Tellus (1987), *39A*, 245–253

The large-scale circulation in the Skagerrak; interpretation of some observations

By JOHAN RODHE, *Dept. of Oceanography, University of Gothenburg, P.O. Box 4038, S-40040 Gothenburg, Sweden*

(Manuscript received 10 March; in final form 17 October 1986)

ABSTRACT

Instantaneous velocity observations with high-space resolution at two sections in the Skagerrak has been repeated during the years 1975 to 1977. The velocity observations are presented together with hydrographic data. The mean currents show a cyclonic circulation. Apart from a narrow baroclinic coastal current, the mean velocities generally increase towards the bottom. The mean velocities at the bottom are highest close to and below the sill depth. In the upper layers, the direction of the circulation occasionally changes, whereas in the deeper layers, the cyclonic circulation is present in all the observations. The advective residence time for the water down to 400–500 m in the Skagerrak is some 100 days. The barotropic transport in the circulation has the same magnitude around the Skagerrak and at the eastern part of the sill west of Norway.

1. Introduction

The Skagerrak is the inner end of the Norwegian Trench (see Fig. 1). The Trench cuts into the shelf sea—The North Sea—from the Norwegian Sea along the coast of Norway to the Baltic entrance between Sweden and Denmark. The Trench has the topography of a large fjord; the sill depth is approximately 270 m and the maximum depth is a little over 700 m. At the inner end, the Trench has a narrow continuation into the Kattegatt with a depth of about 100 m. Svansson (1975) has described the physical and the chemical oceanography of the Skagerrak. The yearly mean fresh water supply to the Baltic is around 15000 m^3/s. To the Skagerrak, there is an addition of some 2000 m^3/s. Apart from river outlets, the salinity ranges from 20–25‰ in the south-east corner to a little more than 35‰ in the deep water. The main part of the low saline water follows the Swedish coast in the Baltic Current and the Norwegian coast in the Norwegian Coastal Current. Outside this current, there is a cyclonic circulation (on the average) with North Sea and Atlantic water entering along the Danish coast and leaving along the Norwegian coast. The surface current north of Denmark is called the Jutland Current. The tidal currents are very weak, of the order of 1 cm/s, in this area.

In this paper, results are presented from the detailed observations of currents and hydrography in the Skagerrak reported in Larsson and Rodhe (1979). Section 2 contains a presentation of the data, the method used for the current observations and the treatment of the data. In Section 3, there is a short discussion of the mean salinity and the variations. The main part of the paper is devoted to the velocity structure. In Section 4, the mean velocity is discussed and in Section 5, the variations and their causes are discussed. Finally, in Section 6, there is a presentation of some calculations of the barotropic transport.

2. Methods and observations

Along two sections in the Skagerrak (Fig. 2), standard water bottle hydrography including some chemical constituents and simultaneous

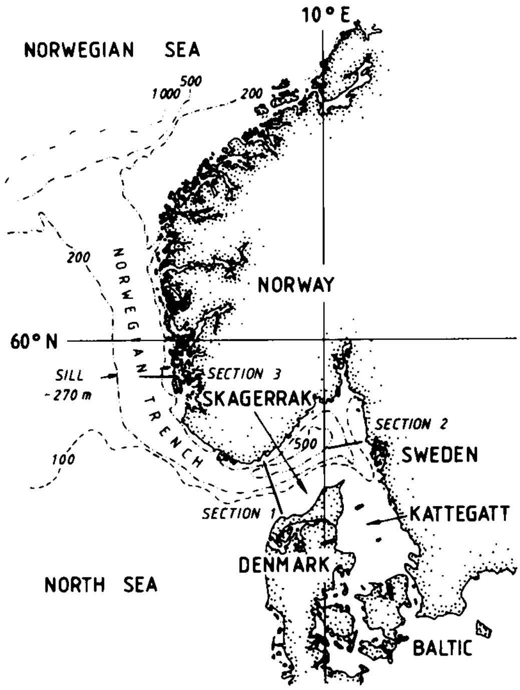


Fig. 1. Map over the eastern part of the North Sea including the Skagerrak and the observed sections.

