

Physical and chemical variability of the Baltic Sea: a joint experiment in the Gotland Basin

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Abstract—An area of 25×30 nmi with a subarea of 20×20 nmi in the Baltic Sea Gotland Basin was surveyed for about one month by vertical CTD and fluorometric chlorophyll *a* casts, and by towed profiles with a chemical profiler (nutrients, CTD, O_2 , pH) and an undulating CTD. Autonomous current meter data were available for the same period.

Five CTD surveys with a 5-mile spacing showed the existence of synoptic eddies and several other perturbations. A first mode eddy (with all the isopycnals lifted within the halocline) had reduced salinities in the upper layer and chlorophyll concentrations were reduced by 2 to 3-fold. A second mode eddy (with the isopycnals lifted in the top of the halocline and lowered in the bottom layers) with a diameter of 20 km was under prolonged observation. Anticyclonic currents at 96-m depth were up to 25 cm s^{-1} . Along the section across the eddy at 80-m depth, the mean nitrate concentration dropped from about 7 to 8 to $5 \mu\text{mol dm}^{-3}$ while other chemical parameters lacked intense variations. An increased activity of the intrusive fine-structure was detected in the eddy center. The Baltic eddies are essentially non-linear, and transport water in their 'nuclei'. An internal front, separating waters with different *T,S* composition, was discovered in the upper layers.

The observations are discussed with respect to discovering long-term trends while monitoring the Baltic environment.

INTRODUCTION

THE control of the marine environment requires the establishment of a representative monitoring system. The present way of chemical monitoring of the Baltic Sea is based on the concept that the distribution of the chemical parameters is homogeneous within the horizontal scales of several tens of kilometers. Thus, it was assumed that assessment of the long-term trends in chemical parameters is possible by taking samples at a few monitoring stations with a considerable spacing (sometimes more than 100 km) at certain depths several times each year.

The intensive studies of the Baltic Sea dynamics carried out by the Department of the Baltic Sea, ITE,‡ during the last 5 years (AITSAM, 1981), among others, have proved that the scales of intense physical variability range from the synoptic scale (with R_d , the internal radius of deformation, about 10 km in the open Baltic) to the fine scale, as in the open ocean. Thereby, the synoptic scale motions (eddies, topographic waves, fronts etc.) can overmask

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the long-term and seasonal variations of physical parameters, and are often triggering smaller scale processes. One can also expect that the physical variability induces variability in the distribution of chemical substances in the marine environment.

In the years 1977 to 1980, a continuously registering system (chemical profiler) for the determination of chemical parameters was developed in the Department of Marine Chemistry, IfM,* to investigate the chemical variability in the Baltic with respect to the monitoring problems. On several test cruises of the chemical profiler on the R.V. *Poseidon*, GRASSHOFF and HANSEN (1980) observed small- and medium-scale variability of nutrients below and above the halocline in different areas of the Baltic Sea. They proposed that the measured nutrient variations might be caused by the dynamics of water masses.

The late Prof. Klaus Grasshoff initiated a cooperation between the Department of Marine Chemistry, IfM, Kiel and the Department of the Baltic Sea, ITE, Tallinn to study the role of water dynamics on the variability of nutrient concentrations in the open Baltic. Here we present the results of the first joint experiment with R.V. *Poseidon* and R.V. *Ayu-Dag* which took place in the Gotland Basin in June 1981.

Obviously, the sampling schemes of environmental monitoring should be an application of variability studies; however, our immediate interests were to describe different variability phenomena and to find out the interrelations between them via an interdisciplinary experiment.

THE EXPERIMENT

The study area, named Gotland-81, of the joint experiment in June 1981 was located in the Gotland Basin, ~50 km southeast from Gotland. The depths in the area range from 100 to 170 m (Fig. 1). To the west of the area lies an escarpment separating the relatively deep

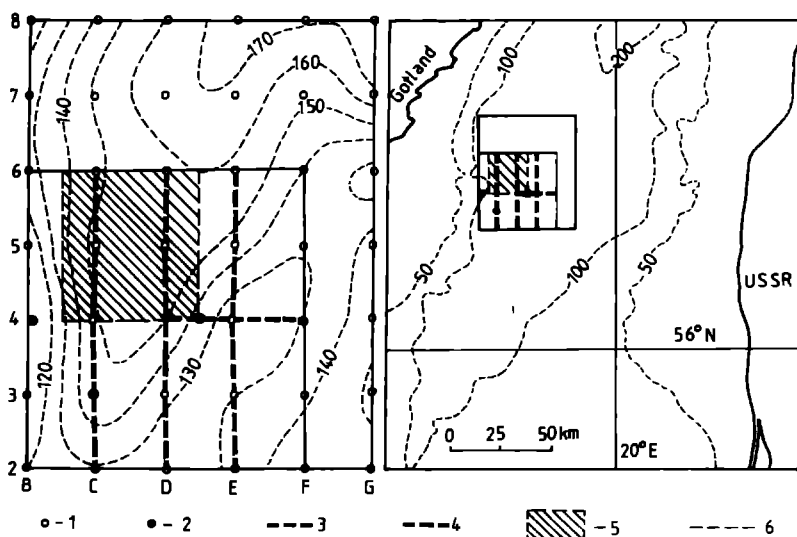


Fig. 1 Scheme of the experiment (left) and location of the study area (right). 1, Stations for the CTD-chlorophyll casts on the 5-mile grid; 2, current meter moorings; 3, a section of CTD casts with a 1-mile spacing; 4, sections with the chemical profiler on 80-m depth; 5, area for surveys with towed undulating CTD; 6, depth contours. The corner stations are: B2 ($\phi = 56^{\circ}31.0'N$; $\lambda = 18^{\circ}55.4'E$), G8 ($\phi = 57^{\circ}01.0'N$; $\lambda = 19^{\circ}40.7'E$)

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Gotland Basin from a shallower area (with depths <60 m) which extends to Gotland. The escarpment is characterized by large bottom slopes. An example of the thermohaline structure is shown in Fig. 2.

