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STUDIES IN THE NORWEGIAN ATLANTIC CURRENT
PART I: THE SOGNEFJORD SECTION

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CONTENTS

Summary. Observations collected in the so-called Sognefjord section during the years 1947—53 have been subjected to dynamical treatment. The results of transport computations for 27 sections, all of them taken during the months May—August, are presented. It appears that very great transport variations occur, even between sections taken at an interval of a few days. In order to obtain a better understanding of the results, the theory of the dynamic computations is surveyed, with special emphasis on the case when a section extends into shallow water. It is suggested that the computed transport variations may not all be real, but that they may partly be explained by varying currents at the reference (zero-) surface. Some special features of the sections with dynamical significance have also been discussed. In the last chapter, a short exposition of the dynamics of the shelf waters is given.

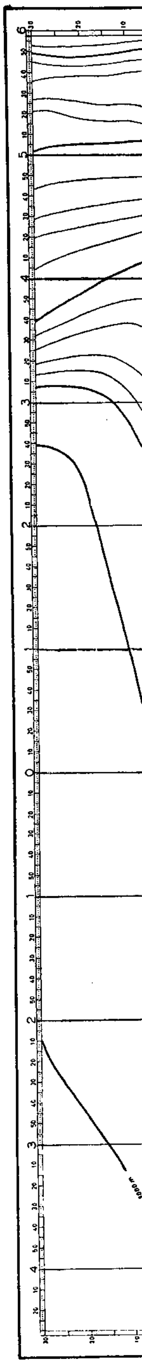
1. Introduction. Early in this century, Helland-Hansen and Nansen (1909) started observations along a line crossing the Norwegian Atlantic Current. The section was named "the Sognefjord section", and its average position is shown by the straight line in Fig. 1, in which the bottom topography is also indicated. This topography should only be considered as indicative, many features will certainly have to be altered when more soundings become available. This is especially true for the ridge extending NE from the Faroes, where recent soundings indicate that the area shallower than 1000 meters may reach farther to the NE than shown on the map Fig. 1, and also that the SE slope of the ridge is much steeper than shown in that map.

During the years 1901—1905 the section was worked every year in May. Since then, it has been occupied with varying intervals, the course always roughly corresponding to the line in Fig. 1. The results of sections taken in 1925, 1927 and 1929 were published by Helland-Hansen in "The Sognefjord Section" (1934). All these section were taken in the end of May or beginning of June, in order to make them comparable. Observations were also made in the section at intervals during the nineteenthirties, but the most intense and systematic work in the section was carried out during the years 1947—53, and it is mainly the investigations made then which will be studied in the present paper. During these years the section was occupied several times each year from May to August. Observations were sometimes made both on the way out from and on the way back to the coast; such pairs of sections will in the following be termed "repeated sections".

The observations were made by the usual method: Nansen reversing water bottles, each containing 2 protected reversing thermometers. One or two unprotected thermometers were also used in each cast. However, only on very rare occasions was it necessary to correct for wire angle. It was nearly always possible to manœuvre the "Armauer Hansen", which carried out all the cruises, so that the line was sufficiently close to the vertical. Wherever possible, observations were made down to at least 1000 meters, with the following standard depths of observation: 0, 10, 25, 50, 75, 100, 150, 200, 300, 400, 500, 600, 800, 1000, 1200, 1500 meters. In addition to such complete stations, vertical temperature registrations were, on most cruises, made at shorter intervals by means of Mosby's thermo sonde (Mosby, 1943) in connection with a limited number of water bottles at selected depths. These "thermosonde stations" have been used as an aid in the drawing of sections, but they have not been used in the dynamical computations.

The distance between stations has been different in the different parts of the sections. In the shelf area, the distance between complete stations was always 20 nautical miles. On the continental slope, the distance was cut down to 5 miles, increasing to 10 miles farther out and to 15 miles in the deep part of the section. Thermosonde stations were as a rule taken every 5 miles.

All water samples were titrated at least twice. The data were transferred to punched cards, and the calculation of σ_t, $\Delta\alpha$ and ΔD was carried out on the calculating punch IBM 602A, according to the method described by Fløisand and Sælen (1953).



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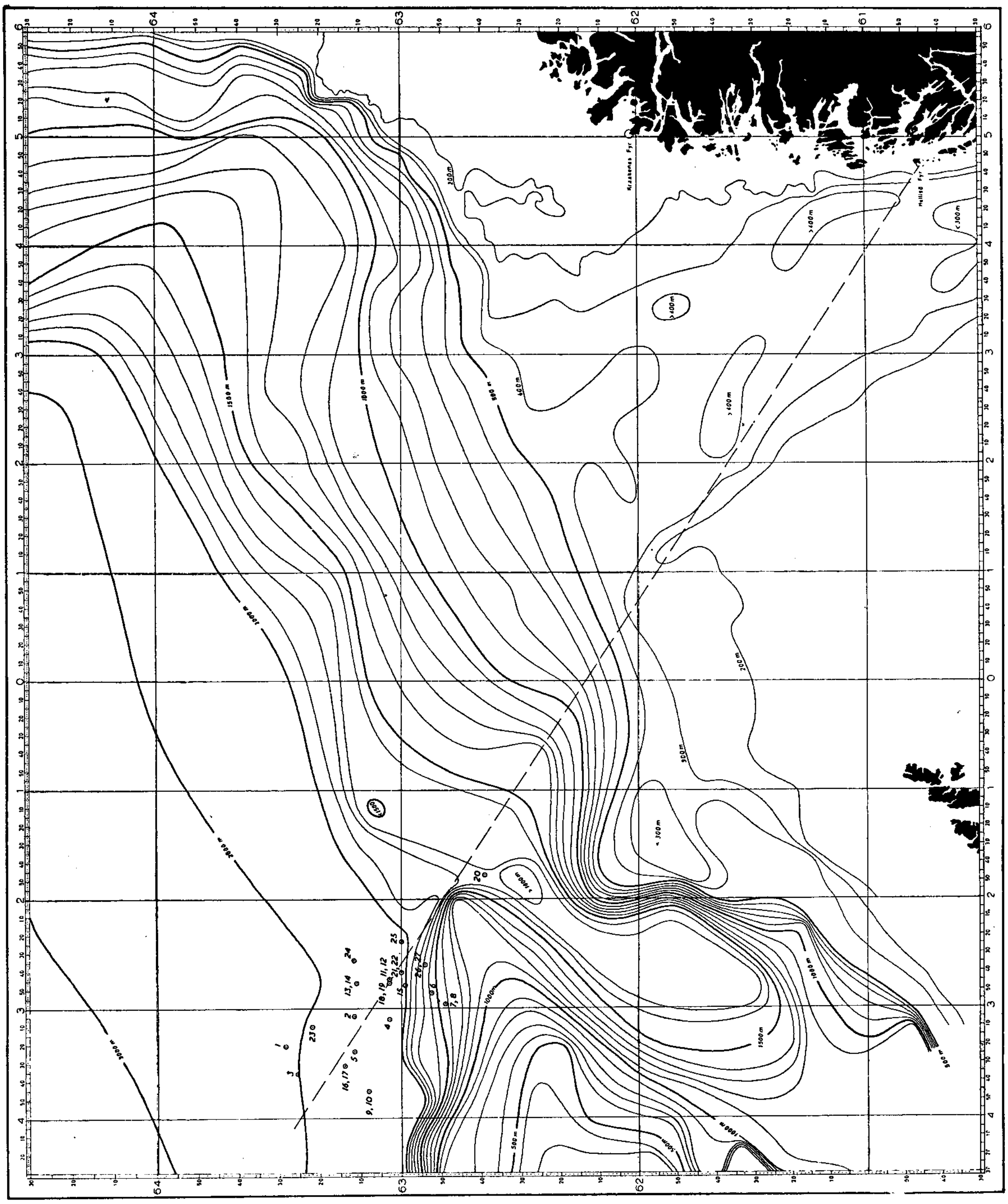


Fig. 1. Bottom topography. Broken line: Average location of the Sognefjord section. Circles: Endpoints of the different sections, the numbering corresponding to that of Table 1.

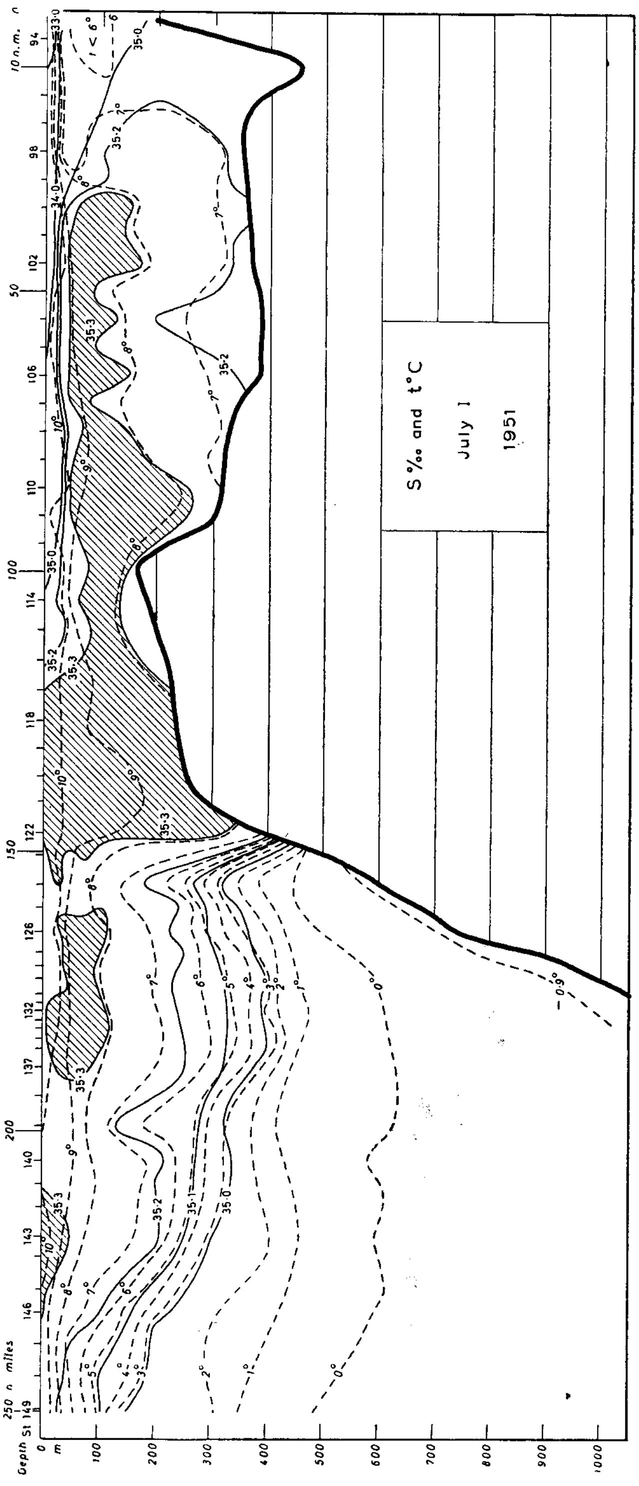


Fig. 2. Temperature and salinity in section No. 18, July 1951.

