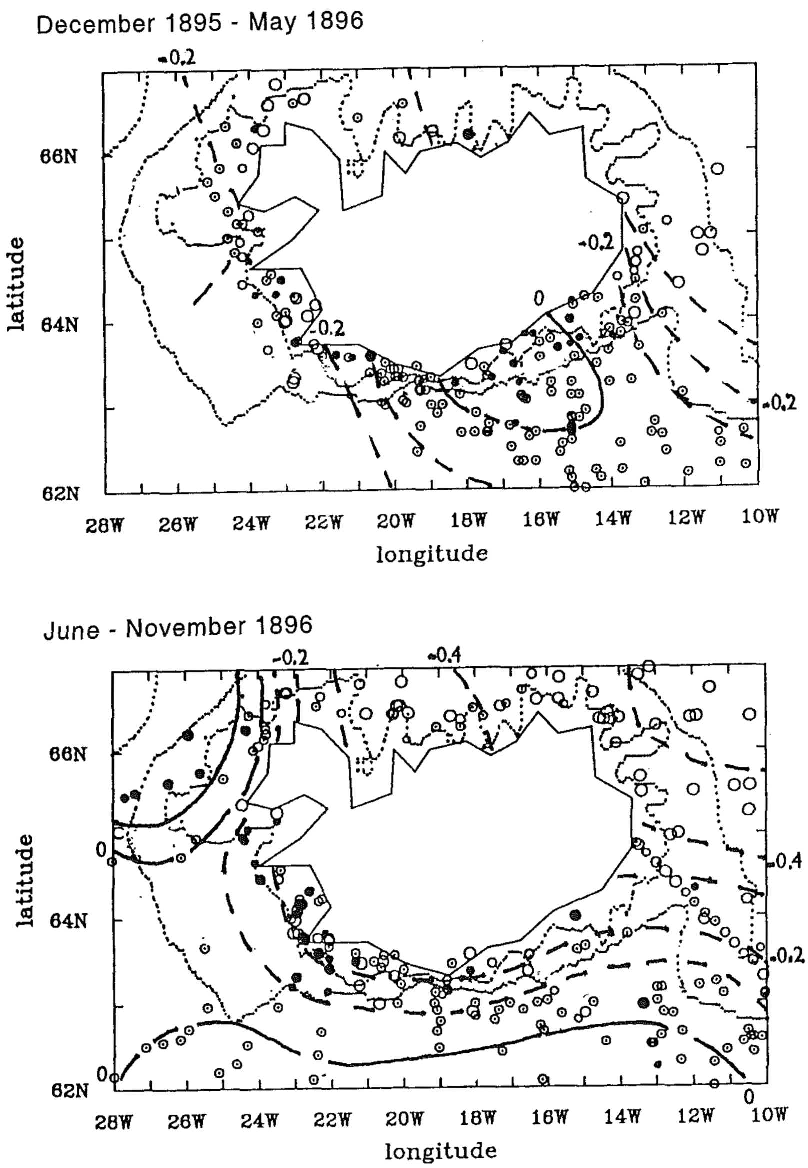

Figure 2. Salinity for two seasons in 1896 off Iceland. The isobaths 150m and 500m are indicated with a dotted line. The deviation from climatology is plotted (contour interval of 0.1: full line for positive deviations; dashed line for negative deviations). Climatological salinities present larger values to the south and west of Iceland than to north and east, with a well defined front to the east of Iceland along the Faroe-Iceland ridge. Individual data are reported by dots: full dots indicate positive deviations from climatology larger than 0.2 and open dots negative deviations less than -0.2.

standards gradually gained ground, with various groups in 1899 using the same standard water prepared by Pettersson. Corrections, made sometimes to correct old data to the new standard, were quite haphazard (in particular for some Norwegian data). On the other hand, Knudsen used different reference waters when systematically carrying out intercomparisons by Volhard's method of titration. Initially, in 1896, he used a normal water prepared by Pettersson, but it was not until May 1901 with his 6th "standard-water" that he achieved a precise estimate of the halogen content of the water. He then back-corrected the estimates made with the earlier waters; the corrections suggested that chlorinities of samples measured before January 1899 had been overestimated by 0.05 normalized to a chlorinity of 19.4 (a 0.258% difference) and samples measured in 1896 and 1897 had been overestimated by 0.08. His work provides a reference against which the other data sets can be compared. This is a relatively simple task for the monitoring organized by Dickson, because of the joint use of the *Laura*. But more careful interpretation is required for the other data sets, based on comments published in the data reports, deep water measurements which are sometimes of dubious quality and comparisons with data collected nearby during other programmes.

What is the accuracy of the salinity data sets?

Typically, a titration of chlorinity using Mohr's method can result in uncertainties of 0.02 in salinity, relative to a reference solution. Pettersson claimed absolute accuracy, but even if the strength of the reference solution had been known perfectly, this was obviously overly optimistic. From intercomparisons between samples of different programmes we now suspect that the relative accuracy of the data was at best 0.05, as was claimed by Dickson. Systematic errors probably amounted to 0.02 or less for the Danish and some of the data in Dickson's set (outside of the subtropics), but were larger, probably of the order of 0.05, for some of the other data sets.

Results of the monitoring

We will illustrate what was achieved with an example from near Iceland of the data for a single season. Figure 2 shows the location together with a mapped field of deviation from a climatological seasonal cycle based on data collected since 1948. Most individual data points are within 0.20 of the climatology to the south and southeast of Iceland which is within the region influenced by saltier water of North Atlantic origin. Knudsen had already estimated the seasonal cycle along the track of the *Laura* between southern Iceland, the Faroes and Denmark based on the data from

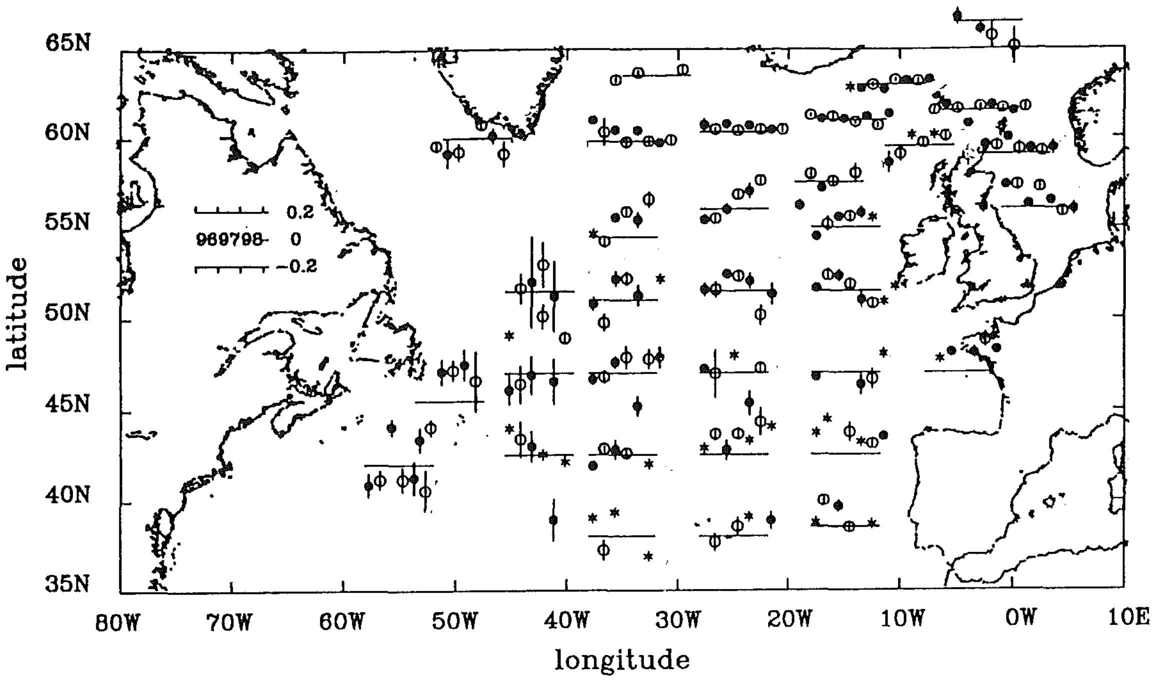

Figure 3. Box-averaged seasonal deviations of surface salinity from climatology in 1896-1898 (6 seasons correspond to the length of the horizontal axis with a scale in the corner of the plot). The full dots correspond to the December-April season and the open dots to the June-October season. Error bars on the averages are indicated, except when there were less than 3 data in the box in which case the seasonal average is indicated by a star.

1897 to 1900 and 1903. He showed that the seasonal cycle in this part of the Atlantic has a peak-to-peak amplitude of 0.10 (maximum in April-May and minimum in August-September). He also showed that during 1903 surface salinities were usually fresher by 0.03 than during the earlier years, although Knudsen remained uncertain as to whether this was a real observation or an artefact resulting from systematic errors caused by changes in "normal water". Deviations in salinity from climatology changed markedly across the normal position of the Iceland-Faroe front. Fresh and cold anomalies to the north of the front were large in 1896 and early 1897, as well as in 1898. They were weakly positive in 1899. In 1896 and 1898, the fresh anomalies also extended to the north of Iceland. This is not surprising, because during these years (1896 in particular) ice was abundant to the north of Iceland (large "Koch" index), which recent data imply is associated with low salinities. Dickson also reported that during 1896 temperatures were very low at Grimsey, a small island to the north of Iceland.

Sampling was not as dense in most of the Atlantic compared to the region close to Iceland. A much larger data set would be necessary to undertake proper mapping of the deviations in the seasonal cycle, so we have just grouped the data into domains of a few hundred kilometres extension where spatial gradients of water masses are not too large. Based on a restricted analysis of post-1950 hydrographic data, we expect that the variability is often coherent on this scale, so that by averaging enough data, the noise related to eddies can be reduced. In each domain, we have constructed a short time series of seasonally averaged deviations from the climatological seasonal cycle (Figure 3). Two seasons are retained: a winter season (full dots) from December through April and a summer season (open dots) from June through October. Waters of the East Icelandic current are omitted on this map, and the sector to the north-east of the Grand Bank was not even sampled during winter. Individual box averages are often only marginally different from zero at the 90% confidence limit. The uncertainties are larger in slope areas where spatial gradients of the anomalies are steep, and smaller in the less "noisy" north-eastern Atlantic. Salinity anomalies are larger in the western Atlantic and on and around the Grand Bank, although the domain south of the Bank is not homogeneous hydrographically. Deviations are smallest east of 30°W near 60°N in areas which have deep winter mixed layers and no boundary current. There, the error estimates are also small (the rms variability of individual anomalies within each box varies in this area between 0.06 and 0.07 psu for the winter season, and is a little larger (0.07 to 0.09 psu) during the summer season). Except for the early 1898 French samples, the continuity of box-averaged salinity anomalies from one season to the next is remarkable considering the uncertainties (Figure 3). It is very tempting to deduce a schematic pluri-annual pattern of variability from the data, which near 60°N is very different from that seen further to the south and in the western Atlantic south of

45°N. The salinity anomaly in the northern North Sea (a domain which does not include the fresher surface waters of the Skagerrak or close to England) has a sign opposite to that of the Faroe-Shetland Channel. This suggests there are meridional displacements of the salty North Atlantic water. Temperature, however, does not show comparable differences between the two areas and its fluctuations are more likely to be related to the atmospheric forcing.

In the earlier months of the sampling (December 1895 to April 1896), anomalies are mostly positive in the North Sea and near 60°N. They were negative to the west of the Britain, as well as on and around the Grand Bank. During the following warm season, fresh anomalies were smaller except in the slope water. Large positive anomalies were found in the east and even to 40°W, south of 45°N. During the 1897 cold season, anomalies were mostly positive except near Iceland, in the Faroe-Shetland Channel and in the European Polar Seas. During the next warm season, salinity anomalies were even more positive than during the preceding cold season, except near 60°N where they were weak. They became positive in the Faroe-Shetland Channel. During the 1898 cold season, positive deviations were found north of 50°N and on the Grand Bank, but there was a domain across the Atlantic from 43°N to 50°N where anomalies were negative during this winter and flip sign during the next season. These data originated from two French vessels in March and April 1898 (*Bourgogne* and *Gascogne*). The large spatial extent and amplitude of the anomaly along each ship track is suspicious, but if the data are indeed correct, then this extreme freshening was probably restricted to a very shallow layer.

It is particularly interesting to find how these eraly data can be merged with more recent measurements of surface salinity, either from other surface sampling or from the near-surface samples of hydrographic stations. The most telling example is for the Faroe-Shetland Channel, where the continuity in the sampling has only interrupted in the war years of 1916-1918 and 1940-1944. In Figure 4, three areas in the Channel (W, E and C) have been distinguished. For each area, the composite anomalies are spline-fitted and then smoothed by a binomial filter removing fluctuations at a period of 2 years. The curve "all" is the average of the three areas, which shows a continuous decrease between 1900 and 1910. The year 1910 corresponded to a period of low salinity in the north-east Atlantic which was also observed during various hydrographic cruises in the north-east Atlantic. This event has been compared to the Great Salinity Anomaly, a more recent low salinity episode which passed through the Faroe-Shetland Channel in 1976.

These pre-ICES data are, therefore, valuable in showing that before the turn of the century salinity was higher in the area, and also in constraining the duration of the event. They do not, however, constitute a time series with sufficient continuity to define the patterns of variability; this had to await the monitoring programme initiated later by ICES. The amplitude of year-to-year fluctuations is comparable, or less than, the amplitude of both the seasonal cycle and of the very low-frequency changes. Hence, it is not surprising that the depiction of the month-to-month changes by Dickson and other early attempts to describe an average seasonal cycle were inconclusive.

Acknowledgments

Much pleasant time was spent in oceanographic libraries, in particular at Lamont Doherty Earth Observatory, the Marine Biological Library in Woods Hole and the Bibliothèque de l'Institut Océanographique in Paris. There, as well as at the Institute of Oceanographic Sciences (Wormley, U.K.) and at the University of Washington (Seattle, Washington State), considerable help and encouragement was provided by librarians and archivists who were instrumental in locating elusive data reports. During a stay at Gothenburg, I received the very kind support of Stig Fonselius and the archivist of the Museum of Natural History. Yves Gouriou at W.H.O.I. also helped significantly in locating documents. The project was supported by NODC under a NOAA grant, and benefited from the encouragements provided by Syd Levitus at NODC (Washington, USA) and Harry Dooley at ICES (Copenhagen, Denmark). Of course, we are indebted to the scientists who initiated the collection of sea water more than a hundred years ago and carried out the time consuming titrations, and to the numerous seamen who were willing to bottle sea water. This is L-DEO contribution number 5378.