A scheme of the experiment is presented in Fig. 1. The area was covered with a rectangular north-south grid with a 5-mile spacing. The grid points (stations) of the standard grid were marked with 'chess' coordinates. The experiment was planned to be flexible: a pilot CTD survey in the area B2-G8 (B2, G8—the southwest and northeast corner stations) was to be made first; the following studies were to be carried out according to the results of the previous step(s).

The measurements made from R.V. *Ayu-Dag* were as follows:

Pilot CTD survey 23/1 (23 is the cruise number of R.V. *Ayu-Dag*) was performed from 3 to 5 June in the area B2-G8, amounting to 42 vertical casts with the spacing of 5 miles. As a result, the sub-area B2-F6 was selected for the continuation of the experiment.

Current meter moorings were installed at the grid points B4 (Sta. I), C3 (Sta. III), and half way between D4 and E4 (Sta. II) from 6 June to 4 July. The depth levels of the current and temperature measurements were: Sta. I—42, 75 and 90 m; Sta. II—43 and 96 m; Sta. III—21, 44, 79, 92 and 115 m.

Recurrent CTD surveys each consisting of 25 vertical casts with the spacing of 5 miles were performed in the area B2-F6: survey 23/2 from 15 to 16 June, 23/3 from 21 to 22 June, 23/4 from 26 to 27 June, 23/5 from 4 to 5 July.

A section with the towed CTD was taken on 16 June along the grid points C4-C7-D8.

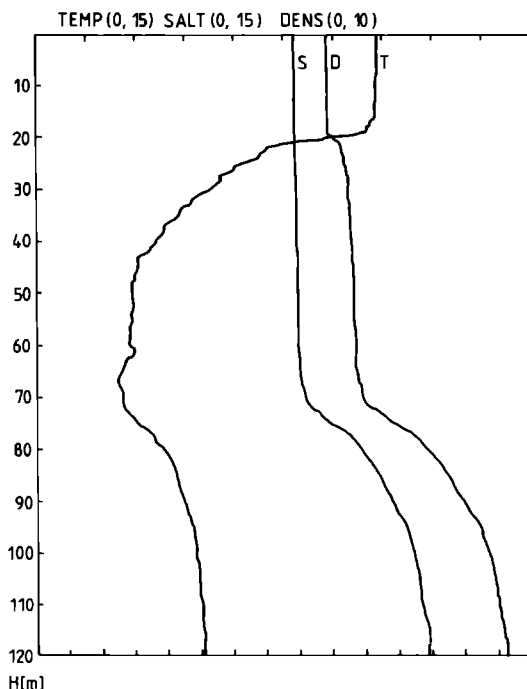


Fig. 2 Typical thermohaline structure with profiles of temperature (T), salinity (S), and density (D , σ_t) Survey 23/5, Sta D4, 5 July, 1981.

A section of 9 CTD casts was taken on 24 June along D4–F4 with a 1-mile spacing to study the structure of the eddy centered at Sta. E4 during survey 23/3.

Two consecutive surveys with the towed CTD were performed from 23 to 24 June in the area BC4–DE6 with a spacing of 2.5 miles between parallel legs. The legs were orientated in the north–south and east–west directions for the first and second survey, respectively. The location of the towed CTD area was chosen in the region of maximum surface temperature variability as registered along the ship track during survey 23/3.

The vertical CTD casts were performed with a Neil Brown Mark III CTD probe from the surface to about 10 m above the bottom. Surveys 23/1 and 23/2 included vertical chlorophyll *a* *in situ* profiles with a Variosens fluorometer mounted on the underwater CTD unit. In the towed CTD system constructed by R. Portsmouth, ITE, Tallinn the Neil Brown Mark III was used, too. The underwater unit of the system, towed at 6 to 7 kn, undulates across the upper 40-m layer with a horizontal resolution of ~ 400 m. At the moored stations Aanderaa RCM-4 current meters were used at the deeper levels while the VACM and Neil Brown ACM current meters were used at the upper levels.

From R.V. *Poseidon* two groups of investigations were made:

Three horizontal profiles (C2–C6, D2–D6, E2–E6) with the chemical profiling system, 20 miles each, scanned the depth level of 80 m from 22 to 23 June. The chemical measurements of these profiles were designed to support the physical studies of the halocline deformations.

Series of horizontal 5-mile sections in the vicinity of the current meter mooring DE4. Due to instrumental failures and a delay in the analysis the series is not considered here.

All chemical measurements were performed with the system 'chemical profiler' (GRASSHOFF and HANSEN, 1979). This system is the combination of an automated wet chemical continuous-flow analyzer with a towed 'fish' body. The 'fish' is provided with a set of sensors (CTD and O_2) and a pump. Through a special carrier cable (combined hose and electrical wires) water is pumped from the actual position of the fish into the ship's lab. An on-line computer controls the fish depths by means of an electro-hydraulic winch and collects the data from the sensor unit and the chemical analyzer. The fish is towed at ship speeds up to 6 kn at depths between the surface and 100 m on either constant depth sections or undulating under computer control.

The system allows a continuous registration of temperature, conductivity, pressure, oxygen partial pressure, pH, total CO_2 , and the concentrations of phosphate, silicate, nitrate, nitrite, and ammonia. A corrected and synchronized data set of all parameters is collected every 2 min by the computer. Fine-scale details within the 2-min interval may be read from a continuous analog record. The wet chemical analytical methods based on the Technicon continuous-flow system are described in detail by GRASSHOFF and HANSEN (1979).