This method gives accurate values for σ_t and $\triangle\alpha$. The integration of $\triangle\alpha$ leading up to $\triangle D$ is performed as a linear one, and the error thus introduced seems to be slight, in most cases.

2. Water transport through the Sognefjord section. In order to illustrate the general features of the section, a fairly typical example is reproduced in Fig. 2, showing temperature and salinity on a cruise in July 1951. The section may be regarded as consisting of two parts: 1) the shallow part on the shelf, where the depths may vary between 200 and 400 meters, and 2) the part outside the shelf, where the bottom slopes down to depths of about 2000 meters. The hydrographic conditions in the shelf sea are relatively homogeneous. Apart from the surface layers and the miles nearest the coast, the salinities are well above $35^0/_{00}$, and the temperatures below the surface layers do not vary much. The relative currents are weak. The conditions of the shelf sea will be discussed later.

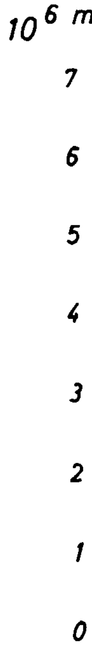
The outer part of the section, beginning where the bottom starts sloping down from the Tampen Bank, presents far greater and more systematic variations, especially of temperature, and consequently higher relative velocities. The "Atlantic water" reaches great depths along the slope, and its thickness decreases with increasing distance from the coast. The term "Atlantic water" is used for convenience for water with salinity higher than $35^0/_{00}$; this is of course a matter of definition.

During the years 1947—53, 27 Sognefjord sections have been taken by the research vessel "Armauer Hansen" of the Geofysisk Institutt in Bergen. The distribution for the separate years is shown in Table 1. Repeated sections are connected by brackets. For all these sections, dynamic depths have been calculated, and velocities and transporst derived by the conventional methods. (See e.g. JAKHELLN (1936)). The 1000 db. surface has been used as reference in those parts of the section where the bottom depth exceeds 1000 meters. For the rest of the section, with bottom depths less than 1000 meters, the method described by HELLAND-HANSEN (1934) has been used for the calculation of the dynamic depths. The reason for the use of that method will be discussed later. The calculation of transport has been limited to the part of the section that lies outside the Tampen Bank. It is felt that transport calculations over the shallow shelf are so uncertain by Helland-Hansen's method, or for that matter by any other known method, that if made they would be of little value. In addition, the relative velocities on the shelf are so small that the shelf part of the section would in most cases contribute an insignificant amount to the transport if the bottom velocity is taken as zero.

The results of the transport calculations are summarized in Table 1. The numbers in the table give the transport normal to the section in 10^6 m^3 per sec. In the column headed "Total transport" is given the total volume of water passing through the section above the reference level (1000 db. or bottom). In the column headed "Atlantic transport" is given the volume transport of water of salinity higher than $35^0/_{00}$. The total transport is in most cases higher than the transport of Atlantic water, that is,

Table 1. *Transport through the section west of Tampen in mill. m³ per sec.*

Section No.	Stations No.	Month	Transport Total	Transport Atlantic
1947				
1	39 – 52	June	3,8	3,5
2	89 – 104	Aug.	2,5	2,3
1948				
3	41 – 53	May	2,1	2,0
4	75 – 88	June	2,0	1,8
5	124 – 137	Aug.	4,2	3,4
1949				
6	24 – 39	May	3,9	3,2
7	179 – 210	July	6,7	5,7
8	210 – 232	»	6,7	5,6
1950				
9	59 – 94	May	4,0	4,1
10	96 – 123	»	4,3	4,3
11	164 – 192	July	2,9	2,9
12	192 – 214	»	3,0	3,4
13	214 – 235	»	3,4	3,2
14	235 – 257	»	2,7	2,6
15	297 – 324	Aug.	4,4	4,3
1951				
16	50 – 65	May	4,6	4,5
17	65 – 78	»	7,0	6,4
18	122 – 149	July	2,0	2,1
19	149 – 168	»	4,0	3,8
1952				
20	63 – 91	May	3,5	3,1
21	118 – 143	June	3,4	2,9
22	143 – 161	»	4,3	4,0
23	216 – 244	July	3,1	3,4
1953				
24	55 – 83	May	6,8	6,4
25	123 – 150	June	4,3	3,9
26	237 – 266	Aug.	4,2	3,9
27	266 – 284	»	6,4	5,7



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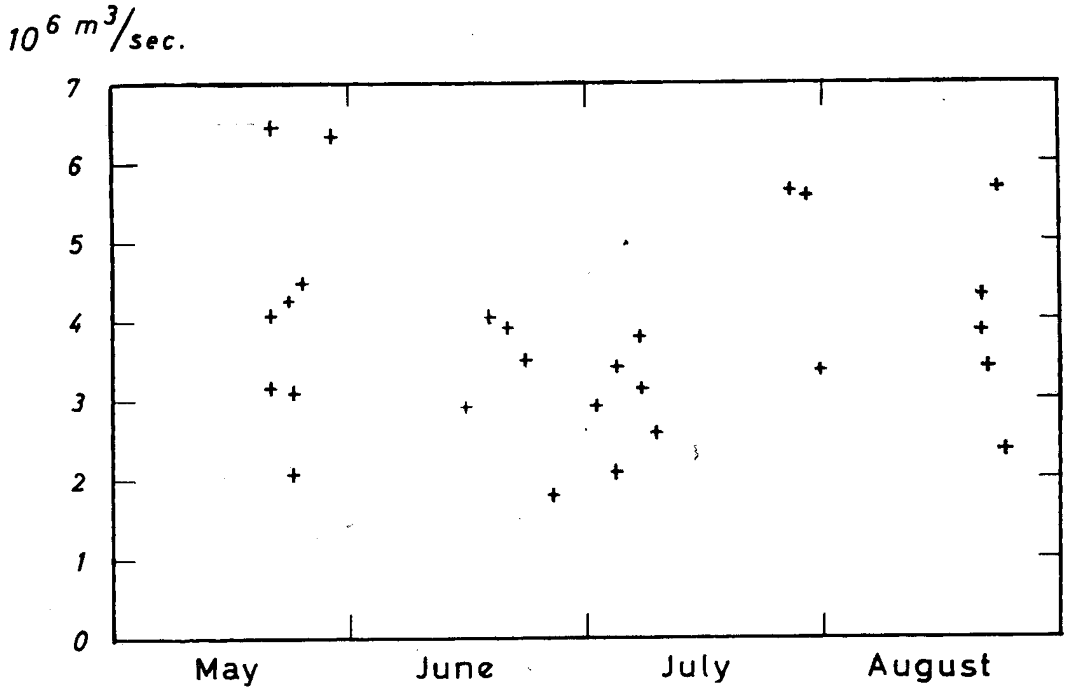

Fig. 3. Transport of Atlantic water plotted against time, regardless of year.

the relative transport of deep water is in most cases directed toward the NE (this applies of course to the component normal the section). The difference between the two transports is as a rule less than 10%.

It is seen from the table that all observations are made during the four months May—August. The transport figures vary between rather wide limits, and there is no indication of any systematic variation with respect to time. In Fig. 3 the transport values from Table 1 are plotted against date, regardless of year. There is obviously no significant systematic variation with time within the four months in which the observations have been made. The question of a possible seasonal variation of the transport of the Norwegian Atlantic Current cannot be investigated with these data. From investigations in the Faeroe—Shetland Channel, however, some results are also known from the months September—April. Jacobsen (1943) has summarized the results of sections up to 1939, including three sections taken in November. He points out that these are too few to warrant any conclusion. Likewise, the apparent difference between the mean values of transport in spring and in summer cannot be taken as a proof of an increase of the intensity of flow from May to August, in Jacobsen's opinion. More recently, Tait (1955) has given values for the transport through the Faroe—Shetland Channel, for the sections taken 1927—1952 inclusive. For the last four years of the period (1949—1952) a number of sections were made during the autumn — winter season, and these give on the whole greater transports than the spring — summer sections of the corresponding years. Tait does not claim that this feature is a regular annual occurrence, he is of the opinion that such a feature may dominate for a group of consecutive years and recur at long-term intervals. It may be mentioned that this finding is contrary to the theory advocated by Krauss (1955), according to which the intensity of flow in the Norwegian Atlantic Current should be coupled to freshwater afflux along the coast, so that there is maximum intensity in summer and a minimum in winter. The data on which Tait's supposition is based are however rather sparse.

