INTERNATIONAL HYDROGRAPHIC INVESTIGATIONS IN THE NORTH SEA

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INTRODUCTION AND WORKING PROGRAMME

The closer international cooperation becomes, the more fruitful hydrographic and fishery-biological studies will be. Bearing this in mind, the International Council for the Exploration of the Sea, in the course of its annual meeting held in October 1959 at Copenhagen, made a change as regards the working methods so far applied in herring investigations. This change will stand out as a significant event in the history of the investigation of commercial fish stock in the North Sea. As the output of herring fishing is subject to considerable fluctuations, which often lead to various unfortunate situations in the economic field, those countries taking part in the herring fishing season began early to define by scientific studies the data concerning this problem. In 1960, for the first time it was decided to study on an international basis the dispersal of herring larvae, of young and adult herring as well as of other commercial fish. The working methods for this International Conjoint Herring Survey 1960 were decided upon in Copenhagen. The knowledge of the annual pattern of the horizontal distribution of temperature and salinity as well as of the layer conditions of the water masses is part of the fundamental theory for the study of almost all hydrographic-biological questions. When considering the comparative data that exist in each individual case, it will not suffice to take mean conditions as the basis. In order to increase knowledge of what kind of connection there is between physico-chemical and fishery-biological phenomena, it is essential to understand correctly the hydrographic conditions prevailing during the relevant period of investigation. Thus, from the very beginning, hydrographic observations presented one of the main tasks of the Conjoint Herring Survey. Under the chairmanship of Mr. B. B. PARRISH (Scotland), who at the same time is the chairman of the Herring Committee of ICES (International Council for the Exploration of the Sea), the herring experts discussed in May, in London, the results of the first observations made on the herring stock, which were made between 26 February and 9 April 1960. In the course of this meeting, it was agreed to entrust the author of this contribution with the evaluation of all the hydrographic data. The processing has so far been carried out by means that were made available by the Deutsche Wissenschaftliche Kommission für Meeresforschung (German Scientific Commission for the

Exploration of the Sea), which acts as liaison between the Bundesernährungsministerium (Federal Ministry of Food) and ICES. The countries participating in the survey, their vessels, the number of hydrographic stations worked, and the number of temperature and salinity measurements carried out are listed in the following table :

International Conjoint Herring Survey I
(26 February - 9 April 1960)

Country	Vessel	Number of stations	Temperature observations $t°C$	Salinity determinations $S‰$
Denmark ...	*Mortensen*	32	100	99
England	*Ernest Holt*	49	98	96
Germany	*Anton Dohrn*	178	621	623
Netherlands .	*Willem Beukelsz*	84	344	340
	Amstel	42	42	40
	Eem	74	74	70
	Grebbe	54	54	54
	Ryn	30	30	29
	Texel	18	18	18
	Vecht	12	12	12
Scotland	*Scotia*	34	162	162
Total		604	1 555	1 543

International Conjoint Herring Survey II
(26 August - 13 October 1960)

Country	Vessel	Number of stations	Temperature observations $t°C$	Salinity determinations $S‰$
Denmark ...	*Dana*	79	221	221
England	*Sir Lancelot*	35	68	67
Germany	*Anton Dohrn*	177	1 038	898
Netherlands .	*Willem Beukelsz*	77	324	324
Scotland	*Scotia*	41	194	194
	Clupea	57	114	105
Total		466	1 959	1 809

For obtaining the horizontal distribution of the surface and bottom water masses, the layer conditions and their intensity, the North Sea was covered with networks of stations as illustrated in figs. 1 and 2. The two station and route charts of the research vessels give an idea of the position of the measuring points and, at the same time, the extent of the work contained in the table. Since the Netherlands ships *Amstel, Eem, Grebbe, Ryn, Texel* and *Vecht* did not undertake any series of measurements, their routes are not portrayed in fig. 1. However, their observations of the

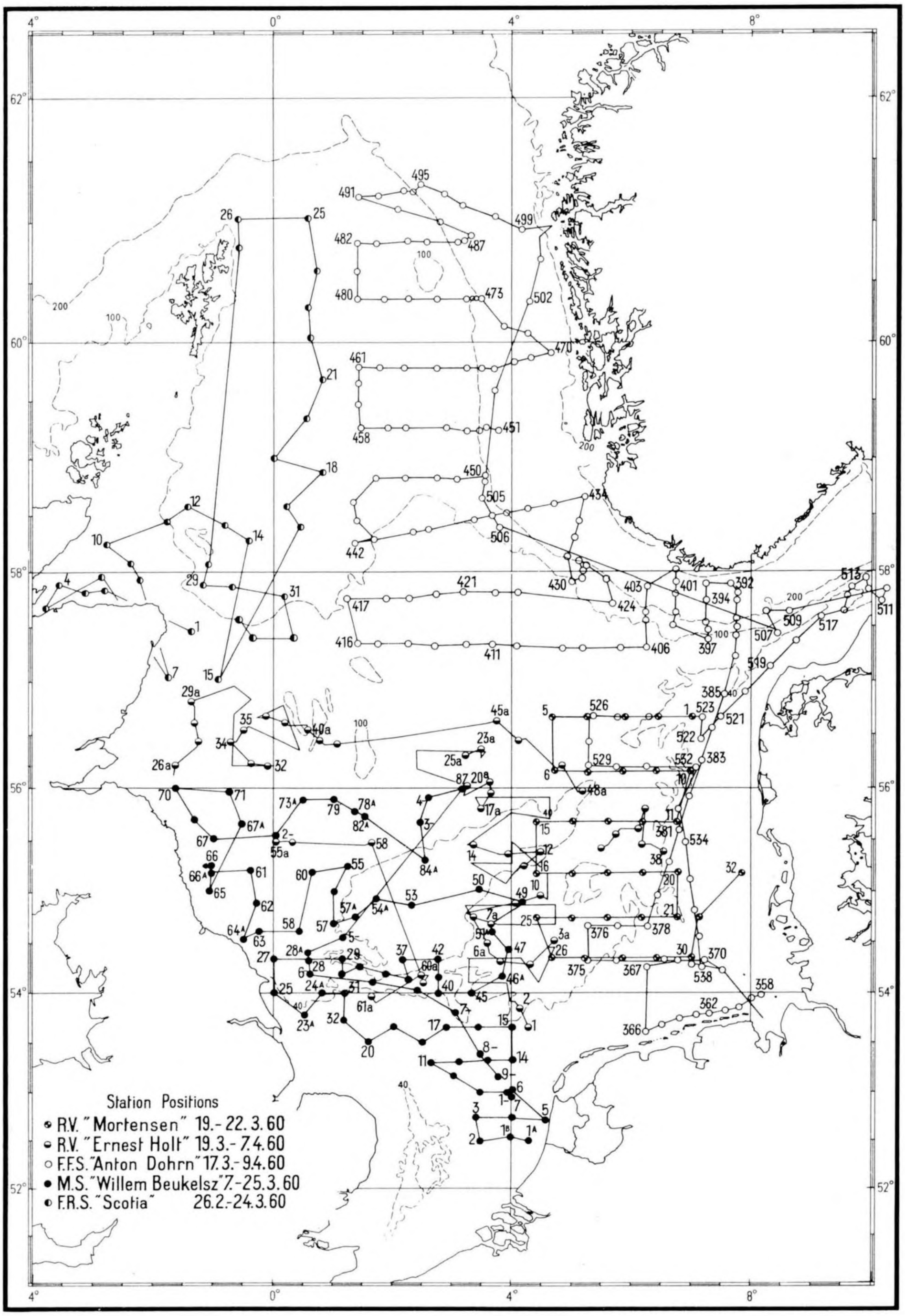

FIG. 1. — Route and station chart for the hydrographic investigations carried out during Conjoint Herring Survey I from 2 February to 9 April 1960.