RESULTS AND DISCUSSIONS

Synoptic variability related to the deep layers density

Several CTD surveys performed in different areas of the Baltic Sea stress the importance of the synoptic scale* density variations (AITSAM and ELKEN, 1982). The typical spatial

* As for the classification of the scales of the ocean variability (MONIN *et al.*, 1974; WOODS, 1980), we can define the *synoptic scale* with the internal Rossby radius of deformation R_d (~ 10 km in the open Baltic) as a horizontal measure of variability. Characteristic time scale for synoptic motions is longer than the inertial period (~ 14 h) according to the Baltic measurements: from a few days to a few weeks.

correlation radius of the isopycnal displacements within the halocline layers is 15 to 30 km. The r.m.s. displacement of the isopycnals is 3 to 8 m within $\sim 50 \times 50$ km areas, corresponding to a high level of the density of available potential energy (horizontally mean values per unit mass in layers 60 to 100 m range from 40 to 200 cm² s⁻²) due to the strong density stratification (N , the Väisälä frequency, is up to 4×10^{-2} s⁻¹). By means of daily series of hourly CTD casts at fixed stations we have established that in the halocline the variance due to high-frequency variations (within a day) is of an order of magnitude less than the variance due to synoptic scale variations, while in the thermocline, they both can be of the same magnitude. Consequently, a certain risk of aliasing error is involved when horizontally interpolating isopycnal depths and/or isotherms within the thermocline from non-averaged data of spatially sparse measurements.

CTD surveys with a spacing of 5 miles between casts guarantee adequate contouring of the synoptic scale density perturbations in the halocline using optimal interpolation (GANDIN, 1965). On the background of several 'chaotic' deformations of the halocline, it is possible to distinguish two types of synoptic eddies (ELKEN, 1984): (a) first mode* eddies with all the isopycnals lifted in the eddy center within the halocline; (b) second mode* eddies with the isopycnals lifted in the top of the halocline and lowered in the bottom layers.

A common feature of both types is a nearly circular pattern of the water density contours which is relatively stable during the drift of the eddies. Characteristic diameters of the first and second mode eddies are 40 to 60 and 20 km, respectively. Eddies are frequently observed on satellite images of the central and western Baltic (HORSTMANN, 1983).

Five CTD surveys (23/1 to 5) made during this study provided three-dimensional pictures of the synoptic scale density distribution. Vertical integration of the density profiles gives the relative dynamic topography (RDT) which is the streamfunction of the relative currents in the geostrophic approximation. In Fig. 3 maps of the RDT are presented, with the RDT given by deviations of the dynamic height of the 50-dbar level relative to the 80-dbar level. This pressure interval comprises the density variations due to the deformations of the top layers of the halocline.

Two prominent eddies became evident from the density data. A first mode eddy was observed around Sta. G7 of survey 23/1 (Fig. 3). In this eddy the cyclonic currents of the 50-dbar level relative to the 80-dbar level reached 10 to 15 cm s⁻¹. Unfortunately, the following survey program excluded this eddy area. The maximum elevation of the isopycnal surfaces at Sta. G7 is shown in Fig. 4 (see sections B7–G7 and G2–G8 of survey 23/1). Temperature and salinity analysis demonstrated a uniform distribution of these parameters at the isopycnal surfaces within the halocline, i.e. no indication of water with remarkably different T, S composition was found in the halocline. At the same time the first mode eddy revealed a considerable decrease of the upper 50-m layer salinity around Sta. G7 (Fig. 5a). However, the decrease in salinity (0.2×10^{-3}) and the corresponding lowering of the isopycnals were dynamically unimportant: the relative currents due to this salinity anomaly as estimated from the geostrophic relations were more than 10 times weaker than the relative currents due to the halocline deformation. The decrease of the upper-layer salinity was also followed by a

* That is, the vertical density structure of the eddies corresponds to the *first* and *second mode* of the Rossby waves above sloping bottom (bottom slope reduces the near-bottom velocities in comparison with flat bottom). However, the above-mentioned eddies are neither Rossby waves (because the time scale is strikingly different), nor topographic waves (because the vertical density structure is strikingly different), although the drift of the eddies corresponds to the phase speed of topographic waves.

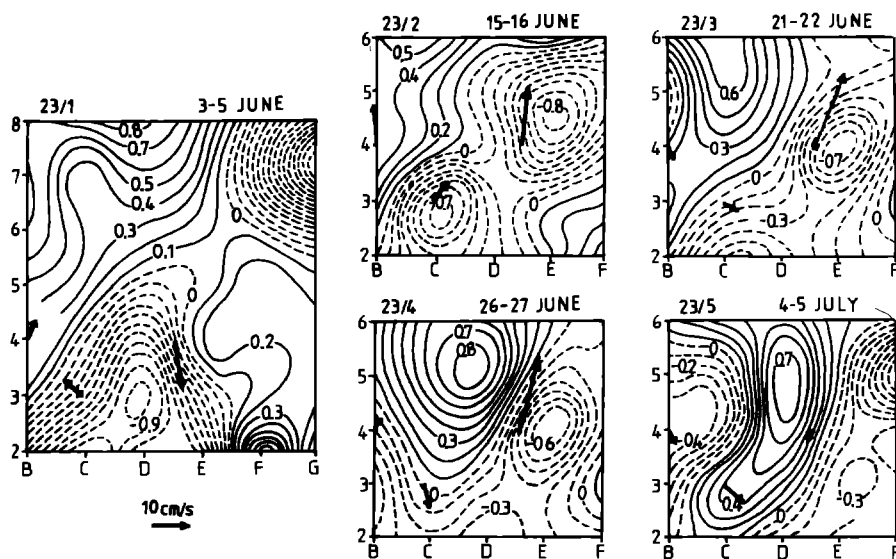


Fig. 3. Maps of the relative dynamic topography (deviations of the dynamic height of the 50-dbar level relative to the 80-dbar level) on surveys 23/1 to 5. The contour interval is 0.1 dyn cm. Vectors of the daily mean currents are given for the depths of 75 m at Sta. I, for 96 m at Sta. II, and for 92 m at Sta. III.