Returning now to the Sognefjord section, the picture given in Fig. 3 indicates very strongly that even if a seasonal variation of the transport really existed, a large number of sections made at all seasons and during many years would be necessary in order to bring this out with statistical significance. Furthermore, the values in Table 1 cannot tell anything about a possible variation of the transport from year to year. In fact, the variations within the separate years seem to be as great as any variation from year to year. On the whole, the great and seemingly unsystematic variations of the transport are the most striking feature of Table 1. In this connection it should be pointed out that the sections are not all made exactly along the same line, nor are the lengths of the sections equal. On the map, Fig. 1, the positions of the outermost stations on the different sections are indicated. The numbers correspond to those in Table 1, first column. The sections were terminated when the temperature observations indicated that the bulk of the Atlantic water had been crossed. In a few cases, bad weather forced us to stop before. One might therefore believe that the great variations of transport were to some extent due to the difference in the lengths of the sections. But, as just mentioned, the bulk of the Atlantic water had in most cases been crossed. Furthermore, the lengths of a pair of repeated sections are approximately equal, and very great differences in transport between two such sections sometimes occur (cf. Table 1, sections 16—17, 18—19, 21—22). It may therefore be taken as certain that great variations of the transport, as computed with the assumption of no horizontal motion at 1000 db. or bottom, really occur in the Sognefjord section. Tait (1957) arrived at a similar result for the transport through the Faeroe—Shetland Channel. The ratio between the maximum and minimum transports computed for the Channel is even higher than for the Sognefjord section, it is about 10 : 1 as compared to about 4 : 1 for the Sognefjord section.

At this stage of the discussion, we shall not take up the question whether the transport variations are real or not (i. e. whether they correspond to variations in the absolute transport). This question will be considered later. We shall first ask the question what could, in general, bring about variations in the water transport through the Sognefjord section. The most important problem in this connection is obviously to assign to the Norwegian Atlantic Current its proper role in the circulation system of the oceans. In later years a number of authors have tried to describe this system in terms of the wind stress distribution. The most successful of these attempts seems to be that of MUNK (1950). His theory agrees qualitatively, in some cases also quantitatively, with many of the broad features of the oceanic circulation. In this system, the Norwegian Atlantic Current is supposed to be linked to a meridional wind system of a relatively local extension. Whether such a supposition is realistic or not, is still a matter of discussion. KRAUSS (1955) considers the winds in these high latitudes too variable to maintain a semi-permanent current. From a recent work by TUCKER (1957) it appears that even the mean wind field can hardly be said to fit in with MUNK's explanation. It should also be noted that the flow of warm water into the Norwegian Sea is obviously connected with an "overspill" from the mid-latitude gyre (MUNK's subtropical gyre) and presumably has some connection with the dynamics of that gyre. This connection may be highly complex, especially if the tentative picture of the intricate branching of the Gulf Stream (the West Wind Drift) sketched by DIETRICH (1957) should prove to be correct. Moreover, this "overspill" need not be in straightforward proportion to the intensity of the main gyre. In fact, ISELIN (1940) has given reason for supposing that the "overspill" increases as the main system decreases in intensity, and vice versa. It is also interesting to note from ISELIN's paper that variations of the Gulf Stream (section Long Island — Bermuda) transport are much smaller in percentage than are the variations of the Norwegian Atlantic Current. The minimum transport of 15 sections during the years 1937—40 was 76 × 10^6 m^3/sec. and the maximum 93. An entirely different approach to the problem is that of KRAUSS (1955). In connection with his opinion referred to above, *viz.* that the winds are too variable to maintain a semi-permanent current, KRAUSS argues that the source of energy for the Norwegian Atlantic Current (and other semi-permanent currents in high latitudes) must be the field of mass maintained, in varying strength, by the freshwater afflux along the coast. The Norwegian Atlantic Current is a secondary phenomenon, so to say dragged along by the coastal current. This theory will not be discussed here, but the present author considers it not very realistic.

From the preceding it is clear that there are several possibilities when considering the cause of variations in the intensity of the Norwegian Atlantic Current: variations in the intensity of the subtropical gyre, resulting from variations in distant wind systems; variations in the partitioning of the "overspill" from the subtropical gyre on different branches of the West Wind Drift; variations in a local wind system; variations in the freshwater afflux along the coast. In short, we may say that variations in the transport through the Sognefjord section depend on factors which are still unsufficiently explained. At this juncture, attention should be directed to a particular point in Table 1, *viz.* the repeated sections. The repeated sections from 1949 and 1950 show insignificant variations in transport between the "out" and "in" sections, and this was at first taken as a proof of the reliability of the transport calculations (SCHJELDERUP, 1954). But the results from the repeated sections in later years tell a different tale. All four pairs of repeated sections during the years 1951—53 show considerable differences between "in" and "out" sections. In the most extreme case (sections 18, 19) the transport of Atlantic water was 81% higher on the "in" section than on the "out" section.

(It is seen that in all these cases the greatest transport is found on the "in" section, the section on the way back to the coast. There seems to be no reason to assign any physical or statistical significance to this fact.) The section west of Tampen takes less than 2 days to complete, so the difference between the median dates of repeated sections is less than 2 days. It appears astonishing that such great differences should really exist between sections taken at such short intervals. It is difficult to see how any of the possible causes of variations in the flow mentioned above could be responsible for such short-period variations. There is of course the question whether the observations are sufficiently synoptic. By normally accepted standards, observations in a section completed in the course of 2 days or less would be considered to be amply so. It should be remembered, however, that in this case the outermost station is common for the "out" section and the "in" section, whereas the maximum time difference is between the innermost stations of the two sections (up to 4 days). The difference in computed transport between two such sections must therefore spring from the differences in the water masses in the innermost parts of the two sections, the outermost station being used as a sort of common reference. As an example, Fig. 4 shows the distribution of $\triangle\alpha$ in the pair of repeated sections of the most extreme variation (sections 18 and 19). It cannot be taken as granted that the conditions at the outermost stations remain the same while conditions at the innermost stations undergo such a remarkable change. Had all stations on each section been taken simultaneously, with a time difference of, say, 2 days between the two sections, the dynamic computations as performed with the previously mentioned zero-surfaces might have given different results for the transports. The cooperation of several ships would be needed to shed light on this. However, the great differences between the innermost parts of the two sections make it most probable that there really is a differance of considerable magnitude between the relative transports through the two sections which are taken with a few days' interval. Any discussion of seasonal or long-term variations would, in the author's opinion, be futile so long as such short-term variations are not better understood. The following pages will therefore be devoted to a survey of the theoretical basis for the dynamic computations.

3. Discussion of theory. The well-known velocity formula of HELLAND-HANSEN (1905), on which the preceding computations are based, is usually derived by specialization of Bjerknes' circulation theorem. In order to make clear the underlying assumptions of the formula, the derivation given below will, however, start directly from the equations of motion. The coordinate system is right-handed, with the z — axis vertically downwards. Disregarding friction and vertical velocity, the equations on vector form are:

$$\frac{d\boldsymbol{v}_h}{dt} = 2\omega \sin \varphi \, \boldsymbol{k} \times \boldsymbol{v}_h - \alpha \nabla p + g\boldsymbol{k} - 2\omega \cos \varphi \, v_E \boldsymbol{k} \qquad (1)$$

$\boldsymbol{i}, \boldsymbol{j}$ and $\boldsymbol{k}$ are the unit vectors of the coordinate system, $\boldsymbol{v}_h = \boldsymbol{i}v_x + \boldsymbol{j}v_y$ is the horizontal velocity component, p is pressure, g is the acceleration of gravity, α is specific

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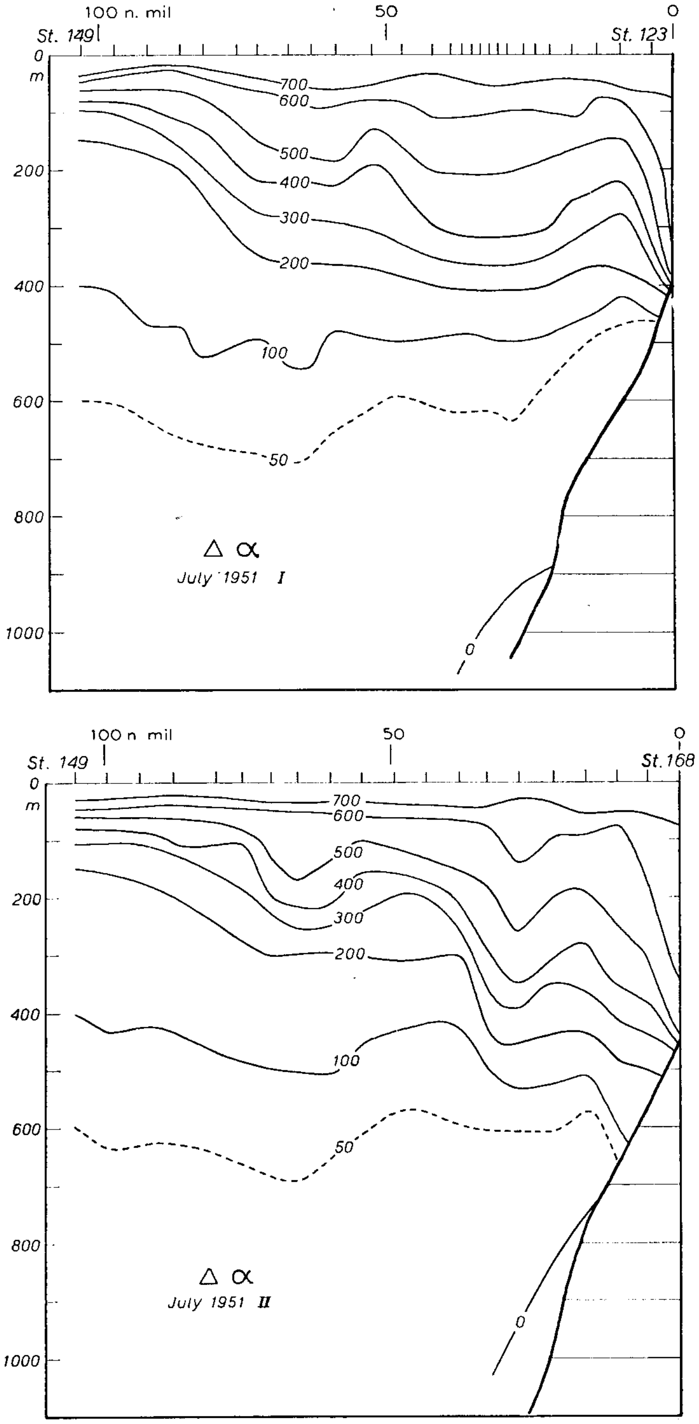

