GEOFYSISKE PUBLIKASJONER
GEOPHYSICA NORVEGICA
VOL. XXI NO. 3

DEEP WATER IN THE NORWEGIAN SEA

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FREMLAGT I VITENSKAPS-AKADEMIETS MØTE DEN 22DE MAI 1959
TRYKT MED BIDRAG FRA NORGES ALMENVITENSKAPELIGE FORSKNINGSRÅD

Summary. Deep water observations have been regularly collected from Weather Ship Station M (66° N, 2° E) since October 1948. They are studied against a broad background of data from the southern part of the Norwegian Sea, collected by the "Armauer Hansen" since 1914. Below a depth, varying from 200 to 800 m, the water is nearly homohaline, the salinity being 34.92 $^0/_{00}$. Due to the great number of observations it is, however, possible to detect minor fluctuations of salinity (Fig. 21) and also annual variations of temperature, salinity and oxygen content (Fig. 24, 27, 29). Maxima and minima occur simultaneously at all deep water levels, but they are out of phase with the seasonal variations of the surface layers.

A study of the possible processes of renewal of the deep layers leads to a physical model, from which conclusions are drawn as to the vertical distribution of temperature and salinity and also concerning the annual variations. It must be expected that the amplitude of temperature be proportional to the vertical temperature gradient and the amplitude of salinity be proportional to the salinity. Observations seem to agree with these conclusions.

When adopting for the eddy conductivity and the eddy diffusivity the same value $A_t = A_s = 2$ in cgs-units, one arrives at a rate of formation of bottom water of 27 m per year and a rate of renewal of the deep water of 14½ per cent per year.

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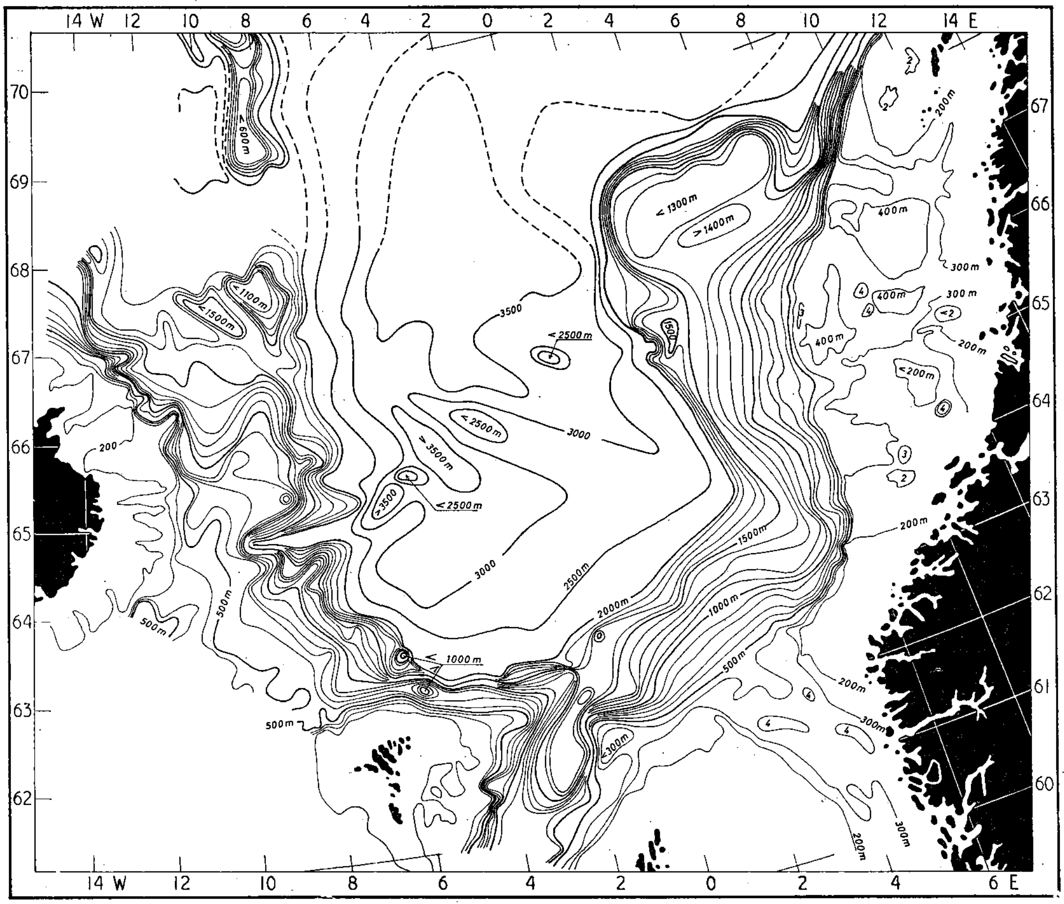


Fig. 1. Bathymetric features of the southern part of the Norwegian Sea.

Introduction. It is well known that the deeper parts of the Norwegian Sea are filled with water of low temperature and of nearly uniform salinity. These conditions were unveiled already during the first cruise of the "Michael Sars" in 1900 (HELLAND-HANSEN and NANSEN 1909).

Since October 1948 regular oceanographic observations have been carried out at Weather Ship Station M. These observations show great and rapid variations of the depth of the transitional layer between the Atlantic water and the homohaline water below (MOSBY 1950). It has not yet been possible to give a full explanation of these variations, reflections of which may be traced to considerable depths. It therefore appears necessary, also when studying possible variations of the bottom water, to consider the observational results of the entire surrounding area. Such information was obtained during cruises of the "Armauer Hansen", especially in 1935 and 1936.

Since possible changes of the bottom water will in any case be small, the accuracy

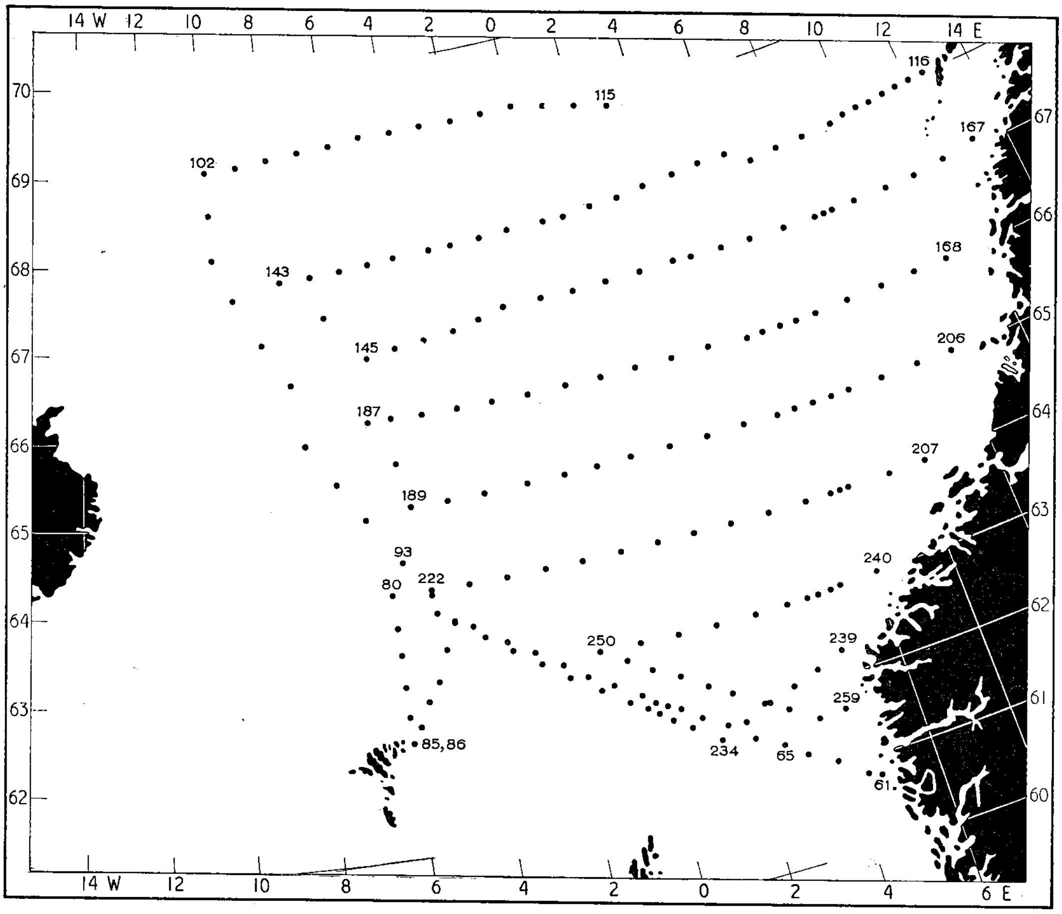


Fig. 2. "Armauer Hansen" stations 1935.

of the observations must be taken into consideration. All data treated below have been collected for, or under the supervision of, the Geophysical Institute, Bergen, where also all titrations have been carried out. Each step of the preparatory work has therefore been uniformly controlled, and it is believed that a high degree of comparability of all data has thus been secured. Possible systematic differences between data collected by different institutions have in this way been avoided.

1. Material of observations. *At Weather Ship Station M,* 66° N, 2° E, the vessels "Polarfront I" and "Polarfront II" have carried out serial observations within the homohaline deep layer 17 times per month on an average since October 1948. The data consist, partly of full series with observations at all standard levels down to 2500 m depth, partly of series with samples from a few standard levels down to 1000 m depth, in connection with temperature records by means of the thermo sonde (Mosby 1943). The mean monthly number of samples from the homohaline layer is 46.

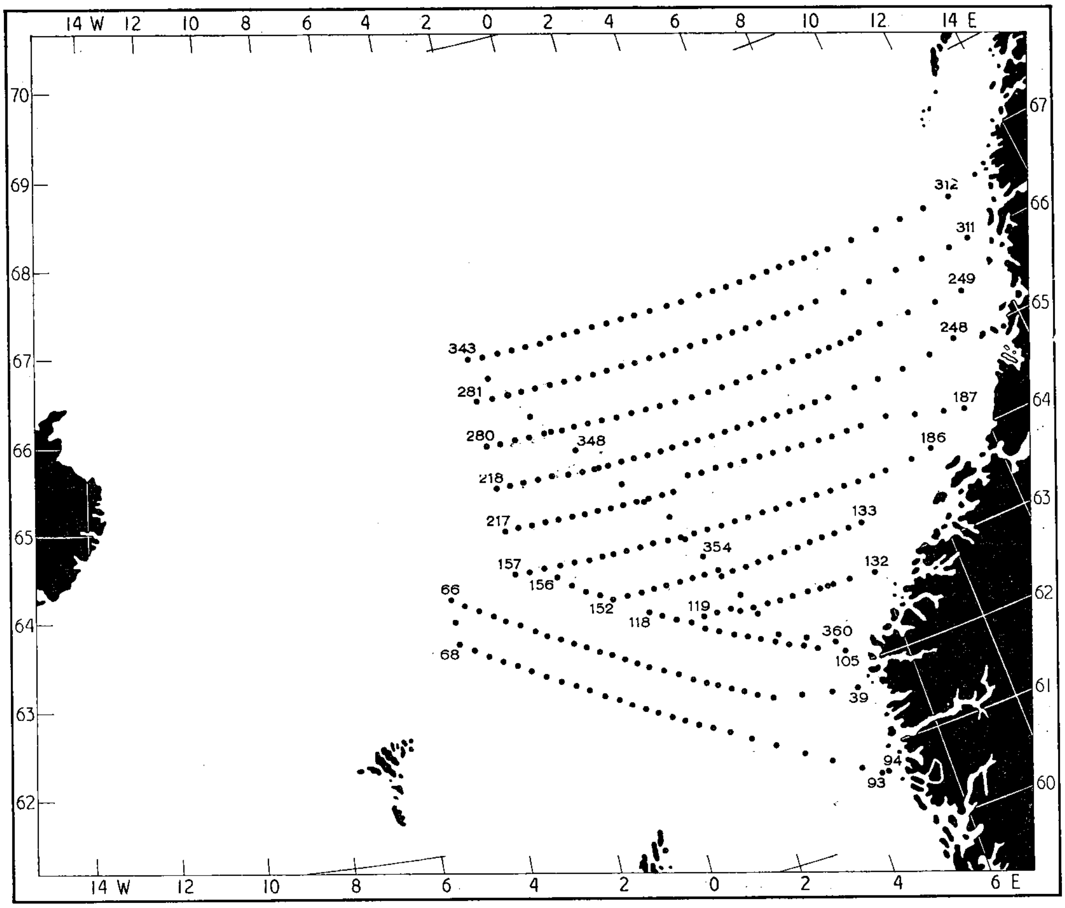


Fig. 3. "Armauer Hansen" stations 1936.

"Armauer Hansen" 1935. From 30th May to 22nd July 1935 the "Armauer Hansen" covered the southern part of the Norwegian Sea with a dense net of 199 stations, as seen from the map Fig. 2. Many of these stations were taken on the continental shelf, where the homohaline deep water does not occur; but from 136 stations a total number of 550 samples were obtained from waters of temperature below zero. During this cruise determinations of O_2, p_H and P_2O_5 were also carried out regularly. Unfortunately the echosounder did not function at depths greater than 1000 to 1400 m; the isobaths in Fig. 1 are mainly based on HELLAND-HANSEN and NANSEN's Bathymetrical Chart (1909) and additional data from the "Armauer Hansen" 1935, 1936 and later years.

"Armauer Hansen" 1936. From 9th June to 23rd July 1936 the "Armauer Hansen" covered the southeastern part of the Norwegian Sea with a still denser net of 312 stations, as seen from Fig. 3. Many of the stations were taken on the continental shelf,

but from 148 stations a total number of 608 samples were obtained from waters of temperature below zero. During this cruise temperature and salinity only were observed.

Sognefjord sections. Through the years the "Armauer Hansen" has carried out detailed observations along the so-called Sognefjord section, from the West Coast of Norway near Bergen towards the WNW to a distance from the coast of about 280 nautical miles (cf. the south-westernmost section, station 68 to 94, of Fig. 3). The dates when these sections were run and the number of deep water samples from each section will be seen from Table 14.

None of the tables of results from the investigations referred to have yet been published, but three of the Sognefjord sections have been treated by HELLAND-HANSEN (1934) and twentyseven by SÆLEN (1959). For the present investigation the complete information available from the original tables has been used, including the readings of each single thermometer and the results of each single titration.

2. Accuracy. *Temperature* was usually determined by means of two thermometers. The differences between corresponding readings yield some information on the accuracy with which the final temperatures are determined. In Table 1 are compiled numbers of cases in which half of the difference between corresponding readings amounted to the values given in the first column of the table. In 1935 and in 1936 temperatures were estimated to the nearest 0.005° C in about 20 per cent of the cases; such values have been counted as belonging to the group of a whole hundredth of a degree above and below by equal numbers to each group. From the Weather Ships nearly all temperatures are given to 0.01° C.

It is seen from Table 1 that in 1935 and 1936 half differences of more than 0.02° C only occur in about 0.5 per cent of the cases. The corresponding percentage from the

Table 1. *Accuracy of temperature determinations.*

t° C	1935	1936	St. M 1948–53
±0.000	174	243	724
.005	171	253	600
.010	30	164	503
.015	11	49	341
.020	2	4	185
.025	2		92
.03		1	56
.04		1	45
.05		1	81
Total	390	716	2627
> 0.02	0.5 %	0.5 %	10.4 %
Stand. dev.	0.006°	0.007°	0.015°

Weather Ship data from October 1948 to September 1953 is 10.4, and half differences of 0.05° or more occur in 3 per cent of the cases. This is due to the difficulty in obtaining perfectly functioning reversing thermometers during those years. For this same reason many temperatures have had to be determined by one thermometer only. The accuracy of the temperature values from the Weather Ships is thus considerably lower than that of the observations from 1935 and 1936. In 1935 and in 1936 the error of each temperature only very rarely exceeds *±0.02°*, the standard error being only 0.007°. For the Weather Ship data the error rarely exceeds ± *0.05°*, the standard error being 0.015°.

Salinity is always determined from at least two titrations; if the two diverge by more than 0.03 $^0/_{00}$, the sample is titrated a third or even, if necessary, a fourth time. As will be seen below, the salinities of particular interest for the present investigation usually occur at temperatures below zero, in some cases also at temperatures between 0 and +1° C. From these data we have complied in Table 2 the numbers of cases in which the difference between corresponding salinities amounted to the values as given in the first column of the table. It is seen that an error exceeding ± *0.01* $^0/_{00}$ only occurs in 4 to 5 per cent of the cases, the standard error being 0.0050 $^0/_{00}$.

Oxygen content. Samples for determination of the oxygen content were collected at Weather Ship Station M at each deep station and from the very beginning, i.e.

Table 2. *Accuracy of salinity determinations.*

S $^0/_{00}$	1935 $t < 0°$	1936 $t < 0°$	All
±0.000	92	80	172
.001	80	102	182
.002	81	98	179
.003	71	86	157
.004	55	74	129
.005	61	53	114
.006	32	46	78
.007	33	34	67
.008	27	14	41
.009	14	12	26
.010	15	10	25
.011	11	9	20
.012	7	8	15
.013	4	4	8
.014	4	5	9
.015	1	4	5
.016		1	1
.017		2	2
Total	588	642	1230
> 0.010	4.6 %	5.1 %	4.9 %
Stand. dev.	0.0050	0.0050	0.0050

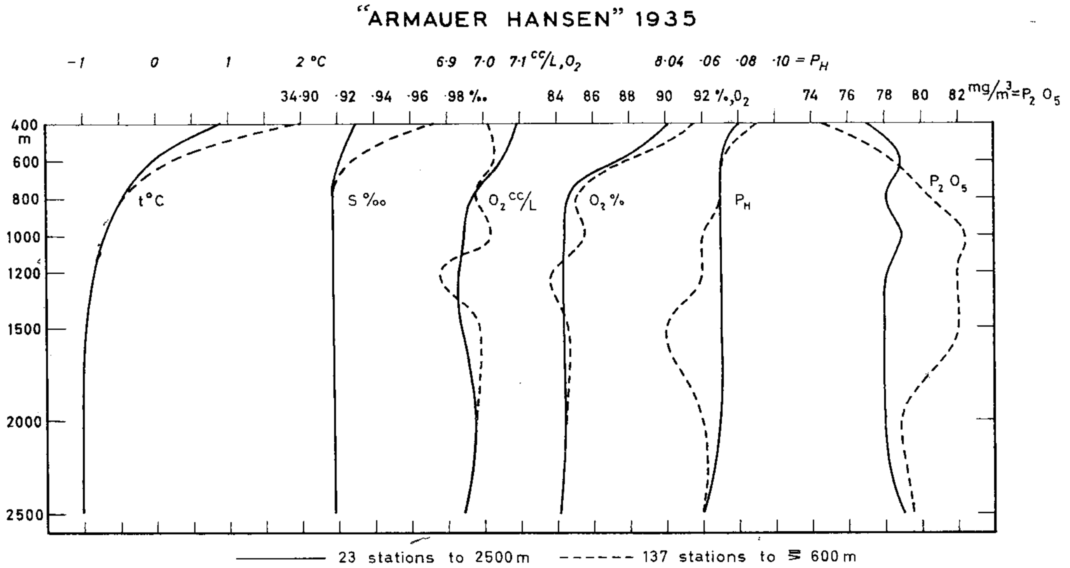


Fig. 4. Mean vertical distribution 1935.

from October 1948, in the hope that careful storing on board might make relatively trustworthy determinations possible. Experiments carried out on board and ashore also seemed to provide a certain basis for the establishment of corrections, possibly sufficient for statistical use of the data. These corrections amounted to 0.01, 0.02 or even 0.03 cc/L per day of storing, and in comparison with the small changes obtained, they appeared so great as to make the results doubtful.

From early 1952 the samples were stowed away in the cold store on board. This resulted in much more regular and uniform values and smaller corrections. Nevertheless, considerable errors may still be envolved, and none of the results has been included in this paper.

From March 1953 facilities were provided for titration of the samples on board both vessels. Due to the difficulties in carrying out the titrations at sea, and to changes of personnel, we did not expect any very high accuracy; in order to check the results and to improve them, two different samples were collected from each depth. From a comparison between the two intependent sets of values thus obtained, it was found that differences greater than 0.13 cc/L occurred in 24 cases out of a number of 657, or in 3—4 per cent of the total number of cases. But in more than 80 per cent of the cases the differences were not greater than 0.03 cc/L. By averaging the values obtained from the two sets of samples collected, fairly accurate and trustworthy data seem to have been obtained.

3. Vertical distribution. For a first guidance we have computed for all stations from 1935 the mean values for the standard depths from 400 m downwards. The result is illustrated in Fig. 4 by curves showing the mean vertical distribution of t, S, O_2, p_H

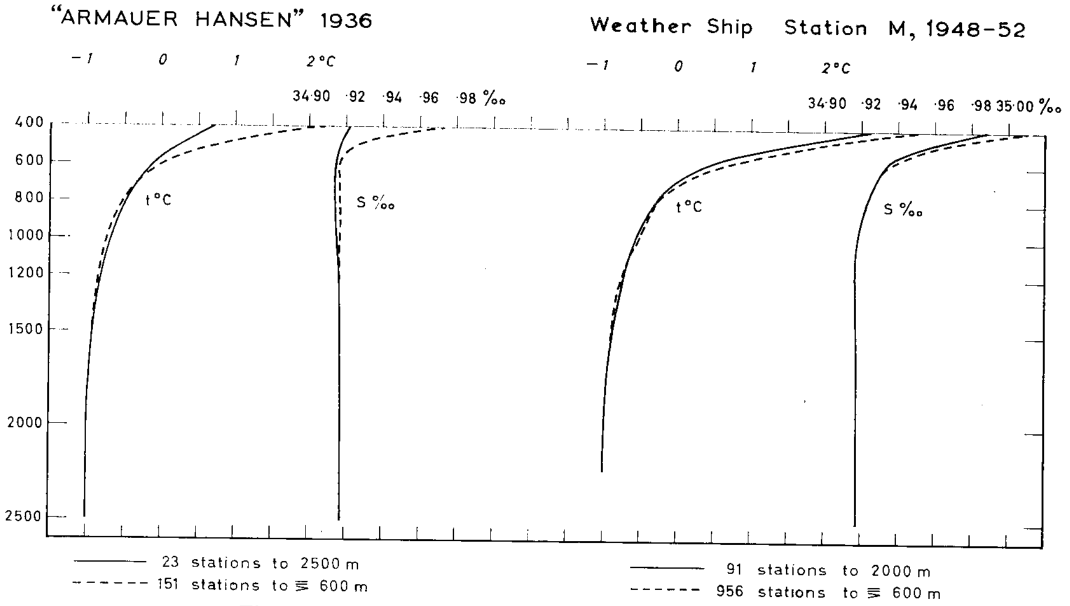


Fig. 5. Mean vertical distribution 1936 and 1948—52.

and P_2O_5. The broken curves are based on 137 stations at which observations were made to 600 m or more, while the fully drawn curves are based on 23 stations at which observations were made to 2500 m.