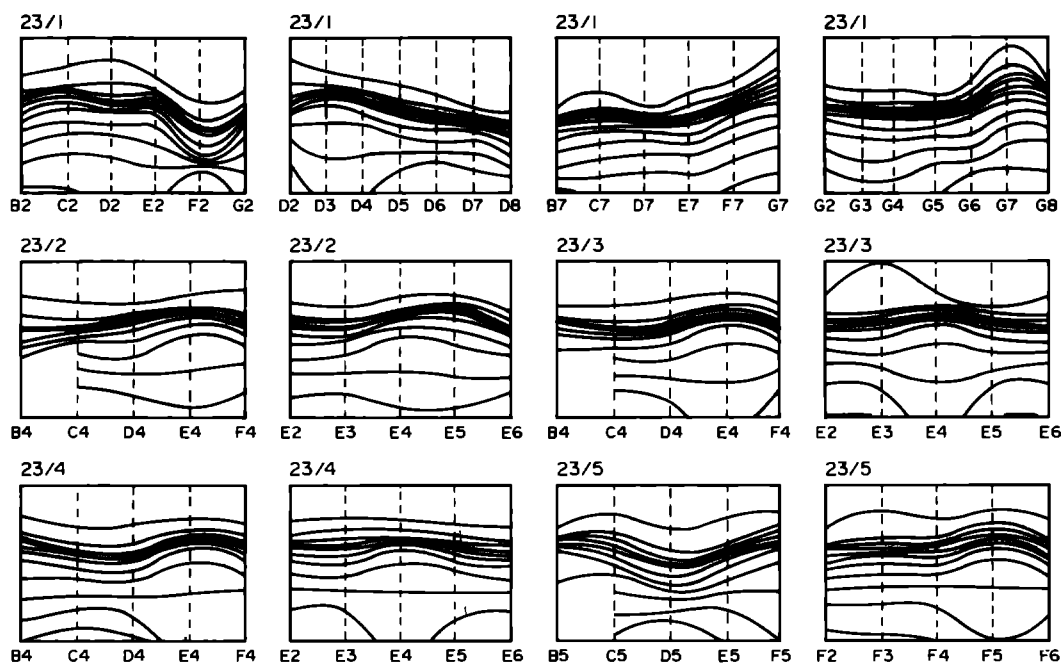


Fig. 4. Isopycnal displacements in the deeper layers (pressure range from 50 to 100 dbar) on surveys 23/1 to 5. The density contour interval is 0.25 σ_t units. The profiling stations are indicated below each section.

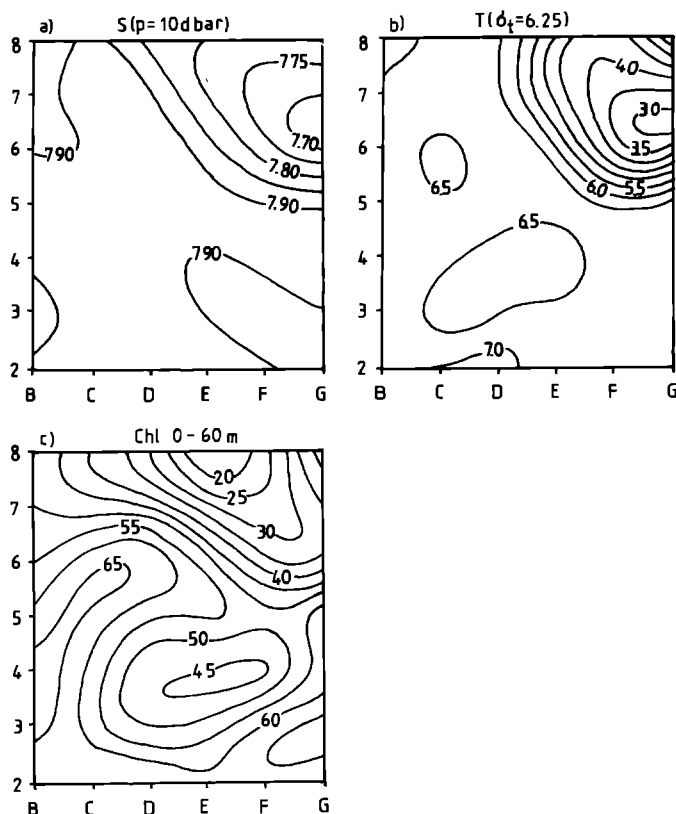


Fig. 5 Maps of salinity (a) at the isobaric surface 10 dbar, temperature (b) at the isopycnal surface $\sigma_t = 6.25$, and chlorophyll *a* (c) integrated over 0 to 60 dbar (mg m^{-2}) on survey 23/1

striking decrease ($\sim 4^\circ\text{C}$) of temperature at the isopycnal surfaces (Fig. 5b). Normally the r.m.s. variations of temperature on isopycnals do not exceed 0.1°C .

Evidence for the fact that first mode eddies are characterized by anomalous salinity values in the upper layers above the halocline has also been given by our previous data. For example, increased salinities were observed on surveys 18/1 and 18/2 in 1980 (AITSAM and ELKEN, 1982). Trapping of anomalous water by migrating eddies indicates the non-wave, advective character of the eddies.

The evolution of a second mode eddy was under close observation, especially during the second part of the experiment. A second mode perturbation was first observed around Stas C2, D2, D3 of survey 23/1 (Figs 3 and 4). Eleven days later, survey 23/2 revealed a system of two second mode eddies. Due to the stormy weather, the time interval between the surveys was too long to follow the evolution of the density field. From survey 23/2 to 23/3 the system of second mode eddies had moved ~ 10 km to the south (Fig. 3) within 6 days. Survey 23/3 was focused to the eddy with its center at Sta. E4. Characteristic isopycnal displacements of the second mode eddy are clearly shown in Fig. 4 (see sections B4–F4 and E2–E6 of surveys 23/3 and 23/4). Within 5 days, from survey 23/3 to 23/4, this eddy stayed at the same place. Between surveys 23/3 and 23/4, we made CTD casts along a section across the eddy with a step of 1 mile. The results show that the RDT and isopycnal displacements (Fig. 6) varied