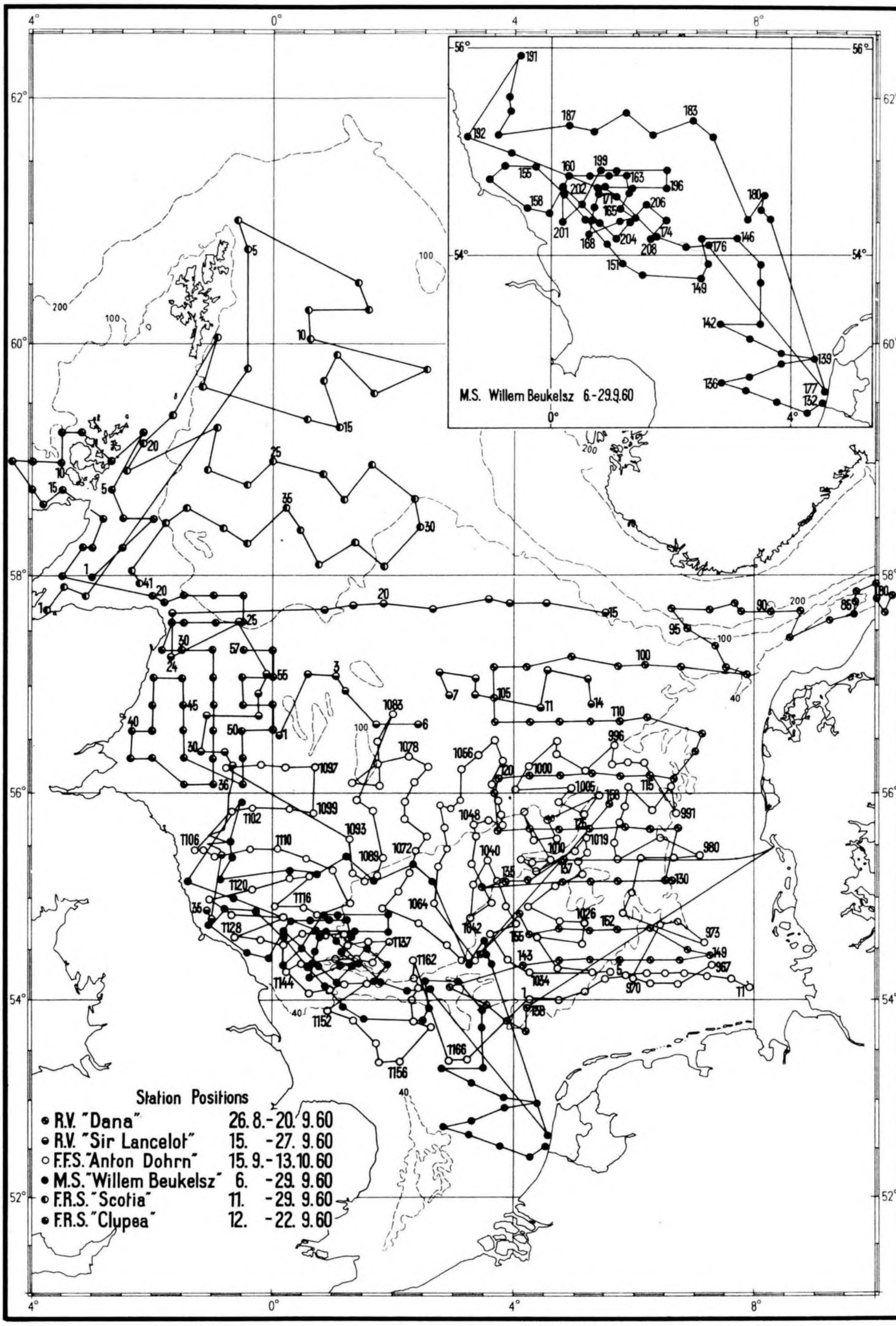

FIG. 2. — Route and station chart for the hydrographic investigations carried out during Conjoint Herring Survey II from 26 August to 13 October 1960.

surface temperature and simultaneous water sampling for obtaining the salinity distribution were an important contribution to the completion of the surface pattern in the region of the south-western North Sea. For position fixing, Decca was applied, the accuracy of which exceeds that of plotting positions on the charts. Owing to the fact that the cruise was planned mainly to study fishery-biological problems, it was not possible to determine the exact extent of all water masses nor to exclude any subjective interpretation when working on the hydrographic observations. The author is indebted to Mr. K. P. ANDERSEN, Mr. K. POPP-MADSEN, Copenhagen; Mr. R. E. CRAIG, Aberdeen; Mr. A. J. LEE, Lowestoft; Mr. J. A. van DUIJNEN MONTIJN, De Bilt; Mr. J. J. ZIJSTRA, Ijmuiden for providing the temperature measurements and the salinity determinations that were obtained on their research cruises. Such cooperation is a necessity for illustrating the hydrographic conditions which determine the *hydrographic milieu* where there is abundance of commercial fish. This contribution concentrates on the illustration of the hydrographic conditions prevailing from 26 February to 9 April and from 26 August to 13 October 1960 in bottom regions of the North Sea. It is to be expected that an international undertaking on such a scale can at present only supply partial results. In the first instance, the programme requires results which are of importance as basic material or as a comparative basis for fishery-biological investigations and fishing operations. As the long-term monthly means of the bottom water of the entire North Sea have not yet been ascertained, the answer to the question of the fluctuations of temperature and salinity values from the mean has to be limited to a few positions that are of significance in fishery-biological problems.

THE DISTRIBUTION OF WATER MASSES

The observations of the temperature and salinity distribution near the bottom, which are based on the charts published in this article, were obtained in the manner that is generally applied in oceanographic research. The temperature was measured by means of reversing thermometers. The mean error of the temperature measurements amounts to $< \pm 0.02°$ C. Bottom water samples taken by special samplers which close by means of a releasing gear, about 0.5 m above the sea floor. The salinity measurements of the water samples were made by chlorine titration with an accuracy of $\pm 0.02\,^0/_{00}$; by salinometers with a salinity mean error of $\pm 0.005\,^0/_{00}$; and by weighing using a torsion balance (K. KALLE, 1957), with which a maximum accuracy of $\pm 0.01\,^0/_{00}$ may be obtained.

The annual variation of temperature and salinity is derived from the sea surface where it is defined in terms of annual meteorological observations. While the water temperature depends on the annual pattern of the radiation of the sun and atmosphere, the salinity varies according to the evaporation, precipitation, formation and melting of sea ice, and on the supply of fresh water from the continental land mass. In accordance with the degree of convection and turbulence, as well as with advective processes, the deeper layers of water are also included in this general process which varies with longitude (G. DIETRICH, 1949, 1950).

