On the structure and dynamics of the water in the Słupsk Furrow*

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Abstract

During 1994–1996 nearly 50 cruises both along and across the Słupsk Furrow were made with the use of an undulating CTD. Special attention was paid to the Słupsk Sill separating the Słupsk Furrow from the Bornholm Deep.

The flow of higher-salinity water over the Słupsk Sill was recorded; it was splash-like in nature. This finding was further confirmed by the temperature and salinity distribution of the deep water in the Słupsk Furrow. The origin, frequency and duration of this flow are not yet clear. The transport of waters flowing into the Słupsk Furrow is very often wave-like. Internal waves were detected, propagating both along the axis and across the channel. The break up of the internal waves and the resultant diapycnal mixing were also noted.

The perturbations in the thermohaline structure resulting from hydraulically controlled transport over the sill were clearly observed. Both convectional mixing in the intermediate layers as well as the formation of mesoscale structures were recorded.

The objective of this paper is to describe and make a preliminary analysis of the dynamic processes related to the transport of the inflowing, dense water in the bottom layers. The various phenomena will be described in greater detail in subsequent publications.

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1. Introduction

The Baltic Sea can be regarded as a large, semi-enclosed sea with a rather narrow and shallow connection to the North Sea. The water balance is influenced mainly by two factors: a relatively large freshwater surplus, and inflows of highly saline waters from the Danish Straits. If not interrupted by wind-generated currents, a continuous inflow of saline water from the Skagerrak forms the deep water of the Baltic (Piechura, 1993). The instantaneous transport rate in the Danish Straits can exceed that caused by the mean freshwater surplus by one order of magnitude (Stigebrandt, 1983).

The inflowing water moves as gravitationally driven, dense bottom currents exerting a considerable impact on the transport of properties within the sea. These currents give rise to marked variations in the salinity, temperature, oxygen and nutrients in the deeper water layers, as a result of which the deep waters of the Baltic are renewed. Several physical factors can influence the flow characteristics of the dense bottom currents: bottom friction, mixing with surrounding water, rotation, and density differences between the inflowing water and the surrounding water masses. Apart from circulation and vertical mixing, the deep waters are strongly dependent on the specific bottom topography of the Baltic Sea: a sequence of deep basins separated and linked by sills and channels (Kõuts and Omstedt, 1993).

The majority of the saline water flows into the Baltic from the Skagerrak through the Great Belt (65%), the remainder through the Little Belt (10%) and Öresund (25%). Whereas the sill depth in the Öresund (at Drodgen) is only 8 m, the water from the Belts has to cross the deeper Darss Sill (18 m). After passing the Darss Sill the bottom water crosses the Arcona Basin (Stigebrandt, 1987) and flows through the Bornholm Channel (Lundberg, 1983; Gidhagen and Håkansson, 1992) into the Bornholm Basin. Finally, it moves through the Słupsk Furrow into the Gotland Basin (Rydberg, 1976; Kõuts and Omstedt, 1993) and Gdańsk Deep (Piechura, 1970).

The inflow of water of intermediate salinity occurs more or less continuously. Normally, however, this water is not dense enough to replace the bottom water in the deep Bornholm and Gotland Basins. Water renewal in the central and western Baltic takes place only after periods of persistent and strong westerly winds, which give rise to a large sea-level difference between the Skagerrak and the Baltic Proper. In the Arcona Basin, bottom water of salinity up to 24 PSU has been recorded, but strong winds can lead to intensive mixing and dilution of dense water in this shallow basin. The bottom water in the central basin can be replaced if the salinity of the inflowing water is only slightly reduced by mixing during its passage through the Bornholm Channel and Bornholm Basin.

The flow of dense, oxygen-rich waters is interrupted by sills separating the different basins and by distinct stratification. Transport of water from the Arcona Basin into the Bornholm Basin through the 46-metre-deep Bornholm Channel is not affected by the bottom topography. However, the Słupsk Furrow is the deepest connection and the only passage between the Bornholm and southern Gotland Basins. The sill here is 60 m deep, and separates the Bornholm Basin from deep basins to the east. In order to enter the Gotland Basin, the oxygen-rich bottom water must fill up the entire Bornholm basin to a depth of more than 60 m or else must be forced across the sill. On the basis of numerical modelling Krauss and Brügge (1991) found that northerly and easterly winds enhance the transport of dense water over the Słupsk Sill.

Kõuts and Omstedt (1993) showed that the Słupsk Furrow is one of the three principal mixing zones (after the Belt Sea and Sound, and the Arcona Basin). Entrainment from surface and intermediate waters adds 28% to the deep volume flow, while flow through the Bornholm Channel occurs with hardly any mixing with surrounding waters. The Słupsk Furrow flow is more intensive than that expected from the geostrophic flow, and the effective sill depth is greater than the topographic one, which suggests the existence of additional mechanisms promoting deep water transport through the channel. The typical time lag for an inflow from the Bornholm Channel to be observed in the Słupsk Furrow is about half a year (Matthäus and Franck, 1992).

Deep water transport through the Słupsk Furrow is subject to pronounced seasonal variability: the temperature in the deep layer falls or rises as a result of inflows, depending on the time of year at which they occur. The decrease in deep water outflow from the Bornholm Basin to the Słupsk Furrow was confirmed for summer months (Kõuts and Omstedt, 1993).

2. Data and methods

During a number of cruises of the r/v 'Oceania' in the Bornholm Basin and Słupsk Furrow region, some transects with a towed scanning CTD probe were carried out. On the basis of the experience of the Institute of Oceanology, RAS, Kaliningrad (Paka, 1996), a special frame was developed to hold a standard CTD probe, in our case a Guideline 8770. The vertical movement of the CTD was controlled by means of winches. The speed of this movement, and thus the frequency of profiling and the distance between profiles, depends on the vessel's speed, the speed of the winch, the weight attached to CTD, and the depth of sampling. In most cases the cruising speed was 4 knots, which made it to record the vertical profiles of tepereture and salinity possible every 300–400 m in a sea 60–100 m deep.

Data were recorded on a PC together with the geographical position monitored continuously by a GPS. The results were presented on the monitor in a depth-time system of coordinates and were later recalculated into a depth-distance system. The on-line presentation of results allowed us to observe what was going on under the ship and to make the necessary corrections to the program or the ship's course. Temperature, salinity and pressure were recorded every 0.15 m and averaged over 1 m. After standard processing, the data were coupled to the GPS records, and a number of other parameters were calculated in order to prepare the final result of the measurement.

Altogether 46 transects were done during the period from September 1994 to June 1996. Apart from two major cruises done specifically for this project in May 1995 (16 transects) and November 1995 (12), data were collected during incidental crossings of the Słupsk Furrow in September 1994 (5 transects), October 1995 (2), February 1996 (7), April – May 1996 (4) and June 1996 (1). Most of the research effort was concentrated at the western end of the Słupsk Furrow and on the sill separating it from the Bornholm Deep (see map – Fig. 1). Although transects both along and across the axis of the Słupsk Furrow were carried out, more of the former were done (29) than the latter (17).