current observations were carried out. The sections were repeated 22 times (section 1) and 9 times (section 2) during the years 1975 to 1977. The crossing time of the sections were about 10 hours. The number of current observations was around 80 at section 1 and 60 at section 2. Gelatine pendulum current meters were used as described in Haamer (1974). The meter consists of a 30 cm wing with a box containing gelatine and a suspended compass needle. The wings are attached to a thin rope at desired intervals with the gelatine heated. The rope is then left by itself with a weight at the bottom, a sub-surface buoy and a small marking buoy on the surface. After 30 min, the gelatine has stiffened and the meters are brought back to the ship. With between 10 and 15 current meters, we get a fairly detailed velocity profile. We chose the deepest current meter to be 10 m above the bottom. The depth of the top current meter varied. At the shallow stations, it was less than 10 m below the surface whereas at the deepest stations it was sometimes 20 m or more below the surface. We thus have good observations of the currents outside the bottom boundary layer but not so good observations of the surface currents, in particular not at the deepest parts of the sections at times when the velocity shear was strong.

From each crossing, a standard matrix representing the section was constructed from the original data by linear vertical interpolations and filling up to the surface with the uppermost and down to the bottom with the lowermost value. In the transport calculations, every point in the matrix was assigned an area depending on the horizontal and the vertical resolution. From these matrices, mean pictures have been calculated as ensemble means. In addition to total means, mean values have been calculated for some months when 2 or more sections have been taken. When looking at statistical properties like mean values and standard deviations, we must keep in mind that the observations represent neither a continuous time series nor a random distribution in time. Many of them are clustered in a few time periods. The standard deviations may be looked upon as a measure of the typical magnitude of the large variations.

3. Salinity and density

In Figs. 2a, b, the mean salinity and the standard deviation at section 1 are shown and Fig. 3a shows the mean salinity at section 2. Note the expanded scale in the top 50 m. In the Skagerrak, the density is essentially given by the salinity. The mean stratification is strongest and the time variations are largest outside the Norwegian and Swedish coasts (section 1, station 1 and section 2, station 1). The mean salinity distribution across the Skagerrak (Fig. 2a) shows that the total horizontal variation of the salinity, in the direction transverse to the estuarine outflow, is practically the same as the total vertical variation. This indicates that the rotation of the earth is as important as the gravity in governing the dynamics of the estuarine circulation in this area. An important consequence of this salinity distribution is that water of all salinities up to 35‰ is at times present over large areas in the surface and is thus available to wind mixing. Fig. 4 shows some different examples of the salinity at section 1.