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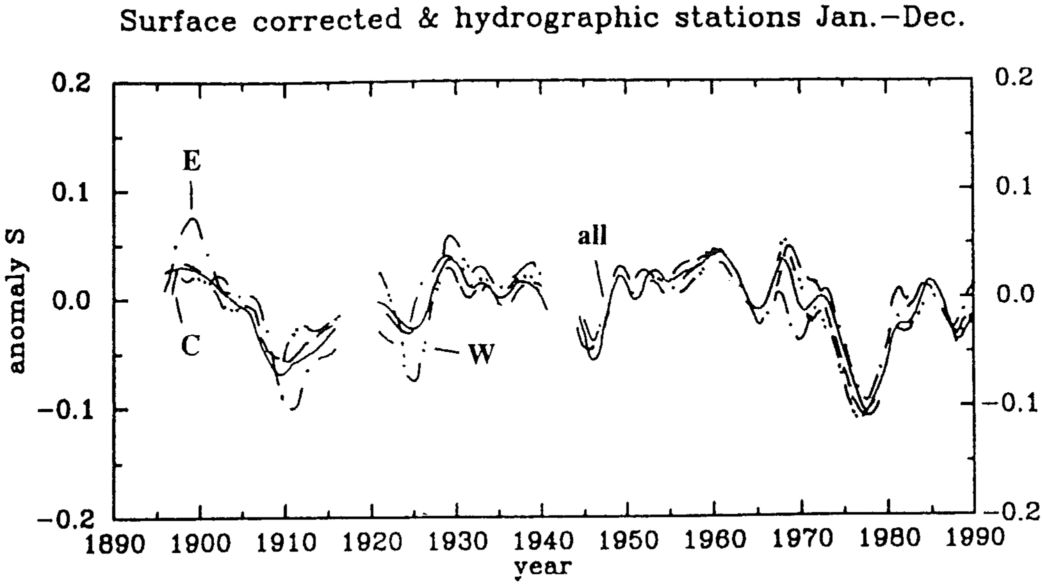

Figure 4. Time series of salinity deviation from climatology in the Faroe-Shetland Channel for different domains across the Channel (E, C, W from the south-east to the north-west). The full line corresponds to the average of the three time series.

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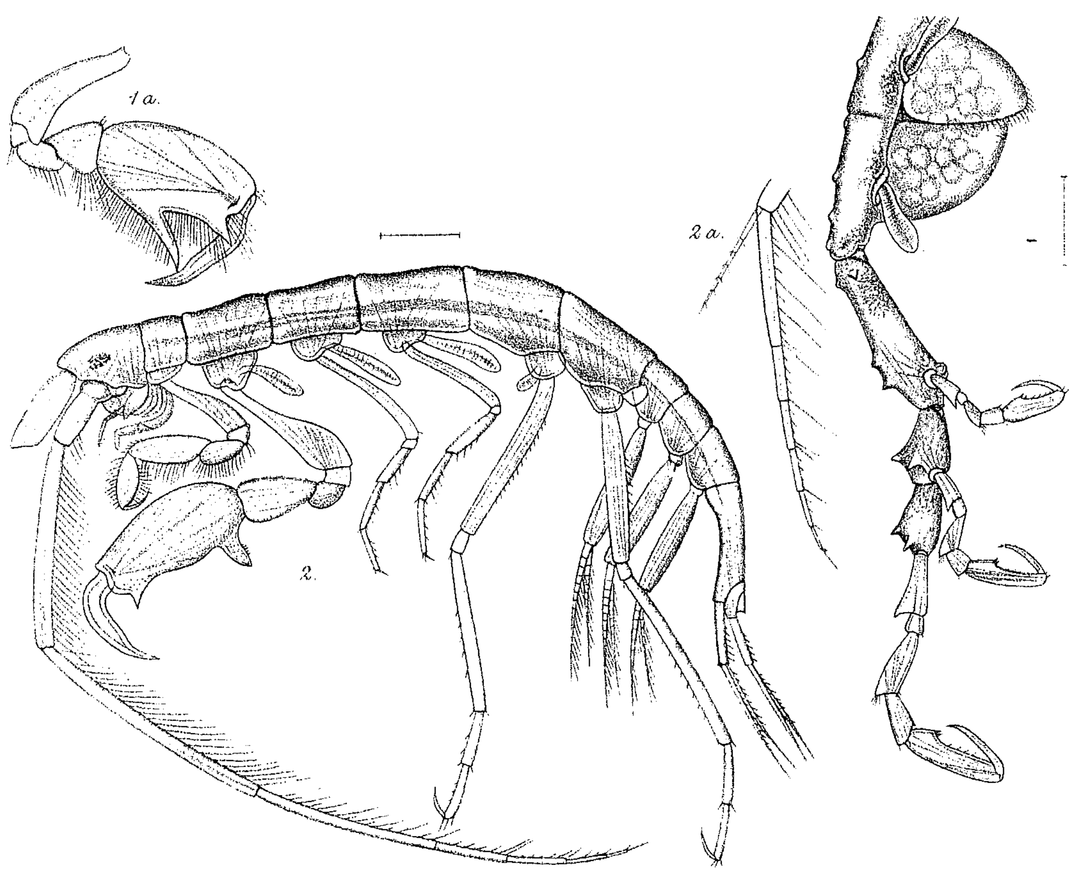


LONG TIME SERIES IN ICELANDIC WATERS

in relation to physical variability in the northern North Atlantic

C. Svend-Aage Malmberg, Hedinn Valdimarsson and John Mortensen

The data used in this article were mainly collected during joint multidisciplinary Danish-Icelandic cruises into the western region of the Iceland Sea in September 1987-1991 (Figure 1). These investigations were a contribution to the International Greenland Sea Project. We are also including some data collected along a number of sections during long-term investigations in Icelandic waters (Figure 2), and other data from adjacent oceanic regions. We will concentrate on clarifying the variability of the hydrographic conditions in time and space.

At depths of 1000-1500m, Bottom Water which originates from the Arctic Basin, flows into the Denmark Strait from the north. Its potential temperature is -0.8°C and its salinity is > 34.92. Also flowing from the north, but at shallower depths of 200-600m is intermediate water which shows interannual variability in the strength of its salinity maximum. In 1987, 1988 and 1991 the core salinities of the intermediate water were higher than in 1989 and 1990, and water with salinities > 34.92 extended over much greater areas (figure 1). Between 1987-92, by far the largest input of Polar Water with temperature < 0°C and salinities < 34.7 occurred during 1988 (Figure 3). This was a year of severe ice conditions in North Icelandic waters, and the East Icelandic Current was transporting unusually cold and low salinity water (Figure 4).

In North Icelandic waters, three hydrographic conditions can be identified. Firstly "polar" conditions occur when cold and relatively fresh surface waters spread in, and the low salinities strengthen the stability of the stratification. "Atlantic" conditions are characterised by there being strong maxima in both temperature and salinity near-surface and at intermediate depths. At times, these maxima may occur underlying the polar waters. While Atlantic conditions prevail the relative warmth of the surface waters helps to strengthen the stability of the stratification. During "Arctic" conditions the Atlantic influence is weakened so that the maxima at intermediate depths are less pronounced. These fluctuations in the intermediate hydrographic conditions can be seen in the 1978-1994 time series of salinities (Figure 5). Normally during spring there is an intermediate salinity maximum to the north of Iceland. But when Arctic conditions spread in, around 1981-83 and 1989-90, intermediate salinities were low, so the vertical stratification was relatively weak.

As said before, salinities in the intermediate waters of the Western Icelandic Sea were also lower in 1989 and 1990, than during the other years (Figure 1). Figure 3 illustrates that the vertical distributions of both salinity and density were also quite distinctive during these two years. Salinities and densities typical of these intermediate waters were lying closer to the surface (50m versus 100m), thus restricting the late summer stratification to a thin near-surface layer in 1989 and 1990. The lower salinity in these intermediate waters is likely to have enhanced vertical mixing with the overlying waters, thus tending to homogenise the water column. The variable hydrographic conditions observed in the Iceland Sea are reflected in the biological populations such as the size of the stock of Icelandic capelin which feeds in the Iceland Sea, and the weight of cod (Figure 5) which exploits the capelin as its main food source (Hansen and Jakupsstovu give another example of the close links between fish stocks and the hydrographic regime).

Discussion

The Arctic conditions which prevailed in North Icelandic waters in 1981-83 have been related to the passage of the "Great Salinity Anomaly". The anomaly was first detected during the ice years north of Iceland in 1965-71. It was detected again, this time to the south of Iceland in 1974-78, and again to the north in 1981-83. Its pan-Atlantic impact on living marine resources has been outlined by Jakobsson (1992). A smaller salinity anomaly was derived from polar water conditions north of Iceland in 1975-79 (Figures 4 and 6), and may have returned to South Icelandic waters in 1985-88, and been associated with the Arctic conditions we observed to the north of Iceland in 1989-90. Hydrographic data from both the Rockall Channel and from along the west coast of Norway also revealed salinity minima in 1985-88 and 1988-90 respectively, and so lend some support to this hypothesis. In 1981-83 there were extremely cold conditions in the West Greenland and Labrador regions. Although it has been suggested that these conditions resulted purely from regional factors, it remains possible that they were also linked to the extreme conditions to the north of Iceland in 1975-79, and even in 1981-83. It is interesting to follow the fate of the 1988 polar conditions in North Icelandic waters which again may be reflected in extreme cold years in the West Greenland and Labrador areas in 1989-92. If so, then a response may be expected to occur in South Icelandic waters in the late nineties, and again in North Icelandic waters around the end of the Millenium.

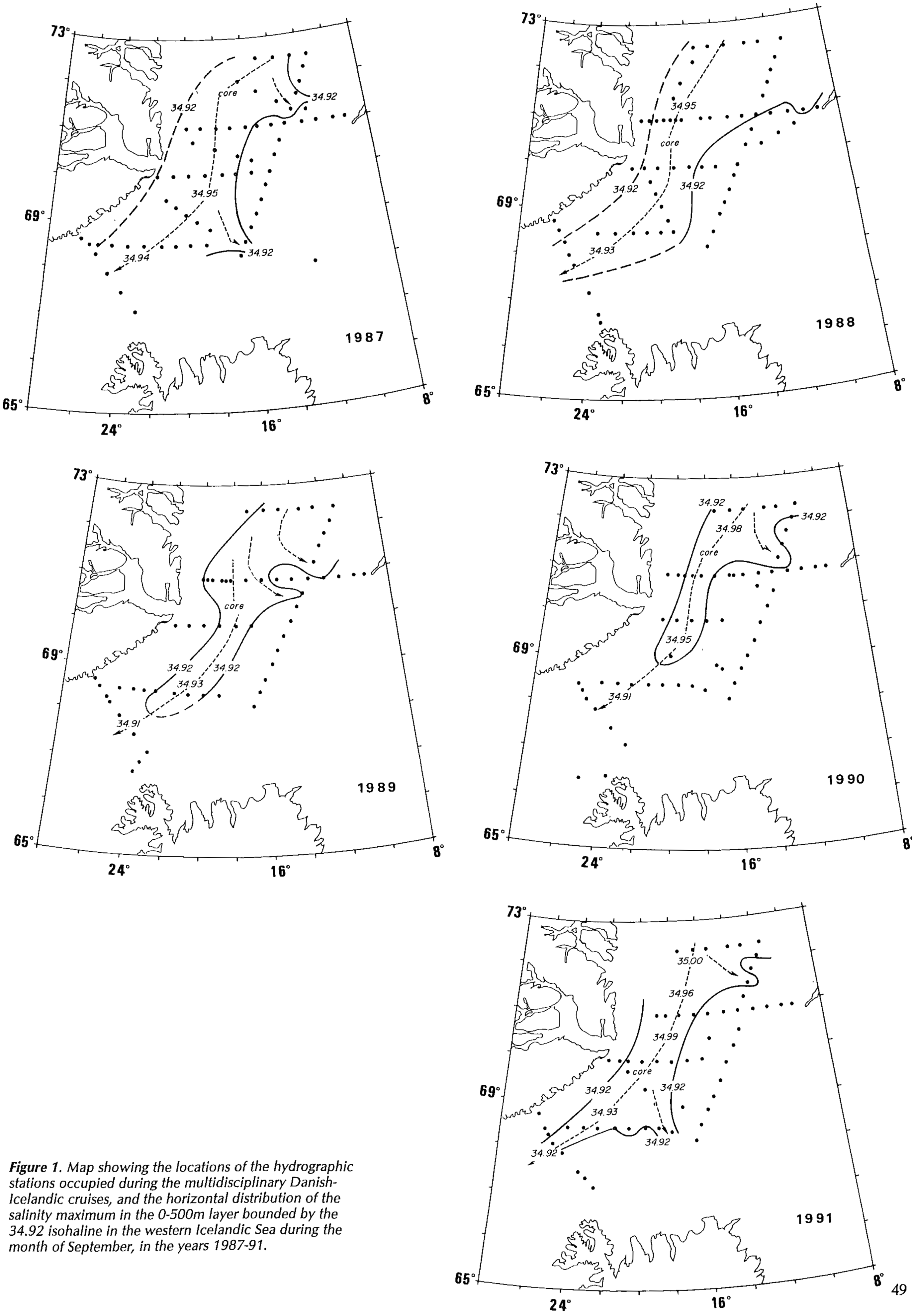


Figure 1. *Map showing the locations of the hydrographic stations occupied during the multidisciplinary Danish-Icelandic cruises, and the horizontal distribution of the salinity maximum in the 0-500m layer bounded by the 34.92 isohaline in the western Icelandic Sea during the month of September, in the years 1987-91.*

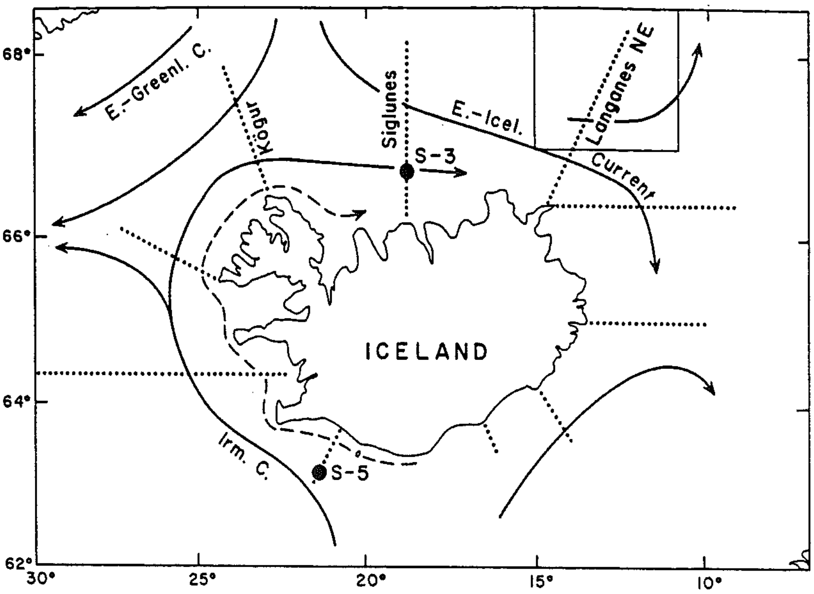


Figure 2. Map showing the patterns of the main ocean currents around Iceland and the location of the sections along which the hydrographic and biological conditions are routinely sampled. The areas and stations from which data has been used in this paper are indicated.