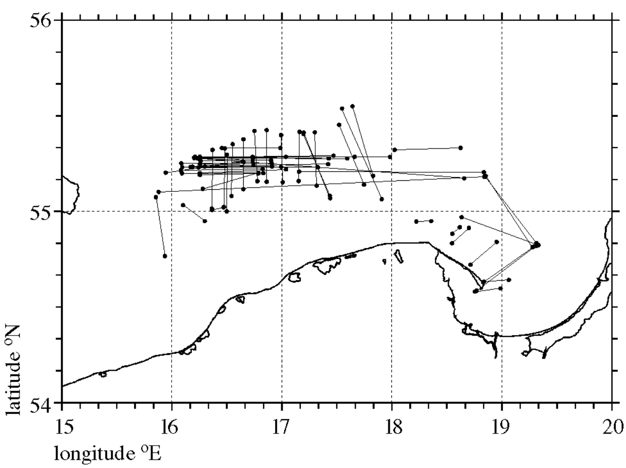


Fig. 1. Location of transects done with an undulating towed CTD probe from September 1994 to June 1996 by r/v 'Oceania'

3. Results

The data reveal a number of interesting features and processes which were known to exist but never recorded, like the flow over the Słupsk Sill or internal waves, and others which were not known before, *e.g.* the splash-like nature of the flow over the Słupsk Sill. The most obvious conclusion to be drawn from the undulating CTD data is that the picture is much more complicated than is generally thought. A number of examples demonstrating interesting features are given below and commented upon. In many cases, the interpretation of data caused difficulties, so certain theoretical studies will have to be undertaken.

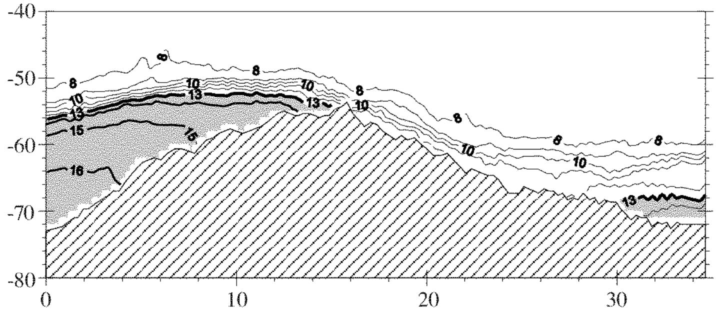
3.1. Flow over the Słupsk Sill

It has to be mentioned that although we are talking here about the 'normal' situation, when no major inflow occurs, water exchange between the Bornholm and Gotland Deeps is practically continuous.

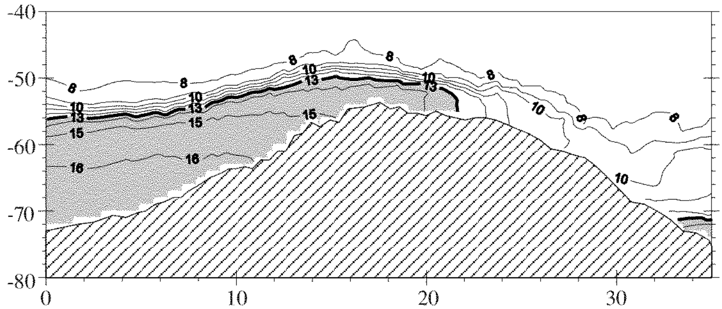
In at least three cases we recorded the moment of flow of warmer and more saline waters from the Bornholm Deep over the Słupsk Sill into the Słupsk Furrow. Since the behaviour of salinity and temperature are very similar, and salinity is a better, more conservative indicator of inflowing waters, we will restrict ourselves here to a description of the salinity. Fig. 2 shows the salinity distribution along 6 W–E transects over the Słupsk Sill made during 31 h on 9 and 10 May 1995. All the transects were done within the 4 Nm belt, so we consider them as having been done over the same area.

The first transect (No. 10; 9 May) shows more saline waters already flowing over the sill. The near-bottom salinity rose to over 13.5 PSU (normally *ca* 9–10 PSU). The isohalines on the Bornholm Deep side of the sill were climbing, while those on the Słupsk Furrow side were falling. The high salinity, over 14 PSU, in the central part of the Furrow was probably the result of the splash which had occurred earlier. During the next few hours (transects 11, 12, 13) the salinity and temperature at the sill were still increasing, the former reaching a maximum of 15.3 PSU on transect No. 13 on 10 May (Fig. 2, Tab. 1). By that time all the isohalines had moved upward by 2–7 m. (Tab. 2). After that, however, the salinity over the sill fell to 9–10 PSU on run No. 15 on May 10 and the isohalines deepened (Tab. 3).

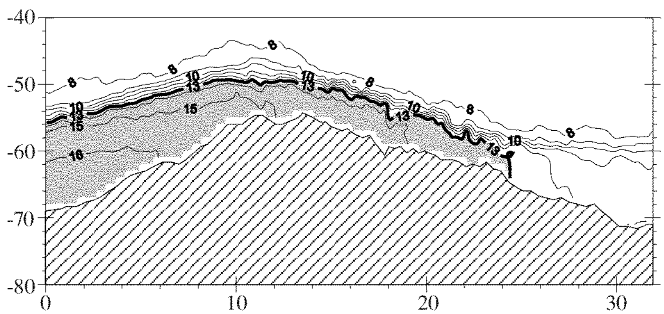
On the Bornholm side of the sill, the salinity was initially already high (> 16 PSU), then fell slightly to 15.4 PSU in the morning of 10 May (transect No. 13). To the east of the sill, the salinity continued to fall until the morning of 10 May, after which it started to rise, which yields a time lag of some 12–18 h and a velocity of *ca* 20–30 cm s^{-1}. Even though we do not know the exact duration of this flow, it is fairly clear that it was a short-lived event. More details on the nature of these flows can be found in the time records of the salinity at the anchored station during 10 h of 20 May 1995 (Fig. 3). The very large fluctuations of high frequency are plain to see: up to 2–3 PSU in a matter of seconds and up to 5 PSU in minutes. The highest amplitude and frequency were recorded near the bottom, and decreased rapidly in the upward direction.



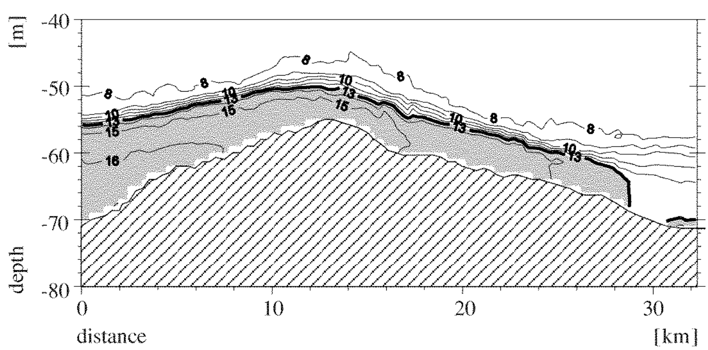
transect No. 10; start – May 9, 10:00, end – May 9, 15:00



transect No. 11; start – May 9, 16:00, end – May 9, 22:00



transect No. 12; start – May 9, 23:00, end – May 10, 03:00



transect No. 13; start – May 10, 03:30, end – May 10, 15:00

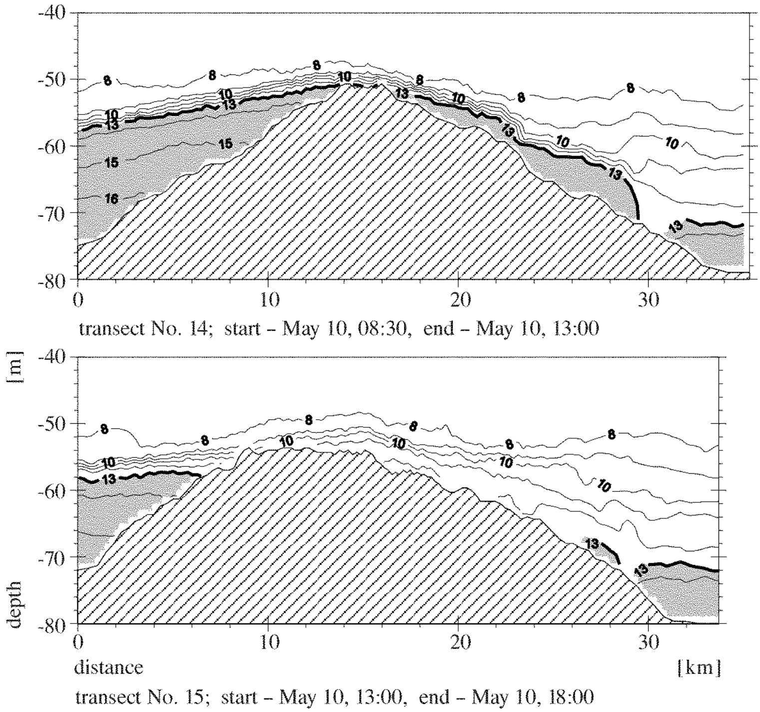


Fig. 2. Salinity [PSU] distribution on the transects across the Słupsk Sill, 9–10 May 1995 (areas of salinity > 13 PSU are shown in grey)