Fig. 4. Distribution of anomaly of specific volume in the repeated sections of July 1951.

volume, φ is the latitude, ω is the earth's angular velocity and v_E is the velocity component towards the east. Scalar multiplication with a line element $\boldsymbol{ds} = \boldsymbol{j}dy + \boldsymbol{k}dz$ in the y-z plane gives

$$\frac{dv_y}{dt}\,dy = 2\omega \sin\varphi\, v_x\, dy - \alpha\, dp + g\, dz - 2\omega \cos\varphi\, v_E\, dz \tag{2}$$

This equation is integrated around a curve in the y-z plane (Fig. 5), where I and III are vertical lines, IV is an isobar and II is an arbitrary line connecting the two verticals. One obtains

$$\begin{aligned}\int\limits_{\mathrm{II}}\frac{dv_y}{dt}\,dy + \int\limits_{\mathrm{IV}}\frac{dv_y}{dt}\,dy = 2\omega\sin\varphi\left[\int\limits_{\mathrm{II}} v_x\,dy + \int\limits_{\mathrm{IV}} v_x\,dy\right] - \int\limits_{\mathrm{I}}\alpha\,dp\\ - \int\limits_{\mathrm{II}}\alpha\,dp - \int\limits_{\mathrm{III}}\alpha\,dp - 2\omega\cos\varphi\left[\int\limits_{\mathrm{I}} v_E\,dz + \int\limits_{\mathrm{II}} v_E\,dz + \int\limits_{\mathrm{III}} v_E\,dz + \int\limits_{\mathrm{IV}} v_E\,dz\right]\end{aligned} \tag{3}$$

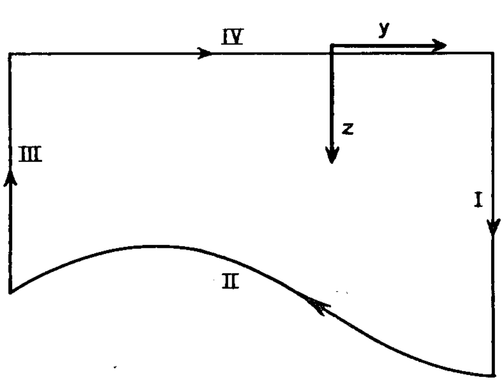

Fig. 5. Coordinate axes and path of integration.

The integration is performed in the direction indicated by the arrows. Helland-Hansen's formula is obtained from equ. (3) by making line II an isobar (giving $\int\limits_{\mathrm{II}}\alpha\,dp = 0$), and by assuming: a) There is no acceleration in the direction of the section (the y-direction), b) the terms containing v_E are so small that they may be disregarded. The correctness of the first assumption is difficult to prove or disprove by observation, but the assumption is commonly made in computations of this kind, and it will be adopted in the following. The second assumption is, in most oceanographical works, made already in the equations of motion. It is reckoned that the order of magnitude of the ratio $2\,\omega\cos\varphi\, v_E/g$ is at most 10^{-5} so that it may safely be neglected. However, in performing the integration leading to equ. (3), g vanishes and the integral of $\alpha\,dp$ around the curve is reduced to a difference of an order of magnitude considerably lower than that of the dynamic depth along any of the vertical lines. Thus, it is not obvious that the terms in equ. (3) containing v_E may be neglected. It should be mentioned that KRAUSS (1957), starting from Bjerknes' circulation theorem, has derived the terms in question in a somewhat different form. In order to estimate the magnitude of the terms containing v_E, we assume for simplicity no acceleration, and that line II is a horizontal isobar. Equation (3), written on differential form, will then reduce to

$$v_x = \frac{1}{2\omega\sin\varphi}\frac{\partial}{\partial y}\int\limits_{p}^{p_0}\alpha\,dp + \operatorname{cotg}\varphi\,\frac{\partial}{\partial y}\int\limits_{z_p}^{z_0} v_E\,dz \tag{4}$$

where z_p and z_0 denote depths at the pressures p and p_0 respectively (corresponding to lines IV and II in Fig. 5). The variation of z_p with y may be neglected in this connection. If we take v_E to vary by 40 cm/sec. per 10 km at the surface, the variation decreasing linearly to zero at 1000 m depth, the resulting value of the last term on the right side of equ. (4) is 2 cotg φ cm/sec. Thus, there may be cases, especially in low latitudes, and when the velocity has an appreciable east component, where this term is of some importance. The values of $\frac{\partial v_E}{\partial y}$ actually occurring in the stationary average circulation in the oceans will however as a rule be considerably lower than that used in the above example. The influence of the v_E-term on the transport across a section of some length, say the order of 100 km, will be still less because the differences of v_E along the section cancel out so that only the difference between the two limiting stations remains. In the high latitude of the present investigation the additional transport will be less than 1% of the total transport, so that we may in the following safely neglect the terms containing v_E.

Omitting the acceleration terms and the v_E-terms in equ. (3), we obtain

$$2\,\omega \sin\varphi \left[\int_{II} v_x\,dy + \int_{IV} v_x\,dy\right] = \int_{I} \alpha\,dp + \int_{II} \alpha\,dp + \int_{III} \alpha\,dp \qquad (5)$$

If line II is not an isobar, the integral $\int_{II}\alpha\,dp$ will as a rule be different from zero. The integral can be computed, however, if the necessary observations exist. Furthermore, if v_x is zero along line II, the mean value of v_x on line IV can be found from equ. (5). In this case the integral $\int_{II}\alpha\,dp$ is equal to the difference in dynamic depth between the end-points of line II. Thus, the velocity field and the transport through the section can easily be computed, as well as the differences in dynamic depth between points on the same isobar. But the difficulty of finding such a zero-line, or more generally a line along which the distribution of v_x is known, is a severe restriction on the applicability of this method of computing water velocities and transports. Although information on relative velocities may be very useful, we should like to know still more the absolute velocities. It has often been assumed that, if line II was chosen as an isobar at a sufficiently great depth, the velocity v_x at such a great depth would be so small that it could be neglected. It is not easy to say to what extent this assumption is permissible. The question has recently been much debated (see e. g. WÜST, 1955; SWALLOW and WORTHINGTON, 1957, STOMMEL, 1956, 1957). But even if such an assumption were permissible in our case, an additional difficulty is met with, *viz.* that the bottom-depth decreases toward the coast (or the banks) to values far to small to allow the use of a deep-lying reference line (see Fig. 2). The difficulty thus arising is, in principle, not different from the main problem of finding a line II along which the distribution of v_x is known. It would be solved if we knew for instance the current component at the bottom at right angles to the section (or the said component along any other line in the section). In this connection, a few words should be said about the expression "at the bottom". In the vicinity of the bottom, turbulent friction originating from the bottom will influence the current velocity, and at the very bottom the velocity should approach zero. In the equations we have used, friction has been excluded and they can thus not cover the bottom layer in which the friction exerts decisive influence. However, recent current measurements have shown that the influence of bottom friction is restricted to a very thin layer, so that the velocity may be supposed to reach its undisturbed (geostrophic) value a few, may be not more than two, meters above the bottom. Such measurements have been carried out in the open sea on the Viking Bank (preliminary results communicated to the General Assembly of the AIOP at Brussels by H. Mosby (1951) by means of an apparatus constructed by Mosby (1947, 1949). For purposes of velocity and transport calculation, the bottom line proper may then be replaced by a line parallel to the bottom a couple of meters above it. A similar artifice has previously been employed by Theisen (1946). When terms like "bottom", "bottom velocity" etc. are used in the following, such a line parallel to the bottom is always understood. The errors introduced in the transport values by the neglect of the thin frictional layer will be negligible.

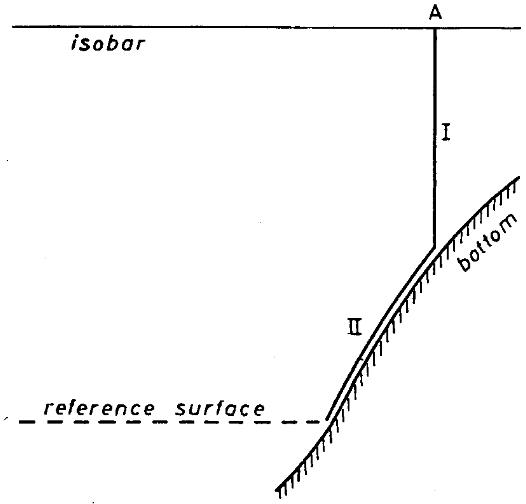

Fig. 6. Illustration to Helland-Hansen's method of estimating dynamic depths when a section extends into shallow water.