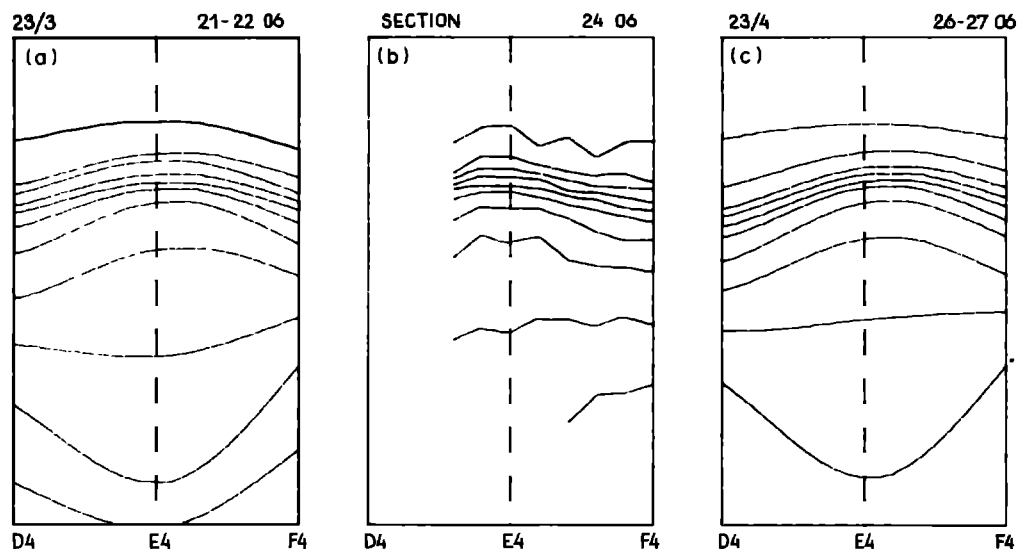


Fig. 6. Isopycnal depths (beginning from $\sigma_t = 6.75$ with $0.25 \sigma_t$ interval) along the 10-mile section D4–F4 across the eddy center E4. The pressure ($\approx$ depth) range is from 50 to 110 dbar. (a, c) Interpolated data from surveys 23/3 and 23/4; (b) section of casts with 1-mile interval.

smoothly between the grid stations of the surveys, and that the interpolation gave nearly the same picture as did the measurements with 1-mile resolution. The current measurements, as well as the chemical structure and the physical fine-structure of this eddy are considered in the next sections. In 8 days between surveys 23/4 and 23/5 the eddy had moved ~ 15 km from Sta. E4 to F5 along the local isobaths with the shallower water to the right (to the ‘topographic west’). A tongue-like positive RDT anomaly travelled during surveys 23/1 to 5 to the south along line C which corresponds also to the ‘topographic west’ (see the map of bottom topography in Fig. 1).

An interesting deformation of the isopycnals was observed at Sta. F2 of survey 23/1 (Fig. 4), where the vertical structure was opposite to the second mode eddies. This perturbation was not observed in the following surveys; however, 16 days later, a similar perturbation with a diameter of 6 to 7 km was observed between Stas C3 and C4 on the horizontal section with the chemical profiler at the 80-m level (Fig. 8).

Current measurements

It has been proved reasonable to divide the variability of currents spectrally into the high-frequency (short-period) and low-frequency (long-period) bands with the characteristic periods less and more than a day, respectively. In most of the current measurements in the Baltic Sea, the inertial oscillations with a period of about 14 h were prevalent in the short-period variability. In the low-frequency range, drift currents of the upper layers, directly induced by the wind, are superimposed by energetic synoptic-scale current fluctuations which are variable in space. Spatial structure of the synoptic-scale currents is not well known due to the inevitably small number of current meters available. Measurements show that the current direction may be opposite in a distance of a few tens of kilometers (e.g., the BOSEX stations, KRAUSS, 1981). However, near the ‘coastlines’ of the halocline (depth contours of 60

to 70 m), the topographic waves with the amplitude trapped both vertically and horizontally by the strongly sloping bottom were observed (TALPSEPP, 1982).

Here we report only the data of the deep currents obtained by the Aanderaa RCM-4 instruments, installed at three mooring stations. The sampling interval was 15 min. Unfortunately, 10% of the data recorded on the 75-m level of Sta. I and 14% of the data of 96 m at Sta. II were faulty and were replaced using interpolations between neighbouring correct values.

Vectors of daily (24 h) mean currents are presented in Fig. 7 to demonstrate the synoptic variability of currents. Synchronous measurements started at noon of 6 June. The currents at the levels of 75 and 90 m at Sta. I were similar. A wave-like variation of the currents with a period of 4 to 5 days can be noticed during the first half of the experiment. The currents were maximal after a storm, between 13 and 18 June, when the amplitude exceeded 20 and 15 cm s^{-1} at the levels of 75 and 90 m, respectively. After 18 June, the daily mean current speed did not exceed 10 cm s^{-1} . The wind speed was generally $<10 \text{ m s}^{-1}$ during this period.

When designing the experiment we expected to observe bottom intensified topographic waves at Sta. I because the bottom topography and the mean stratification were consistent with previous topographic wave observations in the Baltic (TALPSEPP, 1982). However, no evidence of these waves was found.

In the bottom layer of Sta. III, the daily mean currents rarely exceeded 10 cm s^{-1} . The direction of currents at the level of 115 m at Sta. III was irregular. Due to the small values of the current speed, the relative errors were significant.