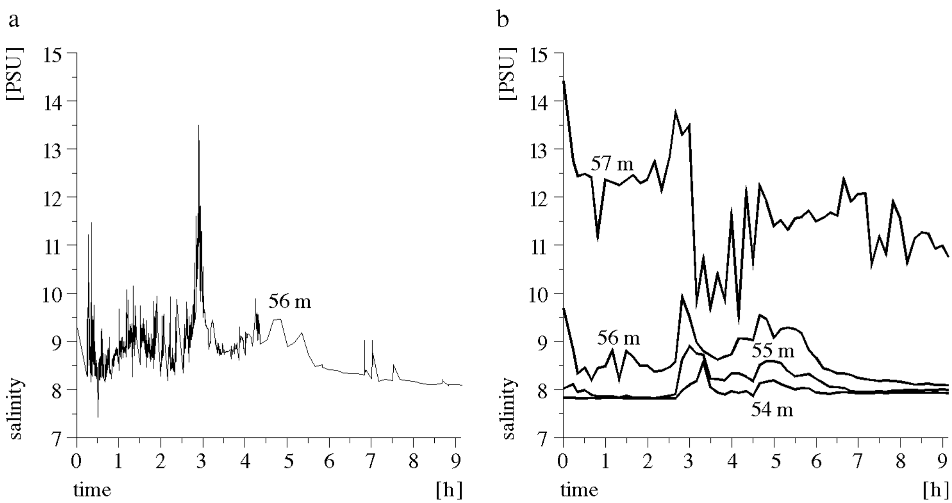


Fig. 3. Salinity [PSU] changes in the near-bottom layer over the Słupsk Sill, 20 May 1995, at a depth of 56 m – raw data (a), and at different depths: 54, 55, 56, 57 m – averaged data (b)

Table 1. Near-bottom salinity over the Słupsk Sill, 15 km to the west (Bornholm Deep) and 15 km to the east (Słupsk Furrow) of it during 9–10 May 1995

Transect No.	Date and time	15 km to the West	15 km to the East	Over the Sill
10	9 May, 11:30	> 15.00 PSU	> 14.00 PSU	≈ 10.50 PSU
11	9 May, 20:00	> 16.50 PSU	> 14.50 PSU	> 14.00 PSU
12	10 May, 00:00	> 16.00 PSU	> 11.00 PSU	> 15.00 PSU
13	10 May, 05:00	> 16.00 PSU	> 12.00 PSU	> 15.00 PSU
14	10 May, 10:00	> 16.00 PSU	> 14.00 PSU	> 10.00 PSU
15	10 May, 15:00	> 15.00 PSU	> 14.00 PSU	> 9.00 PSU

Table 2. The depth of isohalines over the Słupsk Sill, 9–10 May 1995

Transect	Depth of isohalines [m] over the Sill					
No.	8 PSU	9 PSU	10 PSU	11 PSU	13 PSU	14 PSU
10	47.0	52.0	53.0	–	–	–
11	45.0	46.0	47.0	48.0	49.0	52.0
12	44.0	45.0	46.0	47.0	49.0	51.0
13	45.0	48.5	49.5	50.0	51.0	52.0
14	47.0	48.0	49.0	–	–	–
15	48.0	51.0	–	–	–	–

Table 3. The depth of isohalines in the Bornholm Deep (immediately to the west of the Słupsk Sill), 9–10 May 1995

Transect	Depth of isohalines [m]								
No.	8 PSU	9 PSU	10 PSU	11 PSU	12 PSU	13 PSU	14 PSU	15 PSU	16 PSU
10	48.0	50.0	51.0	51.5	52.0	53.0	54.0	58.0	–
11	46.0	49.0	49.5	50.0	50.5	51.0	52.0	56.0	63.0
12	43.0	46.0	47.0	48.0	48.5	49.0	50.0	52.0	61.5
13	48.0	49.5	50.0	50.5	51.0	51.5	52.0	53.0	62.0
14	48.5	50.0	51.0	52.0	52.5	53.0	55.0	60.0	68.0
15	48.0	51.5	53.0	–	–	–	–	–	–

A similar situation was come across in February 1996 (Fig. 4). On crossing the Sill on 7 February we found a more or less normal distribution there; however, both isohalines and isotherms were climbing on the western slope

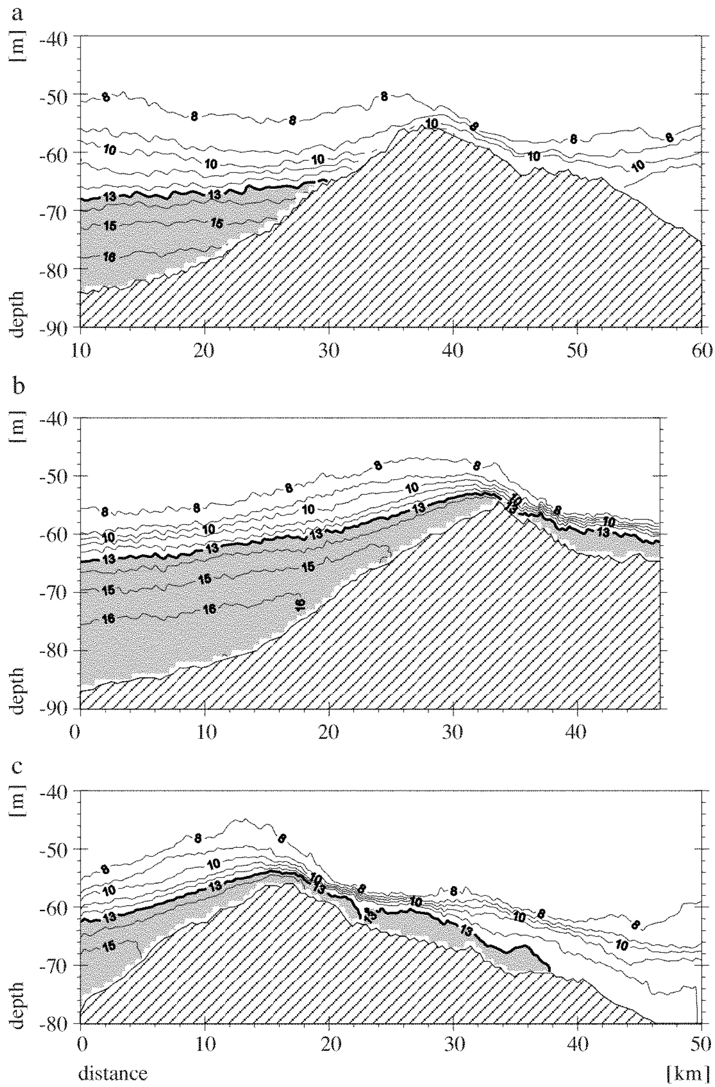


Fig. 4. Salinity [PSU] distribution on the transects over the Słupsk Sill, 7 and 14–15 February 1996: transect No. 2 (a), transect No. 4 (b), transect No. 6 (c); areas of salinity > 13 PSU are shown in grey

of the sill. This indicated the possibility of another over flow. A week later, when we were making another crossing, along the same line, we found a flow over the Sill in progress. The salinity in the Bornholm Deep rose to > 16.5 PSU and over the sill to > 14 PSU and remained high during the next 14 h, showing only a slight decrease in the Bornholm Deep and an increase in the Sill area. For lack of time, however, we were unable to monitor this event to its conclusion.