In temperature it is seen that the divergencies between the two curves are conspicuous in the upper layers, at 400 and 600 m. They are small at 800, 1000 and 1200 m, and from 1500 m downwards the two curves coincide completely.

In salinity the two curves are different at 400 and 600 m, while from 800 m downwards they coincide completely.

In oxygen content, expressed in cc/L as well as in % saturation, the broken curves show relatively great irregularities, while the fully drawn curves are much more regular, showing nearly the same value from 800 m downwards.

In p_H *and* p_2O_5 the divergencies between the two sets of curves are also great; the fully drawn curves are rather regular.

For the present study it shall be noted that the average salinity is exactly the same from 800 m downwards, being slightly below 34.92 ‰, while the average temperature decreases regularly from –0.47° at 800 m to –0.94° at 1500 m, and to –1.02° at 2500 m. The average vertical distribution of O_2, p_H and P_2O_5 depends on the depth at the station; at great depths we have slightly above or below 6.95 cc/L and slightly above 84 % in oxygen from 800 m downwards, 8.07 in p_H from 600 m downwards (with a small decrease at 2500 m) and between 78 and 79 mg/m³ in P_2O_5 from 600 m downwards.

The results of a similar treatment of the temperatures and salinities from the "Armauer Hansen" 1936 and from the Weather Ships from October 1948 to December 1952 (956 stations to 600 m, 91 stations to 2000 m) are given in Fig. 5. In 1936 the

Table 3. *Deep water salinities 1935* ($t < 0°$).

Depth	34.90	.91	.92	.93	.94	Total	Mean
400	1	3	1	1		6	
600	4	17	58	8	1	88	34.918
800	4	29	73	14		120	.918
1000	3	33	75	7	1	119	.918
1200		29	77	6		112	.918
1500		14	32	3	1	50	.918
2000	1	7	21	2		31	.918
2500		5	16	3		24	
Total	13	137	353	44	3	550	34.918 $^0/_{00}$

average temperature decreases from –0.48° at 800 m to –0.94° at 1500 m, and to –1.00° at 2500 m, and the salinity is slightly below 34.92 $^0/_{00}$ even from 600 m downwards. The Weather Ship stations show a decrease of the average temperature from –0.33° at 800 m to –0.88° at 1500 m and a slow decrease to –1.00° at greater depths (the average value for 2500 m is a little higher, but is based on only 5 stations). From 1000 m downwards the average salinity is slightly below 34.92 $^0/_{00}$, while at 800 m it is a little higher.

It thus appears that within the region in question we may define a *homohaline deep water*, extending from about 800 m to the bottom. Within the upper part of this water layer the temperature decreases regularly downwards and also the vertical temperature gradient decreases downwards. From about 2000 m downwards the decrease of temperature is within the limits of accuracy. Below 2000 m we accordingly have a *homothermal and homohaline bottom water*, the homogeneity of which will be discussed below.

In order to study the divergencies of the single cases from these average conditions, we have compiled in Table 3 the number of cases in which each single salinity value observed occurs at each standard depth. The data used are the salinities corresponding to temperature below zero, within the material of observations from 1935. When disregarding the few observations from the 400 m level, and combining the values from 2000 and 2500 m, the mean salinity for every depth is found to be exactly the same, namely *34.918* $^0/_{00}$. From Table 3 it is also seen that the scattering of the values only in a couple of cases exceeds 0.03 $^0/_{00}$, and that the distribution around the mean value is nearly the same at all depths. When disregarding the few values from 400 m, we find from Table 3 that the lowest salinity of 34.90 $^0/_{00}$ occurred 12 times, the highest of 34.94 $^0/_{00}$ occurred 3 times; values beyond the limits 34.91 and 34.93 $^0/_{00}$ thus occurred in less than 3 per cent of the cases. All these observations are within the limits of accuracy of the determinations.

A similar analysis of the temperature observations (Table 4) shows that at 1500 m the mean temperature and the scattering of the single values are much higher than deeper down, while within the bottom water, at 2000 and 2500 m, the differences are

Table 4. *Bottom water temperatures 1935.*

° C	1500 m	2000 m	2500 m
−0.86	2		
.87	2		
.88	1		
.89	3		
−0.90	3		
.91	2		
.92	4		
.93	3		
.94	7		
−0.95	6		
.96	9	1	
.97			
.98	2	2	
.99	1	2	
−1.00		4	8
.01	1	8	5
.02		10	8
.03		3	2
.04		2	1
Total	46	31	24
Mean	−0.89	−1.012	−1.013°

small. The averages of the 24 values from 2500 m and of the 31 values from 2000 m are different by only 0.001° C; but at 2500 m the values are concentrated within an interval of only 0.04°, while at 2000 m they are scattered over an interval of 0.08°, indicating a tendency towards higher temperatures at 2000 m. As was seen above, the error of the temperature determinations in 1935 exceeded ± 0.02° in only about 0.5 % of the cases; it thus appears that the observations from 2500 m do not diverge from the mean value beyond the limits of accuracy.

A study of the tables of observations shows that the constant salinity often extends into layers where the temperature may be above zero. We have, therefore, in Table 5, when compiling the salinity values at the standard depths in 1936, taken into consideration all values corresponding to temperatures below + 1.00° C. When disregarding the 27 observations from 300 m, of which a number are showing an increase of salinity, we also here find very small differences between the mean values at the different standard depths. The average of all values from 400 m downwards is *34.917* $^{0}/_{00}$, based on 752 values. A number of 24 values are beyond the limits 34.91 and 34.93 $^{0}/_{00}$; this corresponds to a little more than 3 per cent of all cases, or less than might be expected according to the above analysis of the accuracy of determination.

The temperature observations from 2500 m and 2000 m are compiled in Table 6. They are scattered at 2500 m within an interval of 0.03° or well within the limits of

Table 5. *Deep water salinities 1936* ($t < 1°$).

Depth	34.90	.91	.92	.93	.94	.95	.96	.97	Total	Mean
300	2	5	4	5	4	3	3	1	27	
400	8	26	59	24	4				121	34.919
600	4	65	68	13	4		1		155	.917
800	3	52	77	5					137	.916
1000		39	76	5					120	.917
1200		36	68	5					109	.917
1500	1	16	29	2					48	.917
2000		15	19						34	.916
2500		9	17	2					28	.917
Total	18	263	417	61	12	3	4	1	779	34.917‰

accuracy of the determinations (compare Table 1). At 2000 m the values are scattered within an interval of 0.05°, showing a tendency towards higher temperatures. The mean values at the two levels are slightly different. The 48 values available from 1500 m are scattered within an interval of 0.15° and give a mean value of −0.93°; they are omitted in Table 6. Towards higher levels the vertical gradient and the scattering increase.

Within the south-eastern part of the Norwegian Sea, where our observations are collected, the processes of mixing between the bottom water and the Atlantic water lead to a usually very clear relation between temperature and salinity. In order to study the relation within the deeper layers, the salinity values from 1936 have been arranged according to temperature intervals of 0.10° for all sets of observations within an upper temperature limit of + 3.00° C. In order to obtain a reasonably high number of data within each group, some of the intervals have been combined. The result is demonstrated by Table 7. It is seen that the scattering of the values up to 1° C is roughly the same as in Table 5 at depths of 400 m or more.

Table 6. *Bottom water temperature 1936.*

° C	2500 m	2000 m
−0.98	2	5
−0.99	3	4
−1.00	14	4
−1.01	9	5
−1.02		12
−1.03		3
Total	28	33
Mean	−1.001	−1.007° C

Table 7. *Distribution of salinity with temperature 1936.*

° C	34.90	.91	.92	.93	.94	.95	.96	.97	.98	.99	35.00	Total	Mean
−1.02		21	44	1								66	34.917
−0.95	3	44	53	4								104	.916
−0.85		27	61	6								94	.918
−0.75		33	52	4								89	.917
−0.60	1	33	65	3								102	.917
−0.25	4	76	67	6								153	.915
+0.25	9	29	39	7	1							85	.916
0.75	3	12	39	22	4	1						81	.922
1.25		3	20	29	27	14	2	1				96	.934
1.75		2	8	11	23	9	6	1				60	.938
2.25	1		4	11	20	25	18	5	5	4	1	94	.951
												1114	

Since double samples were not collected, it is hard to judge of the actual accuracy of the determinations of oxygen content. From March 1953, however, such double determinations were carried out on board the Weather Ships. Among a total number of 657, 80 per cent appeared to diverge by less than ± 0.03 cc/L (see above). The accuracy of the determinations from 1935 was certainly higher, probably limiting the error to about ± 0.02 cc/L.

The mean values from the 23 stations to 2500 m, used for drawing the curve in Fig. 4, are given in the last line of Table 8. Two of these stations, St. 182 and St. 184, give values about 0.2 cc/L lower than the others. The remaining 21 stations to 2500 m are: St. 79, 92, 94, 106, 108, 110, 135, 139, 145, 147, 149, 151, 180, 186, 190, 192, 194, 196, 218, 220, 222. The distribution of the oxygen values from these stations at different standard depths is given in Table 8.

It is seen that the values are scattered within intervals of between 0.12 and 0.17 cc/L, or much more than can be ascribed to the inaccuracy of the determinations. The variability of the values must, therefore, be assumed to represent actual differences in the sea. From Table 8 it is seen that the average value increases from 1000 to 2000 m, but decreases from 2000 to 2500 m. When drawing the oxygen curves for the 23 stations, it is seen that this decrease occurs in 18 cases, an increase in 4 cases, and no difference in 1 case. It therefore seems reasonable to accept as a general fact that in the bottom water the oxygen content decreases slowly downwards.

As seen from Fig. 4 the average values of p_H for the 23 deep stations are nearly the same from 600 m to 2500 m. Within this whole layer the distribution is the following:

p_H	8.03	.04	.05	.06	.07	.08	.09	.10	.11
Number	3	17	35	28	19	25	16	9	8

Table 8. *Oxygen content of deep water 1935.*

cc/L	800	1000	1200	1500	2000	2500	800–2500 m
6.87		2				1	3
.88		1				1	2
.89		2	1				3
.90	1	2	1			1	5
.91	1	2	1	1		1	6
.92		1	3	1	1		6
.93	2	1	4	2			9
.94	1	1	2	1	1	3	9
.95	1	1	1	2	1	2	8
.96	1	3		3			7
.97	4		1	2	1	2	10
.98	1		1	4	4	3	13
.99		2	1		1	2	6
7.00	2		1		3	2	8
.01			2	4	2		8
.02	2	1	1		2	2	8
.03		1	1	1	1	1	5
.04		1					1
.05	2				2		4
.06	1				1		2
.07	2						2
.08					1		1
Mean	6.99	6.94	6.95	6.97	7.00	6.96	6.97 21 St
Mean	6.96	6.95	6.93	6.94	6.98	6.94	6.95 23 St

and the mean value is 8.07. A slight decrease from 2000 m to 2500 m is indicated, but this decrease should hardly be considered as fully established.

From Fig. 4 it is also seen that the mean values of P_2O_5 from the 23 deep stations are nearly the same from 600 m to 2500 m. The single values are scattered between 58 and 106 mg/m^3 with an average value between 78 and 79 mg/m^3. The average values indicate a slight increase from 2000 m to 2500 m, but as the accuracy of the method employed is not great, this increase can hardly be considered as trustworthy.

For further information let us consider the section taken in 1935 along the 66th parallel, the latitude of Weather Ship Station M. The part of this section from the depths above 500 m consists of stations 174 to 187 between longitudes 6° E and 6° W. From Fig. 6 it is seen that the temperature decreases from the surface downwards at all stations; but the vertical gradients are different at different depths, and at the same depths at different stations. In agreement with what was seen from the average stations, the gradients are generally higher in the upper layers than at greater depths. On the whole, it should be noted that nearly all isotherms are roughly parallel, so that similar differences from station to station occur at nearly all levels. At great depths the dif-

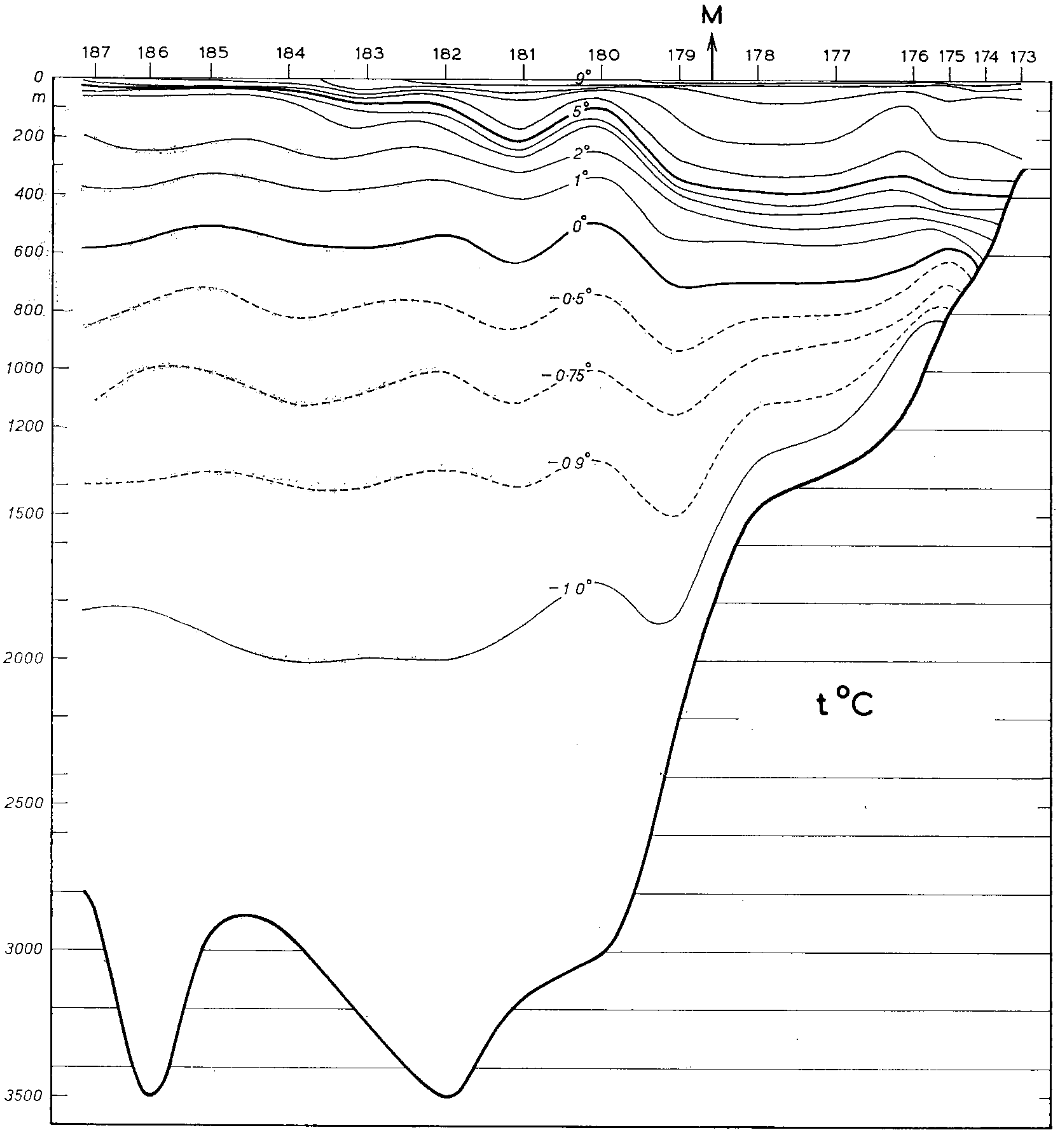


Fig. 6. Section of temperature along the 66th parallel 1935.

ferences are small, but it is seen that a uniform temperature is approached only at depths of 2000 m or more. Finally it should be noted that isotherms corresponding to temperatures above zero are found at greater depths at stations 179 to 174 in the east than at stations 187 to 180 in the west.

The isohalines from the same section show that below 200 to 300 m in the west and below about 500 m in the east there are very small differences from station to

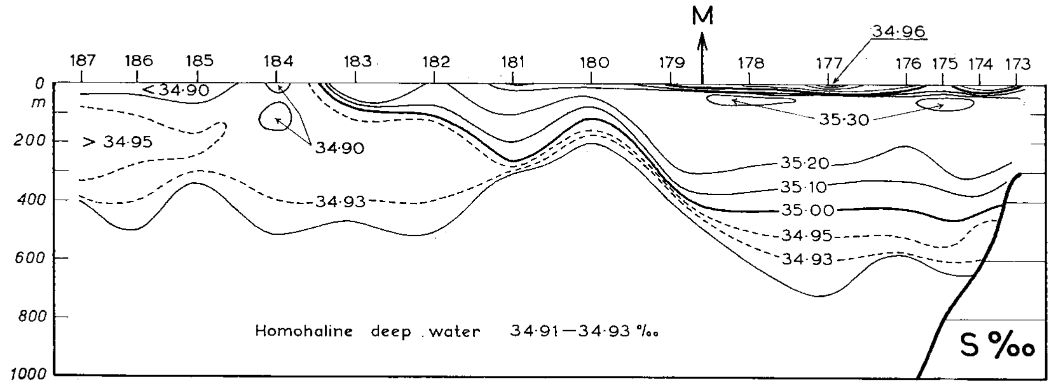


Fig. 7. Section of salinity along the 66th parallel 1935.

station and from level to level (Fig. 7). The high temperatures of the upper layers in the east correspond to high salinities of more than 35 ‰, and indicate the extension of the Atlantic water within the Norwegian branch of the Gulf Stream. This water extends from the continental shelf somewhat beyond Weather Ship Station M; but farther west the upper layers are characterized by specially low salinities, sometimes (e.g. St. 184) even lower than the salinity of the deep water (34.92 ‰). Below a certain level, however, differences in salinity can hardly be traced (the lower fully drawn line in Fig. 7). We shall return to this level later.

The distribution of oxygen content in per cent saturation is illustrated in Fig. 8. In the surface layer the percentages are about 100, decreasing downwards. The values are high, about 95 %, within the entire body of Atlantic water, but also in the less saline water of the westernmost part of the section. Within the Atlantic water a reduction of the values in the central parts (the "core") is visible. Most striking features are exhibited in the deep layers. Below the Atlantic water relatively high percentages are extending deep down; at stations 179 and 180 immediately west of Weather Ship Station M the 85 % curve reaches more than 2000 m. Also in the westernmost part of the section (stations 186 and 187) a relatively high percentage is found at great depths. But between these two parts of the section we have a minimum in oxygen with less than 81 % between 1200 and 1500 m. At these stations (181 to 185) values of 85 % are not found at greater depths than 500 to 600 m. Since the differences within the deeper layers are small, they should perhaps not be studied in too much detail. But the general features described above are probably correct.

When drawing the corresponding sections of p_H and P_2O_5 it is found that within the deeper layers the differences from station to station are often small, but greater than the variation from level to level. As these sections can hardly add very much to the present study, they are not reproduced here.

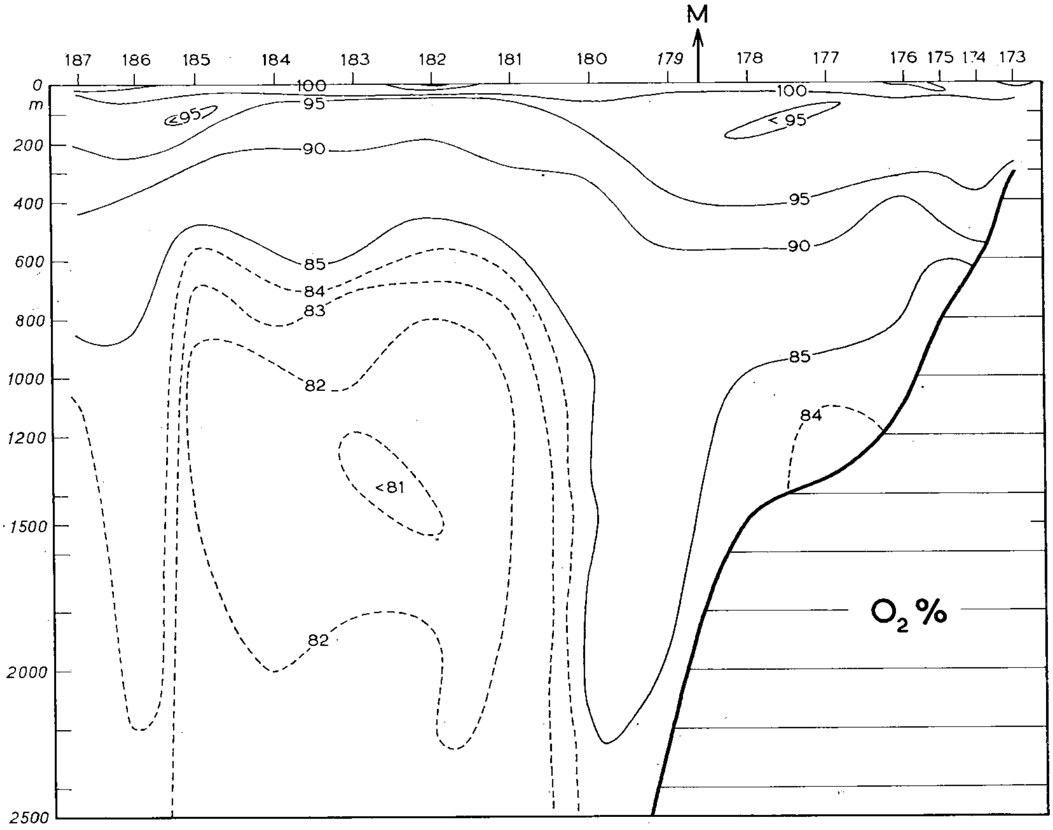


Fig. 8. Section of oxygen saturation along the 66th parallel 1935.

4. Horizontal distribution. From the section Fig. 6 it was seen that the different isotherms are nearly parallel. Irregularities with great thermal amplitudes in the upper layers are reflected with amplitudes which are in some cases smaller at deeper levels.

For an outline of the general features we shall now consider salinity and temperature charts from certain standard levels. When trying to construct such charts on the basis of the observations from 1935, it appeared that in several cases the isotherms might be drawn in ways different in principle. The still denser net of stations from 1936 made this difficulty appear serious. For our present study of the deep water, only the great features of these maps are of importance, and we have tried to draw each isotherm, if possible, as one continuous curve. It may well be that by splitting up the curves into separate parts, the data may be more adequately represented. Such questions will, however, not be discussed on this occasion.

