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II. Field studies in hydrography

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100 years of field work in hydrography: a retrospective of its impacts

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Although ICES is known as an organization concerned with fisheries research and management, it has maintained a wide range of hydrographic activities right from its founding in 1902. Examples of pioneering ICES work are presented, including the synoptic surveys of the northern North Atlantic during the Polar Front Survey in 1957/58, process studies on the exchanges across the Greenland-Scotland Ridge system from 1960 to 1986, on mesoscale mixing in the North Sea in 1965, and on patchiness, both in time and space, in 1976 and 1986. The last examples are products from ICES long-term hydrographic measurements. The examples given are discussed in relation to contemporary studies on the same subject in order to show the impact that ICES has had and still has on North Atlantic hydrography. The contribution concludes by commenting on means of preserving that positive impact in the present situation of financial restrictions which tend to narrow the work spectrum of ICES and make it less attractive to participation by the hydrographic community.

Keywords: mixing, North Atlantic circulation, patchiness, time-series observations.

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Introduction

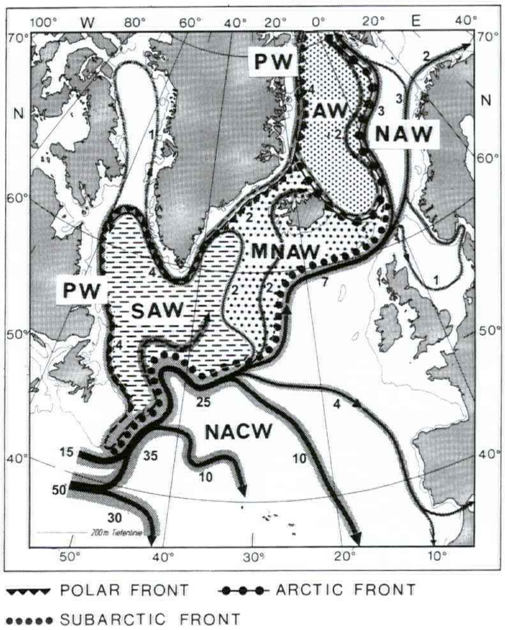
It is the task of an international marine organization like ICES to 1) promote and coordinate field studies that cannot be achieved by individual researchers/laboratories/nations, 2) provide advice and means to ensure measurements of consistent quality, 3) provide an internationally accessible data facility, and 4) manage the dissemination of results including an advisory function.

ICES was the leading international organization for the North Atlantic from its foundation in 1902 to well into the 1970s when the global organizations under the umbrella of the United Nations (UN) or the International Council of Scientific Unions (ICSU) began to dominate the coordination process and when the European Union (EU) started to provide funds for joint investigations.

This contribution will emphasize the impact that ICES has had on North Atlantic hydrography through its role in coordinating most of the pioneering regional and process studies. The results of these studies have served and are serving as a working base for projects on contemporary problems such as the role of physical processes in determining life and productivity in the sea or the ocean's role in climate variability and climate change.

Transoceanic sections: the IGY Polar Front Survey

The meridional overturning circulation is the dominant flow pattern of the North Atlantic Ocean. High latitude cooling and sinking of surface waters allows subtropical warmth and salt to be advected northward to the Arctic Ocean and drives cold and fresh deep waters as well as cold and extremely fresh surface waters southward. This circulation brings waters with very different characteristics into close proximity, separated by strong gradients in the vertical and sharp frontal zones in the horizontal (Figure 1). The intensity of the circulation pattern affects a wide range of conditions in the North Atlantic, ranging from climatic conditions for Europe to the distribution and productivity of boreal and Arctic fish stocks.



PW = Polar Waters
AW = Arctic Waters
SAW = Subarctic Waters
NAW = North Atlantic Waters
NACW = North Atlantic Central Waters
MNAW = North Atlantic Atlantic Waters
num = Transport in Sverdrup ($10^6 m^3 s^{-1}$)

Figure 1. The current branches, related volume transports ($10^6 m^3 s^{-1}$) and surface water masses in the northern North Atlantic, based on the data from the IGY-Polar Front survey 1957/58. Based on Wegner (1973) and Meincke (pers. comm.).

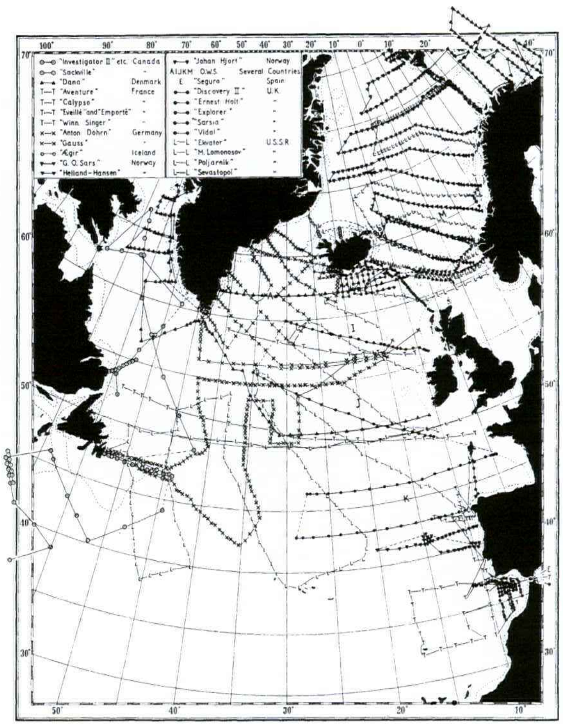


Figure 2. Map of hydrographic stations sampled during the IGY-Polar Front Survey 1957/58. Station locations were chosen to allow for the construction of transatlantic sections. Reproduced from Tait (1961).

The appropriate means for studies of the meridional circulation are zonal sections across the Atlantic from coast to coast. It is not surprising that ICES efforts were directed towards such data from the very beginning. The first potential opportunity came when the United States invited European navy (research) vessels to the opening ceremony of the Panama Canal in 1913, but the intended voyage of seven vessels across the Atlantic and back with a hydro-biological repeat survey of the North Atlantic Current / Gulf Stream system had to be cancelled because of the outbreak of World War I. Lack of funds rather than war prevented the launching of an International Expedition in 1924/1925. For the North Atlantic, it was planned to study the links between the Sargasso Sea / Gulf Stream and the North Atlantic Current as well as the dynamics of the Polar Front between the Labrador Current and the Gulf Stream. The period before World War II saw a number of smaller-scale studies on processes of North Atlantic Current variability. After the war, the mine-infested coastal waters led to oceanic programmes, notably the North Atlantic sections by the Danish "Dana".