Crossing the sill towards the end of April 1996, we again recorded an over flow (Fig. 5). This time we detected the middle of the phenomenon rather than the beginning or the end of the splash. The salinity measured on the sill was about 13–13.5 PSU. What was interesting on this and other eastward transects along the axis of the Słupsk Furrow was the characteristic wave-like shape of the isotherms and isohalines. This could have been due to internal waves, mesoscale gyres or bodies of water travelling eastwards, each one originating from an individual splash as described above. It looked as if the less saline waters at the top of the wave or splash were travelling eastwards faster than the more saline waters close to the bottom.

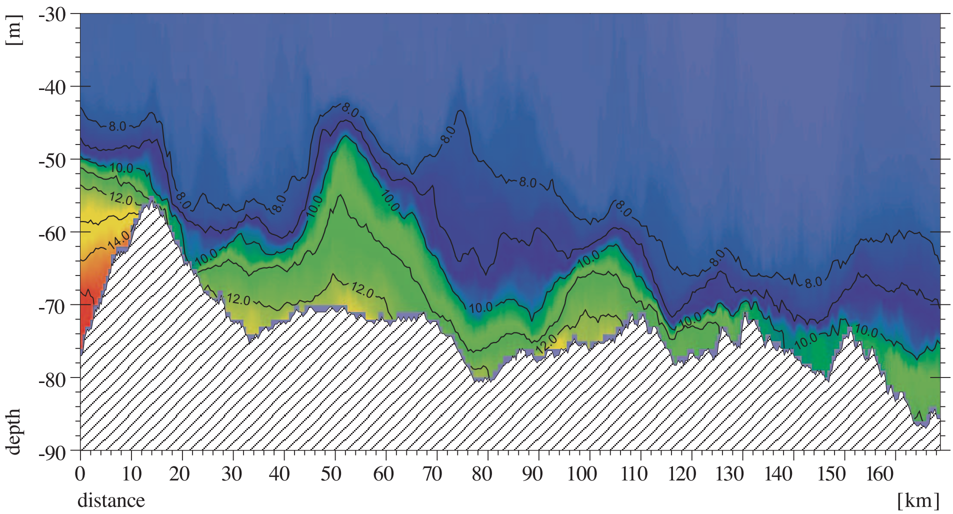


Fig. 5. Salinity [PSU] distribution on the transect along the Słupsk Furrow axis, 24 April 1996

The fact that during 5 random transects across the Słupsk Sill area we recorded 3 on-going flow events suggests that this is quite frequent and a short-lived phenomenon.

3.2. Internal waves, gyres and fronts

In a strongly stratified sea such as the Baltic Sea one can expect the formation of internal waves at layer boundaries marked by strong vertical density gradients. In our undulating CTD data we found many indications that this was happening – the wave-like displacement of the pycnocline, which could be an internal wave, a gyre or something else. Unfortunately, lack of current meter data makes any interpretation difficult.

Internal waves can be seen (Fig. 6) in the coastal zone where a wave approaches the shallow bottom and wave breaking is observed. In our case

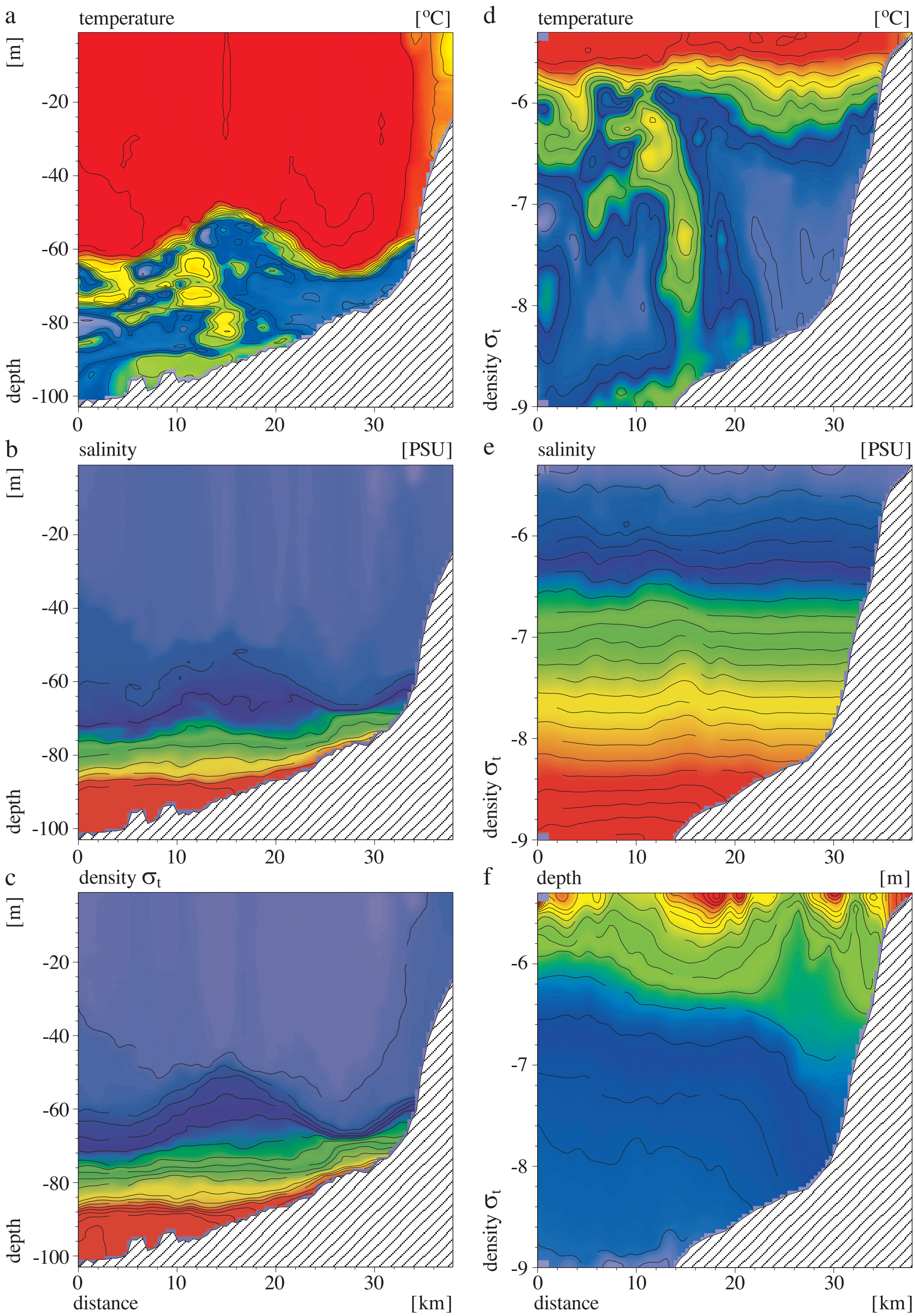


Fig. 6. Distributions of temperature [°C], salinity [PSU], density σ_t and depth [m] at the isobaric (a), (b), (c) and isopycnal (d), (e), (f) surfaces on transect No. 14, November 1995

the breaking up of the wave was observed at the bottom slope of the Hel peninsula. This internal wave was about 17 m high and 20 km long. Disturbance of the pycnocline causes diapycnal mixing, something that is very well demonstrated by the temperature distribution along isobaric and isopycnal transects (Fig. 6). The most intensive mixing took place in the layer between 6 and 9 kg m^{-3} isopycnals. The body of warmer water detected below the thermocline at a distance of 10–15 km could have been the result of the wave breaking up, or of Kelvin-Helmholtz instability.