The salinity distribution at 100, 200, 400 and 600 m is shown in Fig. 9. The Atlantic water of salinity above 35.00 $^0/_{00}$ is found in the east and north at 100, 200 and 400 m, while at 600 m it remains only in the northernmost part of the area covered by the

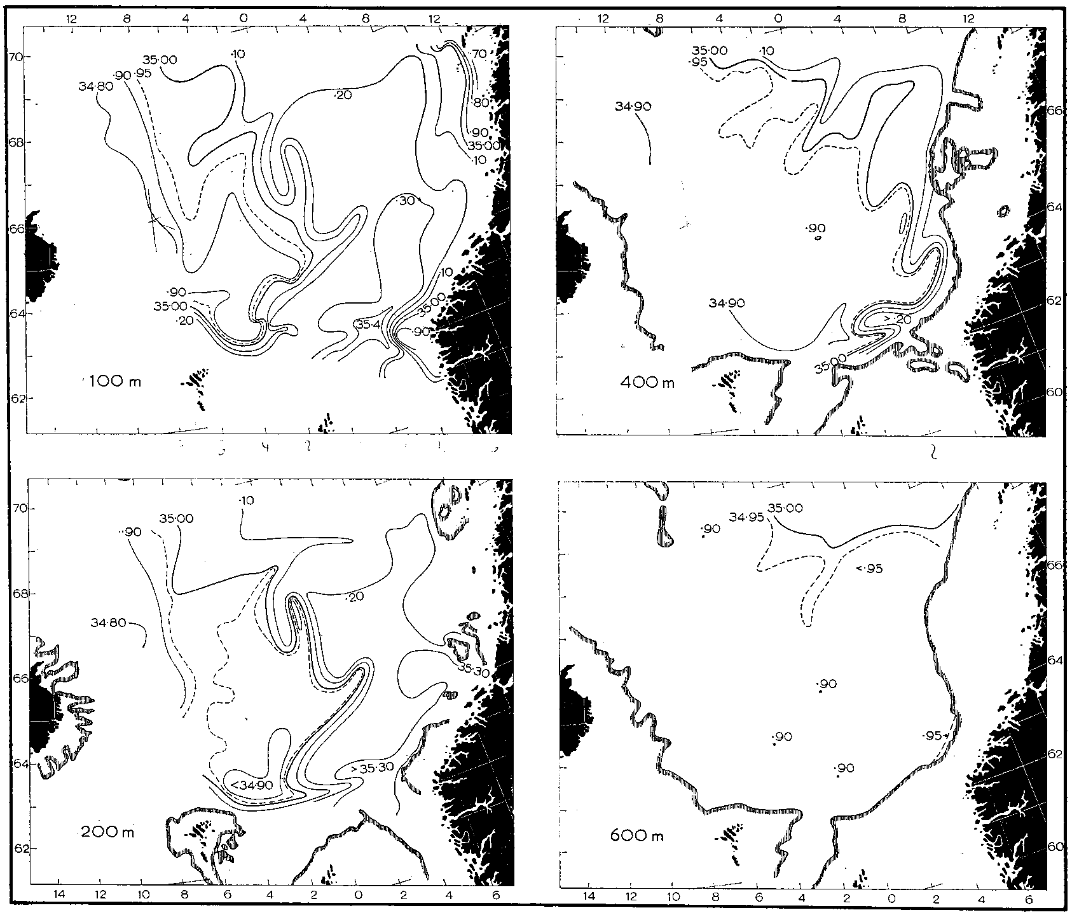


Fig. 9. Maps of salinity 1935 for 100, 200, 400 and 600 m.

stations. Entering through the Faeroe-Shetland Channel, the Norwegian Atlantic Current is forced northward by the continental shelf. On its way towards the north it reaches increasing depths. The ranges of salinity are:

at	100 m	from	34.7	to	35.4	or about	0.7 ‰
-	200 -	-	34.8	-	35.3	- -	0.5 -
-	400 -	-	34.9	-	35.2	- -	0.3 -
-	600 -	-	34.9	-	35.0	- -	0.1 -

At 800 m a maximum value of 34.94 occurs at one station, and the minimum value of 34.90 at two stations; all other values from this depth are between 34.91 and 34.93 or within 0.02 ‰.

The temperature distribution for 400, 600, 800 and 1000 m is shown in Fig. 10 and for 1200, 1500, 2000 and 2500 m in Fig. 11. The higher temperatures are found

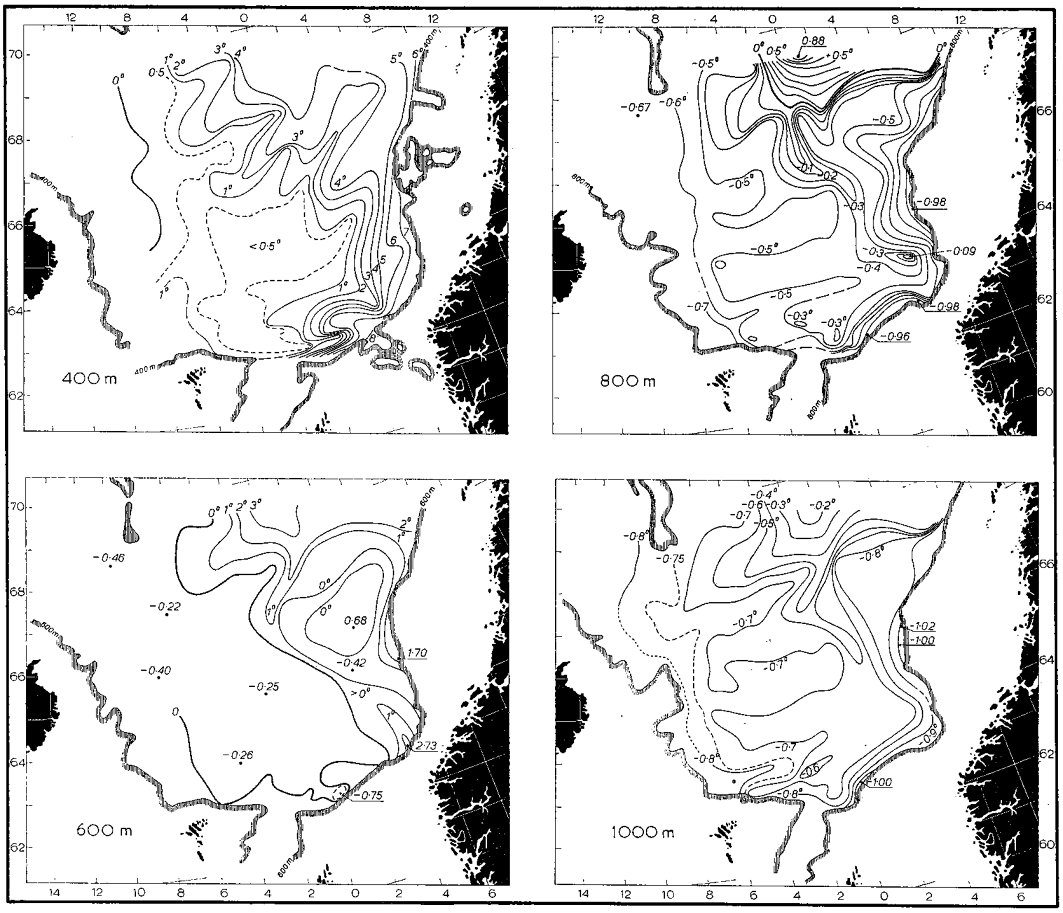


Fig. 10. Maps of temperature 1935 for 400, 600, 800 and 1000 m.

in the north and in the east. To a salinity of 35.00 $^0/_{00}$ corresponds a temperature of about 3° C; such high temperatures are found only at 400 m, and at 600 m in the northernmost part of the area. But the general pattern is nearly the same in all maps. The ranges of temperature are:

at	400	m	from	0	to	8	or	about	8	°C
-	600	-	-	–0.75	-	3.34	-	-	4	-
-	800	-	-	–0.98	-	0.88	-	-	1.8	-
-	1000	-	-	–1.00	-	–0.20	-	-	0.8	-
-	1200	-	-	–1.00	-	–0.50	-	-	0.5	-
-	1500	-	-	–1.00	-	–0.86	-	-	0.14	-
-	2000	-	-	–1.04	-	–0.96	-	-	0.08	-
-	2500	-	-	–1.03	-	–0.97	-	-	0.06	-

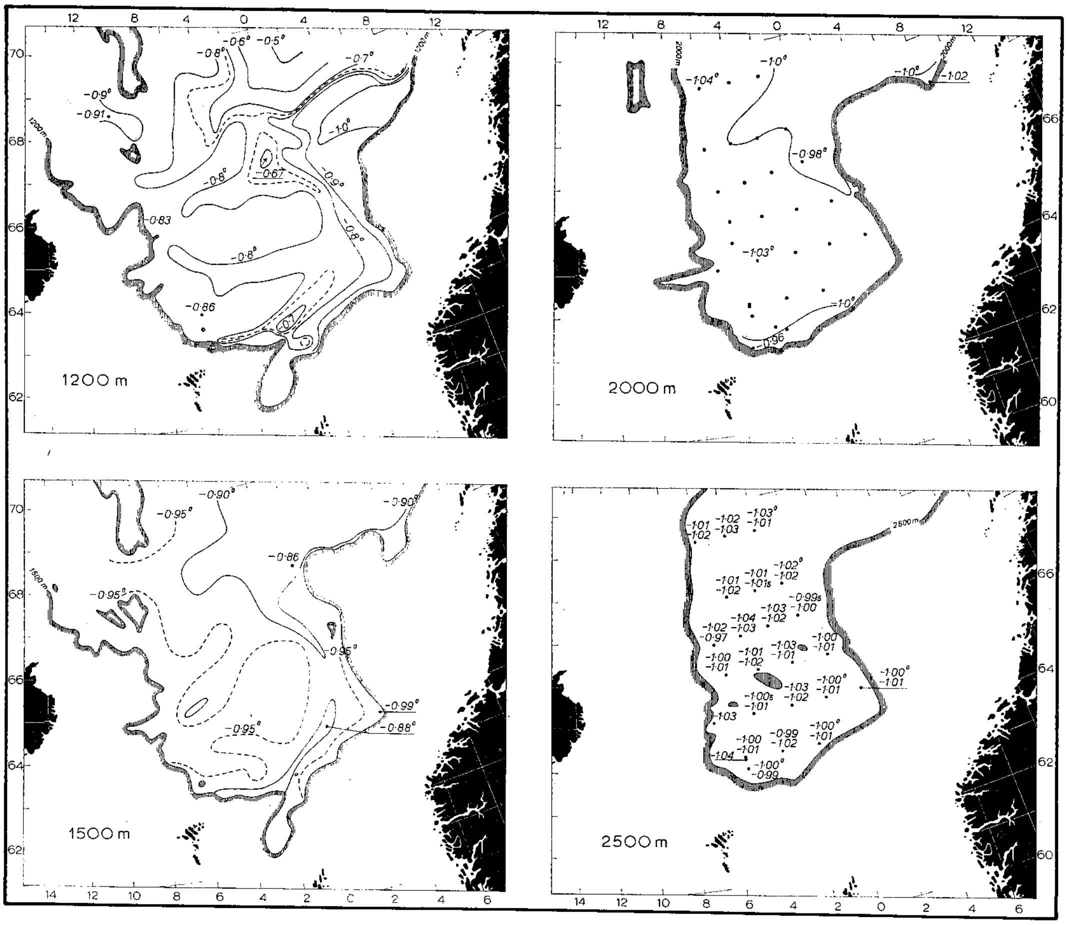


Fig. 11. Maps of temperature 1935 for 1200, 1500, 2000 and 2500 m.

For 2500 m the extremes are referring to single readings of the thermometers. When considering mean values from two thermometers, the range is reduced to 0.04° C and all values are nearly within the limits of accuracy of the determinations. (An isotherm for -1.00^0 may be drawn in the north-eastern corner of the map, but only by analogy to the other maps.)

From this brief examination of the temperature distribution it results that the general pattern of temperatures of the upper layers, mainly governed by the Gulf Stream, is visible at any depth below, but the contrasts are being reduced with increasing depth and disappear completely at 2000 to 2500 m. Similar conditions are revealed by the salinity maps, but here the reduction of contrasts takes place within a short distance below the Atlantic water. Within most of the region the salinity is nearly uniform already at 600 m; at 800 m or more the differences within the whole area are nearly within the limits of accuracy of the salinity determinations.

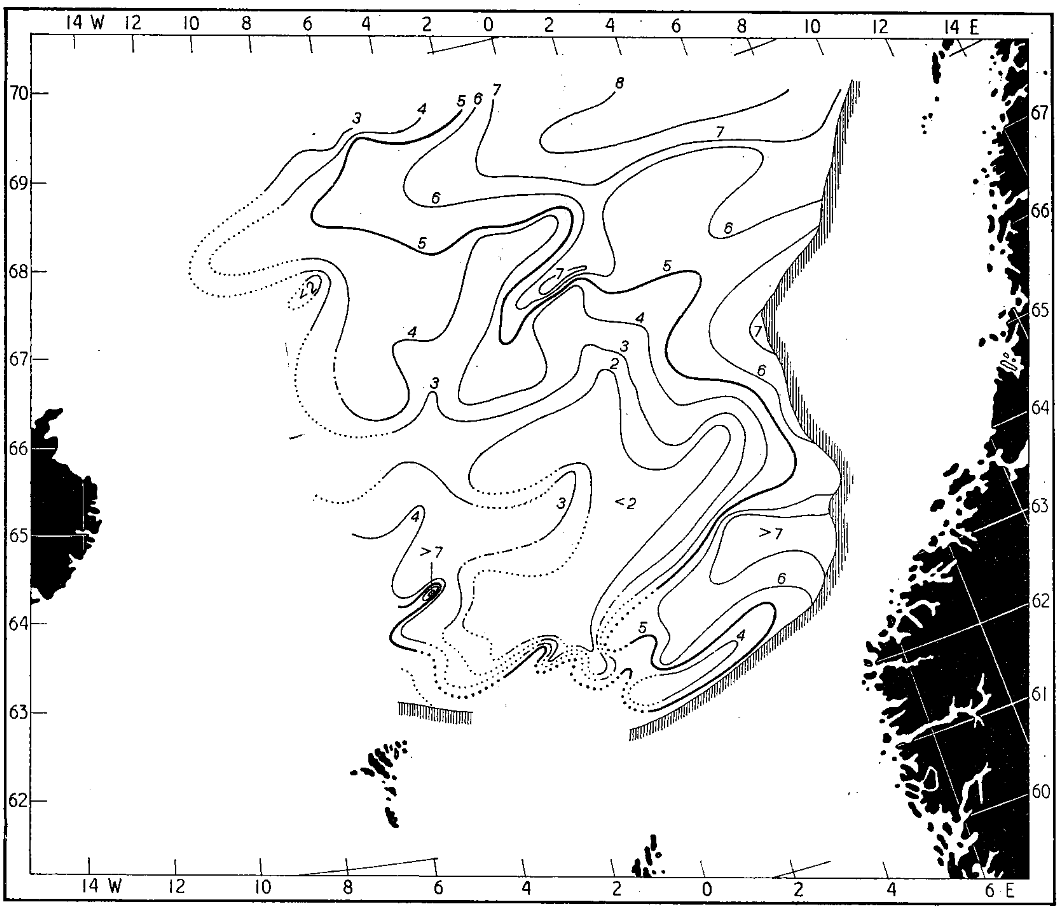
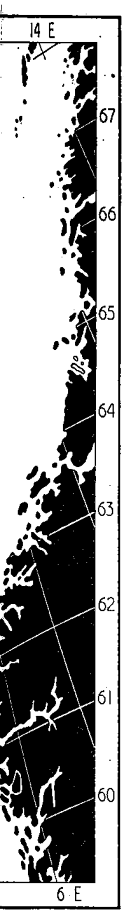


Fig. 12. Top of homohaline water 1935, depths in hectometers.

5. Top of homohaline layer. A study of the salinity curves from every station shows that the salinities are always very nearly equal within the deeper layers, up to a certain level. This level will here be called the top of the homohaline layer, and be defined as the level at which the salinity differs by 0.01 $^0/_{00}$ from the mean value of the salinities from all deeper standard levels. Its depth is easily determined for each station, and when plotting the values on a map, it appears possible to construct isobaths corresponding to the lower curve of the salinity section Fig. 7. These isobaths are represented in Fig. 12, which is thus a bathymetric chart of the top of the homohaline deep water, based on the observations from 1935. Where the isobaths are drawn in full, the salinity increases towards the more saline Atlantic water above. Where lower salinities, i.e. Norwegian Sea water is found at any higher level, the isobaths are dotted.



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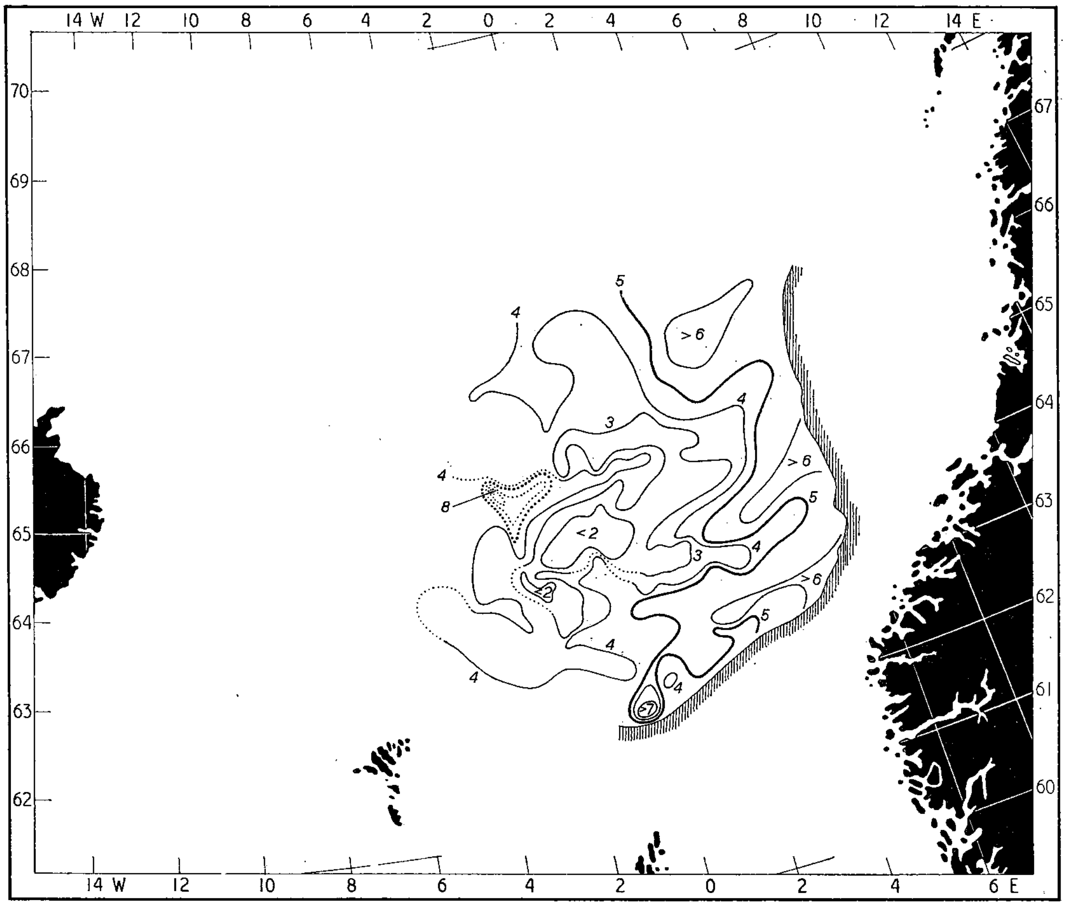

Fig. 13. Top of homohaline water 1936, depths in hectometers.

It is seen from Fig. 12 that the top of the homohaline water 1935 occurs at a depth of more than 800 m in the north, where the Atlantic current penetrates to its greatest depths. It reaches more than 700 m in the east towards the continental shelf and possibly also at one station in the south-western part of the region. But in the central and western areas it is found at smaller depths, up to less than 200 m below the surface. In 1936 the number of station per unit area was about four times greater than in 1935. The map in Fig. 13 therefore shows many more details, and there was less liberty in drawing the curves.

The two maps show great differences. On a close examination of the original maps where the values are visible, it is, however, seen that these differences are not so important as it may appear. Within the open areas between the stations the curves have of course to be drawn in freehand. It can be demonstrated that in many cases a curve for 1935 might have been drawn nearly as the corresponding curve for 1936, without

Fig. 14. Temperature at top of homohaline water 1935.

coming into disagreement with the values at the stations. It must therefore be assumed that the broad features are the same in both cases and that they are probably representing a stationary state. But there are greater differences between the extreme values in 1935 than in 1936. The areas corresponding to more than 700 and 600 m appear much greater in 1935, but they are based on few values and are to a great extent drawn by interpolation; this difference is therefore not serious. The areas of less than 200 and 300 m are also much greater in 1935, and as they are based on relatively many stations, there can be no doubt that this difference between the two maps corresponds to a real difference, independent of the method of construction.