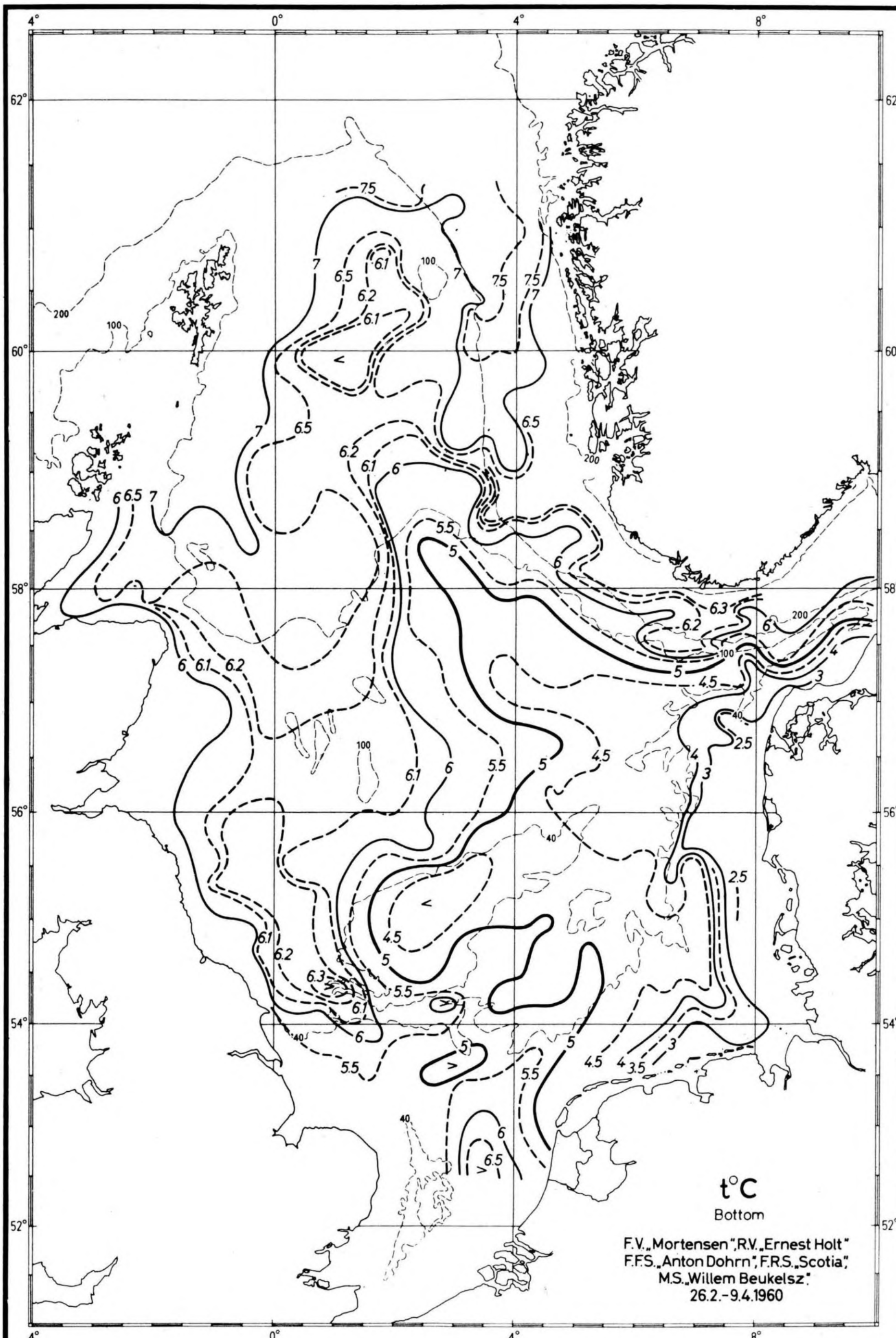

FIG. 3. — Temperature distribution at the bottom of the North Sea according to observations made during Conjoint Herring Survey I for the period between 26 February and 9 April 1960.

Between 26 February and 9 April the heat exchange between atmosphere and sea surface is insignificant. Within the larger part of the North Sea mixing of the water masses due to the winter cooling takes place down to the bottom. In spite of this, fig. 3 shows notable variations in the distribution of the bottom temperature, this largely accounts for the horizontal distribution processes of the water masses. In a shelf sea the data relating to all hydrographic factors are subject not only to pronounced annual changes but to changing weather conditions as well, which, in the case of the North Sea, might affect the entire water column. Thus, the assumption that a certain relationship exists between the meteorological factors affecting the surface water and the distribution and movements of the bottom waters appears to be well justified. To facilitate marine biological-hydrographic investigations, G. WURLITZER (1960) prepared a report in which he described the weather conditions prevailing during Herring Survey I. Towards the end of the winter, a decreased zonal circulation prevailed over the Atlantic-European region. From February to March the cold centre of the lower troposphere moved to the inner Polar basin. North America and North Asia were covered by pronounced tongues of cold air. Between these two regions of cold air, a warm air mass moved across Europe in March towards the Polar region. In accordance with this temperature distribution, the large-scale atmospheric circulation from 26 February until 8 April 1960 showed a wedge of high pressure over Europe. This pattern is about normal. In March these seasonal characteristics became particularly marked. The high pressure, that is normal for the eastern region of the North Sea, had intensified on the one hand, whilst on the other hand an unusually low pressure area covered the Atlantic. As in higher levels, the southerly current also increased in the lower levels as compared with the preceding month. Until April, a southerly current prevailed over Europe, which had an easterly component over the North Sea. The deviations from the long-term mean value (1899-1939) showed a negative anomaly over the Atlantic which could already be observed there in February. The positive pressure anomaly had moved from the Polar region to Finland. Both these pressure distribution anomalies established, in March 1960, the abnormal intensification of the usual southerly circulation over Europe. The extension of the positive pressure anomaly that spread to the south-western North Sea accounts for the fact that the southerly to south-westerly winds, which normally prevail over the southern North Sea, backed south to south-east in March. From the end of February until the beginning of April the surface water of the North Sea was affected by a mean wind component from a predominantly east-south-east direction that characterized the changes in the pressure distribution. Since this exceptional wind is one to which additional importance must be given as, under its influence, the North Sea water between 56°30′ and 58°40′ could be displaced to approximately 2° E. The deviations of temperature from the normal pattern (the mean of 57 years, 1898-1954) can as yet only be given for a few 1°-squares. The long-term means for the bottom water of the North Sea are at present being calculated by E. GŒDECKE and G. TOMCZAK at the German Hydrographic Institute, Hamburg. The author is indebted to them for placing at his disposal the following hitherto unpublished data :

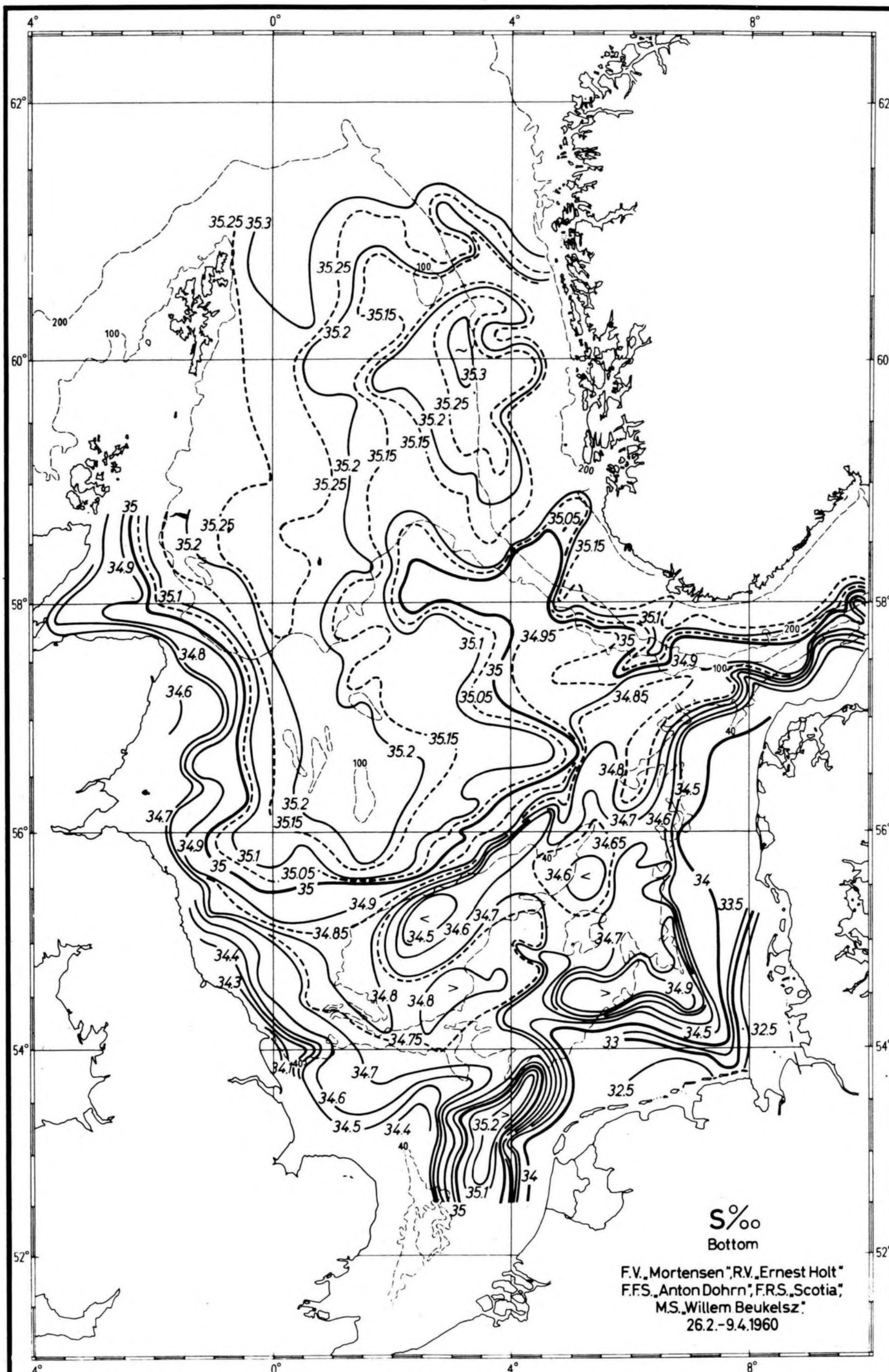

FIG. 4. — Salinity distribution along the bottom of the North Sea according to observations made during Conjoint Herring Survey I for the period between 26 February and 9 April 1960.