It was not until 1957/1958 that a first complete set of transatlantic sections became reality. Within the framework of the International Geophysical Year (IGY), ICES (supported by the International Commission for the Northwest Atlantic Fisheries – ICNAF) coordinated the Polar Front Survey. Twenty-five research vessels were provided and manned by teams from 11 nations to complete a summer-winter repeat survey covering the northern North Atlantic with a grid of some 2500 full-depth physical, chemical, and (some) biological stations (Figure 2). Upon completion, this ocean region changed from being poorly observed (424 1° fields out of a total of 1806 were without any temperature observations in 200-m depth or deeper) to one of the best covered at that time.

The endeavour was highly successful (Tait, 1961; Figure 1). A winter-summer quasi-synoptic set of 13 transatlantic sections and three sections in the Gulf Stream extension area was published as the ICES "Atlas of the Hydrography of the Northern North Atlantic Ocean" (Dietrich, 1969). All data had been quality controlled by the ICES Service Hydrographique. Together with the Woods Hole Oceanographic Institution's "Atlantic Ocean Atlas of Temperature and Salinity Profiles and Data from the IGY 1957/58" (Fuglister, 1960), which included 12 transatlantic sections of the subtropical and tropical North Atlantic and the South Atlantic, the hydrographic data base of the Atlantic Ocean was, for the first time, so complete that all the

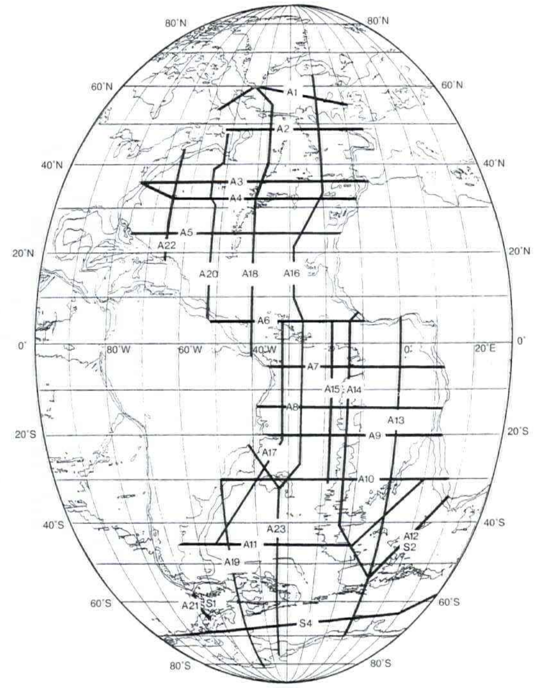


Figure 3. Transoceanic sections (Atlantic only) carried out during the World Ocean Circulation Experiment (WOCE) 1990–1998.

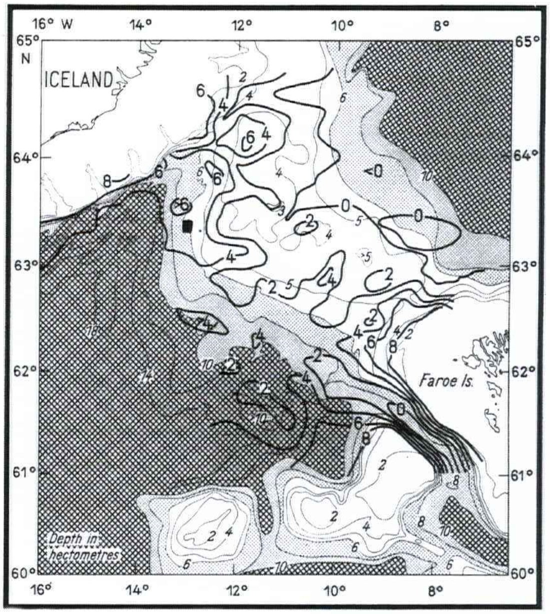


Figure 4. Example of a result from the OVERFLOW '60 investigation: The distribution of bottom temperature in the period 30 May–2 June 1960. Reproduced from Dietrich (1967).

basic numbers on heat and salt transports, overturning rates, etc. could be reliably estimated, and modellers had benchmark numbers available to assist their growing efforts in circulation modelling.

This situation remained unchanged until the 1980s. By then, the methods of reliable measurements of temperature, salinity, oxygen, and nutrients had been improved by an order of magnitude. Measurements of transient tracers, isotopes, and constituents of the oceanic CO_2 cycle matured. Remote sensing from satellites and autonomous moored and drifting instrumentation became available.

Global coupled modelling, however, required global ocean data sets for model initialization and validation. The time had come for a first quasi-synoptic, global ocean survey, the World Ocean Circulation Experiment (WOCE). This experiment was coordinated within the framework of the World Climate Research Programme (WCRP) by a joint effort of the World Metereological Organization (WMO), Intergovernmental Oceanographic Commission (IOC), United Nations Environment Programme (UNEP), and ICSU. Though ICES was only involved in the regional coordination of northern North Atlantic activities, the methods devised by ICES three decades earlier were copied for the global exercise. These included coordination of national contributions, the provision of agreed methods for sampling and sample analysis, intercalibration, and central data quality control (Figure 3). WOCE thereby achieved its central goal of a status description of the global oceans for the 1990s, and for the North Atlantic, it provided another snapshot of its hydrographic status so that decadal-scale changes became evident. This is of particular importance for testing the predictive capabilities of coupled models at interannual to decadal time scales.

Process studies I: North Atlantic - Nordic Seas exchanges

The submarine ridges that lie between Greenland and Scotland form a barrier that constrains, but does not block, the exchange of water between the North Atlantic and Nordic Seas. Across these ridges, warm and saline Atlantic waters flow northeastwards providing the surface inflow to the Nordic Seas. Cold and fresh polar and Arctic waters return southwestward along the Greenland coast as surface outflow and cross the Greenland-Scotland Ridge at several locations as deep, dense over-