The top of the homohaline layer must certainly be a surface of very small stability. Extremes of very limited extension, occurring in both maps, support the view that rapid changes do sometimes take place. That this is actually true, has been demonstrated by means of observations from Weather Ship Station M (Mosby 1950). Nevertheless,

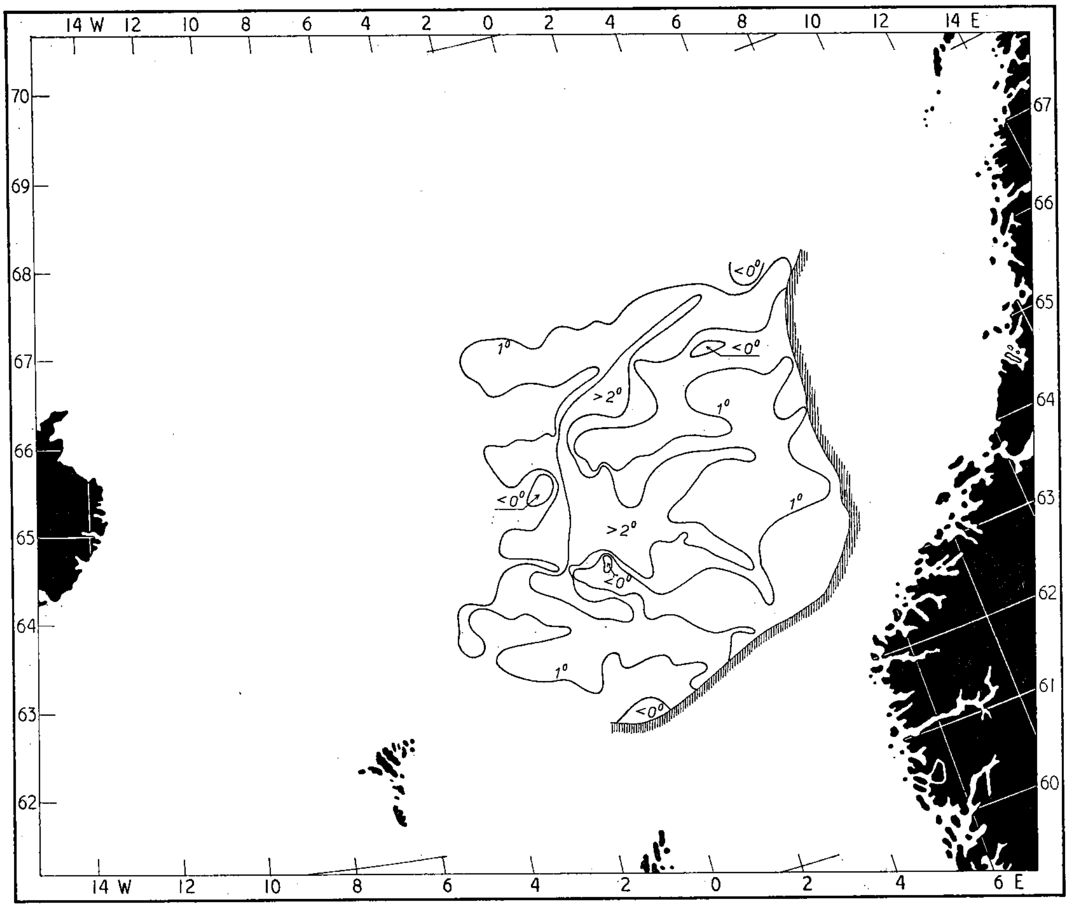

Fig. 15. Temperature at top of homohaline water 1936.

the broad features do always remain the same, exhibiting the trough where the Atlantic current runs towards the north along the continental shelf, and the high in the west, partly covered by Norwegian Sea water of a lower salinity.

When determining from the station curves the top of the homohaline layer, we may also easily determine the corresponding temperature. Plotting these values on a map, we may draw isotherms demonstrating the distribution of temperature along the upper limit of the homohaline water. Such maps are reproduced in Figs. 14 and 15. It is seen from the map for 1935 that in the west and at a few isolated stations along the continental shelf in the east, the temperature is below zero, while the highest temperatures of up to 4.6° C occur in the central part of the south-eastern area. From Fig. 15 it is seen that in 1936 conditions were different, no single temperature reaching 3.0° C; but also this year the higher temperatures are found in the central part of the south-eastern area. Values below zero only occur at a few isolated stations.

By comparison with the maps of Figs. 12–13 it is seen that the highest temperatures occur where the top of the homohaline water is nearest to the surface of the sea, in the region west of the main branch of the Atlantic current, but where it is still covered with Atlantic water. In order to control this resemblance between Figs. 12–13 and Figs. 14–15, the temperatures determined for the top of the homohaline water were plotted against the corresponding depths. The data from 1935 are much more scattered than are the 1936 values; this is due to the net of stations in 1935 being extended farther towards the north and west, where at many of the stations the homohaline water is covered by layers of Atlantic as well as of Polar origin, occurring separately so that salinities below 34.92 and above 35.00 $^0/_{00}$ are found at the same station. Also the data from 1936 are scattered, but the general tendency is very clear; where the top of the homohaline water is found at great depths, the temperature is low and vice versa. The average situation corresponds to an increase of the temperature by about 0.5° C per 100 m reduction of the depth.

This phenomenon is closely connected with that discovered by Le Floch (1953), who found that for any definite salinity observed at Weather Ship Station M, the temperature was higher the closer to the surface the observations were taken. Within most of the area under consideration the homohaline deep water is, as mentioned, covered by Atlantic water of a higher salinity and a higher temperature, as seen for instance from the sample station curves from Weather Ship Station M reproduced by Mosby (1950, p. 2). The transitional layer between the two water masses is characterized by strong vertical gradients of temperature and salinity. The top of the homohaline water may be considered as the bottom of the transitional layer, and a change from station to station of the depth of the top of the homohaline layer therefore means a similar change of the depth of the whole transitional layer. From the above study of the horizontal distribution, however, it appears possible to arrive at a clearer understanding of the cause of the variation of the t-S-relation with depth.

At a first glance this phenomenon might be described as follows: at smaller depths the thermal influence from above (heating) is stronger than the haline influence when compared to the conditions at greater depths. Since the thermal and the haline influences between two water masses must, however, under equal conditions be nearly alike, and since the deep water is very nearly the same in all cases, the reason can only be that the t-S-relation within the upper layer of warm and saline water varies from place to place and in rough agreement with the variation of the thickness of the same layer.

Where the Atlantic current moves northward along the continental shelf, the homohaline water is pressed downwards so as to form a trough or a "bed" for the current to follow. Here the top of the homohaline water and the whole transitional layer is found at great depths. Due to the current, the Atlantic water is here constantly renewed and keeps a probably nearly constant t-S-relation. But in the central area to the west, where the transitional layer occurs at smaller depths, the upper layer has not the same t-S-relation. This water circulates slowly within the central area of a quasi-stationary eddy, where it is renewed partly from the Atlantic current in the east, and partly from the "Central Water Masses of the Southern Norwegian Sea" (HELLAND-HANSEN and NANSEN 1909, p. 82). The result is an upper layer in this area, within which the temperature at any given salinity is somewhat higher than within the Atlantic current. This can be shown by plotting in a t-S-diagram observations from the transitional layer partly from stations within the Atlantic current and partly from stations within the central area mentioned above. In a similar way it appears possible to explain the relatively great scattering of the observations from Weather Ship Station M in the lower part of the t-S-diagram in Fig. 2 of the paper by MOSBY (1950, p. 3) mentioned above (salinities below 35.00 $^0/_{00}$). A closer study of these features will, however, not be undertaken here.

6. Homohalinity of deep water. The top of the homohaline water has been treated at some length, because all salinities below this surface are very nearly equal. In order to study more closely the degree of homohalinity of the deep water, we have

Table 9. *Distribution of mean salinities within the homohaline deep water at each station.*

S $^0/_{00}$	1935	1936	Total
34.904		1	1
.905		1	1
.906	1	1	2
.907	1	1	2
.908	1	4	5
.909	2	2	4
.910	3	2	5
.911	4	6	10
.912	6	4	10
.913	6	5	11
.914	14	17	31
.915	6	17	23
.916	10	27	37
.917	5	16	21
.918	11	18	29
.919	10	14	24
.920	14	14	28
.921	7	6	13
.922	5	14	19
.923	4	8	12
.924	8	10	18
.925	3	3	6
.926	8	4	12
.927	2	1	3
.928	3	3	6
.929	1	1	2
.930	1		1
Total	136	200	336
Stand. dev.	0.0049	0.0044	0.0046

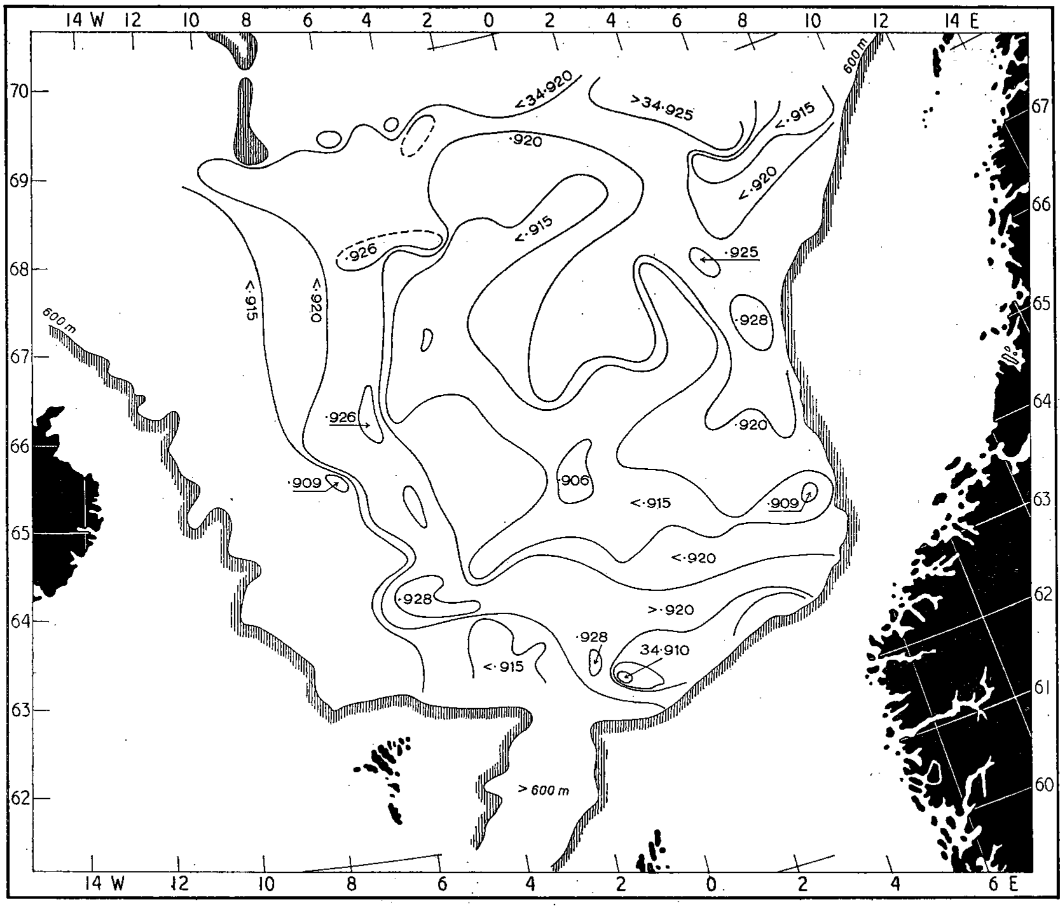

Fig. 16. Salinity of homohaline deep water 1935.

computed the mean values of the salinities within the homohaline layer at each station. The distribution of these mean values is seen from Table 9, in which the second column shows the values from 1935, the third column those from 1936 and the last column all these values put together. It is seen that the extreme values are 34.904 and 34.930 $^0/_{00}$, and that the distribution tends towards a normal distribution around the average value 34.918 $^0/_{00}$ — the standard deviation being 0.0046 or slightly less than that found above when discussing the accuracy of the observations. Since each mean value is based on a number of between 1 and 8 values or on between 2 and 16 single titrations, the differences may perhaps still to some extent be due to the differences in geographical position. They were therefore plotted on a map, and curves were drawn for every 0.005 $^0/_{00}$ (Fig. 16). It is seen that the values above 34.920 $^0/_{00}$ are found within a belt in the southern, western and northern part of the region as well as in its north-eastern part, while the lower values are found within the central areas and at the borders in

Fig. 17. Salinity of homohaline deep water 1936.

the south and west. Since the mean values are based on variable numbers of single determinations, and since the differences are so small, these features should not be studied in too much detail. But if the general features are considered reliable, a possible explanation of their origin may be imagined. The regular transport of Atlantic water towards the north along the continental shelf may, in the course of time, bring about a cyclonic circulation of the deep water in the southern part of the Norwegian Sea. The formation and renewal of this water takes place in the regions towards the north-west, as explained by NANSEN (1912). If a relatively "young" deep water has a slightly higher salinity than an "older" mass of deep water, then the circulation mentioned may lead to a distribution similar to that demonstrated by Fig. 16, because the "old" deep water must be expected to remain for a relatively long period of time within the central area. The wedge of lower values, which are in the south-east separating waters of higher salinity farther north and farther south, must then be considered as a moving wedge

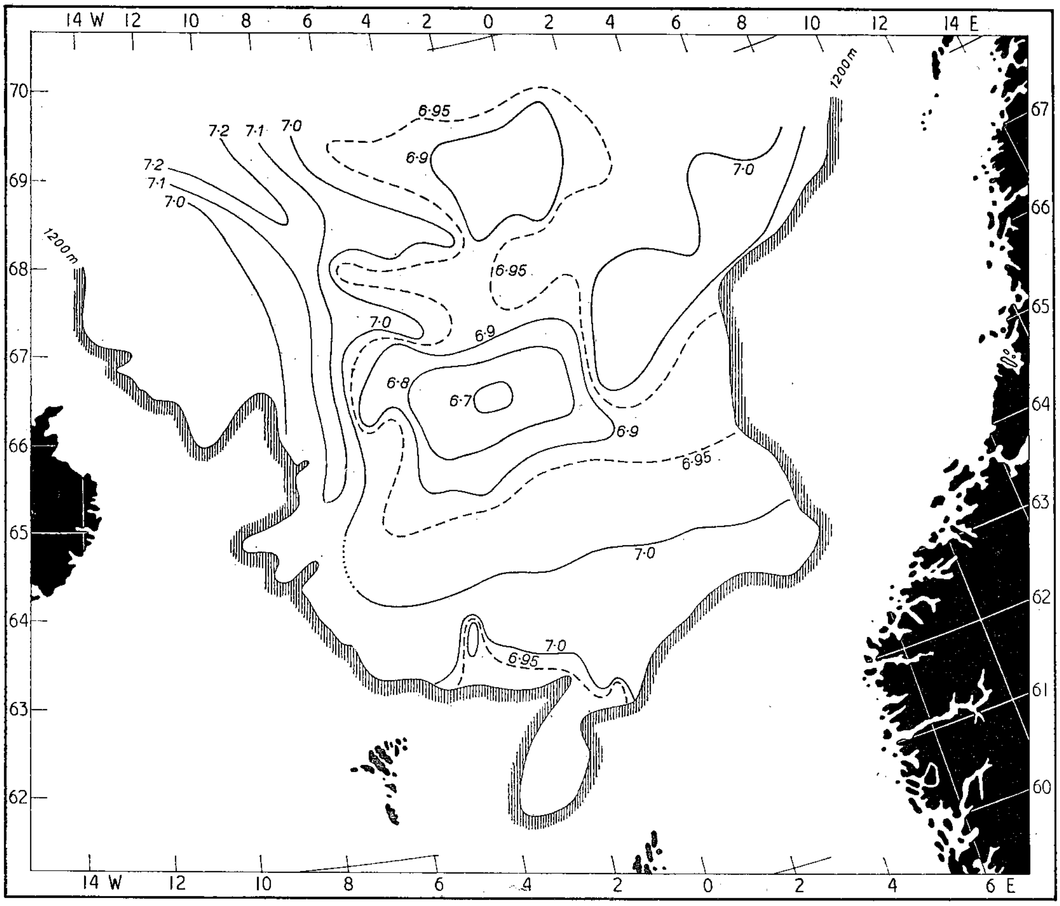

Fig. 18. Map of mean O_2 cc/L below 1200 m in 1935.

between a front of younger deep water approaching from the south and a rear front of an older and more saline deep water in the north.

Such ideas, however, may appear rather far-fetched, when the features of the map from 1935 are compared with those exhibited in Fig. 17, representing the observations from 1936. In the southern part of this map we also find a belt of relatively high salinities, but the lower values in the central area are here concentrated within very narrow limits. The general features are therefore not the same in the two years, and the only conclusion to be drawn from the two maps is therefore probably the following. If the deep water is not completely homohaline and all differences therefore not only due to errors of determination, then the deep water must be in motion, since the features are changing from year to year. The above ideas about the origin and nature of this motion cannot be controlled by our observations, and no information can be obtained from these observations as to the velocities within the deep water.

An interpretation of Figs. 16–17 as that given above may appear less imaginative

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when compared with the results of the observations from Weather Ship Station M. As will be demonstrated below the salinity of the whole column of deep water here appears to be subject to many minor and sometimes also to greater sudden changes.

It was seen above (cf. Fig. 4) that the oxygen content in cc/L for the deep stations 1935 was approximately constant from 800 m downwards. A study of the single stations shows that the distribution below 1200 m is the same in nearly all cases, and an average value for the deep water below 1200 m may therefore be determined by reducing the observed values as follows: + 0.019 cc/L at 1200 m, + 0.007 cc/L at 1500 m, –0.033 cc/L at 2000 m and + 0.007 cc/L at 2500 m. In this way comparable values are obtained from a great number of stations; these values were used as a basis for the map of Fig. 18. The highest values, above 7.00 cc/L up to 7.29 cc/L, are found in the north-west and within a belt along the western and southern part of the area (here limited by the 1200 m isobath), as well as in the north-east, while the lowest values, down to 6.67 cc/L, occur in the central area. The general features are thus similar to those of Fig. 16, but no detailed congruency can be pointed out. Nevertheless, this map may be said to support the above ideas of a circulation of the deep water, the lower oxygen content being considered as characteristic of the "older" masses of deep water, while the higher values belong to the masses which are more recently formed in the regions towards the north-west. Also in oxygen content relatively sudden changes may of course be expected to occur during the passage of "fronts" between water masses formed in different winter seasons.

7. Variation of salinity[1]. In order to judge on the degree of homohalinity predominating within the whole vertical column of deep water at each station, we have computed in Table 10 the distribution of the salinities of the single water samples around the mean value for the corresponding station. Since the divergencies are counted regardless of sign, the numbers of cases of $\triangle S = 0.000\,^{0}/_{00}$ must be multiplied by 2. It is seen that the distribution is roughly the same in 1935 as in 1936. and in the last column of the table all values have therefore been totalled. Comparing these values with those of Table 2 (p. 6), it is seen that the scattering is nearly the same in both cases.

When taking into consideration only stations where observations were taken to at least 1500 m depth, the distribution of the salinities around the mean value for each station is found to be as seen from Table 11, or very nearly as in Table 10.

Finally, the distribution of the single salinities around the common mean value within the whole volume of homohaline deep water of the southern Norwegian Sea: $34.918\,^{0}/_{00}$, is demonstrated by Table 12. It is seen that the scattering is greater in this case than in the above mentioned cases.

When plotting the data in histograms, it is seen that the distribution is in all cases approximately a normal distribution. In some cases the values 0.002, 0.004 etc. are more frequent than 0.001, 0.003 etc., an irregularity which may be attributed to the well known human tendency to prefer equal numbers.

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[1] A preliminary report has been published by MOSBY (1953).

Table 10. *Distribution of salinities of samples of deep water around the mean value for the corresponding station.*

ΔS ‰	1935	1936	Total
±0.018	3		3
.017			
.016			
.015	1	1	2
.014	7	4	11
.013	3	4	7
.012	10	10	20
.011	11	4	15
.010	17	14	31
.009	16	19	35
.008	33	24	57
.007	38	35	73
.006	47	53	100
.005	49	62	111
.004	81	90	171
.003	77	98	175
.002	118	121	239
.001	85	150	235
.000	60	84	144
Total	656	773	1429
Stand. dev.	0.0053	0.0046	0.0049

Table 11. *Distribution of salinities of samples of deep water around the mean value for the corresponding station, based on stations to at least 1500 m depth.*

ΔS ‰	1935	1936	Total
±0.015		1	1
.014	4	1	5
.013	2	1	3
.012	4	5	9
.011	5	3	8
.010	8	4	12
.009	8	9	17
.008	19	6	25
.007	16	17	33
.006	24	19	43
.005	26	19	45
.004	45	40	85
.003	32	42	74
.002	51	55	106
.001	41	66	107
.000	22	35	57
Total	307	323	630
Stand. dev.	0.0053	0.0045	0.0049

Table 12. *Distribution of single values of salinity around 34.918* $^0/_{00}$.

ΔS $^0/_{00}$	1935	1936	Total
±0.024		2	2
.023			
.022	3		3
.021	1		1
.020			
.019	3		3
.018	10	2	12
.017	1		1
.016	7	5	12
.015	7	3	10
.014	16	12	28
.013	15	2	17
.012	27	23	50
.011	11	9	20
.010	33	40	73
.009	19	15	34
.008	54	49	103
.007	27	29	56
.006	74	109	183
.005	26	58	84
.004	86	114	200
.003	44	61	105
.002	103	145	248
.001	38	67	105
.000	58	64	122
Total	663	809	1472
Stand. dev.	0.0074	0.0060	0.0066

When computing the standard deviations we arrive at the following results:

Accuracy, titrations	(Table 2, p. 6)	0.0050
Samples — station mean	(Table 10, p. 30)	.0049
Stations — 34.918 $^0/_{00}$ ..	(Table 9, p. 25)	.0046
Samples — 34.918 $^0/_{00}$ ..	(Table 12, p. 31)	.0066

where the last decimal space is not reliable. The values are based on the observations from 1935 and 1936. If the deviations of the single sample salinities from the mean value for the station in question, and the deviations of the mean values for the stations from the mean value for the whole area, are considered as independent "errors", one may expect, from the law of accumulation of errors that the sum of the squares of the standard deviations for these two cases be equal to the square of the standard deviation of the single sample salinities from the mean salinity of the area. In fair

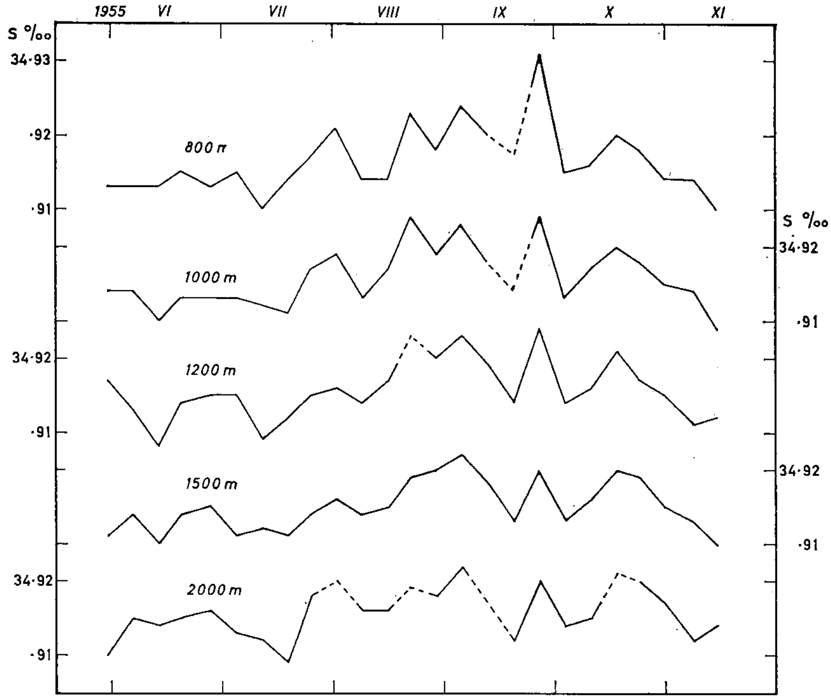

Fig. 19. Variations of deep water salinity June–November 1955.

agreement with this we find that: $0.0049^2 + 0.0046^2 = 0.0067^2$ or rather near to 0.0066^2.