The question remains whether these anomalies are just local variations or whether they are part of much larger-scale processes linked to variability in the circulation throughout the whole of the North Atlantic Subpolar Gyre. Speculations include that there is an interaction between ocean and atmosphere and variable regional conditions lead to a strengthening or weakening of the processes operating along the long track of the circulation across the North Atlantic. It is most exciting to anticipate what might be found during future oceanographic programmes which will help to answer the intriguing and important questions posed by these variations. We need to stress the importance of international collaboration in oceanographic research if we are ever to understand the compex impacts of these marine environmental conditions on the biology and climate of the regions.

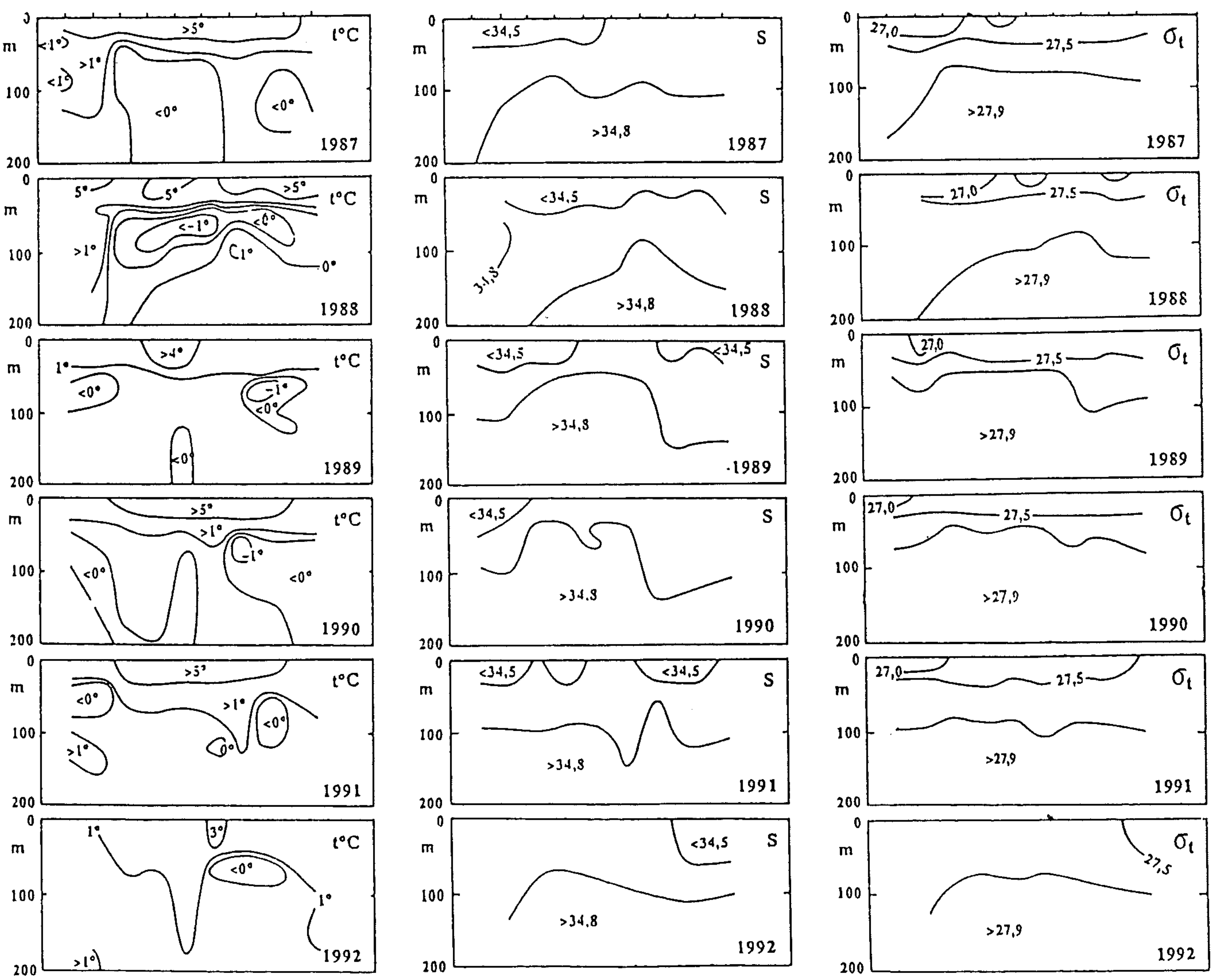


Figure 3. Variations in the vertical distributions of temperature, salinity and density observed along the northwards bent section (indicated in figure 1) across the Icelandic Sea, in September 1987-91 and October 1992.

Figure 4. (right) Anomaly of temperature and salinity in springtime from 1975-1994 at a depth of 25m in the East Icelandic Current. A salinity of 34.7 is the critical point for whether or not there is ice formation. The average for the years 1950-58 is shown as well as a brief classification of ice years in Icelandic waters. A - ice free; B1 insignificant ice (NW ice); B2 - moderate ice (N and NW ice); B3 - heavy ice (NW, N, and E ice) (from Sigurdsson and Jakobsson 1991; Malmberg and Kristmannsson, 1992).

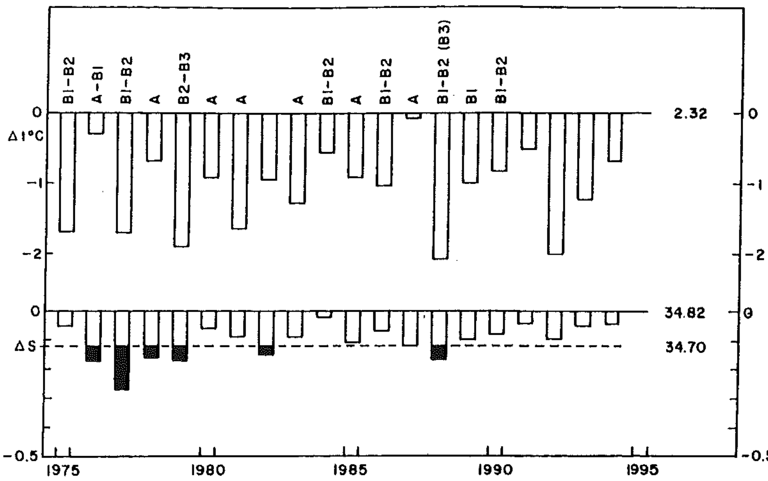


Figure 5. (below)
a. Maximum salinity in the near-surface or intermediate depths observed in North Icelandic waters (S-3) in spring 1978-94 (solid thin line).
b. The abundance of the Icelandic capelin stock in 1978-94 (H. Vilhjalmsson pers. comm.)(solid thick line).
c. Weight of five-year old cod in Icelandic waters in 1977-94 (Anon. 1992)(broken line).

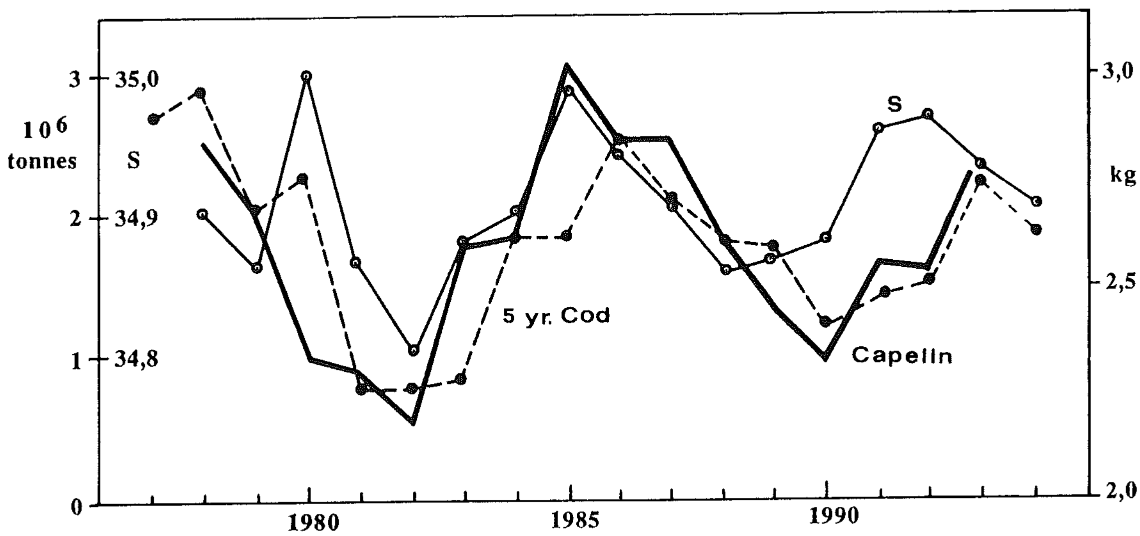
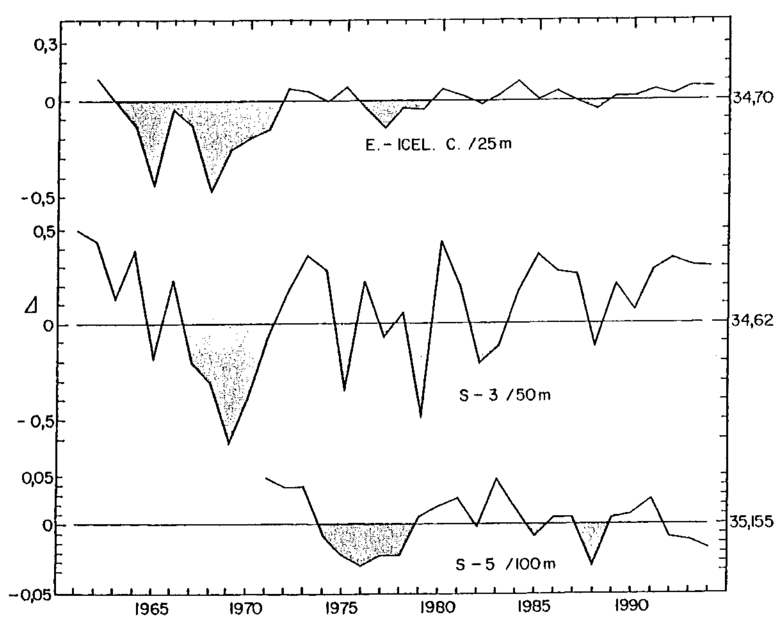


Figure 6. Salinity deviations in spring at 25m depth in the East Icelandic Current, 1962-94; at 50m in North Icelandic waters (S-3), 1961-94; and at 100m in the Irminger Current south of Iceland (S-5), 1971-94.



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The 1989/91 HIGH SALINITY ANOMALY *in the North Sea and adjacent areas*

Gerd Becker and Harry Dooley

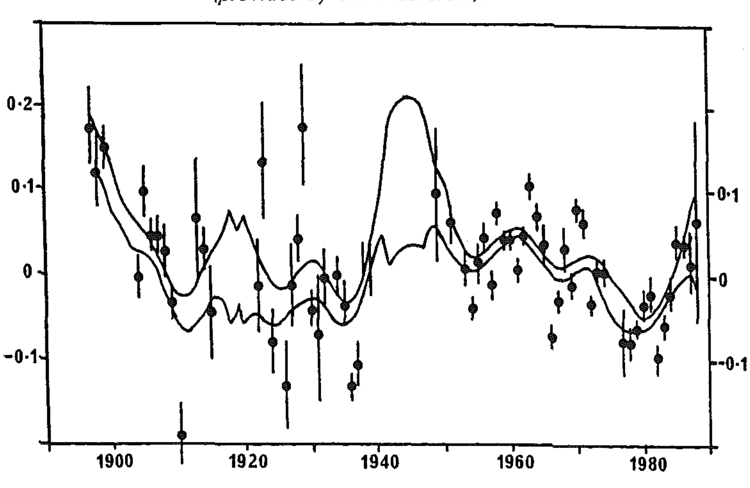
Introduction

In the late 1980s and early 1990s salinity levels in the English Channel, the southern North Sea and western German Bight were extremely high with some reported values exceeding 35.5. The salinity increase affected a large area of the North Sea and the adjacent Atlantic, but relative to the historical data base which contains data from the early 1900s, the 1990 levels were not that exceptional. The magnitude of that anomaly approached that of the Great Salinity Anomaly event which was observed in the northern and central North Sea during the years 1977-79. However, the High Salinity event was connected with a large positive temperature anomaly in the North Sea; 1989 and 1990 seem to have been the mildest North Sea winter climate years of the last 50 years.

Observations

Oceanographers became aware of high salinities in the Irish Sea, the English Channel and the North Sea by observations of British oceanographers in 1991. Examining the salinity data and comparing them with the historical data, the treatment of the data was carried out with some caution and suspicion. However, subsequent observations by different laboratories from several countries confirmed that the salinities were indeed high. The earliest high salinity data from the English Channel were reported by RV *Cirolana* (35.43) and RV *Gauss* (35.46) in November/December 1990. Exceptionally high salinities were reported in the Atlantic inflow region above the western flank of the Norwegian Trench in January 1990. Bottle salinity data (RV *Gauss*) from February 1991 showed salinities >35.5 in the Dover Strait. From an examination of data from the Rockall Channel and the Faroe-Shetland Channel it was concluded that the salinity over deep water west of Scotland and the shelf-edge west of Shetland was higher in late 1989 and 1990 than at any time since the high salinity period of the late 1960s. The temperature anomaly signal was of the order of 0.1 to 0.2 in the eastern North Atlantic (Figure 1 provided by G. Reverdin). Clearly there has been recovery from the salinity minimum of the Great Salinity Anomaly. The larger standard deviation of the salinity observations at the end of the 1980s point to an enhancement in the smaller scale variability of surface salinities, and not to increases in the problems of estimating the salinities. The signal increased on its way through the English Channel and into the Southern Bight and the western border of the German Bight to about 1. Figure 2 shows the salinity distribution in the English Channel in 1989 to 1991 (all data are contained in the ICES data bank). In 1991 the anomaly is marked in the central part of the Channel. In Figure 3 the time series of salinity along the Fair Isle-Munken section is shown. The minimum salinity values during the Great Salinity Anomaly (GSA) and the peak values in 1989/90 are well observed. Figure 4 shows the results of some analyses of the ICES International Young Fish survey salinity data carried out for 1979 during the GSA event (Figure 4a) and in 1991 during the High Salinity Anomaly. During this period analyses of sea surface temperatures (SST) for the North Sea also revealed marked changes between 1979 and 1990, in not only the annual mean SST but also the standard deviations. Seasonal temperature deviations in the English Channel for the years 1988 to 1990 show remarkable positive anomalies, which were about 2.2°C in the period March-November 1989 and 2.85°C in the period November-March 1989/90. The year 1989 was the second warmest year in the UK Meteorological Office's temperature record for Central England since records began in 1659, being 1.1°C above normal. While 1989 and 1990 seem to be the mildest North Sea winter climate years of the last 50 years or may be 130 years, the coldest were 1977 to 1979 and perhaps 1942.