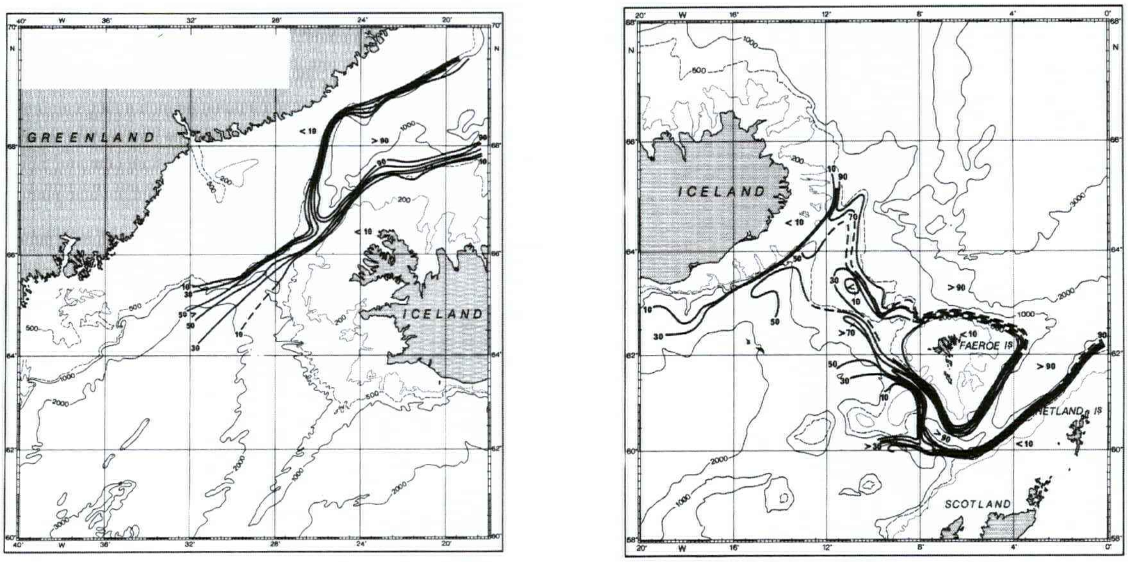


Figure 5. The percentages of Arctic deep and intermediate water in the near-bottom layer during OVERFLOW '73 in August/September 1973. Reproduced from Meincke (1983).

flows from the Nordic Seas. All three components of water exchange across the ridges are of fundamental importance for the global thermohaline circulation as well as for the regional climate of Europe and for European fisheries. It makes the Greenland-Scotland Ridge a key region for studies of the processes which govern the intensity and path of these flows as well as their variability. This had become evident from the early observations by Knudsen (1899), Helland-Hansen and Nansen (1909), and Nansen (1912), and since then, many individual (e.g., Herman, 1953) and national (Tait, 1957) efforts had confirmed the need to study the inflows and the deep overflows in a synoptic manner with mesoscale resolution.

ICES took on this task by coordinating Overflow '60, a nine-ship operation which made three synoptic surveys of the Iceland-Faroe Ridge from 30 May to 16 June 1960 (Tait, 1967; Figure 4). This was followed by Overflow '73 which involved 14 research vessels and covered the Greenland-Scotland Ridge system during the period 15 July–15 September 1973 (Meincke, 1983; Figure 5). It may be noted that Overflow '60 was the first survey that could benefit from moored recording current meters. From these two Overflow campaigns, a basic data set became available on water mass transports, flow paths, etc. However, we continued to lack details of the surface outflow along East Greenland and information on the longer-term variability of these flows. The latter challenge was taken up in the ICES-coordinated project MONA (Monitoring the Overflow into the North Atlantic), a 1-year (1974–1975) pioneer experiment which featured five current meter moorings located at positions between Greenland and Scotland which exerted a strong topographic control on the deep overflow (Aagaard and Malmberg, 1978; Willebrand and Meincke, 1980). There was a period in the 1970s and 1980s of intense follow-up studies on exchange processes which made use of new technologies such as surface drifters and new water mass parameters such as transient tracers. The NANSEN (North Atlantic Norwegian Sea Exchanges) study, initiated by ICES, was an especially intense observing effort between 1986 and 1989. All water mass data were managed by ICES and the scientific results were presented at the ICES Annual Science Conferences (van Aken and Becker, 1996; Hansen and Østerhus, 2000).

ICES remained involved in the ongoing studies of exchanges across the Greenland-Scotland Ridges acting as project data centre for NORDIC WOCE and VEINS (Variability of Exchanges in the Northern Seas), an EU-funded study of exchanges between the North Atlantic and the Arctic. These projects focus on the climate role of the Atlantic-Arctic exchanges and are aimed at understanding their interannual-decadal variability in order to develop an optimized array for high-latitude, ocean climate monitoring. The importance of such long-term measurements is stressed by sensitivity studies with contemporary circulation models.

Process studies II: mixing in the sea

Mixing is one of the most important processes in the sea. It is effective on all scales from molecular to global and jointly, with advection, determines the distribution and re-distribution of physical and biogeochemical

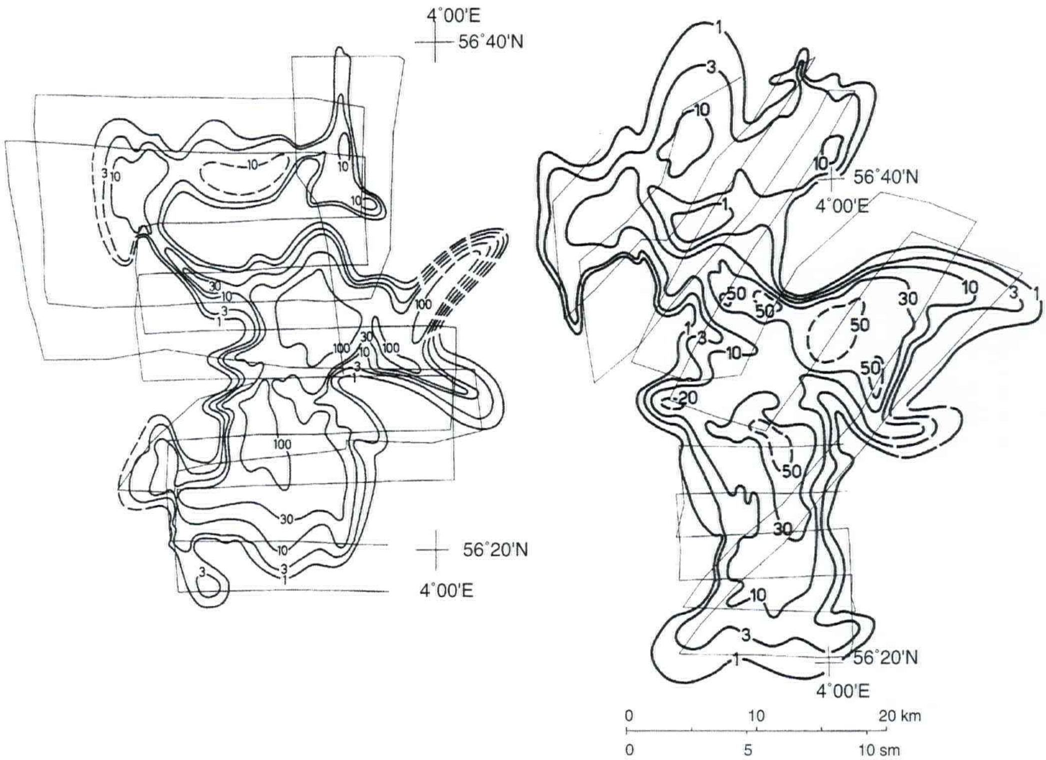


Figure 6. The distribution of Rhodamine-B 173 hours (left) and 222 hours (right) after release during the RHENO Experiment in the North Sea in August 1965. Units are 10^{-11}g ml^{-1}. Reproduced from Weidemann (1973).

properties of seawater, allowing zooplankton to encounter its prey and contaminants to disperse when dumped at sea. The energy for mixing comes from the potential energy of ocean stratification and from all forms of water movement. Most of its understanding is derived from statistical theories. For its application in studies of oceanic processes, mixing is parameterized by a scale-dependent mixing coefficient. This number can be estimated in many different ways, of which the most direct is by tracer release in the region and time scale of concern. The major problems are those of binding repeat synoptic mapping of the tracer distribution, which require good intercalibration of methods and ample, well-coordinated ship time.