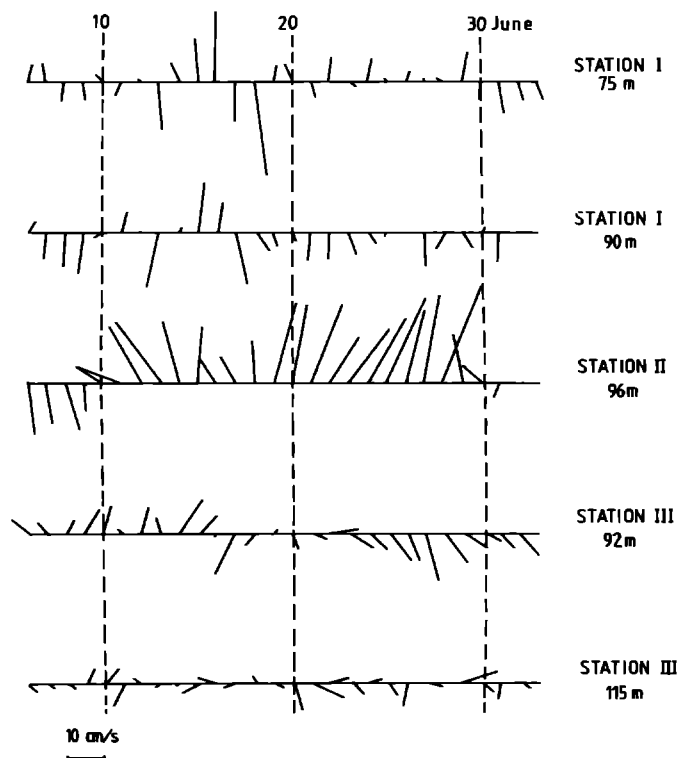


Fig. 7. Vectors of daily mean currents.

In relation to other measurements, the most interesting currents recorded appeared at the level of 96 m at Sta. II. Strong northward currents up to 25 cm s^{-1} dominated, except for the beginning and the end of the experiment. Such intense mean currents are uncommon in the open Baltic, all the more in its deep layers. Interpretation of these currents can be done on the basis of the observed density field. On surveys 23/3 and 23/4, a second mode eddy was observed around grid point E4. By the eigenfunction analysis (see footnote on p. 295) (ELKEN, 1984), it has been hypothesized that in the second mode eddies the anticyclonic currents are maximal on depths of 80 to 90 m, but in top layers above the halocline, the 'eddy' currents are weak. Station II was located between the grid points D4 and E4, just in the area where the maximum horizontal density gradients of the eddy were observed. Hence, the direction of the observed currents was in good agreement with the density data and the concept of eddy structure, but the observed current speed exceeded 2-fold the predicted speed. Unfortunately, it was impossible to test the consistency of the geostrophic thermal wind relation with the data as current data were available from one level only. A comparison of the maps of the dynamic topography with the daily mean currents in the deeper layers is displayed in Fig. 3.

In the following interpretation of the chemical data, the concept of the first and second mode eddies is important. Both the density and the current data suggest that second mode eddies have a 'ring' of maximum currents in the layer below the top of the halocline surrounding the 'nucleus' of the eddy which consists of the water advected by the eddy from the place of its formation.

Measurements with the chemical profiling system

While conventional chemical sampling provides a set of spatially sparse data, the chemical profiling system enables measurement with a fine horizontal resolution, and has proved to be a valuable tool in studying the chemical variability in relation to physical processes. In the previous experiment in 1980 (GRASSHOFF and HANSEN, 1980), a close relationship between variations in chemical and physical parameters was established. On an 80-mile horizontal profile at the level of 30-m depth, especially temperature, pH, nitrate, and silicate seemed to have regularities: even fine-structures in the temperature profile were repeated or mirrored by the chemical parameters. Comparison of the variations of temperature and chemical parameters with their vertical stratification suggests that the chemical variability at fixed levels is mainly induced by the kinematic effect of internal waves, i.e., all the isotherms and the isopleths of chemical parameters are displaced up or down together with the corresponding isopycnals without any irreversible change in the environment.

The data collected on three horizontal profiles (Fig. 1) at the level of 80 m revealed two significant synoptic scale and several smaller scale variations of the chemical and physical parameters. Profiles of selected parameters are presented in Figs 8 and 9. These profiles are contaminated by small (~ 1 m) undulations of the towed body around the mean depth of 80 m. We found it reasonable not to correct the data by extrapolating onto the constant depth as the vertical gradients were variable in space. Thus, some small-scale variations were caused by the 'kinematic effect' of the towed body.

Between the grid points C3 and C4 we observed a considerable decrease of density as well as of temperature, salinity, and the chemical parameters except pH. A similar density variation was observed at Sta. F2 of survey 23/1 (Fig. 4). This 'multiparameter' anomaly had a diameter of 6 to 7 km and remained undetected in surveys 23/3 and 23/4 performed on the 5-mile grid approximately at the same time. Since, in the halocline, both the physical and

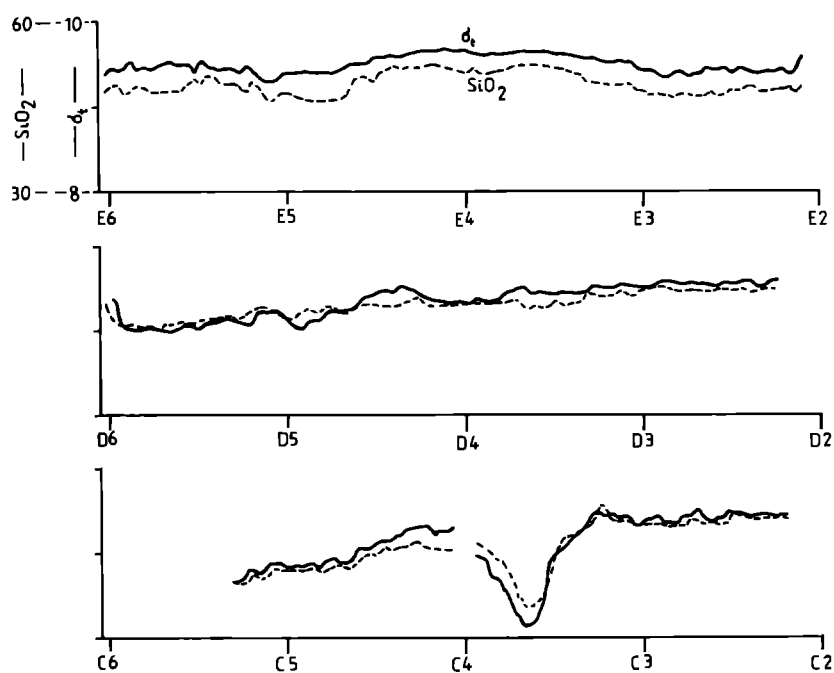


Fig. 8. Horizontal profiles of density (solid line, 8 to 10 σ_t units) and silicate concentration (dashed line, 30 to 60 $\mu\text{mol dm}^{-3}$) measured with the chemical profiler on 80-m depth. 'Chess' coordinates are given as horizontal pointers