Figure 1. Seasonal average salinity anomalies from an average seasonal cycle in the area 46° to 50°N and 8° to 11°W based on surface and hydrographic casts. Dots represent the median of the anomalies for a year period and the bars indicate the median's error (based on rms value). The curves enclose the rms likely range of the binomial filter of a spline-fit to the annually binned data (provided by Gilles Reverdin).



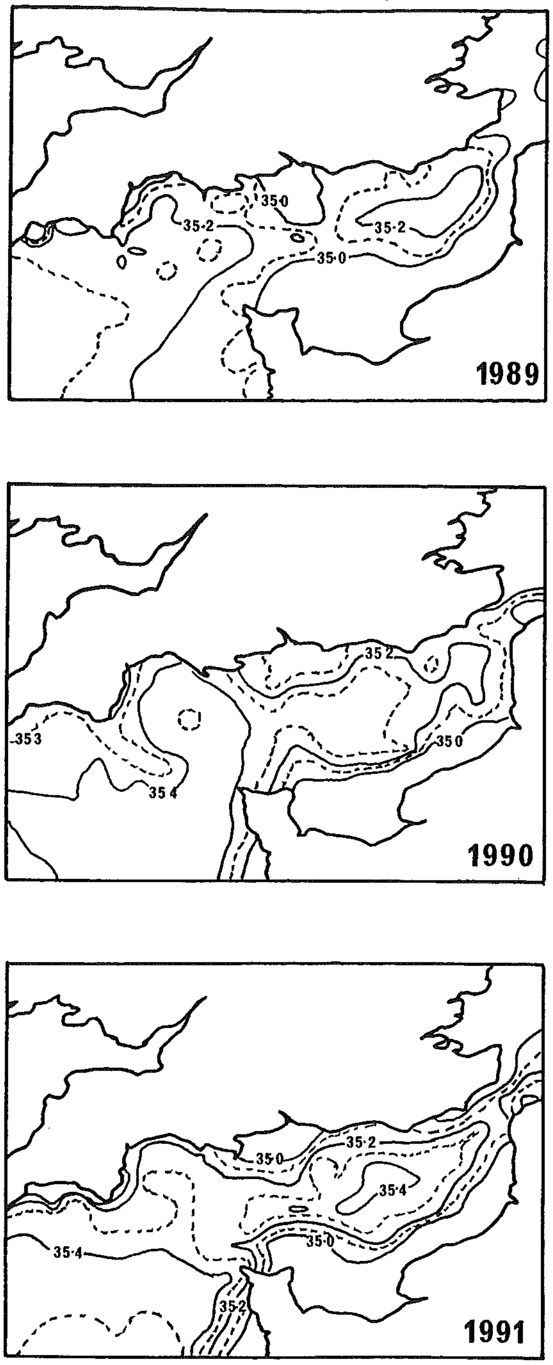


Figure 2. The distribution of salinities in the English Channel in 1989, 1990 and 1991.

Atlantic water is the main source of nutrients to the North Sea, the variable Atlantic inflow combined with a variable wind climate and variable heat content are the main factors which determine the biological productivity in large parts of the North Sea. These climatic variables have been demonstrated to influence directly or indirectly the recruitment of several commercial fish species in the North Sea. The occurrence of marine species of more southerly origin (e.g horse mackerel) has been reported from the English Channel and the North Sea at the end of the 1980s. Unusual plankton species were also observed in the German Bight and in Continuous Plankton recorder samples from the northern North Sea. All these observations suggest a link between the ecology of the North Sea and climatic variability in the North Atlantic. They also demonstrate the importance of developing more structured sampling programmes in the future, especially regular sampling in the North Atlantic Current system.

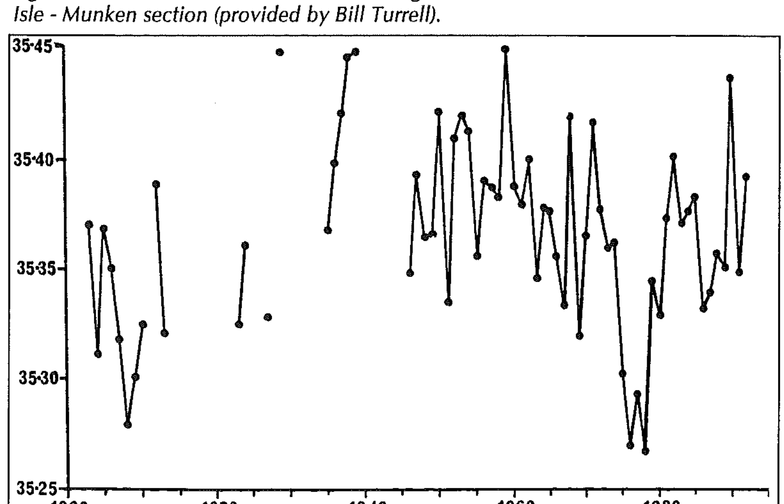
Discussion

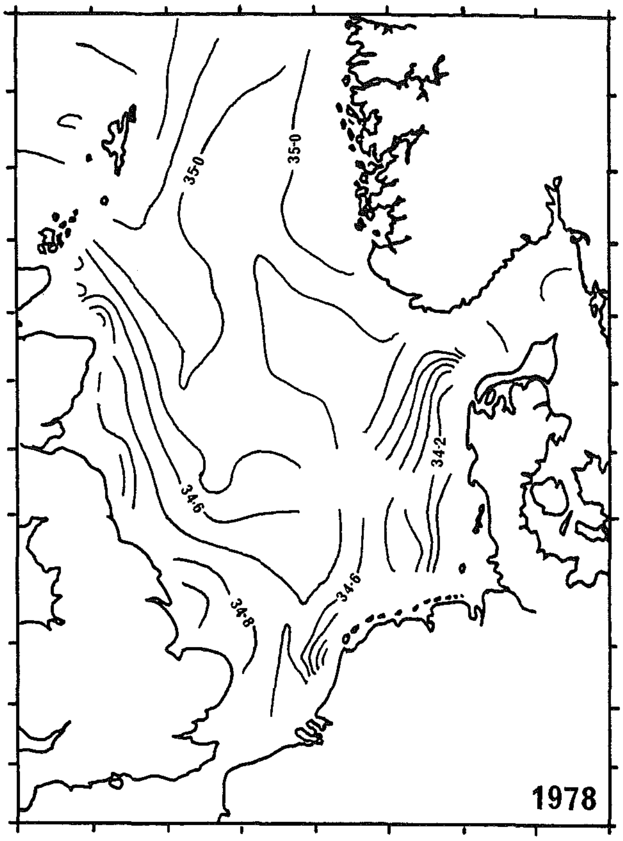
No clear and obvious explanation for the anomaly can be suggested at present. The reason is the lack of data from the North Atlantic current system. Ocean circulation models at this stage of their development are not able to simulate or to hindcast these scales in time and space. However, some questions which arise from the anomaly need to be addressed:-

- Where was the origin of the high salinity water?
- What caused this water to appear off the North Sea entrances and in the North Sea?
- What was the reason for the amplification of the salinity signal on its way through the English Channel?

The origin of the high salinity water must have been from outside the North Sea; the anomaly signal arrived in the North Sea from the Atlantic via the English Channel and the northern entrances. Unfortunately no large scale subsurface salinity data are available for the second half of the 1980s. However, the correlation between the surface temperature and surface salinity is rather close in the North Atlantic. Therefore, examination of the monthly SST distribution and anomaly maps from the North Atlantic (NOAA) might be of some help in characterising the more genera North Atlantic current system and its variability.

Figure 3. Time series of mean salinities along the Fair Isle - Munken section (provided by Bill Turrell).





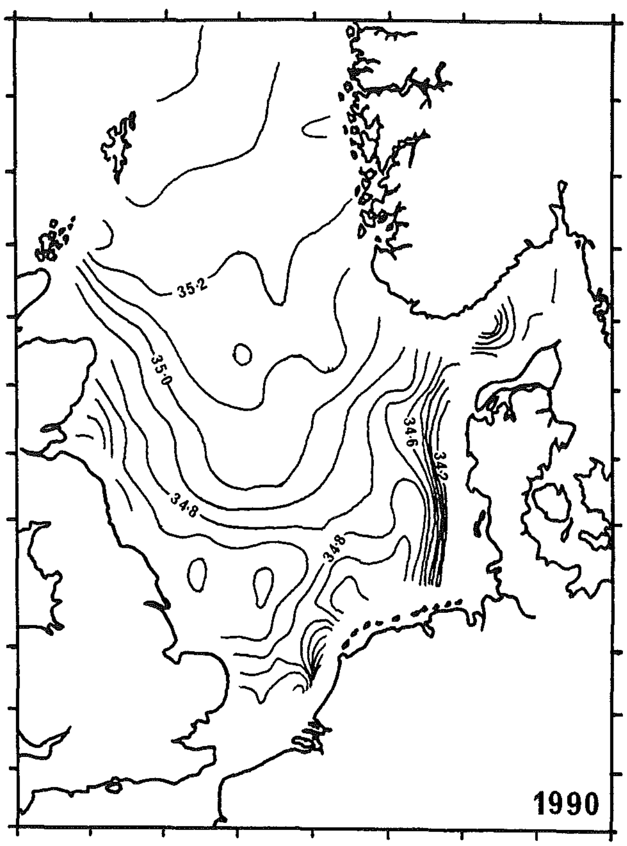


Figure 4a. *IYFS Bottom salinity distribution in 1978, the year of the Great Salinity Anomaly.*

Figure 4b. *IYFS Bottom salinity distribution in 1990, the year of the High salinity Anomaly.*

North Atlantic SST anomalies 1988 to 1992

Figure 5 shows as a typical example for the period of interest, the monthly SST anomalies for 1990. In general, weak SST anomalies are more or less always present in the North Atlantic. Negative anomalies normally occur within the subarctic domain, whereas positive anomalies are associated with Gulf Stream with respect to the North Atlantic current system. Looking at the time series of anomalies, in 1988 there was a propagation of positive anomalies from west to east starting in March off the east coast of America. In the last quarter of the year, the stronger positive anomalies vanished, but weaker anomalies covered the eastern North Atlantic. In 1989, there was a remarkable contrast between subpolar and the subtropical regimes. The SST anomaly difference between the subarctic and subtropical regions exceeded 3° to 4°C (February to July). A positive anomaly (which started in December 1988) moved across the Atlantic. From June to August stronger positive anomalies occurred off the African coast, the Iberian Peninsular and off the English Channel. In December 1989, a strong negative anomaly developed off the east coast of America.

The year 1990 (Figure 5) was characterised by the occurrence of strong negative anomalies in the western part of the North Atlantic. The temperature gradients were strong (4°C). In 1991 the negative anomalies (and strong temperature gradients) persisted throughout the whole year. A tongue of warm water moved from the American coast to the European continent. In the last quarter of the year, SST throughout almost the whole of the North Atlantic was lower than the long term mean (the exception being the warmer belt of the North Atlantic Current system). In the second half of 1992, SST in the northern part of the North Atlantic was lower. North-west Europe became more under the influence of the subarctic regime. In general during the period 1988-92, the North Atlantic SST anomalies showed pronounced differences between the subarctic and subtropical regimes, and the south-north temperature gradient increased significantly particularly in 1989-91. The zonal circulation was reinforced by the anomaly pattern, and this can be checked by examining the North Atlantic Oscillation Index (NAO).

North Atlantic Oscillation Index (NAO)

The North Atlantic Oscillation Index is defined as the difference between the normalized pressure anomalies in winter at Ponta Delgada (Azores) and Akureyri (Iceland). The 30-year mean period is 1961-90. A high index (> 1) is associated with strong westerlies, and a low index (< -1) with weak westerlies. A normal index covers the midrange -1 to +1 and stands for a zonal circulation of average strength. Figure 6 shows the NAO winter index from 1879 to 1992. Superimposed on the NAO index is the