In mid-August 1965, ICES coordinated a pioneering tracer release study on the mesoscale. Twenty tonnes of a solution of the fluorescent, dye substance Rhodamine-B were pumped into the central North Sea and the spreading dye patch was subsequently mapped in 10 surveys carried out within the next 22 days by four research vessels and one aircraft (Figure 6). The results of this project RHENO (Rhodamine Experiment in the North Sea) were edited by Weidemann (1973; Figure 7). These demonstrated the eminent value of such a direct method, but also showed its limitations in the sense that the strengths of the various sources for mixing energy varied considerably during the experiment. Therefore, the outcome of such efforts are integral mixing coefficients valid for the particular locations and the particular environmental conditions. Nevertheless, the RHENO methodology and RHENO results served as basis for mixing studies in the ICES-coordinated FLEX (Fladen Ground Experiment) programme in 1976, where information on mixing coefficients was vital for investigating the availability of nutrients for plankton blooms.

Contemporary mixing studies by purposeful tracer releases are still an important tool in hydrography, for example, in the ESOP-2 (European Sub-Polar Ocean Programme) experiment which investigated convection in the Greenland Sea. In this EU-funded experiment in which ICES acted as project data centre, sulphurhexafluoride (SF_6) was released in the summer of 1996 in the centre of the convective gyre in the isopycnal range occupied by upper Arctic Intermediate Water. Open-ocean winter convection may be described as an annual mixing event, and several of these events are normally needed before the waters in the convective gyre have spread to the boundary currents, where they are entrained and finally exported from the gyre. Figure 8 shows the spreading of the SF_6, amounting to a horizontal mixing coefficient of $10^4 m^2 s^{-1}$ as an average over

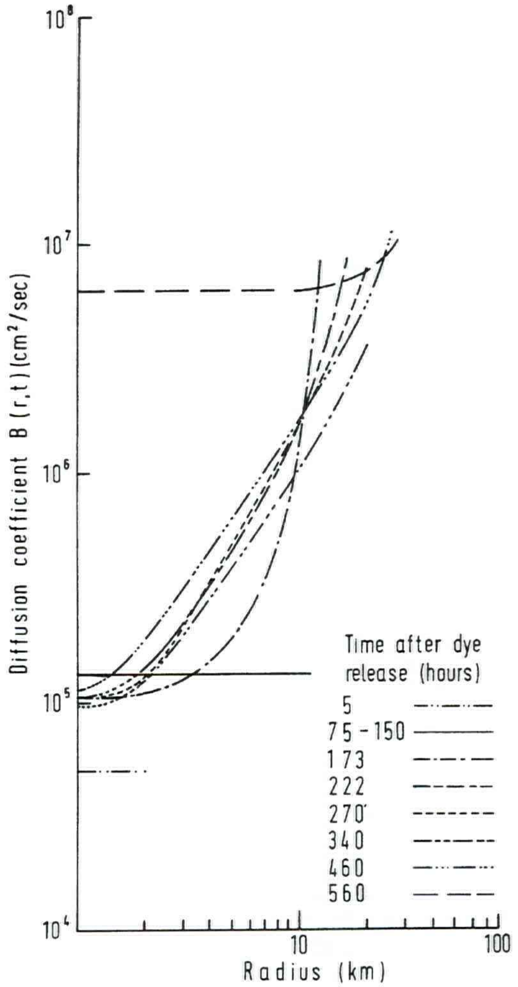


Figure 7. Diffusion coefficients for the central North Sea, as estimated from the RHENO data. Reproduced from Talbot and Sendner (1973).

the 2-year spreading period. It is only after 5 years that the SF_6 signal has begun to penetrate Fram Strait and Denmark Strait. This fact alone illustrates how much improvement has been made in the detection of tracers at low concentration.

Process studies III: patchiness in the sea

Since the advent of high-resolution measurements in space and time in the 1970s, it has become more and more apparent that physical, chemical, and biological parameters in the sea show a complex 4-dimensional structure, termed "patchiness". It is controlled by physical and biological processes, e.g., by a field of randomly distributed synoptic eddies or by up- and downwelling related to fields of Ekman divergences and convergences and the effects of frontal activity and mesoscale current filaments. The understanding of patchiness is important for the nutrient/plankton/fish interdependence or for the design of proper sampling schemes, such as are needed for monitoring programmes.

ICES was involved in the coordination of two pioneering field studies on the problem of patchiness: FLEX-76 and PEX-86 (Baltic Patchiness Experiment). In FLEX, the emphasis was on understanding the dynamics of the plankton spring bloom in relation to the development of stratification from winter homogeneity to summer vertical gradients. The FLEX area was the Fladen Ground in the northern North Sea, the FLEX period was 25 March to 15 June 1976. In the FLEX field programme, a central station was occupied continuously by at least one ship, and a total of 15 ships conducted current-meter work and spatial observations in the FLEX box around that central station. The results of FLEX are the most extensive data set ever available at such high temporal resolution, and marked the start of coupled physical-biological modelling (Figure 9), which has certainly grown in complexity since then.

Even though FLEX had provided high-resolution data on the development of plankton, nutrients, and stratification with time, the processes responsible for spatial patchiness were not known. Since the Baltic Sea shows such marked patchiness, suggestions within the ICES community resulted in the planning of PEX-86 under ICES coordination.

The objective was to obtain detailed maps of the distribution of the most important parameters and try to explain some of the dynamics by following the changes from day to day (Dybern and Hansen, 1989).

Following detailed planning of methods and logistics as well as intercalibrations and a four-vessel pilot study in 1985, the joint Baltic Patchiness Experiment, PEX-86, was launched in April/May 1986 during the vernal bloom in the central Baltic (Figure 10). Seven ships collected data in two grids; two ships were anchored, two took observations with towed instruments, and 12 moored current-meter arrays were in place. Satellite data were closely integrated into this study, which was the largest international cooperative marine science investigation in the Baltic. The ICES Oceanography and Environment Secretaries put a huge amount of effort into data quality control, with results edited by Dybern and Hansen (1989) and Dybern (1994). With the PEX data set, this ICES field study generated the most comprehensive data base to date into the spatial patchiness and related phenomenon (Figure 11). Consequently, coupled physical-biological modelling, (i.e., ecosystem modelling) is making use of these data for conceptual development, model initialization, and model verification. An example of a modelled distribution of chlorophyll *a* with mesoscale resolution for the Baltic is given in Figure 12.