Several methods have been proposed to cope with the difficulty arising when the section extends into shallow water. As seen from equ. (5), the whole problem would be solved if we knew the bottom velocity (velocity along line II), exactly in the same way as for any other reference surface. Helland-Hansen's (1934) method, which we have preferred to use, is simply equivalent to assuming that the bottom velocity is nil. Helland-Hansen formulated his method by saying that the dynamic depth (or height) of a point A of an isobaric surface above the slope (Fig. 6) should be computed as $\int_{II} a\,dp + \int_{I} a\,dp$. If we write equ. (2) without the acceleration- and v_E -terms, we obtain for the differential of dynamic depth:

$$gdz = a\,dp - 2\omega \sin \varphi \, v_x \, dy \tag{6}$$

This shows that Helland-Hansen's statement is correct only if the velocity component v_x is zero at the bottom (unless it has a very peculiar and unlikely distribution along the bottom line). Helland-Hansen was of course aware of this, as he writes: "The

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computation will give a correct result only if the velocity of the current at the bottom is nil, otherwise some uncertainty arises".

Two other methods to cope with this difficulty shall be mentioned here. First, a method sketched by SVERDRUP in "The Oceans" (1942, p. 451). The method is based on a formula giving the slope of an isobaric surface in a point 1 relative to the slope of another isobaric surface in a point 2 vertically beneath 1 by means of the density field between the two isobaric surfaces. The formula may be written

$$(\varrho\, i_p)_1 - (\varrho\, i_p)_2 = -\overline{i_\varrho}\,(\varrho_2 - \varrho_1) \tag{7}$$

ϱ is the density, i_p is the slope of the isobaric surface (line) and i_ϱ is the slope of the isosteric surface (line). The bar denotes the mean value between points 1 and 2, and the suffixes 1 and 2 refer to points 1 and 2. Sverdrup then proposes that this formula be used between points not lying on the same vertical, *in casu* points along the bottom. As the velocity, in the geostrophic case, is proportional to the isobaric slope, this will result in a certain distribution of the velocity component v_x along the bottom, so that the absolute velocities can be found from equ. (5). However, the use of equ. (7) in a non-vertical direction introduces again the same basic undeterminedness as that present in equ. (5), one which will always be present in expressions derived from the equations of motion alone. In our case, it should also be remembered that the actual slope of the bottom is not more than 1 degree or so, so that it is in fact quasi-horizontal. To sum up, Sverdrup's method is as much of a guess as is Helland-Hansen's method. The same is the case with a method proposed by GROEN (1948). In that method, the block of solid earth beneath the bottom line is replaced by a fictitious water mass of such a composition that along every horizontal line the isosteres (lines of equal value of the anomaly of specific volume) have a constant inclination equal to the inclination at the point where the horizontal intersects the bottom line. As Groen points out, the method is not aimed at giving the correct answer; its chief advantage is perhaps that it gives a picture that is pleasing to the eye. It should perhaps be noted in this connection that Helland-Hansen did *not* introduce the concept of a fictitious water mass below the bottom; the horizontal lines in continuance of the isosteres were clearly intended only as a help in making the numerical computations.

Thus, with respect to correctness, all the three methods are equally and necessarily defective. The criterion for the choice of method must then be one of expediency. In this respect, Helland-Hansen's method seems to be superior, in the author's opinion. Firstly, the underlying physical assumption is extremely simple and easily understood (velocity component normal to section equal to zero at the bottom), and this also makes the computations simple and easily reproduceable. There is no graphical evaluation of slopes. Secondly, the computed values of velocity or transport are very easily converted if it should so happen that velocities along the bottom or any other reference line come to be measured or deduced in any other way.

Table 2. *Transport variations in "repeated sections".* (*transport in mill.* m^3 *per sec.*)

Section No.	Stations No.	Month	Total transport	% increase	Atlantic transport	% increase
1949						
7	179 – 210	July	6,7		5,7	
8	210 – 232	»	6,7	0	5,6	– 2
1950						
9	59 – 94	May	4,0		4,1	
10	96 – 123	»	4,3	+ 8	4,3	+ 5
11	164 – 192	July	2,9		2,9	
12	192 – 214	»	3,0	+ 3	3,4	+ 17
13	214 – 235	»	3,4	+ 13	3,2	– 6
14	235 – 257	»	2,7	– 21	2,6	– 19
1951						
16	50 – 65	May	4,6		4,5	
17	65 – 78	»	7,0	+ 52	6,4	+ 42
18	122 – 149	July	2,0		2,1	
19	149 – 168	»	4,0	+ 100	3,8	+ 81
1952						
21	118 – 143	June	3,4		2,9	
22	143 – 161	»	4,3	+ 27	4,0	+ 38
1953						
26	237 – 266	Aug.	4,2		3,9	
27	266 – 284	»	6,4	+ 52	5,7	+ 46

4. The fluctuations of the relative transport. With the underlying assumptions for the transport calculations in mind, let us then go back to the problem discussed at the end of chapter I, *viz,* the astonishingly large short-term fluctuations of the computed transports. In order to give a clear view of the problem, the relevant figures are concentrated in Table 2. As pointed out previously, it is difficult to find any reasonable explanation of an increase of up to 100% in the transport within a couple of days. If such an increase were linked to variations in the large-scale circulation, it is improbable that this increase would be effected in such a short time; and if it should take place on a more local scale, its magnitude is such that one would think it difficult to fit in with conditions of continuity. Thus, in view of the considerations above, it seems natural to investigate the possibility that such large short-term variations do not represent, or do not in entirety represent, real variations of water transport through the section. We have just shown that the transport values are left undetermined by a term that depends on the velocity at the bottom, and this velocity cannot be found by means of the observations of temperature and salinity alone. On the other hand, if this velocity could be determined by other means, the absolute velocity at any level could be found by adding, with proper sign, the bottom velocity to the relative velocity at that level.

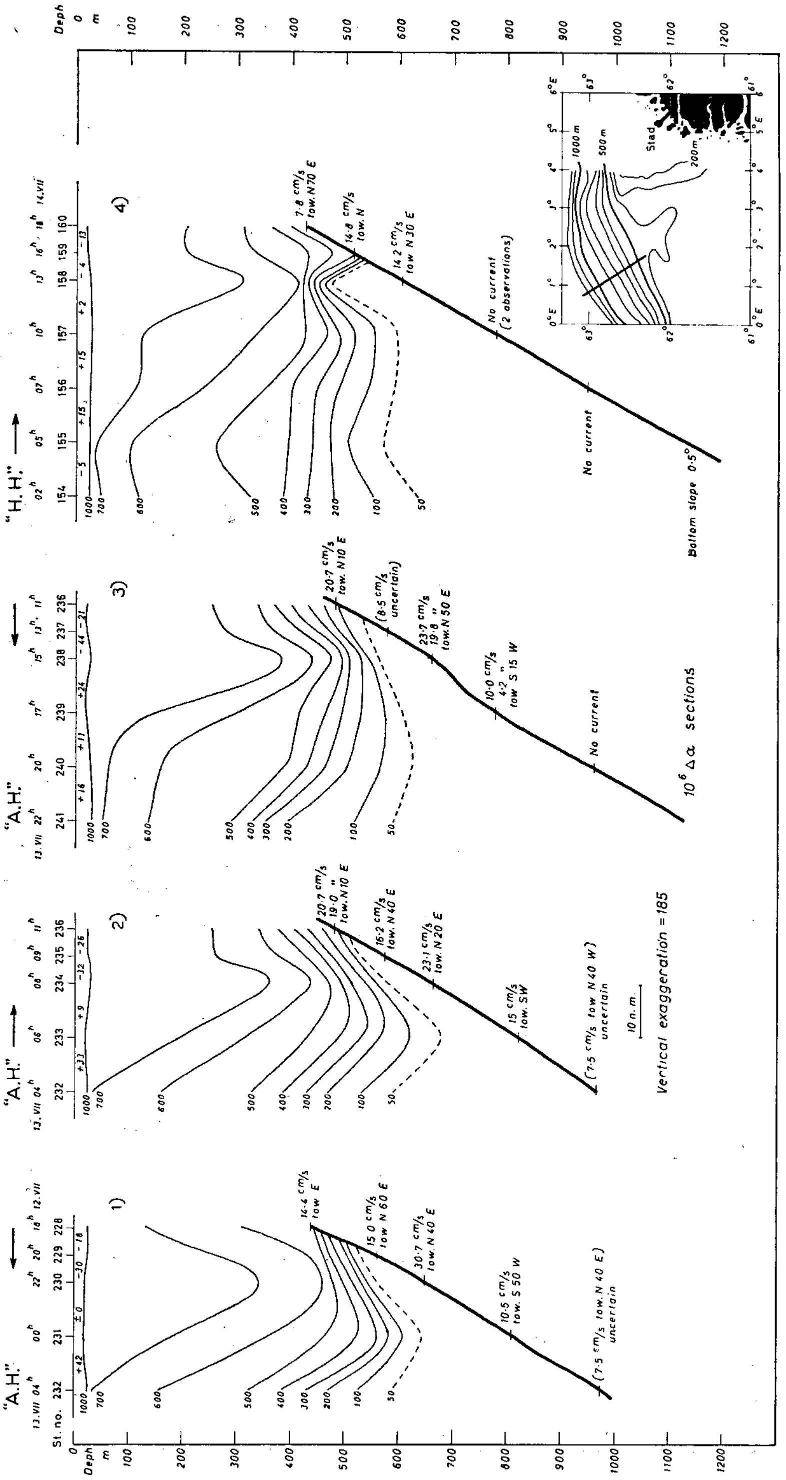

Fig. 7. Distribution of anomaly of specific volume in the section of 1957. Map insert shows location of section.