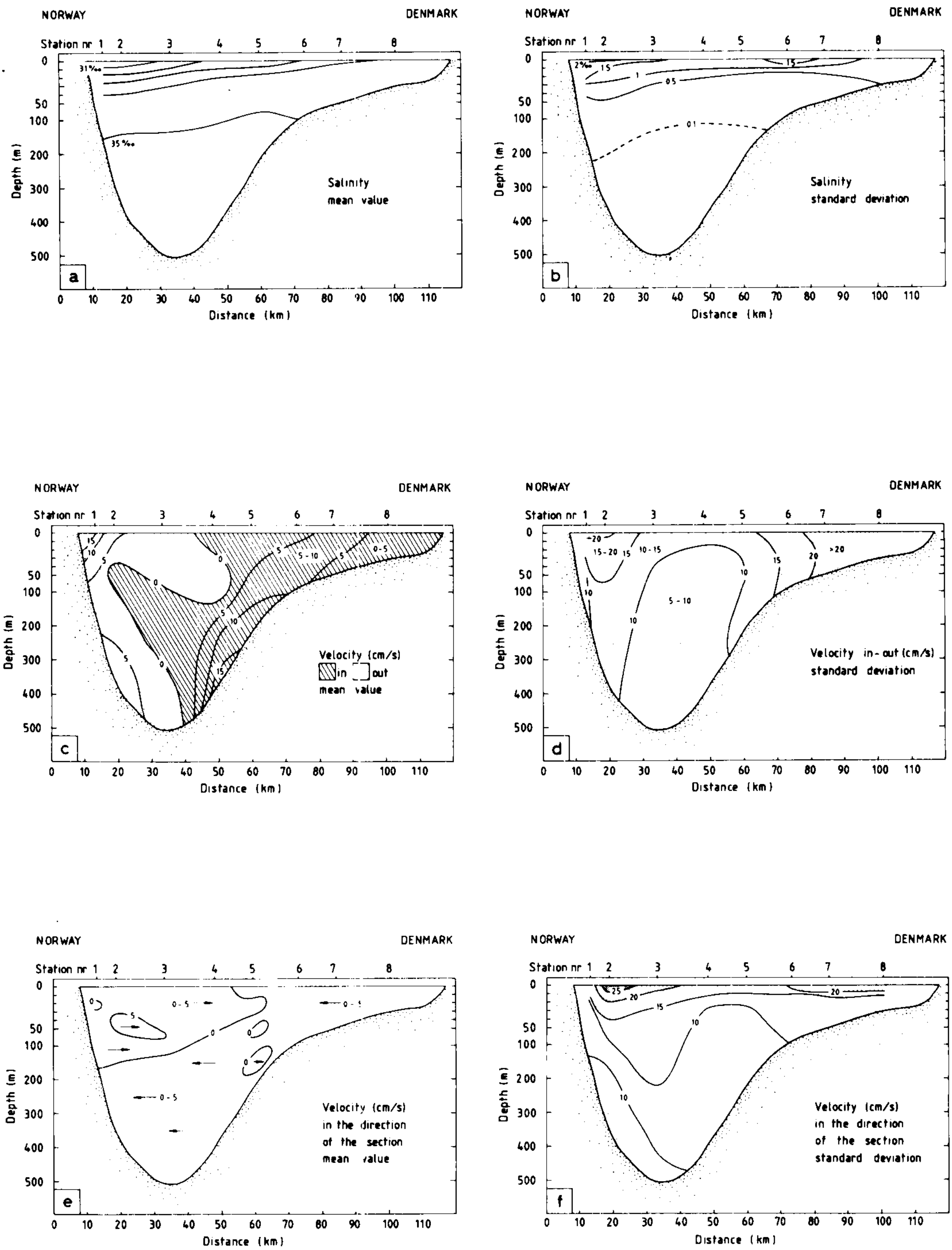


Fig. 2. Calculations from 22 observations of velocity and salinity at section 1. Note in (c) the basic cyclonic circulation with maxima in the velocities at the bottom below the sill depth (270 m) and further, the Norwegian coastal current in the surface.

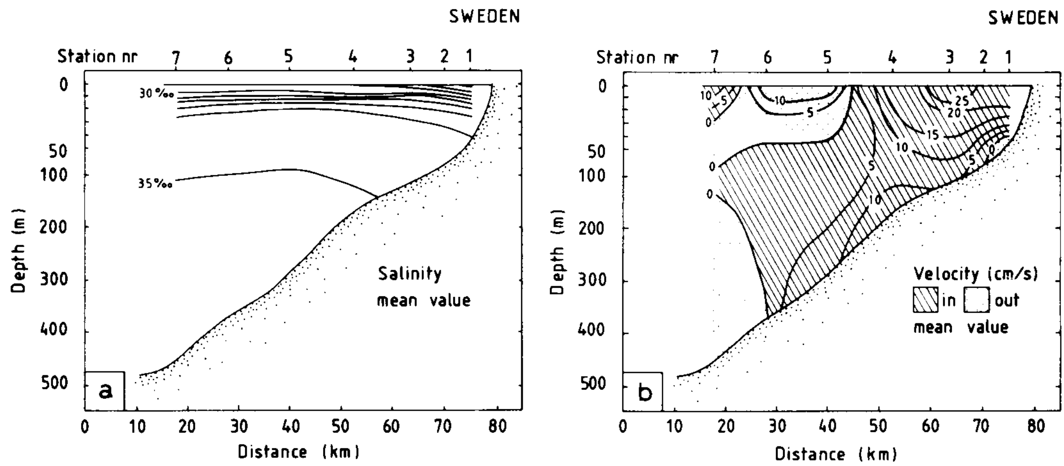


Fig. 3. Calculations from 9 observations of velocity and salinity at section 2. Note in (b) the north-going basic current with local maximum in the velocity at the bottom and further, the high velocity in the surface in the outer part of the Baltic current together with the weak counter current at the bottom close to the coast.