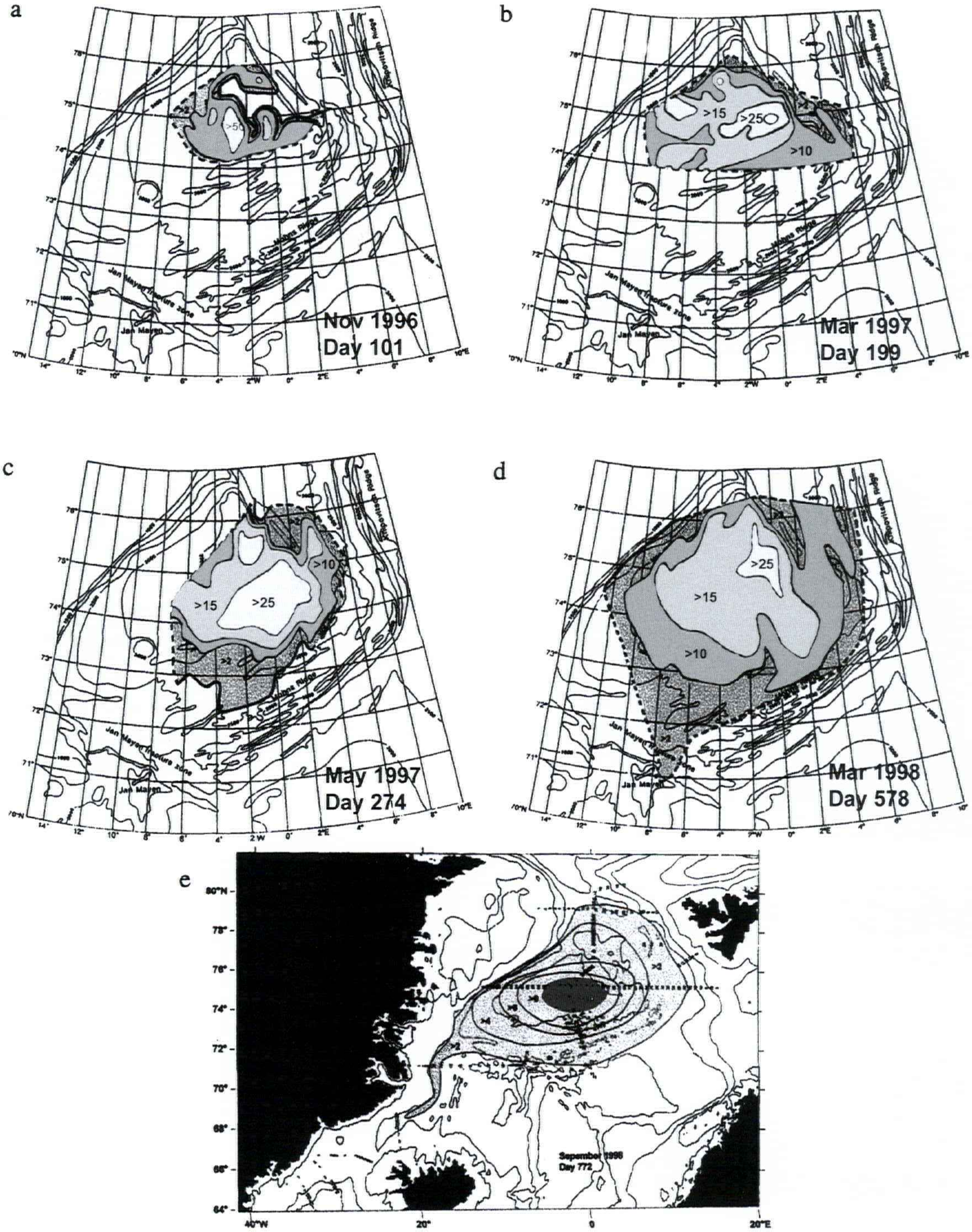


Figure 8. A large-scale diffusion experiment carried out by tracing the distribution of sulphurhexafluoride (SF_6) which was released into the central Greenland Sea in August 1996 during the ESOP-2 project. Contours are nmol m^{-2}: a) 101 days after release (November 1996), b) 199 days after release (March 1997), c) 274 days after release (May 1997), d) 578 days after release (March 1998), and e) 772 days after release (September 1998). Reproduced from Messias *et al.* (1999).

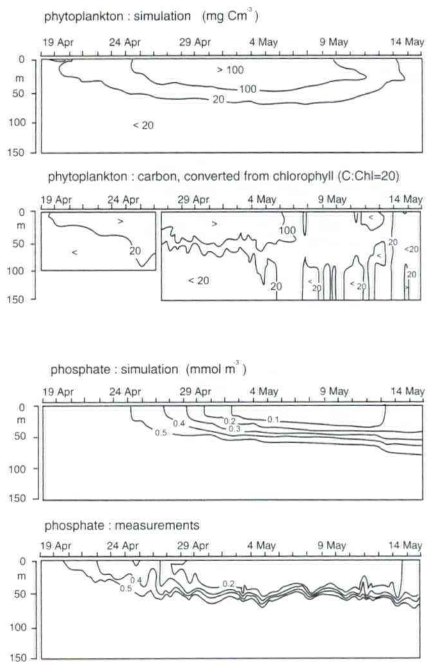


Figure 9. Simulated and observed development of phytoplankton and phosphate at the central station of the FLEX project in 1972. The model used was among the first in coupled physical-biological modelling. Reproduced from Radach (1983).

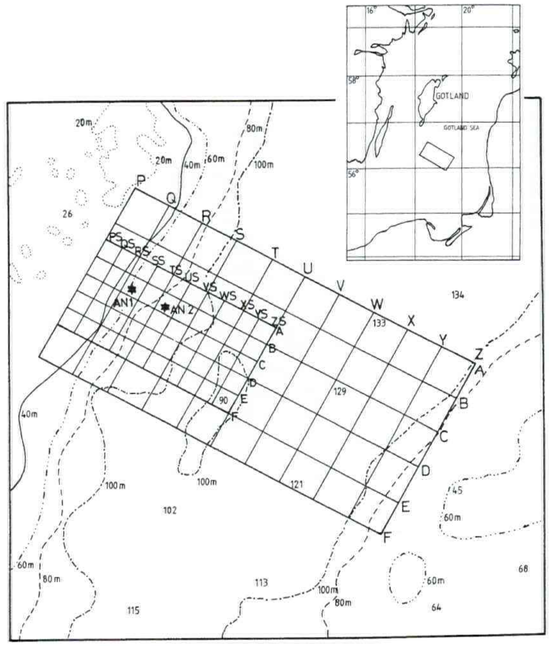


Figure 10. The two investigated station grids (the larger Eddy grid and the smaller Slope grid) and the positions of anchored vessels during the Baltic Patchiness Experiment in April 1986. Reproduced from Dybern and Hansen (1989).