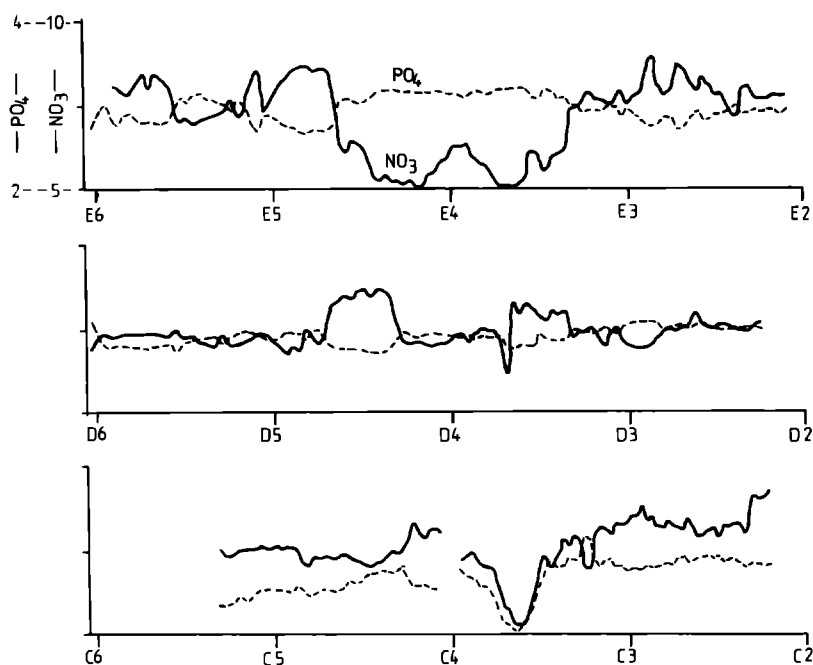


Fig. 9. Horizontal profiles of the concentration of nitrate (solid line, 5 to 10 $\mu\text{mol dm}^{-3}$) and phosphate (dashed line, 2 to 4 $\mu\text{mol dm}^{-3}$) on 80-m depth.

chemical parameters generally increase with depth, the observed variation may be interpreted as a kinematic deformation (~ 10 m lowering) of the horizontal layer system. This may be regarded as a 'normal' type of chemical variability in the Baltic as most of our traces show this close relationship between the chemical and the density fields.

A 'strange' anomaly was found between grid points E3 and E5. This variation appeared in only one of the chemical parameters registered—nitrate—while no significant variation of the other chemical and physical parameters was observed on the 80-m depth. The mean nitrate concentration of about $7\text{--}8\ \mu\text{mol dm}^{-3}$ dropped to $5\ \mu\text{mol dm}^{-3}$ between E3 and E5 (Fig. 9). The oxygen concentrations above $1\ \text{cm}^3\ \text{dm}^{-3}$ and the absence of remarkable changes in other nitrogen components (nitrite and ammonia) exclude the effects of denitrification processes. Traces of the vertical distribution of chemical parameters which were performed on the starts of the legs showed no evidence of a waterbody with the corresponding nutrient composition at any depth. A possible explanation may be given on the basis of the density and current data. Recall the second mode eddy found around Sta. E4 at the same time (Figs 3, 4, and 6) with the anticyclonic currents up to $25\ \text{cm s}^{-1}$ at the level of 96 m (Fig. 7). In this eddy, the density remained nearly undisturbed at the level of 80 m but the vertical density gradient was reduced in the nucleus of the eddy around the 80-m depth (Fig. 6). Because of the reduced density gradient, the chemical profiles in the eddy, except for nitrate, lack the small-scale variations due to the towed body undulations. As far as eddies can transport water in their nuclei, we propose that an isolated waterbody of this particular nitrate content originated from somewhere outside the investigated area.

Smaller scale variations of the chemical parameters shown in Figs 8 and 9 have no obvious explanation because of a complex relationship with the density. Variations of nitrate and phosphate in many segments are of opposite sign, while the corresponding density variations may be both up and down. We guess that the 'reverse' variations of nitrate and phosphate are a result of chemical and physical patchiness and not due to a kinematic effect of reverse stratification, since we did not observe a decrease in nitrate values with depth in these layers.

Fine-structure in the synoptic eddies

The energy cascade model (WOODS, 1980) proposes that the fine-structure is an important link between the synoptic-scale processes, internal waves, and turbulence. Earlier, observations have been made of the vertical mixing signatures in centers of ocean eddies (FEDOROV *et al.*, 1981) as well as of increased internal wave amplitudes in the eddy periphery (DYKMAN *et al.*, 1980). Since the Ozmidov scale of turbulence is of the order of 10 cm in the deep layers of the Baltic, the detection of turbulent fluctuations is beyond the possibilities of the Neil Brown Mark III CTD.

The main processes generating the fine-structure in the deep layers of the Baltic Sea are the intrusions and the kinematic effect of the internal wave field. As a qualitative characteristic, we can introduce the ratio $\bar{\xi}_T/\bar{\xi}_S$, where $\bar{\xi}_T$ and $\bar{\xi}_S$ are the r.m.s. vertical displacements of isotherms and isohalines, respectively. If $\bar{\xi}_T/\bar{\xi}_S = 1$, the temperature and salinity fluctuations of the particular scales are generated by the kinematic effect of internal waves; in the case of $\bar{\xi}_T/\bar{\xi}_S \neq 1$, a certain part of the structure is formed by intrusion-like processes.