That the mean salinity within the whole column of deep water may be considered as a characteristic value, is demonstrated by Fig. 19, in which the salinities from Station M for June to November 1955 from the standard depths of 800, 1000, 1200, 1500 and 2000 m are plotted. It is seen that the changes from station to station are small, in most cases smaller than 0.01 $^0/_{00}$; nevertheless they occur nearly simultaneously at all depths. When comparing each observed change of salinity with the average change for the standard depths 800 to 2000 m, it is found that only in 1 case out of 100 are the differences greater than 0.01 $^0/_{00}$, in 7 cases out of 100 they are greater than 0.005 $^0/_{00}$, while in 81 cases out of 100 there are no differences at all.

The changes themselves are usually small: they are greater than 0.01 $^0/_{00}$ in 4 cases out of 100, greater than 0.005 $^0/_{00}$ in 12 cases out of 100, while in 61 cases out of 100 there are no changes.

From what has been said above it seems possible to represent even small changes of the salinity of the deep water by the mean values from each station. Such mean values are plotted in Fig. 20. Some of them are based on one single sample only (two titrations), others on more samples, up to 7 or 8. The accuracy with which these values are determined, therefore, varies from point to point, and a number of minor changes

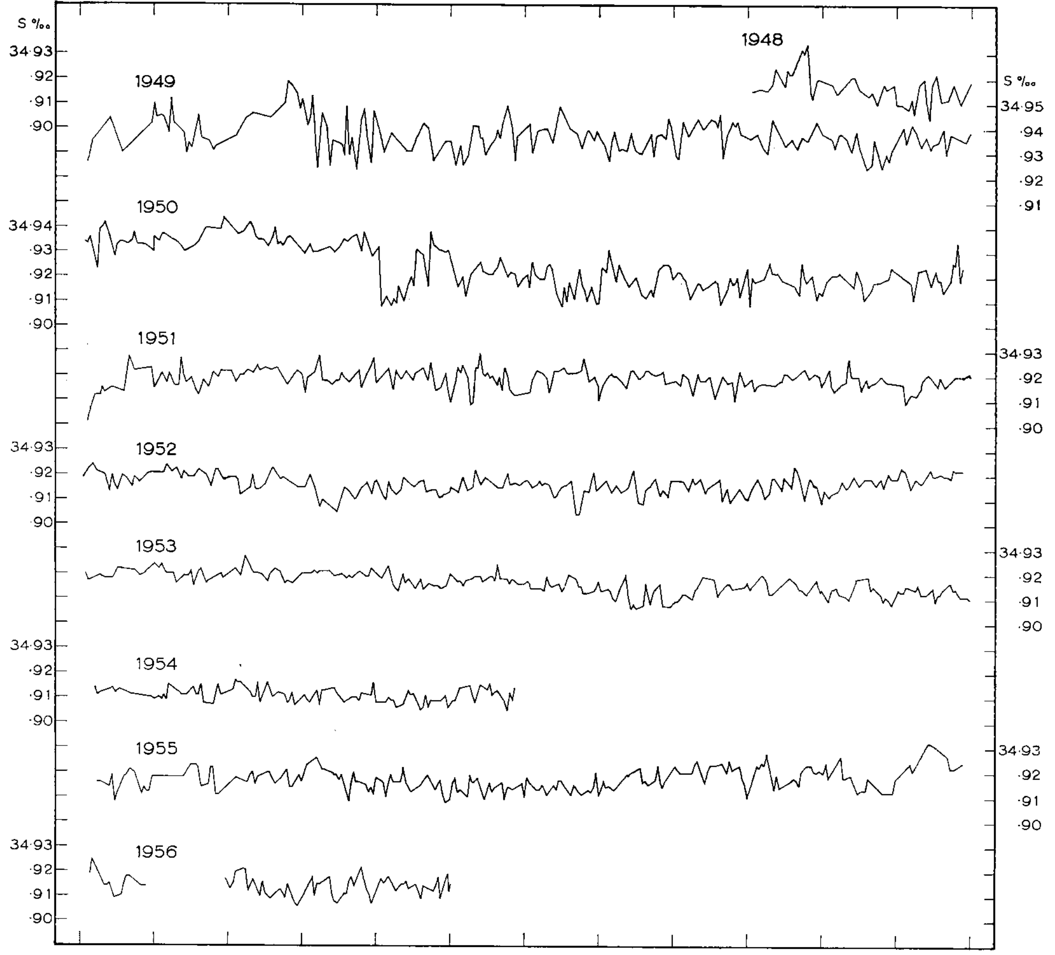

Fig. 20. Variations of deep water salinity 1948–56.

may be due to observational errors. Nevertheless, it seems that perhaps even several details of the curve are representing actual conditions. It is seen that in January 1949 the values increased from between 34.91 and 34.92 $^0/_{00}$ to between 34.94 and 34.95 $^0/_{00}$. A great decrease took place in May 1950. From this time on most values are near, or slightly below, 34.92 $^0/_{00}$, and it is seen that the changes from station to station are smaller than before May 1950. It is not possible to say why this is so, but it seems reasonsable to expect greater irregularities in periods of greater changes of the mean values, for instance in the early months of 1949 and in May 1950.

In order to obtain a clearer picture of the changes, 10-day means have been computed as mean values of all values obtained by titrations of deep water samples collected within each 10-day period. These values are compiled in Table 13 together with the

Table 13. *Ten-day means of deep water salinity and number of titrations.*

	1948	1949	1950	1951	1952	1953	1954	1955	1956
Jan. 5		34.933 15	34.936 25	34.910 49	34.921 36	34.919 34	34.912 6	34.916 11	34.923 16
15		35 5	34 25	15 30	18 39	22 22	13 18	14 49	15 32
25		39 19	34 17	20 8	15 46	22 32	10 16	14 26	14 18
Feb. 5		47 23	36 21	18 40	22 27	20 30	11 36	12 22	
15		38 24	33 7	18 44	19 25	20 32	12 39	20 26	
25		31 20	41 13	18 25	19 25	18 14	11 19	15 18	17 2
Mar. 5		42 27	39 24	21 46	15 39	21 23	14 36	19 13	15 32
15		44 10	35 32	23 29	16 34	20 30	12 41	19 24	12 20
25		53 42	34 22	20 18	18 33	18 24	10 29	18 40	10 11
Apr. 5		33 52	31 24	20 39	16 23	20 34	11 49	23 28	15 28
15		31 43	34 32	17 54	13 25	19 34	11 19	18 34	13 54
25		29 48	31 20	21 37	15 56	21 40	11 34	16 55	13 29
May 5		35 16	13 34	19 35	13 40	17 26	08 24	15 34	15 27
15		35 32	23 30	21 28	16 45	17 33	09 36	12 24	14 47
25		35 18	28 53	15 77	13 42	16 44	08 16	14 43	14 40
Jun. 5		29 52	21 22	18 36	17 25	16 42	11 38	16 51	14 27
15		35 43	23 30	20 46	16 33	19 52	13 28	14 33	15 25
25		41 40	21 32	16 45	17 35	17 24	10 24	16 50	14 30
July 5		39 20	21 39	19 39	15 44	16 55		16 36	
15		42 15	14 36	22 13	14 37	15 31		15 35	
25		37 35	14 33	20 34	12 45	15 58		14 55	
Aug. 5		33 35	22 38	18 53	16 31	12 34		15 22	
15		32 34	14 24	20 34	14 43	11 41		16 41	
25		35 32	21 42	20 31	15 44	09 46		17 31	
Sep. 5		33 30	12 27	18 38	17 31	11 47		22 40	
15		42 37	14 30	18 43	15 38	15 22		22 24	
25		40 29	17 51	19 31	13 30	16 26		19 42	
Oct. 5	34.916 27	35 13	19 24	17 26	15 32	16 27		24 28	
15	19 26	34 15	20 25	18 42	18 35	18 6		16 37	
25	19 40	38 12	18 41	20 24	14 39	14 49		21 34	
Nov. 5	18 14	35 14	21 34	17 50	14 36	13 31		19 42	
15	17 25	32 13	17 31	19 48	19 36	15 41		14 24	
25	16 22	31 20	19 26	18 24	19 24	11 32		14 20	
Dec. 5	12 24	38 12	18 18	13 33	20 16	14 43		21 20	
15	15 18	35 24	18 24	18 40	20 31	12 34		32 6	
25	20 20	37 19	24 47	20 27	21 29	13 28		24 9	

number of titrations on which each value is based. It is seen that the smallest numbers occurring are: 2, 5, 6, 6, 6, 7, 8, 9, while the remaining 250 numbers are higher. The average number is 32. The 10-day means are plotted in Fig. 21. Also from this curve it is seen that after the great increase of salinity about new year 1949 the variations are great; they are gradually decreasing until the sudden drop of the mean value in May 1950, and also this drop is accompanied by relatively great variations.

As seen above the salinity of the deep water is very nearly the same within the

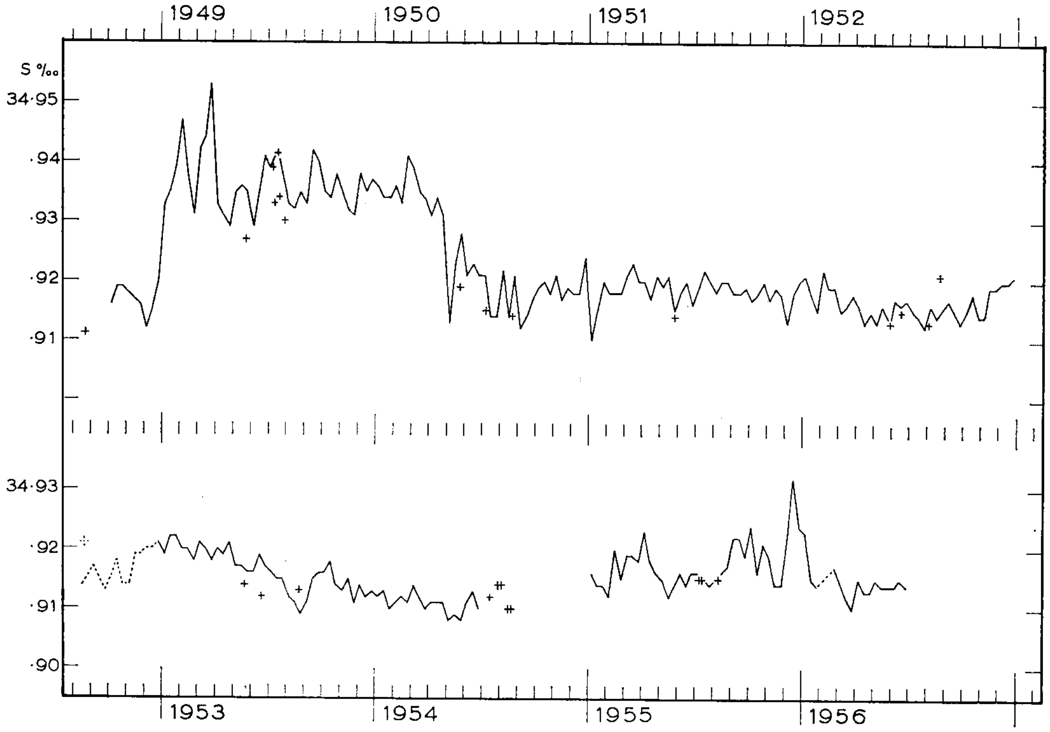

Fig. 21. Deep water salinity 1948–1956, 10-day means.

whole of the southern part of the Norwegian Sea. When computing the mean values for each of the sections from 1935 (cf. Fig. 2), we arrive at the values given in Table 14 under 1935, d-i and k. These values are nearly equal. A similar result is obtained when studying the sections from 1936 (cf. Fig. 3), as seen from Table 14 under 1936, d-k.

We may, therefore, expect the "Armauer Hansen" observations from the Sognefjord section and from other sections to be representative of the deep water salinity of the Southern Norwegian Sea. Such values are compiled in Table 14. Where relatively few deep water samples were collected, the mean value is of course less accurate. When drawing histograms it is seen that the single values are clearly more scattered in 1914, 1925, 1927, 1928, 1929 and 1934 than in most other cases. This may be due to the relatively small number of samples collected these years, but also suggests that the accuracy was perhaps not quite so high during these early years as later.

Computing from Table 14 the mean value for each year, we arrive at the values plotted in Fig. 22. They show a fairly regular increase of 0.03 $^0/_{00}$ from 1925 to 1932. The 1949 value is higher than any other.

Of special interest will be a comparison between the values from later years with the simultaneous values from Weather Ship Station M. The values in Table 14 are

Table 14. *Mean deep water salinities from "Armauer Hansen" stations in the Southern Norwegian Sea.*

Year	Date	Stations	Samples	Titr.	Salinity	Sections etc.
1914	7—11. V	4—11	33	66	34.902	Sognefjord Sect.
1925	6—8. VI	6—8	29	58	.891	—
1927	31. V—1. VI	42—48	34	69	.899	—
1928	25. VIII	90—93	17	35	.906	—
1929	26—27. V	23—29	29	59	.912	—
1932	12—14. VIII	91—98	39	79	.922	—
1934	26—27. VIII	110—116	24	49	.908	—
1935, a	1—3. VI	70—79	57	124	.920	—
- b	3—7. VI	81—83, 88—93	41	90	.919	Faeroer Bank
- c	7—10. VI	93—102	55	121	.916	6—10° W
- d	10—13. VI	102—115	62	140	.916	69° N
- e	19—23. VI	122—143	99	211	.916	68° N
- f	23—27. VI	144—159	76	176	.917	67° N
- g	2—4. VII	175—189	71	151	.917	66° N
- h	4—7. VII	188—200	73	164	.916	65° N
- i	11—14. VII	211—222	61	138	.916	64° N
- j	14—15. VII	223—231	44	102	.917	Sognefjord Sect.
- k	20—21. VII	244—254	30	71	.916	63° N
1936, a	10—12. VI	48—66	56	162	.919	Frøysjø—WNW
- b	12—13. VI	67—81	46	114	.920	Sognefjord Sect.
- c	20—21, 24. VI	111—118, 152—156	37	101	.915	Stad—WNW
- d	21—22. VI	120—132	10	28	.916	63° N
- e	22—24. VI	133—151	40	108	.917	63° 30' N
- f	24—27. VI	157—186	76	206	.913	64° N
- g	30. VI—2. VII	195—217	84	231	.916	64° 30' N
- h	3—5. VII	218—240	74	225	.917	65° N
- i	10—11. VII	260—280	62	172	.917	65° 30' N
- j	12—14. VII	281—302	54	159	.916	66° N
- k	17—20. VII	320—343	70	211	.916	66° 30' N
- l	20—22. VII	343—357	82	268	.915	NW—Stad
- m	27—29. VIII	383—398	41	107	.916	Frøysjø—NW
- n	29—30. VIII	399—415	40	126	.918	Stad—NW
1947, a	23—25. VI	93—105	62	183	.912	Sognefjord Sect.
- b	23—25. VII	141—152	68	175	.902	—
1948, a	23—25. V	43—53	52	121	.916	—
- b	22—24. VI	80—89	57	142	.911	—
- c	20—22. VIII	128—137	52	144	.911	—
1949, a	22—23. V	33—40	34	111	.927	—
- b	7—9. VII	62—80	26	61	.939	S of St. M.
- c	9—11. VII	81—99	36	79	.933	Near St. M.
- d	14—17. VII	114—130	35	77	.941	N of St. M
- e	17—19. VII	131—150	51	122	.934	S of St. M.
- f	27—29. VII	191—225	77	197	.930	Sognefjord Sect.
1950, a	21—25. V	64—119	122	271	.919	—

Table 14. *Mean deep water salinities from "Armauer Hansen" stations in the Southern Norwegian Sea* (Cont.)

Year	Date	Stations	Samples	Titr.	Salinity	Sections étc.
1950, b	3—10. VII	156—170	201	477	.915	Sognefj. Sect.
- c	20—21. VIII	304—325	47	120	.914	—
1951	24—27. V	56—74	95	213	.914	—
1952, a	26—27. V	73—91	40	118	.913	—
- b	16—19. VI	123—159	104	281	.915	—
- c	1—4. VIII	219—248	89	253	.913	—
- d	22. VIII	292—299	15	39	.921	—
1953, a	20—23. V	61—86	85	204	.914	—
- b	19—20. VI	129—154	81	233	.912	—
- c	20—23. VIII	246—280	100	269	.913	—
1954, a	16—21. VII	35—74	99	240	.912	Ca. 63° N, 3° E
- b	31. VII—5. VIII	77—117	93	204	.914	—
- c	6—9. VIII	123—150	59	145	.914	—
- d	21—23. VIII	200—225	75	187	.910	Sognefjord Sect.
- e	23—26. VIII	226—239	31	122	.910	Ca. 63° N, 3° E
1955, a	7—9. VII	53—76	66	152	.915	Sognefjord Sect.
- b	9—12. VII	77—102	61	150	.915	NW—Stad
- c	3—10. VIII	108—163	100	244	.915	Ca. 63° N, 3° E

therefore plotted as crosses in Fig. 21, from which it is seen that the agreement between the two sets of data is strikingly good. Only in very few cases are the differences greater than 0.005 ‰. In these cases, viz. in May 1949 and in June and August 1953, the agreement would be perfect if the values were compared with the Weather Ship values at later dates, viz. 2, 6 and 2 weeks later. If the other values from the Sognefjord section are compared with values from Station M taken from 2 to 6 weeks later, the agreement keeps nearly perfect. It is true that all these differences are very near to the accuracy of determination, and they should perhaps not be studied in too much detail. Nevertheless it may be justified to think that they may be due to a general motion towards the north or north-east of the deep waters in this area. Minor inhomogeneities as those exhibited by Fig. 16 and Fig. 17 would cover the average distance from the Sognefjord section of

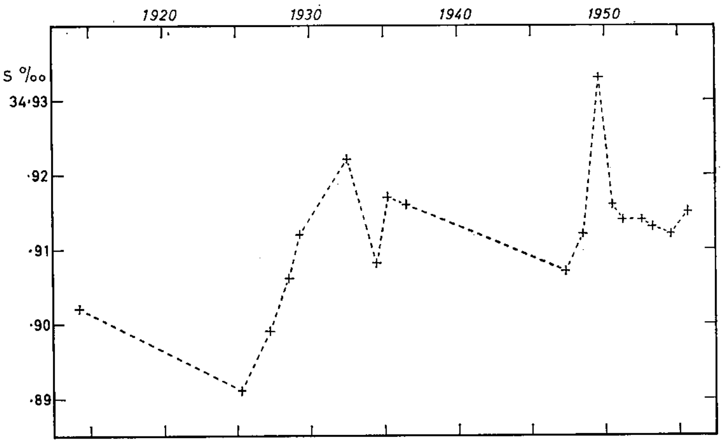

Fig. 22. Annual mean deep water salinities 1914–1956.

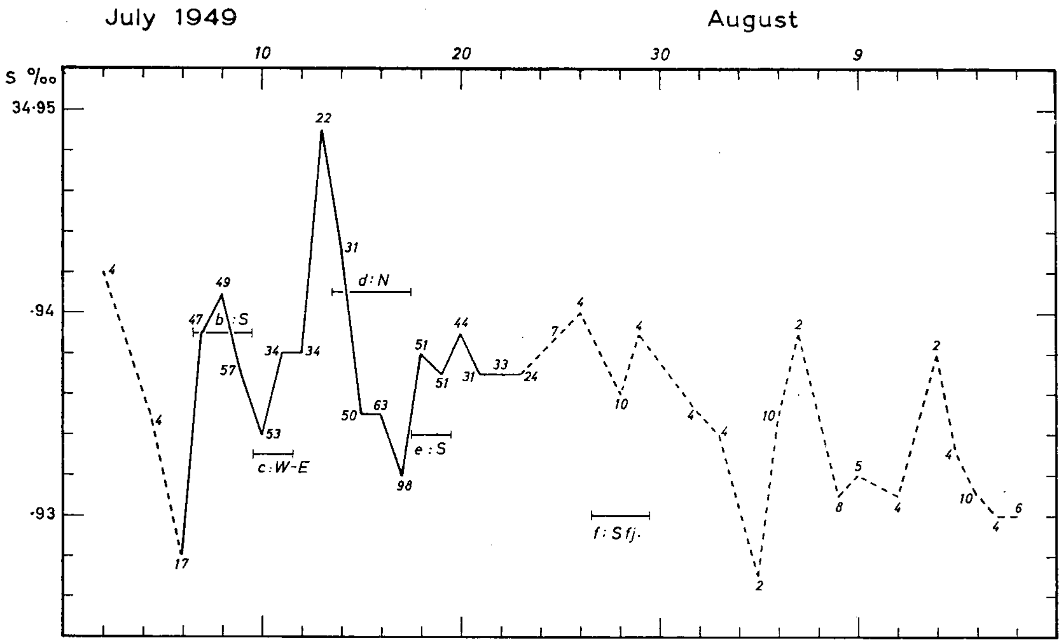

Fig. 23. Mean deep water salinities from single stations July–August 1949.

some 200 or 250 n.miles during 2 to 6 weeks when moving at a speed between 10 and 40 cm/sec. That velocities up to 20 cm/sec are not at all unlikely has been clearly stated by direct current measurements near the bottom down to depths of more than 1000 m. These measurements will not be dealt with in this paper.

In July 1949 the "Armauer Hansen" made investigations in the Sognefjord section, in a section along the meridian 2° E from the latitude of the said section up to Station M, in sections along the 66th parallel east and west of Station M and in the area north of Station M. From the 7th to the 23rd of July stations were taken by both ships at regular intervals of two hours (Mosby 1950). Mean values of the deep water salinities are included in Table 14 and plotted in Fig. 21. The many samples permit of a more detailed study; the mean values for each day from Station M are plotted in Fig. 23 together with the "Armauer Hansen" values in Table 14 under 1949, b-f. The value b is based on samples from stations taken south of Station M on 7–9th and should probably be compared with the Weather Ship values a few days later. The values c refers to the near vicinity east and west of Station M. The value d is derived from stations farther north and should be compared with the Weather Ship value a few days earlier. The value e from stations in the south must probably be compared with the curve for a fortnight later. The value f from the Sognefjord section will correspond to the Weather Ship values two or perhaps rather three weeks later. It thus appears that if a sufficient number of samples are available, the results will fit into a general picture even in details as those just described. In the case of the Sognefjord section from the 22nd of August

Table 15. *Mean monthly values of deep water salinity.*

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1948										34.918	.917	.915
1949	34 936	.939	.948	.931	.935	.934	.939	.933	.939	.936	.932	.936
1950	.935	.937	.936	.932	.922	.922	.917	.920	.915	.919	.919	.921
1951	.912	.918	.921	.919	.917	.918	.920	.919	.918	.918	.918	.917
1952	.918	.920	.916	.915	.914	.917	.914	.915	.915	.916	.917	.920
1953	.921	.920	.920	.920	.917	.918	.915	.911	.913	.915	.913	.913
1954	.912	.911	.912	.911	.908	.911						
1955	.914	.916	.918	.918	.914	.916	.915	.916	.921	.920	.916	.922
1956	.917	.917	.913	.914	.914	.914						
Mean	.921	.922	.923	.920	.918	.919	.920	.919	.920	.920	.919	.921
	.916	.917	.917	.916	.914	.916	.916	.916	.916	.918	.917	.919

1952 (Table 14 under 1952, d and Fig. 21) the 10-day means conceal that 20 days later the difference is only 0.002 $^0/_{00}$.