4. Mean velocities

The mean velocity fields (section 1, Fig. 2c and section 2, Fig. 3b) show a basic, deep-reaching cyclonic circulation, into the Skagerrak along the Danish slope of the Trench, to the north outside the Swedish coast and out again along the Norwegian coast. The circulation reaches down to the bottom at 400 to 500 m, i.e., far below the sill depth. The mean velocities have local maxima close to the bottom. The maximum velocity in the deep part of the circulation gets smaller following the flow around the Skagerrak. It is 15–20 cm/s at the Danish slope of the Trench, 10–15 cm/s outside the Swedish coast and 5–10 cm/s where the water leaves the Skagerrak along the Norwegian coast.

In addition to the basic circulation, there is, outside the Swedish and Norwegian coasts, a narrow low saline baroclinic coastal current with high velocities. The velocities outside the Swedish coast are highest away from the coast where this coastal current adds to the basic circulation of high saline water. The vertical shear of the velocity, however, is strongest at the coast. Close to the Swedish coast, there is, at the bottom, a south-going counter current (see Fig. 3 b). Outside the very steep Norwegian coast, the current system is more concentrated at the coast and the horizontal spacing of the observations is too large to resolve such details, if there are any.

If we compare the salinity and the velocity outside the Norwegian coast (Fig. 2a, c), we see that the low saline Baltic water is by no means confined to the coastal current. The baroclinic coastal current is a dynamic phenomenon, but not a barrier for the low saline water. Close to the Danish coast, where there is no baroclinic coastal current, the mean velocities are small.

Apart from the basic circulation and the coastal current there is, as shown by Fig. 2c in connection with Fig. 2a, a pronounced estuarine circulation; i.e., inflow of high saline deep water and outflow of low saline surface water.

The cross-topographic component of the mean velocity is very weak. As it shows up in Fig. 2e, it is of course very sensitive to the direction of the section. The vertical shear at the northern part of the section, however, indicates a slow outflow of low saline water from the Norwegian coastal current and a compensation inflow of high saline water.

5. Velocity variations

Fig. 4 shows large-scale changes in the horizontal circulation, reflected by the in–out component of the velocity at section 1. The circulation in the upper part can change to an anticyclonic direction (see Fig. 4d). Even below the sill depth, there are large changes in the velocity field, but here the cyclonic circulation is always present. The core of the bottom current seems to slide up and down the sloping sides of the Trench. The last 2 examples (Fig. 4e–h) are from a strongly stratified summer situation and a weakly stratified winter situation, respectively. Nevertheless, the velocity fields do not differ very much, neither in the magnitude of the velocities nor in the structure of the field. Our interpretation is that the variations of the basic circulation, exemplified above, are not strongly dependent on the stratification.

The standard deviation of the velocity at section 1 (Fig. 2d and f) shows many interesting details. One is the difference in magnitude and structure between the 2 components below the surface layer, being most pronounced at the weakly stratified southern part of the section. The direction of the bottom slope is thus important for the type of motion that gives the main contribution to the standard deviation of the velocity. Our interpretation of this is that the dominating part of the transient motion is quasi-geostrophic, since the standard deviation of the velocity component along the depth contours is much larger than the cross-topographic component, at least at the weakly stratified parts of the section.