Region		t° C Period March 1898-1954	t° C March 1960	t° C
N	E			
1. 54°-55°	07°-08°	3.66	4.49	0.83
2. 55°-56°	05°-06°	4.61	4.55	—0.06
3. 56°-57°	00°-01°	6.23	6.15	—0.08
4. 52°-53°	03°-04°	5.27	6.23	0.96

While region 2 within the North Sea, which is a mixture of other water types, and region 3 in the North Atlantic indicate a slight temperature decrease from 0.06 to 0.08° C, the considerable temperature increase in regions 1 is explained by the continental inflow, and that of region 4 by the more intense than normal invasion of Atlantic Channel water into the Flemish Sea or Hoofden Region. Since systematic oceanographic research in the North Sea began more than 60 years ago, it has been known that in summer, under a relatively homothermal covering layer of a thickness of up to 40 m there exists a transition layer reaching down to relatively cold bottom water. So far, it has been assumed that this changeover is brought about by a gradual temperature decrease. At the bottom, within the central and northern North Sea, temperatures of 6° C were recorded even in mid-summer, which were almost the same as those at the surface during winter. Hence it might be concluded that this summer bottom water originates from the preceding winter. G. Dietrich (1955) pointed out that the assumption of a gradual temperature decrease with depth is related to a gradual increase in density, and that the latter makes turbulent motion difficult, but is not able to prevent it altogether. As long as vertical turbulence exists, the heat transfer will also extend down to the sea bottom. Under these circumstances, the winter temperatures could not remain constant until well into mid-summer and autumn. Physical theories, based on recent research on turbulence, require that the decrease in temperature and, consequently, the increase in density be confined to a thin intermediate layer. Winter temperatures can be maintained only if a thin discontinuity layer is present, which for vertical turbulence and thus for the downward heat balance assumes the character of an insulating layer. Fig. 5 demonstrates the temperature distribution of the bottom water that had been maintained because of the discontinuity layer in the central and nothern North Sea. The islands of cold bottom water, the extent of which is considerable each summer and whose location and temperature, especially when below 6.5° C, are thought to be of notable influence on the rate of migration and concentration of commercial fish (G. Dietrich, D. Sahrhage, K. Schubert, 1957). For the region between 56°-57° N and 01°-05° E a long-term mean temperature of 6.41° C was computed for September. The temperature deviations amounted to + 0.83° C in 1960. In the centres of both the cold water islands, temperatures of approximately 6.8° C were measured. For the region between 58°-60° N and 00°-01° E a mean value of 6.79° C was computed for September 1960. As the long-term mean of this region is not yet available, the temperature deviation from the normal of the bottom water found in the northern

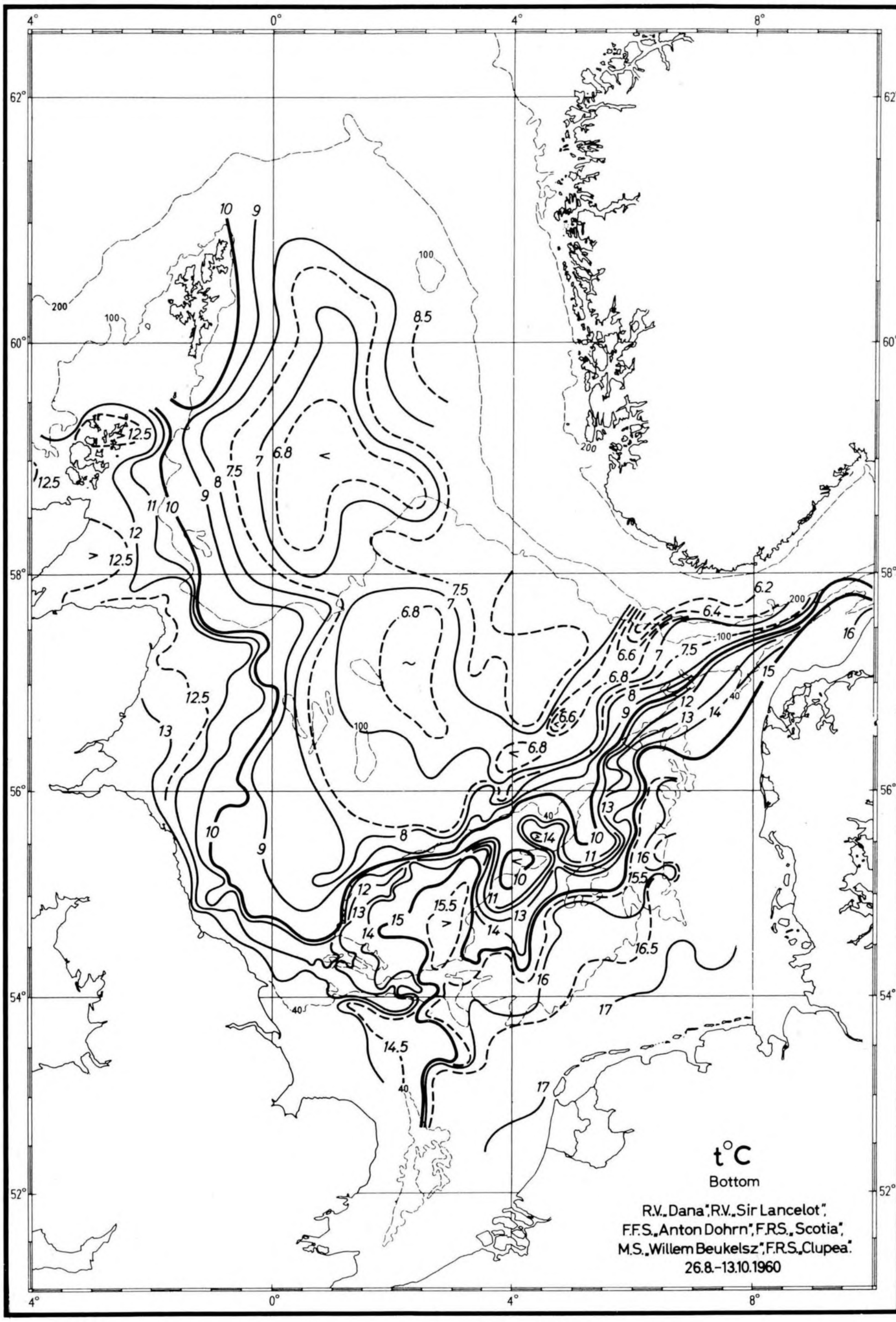

FIG. 5. — Temperature distribution along the bottom of the North Sea according to observations made during Conjoint Herring Survey II for the period between 26 August and 13 October 1960.

North Sea cannot be explained for the time being. At a latitude of about 57°50′ N the cold bottom water is concentrated in two centres, which are bounded by the 7°-isotherm. The warm and well-mixed water masses of the Scottish coastal regions are swept from west to east along the southern flank of the large cyclonic system of the northern Nort Sea, causing this separation between the two centres. To the south-east of the Dogger Bank, at 55° N and 4° E, a small area of cold bottom water with a temperature of 10° C was recorded. The water in question attained its temperature in spring before being stored under a strongly defined discontinuity layer. Furthermore, in Herring Survey I, G. WURLITZER (1961) has also analysed the weather conditions of the North Sea region for the period 26 August to 13 October 1960. At the beginning of July 1960, a strong, large-scale circulation of quite long duration commenced. The path of the low pressure areas ran from the west coast of North America across the North Atlantic to eastern Europe and was situated further south than is usually the case at this time of year. Over Europe this deviation from the normal pattern reached its maximum in September. It could sometimes be observed as a separate circulation over the Northern Hemisphere, and was associated with an extensive positive pressure anomaly above the Polar ice cap. From August until October the arctic high pressure reached as far as northern Europe, and during the month of September occasionally extended to central Europe. As is customary for frontal zones extending far southwards, weak gradients appeared on the Polar side so that variable current conditions prevailed over the North Sea. Following the mean distribution of atmospheric pressure for September 1960 over the North Sea, light to moderate winds prevailed from south-west to south and partly from the south-east. The illustration of the deviations from the long-term mean showed the existence of light to moderate easterly anomalous winds over the southern half of the North Sea in September, as well as during the last days of August and the first ten days of October. Over the northern North Sea they indicated a weak southerly component and were stronger. It is easily understood that due to the anomalous gradient, in contrast to the normal north-south pressure gradient found in these latitudes of the northern hemisphere, the dimensions of the current differ considerably in time. For separating the North Atlantic and the Channel water from the North Sea water, the 35 ‰-isohaline was chosen. The separation of the North Sea water from the continental coastal water and the Baltic water, as well as from the English coastal water, follows the 34 ‰-isohaline. As is evident from figs. 4 and 6, the area of the North Atlantic water has grown appreciably during Herring Survey II. With regard to the Atlantic Channel water, the contrary has been found. Apart from coastal regions affected by the inflow of river water, the water salinity near the bottom and its variations have to be attributed in the first instance to the water exchange with adjacent seas. Hence, from the changing pattern of the isohalines and the isotherms, conclusions may be drawn as to the current system. Not only would it be a waste of time to derive by theoretical methods the current system that would correspond to the actual conditions, but it would also be useless since the conditions are made even more complicated because of the continuous change in the meteorological situation.