Another example of internal waves is shown in Fig. 7. One of these formed at the western end of the Słupsk Furrow and later broke up on the sill slope, causing diapycnal mixing. The results of this process are clearly seen on the temperature transect, where a body of water warmer by about 2°C was pushed down into much colder surroundings.

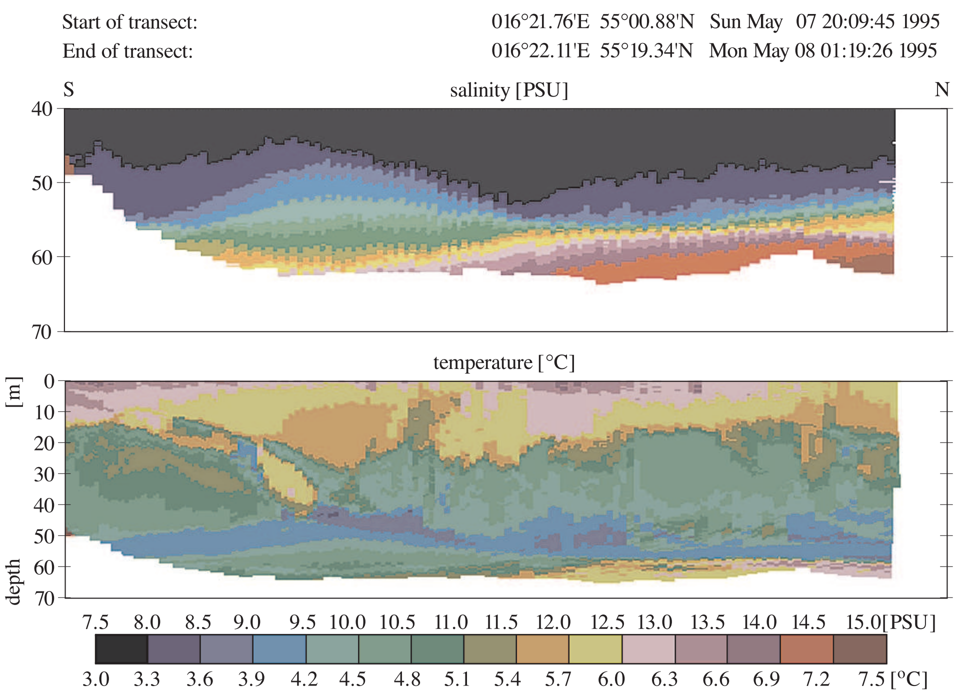


Fig. 7. Salinity [PSU] and temperature [°C] distributions on the transect along the Słupsk Furrow, 7–8 May 1995 (raw data from measurements made using an undulating CTD probe)

The results also suggest that in many cases disturbances in the pycnocline were due to cyclonic gyres moving along the axis of the Słupsk Furrow. Such gyres were recorded in November 1995 when 5 transects were made: three perpendicular and two parallel to the channel axis in its central part

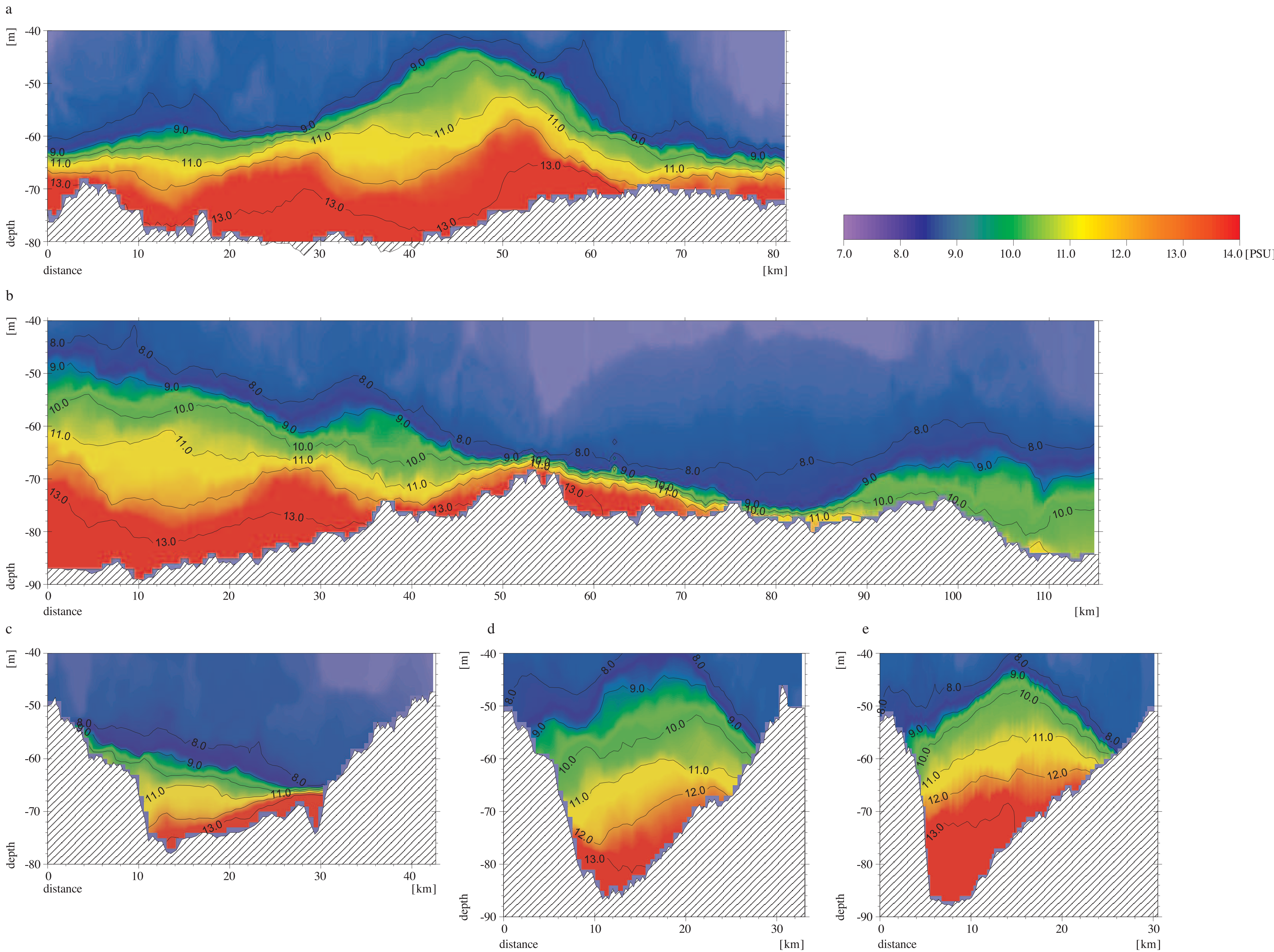


Fig. 8. Salinity [PSU] distributions: along the Słupsk Furrow axis, transect No. 8 (a), transect No. 12 (b); across the Słupsk Furrow, transect No. 9 (c), transect No.10 (d), transect No. 11 (e), November 1995

(Fig. 8). Transects 8, 9, 10, 11 and 12 show a nearly stationary cyclonic gyre *ca* 40 km in diameter. During 16 h the vertical temperature and salinity profiles and the position of the pycnocline at the same location changed very little (Fig. 9). On transects 10 and 11 eastward geostrophic transport prevails over such transport westwards by about 50 000 m^3 s^{-1}, the result being a mean eastward velocity estimated at 2.4 cm s^{-1}.