The curves of Figs. 20–21 do not indicate any regular annual variation of the salinity, a variation which might be expected if the renewal of the water were due to a direct effect of the cooling in winter. In order to decide on the question, as far as the salinity values are concerned, mean monthly values were computed; they are given in Table 15. The mean monthly values which are based on all observations, show slightly higher values in February and in March than in the other months. The mean monthly values which are based only on the observations after May 1950 (last line of Table 15), viz. after the sudden drop of the mean values (cf. Fig. 21), may perhaps be said to give slightly higher values in October and in December than in the other months. The differences are, however, on the whole very small, 0.001 or 0.002 $^0/_{00}$, and we may thus conclude that only a slight indication of an annual variation of the

Table 16. *Mean annual variation of salinity October 1948 to June 1957, based on 6-months means (July to December lacking in 1954 and in 1956).*

Depth	Amplitude	Minimum	Maximum	S $^0/_{00}$
150	0.019$^0/_{00}$	March.	Sept.–Oct.	35.23
200	.018	March–Apr.	October	.19
300	(.027)	March?	Sept.–Oct.	.06
400	.013	August	February	34.975
500	.008	Aug.–Nov	Feb.–May	.944
600	.007	August	February	.930
800	.003	August	February	.923
1000	.003	July	February	.921
1200–2500	.002	July	February	.920

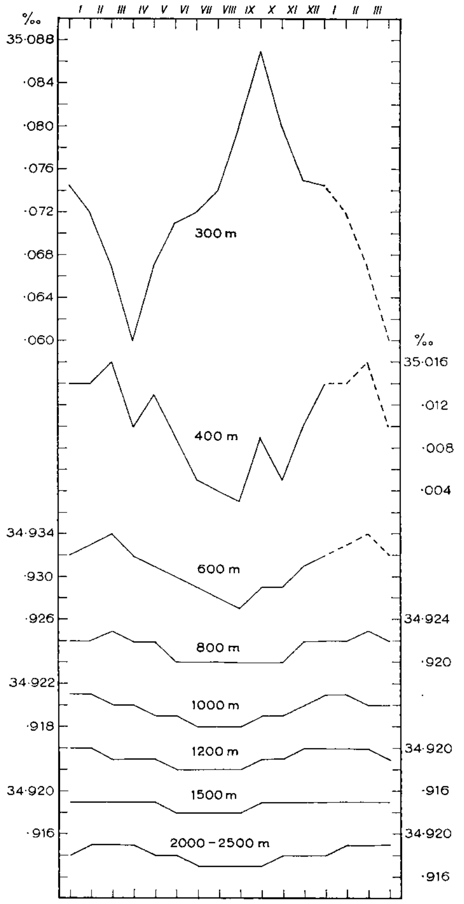

Fig. 24. Mean annual variation of salinity 1948–1956.

salinity of the deep water can be traced by this treatment of the observations.

As even this slight indication appears of interest in connection with the attempt made below to study the renewal of the deep water, we shall, however, at once make one more effort to "squeeze" the observations in this respect.

Studies of the upper layers, the results of which will be published later, show a clear seasonal variation of the salinity. The amplitude decreases from about 0.25 $^0/_{00}$ at the surface to about 0.05 $^0/_{00}$ at 300 m depth. The minimum values appear in July at the surface, but are retarded regularly with increasing depth until March–April at 200 and 300 m. At these depths the variation is rather irregular; but in smoothing the curves by using consecutive 6-months mean values, a clear change can be seen to occur between 300 and 400 m. As illustrated by Fig. 24, in which the variations from 300 m downwards are presented, the amplitude is decreasing towards greater depths, but from 400 m on the minimum suddenly occurs in summer, in July or August. The use of consecutive 6-months means will, of course, reduce the computed amplitudes; but in this way it is possible to determine the amplitudes as well as the months in which they occur as given in Table 16. Below 300 m the amplitudes are very small, but the values are consistent; it thus seems justified to conclude that *in the lower layers a small annual variation occurs, the amplitude of which decreases with increasing depth, and the extreme values of which occur nearly simultaneously in July or August (minima) and in February (maxima) from 400 to 2500 m.* This variation and the seasonal variation originating in the surface layers seem to be in interference at 300 m, where irregularities occur, making it difficult to point out maximum and minimum; the amplitude of 0.027 $^0/_{00}$, found by direct computation, is hardly representative.

Although numerically small, these values indicate a regular reduction with depth, and a similar reduction is found when studying the slow variations. For this study consecutive annual means have been computed; they are plotted in Fig. 25, from which it is seen that from 600 m downwards there occurred a regular drop from 1949 towards the end of 1950, whereafter nearly constant low values are found

Table 17. *Drop in salinity 1949—1950.*

Depth	△S ‰	S ‰
400	0.063	34.975
500		.944
600	.030	.930
800	.018	.923
1000	.015	.921
1200	.014	.920
1500	.014	.920
2000	.013	.920

up to the end of 1953. At 400 m we find high salinities in 1949, low values in 1951, high values in 1952 and low values towards the end of 1953. The 400 m surface thus seems to represent the variations going on in the upper layers, while at 500 m depth the changes are seen to be governed partly from above and partly from below. Sufficiently accurate values of the deep water salinity are not available from the months of July to December in 1954 and in 1956 when the "Polarfront I" and the "Polarfront II" occupied Station A (62° N, 33° W). The continuous curve of annual means therefore only covers the period April 1949 to January 1954. But the drop in salinity in 1949 to 1950 appears very clearly at all depths. As seen from the compilation in Table 17, this drop in salinity *decreases* not only from the high values for 400 m, but also *from 600 downwards*. We shall return to these details below.

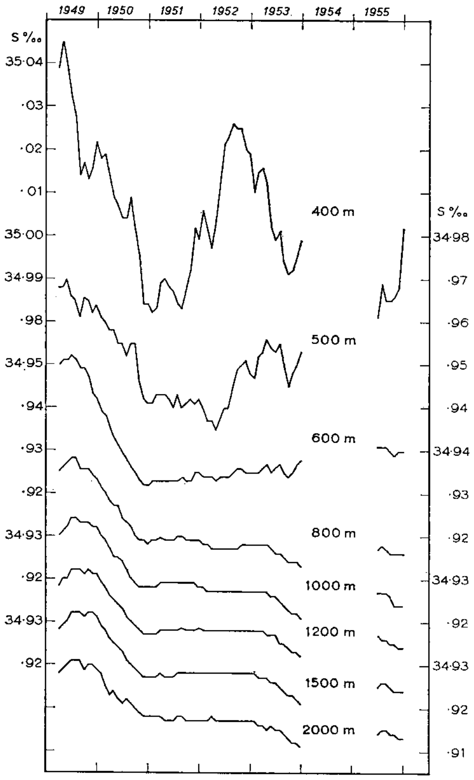

Fig. 25. Variation of annual mean values of salinity.

8. Variation of temperature. A study of the possible variations of temperature is made difficult by the change of temperature with depth. The observations have to be treated separately for each standard depth, whereby a smaller number of data are available than in the case of salinity, where all observations from within the whole of the homohaline deep water could be treated together. Due to the variation of temperature with depth also errors in the deter-

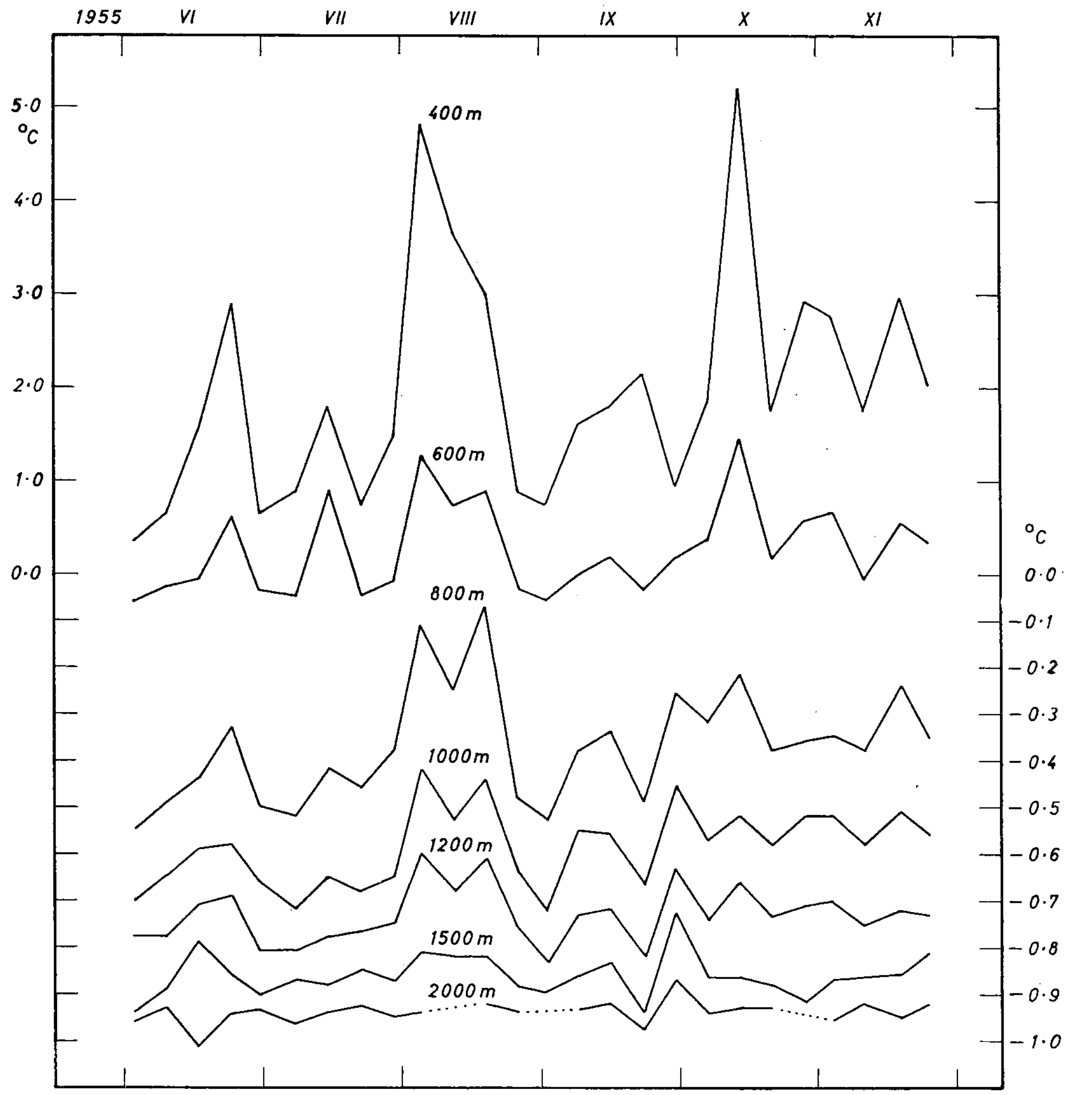

Fig. 26. Variations of temperature June–November 1955.

mination of depth will be of importance. For these reasons it hardly appears possible to study similar details of variation of temperature as those demonstrated in the variation of salinity by Fig. 21 and Fig. 23. That sudden changes from station to station occur at Weather Ship Station M also in temperature, is, however, clearly demonstrated by Fig. 26, where the variations of temperature during June–November 1955, from 400 m downwards are illustrated, using only observations from stations to at least 1500 m depth (note the different scale values of the diagram). All changes are decreasing from 400 m downwards, but they are on the whole running parallel, and thus indicate a similar horizontal heterogeneity in temperature as that found above in salinity. It is obvious from this that no representative value can be found from observations, made in one single section.

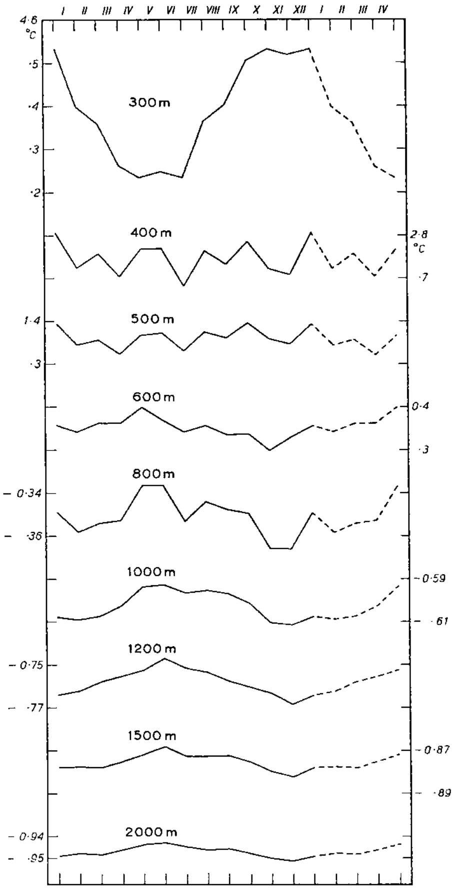

Fig. 27. Mean annual variation of temperature 1948–1957.

For a study of possibly occurring annual variations the Weather Ship data may, however, be treated in a similar way as done above with the salinities. As the effects of erroneous depth determinations may here be important, corrections have been applied. As reliable unprotected thermometers have been at disposal only at a few of the stations, reductions have been based on determinations of the deviations of the wire from the vertical, measured in each case. The reductions have been computed by the method developed by the present author[1] (1952). When computing the mean monthly values for the whole period October 1948 to June 1957, great irregularities are found. Consecutive 6-months means were therefore applied. The resulting curves are shown in Fig. 27. It is seen that the 300 m curve has its maximum in November, the retarded summer season of the upper layers. No regular annual variation can be distinguished for 400 or for 500 m; but from 600 m downwards a simultaneous annual variation can be seen to occur at all depths. The amplitudes and the months of maxima and minima are given in Table 18. Where the curves are still somewhat irregular, as for 1200 and 1500 m, the amplitudes (third column) have been estimated slightly lower than the full range of variation (second column). In view of the small values found for the amplitudes, their decrease from 600 m downwards must be said to be unexpectedly regular.

In order to study the slow variations from year to year, consecutive annual mean values were also computed for each standard depth. The results are plotted in Fig. 28, from which it is seen that the variations of the lower layers are different from those of the upper layers.

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[1] The validity of this method has been doubted by E. E. Watson (1953). It will, however, be seen from Mosby (1955) that such doubt is not justified.

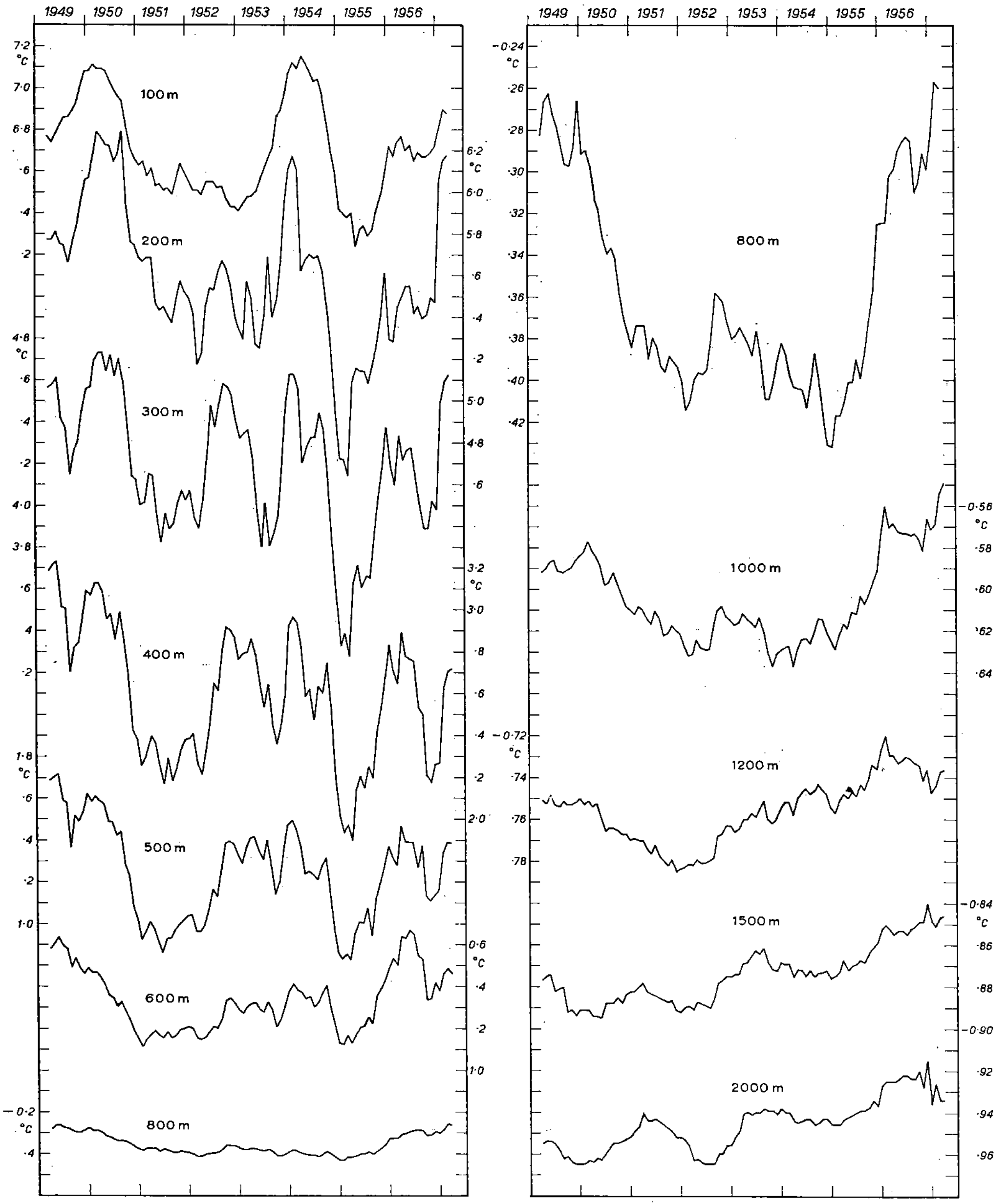

Fig. 28. Variation of annual mean values of temperature.

Table 18. *Mean annual variation of temperature October 1948 to June 1957 (all months included), based on 6-months means.*

Depth	Range	Amplitude	Minimum	Maximum	$\frac{dt}{dz}$
300	0.30	0.30	May	November	
400	.12	?	?	?	
500	.07	?	?	?	
600	.100	0.080	Oct–Nov	Apr–May	-55.10^{-6}
800	.030	.030	November	May	-19 -
1000	.020	.019	Nov–Dec	May–June	-10 -
1200	.022	.014	Nov–Dec	May–June	-6 -
1500	.014	.010	Nov–Dec	May–June	-3 -
2000	.008	.007	Nov–Dec	May–June	-1 -

9. Variation of oxygen content. The samples collected since March 1953 have been used for a study of the annual variation. They cover the period from March 1953 to February 1958, excluding the autumn seasons from July to December in 1954 and 1956, when the "Polarfront I" and the "Polarfront II" occupied Station A. Mean monthly values were determined for all standard depths, and consecutive 6-months means were then computed. The result is presented in Fig. 29, from which it is seen that the variation at 300 m depth, with maximum values in summer, is the opposite of those observed at greater depths. At 400, 500, and 600 m the minimum occurs in spring, about May, and the maximum in autumn, about November, the amplitudes at these depths being about 0.05, 0.03 and 0.02 cc/L respectively. At 800 m no regular annual variation is found, but below this depth minimum again occurs about May and maximum about November, the amplitude now increasing downwards, being about 0.03, 0.04, 0.05 and 0.06 cc/L at 1000, 1200, 1500 and 2000 m respectively.

As these amplitudes are small, it should be mentioned that the curves in Fig. 29 are based on about 160 double determinations from each depth, corresponding to 13 double samples per month at each depth on an average: in summer up to 21 in June, in winter down to 6 in October. One may, therefore, expect a numerical accuracy of about 3 times that of the determination. It thus seems justified to consider Fig. 29 to be, in the main features, representative of the actual conditions. Nevertheless, considerable alterations of the picture may be expected when in future a longer series of observations will become available.

10. Processes of renewal[1]. From the diagrams in Fig. 4 and Fig. 5 it is seen that within great areas of the Norwegian Sea high values of temperature and of salinity prevail in the uppermost layer, low values at greater depths. The upper layer originates from the Gulf Stream System, and the inflow of this Atlantic water into the Norwegian

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[1] A preliminary report on the contents of this and the following section has already been printed (MOSBY 1959).

Sea maintains the high temperature and salinity values. Also the low values of temperature and salinity in the deep and bottom water are maintained by processes of renewal.

Between the Atlantic water and the deep water the station curves show a marked transitional layer, through which heat is transported downwards by turbulent conduction, and salt by diffusion. The quantities of heat and of salt thus lost by the layer of Atlantic water must equal the quantities received by the inflow from the Atlantic Ocean, as the stratification is maintained apparently unaltered from year to year. It is not easy to evaluate these quantities, but an idea of their ratio can be obtained as follows.