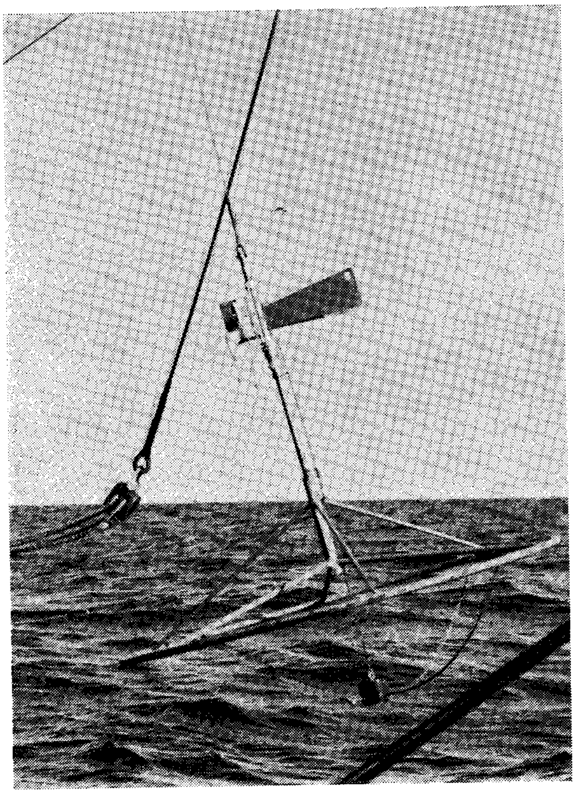

Fig. 8. Mosby's bottom current meter.

As previously mentioned, the assumption of zero velocity at the bottom is completely arbitrary and made only for simplicity in computations. There is no reason whatsoever to believe that the bottom velocity is everywhere zero. There is in fact strong reasons for supposing that it may attain relatively high values, at least along part of the bottom line. This would in turn imply the possibility of variations in the bottom velocity. Such variations could take place fairly quickly, and would give rise to transport variations that would not be disclosed by the ordinary dynamic computations. Thus, a possible explanation of the large short-term variations of the computed transport could be that the bottom velocity has varied in such a manner as to compensate for the variation in the computed relative transport.

As an illustration to the above remarks, we shall present the results of an experiment made in 1957 in a section across the Norwegian Atlantic Current a little north of the Sognefjord section (Fig. 7). This short section (see map insert for location) was intended to cover the slope between 400 and 1000 meters, approximately, and was traversed four times in as rapid succession as possible. The water sampling on the stations of the first three sections was carried out by M/S "Armauer Hansen", while current measurements close to the bottom were simultaneously made from M/S "Helland-Hansen". On the last section, both water sampling and current measurements were made by the "Helland-Hansen", the current measurement being made immediately after the hydrographic casts on each station. The current measurements were made by means of an apparatus constructed by Mosby (1953). This apparatus is essentially an Ekman current meter mounted on a vertical rod that is based on a large, heavy iron ring (Fig. 8). The apparatus is lowered from the ship until the ring hits the bottom, when a releasing mechanism sets the meter free to operate. When the apparatus is lifted from the bottom again (usually after 5 to 10 minutes), the meter is automatically relocked. In this way we obtain current measurements very close to the bottom (about 130 cm above it) uninfluenced by the ship's movements. In practice, it appeared that the apparatus could be relied on down to depths of about 1000 meters. The results of

Table 3. *Bottom current measurements in 1957 (see Fig. 7).*

Depth m	Section no.	Date (July)	Time h m	Velocity cm/sec.	Direction (toward)
430	1	12	18 30	14,4	E
480	2,3	13	11 10	20,7	N 10° E
480	2,3	13	11 40	19,0	N 10° E
425	4	14	18 10	7,8	N 70° E
550	1	12	19 50	15,0	N 60° E
575	2	13	09 20	16,2	N 40° E
570	3	13	13 30	8,5	N, uncertain
515	4	14	16 00	14,8	N
650	1	12	22 20	30,7	N 40° E
660	2	13	08 10	23,1	N 20° E
660	3	13	14 40	23,7	N 50° E
660	3	13	15 20	19,8	N 50° E
605	4	14	13 30	14,2	N 30° E
810	1	13	00 05	10,5	S 50° W
825	2	13	06 30	15,0	SW
800	3	13	17 20	10,0	S 15° W
800	3	13	17 50	4,2	S 15° W
780	4	14	10 30	no current	
780	4	14	11 10	»	
960	1,2	12	04 30	7,5 uncertain	N 40° E uncertain
960	3	13	19 40	no current	
960	3	13	20 30	»	
950	4	14	07 40	»	

the current measurements are compiled in Table 3, and are also entered into Fig. 7. The times at which the stations were occupied are entered above the sections, and it is seen that there are 48 hours between the first and the last stations of the program. It is readily seen that significant variation in the hydrographic situation have taken place within this short period. We shall in this connection only point out the facts that are relevant to the problem under discussion.

1) Considerable velocities are found close to the bottom. Above 700 meters the directions are between N and E, and the magnitudes range from 8 to 30 cm/sec. At about 800 meters, currents up to 15 cm/sec. were measured, with directions between S and SW, that is, in the opposite direction to the currents at higher levels. This is surprising, but, as similar results were found on three different occasions, there can be little doubt that the observations are correct. It is also worth mentioning that both the measurements at 800 meters and those on the next "step" (600—700 m) are taken within the cold bottom water with temperatures slightly below — 0,90°C and

salinity 34,91— .92$^0/_{00}$. Thus, it seems that the current boundary does not necessarily coincide with the boundary of the Atlantic water, and that there may be considerable current shear within the cold bottom water. However, interesting as these observations may be, they are insufficient for ascertaining whether these features are more than the effects of a transient slope. At the lowest level of observation, about 950 meters, no currents were observed with certainty.

2) Although the general direction of the bottom currents is maintained during the period of investigation, their magnitude varies considerably. There is of course a possibility that part of this variation may be ascribed to the tidal currents, about which we know very little in this area. The current measurements made on this occasion are too few to allow an elimination of the tidal part of the current by means of harmonical analysis. The data in Table 3 seem to show, however, that it would be very difficult to fit the observed current variations into the tidal period. Thus, these observations show a real possibility of a substantial variation of the bottom currents within a few days, that is, within a period of the same duration as that found for the rapid variations of the relative transports computed for the Sognefjord section.

3) The hydrographic situation undergoes a marked change, especially from the third to the fourth section. The data are too sparse for any closer comparison with the bottom currents, but it should be pointed out that the remarkable downward bending of the isosteres on the innermost part of the fourth section is accompanied by a marked decrease in the bottom current. — It is seen that the isosteres in the sections have an upward slope toward the coast, a rather unusual occurrence in this region. This means that the geostrophically computed currents relative to the bottom will be directed toward the southern side of the section, in the part of the section adjacent to the coast. The geostrophic surface currents have been computed between successive stations, with the bottom as reference surface, and the velocities in cm/sec. are entered just below the surface line in Fig. 7. A positive sign means current toward the northern side of the section. If the observed bottom current can be regarded as quasi-stationary, the absolute currents at the surface can be deduced, and it is found that the negative values will be considerably reduced.

It is also interesting to note that the application of Sverdrup's (or Groen's) method would give bottom currents directed toward the southern side of the section, opposite to the observed currents.

The experiment just described seems to lend support to the idea that the large short-term variations in the computed transport through the Sognefjord section may not be real, but are compensated for by variation in the bottom current, in any case to such a degree as to leave variations whose magnitude can more easily be accepted.

In order to see what this idea would imply in an actual case, let us once more revert to the case of the highest percentage variation of transport in the "repeated sections", that is, the sections of July 1951 (Fig. 4). In this case, the relative transport increased by 2.0 mill. m^3 pr. sec. from the first section to the second one. In order to ascribe this difference to a difference in the bottom current in the two cases, we must assume that the bottom velocity component normal to the section has decreased from the first section to the second one (with the convention of positive sign for velocity toward the northern side of the section). It is found that the amount of decrease needed to balance the increase in the computed relative transport is surprisingly small. In fact, a decrease of 10 cm/sec. along 20 n. miles of the slope (approximately between depths of 300 and 700 meters) is sufficient. Furthermore, it should be remembered that our transport calculations have been restricted to the parts of the sections that lie west of St. 122 of St. 168 (Fig. 4). This makes little difference to the relative transports, as the velocities relative to the bottom are small in the eastern parts of the sections. The absolute transports through these parts of the sections would however vary if the bottom velocities varied. Evidently, a decrease of bottom velocity in this part of the section along with a decrease of bottom velocity in the slope part of the section would bring the amount of decrease necessary to restore balance down to considerably less than 10 cm/sec. In view of the results of the experiment in 1957, this seems to be safely within the limits of possibility.

The results of the above discussion show that any conclusions on variations of the transport in the Sognefjord section arrived at on the basis of the geostrophically computed transports at hand would be extremely uncertain. This applies equally to short-term and long-term variations. In the case under discussion, our findings were that variations of the bottom currents along the slope possibly could explain the seemingly enormous variations of the relative transport. We have no evidence to show whether similar effects occur over the deep sea bottom, when the transport is computed relative to a deeplying reference surface. It seems reasonable, however, to think that the piling-up of water against the slope, or the coast, must be responsible for most of the bottom current variations. If such is the case, transport computations by the geostrophical method in the deep, open sea would be less likely to be confused by varying currents at the reference surface than would computations across the continental slope. In this connection, the previously mentioned transport computations by Iselin (1940) across the Gulf Stream may be of some significance. In this section, where the transport computations start well off the slope with a reference surface of 2000 db. all over, the percentage variation of the transport was found to be small as compared with the Sognefjord section (p. 9).