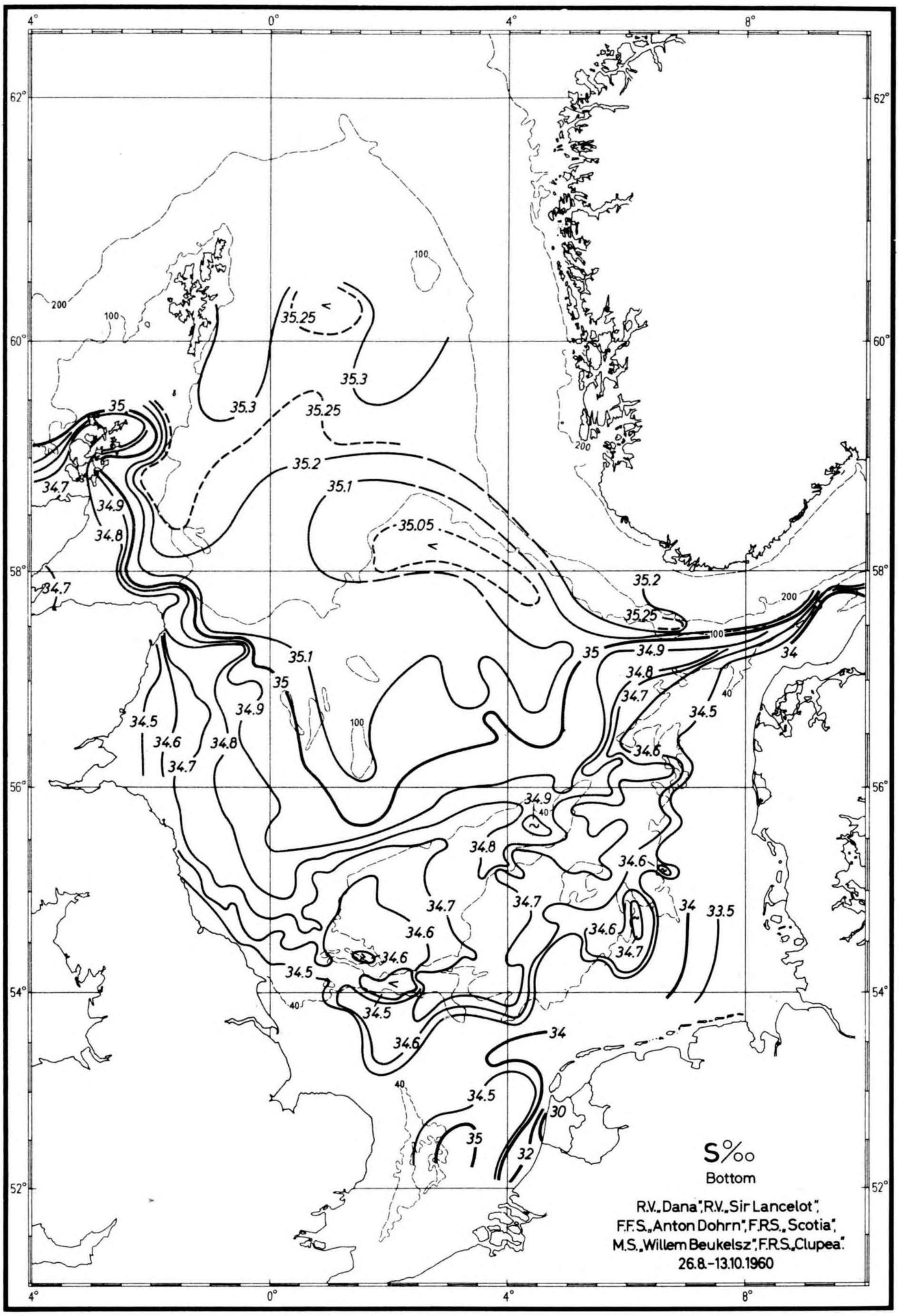

FIG. 6. — Salinity distribution along the bottom of the North Sea according to observations made during Conjoint Herring Survey II for the period between 26 August and 13 October 1960.

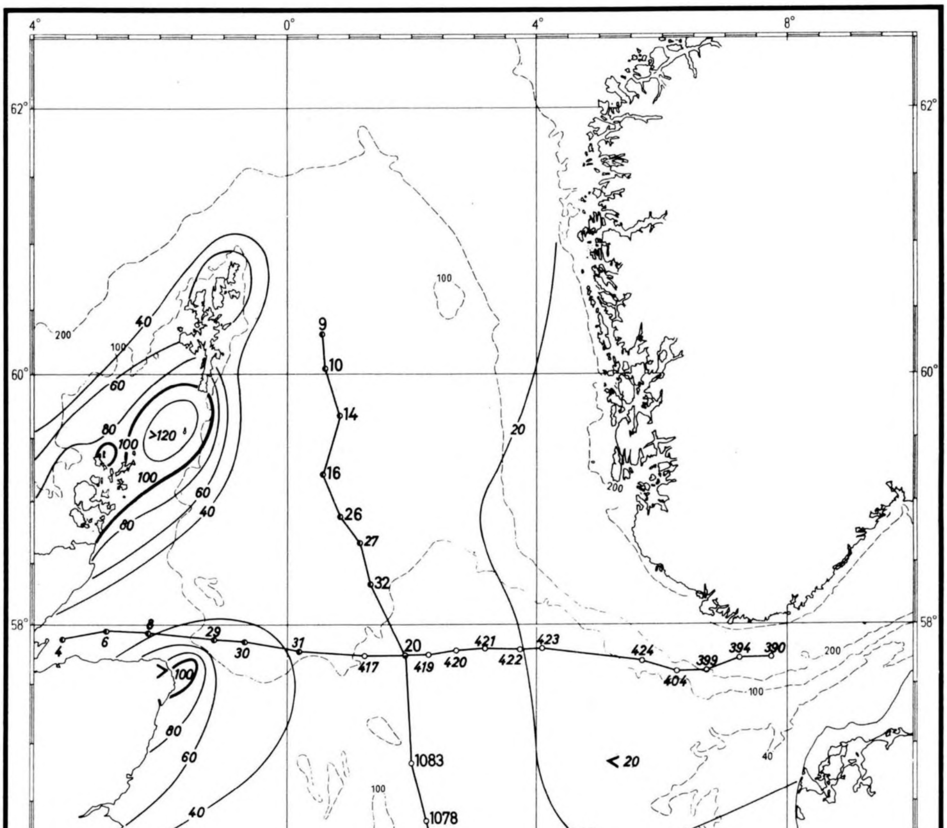

FIG. 7. — Lines of the vertical cross-section with hydrographic stations worked during the Conjoint Herring Survey 1960.
Maximum tidal current velocities on the surface at spring tide in cm/sec.