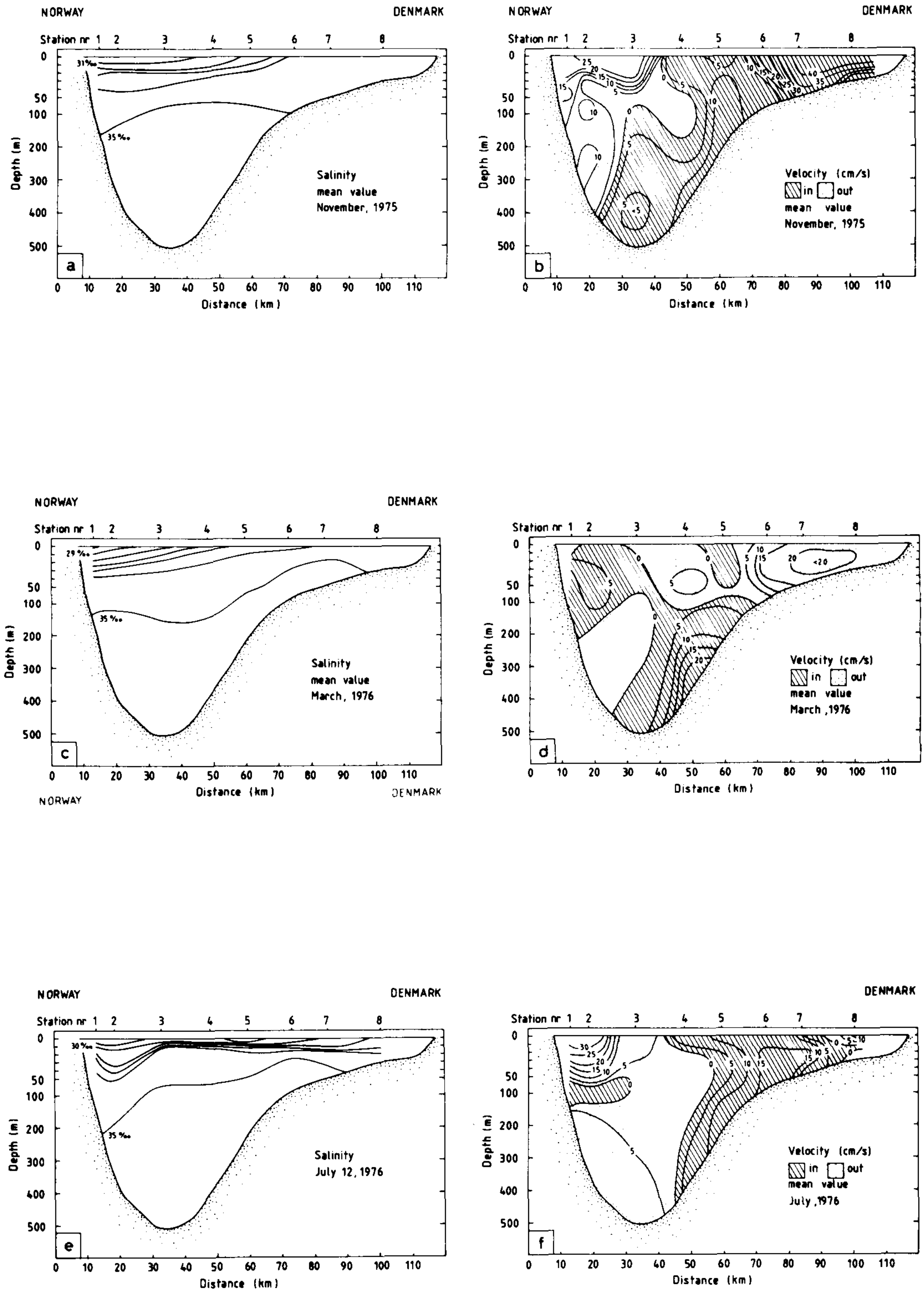
The main feature of the cross-topographic velocity component (Fig. 2f) is the large variation in a thin surface layer and decreasing variations below. The relatively small variations in the surface layer at the deep part of the section, as shown by this figure, is probably a consequence of an underestimate of the surface velocities at the deepest stations, see Section 2. Taking this into account, we make the following interpretation. The observations in the surface layer reflect the Ekman velocity forced by the transient wind. The magnitude of the transient Ekman velocity is about 20 cm/s and the depth of the Ekman layer is some 10–20 m. The fact that the velocity variations at the surface are a little larger and penetrate a little deeper in the stratified coastal current outside Norway, may be attributed to internal wave effects. The magnitude of the transient Ekman transport can then be estimated to 2–4 m^2/s. We can compare this result with an estimate of the Ekman transport based on the wind observations on board the ship (Larsson and Rodhe, 1979). The standard equation relating the Ekman transport, m_e, to the observed wind at 10 m, W_{10}, is:

$$m_e = C_{10} \cdot (\rho_A/\rho_0) \cdot f^{-1} \cdot (W_{10})^2. \quad (1)$$

C_{10} is a drag coefficient, $\rho_A/\rho_0 (\approx 1.3 \cdot 10^{-3})$ is the density ratio between air and water, $f(\approx 1.2 \cdot 10^{-4}$ s$^{-1})$ is the Coriolis parameter. Following Csanady (1982), page 11, we use $C_{10} = 1.6 \cdot 10^{-3}$ for wind speeds below 7 m/s and $C_{10} = 2.5 \cdot 10^{-3}$ for wind speeds above 10 m/s. The mean magnitude of the Ekman transport is then calculated to 2.5 m^2/s. This means that our interpretation of the velocities in the surface layer is consistent with what is expected from Ekman theory.

Within a distance from the coast, smaller than the external and larger than the internal Rossby radius of deformation, we can expect a barotropic compensation flow to the surface Ekman transport in the direction perpendicular to the coast, i.e., if the time scale is short enough to ignore the bottom stress. These conditions ought to be approximately fulfilled at, for example, station 6 on section 1, if we consider transient wind forcing. Here the depth is 100 m and we could thus expect a contribution to the standard deviation of the cross-topographic velocity of 2–4 cm/s to get the same transport as the Ekman transport. Looking at Fig. 2f, we see that this estimate is well within the observed amplitude of the variations of the velocity below the surface layer. This means that most of the contribution to the observed standard deviation of the cross topographic velocity component below the surface layer must come from other types of motion.

The standard deviation of the velocity component along the depth contours (Fig. 2d) shows a totally different picture. Apart from the coastal current at the Norwegian coast, the main impression is a standard deviation with only a small decrease in the surface Ekman layer. Below this, it is essentially constant with depth. The standard deviation decreases out from the coast with increasing depth. Our interpretation of this is that the standard deviation is dependent on large-scale motion, since it obviously "feels" the depth. The type of motion giving the main contribution to this standard deviation at the southern part of section 1 is barotropic. This can be seen by comparing with the standard deviation of the transport per unit width in Table 1.


NORWAY
DENMARK
Station nr 1 2 3 4 5 6 7 8
Depth (m)
Distance (km)
Salinity
mean value
November, 1975
a
Velocity (cm/s)
in
out
mean value
November, 1975
b
Salinity
mean value
March, 1976
c
Velocity (cm/s)
in
out
mean value
March, 1976
d
Salinity
July 12, 1976
e
Velocity (cm/s)
in
out
mean value
July, 1976
f

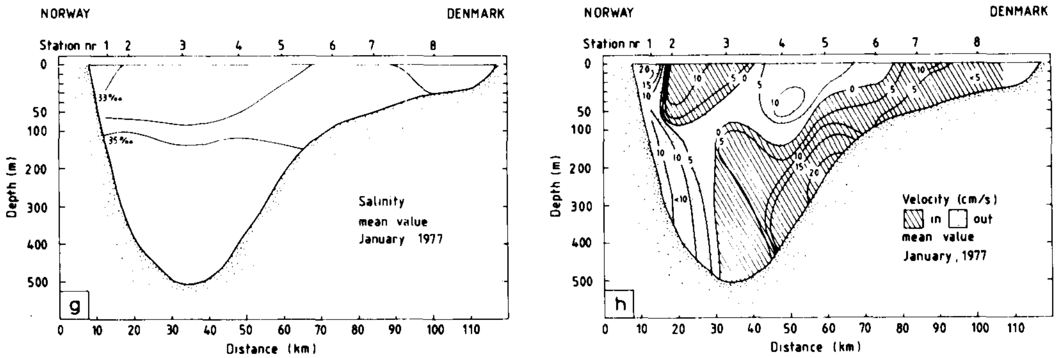


Fig. 4. Calculations from observations of velocity and salinity at section 1: (a) and (b) 4 crossings in November 1975, (c) and (d) 5 crossings in March 1976, (e) and (f) 2 crossings in July 1976, (g) and (h) 3 crossings in January 1977.