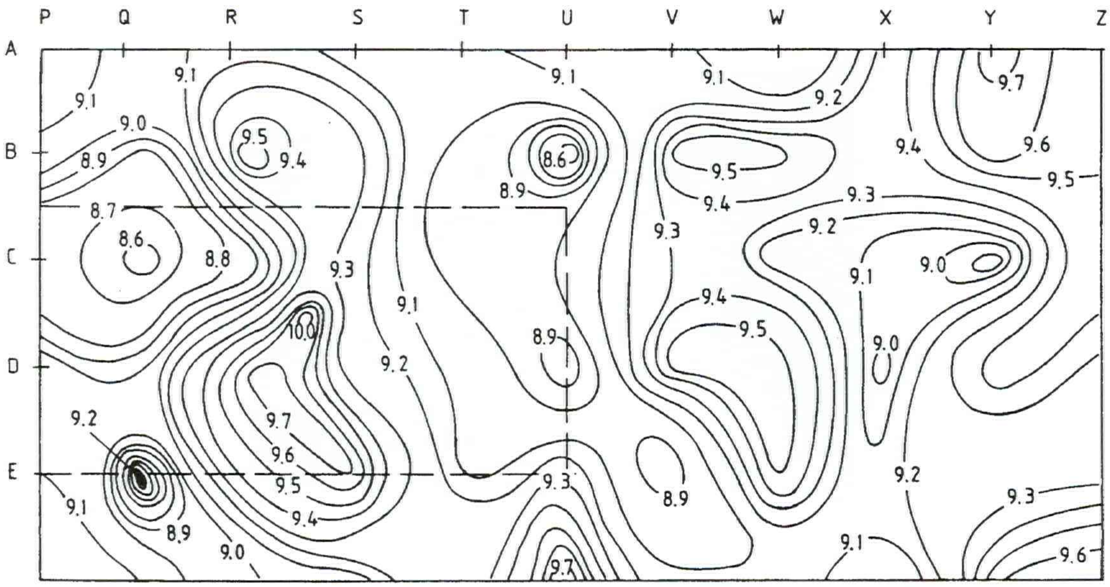


Figure 11. The observed mesoscale oxygen distribution for the Eddy grid on 25 April 1986 at the 10 dbar level. Reproduced from Dybern and Hansen (1989).

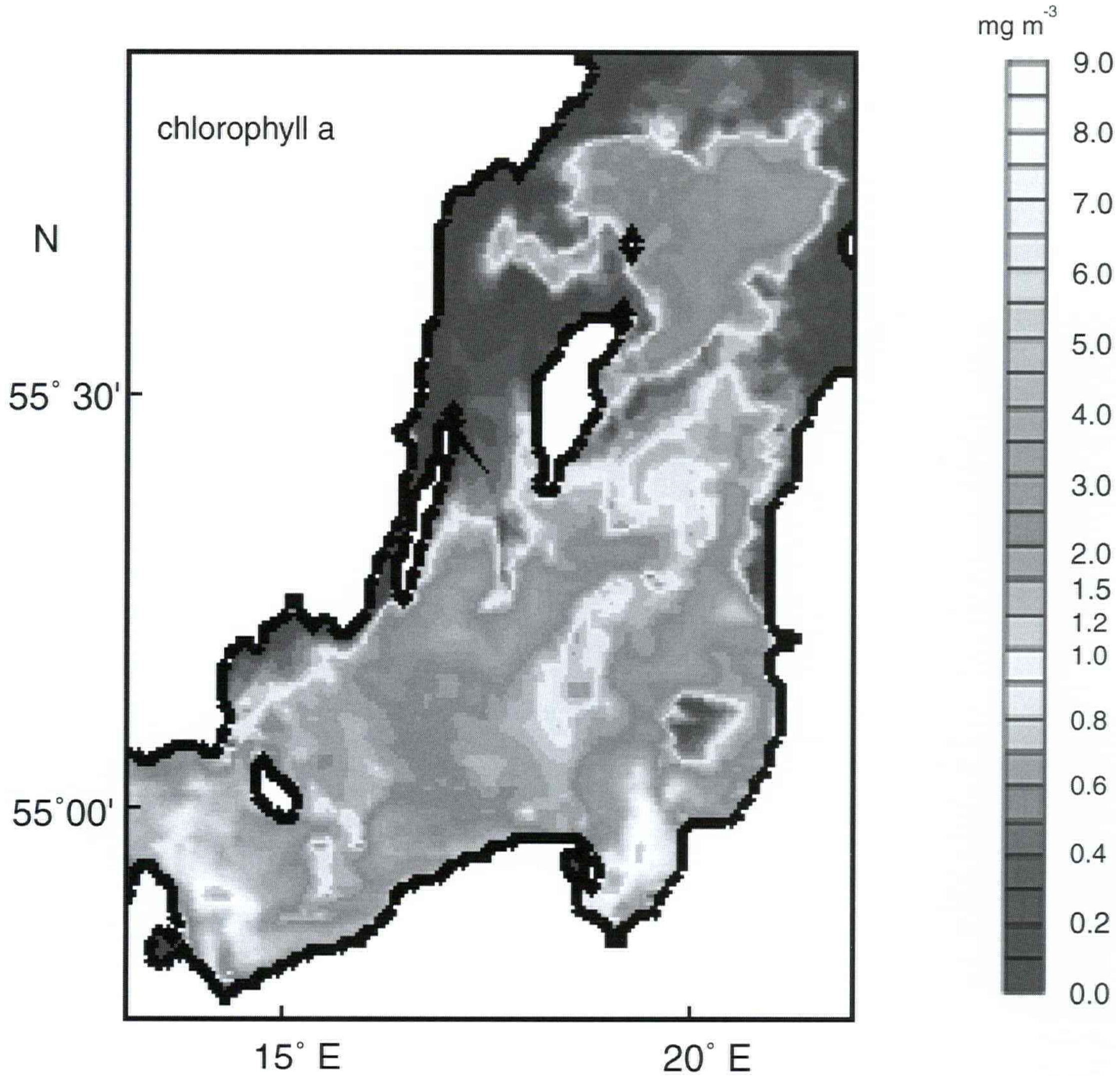


Figure 12. The modelled mesoscale distribution of chlorophyll *a* near the surface on 9 April 1986. The model is the coupled physical-biological model developed at the Institute of Baltic Sea Research, Warnemünde, Germany. Courtesy of W. Fennel and T. Neumann.