5. Special features of the Sognefjord section.

a) Wave-like appearance of the isolines. In the sections reproduced on p. 11 (Fig. 4), it is seen that the isosteres have a somewhat wavy appearance. In some of the sections this feature is less pronounced, in others more. One of the most extreme sections in this respect is reproduced in Fig. 9. Two very pronounced "crests" are seen, with an indication of a third one farthest to the west. It might be tempting indeed to interpret such a feature as an indication of the presence of internal waves. The succession of the four short sections of 1957 described in the last chapter (Fig. 7), especially the

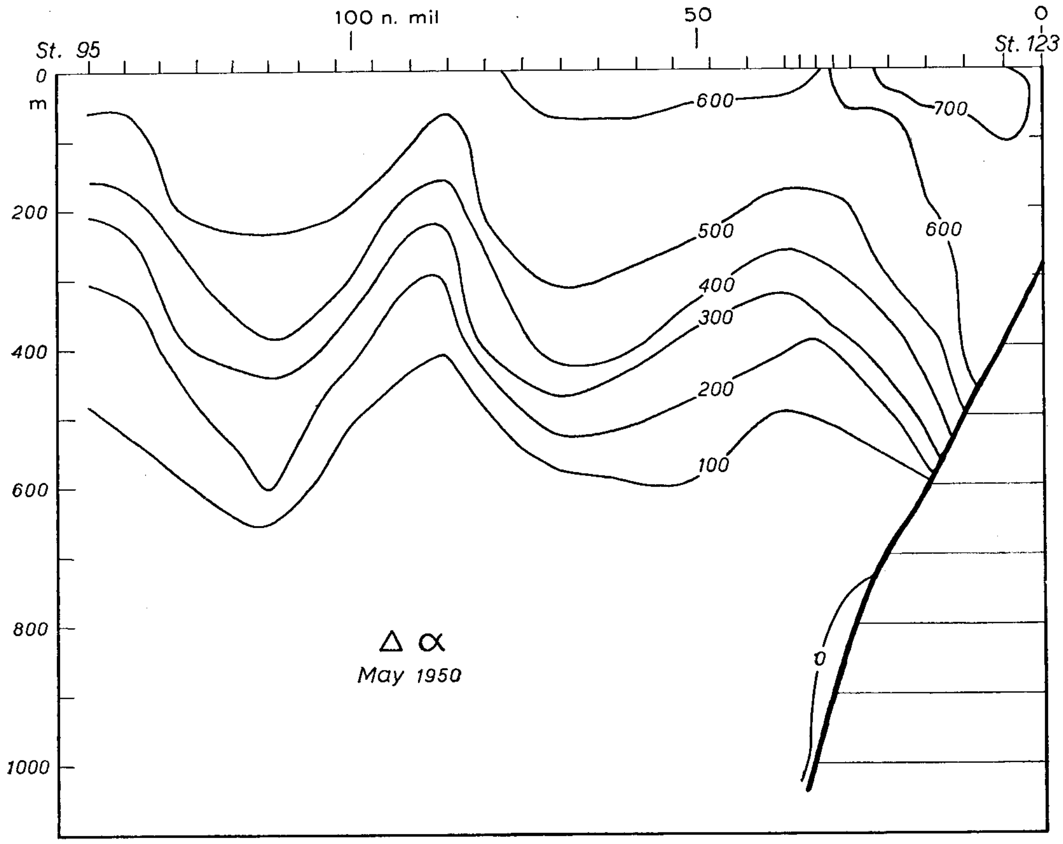

Fig. 9. Distribution of anomaly of specific volume in section No. 10 (May 1950), showing wavelike appearance of isosteres.

transition from the third to the fourth section, would undoubtedly also be considered, by many oceanographers, as a strong indication of an internal wave. Such an interpretation may, however, be premature. Already HELLAND-HANSEN and NANSEN (1909) had noticed, in sections across the Norwegian Atlantic Current, that the isolines were often wavy, and after a detailed discussion concluded that this most probably was due to large vortices with vertical axes. This conclusions seems to be corroborated by special investigations made by the Geofysisk Institutt in later years. Efforts were made in the years subsequent to 1953, when work in the Sognefjord section was discontinued, to shed more light on the internal structure of the Norwegian Atlantic Current, among other things on the possible existence and characteristics of such vortices. Detailed mappings of selected regions were carried out, and in many cases we found configurations that would be difficult to interpret as anything other than vortices with vertical axes. An example is reproduced in Fig. 10; a more detailed report on these investigations will be given in a later part of this work.

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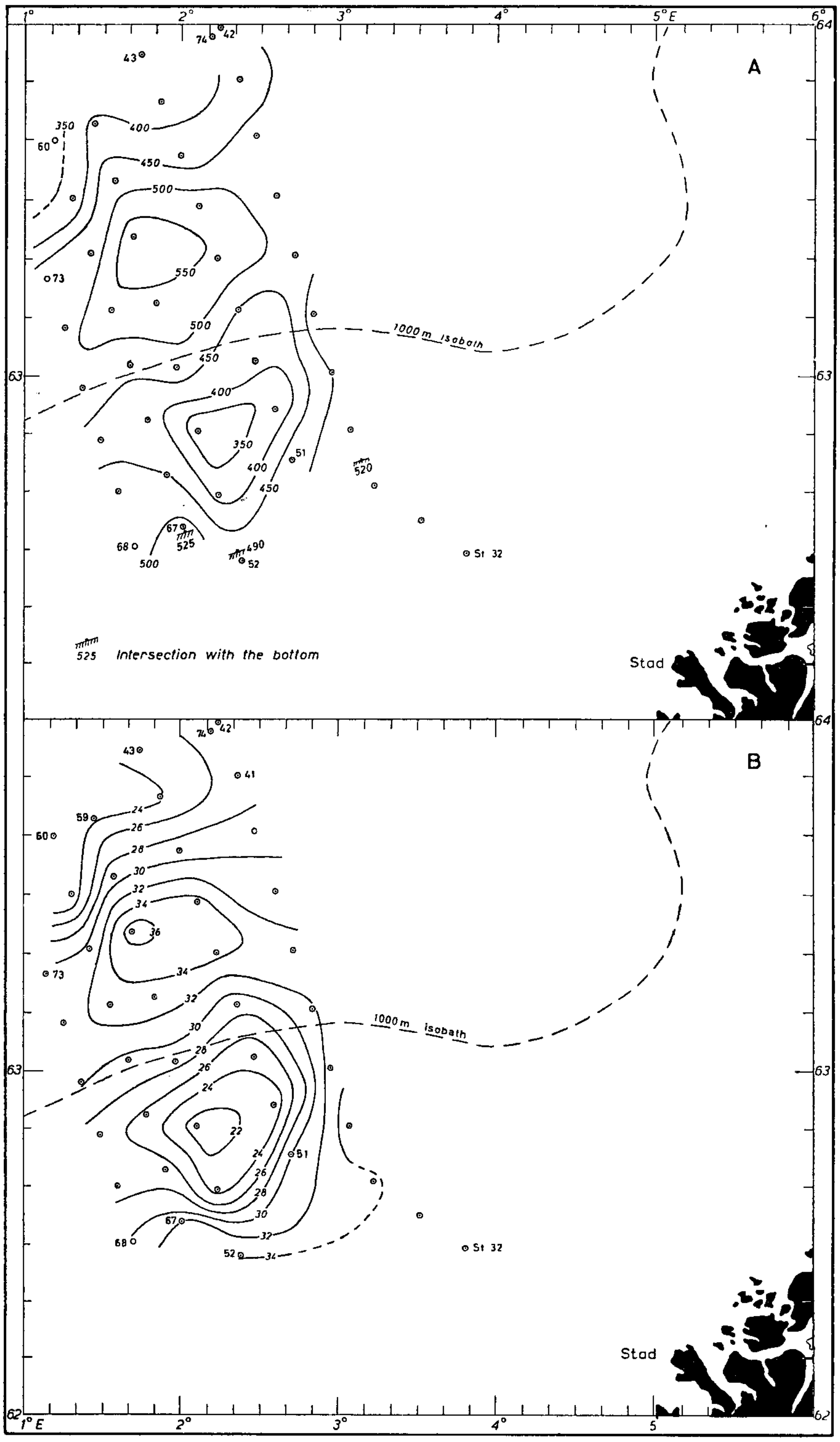

Fig. 10. Vortex-like patterns from cruise 16—22 July, 1954. *A.* Depth in meters of $10^6 \Delta\alpha = 200$. *B.* Anomaly of dynamic height of sea surface in dyn. cm, referred to 1000 db. (or bottom).

b) *Conditions along the slope.* In an early stage of the work in the Sognefjord section, it was recognized that the water masses above the slope were characterized by strong gradients, both horizontally and vertically, of temperature and salinity. When approaching the slope, the isolines in the transition layer between the Atlantic water and the deep water most often converged, and sometimes made sudden bends. Over the slope, the stations were therefore taken with short intervals, as a rule five nautical miles. Additional depths of observation were also introduced between the standard depths. This revealed the existence of gradients of magnitudes even greater than suspected beforehand. In some cases, temperature gradients of 1 degree centigrade per 10 meters were found in the said layer. In Fig. 2, this convergence of the isolines is indicated both by the isotherms and the isohalines, and it is also clearly seen in the isosteres in Fig. 4. It is a fairly regular feature, although it may be more or less pronounced. In the middle of the sections the isolines are more widely spaced. Thus, it appears that the transition between the two main water bodies of this region, *viz.* the warm Atlantic water and the cold deep water, is much more sudden over the slope than in the mid-section. Over the slope, the two water bodies must therefore have come into contact relatively recently without having had much time to mix. The Atlantic water in its undiluted form (salinity mostly above $35{,}30^{0}/_{00}$) enters the Norwegian Sea across the Wyville Thomson Ridge. From there on, it starts mixing with the cold deep water of the Norwegian Sea. Depending on the conditions just north of the Wyville Thomson Ridge, the initial transition between the two water bodies may be more or less sharply defined. This feature indicates that the water found over the slope has taken a relatively direct route from the Faeroe-Shetland Channel, so that the time available for mixing between the two water bodies has been short, whereas the water found in mid-section has been moving more sluggishly and probably also taken part in vortex movements. In other words, there seems to be a concentration of the current along the slope, a conclusion which agrees with the general experience of sailors and fishermen.