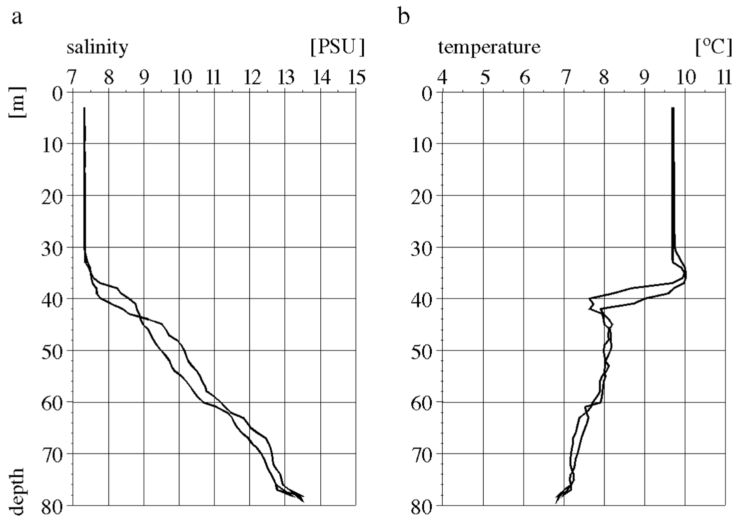


Fig. 9. Vertical profiles of salinity [PSU] (a) and temperature [°C] (b) at the same location (interval of 16 h), November 1995

Transect No. 9 cuts the gyre at its periphery, and the resulting geostrophic flow is directed towards the west with a mean velocity of 1.9 cm s^{-1}. It also demonstrates the common phenomenon of baroclinic layering: the near-bottom isopycnals are bent down towards the southern slope and run up the northern slope to shallower depths. This is indicative of flows in two directions: eastwards close to the bottom, and westwards above it. The flow in the 65 m-to-bottom layer towards the east has been calculated at 7793 m^3 s^{-1} in volume and *ca* 3.1 cm s^{-1} in velocity.

Data collected on transect No. 2 (Fig. 10) could be of assistance in understanding the mechanism of cyclonic gyre formation in the Słupsk Furrow. A large body of water with a salinity of > 12 PSU flowing over the sill enters the Słupsk Furrow and pushes local waters away to the east and upwards. The bottom topography may restrain the movement, causing the accumulation of large amounts of relatively saline and dense water, and the formation of a cyclonic circulation. It is interesting that the gyre develops at the pycnocline, entraining the waters above but not the denser waters

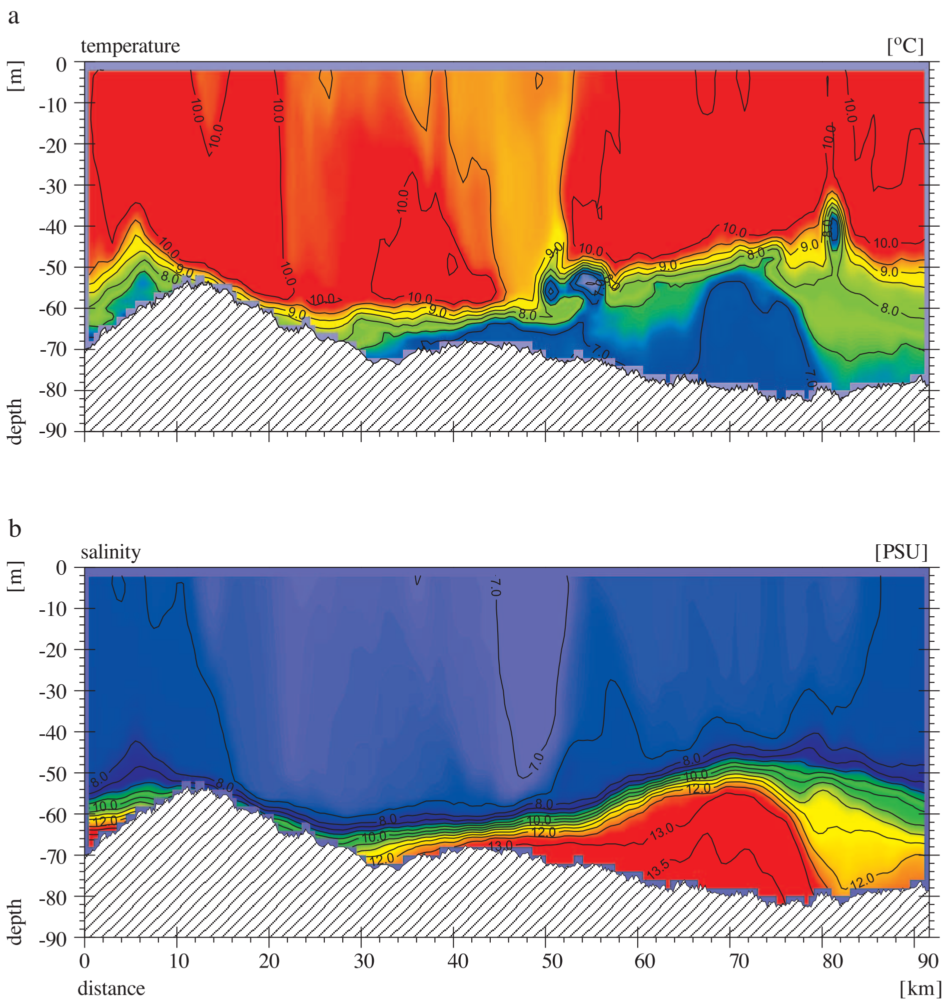


Fig. 10. Distribution of temperature [°C] (a) and salinity [PSU] (b) on transect No. 2, November 1995

from below. Moreover, it develops downwards only at the head of the front (Fig. 11). On comparing transects No. 8 and 2, separated by 4 days, it is obvious that we are very probably dealing with the same gyre but at different stages of its existence. The presence of small bodies of cold water in the outer part of the gyre recorded in both transects supports this conclusion.

Our data do not allow us to estimate exactly the lifetime of such a gyre; in our example it was longer than a few days. Over a period of 100 h, its vertical axis had shifted by about 8 km, which yields a velocity of *ca* 2.2 cm s^{-1}.

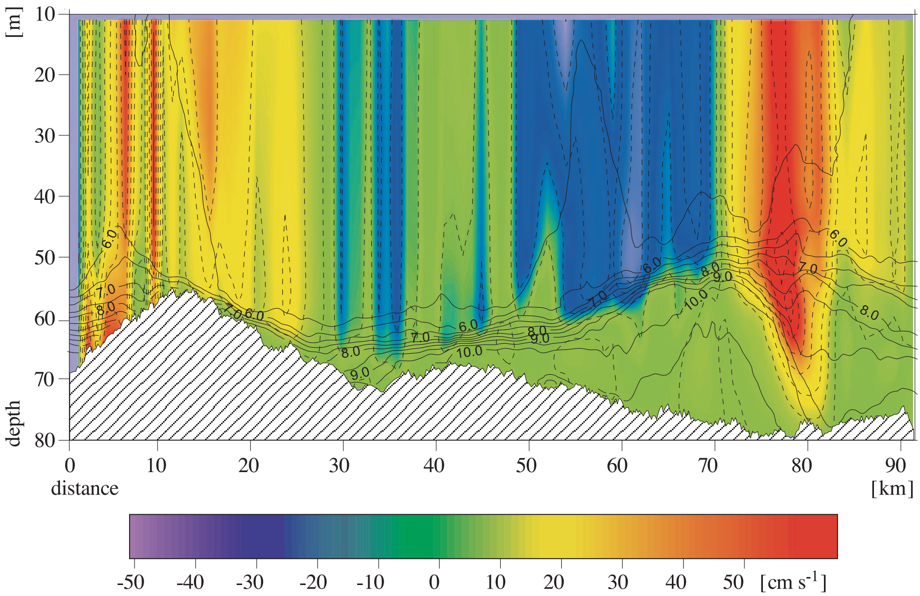


Fig. 11. Distribution of density σ_t (isopicus) and geostrophic current velocity [cm s^{-1}] (colour scale) on transect No. 2, November 1995

A similar circulation structure was recorded in May 1995 along transect 16. Gyres and eddies cause vertical mixing, which reaches maximum intensity at their edges. This transect (Fig. 12) shows that cold water from just above the halocline was raised to the surface at the edges of the eddy, while warmer water was depressed in its centre.