Table 1. *Transport per unit width perpendicular to the sections, mean value and standard deviation; positive value means out from the Skagerrak at section 1 and northward at section 2; unit:* m^2/s

(a) Section 1, 22 observations								
Station no.	1	2	3	4	5	6	7	8
Mean value	6	12	5	−24	−14	−8	−3	0
Standard deviation	8	37	24	20	17	19	13	6
(b) Section 1, 9 observations								
Station no.	1	2	3	4	5	6	7	8
Mean value	9	29	9	−17	−9	−11	−3	0
Standard deviation	5	23	18	17	21	11	6	3
(c) Section 2, 9 observations								
Station no.	1	2	3	4	5	6	7	
Mean value	4	8	16	18	8	8	−6	
Standard deviation	3	7	10	14	12	12	13	

One well-known mechanism for the acceleration of long-shore currents by the changing wind is local spin up, i.e., a flow perpendicular to the coast, compensating the Ekman transport, gives rise to an acceleration in the direction of the coast. This acceleration is given by eq. (2).

$$\partial u/\partial t + f \cdot v = 0. \qquad (2)$$

u and v are the velocity components parallel and perpendicular to the coast, respectively. Eq. (2) states that the magnitude of u is given by the duration time of the acceleration and the magnitude of the velocity component v. If u and v are known, we can calculate the duration time, T, of the acceleration. From (2) we get:

$$T = (u/v) \cdot f^{-1}. \qquad (3)$$

We can perform a calculation according to (3) with the observations at station 6. From the estimate of the Ekman transport above, we take v = 2.5 cm/s (the Ekman transport divided by the depth of 100 m) and from Fig. 2d we take u = 17 cm/s. The resulting duration time according to (3) is then a day, which is of the same order as the typical duration time of the wind in this area. Our conclusion from this is that the magnitude of the transient velocity component along the topography is what we could expect if it were the result of a local wind forcing according to the discussion above.

6. Transport calculations

Presented in Tables 1a–c are the transports per unit width at the 2 sections, including the standard deviation. 2 sets of calculations are performed with the observations at section 1, the first one with all observations and the second one with the observations that are taken the day before or the day after the observations at section 2. The second one is also presented together with the observations at section 2 in Fig. 5. If we first look at the variations of the transport at section 1 as it shows up in the standard deviation in Tables 1a, b, we see an increase from the shallow stations at the coasts to a more-or-less constant value around 20 m^2/s. (Station 2 in Table 1a provides an exception which without any doubt is due to problems with the positioning at this

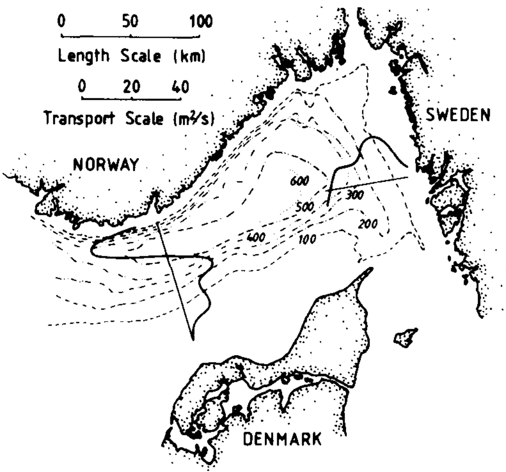


Fig. 5. Transport per unit width. Calculated mean value from 9 velocity observations with high spatial resolution at the 2 sections. The integral under the curves gives the circulating barotrophic transport. It is $\sim 5 \cdot 10^5$ m^3/s.