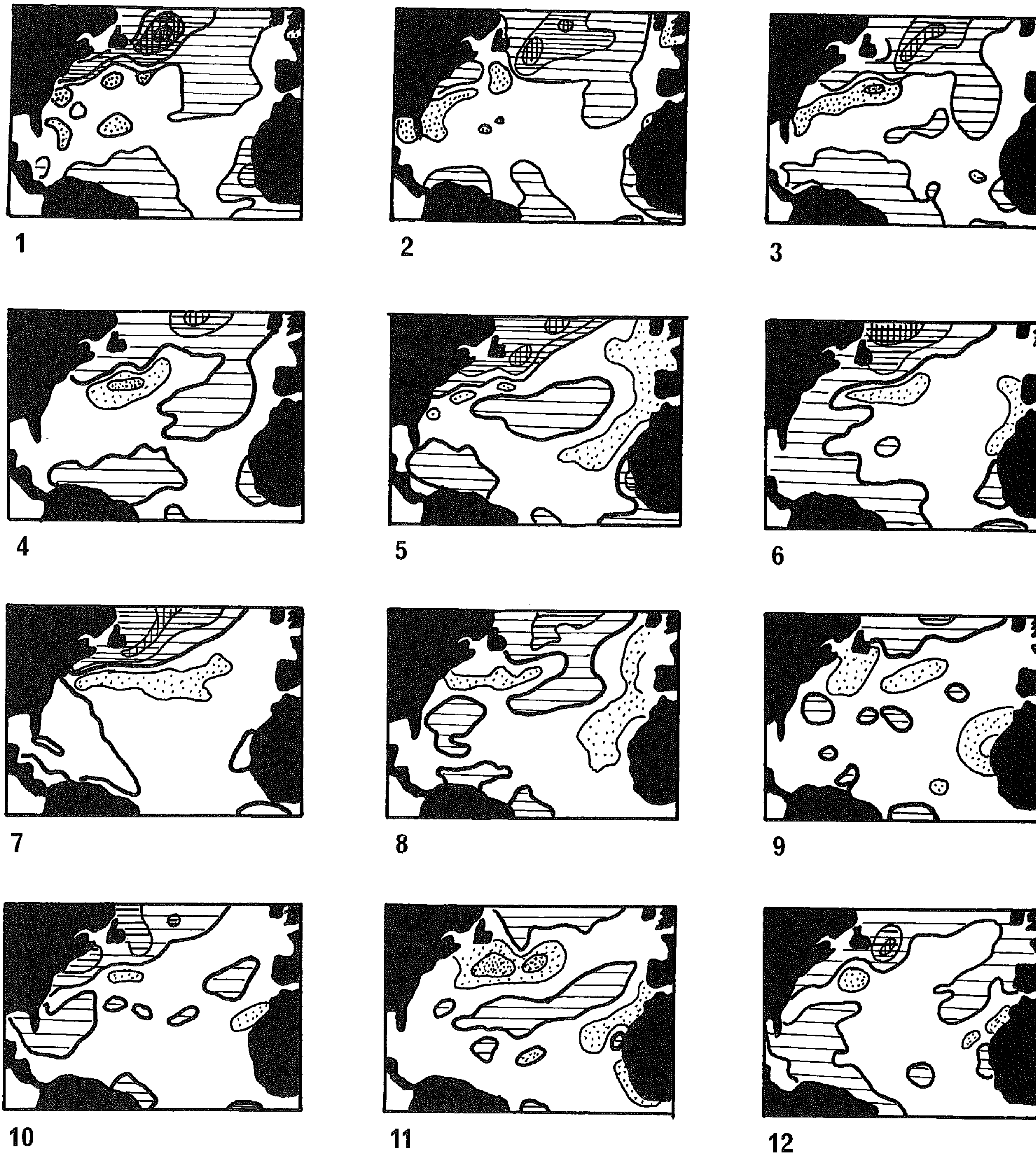


Figure 5. Monthly North Atlantic SST anomalies (from the Equator to 55°N and 0° to 90°W) for the year 1990 taken from global monthly SST anomaly maps produced by NOAA. Key:-Dotted areas > 1: 1 > blank > 0; 0 > wide line > -1; -1 > close lines > -2; -2 > cross hatch > 3

time series of salinities in the English Channel from the beginning of this century until 1992. The period 1920-26 is characterised by a *very strong* zonal circulation (NAO index 2-3) and very high salinities in the English Channel. In the North Atlantic the period (1972-76) of the Great Salinity Anomaly (GSA) is marked by *strong* zonal circulation (NAO index ca.2). The GSA arrived off northwest Europe during 1976, and appeared in the North Sea in 1977-79. At the time there was stronger meridional circulation (NAO index < -1). In 1989, the NAO index reached its maximum (> 3) for the whole period from 1879 to 1992. However, 1989 is comparable to the 1920-26 event. In general there seems to be a good correlation between the NAO index and the salinity variations in the English Channel, but with a phase shift of about 2 years. Changes in the index can also be related to variations in the winds in the North Sea. The time series investigated show a distinct increase of wind power (W m^{-2}) anomalies starting around 1986-87 which

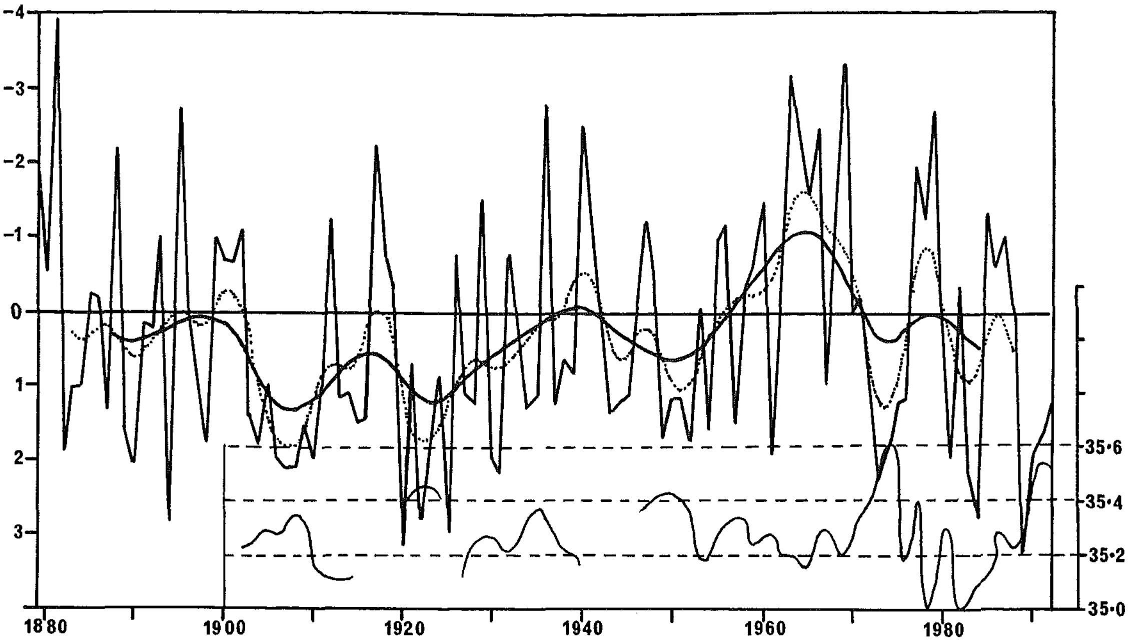


Figure 6. NAO winter index from 1879 to 1992 (upper panel); shown are the yearly NAO winter indices. Dashed and heavy solid lines represent the smoothed time series obtained by applying a Gassing low pass filter of 10 and a cut off period. The lower panel shows the Southern Bight (52° to 54°N, 2° to 4°E) salinity time series. The line is an envelope of the highest observed salinities (with no averaging or smoothing).

rose to a maximum in 1989. There is evidence of higher transports leaving the North Sea across the Utsira section at the end of the 1980s, indicating that there was increase transport into the North Sea via the English Channel and the inflow to the east of the Shetlands.

Upwelling/transports

Indications of substantial multidecadal increases in upwelling-favourable wind stress were observed off Morocco and the Iberian Peninsular and it was also suggested that there had been intensification of upwelling off Iberia. The typical upwelling season off Iberia is April to September. There were reports of active upwelling off Portugal in June 1987. It is assumed that off the Bay of Biscay and the west coast of Ireland deep convection from November to March interacts with the core of high salinity water at the slope, and can result in increases in surface salinities. Deep convection in this region can eventually penetrate to depths of 800m and so result in high salinity Mediterranean Outflow Water being upwelled to the surface; the scale of some of the convection and upwelling cells is of the order of a few kilometres.

There appears to be a shallow northward flowing current which passes between the Gorringe Seamount and the Portuguese coast. The observation of abnormally high surface temperatures (+1.5°C) and salinities (0.4) during AZOR-87, indicates that there was a northward intrusion of southern surface waters, i.e Eastern North Atlantic Water (ENAW). In the frontal zone eastward velocities of ca.6cm s^{-1} were reported. Assuming an average northward velocity of 3cm s^{-1} for the current over the slope, the transit time for this abnormally high salinity water from 32° to 50°N off the English Channel would be about 20 months. There are also reports that around this time there were increases in the outflow from the Mediterranean, and hence there would have been increased transport of Outflow Water to the north. In 1987-88 there were increases in the inflow of Atlantic Water into the Mediterranean, and in 1988 there was an increase in surface salinities at 12°W, off Iberia. Again in 1989 a narrow band of high salinity water (> 36.2) was observed off Iberia, and current meter records showed that over the slope there was a narrow band in which high salinity water was being carried northwards. All these observations suggest that there was an intensification of the North Atlantic current system linked to the high zonal NAO index, and that the source of the high salinity water eventually seen in the North Sea was to the west of the Iberian Peninsular.

Run-off

The amplification of the anomaly as it passed through the English Channel must have been caused by evaporation exceeding precipitation and run-off. The annual range of run-off along the Channel is 9 to 37 km^3 (taken from the North Sea Quality Status Report for 1993). Assuming the volume of the Channel is 2,900m^3, the salinity of Atlantic Water entering the Channel is 35.4, the residence time for water in the Channel is 295 days, and the mean volume transport via the Channel into the North Sea is 3,600km^3, run-off along the Channel will reduce salinities by 0.11 to 0.42. In this simple mixing model, no phase shift has been applied, run-off and transport have been assumed to be constant throughput the year. In fact the period August 1988 to October 1989 was drier than usual, so that both river discharge and direct precipitation was only 75% of normal. Salinity data from the NERC North Sea programme suggest that the reason for the amplification of the salinity anomaly along the Channel and in the Southern Bight was this reduction in run-off and precipitation.

Conclusions

The North Atlantic circulation and deep water convection play an important role in modulating climatic conditions in Europe. The Great Salinity Anomaly which was a negative salinity anomaly will have reduced convection and SST along the course of its circuit of the subpolar gyre. The "High Salinity Anomaly" seems to have been linked with an increase in convection in the Labrador Sea and an increased volume of Labrador Sea Water (Sy, pers comm.) In 1989 the NAO index was the highest that had been reported since records had begun (1879-1992), pointing to an intensification of transport within the northern part of the subtropical gyre. Within the subtropical gyre, water that was both warmer and more saline arrived at the eastern side of the North Atlantic, probably along the Azores Front. This water was probably transported northwards within the slope current. There is evidence that upwelling activity was intensified off the Iberian Peninsular, which will also have resulted in the injection saltier water into the surface layers. Deeper convection and interaction between the cores of high salinity waters over the slope may have also played a role, but there were no observations made of these smaller scale effects.

The patchiness (in both time and space) of sampling programmes make it difficult to draw firm conclusions as to the nature and the intensity of this and other temporal salinity events during the present century. This highlights the need for more structured sampling programmes, particularly involving the regular observations of the North Atlantic Current system.

Acknowledgements

This contribution is based on discussions among members of the ICES Oceanic Hydrography Working Group. We would like to thank Gilles Reverdin, Bill Turrell and Peter Löwe for providing figures 1,3 and 6. We are indebted to E. Mittelstaedt, Jan Backhaus, David Ellett, Ken Medler, Bob Dickson and Rolf Käse for helpful information and discussions. Robert Gelfeld, Sigrid Podewski and H.H. Hinrichsen kindly provided hydrographic data from the North Atlantic.

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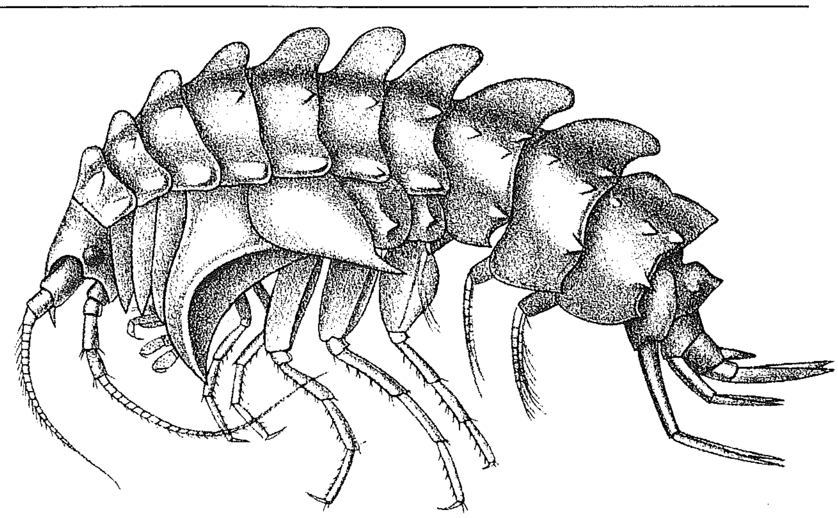
Harry Dooley: ICES, Palaegrade 2, 1261 Copenhagen K, Denmark.



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A CENTURY OF HYDROGRAPHIC OBSERVATIONS *in the Faroe–Shetland Channel*

Bill Turrell

Hydrographic surveys along two standard lines crossing the deep-water channel lying between the European continental shelf and the Faroese Plateau (the Faroe-Shetland Channel) were begun in 1893. The first surveys were conducted by Dr H N Dickson for the Fishery Board for Scotland, in support of international multi-disciplinary studies in the northern North Sea and north-east Atlantic, which subsequently resulted in the formation of the International Council for the Exploration of the Sea (ICES). Since the initial surveys, the two lines have been frequently resampled by Scottish, Norwegian, Swedish, Danish and Russian oceanographers. The accuracy of the early salinity data (pre-1960) is questionable because of the indeterminate chemical techniques used. In order to improve their accuracy, all available hydrographic data obtained across the two survey lines (Nolso-Flugga section and Fair Isle-Munken section) have been collated, and pre-1960 salinity data have been recalibrated against the highly conservative characteristics of Norwegian Sea Deep Water. This reconstructed time-series is one of the longest series of oceanographic observational records available, and is providing indices of environmental change within the Northeast Atlantic, Norwegian Sea and northern North Sea.