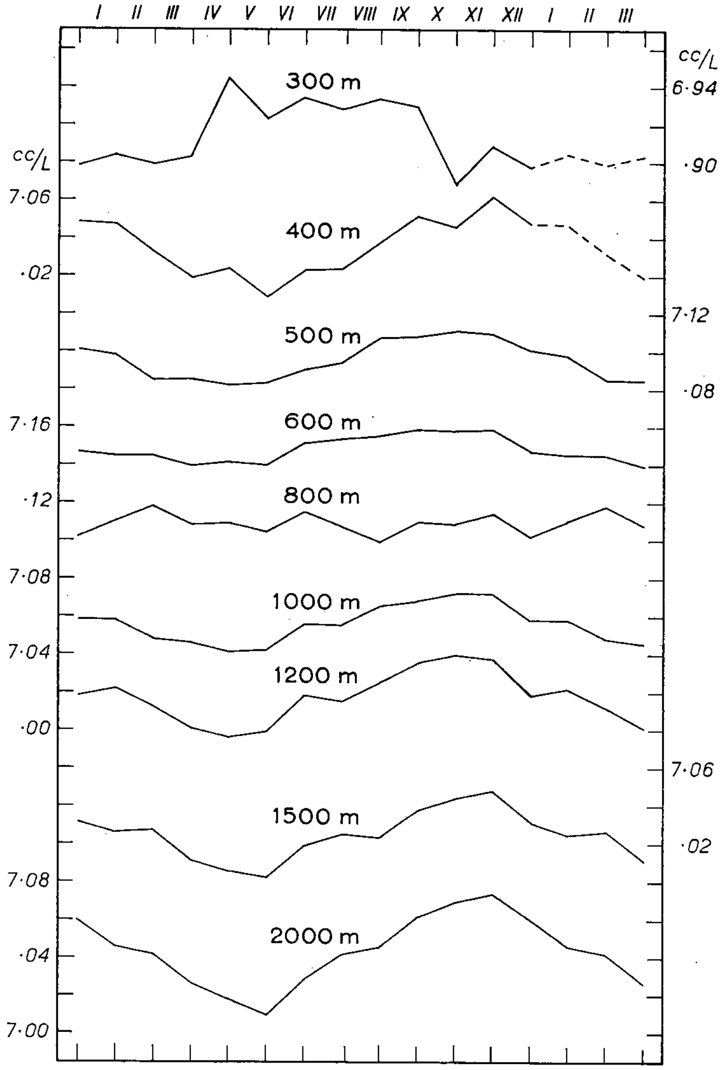

Fig. 29. Annual variation of oxygen content March 1953 to February 1958.

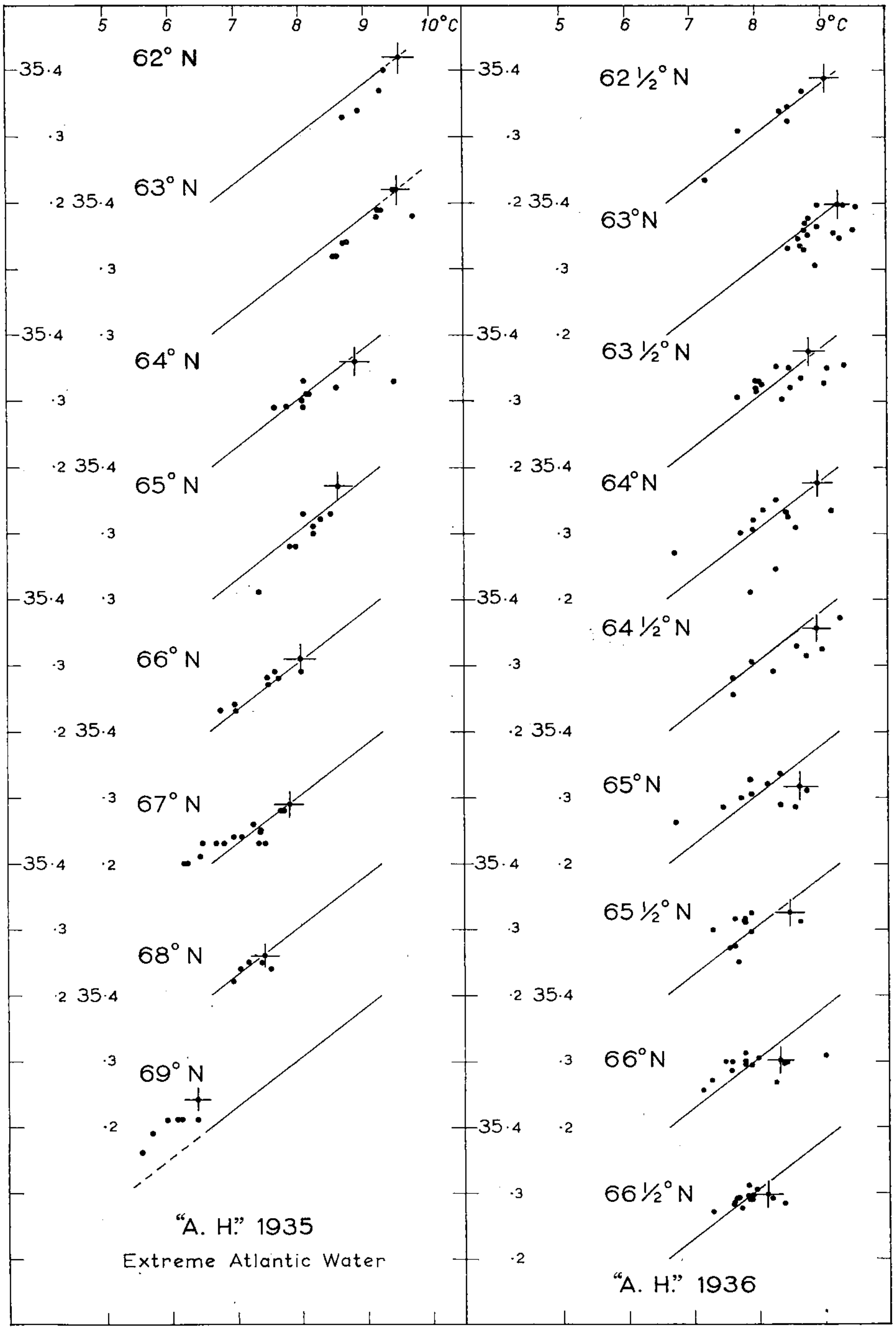

Fig. 30. Extreme Atlantic water in 1935 and 1936.

From the latitudinal sections of the "Armauer Hansen" in 1935 and 1936 so many observations are available that extreme values of corresponding temperatures and salinities can easily be determined from each section. A number of the pairs of high values are plotted in t-S-diagrams in Fig. 30, in which a thin line illustrates the approximate t-S-relation; this line is equal in all diagrams, and the values of temperature and salinity thus chosen are plotted against latitude in Fig. 31. It is seen that in both years the decrease towards the north is about the same: $\triangle S = 0.026\ ^0/_{00}$ in salinity and $\triangle t = 0.35°$ C in temperature per degree latitude. When comparing the reductions of temperature and salinity towards the north we find a ratio of $\triangle t : \triangle S = 0.35 : 0.026 = 13.5$.

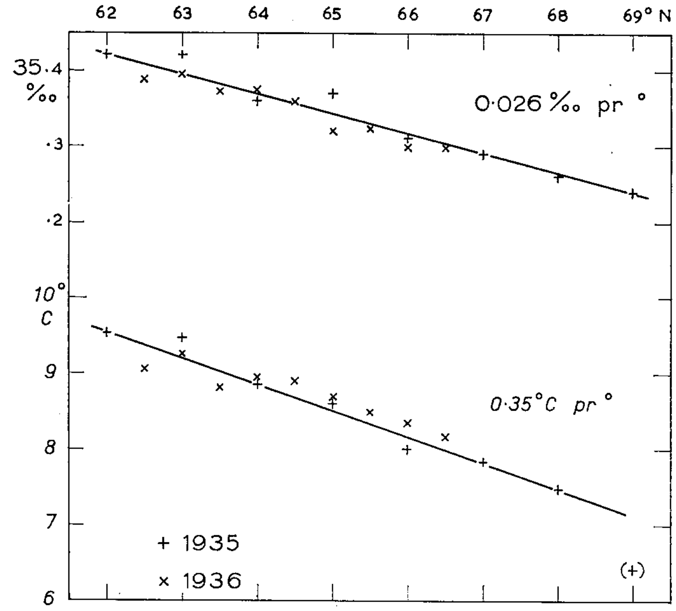

Fig. 31. Decrease towards the north of extremes of temperature and salinity within the Atlantic water.

If these reductions take place mainly through the transitional layer, the ratio of the quantitites of heat and of salt transported through this layer must of course also be about 13.5. Before studying this, let us consider a practical problem in connection with the treatment of the observations.

It is true that the station curves are always of very nearly the shape illustrated by Figs. 4 and 5; but it has been shown (Mosby 1950) that e.g. at Station M the transitional layer is found at different levels from not much more than 200 m down to 800 m depth. The variation in level is rapid; observations have shown apparent changes by 3–400 m within 2 hours. For the present investigation such changes are of secondary importance, they may have an effect on the eddy conductivity and the eddy diffusivity.

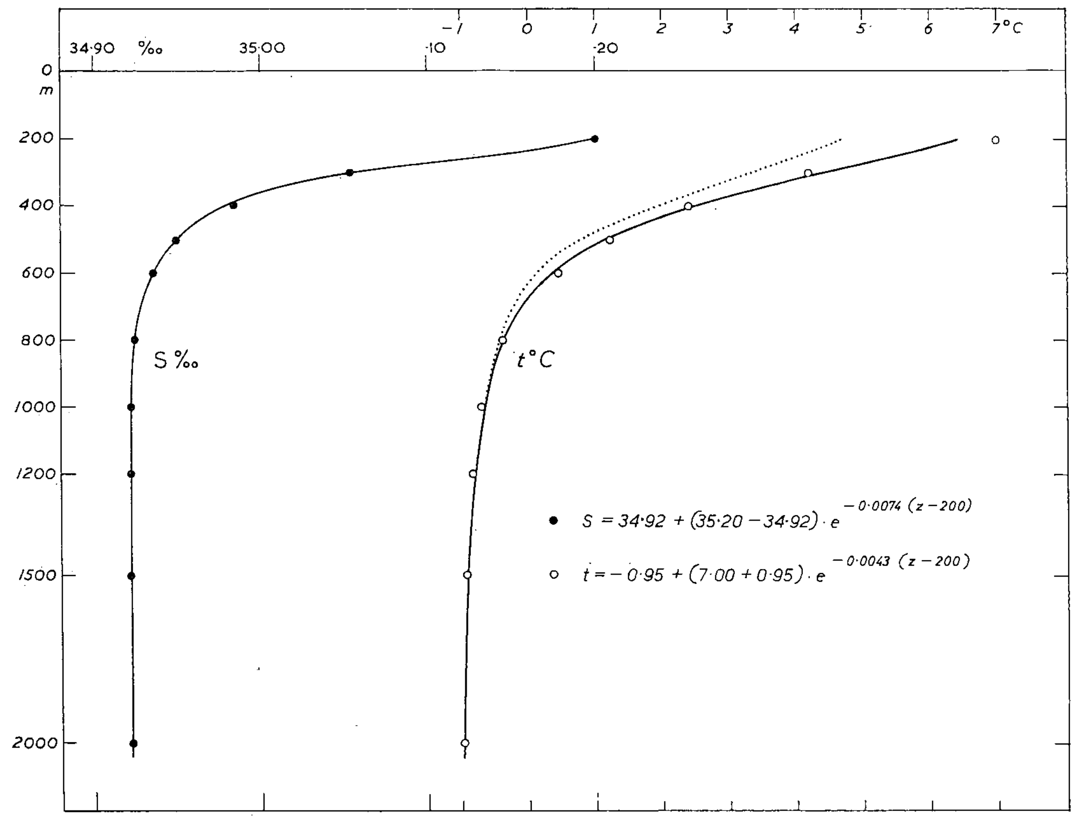

Fig. 32. Normal distribution of temperature and salinity at station M, October 1948 to June 1954.

For an explanation of the stationary conditions we shall have to deal mainly with the average situation. This may of course be found in computing average values for each standard depth, as done in Figs. 4 and 5. But as we shall be particularly interested in the vertical gradients of temperature and salinity in the transitional layer, it is easily understood that this procedure may give misleading results. Imagine, as an example, two or more station curves of exactly the same shape but showing the transitional layer at different depths. Direct mean values for selected depths will give an average station curve showing smaller vertical gradients in the transitional layer than either of the original curves. To preserve the gradients one may select a number of values of temperature and salinity, and read the corresponding depths from each station curve. By averaging these values of depth a representative "normal" distribution within the transitional layer is obtained. In this way the normal distribution of temperature and salinity at Station M has been determined from 269 deep stations from the period October 1948 to June 1954. The values are given in Table 19 and reproduced in Fig. 32

Table 19. *Normal distribution of temperature and salinity at Station M, October 1948 to June 1954.*

m	t° C	S °/₀₀
200	6.35	35.19
300	4.50	.06
400	2.30	34.975
500	0.95	.944
600	0.20	.930
800	—0.40	.923
1000	—0.62	.921
1200	—0.75	.920
1500	—0.87	.920
2000	—0.95	.920

as fully drawn curves from 200 m downwards. From these curves the maximum values of the gradients have been found:

$$\frac{\partial t}{\partial z} = -21 \cdot 10^{-5} \ ^{\circ}\mathrm{C} \text{ per cm}$$

$$\frac{\partial S}{\partial z} = -1.5 \cdot 10^{-5} \ ^{0}/_{00} \text{ per cm}$$

The ratio is seen to be 14, in good agreement with the ratio $\triangle t : \triangle S = 13.5$ found above for the reduction towards the north of temperature and salinity within the extreme Atlantic water. Equal ratios should of course be expected if the eddy conductivity A_t and the eddy diffusivity A_s be equal[1].

The agreement mentioned is perhaps better illustrated by Fig. 33, in which the fully drawn curve represents the t-S-relation corresponding to the normal distribution at Station M; dots indicate the standard depths 150, 200, 300, 400, 500, 1000 and 2000 m. By crosses are shown the extreme values of Figs. 30 and 31, and by the small circle is denoted the extreme Atlantic water north of Spitsbergen as determined by the Swedish-Norwegian Arctic Expedition in the summer of 1931 (Mosby 1938). It is seen that the extreme values are all falling very nearly along a straight line, which roughly coincides with the t-S-relation of Station M from 150 m down to nearly 300 m depth. Parallel with this line is the thin broken line that intersects the station curve at a value of the density of $\sigma_t = 28.04$. We shall return to this later, in connection with Fig. 34, which on a greater scale represents the part of Fig. 33 falling within the limits of the small rectangulum below to the left.

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[1] When using the above mentioned mean values of temperature and of salinity for the standard depths for establishing the average vertical distribution, the vertical gradients derived are -15.10^{-5} °C per cm and $-0.7 \cdot 10^{-5}\ ^{0}/_{00}$ per cm. This would correspond to a ratio $A_s : A_t = 1.7$, which does not seem reasonable.

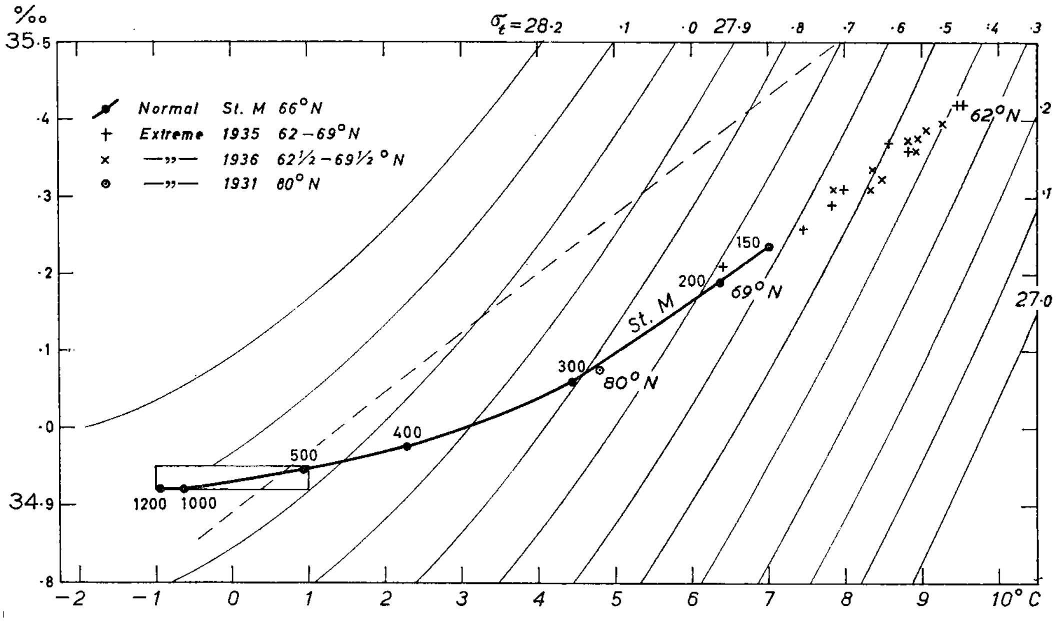

Fig. 33. Normal station M in t-S-representation (fully drawn curve).

The agreement between the ratio of decrease towards the north of the extreme values of temperature and salinity, and the ratio of the vertical gradients of temperature and salinity within the transitional layer, seems to indicate that the decrease towards the north is governed mainly by processes of heat conduction and salt diffusion to the deep water. This is somewhat astonishing, as other processes may well be imagined to be of importance in this connection, thus for instance the evaporation from the surface. By the evaporation of 1 m of water per year or about 3 mm per day, the generally accepted average value for all oceans, an amount of heat of about 59 kgcal per cm^2 per year is needed, and in addition for the accompanying flux of "sensible heat" about half this amount; the quantity of salt liberated is about 3.5 g per cm^2 per year. A surface layer of 100 m thickness would then have its temperature reduced by about $\Delta t = 8.8°$ C per year, while its salinity would increase by $\Delta S = 0.35\,^0/_{00}$ per year. The ratio $\Delta t : \Delta S = -25$ is seen to be very different from the values found above. At first glance it may appear difficult to understand why no effect of the evaporation is traced in the decrease of the Atlantic water towards the north. It must then be remembered that the extreme values are all determined from measurements made in summer, when the Atlantic water is covered by a surface layer of higher temperature and of lower salinity. The effects of physical processes in the surface, as evaporation and radiation, will then be accumulated in the surface layer, until in autumn the vertical convection penetrates the surface layer and in winter also the layer of Atlantic water. This complex of problems will be treated later in a separate paper.

The transport of heat and salt downwards through the transitional layer, of course, must mean that the transition moves slowly downwards. When, nevertheless, the transition is observed as remaining at the same level from year to year, this can only be understood by assuming that the water particles are moving at the same speed in the opposite direction, i.e. vertically upwards towards the surface. In other words: deep water particles are continuously being transformed into particles of Atlantic water, the characteristics of which are the high values of temperature and salinity only.

That such a vertical motion and such a transformation must be taking place will also have to be admitted if it is at all assumed that deep water is renewed through formation of bottom water.

When taking into account only two processes of renewal: that of the Atlantic water by the Norwegian Atlantic Current, and that of the bottom water by formation and injection near the bottom, a simple model may be formulated as follows. At a depth z the change of temperature due to vertical motion of the water particles may be expressed c $\frac{\partial t}{\partial z}$, while the change of temperature due to heat conduction is $\frac{\partial}{\partial z}\left(A_t \frac{\partial t}{\partial z}\right)$. When the temperature remains constant, the sum of these two expressions must vanish

$$\mathrm{c}\frac{\partial t}{\partial z} + \frac{\partial}{\partial z}\left(A_t \frac{\partial t}{\partial z}\right) = \frac{\partial t}{\partial \tau} = 0 \tag{1}$$

where

t denotes temperature
τ — time
z — depth
c — vertical upward speed of motion
A_t — eddy conductivity

On the simple assumption that c and A_t are both constant, i.e. independent of z, the solution of this equation may be written

$$t = t_* + (t_0 - t_*)\, e^{-\frac{c}{A_t}(z - z_0)} \tag{2}$$

Introducing

$t = -0.95°$ C for $z = \infty$ and
$t_0 = 7.00°$ C for $z = z_0 = 200$ m

we find that the formula

$$t = -0.95 + (7.00 + 0.95)\, e^{-\frac{c}{A_t}(z - 200)} \tag{3}$$

yields values in fair agreement with the observed normal temperature distribution if $\frac{c}{A_t} = 0.0043$ (see Fig. 32, where computed values are introduced as open circles). As z is measured in metres this means that in cgs-units

$$c \approx 0.000043 A_t. \tag{4}$$

A similar treatment for the salinity and the introduction of

$S_* = 34.920\ ^0/_{00}$ for $z = \infty$ and
$S_0 = 35.200\ ^0/_{00}$ for $z = z_0 = 200$ m

leads to a formula in good agreement with the observations if

$$c \approx 0.000074 A_s$$

where A_s denotes eddy diffusivity (see Fig. 32, where full circles represent computed values).

As c must necessarily be equal in both cases, this would mean that $A_t : A_s = 1.7$. This appears equally improbable as the inverse ratio $A_s : A_t = 1.7$ mentioned in the footnote on p. 50. Our conclusion must be that the simple model just applied to the temperature distribution, does not apply to the salinity distribution, and cannot explain the difference in vertical distribution between temperature and salinity. This difference can be seen directly from Fig. 32, but is more clearly demonstrated by Fig. 33: from 150 m to about 300 m depth the t-S-relation is nearly linear, but from the latter depth it is gradually curved until about 1000 m depth, from where it shows slowly decreasing temperatures and a very nearly constant salinity down to 2000 m depth.

These conditions can obviously not be explained from the two processes of renewal already mentioned, that of the Atlantic water and that of the bottom water. A third process is needed, and it appears reasonable to expect this to be an advective process of renewal, acting horizontally from the surroundings.

Let us adopt in principle the explanation of NANSEN (1909, 1912) of the formation of the bottom water: in a region where the circulation is slow, the stability is so low that the cooling of the surface in winter can set up an effective vertical convection. In such a region the deep water will probably be found relatively near to the surface, a situation which may well be expected in one of the regions of cyclonic circulation exhibited by the schematical current map of the Norwegian Sea by HELLAND-HANSEN and NANSEN (1909).

The mere thought of constructing a vertical section across the Norwegian Sea, using the same scale in the vertical as in the horizontal, is sufficient to convince that within such a cyclonic region the section must have a horizontal extension which will be 10 or 100 times the vertical extension.

Within the area of cyclonic circulation we must assume the deep water to be situated nearest to the surface in the central region. In the central parts the cooling in winter will, therefore, have its earliest chances of setting up a vertical convection. The further away from the centre, the higher the summer surface temperature and the longer the period of cooling needed to set up convection. In principle we must thus expect vertical convection within an inverted cone of increasing width and depth. It is possible that this cone may relatively early reach the bottom of the sea in the middle, and gradually extend over a wider area. But in principle we must still expect a boundary surface tilting inwards-downwards while moving outwards.

It may perhaps appear possible to have this picture confirmed by suitable observations, although it seems more reasonable to expect that the imaginary "disk" will in nature appear completely or partly divided into several changing cells, making adequate observations difficult. Nevertheless, the general process may in principle be correctly described by our model, from which, therefore, further deductions will be made.