station where the bottom is very steep and the current is very narrow, c.f. Fig. 5.) The same tendency is seen at section 2, but the constant value is somewhat less. The constancy of the magnitude of the transient barotropic transport in the deeper parts indicates a forcing that is constant over the area, which again points to local wind forcing. The increasing value from the coasts up to a depth of ~ 100 m may be attributed to a decreasing rôle of the bottom friction on the transient currents when the depth increases. The mean values in Fig. 5 shows the barotropic cyclonic circulation in the Skagerrak, into the Skagerrak at the slope of the Trench north of Denmark, north outside the Swedish coast and out again in a narrow current at the steep slope outside the Norwegian coast. The integrated transport is the same at the 3 places, $\sim 5 \cdot 10^5$ m^3/s. This figure is the mean value of only 9 observations and is probably not valid as a true mean value of the transport in the circulation in the Skagerrak. Furnes and Saelen (1977) and Furnes (1980) report transport calculations carried out with the same method as used in this paper. Their data are from RCM moorings on a section (noted as section 3 in Fig. 1) reaching half way over the Trench from the Norwegian coast. For 1½ months in spring 1976, they report a mean northward flow of $\sim 10 \cdot 10^5$ m^3/s. Fig. 6 shows

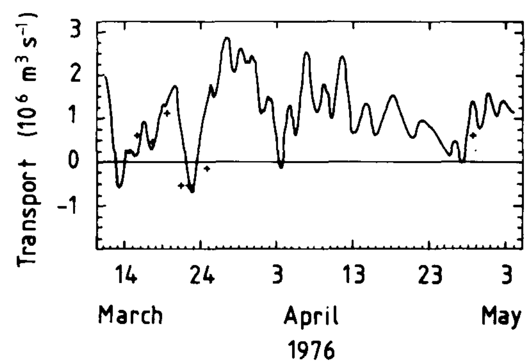


Fig. 6. Transport at the eastern side of the Norwegian Trench at the sill to the Skagerrak, from Furnes (1980). The observations from the southern part of section 1 during the same period are inserted. A positive sign stands for a cyclonic direction of the circulation in the Trench.

our transport calculations from the southern part of section 1 during the same time inserted in a figure from Furnes (1980). There seems to be no significant difference in amplitude or phase between the transports at Sections 1 and 3.

7. Summary

The velocity observations show the cyclonic circulation in the Skagerrak. The mean velocities in this circulation increase towards the bottom far below the sill depth. Judging from the magnitude of the mean velocities, the residence time of the water in the Skagerrak is some 100 days. This should hold for the water down to at least 400 to 500 m. According to the observations, the cyclonic circulation is always present in the deep layers, whereas in the upper layers, the circulation can occasionally change direction. Apart from a thin surface layer, the varying and the mean part of the velocity are practically parallel to the depth contours. The transient part of the cross-topographic velocity component shows, we believe, in the surface layer, the effect of the changing Ekman transport forced by the wind. The magnitude of the Ekman velocity is ~ 20 cm/s and the depth of the Ekman layer is some 10–20 m. The magnitude of the variations of the velocity component along the depth contours is, below the surface, what could be expected from transient local wind forcing. The transport in the

barotropic circulation is the same around the Skagerrak and out over the sill west of Norway.

8. Acknowledgements

I wish to thank the staff of the Department of Oceanography at the University of Gothenburg for help with and comments on this work, especially Lars Andersson, and Bert Rudels for field work, Kristina Hansson, drawings, Ulf Jonasson, computing; and Ulf Cederlöf and Gösta Walin for valuable discussions. The field part was financed by the Nordic Council for Physical Oceanography and the Swedish Natural Science Research Council.

REFERENCES

Csanady, G. T. 1982. *Circulation in the coastal ocean.* Riedel, Holland. 279 pp.

Furnes, G. K. 1980. Wind effects in the North sea. *J. Phys. Oceanogr. 10*, 978–984.

Furnes, G. K. and Saelen, O. H. 1977. Current and hydrography in the Norwegian Coastal Current off Utsira during JONSDAP 76. Norwegian Coastal Project, Rep., 2/77, University of Bergen, Norway.

Haamer, J. 1974. Current measurements with gelatine pendulums. *Vatten 1*, 49–52.

Larsson, A.-M. and Rodhe, J. 1979. *Hydrographical and chemical obervations in the Skagerrak.* Dept. of Oceanography, Univ. of Gothenburg, Sweden, Report no 29.

Svansson, A. 1975. Physical and chemical oceanography of the Skagerrak and the Kattegat. 1. Open sea conditions. *Rep. Fish. Board. Swed. Mar. Res. 1*, 88 pp.