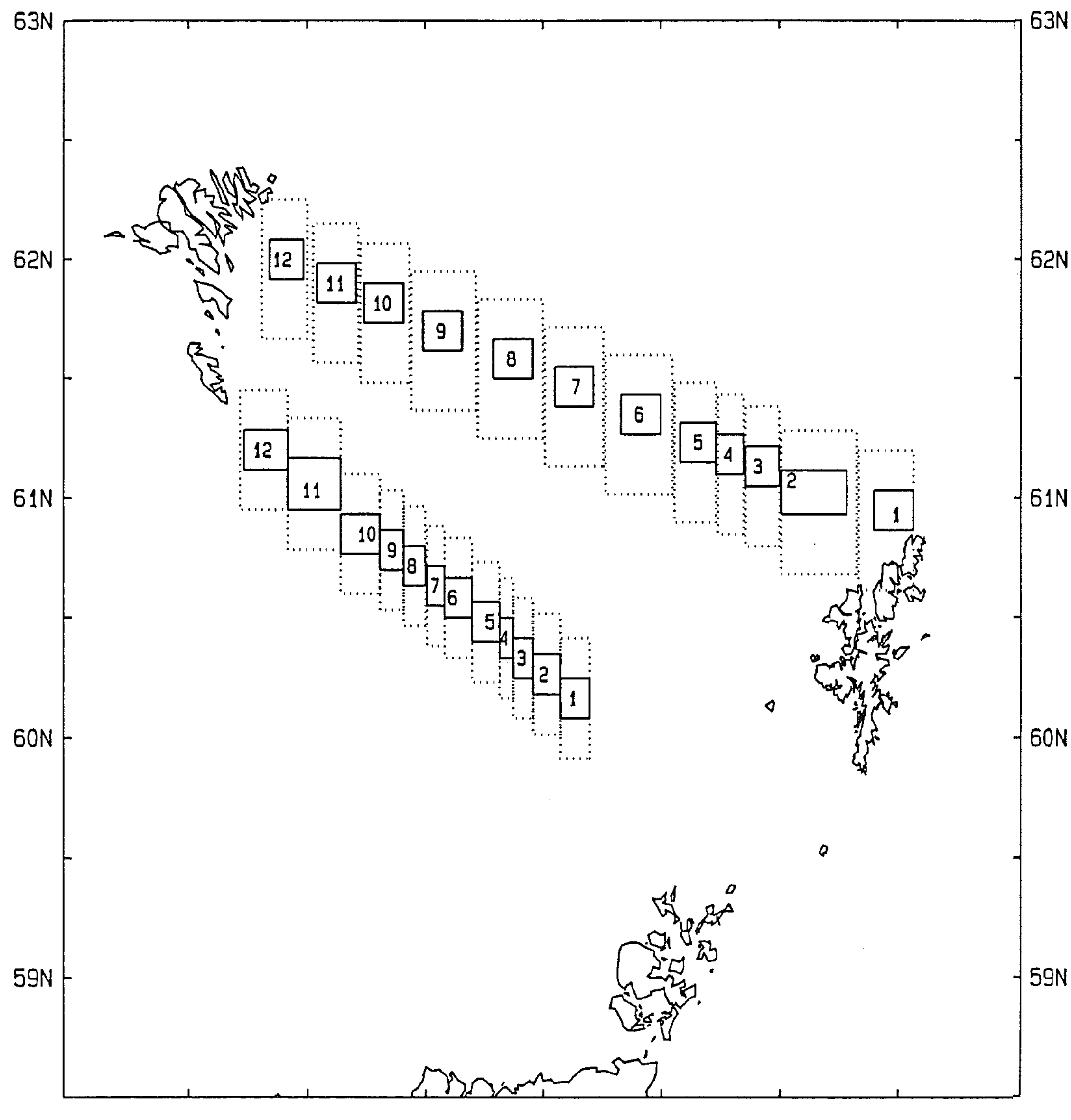


Figure 1 Map showing the locations of the two standard Faroe-Shetland Channel sections as currently worked (centred figures), as used to summarise post-1960 data (solid boxes) and as used to summarise pre-1960 data (broken boxes).

Introduction

At 1230 GMT on 4 August 1893 on board the fishery protection vessel HMS *Jackal*, Dr H N Dickson, who was contracted to the Fishery Board for Scotland, performed the first hydrographic station (Station 1) of what was to become the standard Nolso-Flugga Faroe-Shetland Channel section. He went on to perform water bottle casts (using the Scottish designed Mill's self-locking slip water bottle and reversing thermometers mounted on the Scottish pattern frame) at stations 2, 5, 7 and 9 of the present day Nolso-Flugga section and stations 11, 9 and 6 of the Fair Isle-Munken section (Figure 1).

Dickson surveyed the same sections again in 1896, occupying fewer stations but making deeper casts to depths greater than 1,000 m. Sampling the full set of station along the Nolso-Flugga line began in 1903, and since then has been continued more or annually with interruptions during the war years and a five year period in the early 1980s.

Data Archaeology

In 1990 a review of the historic time series was undertaken at the Marine Laboratory Aberdeen. All post-1960 hydrographic data had already been calibrated and archived in computer files. However, the earlier data were held in various forms on paper, and even those which were available from international data centres had been subject to inconsistent corrections and re-calibration. So the original raw data were recovered and used in preference to the previously archived information. These early data for the hydrographic parameters were of uncertain quality, because they had been derived by a variety of methods; this was particularly true for salinity. Prior to 1960 salinity had been determined by chemical techniques, whereas post-1960 salinity has been determined by conductivity methods and calibrated against standard sea water.

The early salinity data had already been extracted from the archives, and used to produce a time-series which has been published several times before and used for a variety of purposes (e.g Dooley and Martin, 1984; Martin, 1976; Martin 1993; Walsh and Martin, 1986). However, the calibrations of these early data had been performed subjectively based upon examination of individual sections and tS diagrams, and since the data had not been computerised, it was not possible to apply an objective calibration routine. Consequently neither the long time-series could be reconstructed, nor could a new time-series be calculated for the parameters and locations.

So in 1990 a data archaeology project was begun with the goals of collating all the available historic data collected along the two standard sections, computerising them, and devising an objective calibration routine for the old salinity records. The outcome was the derivation of a long time-series of the salinity data for North Atlantic water which can be used as a basis for comparisons with previous estimates of this key variable.

Past Measurement Techniques

The data available from across the Faroe-Shetland Channel include:- 1. geographical position of each station; 2. the sounding on station; 3. the sampling depths; 4. temperature and salinity at each depth.

During the century of observations, each parameter has been measured by a variety of techniques, each with its own limitation and accuracy. Briefly, the following methods have been employed on Scottish surveys during the 100 year period under consideration:

1. Position: The locations of the station positions during the original surveys were determined by astronomical observations and dead reckoning. Decca navigation systems were introduced on Scottish research vessels in the early 1950s, and were replaced in the 1980s by satellite navigation systems with the GPS system being used during the present decade.

2. Sounding: The earliest soundings were made by lead and line methods, using sounding machines such as the Thomson sounder (1893-1902) and the Lucas sounding machine (1903). Acoustic sounders only became available on Scottish research vessels after about 1950.

3. Depth of individual observations: Initially the amount of wire paid out was used to estimate the depth at which a water sample was collected, but this resulted in large overestimates particularly when the ship was drifting. Since the earlier part of this century unprotected thermometers have been used in conjunction with protected thermometers to determine depth of reversal. Now *in situ* pressure sensors mounted on conductivity, temperature and depth (CTD) probes are used to determine the depth to a high degree of accuracy.

4. Temperature: The earliest measurements were made with Negretti and Zambra reversing thermometers, calibrated at the Kew observatory (1893-1901). Subsequently Nansen-Richter thermometers were used. Data from reversing thermometers were supplemented by taking the temperature on deck, of water samples collected in insulated bottles, such as the Pettersson bottle. Nansen thermometers were used between 1927 and 1939. Early on a single thermometer was used at each depth, but after the late 1920s pairs of thermometers were employed. From 1940 onwards a pair of protected reversing thermometers were used, in conjunction with a third unprotected thermometer, mounted on Knudsen reversing water bottles. Nowadays the majority of thermometers in use are either of Negretti-Zambra or Gohla manufacture. Calibrations once carried out at the National Physical Laboratory (UK) are now undertaken by Gohla (Germany). Discrete temperature measurements by glass/mercury thermometers have now been replaced by continuous profiles measured *in situ* by CTDs.

5. Salinity: Samples of water for the laboratory determination of salinity have been collected using a variety of sampling bottles. Mill's self-locking slip water bottle, used on the first surveys have been replaced by Petterson-Nansen and Knudsen bottles.

Salinity was initially determined by density measurements using hydrometers and Sprengel tubes. Calibration samples were analyzed for chlorinity using titration methods. These chemical analyses were performed at several laboratories including Oxford and University College, Dublin. Between about 1930 and 1960 titrations were performed by the UK Government Chemist, but the accuracies achieved were poor as none of the analysts were marine chemists, moreover long sample storage times were commonplace. There were systematic errors not only between batches of samples but also there were internal inconsistencies within them.

Electronic determination of conductivity commenced in 1960 with the acquisition of a Cox salinometer. This was replaced with a CSIRO model in the mid-1960s, a Guildline Autosal in the early 1980s and finally a Guildline Portasal in 1992. As with temperature, CTDs now provide continuous *in situ* conductivity profiles.

Calibration

Other than noting the possible limitations of accuracy of the measurements of position, sounding, and depth of individual measurements, it may be impossible to improve upon the recorded values. Historical measurements of temperature particularly at the sea surface have been re-calibrated following careful research of past methods, but temperatures observed at depth within the Faroe-Shetland Channel have to be left uncorrected.

The early measurements of salinity were prone to large errors owing to the methods of salinity determination. A method for adjusting these observations so that they correspond more closely to modern measurements is described below.

Data Sources and Collation

A number of data sources were employed during the collation of historic data from the Faroe-Shetland Channel. Data from early cruises were extracted from reports of the Fishery Board for Scotland, from the ICES Bulletin Hydrographique and from the volume by J B Tait (Tait 1957) summarising data from the surveys conducted between 1927 and 1957. Original station books and loose records were searched for additional data obtained in the Faroe-Shetland Channel.

These original data were entered into standard hydrographic data formats on the Laboratory's computer. Cruise files were constructed for each survey, and these were then searched for data collected more or less along the standard sections (Figure 1). Larger search areas were used for the earlier data to ensure as much data were recovered as possible without significantly compromising accuracy.

100 Year Data Set

Once the search of the historic data set had been completed, a database was constructed containing all the full and part sections across the Fair Isle-Munken and Nolso-Flugga sections. There are now 290 Nolso and 108 Munken sections available for the period 1893-1993. The availability of data at each of the 12 standard stations along the two survey lines may be seen in Figure 2. Coverage of the Nolso-Flugga line is the most complete, whereas surveys along the Fair Isle-Munken section were only carried sporadically prior to 1970.

Salinity Calibration

The quasi-stationary characteristics of the Norwegian Sea Deep Water (NSDW) were employed to calibrate the older salinity observations. The mean salinity of NSDW along the two sections was calculated for the post-1960 data. After the removal of notable outliers the mean salinity of NSDW was:

Section	Mean	Standard deviation
Noslo - Flugga	34.921	0.017
Munken - Fair Isle	34.919	0.010

A comparison of the temperature-salinity diagrammes for post-1960 and pre-1960 data demonstrated that the scatter in the earlier salinity was the larger, not only in the NSDW with its well-defined characteristics but also in the North Atlantic (NA) and Modified North Atlantic (MNA) waters.

The older data were calibrated by selecting all data within the NSDW (at depths greater than 800 m) for each cruise, and then calculating the mean value. The difference between this mean and the post-1960 mean value was then used systematically to correct each individual value of salinity at every depth for that particular cruise.

Once these corrections had been applied, the pre-1960 t-S diagrammes more closely resembled the post-1960 profiles. Not only did the salinities in the NSDW water lie within limits of acceptability based on modern data, but also the distribution of t-S characteristics for NA and MNA water appeared more reasonable.

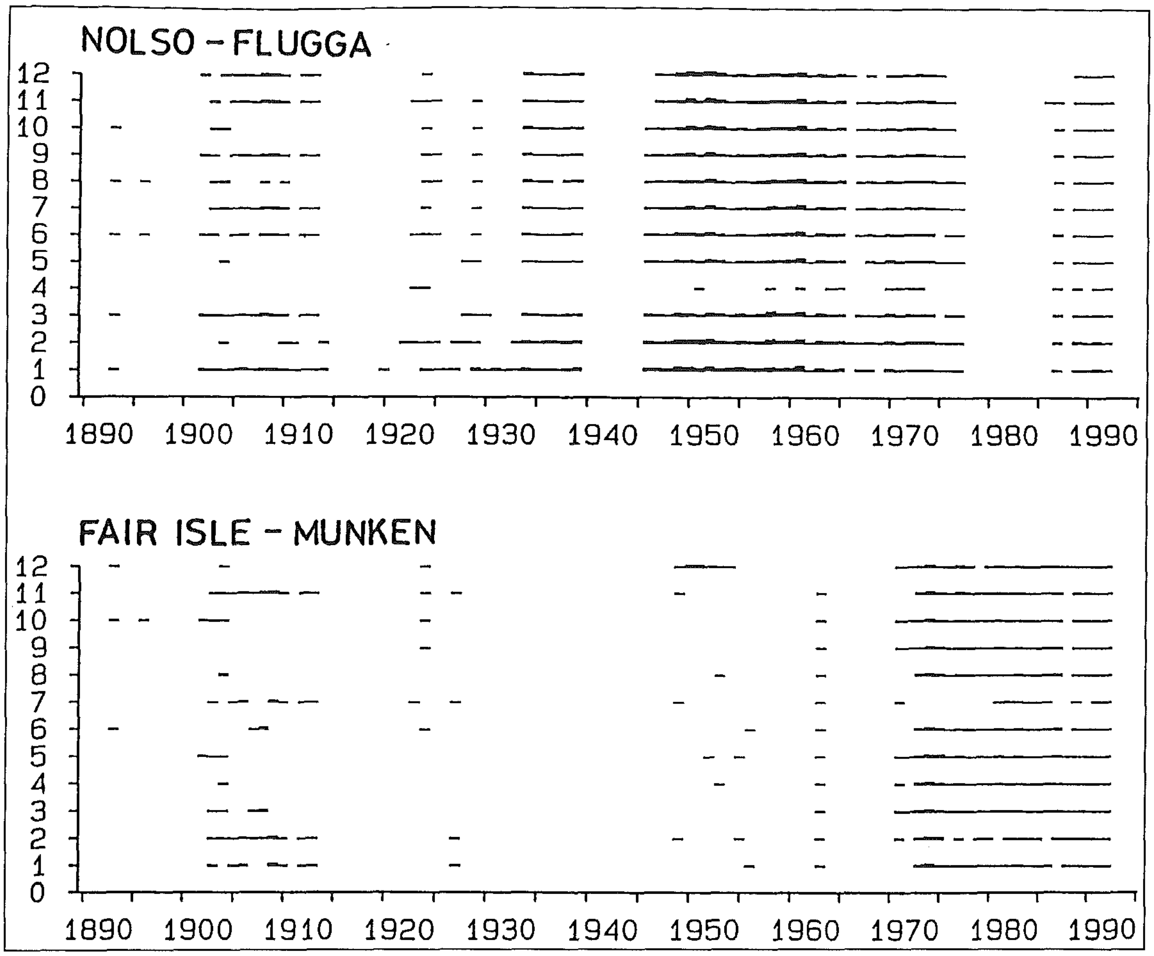


Figure 2. Summary of station data availability along the two Faroe-Shetland standard sections following the merging of the two data sets:- a) Nolso-Flugga section; b) Fair Isle-Munken section.

Re-Calibrated Time-series of NA Water

A time series of NA salinities was constructed in order to compare the salinities of NA water as determined by our objective re-calibration routine with the previous series based on subjective readjustments. The salinity of the NA water was defined, after combining re-calibrated pre-1960 data from both the standard sections, as the maximum recorded salinity value recorded in any one year at the four stations lying inshore from the 200 m contour on the Scottish shelf edge. From this time series (Figure 3) it is evident that while the time-series used in the past have not been entirely consistent with one another, most major features are reproduced - namely, the low salinity prior to 1910, high salinity between 1935 and 1940, high salinities in 1960 and the early 1970s and the low salinity event in the mid-1970s, followed by recovery in the 1980s.