THE LAYERING OF WATER MASSES

As the physical heat conductivity of the water is insignificant, it is of no practical importance to the vertical heat transfer. The turbulent mixing process is decisive because it transfers this heat. The latter is governed by the heat balance involving the heat exchange due to radiation, by evaporation and by the direct heat transfer between the atmosphere and the water surface, as well as by the horizontal and vertical heat transfer due to sea currents and mixing processes. The cause of the turbulence may also be ascribed to gravity which ensures that heavier water sinks and lighter water rises. The layer conditions that were found in the North Sea between 27 February and 25 March, and between 7 and 26 September 1960 are portrayed in figs. 8-11. The line of both cross-sections is plotted in fig. 7. It was chosen in such a way that most of the water masses recognizable in the distribution charts (figs. 3-6) are shown in cross-section and their characteristic features are confirmed by as many measurements as possible. The observations upon which both profiles are based were ascertained by employing reversing thermometers which are fixed to the reversing water samplers. The cross-section cuts the North Sea between Tarbat Ness and Kristiansand from west to east. It begins with station 4 of FRS *Scotia* and ends with station 390 of FFS *Anton Dohrn*. The longitudinal section runs approximately from north to south and commences with station 9 of FRS *Scotia,* ending with station 135 of MS *Willem Beukelsz*. In addition, these charts contain the maximum velocities of the tidal streams at the surface during spring tides, expressed in cm/sec according to W. HANSEN (1947, 1950) and G. DIETRICH (1950, 1955). Due to winter cooling, which reaches its maximum in February, the convection movements of by far the largest part ot the North Sea penetrate down to the sea bottom. Figs. 8 and 9 give an idea of the vertical distribution of temperature and salinity and represent the state of total mixing. Only the region of the Norwegian trough represents an exception. The Baltic current is responsible for this as it transports cold and slightly saline Baltic water into the North Sea. Fig. 9 indicates the formation of a very well-marked saline layer. It is known that this layer is present the whole year through. A relatively thin homohaline covering layer of relatively low salinity is separated by a steep gradient from the slightly layered but very saline North Sea water. The accumulation of planktonic organisms is related to this discontinuity layer and, according to J.H. STEELE (1960), is supposed to be one of the causes for the concentration of schools of fish in search of food at the western flank of the Baltic current.

After the stable winter vertical temperature and salinity distribution, strong layering develops. It is characterized by a homothermal covering layer about 15 to 20 m thick, slowly penetrating into deeper levels at the beginning of the autumn convection until December, when again it is turned into the state of complete mixing. Figs. 10 and 11 give an idea of the layer distribution of temperature and salinity. It has already been pointed out that the vertical heat transfer which begins during the spring warming terminates by descending beneath the covering layer which is mixed by wind and waves. As the discontinuity layer becomes an insulating

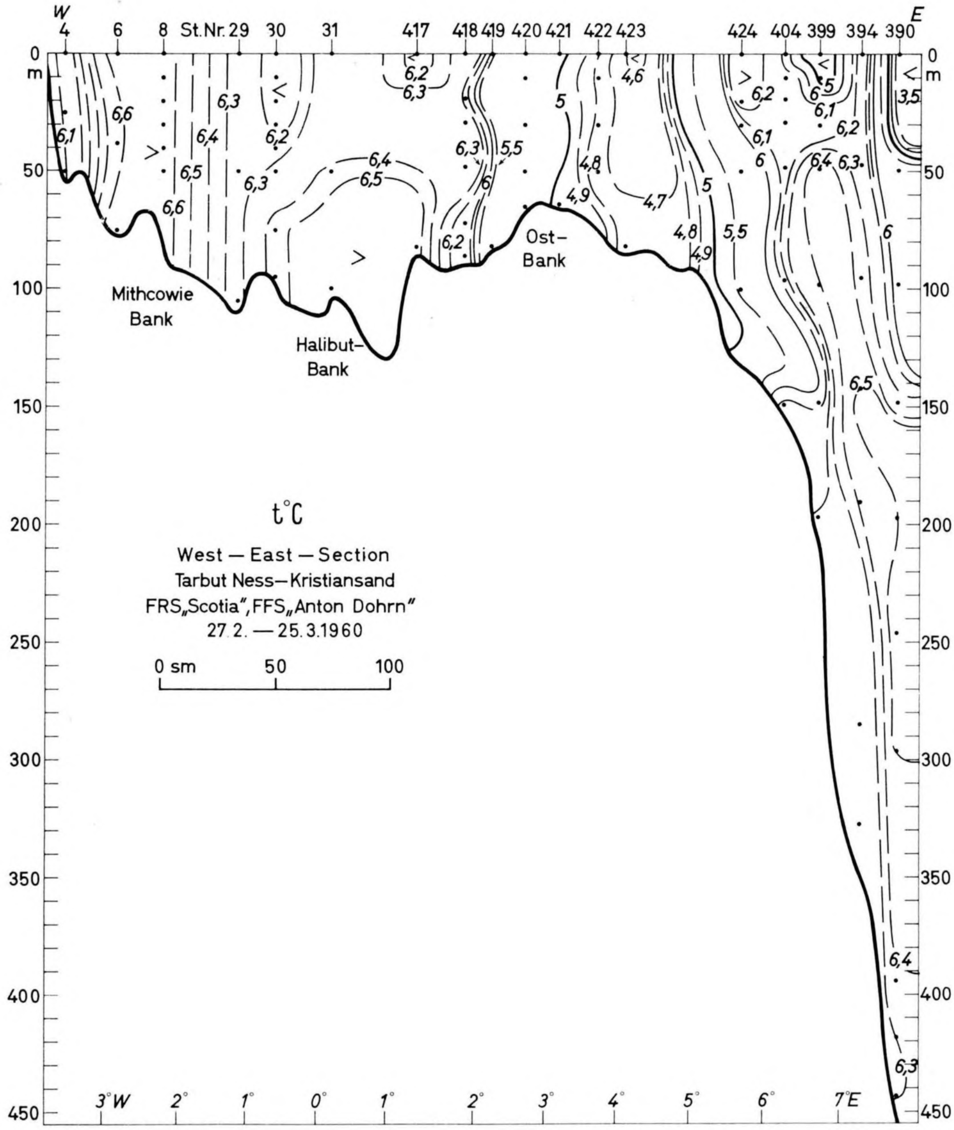

FIG. 8. — Temperature distribution at a vertical cross-section through the North Sea. The observations were made between 27 February and 25 March 1960.

layer for vertical turbulence, it separates two distinctly different zones in which the physico-chemical and biological processes also proceed entirely separately. Optical measurements of turbidity of the water (J. JOSEPH, 1950, 1950, 1961) proved that the turbid layer coincides with the thermocline in the North Sea. This turbidity should be regarded as a heavy accumulation of phyto- and zooplankton. So far, it is not exactly known why the discontinuity layer is preferred as biotop by the plankton, as the light at a depth of approximately 40 m (fig. 10) is already relatively weak when considered as the basis of all plant life. This suggests that the organisms are attracted by the summer discontinuity layer which is almost without turbulence. Fishery-biological investigations on the vertical