Another remarkable feature of the Sognefjord section is also apparent on Fig. 2. In that figure, the isotherm for — 0,9°C is drawn, and it is seen that it ascends along the bottom to a depth between 500 and 600 meters. The occurrence of very cold water up to high levels on the slope is a permanent feature of the Sognefjord section. It has been found to a more or less pronounced degree every time the section has been occupied. It is seen that the — 0,9° isotherm runs very close to the bottom, and the feature can be appreciated in full only if observations are taken sufficiently close to the bottom. For example, on station 125 of Fig. 2 the temperature at 600 meters is — 0,78°, but at 650 meters it is — 0,92°. On stations in the middle of the section, such low temperatures are met with only at much greater depths, as a rule 1500 meters or more, even if potential temperatures are used. Thus, it seems as if the bottom water on the slope has a relatively direct connection with the region where the cold deep- and bottom water of the Norwegian Sea is formed. On the strength of the available observations it is difficult to say anything about the nature of this connection. One might think that the movement of the cold water has a component up the slope. Or, that it circulates in a cyclonic direction along the slope in the southern part of the Norwegian Sea, or a combination of both. The feature under discussion is also encountered in other sections across the continental slope of the southern Norwegian Sea, although in many of them only sporadically. In one of them, however, *viz.* the so-called Køgur-section which runs NNW from the northwestern extremity of Iceland, the features appears to be as permanent as it is in the Sognefjord section. (U. Stefansson 1949, 1950, 1951, 1952, 1953, 1954, 1955). This section is similar to the Sognefjord section in that it crosses a current of Atlantic water flowing into the Norwegian Sea. The similarity of the two sections may indicate some common mechanism, but more data would be necessary for a closer examination of these questions.

6. The movements of the shelf water. In the first chapter, it was stated that, when the movements are referred to the bottom as zero surface, the geostrophic currents in the shelf part of the Sognefjord section are weak. Accumulation of low-salinity water near the coast may sometimes cause strong currents, but such currents are locally restricted. When the shelf waters are taken as a whole, the water transport due to geostrophic currents is always small, and may be directed toward the southern side of the section as well as toward the northern side. The part of the Sognefjord section that is within the shelf has a length of the order 100 nautical miles. Apart from the 20 miles nearest to the coast, the current is as frequently directed toward the southern side of the section as toward the northern side. In Fig. 11, two velocity sections over the shelf are reproduced. The velocity is computed relative to 300 db. The two sections are selected to show two extreme cases: one with negligible current in the vicinity of the coast (July 1951), and one with a high current velocity in that region (August 1950). It is seen that the currents are in both cases very weak in the greater part of the section, and such is the case also in the sections which are not reproduced here. The high velocities near the coast in the section of August 1950 are concentrated in a narrow coastal region, and a wide belt of water with slow and irregular movements separates this coastal current from the Atlantic current outside the Tampen bank. Thus, there can be found, in these sections, little support for the theory advocated by Krauss (1955) which was mentioned on p. 9.

Where sufficient observations exist, the water transport through the shelf part of the sections has been computed; they are summarized in Table 4.

The transports are computed between the station nearest to the coast and the first station used in the transport computations for the oceanic part of the sections (Table 1). As reference surface we have used standard observational depths as near to the bottom as possible. That means, as a rule, the 300 db. surface for the innermost 80—100 miles, and 150 or 200 db. for the rest of the shelf (above the Tampen bank). The maximum velocities at the surface are also entered in the table. It should be noted that there is as a rule 20 miles between the stations on the shelf, so that the velocities given in the table are averages over that distance. Often, but not always, the maximum velocities will occur close to the coast. It is seen that, in all cases but four, the transport is less

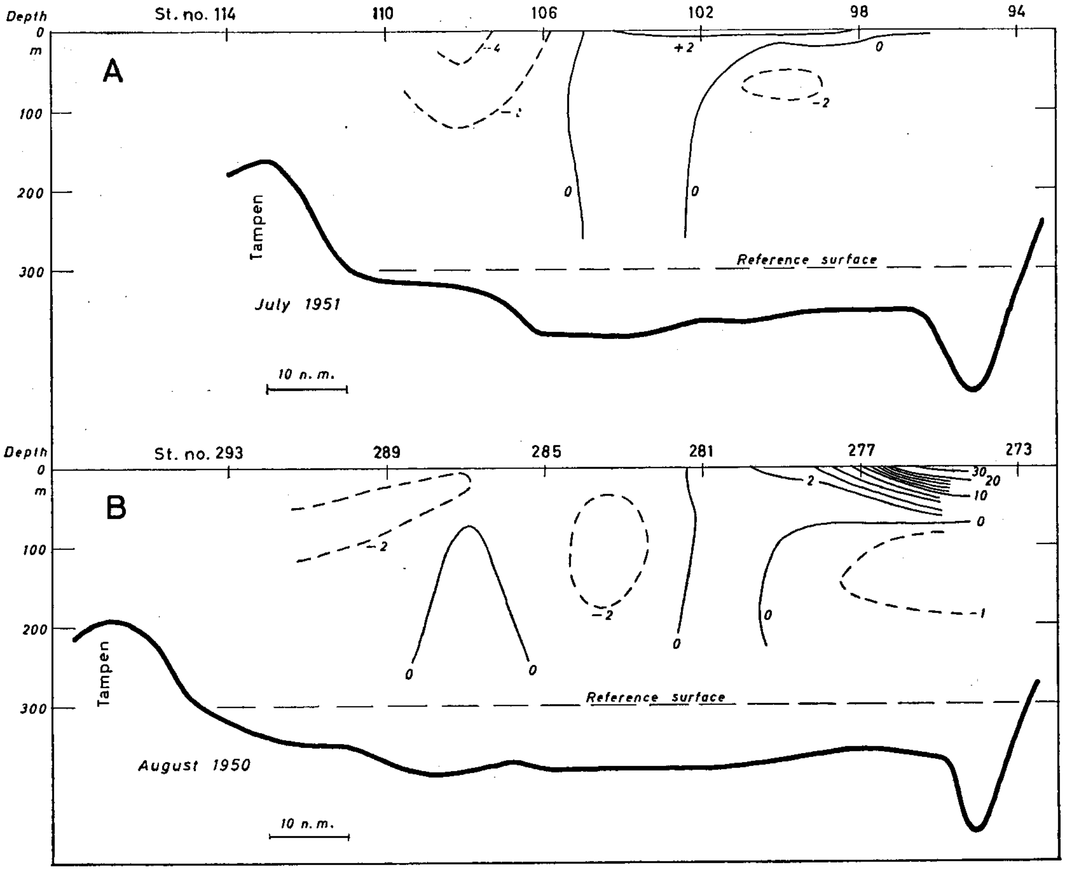

Fig. 11. Distribution of velocity in the shelf part of the Sognefjord section. *A.* July 1951. *B.* August 1950.

than 0,2 mill m^3 per sec. In all the four cases with transport more than 0,2 mill. m^3 per sec., the transport is directed toward the southerly side of the section, and must be supposed to have little connection with the main flow of Atlantic water outside the Tampen bank. It may also be noted that the transport is negative in 10 out of 16 cases. This is because the coastal current is shallow and as a rule carries little water as compared to the slower-moving but more extended water masses farther away from the coast, the movement of which very often has a southerly component.

The above remarks pertain to the geostrophic current, computed on the assumption of motionless deep water. In view of the smallness of the velocities computed in this manner, currents due to additional slopes will play relatively an even greater part than in the oceanic part of the sections. In fact, an additional velocity of only 1 cm/sec. throughout the shelf party of the section will mean an additional transport of about 0,6 mill. m^3 per sec., that is, more than any of the transport figures of Table 4. Thus,

Table 4. *Transport through the shelf part of the Sognefjord section.*

Year	Month	Transport 10^6 m^3/sec.	Max. surf. velocity cm/sec.
1947	June	− 0,40	+ 7,3
1948	May	− 0,01	+ 9,0
	June	− 0,09	+ 7,8
1949	May	− 0,15	+ 11,9
	July	− 0,39	− 7,2
1950	May	+ 0,09	+ 5,1
	July	+ 0,02	+ 9,9
	Aug.	+ 0,02	+ 33,7
1951	May	+ 0,15	+ 4,8
	July	− 0,16	− 4,7
1952	May	+ 0,03	+ 4,5
	June	− 0,35	+ 6,3
	July	− 0,07	+ 5,8
1953	May	+ 0,18	+ 9,4
	June	− 0,39	+ 8,9
	Aug.	− 0,03	+ 16,6

we may expect that the velocities and transports computed in the above manner as a rule will be very different from those actually occurring. But we may in any case be allowed to suppose that the water movement in most of the shelf water (when tidal currents are disregarded) is sluggish and irregular, unless "additional slopes" occur in a systematic manner. Without extensive current measurements it is impossible to say whether this is the case or not.

Acknowledgement. The present paper has been prepared at the Geofysisk Institutt, Universitetet i Bergen, and I am greatly indebted to Professor H. Mosby for permission to use the data on which this investigation is based, as well as for his interest and encouragement. Mr. J. Schjelderup has kindly put at my disposal his results of transport computations for the years 1947—49. It is not possible to mention everyone who has assisted in the field work; they include the whole staff of the Institute and a good many more. I should only like to say that the long experience and careful work of Mr. O. Aabrek has been heavily drawn upon. He has also prepared the diagrams for publication. Mr. E. Nydal has assisted in the calculations, and Mr. N. [illegible]ND and Mr. K. Erichsen have carried out most of the salinity titrations.

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