These major features are also evident in the new time-series based on the re-calibrated data (Figure 3). The RMS errors associated with the different time-series suggest that, at best, the salinity of NA water has been estimated to an accuracy of about 0.03. But since the maximum amplitude of interdecadal variation over the past century has been of the order of 0.2, it has been resolved despite the variety of the methods used to measure and determine NA salinity.

Summary

The long term monitoring along the standard Faroe-Shetland Channel hydrographic sections, begun in 1893, should be continued so that this time-series can be extended. At present, the Marine Laboratory Aberdeen plans to continue to survey the standard sections at least three times each year, and other European nations may also work part or all of these sections and report the data to ICES.

The databases resulting from this data archaeology are being used to extract more information. Time-series of salinity in other water types are being constructed (Figure 4), and used not only to examine events such as the Great Salinity Anomaly and the more recent 1989-91 high salinity event, but also the annual cycles within the Faroe-Shetland Channel (Figure 5).

These data-sets are amongst of the longest directly observed environmental time-series in the world, but even so the period covered is still quite short compared to the time-scales involved with many climatic and biological processes. For example 100 years represents just six circulation periods of the North Atlantic sub-polar gyre (period of 15 years), 13 flushing periods of the Norwegian Sea (period seven years) and possibly just 20

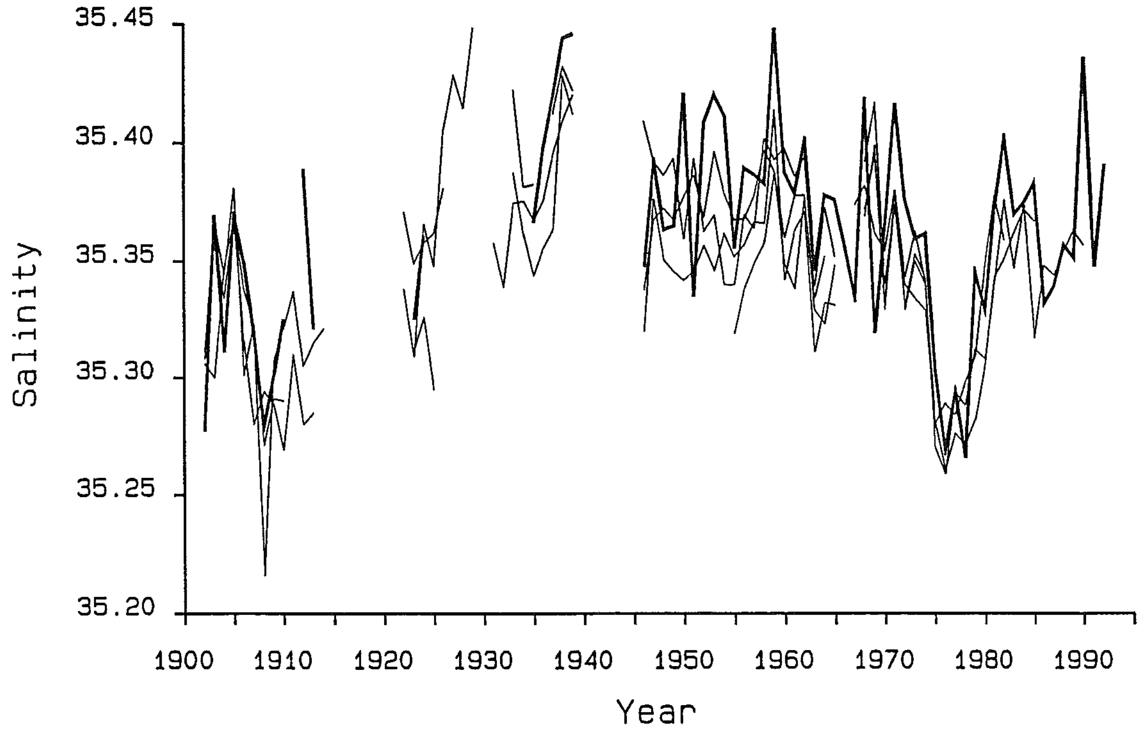
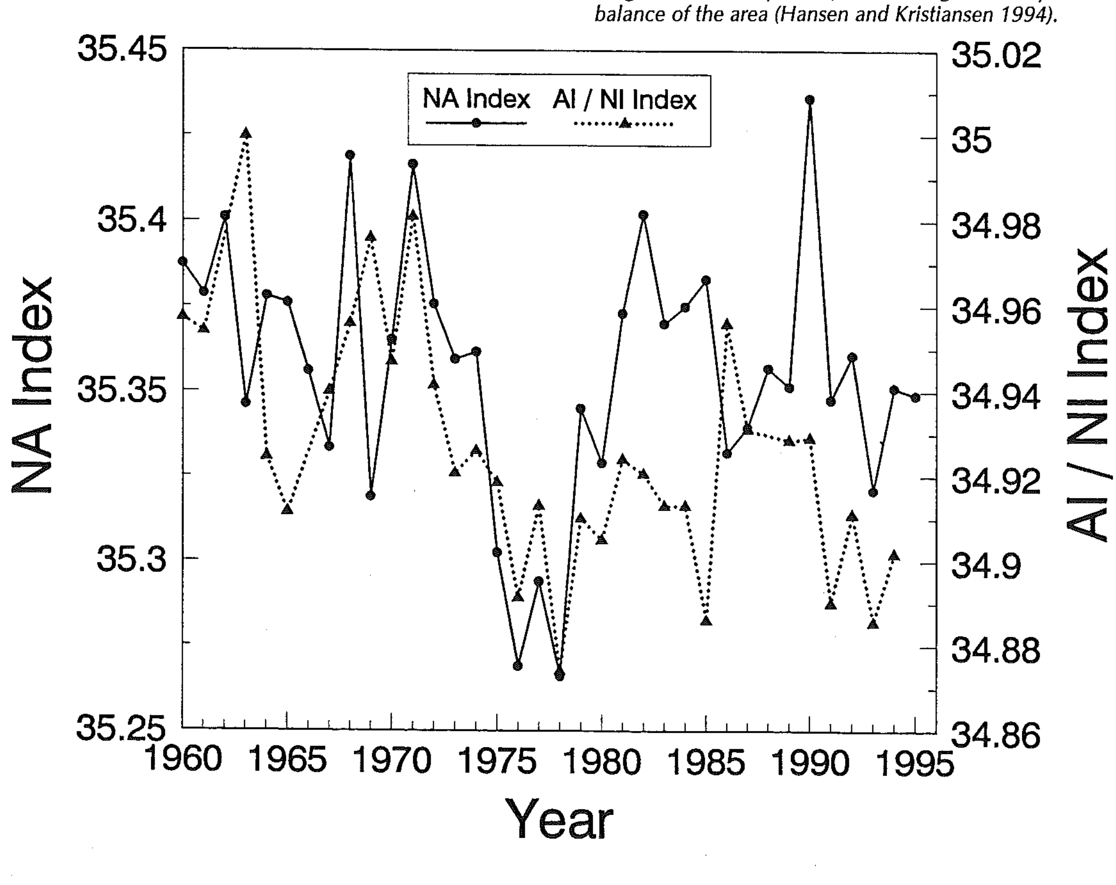


Figure 3 (above). Time-series of salinity of North Atlantic water derived from observations made along the two standard Faroe-Shetland Channel sections. Thin multiple lines are derived from literature; Martin (1976), Walsh and Martin (1986), Martin (1993), Dooley and Martin (1984). Heavy solid line derived from our re-calibrated data set.

Figure 4 (below). Mean annual salinity of two water masses in the Faroe-Shetland Channel. AW Index - derived from data collected at the four standard stations inshore from the 200m contour on the Scottish shelf. AI / NI Index - derived from data collected at depths between 500 dbar and 800 dbar, with temperatures > 1 °C, adjacent to the Faroese continental slope. The simultaneous decline of salinity within both water masses in the Faroe-Shetland Channel in the mid-1970s suggests that the Great Salinity Anomaly may not have been the result of the advection through the area of a 'slug' of low salinity water, but a change in the dynamic balance of the area (Hansen and Kristiansen 1994).



generations of a pelagic fish such as the Atlantic salmon (*Salmo salar*).

The period has included, however, several significant climatic events marked by the high and low salinity anomalies, and studies of the processes driving these events will help climate modellers. The period also encompasses the last century of industrial development, and the continuation of the time-series is of global importance if we wish to observe possible effects of the emission of "greenhouse" gases.

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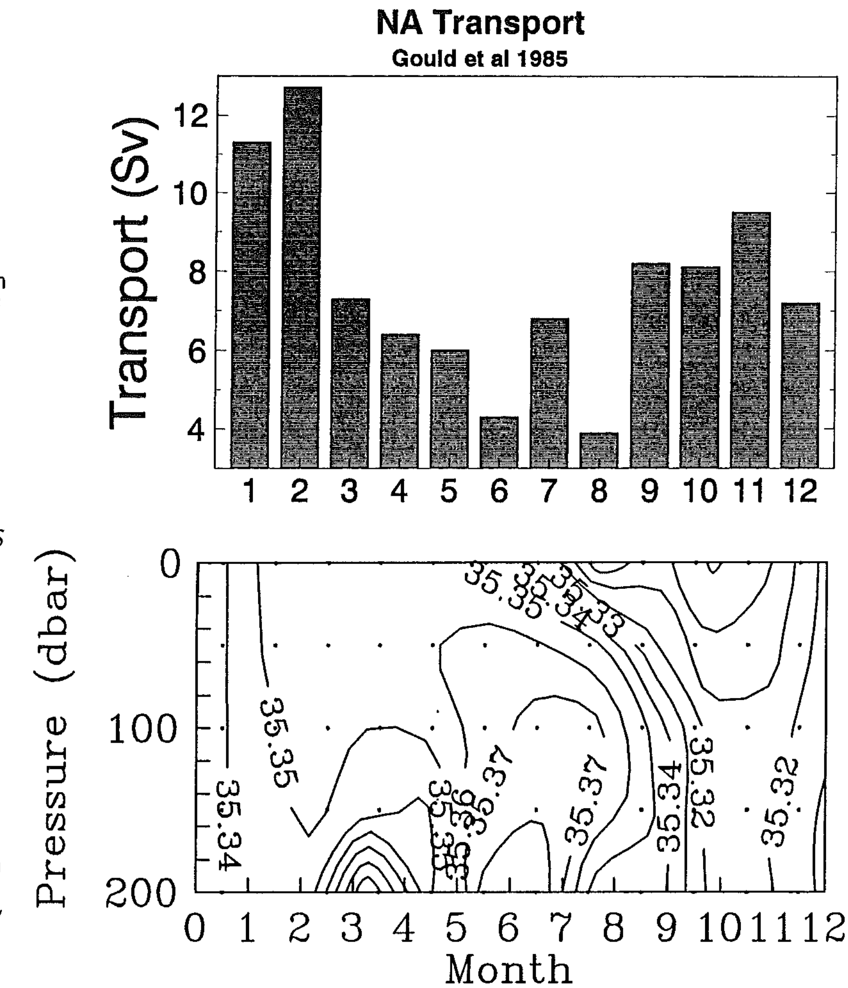

Figure 5. Comparison of the annual cycle of transport of North Atlantic (NA) Water in the Faroe Shetland Channel with the annual cycle of NA salinity variation at the shelf edge north of Shetland. The transport is derived from a year long deployment of current meters between the 200 m and 1000 m contours northwest of Shetland (Gould et al. *1985). The seasonal minimum in transport in the summer coincides with a salinity maximum. As in Figure 4, this suggests that changes in the dynamic balance of the area may control changes in salinity. When transport of NA water is at a minimum, greater proportions of water at the shelf edge north of Scotland will be composed of the more saline NEAW derived from the shelf edge area west of the UK, rather than pure NA water derived from the North Atlantic Drift.*

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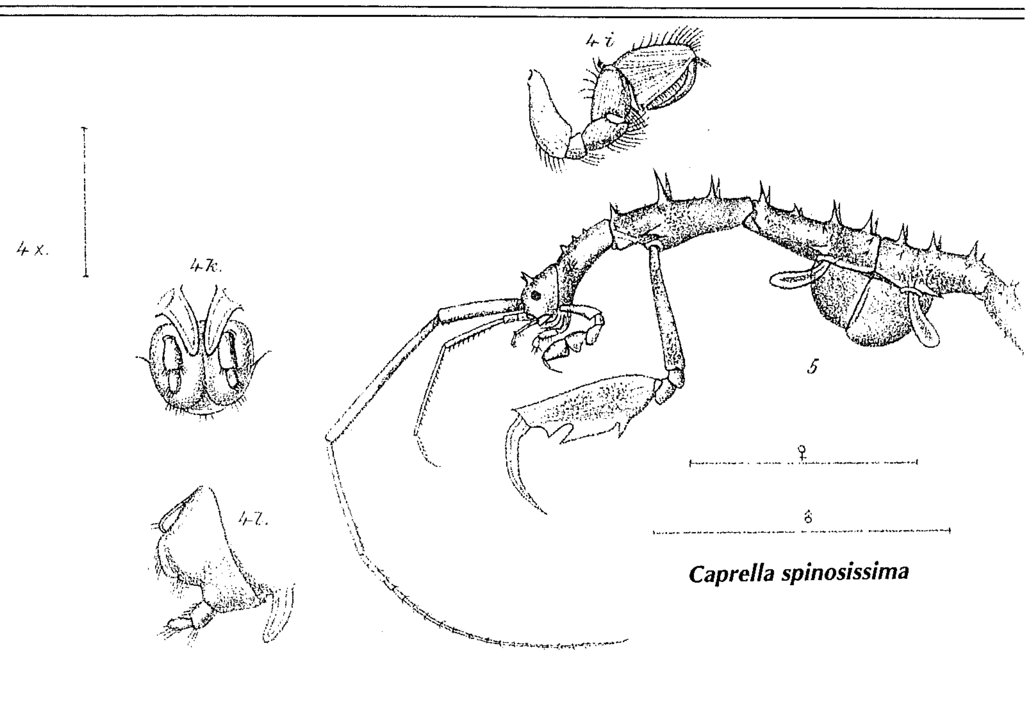