When in a certain place and at a certain time the vertical convection has reached to a certain depth, we must have, within the whole of the vertical column from the surface to the said depth, a uniform temperature, a uniform salinity and a uniform density equal to the density of the surrounding stable water at the said depth. This column of homogeneous water will exert a higher total pressure than any corresponding column of stable water layers in the surroundings. It must, therefore, tend to penetrate into the surrounding stable water layers, and this will be true at all depths, because the convectional process will always reach to different depths in different places. In this way the stable water layers will be gradually renewed by absorbtion of water of a uniform salinity S $^0/_{00}$ and of such a temperature that its density exactly equals that of the water layer to be renewed. As the deep water and the bottom water of the Southern Norwegian Sea have a uniform salinity of very nearly 34.92 $^0/_{00}$, we must be justified in assuming that the water formed by convection will usually also have a salinity of $S = 34.92\ ^0/_{00}$, or perhaps a little lower.

Obviously the original water masses within the "disk" must ultimately be removed and be replaced by the surrounding water masses. The only possible renewal seems to be the one just described, because no single drop of water can enter into and remain stable within a layer unless its density is exactly that of the layer itself. One may, however, imagine such water to be produced through consecutive mixing processes: homogeneous water from the column of convection may slide out into the surrounding water of lower density (higher temperature and higher salinity), and produce a mixture, which is still too heavy to remain stable at the level at which it is produced. Sinking deeper it may be mixed with stable water of a slightly lower density, and so on. The "old" waters thus included in the ultimate mixing product do not give any real renewal, and the result of this more complicated process must be a less effective renewal than that obtained by direct injection from the column of homogeneous water into the stable layers. As the latter process must be stimulated by the high total pressure of the column, it seems reasonable to expect that this is the dominating process of advective renewal. If this complicated process of consecutive mixing does have an effect at all, it must mean that by disregarding it the renewal is being exaggerated. In other words, the percentage of annual advective renewal p, which has below been estimated at some 14 to 15 per cent per year, may be slightly too high.

A t-S-diagram of the deeper layers of the normal station M is reproduced in Fig. 34, in which curves of equal density are also drawn. It is simple from this diagram to determine the temperature of a water of salinity 34.92 $^0/_{00}$ that has a density equal to the density at any depth of the normal station. The result of such determinations is illustrated in Fig. 32 by a dotted curve. These temperatures are of course lower than the normal temperatures, but the differences are not great when compared with the divergencies of the normal temperatures from the bottom temperature –0.95° C. Actually they are 15 to 20 per cent of these divergencies, increasing to 23 per cent at 200 m depth.

The dotted curve in Fig. 32 represents the temperatures towards which the original temperatures will tend by the advective renewal from the "disk". The tendency in

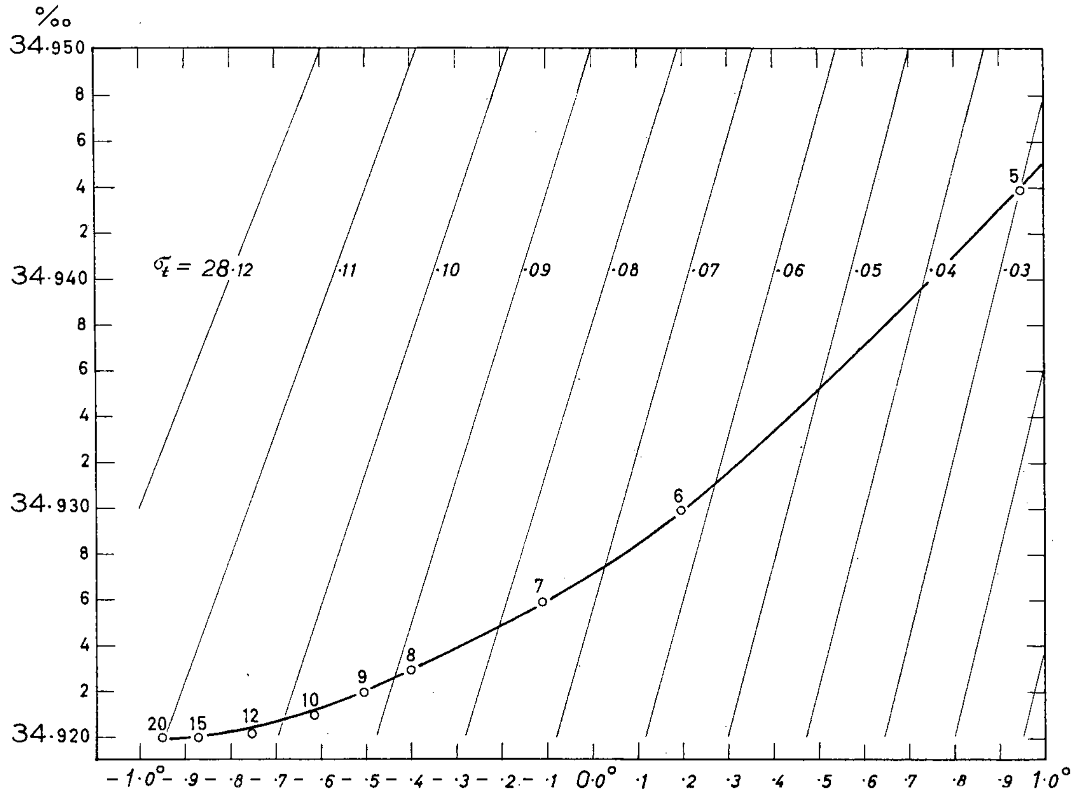

Fig. 34. Normal station M in t-S-representation, deeper layers.

salinity, on the other hand, is towards the value of 34.92 ‰. It is therefore immediately understood that the effect of this renewal must be much more important in salinitity than in temperature. If as a rough guess the renewal is assumed to be a few per cent P per year, the reduction of the differences of the various temperatures from that of the bottom water will amount to only 15 to 20 or perhaps 23 per cent of this percentage P. Our simple model with the vertical motion of the water particles may therefore still give a fair approximation as far as the temperature distribution is concerned. It should, however, be borne in mind that by disregarding the effect of the advective renewal on temperature we are to some extent exaggerating the vertical speed of the water particles *c*.

For an explanation of the salinity distribution, however, the situation is different. For this purpose the advective renewal must be taken into consideration. The effect of this process may be formulated

$$p\ (S - S_*) = \frac{\partial}{\partial z}\left(A_s \frac{\partial S}{\partial z}\right) \qquad (5)$$

where p denotes the part of the water renewed per year. But obviously the vertical motion of the water particles must also be taken into consideration in this case. Taking account of both processes, we may write

$$p\,(S - S_*) - c\,\frac{\partial S}{\partial z} - \frac{\partial}{\partial z}\left(A_s\,\frac{\partial S}{\partial z}\right) = \frac{\partial S}{\partial \tau} = 0 \tag{6}$$

The value of p may vary with depth. On the assumption that p, and also A_s, may be considered constant, our equation becomes

$$\frac{\partial^2 S}{\partial z^2} + \frac{c}{A_s}\cdot\frac{\partial S}{\partial z} = \frac{p}{A_s}\,(S - S_*) \tag{7}$$

the general solution of which is

$$S = C_1 + C_2 e^{r_1 z} + C_3 e^{r_2 z}$$

where

$$r_1 = -\frac{c}{2A_s} + \sqrt{\frac{p}{A_s} + \frac{c^2}{4A_s{}^2}}$$

and

$$r_2 = -\frac{c}{2A_s} - \sqrt{\frac{p}{A_s} + \frac{c^2}{4A_s{}^2}}$$

Both c, p and A_s are positive, and the value of the square root is greater than $\frac{c}{2A_s}$. As S must decrease with increasing depth, the integration constant C_2 must disappear, and we have

$$S = C_1 + C_3 \cdot e^{-\left(\frac{c}{2A_s} + \sqrt{\frac{p}{A_s} + \frac{c^2}{4A_s{}^2}}\right)z} \tag{8}$$

When introducing

$$\begin{aligned} S &= S_* = 34.920\ ^0/_{00} = C_1 \text{ for } z = \infty \text{ and} \\ S &= S_0 = 35.200\ ^0/_{00} \text{ for } z = z_0 = 200 \text{ m} \end{aligned} \tag{9}$$

we obtain a good agreement with the observations (cf. Fig. 32) by putting, in cgs-units,

$$\frac{c}{2A_s} + \sqrt{\frac{p}{A_s} + \left(\frac{c}{2A_s}\right)^2} = 0.000074 \tag{10}$$

From the temperature distribution we found above

$$c \approx 0.000043 \cdot A_t$$

On the assumption $A_t = A_s = A$ we therefore find

$$\begin{aligned} \mathrm{p} &= 23{\cdot}10^{-10}A \\ c &= 43{\cdot}10^{-6}A. \end{aligned} \tag{11}$$

In order to see what this really means, let us introduce as a reasonable value $A = 2$. We then arrive at an advective renewal of 14—15 per cent per year and a vertical speed of the water particles of 27 metres per year. As the average depth of the Norwegian Sea is about 1600 m, the latter would correspond to a complete renewal of the water masses during 60 years due to the bottom water formation only. But the by advective processes the renewal should amount to 90 per cent in 13 years and to 99 per cent in 26 years.

As mentioned above these results may be somewhat exaggerated. By neglecting the effect of the advective renewal on temperature, the value of c obtained may be estimated to be perhaps up to 3 per cent too high. As to the value of p it is hardly possible to make any real estimate of the effect of the above mentioned consecutive mixing processes. If for instance the percentage 14 to 15 should be reduced to about 10, this would mean a renewal by 90 per cent in about 22 years and by 99 per cent in 44 years.

In order to arrive at real estimates of the speed of renewal we shall need a trustworthy knowledge of A, but also we shall need to know the possible variation of p with depth. But even without this knowledge it seems that our really very simple model can supply a reasonable explanation of the stratification at Station M as represented by the normal vertical distribution of temperature and salinity, including the characteristic difference between the two, as illustrated by the curved t-S-diagram. The equation of the t-S-curve is easily derived from equations (2) and (8) to be

$$S = S_* + (S_0 - S_*) \left(\frac{t - t_*}{t_0 - t_*}\right)^{\frac{A_t}{c}\left(\frac{c}{2A_s} + \sqrt{\frac{p}{A_s} + \left(\frac{c}{2A_s}\right)^2}\right)} \tag{12}$$

or by equations (3), (4), (9), (10) and (11):

$$S = 34.920 + (35.200\text{–}34.920)\left(\frac{t + 0.95}{7.00 + 0.95}\right)^{1.72} \tag{13}$$

which agrees very well with the normal diagrams in Figs. 33 and 34.

11. Theory and observations. From the physical model of the processes of renewal outlined above further general conclusions may be drawn. In this way a more complete comparison between theory and observations is made possible, and for this purpose the observations from Weather Ship Station M have been treated in such great detail in the preceding chapters.

a. *Annual variation of temperature.* The temperature distribution was explained above mainly by the vertical motion of the water particles, and this motion in its turn depends on the formation of bottom water. If such formation takes place regularly every, or nearly every year, one must expect a mean annual variation of temperature at all depths. In the surface layers this variation may be blurred by the seasonal variation

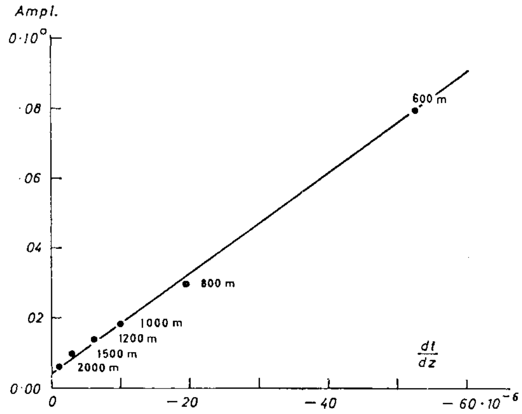

Fig. 35. Annual amplitudes and vertical gradients of temperature.

originating from the surface. But from a few hundreds of metres of depth downwards the dominating processes are the following two:

The distribution of temperature remains the same throughout the year, but due to the conduction of heat the temperature curve may be said to move slowly downwards at a speed *c*, which we have assumed to be constant. The effect of this is a regular increase of temperature, proportional to the vertical gradient.

The bottom water, on the other hand, is formed by cooling of the sea-surface in winter. During the period of formation and in the following months it spreads out near the bottom of the surrounding basin. Thereby the original water layers are lifted to a slightly higher level above the bottom, and the temperature at any level is reduced, also in this case in proportion to the vertical gradient.

The result of these two processes must be an annual variation of temperature at all levels, with amplitudes proportional to the vertical gradients and with maxima and minima occurring simultaneously at all levels, probably some time in the autumn.

From Fig. 27 it was seen above that at 300 m the seasonal variation originating from the surface is dominating, while from 500 m downwards the observations agree with our predictions. In the last column of Table 18 (p. 45) the vertical temperature gradients are given. They are plotted against the corresponding amplitudes in Fig. 35, from which it is seen that even these very small values are in linear relationship, as predicted. The amplitude is approximately equal to –1300 dt/dz.

When the vertical convection reaches the bottom, the formation of true bottom water commences. Its accumulation at Station M may be expected to start slowly and to increase during the summer months. The accompanying decrease of temperature may tentatively be expressed by $\frac{\Delta t}{1+e^{r(x-m)}}$, where Δt is the total decrease, m is the month of maximum effect and x is the number of the month considered, varying from -6 to $+5$, while r is a constant determining the speed of the temperature decrease. The total temperature variation will then be $\Delta t \left(\frac{1}{1+e^{r(x-m)}} + \frac{x+6}{12}\right)$. If the main effect of the bottom water occurs in July, August and September, we may introduce $m = 8$ for August and $r = 2$. Smoothing the obtained values by consecutive 6-months means, we obtain a curve with its maximum in May, its minimum in November and an amplitude $= 0.4\,\Delta t$. Putting this equal to –1300 dt/dz, we find $\Delta t = -3250$ dt/dz. In other words: the vertical motion of the water particles is 3250 cm per year. As

$c = 43 \cdot 10^{-6} A$, this gives $A = 2.4$. As the advective processes are in part responsible for the reduction of temperature, this value must be expected to be slightly too high. As a probable value, therefore, we have above adopted $A \approx 2$. This value is, however, also greatly dependant on the choice of value for r, and should not be considered as in any way reliable. But it may be admitted that the order of magnitude seems reasonable.

b. *Annual variation of salinity.* The salinity distribution was explained above mainly by the advective process of renewal. Also the effect of this process must appear simultaneously at all depths, but it must be expected at an earlier time than the effect of the bottom water formation. As the advective renewal is assumed to be a renewal by injection of water of a uniform salinity of very nearly $S_* = 34.920\ ^0/_{00}$, the effect must be a reduction of the salinity proportional to the salinity itself (or rather to the salinity $- S_*$). As seen from Fig. 24, this is in full accordance with our observations, the minimum salinity occurring in July or August at all depths from 400 m downwards. The amplitudes are compiled in Table 16 (p. 39); they show a small decrease downwards. The last column of the table gives the normal salinities; plotting the amplitudes against the latter, we find a fair linear relationship, as seen from Fig. 36. The amplitudes are roughly equal to $0.005 + 0.14.\ (S–S_*)$.

At first glance it may appear surprising that amplitudes are found also at the great depths, where the normal salinity is uniformly $34.920\ ^0/_{00}$. But it must be remembered that our results are based on several years' observations. The normal salinity of the deep layers is a mean value for these years, and the amplitudes are mean values of the actual amplitudes for each year. In considering the normal mean value as a constant value, its fluctuations from year to year are disregarded. But when computing the mean amplitudes, the effect of these fluctuations have not been taken into consideration. This may well account for the small amplitudes obtained at great depths. In our simplified picture we may, therefore, limit further considerations to the last term, $0.14.\ (S–S_*)$, and disregard the constant 0.005.

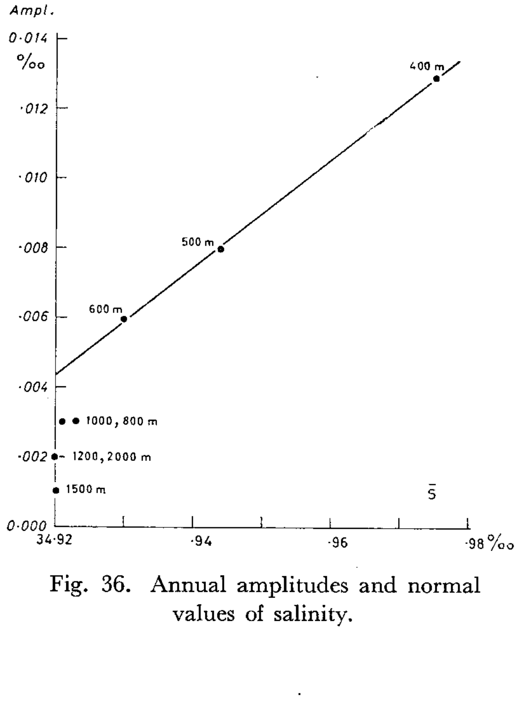

Fig. 36. Annual amplitudes and normal values of salinity.

If it is assumed that both decrease of salinity due to advective renewal and increase of salinity by diffusion go nearly linearly in time, it may be expected that the smoothing of the curves by consecutive 6-months means has reduced the amplitudes to about one half of its real value. In this case we may, therefore, put $2 \cdot 0.14 \cdot (S–S_*) \approx \mathrm{p}(S–S_*)$, i.e. $p = 0.28$ per cent per year or $89 \cdot 10^{-10}$ per cent per second. As we have found

$p = 23 \cdot 10^{-10} A$, this means $A \approx 3.9$ in cgs-units, a value which is higher than the value found above from the temperature amplitudes. This appears reasonable, because also the vertical motion of the water particles is partly responsible for the reduction of salinity. When combining the above assumption on the bottom water formation ($m = 8$, $r = 2$) with a suitable assumption on the advectional reduction of salinity (e.g. an exponential decrease), it seems possible to arrive at a more complete picture. But in this way so many arbitrary assumptions are involved, that the final result can hardly be trusted.

c. *Annual variation of oxygen content.* The processes of renewal must be expected to result also in annual variations of the oxygen content. The renewal of the bottom water must produce an increase of the oxygen content near the bottom with maximum values at the time of minimum temperature, in November–December. This agrees with our observations, and also seems to explain the increase observed of the amplitude from 1000 to 2000 m. Also the advective renewal must be expected to produce a seasonal variation, probably of dominant importance, within a layer from about 400 to 6–700 m, where gradients of salinity are found (compare Fig. 36). As the renewal is depending on $S – S_*$, this would explain the decrease of the annual amplitude of oxygen from 400 to 600 m; these amplitudes are proportional to the amplitudes of salinity and to the salinity gradients. But it is difficult to understand why in this layer the oxygen maxima occur in October–November, not in August–September, as do the salinity minima. The reason may be sought in the processes of consumption of oxygen, which may well be imagined to vary seasonally. As long as these processes are not better known, it appears hardly possible even to arrive at a rough estimate of A on the basis of the oxygen determinations. As to the results of these measurements it will here only be mentioned that the averages for 1953 to 1958 show a regular increase from 6.65 cc/L at 150 m to 7.15 cc/L at 600 m, then a regular decrease to 7.02 cc/L at 1200 m and finally an indication of an increase to 7.04 to 7.05 cc/L at 2000 m. As seen above (Table 8) these values do not agree to well with the averages from "Armauer Hansen" 1935.

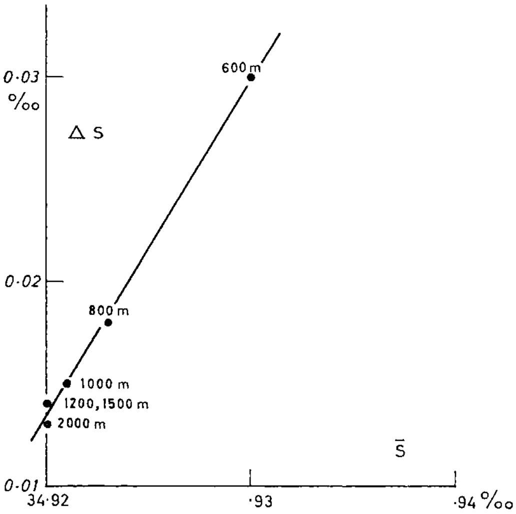

Fig. 37. Relative figures for slow changes of salinity against normal values of salinity.

d. *Slow changes of salinity* must be expected when the water formed by vertical convection has a salinity different from the prevailing deep water salinity. A probable reason for such changes may be sought in the salinity of the East Greenland Current. According to our interpretation these changes must be expected to occur simultaneously at all

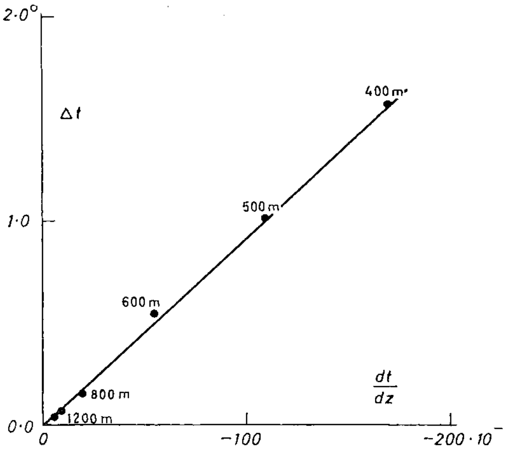

Fig. 38. Relative figures for slow changes of temperature against normal temperature gradient.

levels and to be proportional to $S – S_*$. The drop in salinity from 1949 towards the end of 1950 illustrated by Fig. 25 and Table 17 is a good example. It is seen immediately from Table 17 that from 600 m downwards this drop is nearly proportional to the salinity. By comparison of all observations from the different levels it is easy to determine "relative figures" $\triangle S$ for the changes; as seen from Fig. 37 these are proportional to the salinity.

e. *Slow changes of temperature.* If in one winter season the cooling is stronger and, therefore, more bottom water is formed than usually, a semi-permanent reduction of temperature must be expected. Also this reduction must be proportional to the temperature gradient. The slow changes of temperature illustrated by Fig. 28 have been compared in plotting the values from one depth against those from another. In this way "relative figures" $\triangle t$ have been established, and these are plotted against the temperature gradients in Fig. 38. They show a linear relationship as expected.

If in one year the salinity of the new bottom water is lower than usually, also the temperatures must become lower than usual in order to produce sufficiently high densities. This case is exemplified in 1949–50, when the drop of the temperature is accompanied by a drop also of the salinity, as seen from Figs. 25 and 28. But changes of temperature may, of course, also occur without any corresponding change of salinity; such changes are seen from Fig. 28 to occur after 1950.

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