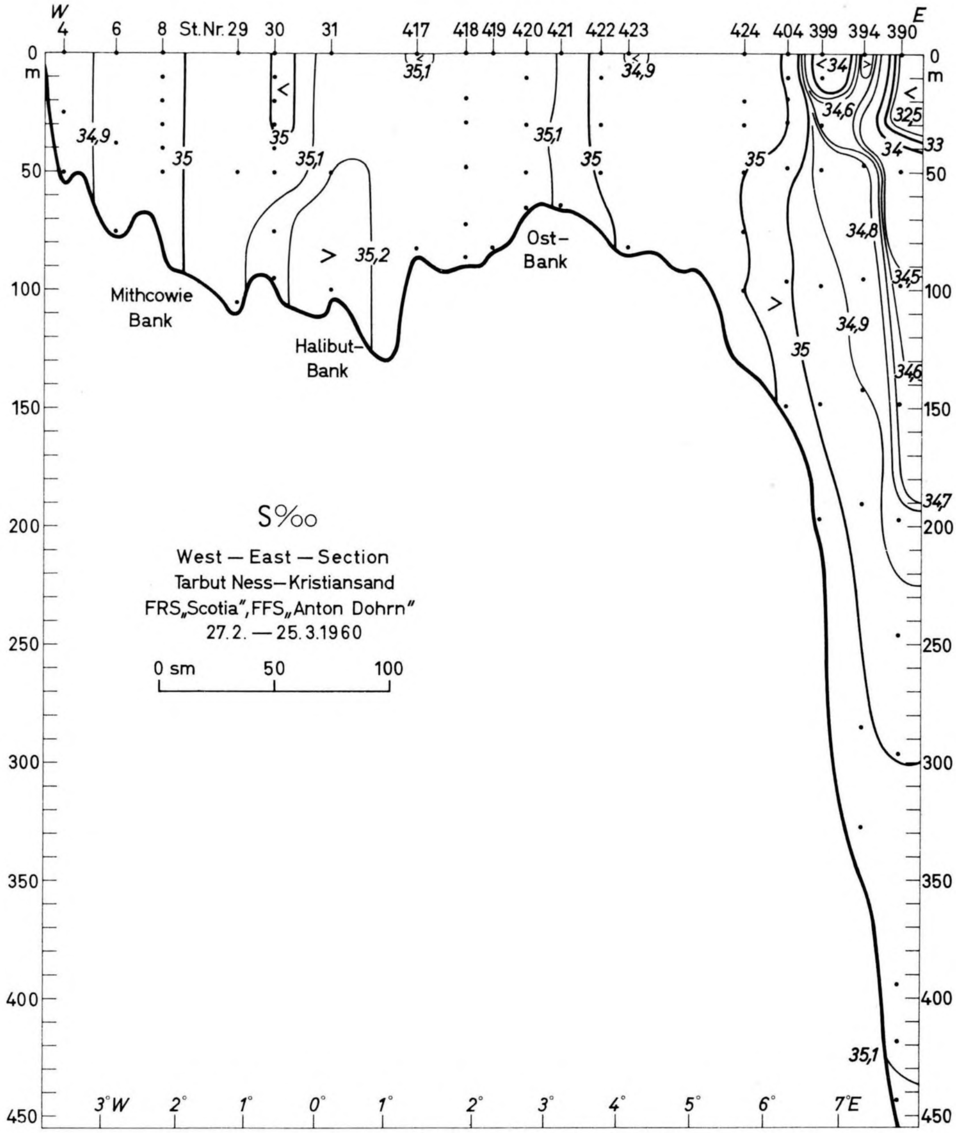

FIG. 9. — Salinity distribution at a vertical cross-section through the North Sea. The observations were made between 27 February and 25 March 1960.

behaviour of herring schools support the theory that the herring find rich food in the zooplankton for which they come up to a higher level at night. In this connection, the knowledge of the level of the thermocline is also of practical value to pelagic fisheries. Apart from the wind-produced turbulence, a tidal stream turbulence occurs at the surface. As is generally known, the tidal waves and thus the tidal streams affect the entire water column. The higher the velocities, the more intense the turbulence near the bottom will be, setting up the mixing of the sublayer. In the northern North Sea, where the tidal streams are weak according to fig. 7, the water of the sublayer masses shows a thermo-haline layering of oceanic character (figs. 10 and 11, north of station 16 of FRS *Scotia*). Within the central

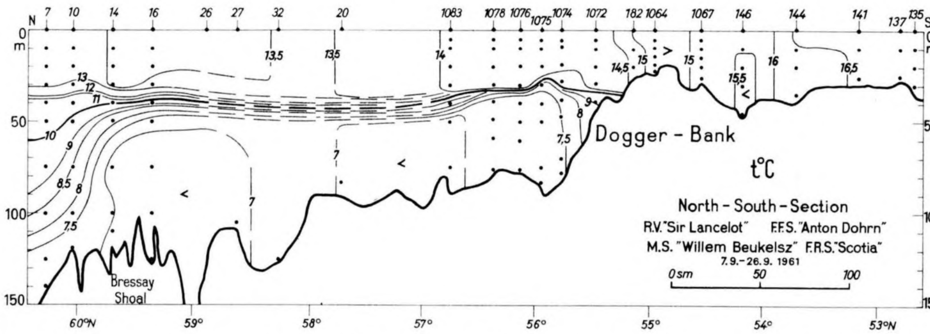

FIG. 10. — Temperature distribution along a north-south cross-section through the North Sea according to observations made during the Conjoint Herring Survey.

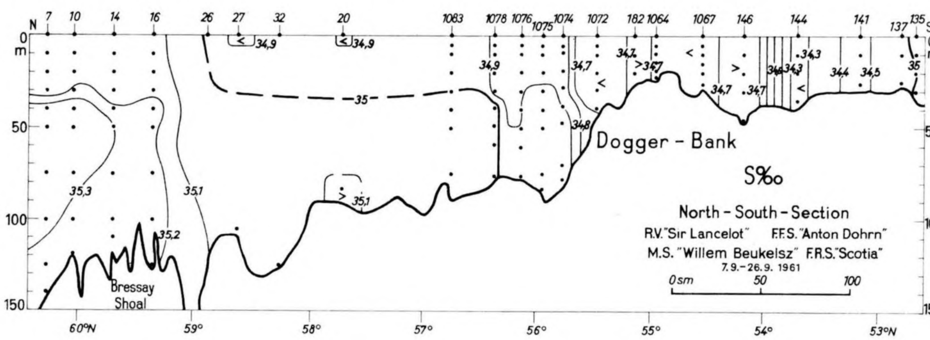

FIG. 11. — Salinity distribution along a north-south cross-section through the North Sea according to observations made during Conjoint Herring Survey II.

North Sea, where the tidal streams are stronger, the vertical mixing processes of the bottom water become clearly perceptible. Here the areas of cold homogeneous bottom water are maintained by a discontinuity layer (intermediate water) about 15 m thick. South of station 1 083 of FFS *Anton Dohrn* the discontinuity layer is narrowed down from the bottom to a distinctly marked area by the intense tidal stream mixing and terminates at a depth of 35 m at the northern edge of the Dogger Bank. As is demonstrated by the illustration of the intensity of the discontinuity layer (fig. 13), the strong tidal streams in the south-western North Sea and in Scottish waters together prevent the establishment of summer layering.

THE INTENSITY OF THE THERMAL LAYERING

The observations available do not permit a determination of the actual vertical temperature gradient of the discontinuity layer for all positions quoted in the station chart. Under these circumstances, one has to be satisfied with indicating the intensity of the discontinuity layer. By this one understands the total temperature decrease from the upper to the lower boundary of the discontinuity layer. This gives quite a useful indication of the intensity of the layering and is, in addition, easily ascertained. As may be seen from figs. 10 and 11, the summer thermal discontinuity layer in the North Sea separates the homogeneous covering layer from the homogeneous or slightly stratified sublayer. Since the covering layer and the bottom water are almost completely homothermal, the intensity of the discontinuity layer is obtained by the temperature difference between surface and bottom. The water column is considered to be thermally unstratified as long as the temperature difference between the covering water and the bottom water remains less than 1°. In marked areas of mixing, slight layering amounting to less than 1° may occasionally also occur when the weater is favourable for radiation. Fig. 12 indicates the distribution of Δt °C values for the research period of Herring Survey I and confirms fully the statements made in the previous paragraphs on the non-stratification of the larger part of the North Sea due to winter cooling and to the deep convection caused by it. The unique character of the Norwegian Trough region is due to the Baltic current. Its western boundary approximately corresponds to the 1°-isoline. The inflow of relatively warm Channel water of high salinity into the Hoofden Region and the rapid inflow of warm and very saline North Atlantic water at the western boundary of the Norwegian Trough produce an intensity of the layering of Δ-2 °C. From spring until autumn (fig. 13) the convective replacement of the bottom water within large parts of the North Sea is made impossible by the stability of the stratification. The completely secondary processes of diffusion and physical heat conduction do not have any important influence. The replacement of the bottom water is then limited to advective processes, and to the east restricted supplies come from unstratified regions. In the North Sea internal waves are apt to cause fluctuations within a certain range of the level of the discontinuity layer. A breakdown of the summer discontinuity layer from the sea bottom and, consequently, a decrease of its intensity only result from tidal streams. The changeover from the summer water stratification to the unstratified water found each year is dependent on a maximum tidal stream velocity of about 80 cm/sec (G. DIETRICH, 1950). In association with the narrow transition zone to high tidal stream velocities (fig. 7), the changeover from the stratified to the unstratified water along the Scottish and English east coasts also takes place within a relatively narrow zone. If, instead of the 1° isoline being selected at random, the 2° line is chosen (fig. 13), the boundary of the region of the unstratified water in the southern North Sea, in the German Bight, and off the Danish coast is not appreciably displaced.