Monitoring environmental changes in ICES waters: the backbone of ICES hydrography

The last section of this contribution is devoted to the 1902 foundation stone and the backbone since then of ICES hydrography: organizing a continuous flow of hydrographical data into time-series and providing access to and analyses of them to the community. A careful account of this activity has been given by Smed (1968), the ICES Hydrographer from 1946 to 1984. The ICES work started with the quarterly international cruises in 1902 (Figure 13), which were highly coordinated in terms of cruise scheduling, modes and means of sampling, and measures for data quality, e.g., through the provision of Copenhagen Standard Seawater by the Council's Central Laboratory. The Hydrographer, a member of the Central Bureau, edited and published the data within one month of the completion of the cruises and prepared maps of surface temperature and salinity for the ICES area. This scheme was maintained until World War I. After the war, the international cruises became the business of independent, national contributions to ICES. They remained a major effort, and ICES continued to be the only authoritative organization for data archiving, quality-control, and dissemination of data lists and analyses in the North Atlantic area. This changed after World War II, with the political changes in the ICES area and with other governmental and inter-

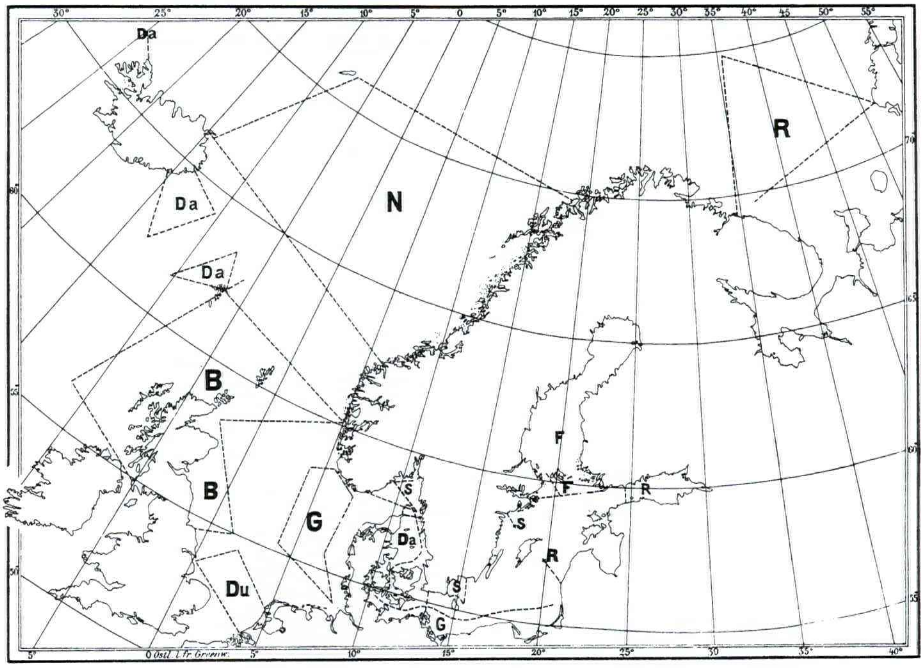


Figure 13. Hydrographic sections worked during the quarterly international cruises from 1902 to 1913. Letters denote nations providing the data. Reproduced from Smed (1983).

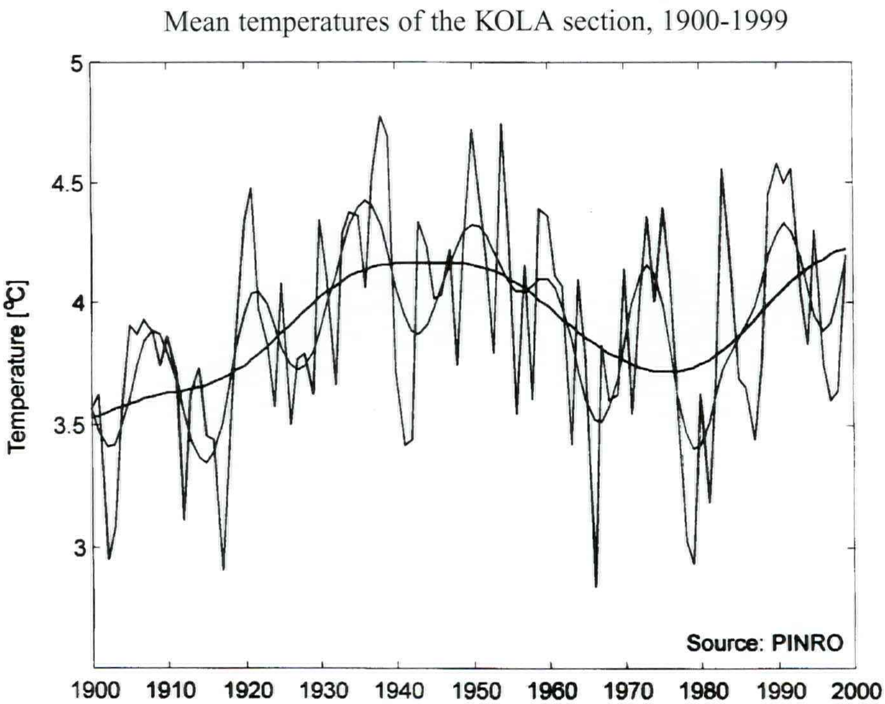


Figure 14. The 100-year time-series of temperature integrated over the upper 200 m along the Kola sections, carried out by the Fisheries Institute in Murmansk. The 10-year and the 30-year low-pass filtered series are also shown. Courtesy of PINRO, Murmansk.

governmental organizations entering the marine science field. ICES coped with this situation by actively maintaining a readiness for cooperation. The cooperation with ICNAF widened the North Atlantic area covered by regular hydrographic work to Greenland and the east coast of Canada, joint work with IOC/UNESCO panels led to much improved definitions and algorithms for the properties of seawater, and the tasks of newly founded regional commissions and the European Commission required considerable expert ICES advice on the measurement, data banking, and interpretation of environmental parameters.

The ability of ICES to provide a large and ever-growing stock of data on North Atlantic hydrography put ICES at the centre of numerous pioneering studies in the postwar period – examples of regional synoptic surveys and process studies have been given in previous chapters. The most eminent studies, however, are the ones that make use of the systematic collection of hydrographic data over a whole century. One hundred years of data do allow valuable analyses of the climate status of the North Atlantic region and its variability, which really was the initial mission of the ICES hydrographic work. The following examples cover a range of "products" from its long-term database.

The most obvious product is the compilation of atlas-type information on the mean state of the system. A well-known example is the atlas on "Mean Monthly Temperature and Salinity of the North Sea and Adjacent Water 1905–1954" (Dietrich, 1962), complemented by an atlas on "Monatskarten des Salzgehaltes der Nordsee, dargestellt für verschiedene Tiefenhorizonte" (Goedecke *et al.*, 1967).