Caprella spinosissima

The Natural Environment Research Council's
SHELF EDGE STUDY

John Huthnance

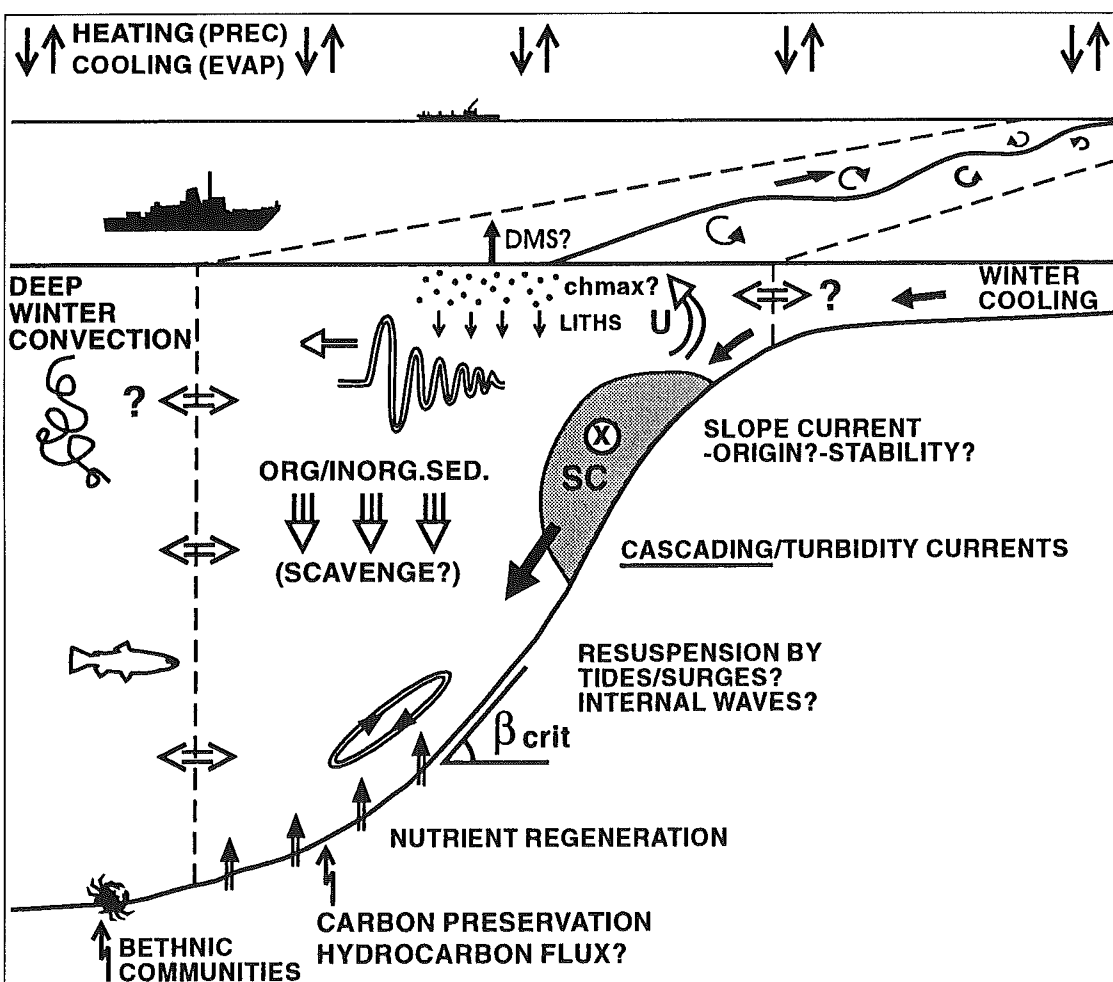
This shelf-edge study forms part of the Land-Ocean Interaction Study Community Research Project LOIS. Accordingly, the objectives are:

- to identify the time and space scales of ocean-shelf momentum transmission and to quantify the contributions to ocean-shelf water exchange by physical processes;
- to estimate fluxes of water, heat and certain dissolved and suspended constituents across a section of the shelf edge, with special emphasis on net organic carbon export from, and nutrient import to, the shelf'
- to incorporate process understanding into models which will be tested by comparison with observations and provide a basis for estimation of fluxes integrated over time and the length of the shelf edge.

Physical processes control the large-scale movement and irreversible small-scale mixing of water and its constituents. At the shelf edge, steep bathymetry may inhibit ocean-shelf exchange but, in combination with stratification, gives rise to special processes and modelling challenges. Some processes contributing to shelf-edge fluxes are illustrated in the figure.

Measurements are taking place over the shelf edge west of Scotland during 1995 and 1996.

An initial survey of bathymetry and sea-bed features took place over the slope in 56° to 57°N during March 1995, including side-scan sonar and some coring. Although the cruise was severely constrained by weather, a high-resolution bathymetric survey was largely completed in depths 150m to 1000m. It used the swath bathymetry system fitted to RRS *Charles Darwin*, producing charts at 1:50,000 resolution, excellent for the development of fine-resolution models of the area. Some 85 hours of side-scan sonar data were also obtained using the Towed Ocean Bottom Instrument (TOBI). The records show slumps, slides, channels, levees, ridges, wavy



bedforms and changing geological structures. These features will help to guide the coring and geochemical sampling in later SES cruises.

Six seasonal cruises (about 30 days each) are taking place at ~3 month intervals from May 1995, including intensive surveys (ADCP, CTD; SeaSoar is also planned from November 1995) and sampling (for chlorophyll, nutrients, tracers) over an area ~40 x 25km near 56½°N. The May cruise documented a spring bloom, including phytoplankton sinking to about 200m and also reappearing at the bottom without being detected in between.

An array of moorings is being maintained, some for the 18 months period of measurements, in two cross-slope sections separated by ~20km along-slope; instruments include current meters, ADCPs, bottom pressure recorders, a meteorological buoy, thermistor chains, transmissometers, sediment traps at greater depths, fluorometers and nutrient analysers; a turbulence profiler and a bottom lander for near-bed turbulence and suspended sediments will be deployed within a summer and a winter cruise. The initial seabed survey had immediate benefit by influencing the choice of positions for moorings laid at the end of March 1995. Coring and sea bed photography carried out then showed the bottom to be covered with boulders on the shelf and smaller pebbles down to 300m.

Instrumented drogued buoys are being tracked.

Satellite remote sensing is supplementing *in situ* measurements.

Prior measurements of flow through the North Channel were made for a year in 1993-94. Ocean Surface Current Radar (OSCR, resolution ~20 minutes, 1km) enabled a good estimate of the volume flux through the North Channel, despite some data losses, overall mean currents showed a net outflow with significant spatial variability, the main outflow being confined to the Scottish side of the North Channel. An Acoustic Doppler Current Profiler near the centre of the North Channel showed that typically, winter storms pushed water out of the Irish Sea in pulses of a few days at all depths (one such surge was twice as strong as all others). During the summer there was a weak flow into the Irish Sea at all depths. The data are being studied for the dynamics of the significant surge events and to relate the flow to forcing by winds, non-linear tides, pressure and density gradients. Surface elevations continue to be monitored and, together with continuing meteorological data and a flow-forcing relation, will provide a basis for continuing estimates of North Channel flow in to the shelf sea west of Scotland.

Models are seen as the key to integrating up from local and process studies to estimate total cross-slope exchanges and budgets.

A 3D numerical hydrodynamic model, resolution 1/12° x 1/12°, has been used to study spatial variability of the tides and wind-driven circulation. It reproduced observed areas of locally-intensified tidal currents near the shelf edge (for example). Modelled flow fields produced by a westerly wind, a southerly wind or by a northward flow out of the Irish Sea through the North Channel showed very similar patterns, and were in good agreement with the long-term flow fields derived from radioactive tracer studies. The direction of the flow field at depth is clearly influenced by the effects of bottom topography.

The model has been used in the form of a cross-shelf section to examine the generation of internal tides and associated turbulence energy and mixing. To resolve internal tides accurately over the shelf break, a fine cross-shelf grid (about 1km or less) was found necessary. Results showed that the intensity and spatial variability of the internal tide are sensitive to the (summer, winter, up- or down-welling) density field and to the shelf-slope depth profile. Near the shelf break, short internal waves are formed. At the sea surface, above the shelf break, internal tidal shear enhances mixing, which can influence sea-surface temperatures (cooling by this means is observed near the Celtic Sea shelf edge); the mixing may also supply nutrients upwards, near enough to the surface (in the presence of light) to "fuel" production.

The model simulates upwelling in a bottom boundary layer with enhanced mixing over the shelf, giving a shelf-edge front. In downwelling, where less dense water is drawn below heavier water, instantaneous vertical mixing takes place in the model.

A 2D model of the cross-slope section has also been run for the seasonal cycle of circulation in response to tidal, wind and thermal forcing. Appropriate formulations for fine near-surface resolution, advection and dynamical pressure gradient over the slope showed encouraging improvements. Data from 25 years of DML CTD sections across the Hebrides shelf near 57°N were analysed to provide a mean annual cycle (and variance) for comparison.

These model calculations of the scales and locations of expected flow structures have helped in designing the SES array for moorings, surveys and near-bed sampling. For example, high concentrations of suspended particulate matter (SPM) are expected where bed stresses are large.

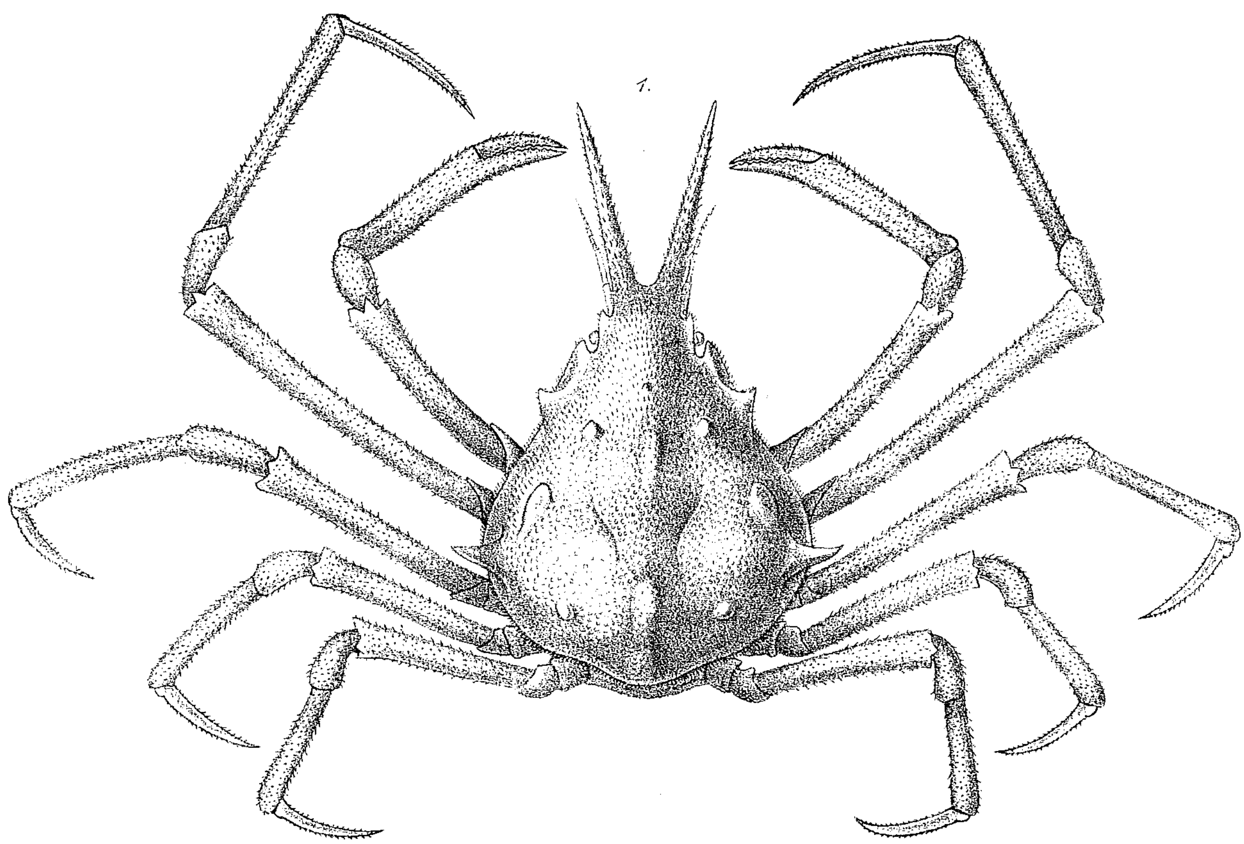
Towards microbiological modelling, the seasonal cycle on the Hebrides Shelf has been simulated in 1D (vertical) with coupled physics, suspended particulate matter (including deposition and resuspension) and microbiology. Results predict a spring bloom at the end of May, in an average (meteorological) season, to be compared with the slightly earlier bloom recorded in the May 1995 cruise.

The "core" measurements of SES are funded by LOIS. Associated studies which are at least partly funded through NERC institutes or explicitly by LOIS (most through the LOIS Special Topic) include:

- internal tides and waves;
- the slope current and the question of its continuity;
- tracking of instrumented drogued buoys, and their interpretation (eddies, dispersion, exchange);
- ocean-shelf exchange by tracers/water mass;
- 3-D prognostic numerical models for physics;
- laboratory models (internal and long waves);
- nutrients and primary production - measurements and models;
- suspended sediment characterisation and estimation of downward flux;
- organic carbon cycling in sediments;
- trace metal distributions and the relation of "front" therein to metals in sediments;
- determination of dissolved organic carbon.

SES involves POL as "host" laboratory, DML, PML and six university departments.

John Huthnance: Proudman Oceanographic Laboratory, Marine Physics Group, Bidston Observatory, Birkenhead, Merseyside L43 7RA



Scyramathia carpenteri

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OCEAN Challenge

The Magazine of the Challenger Society for Marine Science

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Articles for *Ocean Challenge* can be on any aspect of oceanography. They should be written in an accessible style with a minimum of jargon and avoiding the use of references. If at all possible, they should be well illustrated (please supply clear artwork roughs or good-contrast black and white glossy prints). Manuscripts should be double-spaced and in a clear typeface.

For further information, please contact the Editor: Angela Colling, Department of Earth Sciences, The Open University, Walton Hall, Milton Keynes, Bucks MK7 6AA, UK. Tel: 01908-653647; Fax: 01908-655151; Email: A.M.Colling@open.ac.uk

CONTENTS

Articles arising out of a symposium on 'A Century of Hydrographic Work in the Faroe–Shetland Channel', held in Aberdeen in 1993, and involving the ICES Oceanic Hydrography Working Group and the ICES Data-Management Working Group.

Among the topics covered are: the history of research in the region, from Danish and Scottish perspectives; the hydrography of the north-east Atlantic; long time-series; tidal oscillations; salinity anomalies; fish migration; and studies of the shelf edge.