SUMMARY AND CONCLUSIONS

In the course of the International Conjoint Herring Survey 1960 from 26 February until 9 April and from 26 August until 13 October, systematic fishery-biological-hydrographic investigations were carried out throughout the entire North Sea. Those vessels participating in the programme were from Great Britain, the Netherlands, Denmark and the Federal Republic of Germany. In order to obtain information as to the dispersal of herring larvae, the distribution of young herring, of adult herring stock and of other commercial fish in connection with hydrographic features, hydrographic observations were made at altogether 1 070 stations. They comprise 3 514 temperature observations and 3 352 salinity determinations. Studying the

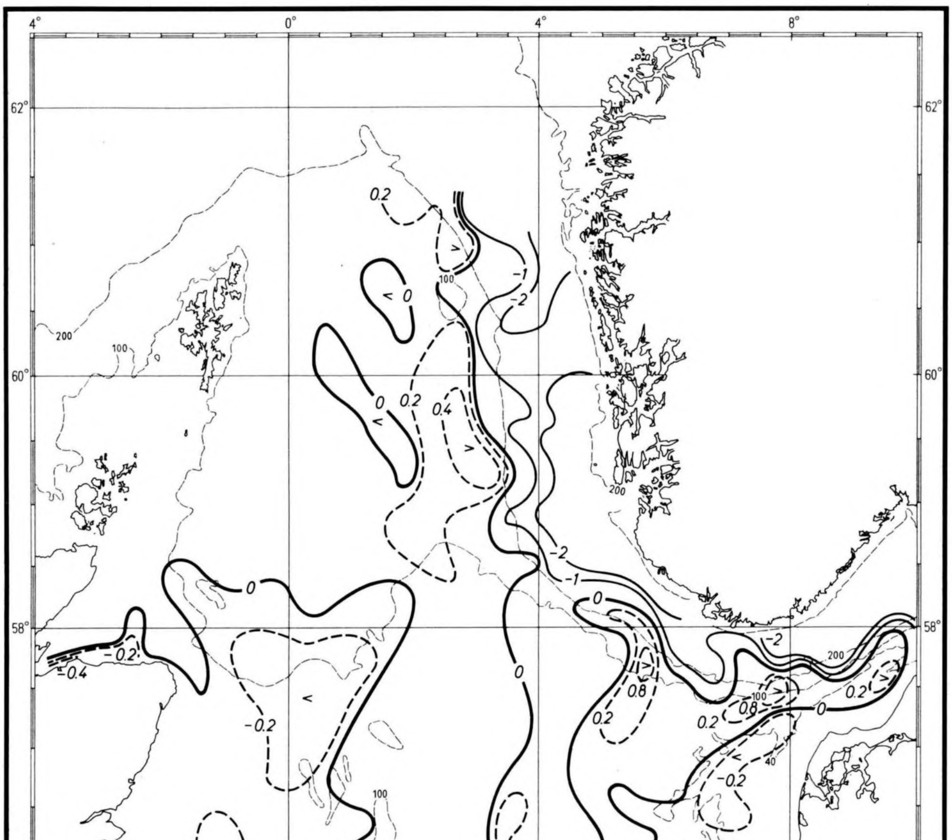

FIG. 12. — Intensity of the thermal layering during Herring Survey I from 26 February to 9 April 1960.

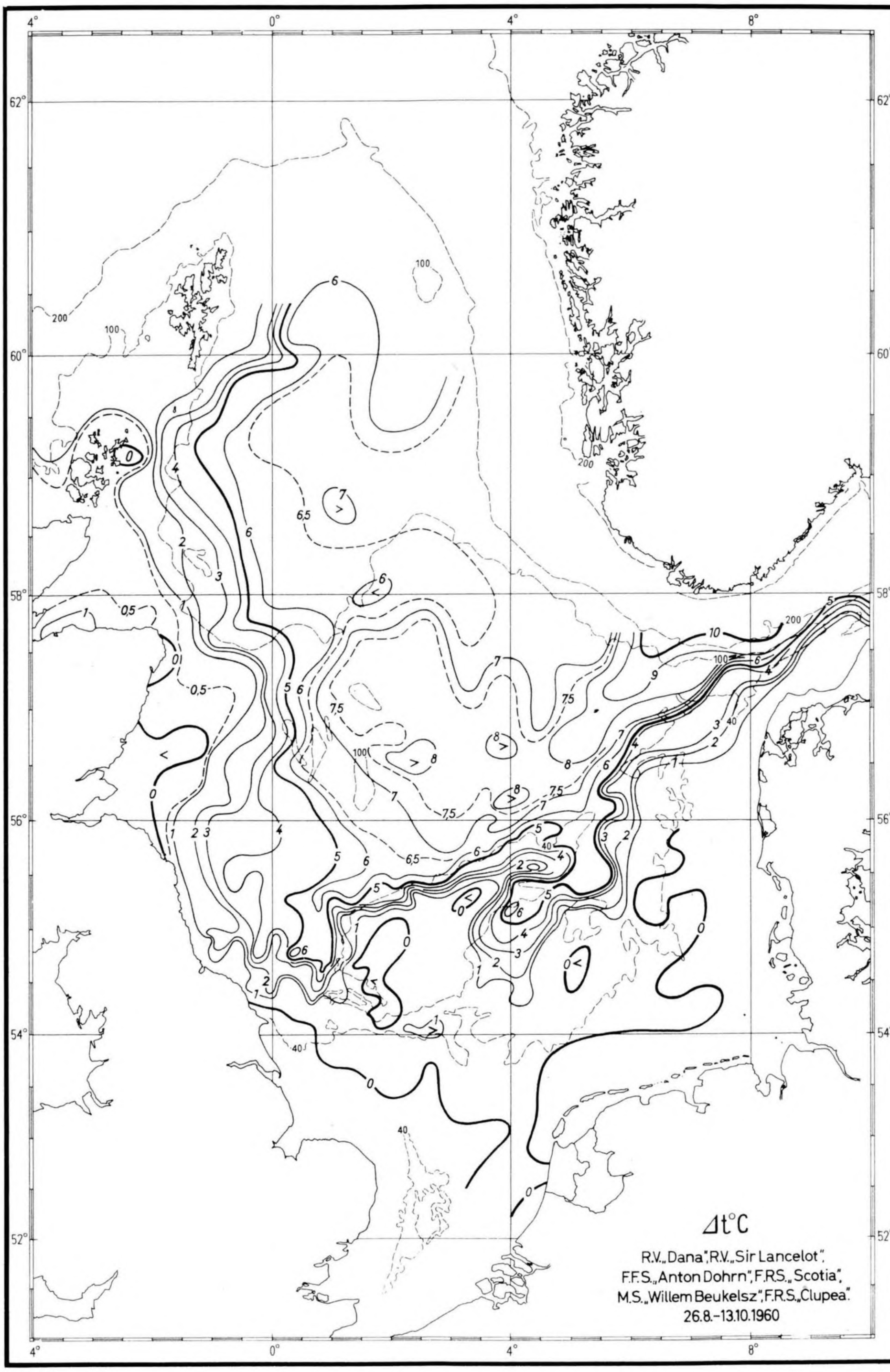

FIG. 13. — Intensity of the thermocline
during Herring Survey II from 26 August to 13 October 1960.

magnitude of the hydrographic phenomena which strongly affect life within this shelf sea has led numerous research workers to proceed under complettely different conditions. Efforts extending over many years were necessary to accomplish such excellent publications which not only added to our knowledge of the hydrography of the North Sea, but were also of value for oceanography. The illustrations of the hydrographic conditions near the bottom of the thermohaline layering conditions and of the intensity of the thermal layering are based on measurements carried out by a number of vessels and are given in this article in the form of 10 drawings. An almost synoptic working method was used which in the case of special problems, found in such a shallow tidal sea as the North Sea, gives a picture of the horizontal distribution of the water masses, their movement and their vertical structure. While on the one hand the problem of the migration, the concentration and the dispersal of fish is difficult to solve, on the other hand it is of considerable practical significance. The international investigations outlined are being continued in the year 1961.

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