These compilations have since served as references for the evaluation of time-series and as descriptions of the ocean's environmental status as well as for the validation of model results. Another product is the time-series from ICES standard sections. One example is given in Figure 14, which shows the fluctuations of the temperature of the Atlantic water inflow to the Barents Shelf as measured along the Kola section for 100 years. Another example is the time-series of derived quantities such as transports. Figure 15 shows Atlantic inflow and deep outflow through the Faroe–Shetland Channel, based on the 100-year hydrographic sections carried out by the Aberdeen Laboratory (Dye and Bigg, 1999). These numbers are among the most important parameters for assessing the climate variability and climate status of northwestern Europe. A third example of a product, illustrated in Figure 16, is the map of present-day ICES-ICNAF standard sections, analyzed annually by the ICES Working Group on Oceanic Hydrography. An "Annual ICES Ocean Climate Status Summary" is published for the guidance of climatologists and environmental and fisheries managers and scientists. This is an ICES contribution to GOOS (Global Ocean Observing System), the effort which attempts to provide a globally coordinated routine collection and dissemination of ocean data. An integrating product for all of these efforts is the scientific "Decadal Symposia on the Hydrobiological Variability in the ICES Area" and the relevant volumes of the *ICES Marine Science Symposia* series. The Symposia are organized by ICES once a decade to provide an integrated and interdisciplinary overview and interpretation of the changes observed in the North Atlantic marine system during each decade and have been extremely well received.

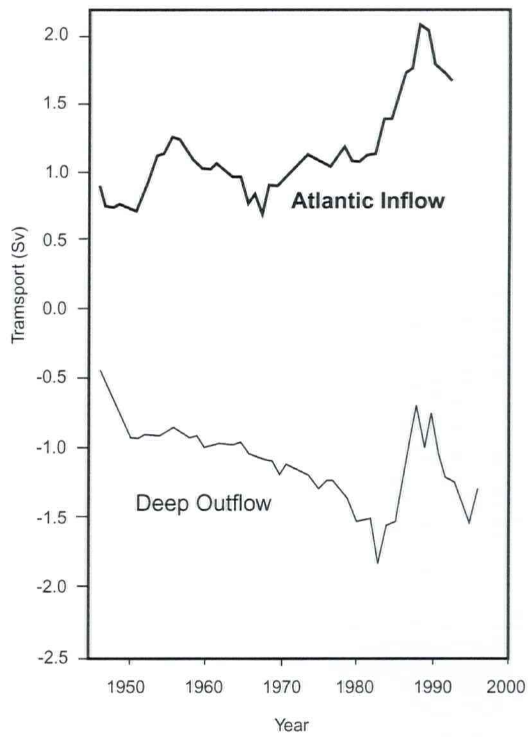


Figure 15. Time-series of Atlantic Inflow and Deep Outflow through the Faroe–Shetland Channel. The analysis of transports is based on inverse modelling for the inflow and simple geostrophic estimates for the outflow. Reproduced from Dye and Bigg (1999).

ICES today: how to keep its impact on North Atlantic hydrography

ICES is an international, intergovernmental organization for the North Atlantic marine system which has operated now for 100 years along the lines set out in the introduction. ICES has changed from being the only authoritative marine organization in the North Atlantic area to being one of several such organizations during the second half of its existence. The examples of ICES activities presented in the foregoing sections have clearly shown their impact in advancing our knowledge of

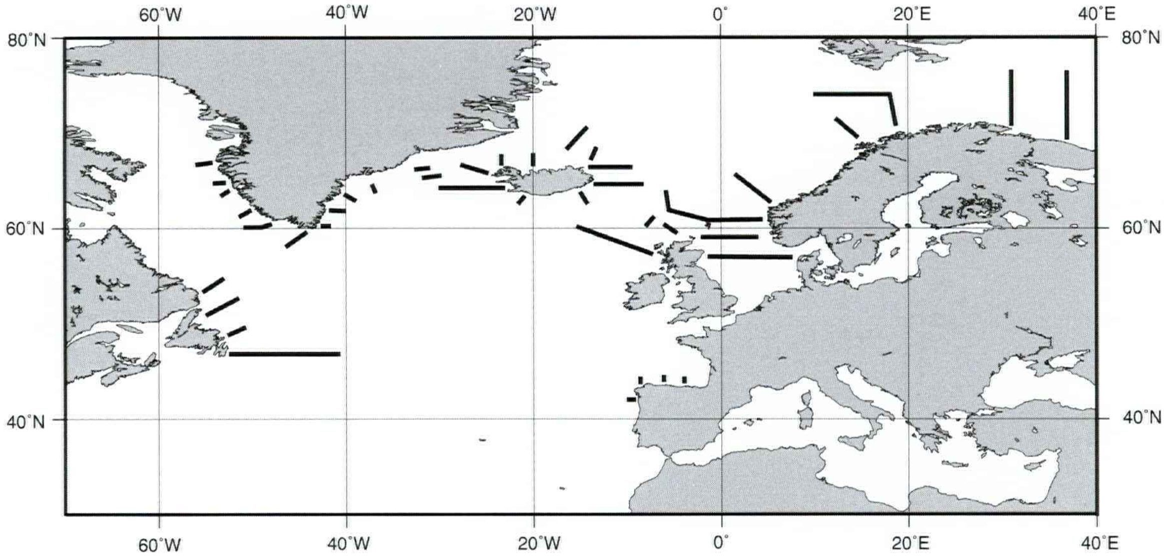


Figure 16. The set of present-day standard sections used in the annual ICES Ocean Climate Status Summary, prepared by the ICES Working Group on Oceanic Hydrography (W. Turrell, ed.).

physical conditions and their variability in the North Atlantic. ICES has initiated and coordinated most of the pioneering studies needed to assess the role of physical processes in shaping environmental conditions. ICES has been successful in its work because its activities have been and are carried out by working scientists, both from applied and basic science, who found highly attractive opportunities for joint planning, access to ship time, professional data service, and publications and symposia. As a result, ICES hydrography can be characterized by a balanced give-and-take between an organization geared to monitoring the physical conditions in the sea and the needs of "academia" in providing new insights into marine systems and a process at work.

With growing financial pressure on national contributions to ICES in the form of ship time and scientists and with the European Commission providing considerable funds for work on a short-term project basis, there is a tendency for the ICES work spectrum to narrow down towards the most "applied" aspects of advice in fisheries and environmental management. This will make ICES less attractive to scientists from basic fields of marine science and will certainly decrease the impact of ICES on North Atlantic hydrography, and vice versa. This would be detrimental to the unique role of ICES as an organization driven by the science necessary to serve its mission. Hydrographers should realize that the undisputed existence of ICES is related to the permanent need for a long-term sustained fishery, which implies developing our understanding of the marine environment. Therefore, hydrographers in close contact with fisheries and environmental groups should thoroughly investigate the impacts that hydrography has on modern management issues in ICES and a well-justified, integrated approach to future ICES activities should depict hydrography as a balanced and varied effort between long-term data collection, necessary process studies, and ecosystem modelling. Described in this way, ICES hydrography should be of continuing mutual interest to both the Contracting Parties and the North Atlantic hydrographic community.

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