3.3. The internal structure of layers and their interdependence

Very often, when speaking about layering and layers in the Baltic Sea, we have in mind two or three more or less homogeneous bodies of water separated by a strong pycnocline caused by the halocline (the main pycnocline) or the thermocline (the seasonal pycnocline). However, our data show that this is true only as far as the salinity of the surface layer is concerned. In all other cases the layers are very far from homogeneous. Records made along the Słupsk Furrow in May and November 1995 could serve as good examples of the complicated internal structure of these layers, the deep layer in particular. In May (Fig. 12) the temperature of both layers undergoes considerable changes in both the vertical and horizontal plane. The existence down to 40–50 m of vertically homogeneous bodies of water alongside stratified ones indicates vertical mixing caused not only directly by wind stress but indirectly by mesoscale structures as well. This also creates big

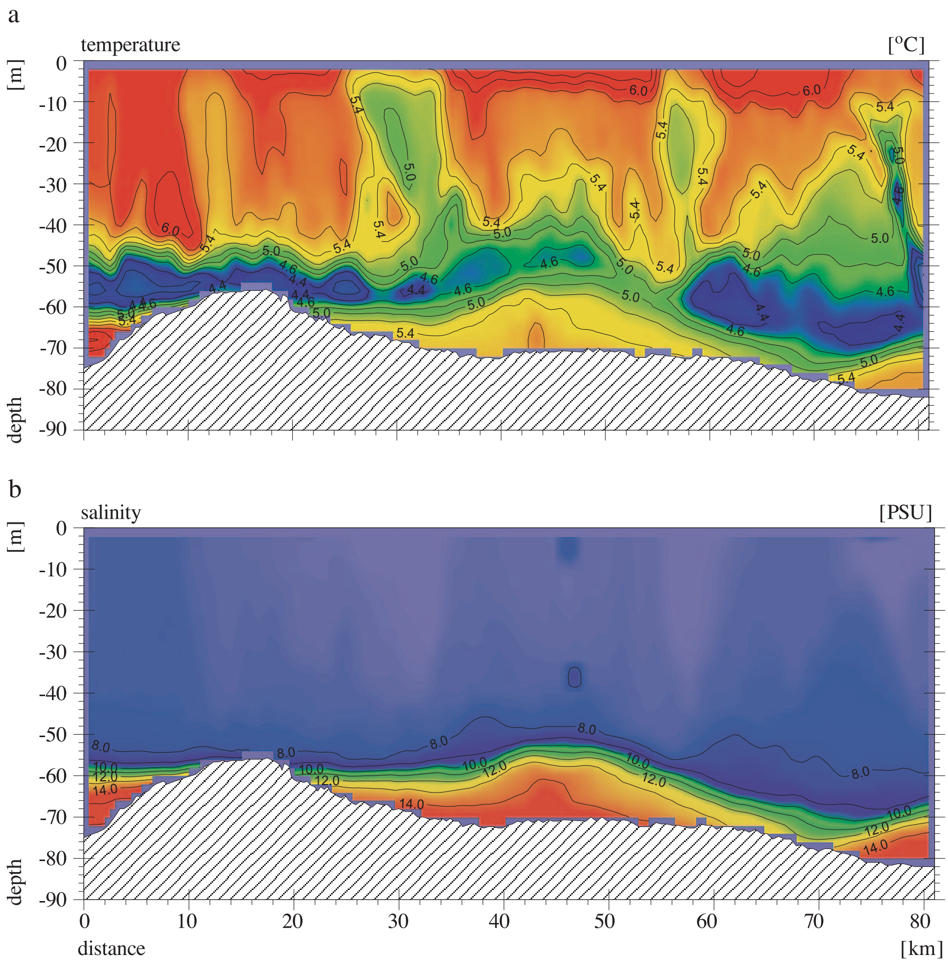


Fig. 12. Temperature [°C] (a) and salinity [PSU] (b) distributions on transect No. 16, 19 May 1995

horizontal temperature gradients in some places. Sublayers of deep waters were also examined and were found to behave differently.

The transect made in November (Fig. 13) additionally shows the intrusion of cold water, caused most probably by a cyclonic eddy and entrainment of colder waters at its periphery. The big horizontal temperature gradient and the internal layering are also clearly in evidence.

It looks as if the two or three layers of the Baltic Sea waters are closely related to one another: a disturbance in one layer is reflected sooner or later in another. There are many examples of the relationship between the depth of the halocline and salinity in the upper layer: the upward displacement of

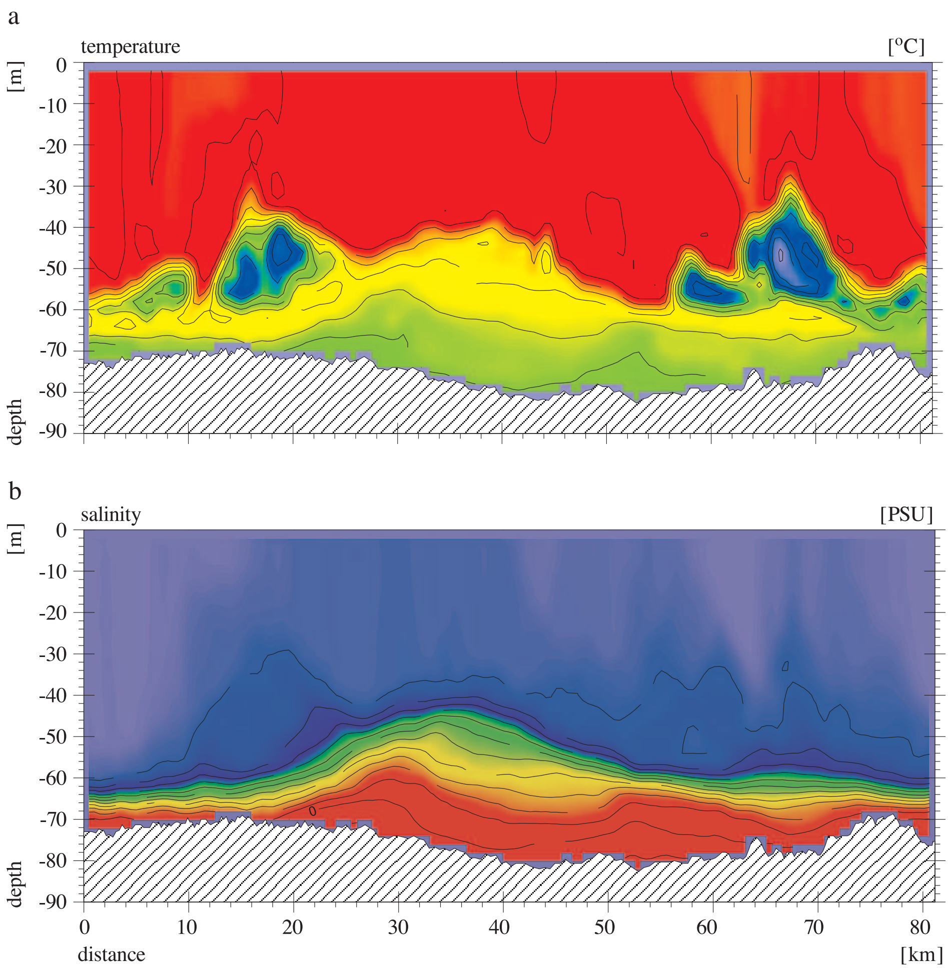


Fig. 13. Temperature [°C] (a) and salinity [PSU] (b) distributions on transect No. 8, 12 November 1995

the halocline is usually connected with higher salinity in the surface layer, and conversely, a deeper halocline goes hand in hand with a lower salinity above. This is in agreement with the results obtained by Stigebrandt (1983) from his models showing that the upward movement of the halocline has to be balanced by vertical movements and mixing.

Disturbances in the halocline layer and very often in the deep layer are caused by the reaction of the stratified channel to wind stress along the channel (Bennet, 1974; Krauss, 1979; Fennel, 1986). Ekman transport across the channel causes downwelling on the right-hand side and upwelling on the left, resulting in a baroclinic circulation in the channel. Such a situation is well illustrated by transect 9, done in November 1995 (Fig. 14).

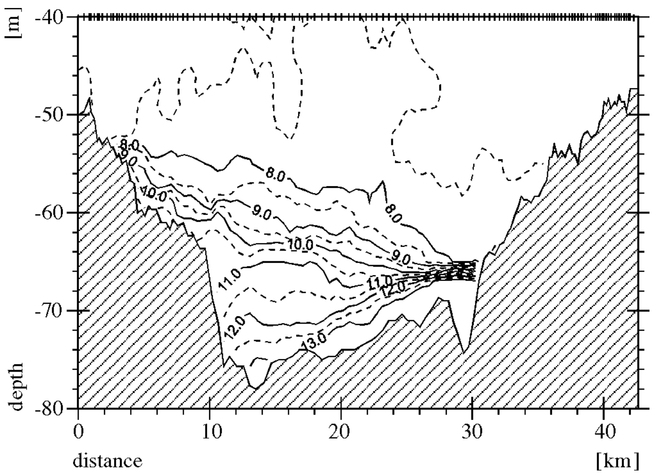


Fig. 14. Salinity [PSU] distribution on transect No. 9, November 1995

3.4. Convection

Thermohaline convection plays a major role in vertical mixing in the upper layer of the sea at high latitudes. This process has been extensively investigated and is well known. Some parameters, like the depth of the mixed layer, the quantity of heat transmitted from the sea to the atmosphere, or the ice thickness are readily calculated. But with our data we can track the progress of convection directly in the water column. We made a number of measurements during the convection period (autumn, winter, early spring). Fig. 15 shows temperature records in October, November, February and April on transects along the axis of the Słupsk Furrow across the Słupsk Sill and into the eastern part of the Bornholm Deep.

In October mixing was found to be in progress and to have reached a depth of 30–50 m. In November thermal convection was well in evidence along the whole transect but went deepest, down to 60 m, in its central part; moreover, the temperature of the mixed layer was lower than elsewhere in the Furrow. Distributions of the other parameters (salinity, density) suggest that in addition to convection, some other processes, *e.g.* eddies, may have caused such deep mixing and low temperatures. In February we 'caught' the situation when the temperature of the surface layer was falling below that of maximum density, 2.3–2.4°C in these waters, and stratification began, with the colder waters on top of the warmer ones. In the deeper part of the mixed layer, where the waters were still warmer, the process was going on very vigorously. In the eastern part of the Furrow we recorded the situation when a water particle could easily move up or down over a distance of *ca* 60 m.

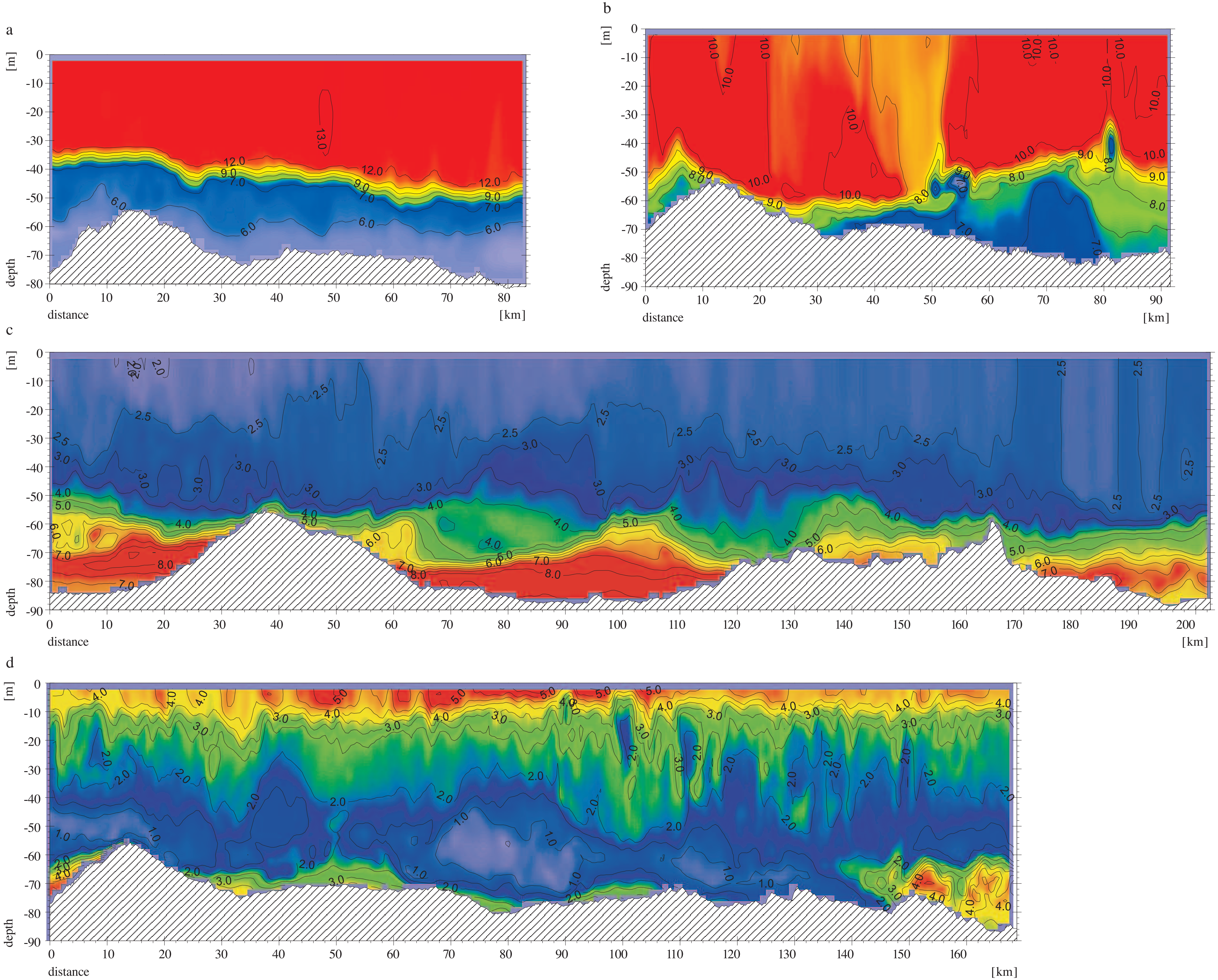


Fig. 15. Temperature [°C] distribution on the transects along the Słupsk Furrow, October (a), November (b), February (c) and April (d)

During March and April convection recommenced as a result of sea surface warming. Thus very intensive mixing occurred in the 10 to 40–70 m layer on the transect of 24 April. Very steep horizontal temperature gradients were observed (up to 2.5°C) over a range of a few hundred metres. It should be noted that the *ca* 10 m thick surface layer was also highly differentiated in the horizontal plane. This particular phenomenon was recorded not only in this single instance but on many other occasions as well.

4. Conclusions

- The inflows of more saline waters from the Bornholm Deep into the Słupsk Furrow are of a splash-like nature and are frequent, though short-lived (tens of hours).
- These inflowing bodies of water disturb the regular layer structure and water movement and, together with the bottom topography, determine the nature of the water circulation in the Słupsk Furrow.
- Internal waves, and especially gyres and eddies, are dominant features of the water transport through the channel.
- The dynamics of the Słupsk Furrow make it one of the principal areas of intensive mixing and transformation of deep inflowing waters on their way farther east and north.

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