Intrusive and wave-induced parts of the fine-structure (scales from 0.5 to 7.5 m) in relation to the synoptic eddies were studied by the vertical CTD casts performed in surveys 23/1 to 5. The mean profiles for the determination of $\bar{\xi}_T$ and $\bar{\xi}_S$ were calculated using a 7.5-m cosine filter. *A posteriori* justification of this procedure was given by a nearly linear pattern of the

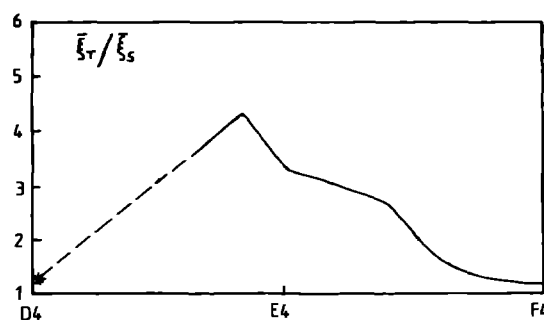


Fig. 10. Distribution of $\bar{\xi}_T / \bar{\xi}_S$ (from $\sigma_t = 8$ to 95-m depth) along section D4–F4 with a 1-mile step (solid line) across the eddy (E4). Dashed line connects the last cast of the section and the survey cast of D4

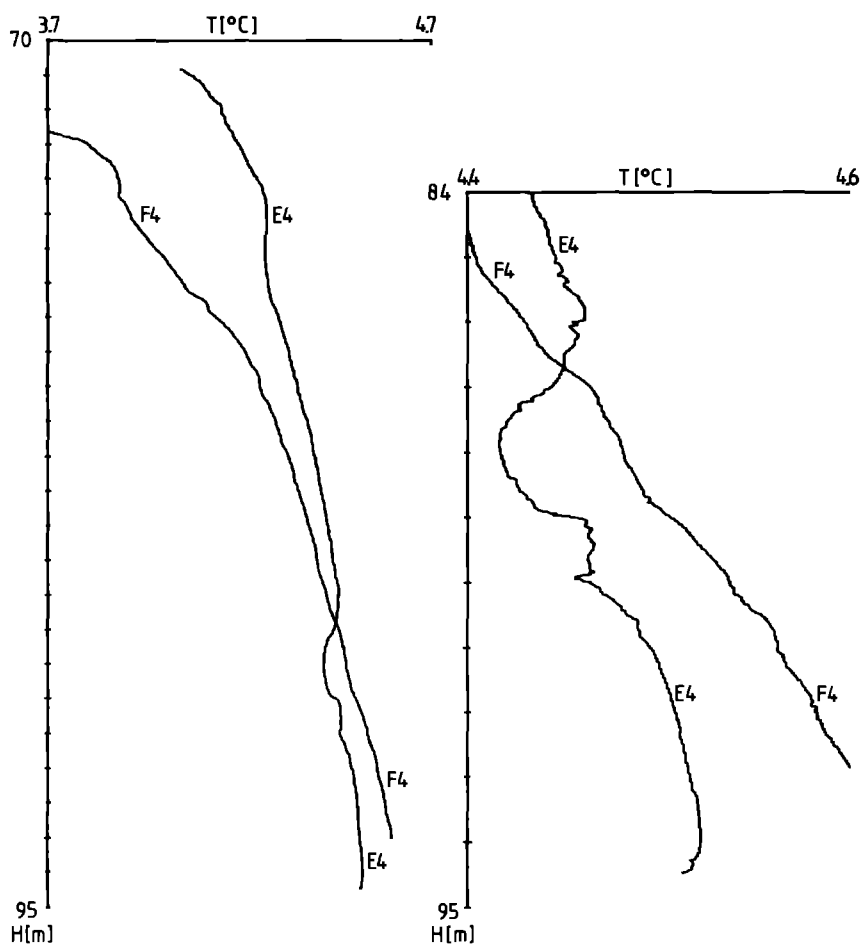


Fig. 11. Profiles of temperature at Stas E4 and F4 on the section across the eddy (a) Plots over the whole halocline; (b) expanded plots over 84 to 95-m depth range

calculated mean profiles in the deep layer below the top of the halocline. In relation to the synoptic-scale variability, the highest ξ_T/ξ_S values were observed in the near-bottom layers where convergence had occurred near the bottom and the isopycnals were like domes resting on the bottom. A special section (D4–F4) with a 1-mile step was made on 24 June across the eddy at Sta. E4 (see the density structure of the eddy in Fig. 6). The distribution of ξ_T/ξ_S (calculated from the density level $\sigma_t = 8$ down to 95-m depth) along the section through the eddy is presented in Fig. 10. It is evident that in the nucleus of the developed, second mode eddy (it had been existing more than a week), the intrusive part of the fine-structure was increased. Since the formation of second mode eddies must be accompanied by convergent currents in the halocline, carrying different waters nearly isopycnally (the vertical mixing is weak) to the nucleus of the eddy and increasing the layer thicknesses between the isopycnals, the effect shown in Fig. 10 is not surprising.

Intrusion in the eddy is visualized in Fig. 11 where the temperature profiles of the deep layers at Stas E4 (eddy center) and F4 (eddy periphery) of the section are presented. At Sta. E4, a $\sim 0.1^\circ\text{C}$ temperature inversion (related to the intrusion) with a thickness of a few meters can be observed in the interval from 86 to 90 m, while at Sta. F4 the profiles do not display intrusive layers.

*Correlations between chlorophyll *a* distribution and the physical fields*

Chlorophyll *a* as an index of phytoplankton biomass reflects both the origin of the water mass and the local growth–decay processes. The dominant horizontal scales of chlorophyll variability, inferred from the spatial correlation functions, are generally between 10 and 20 km (KAHRU *et al.*, 1982) with the coarse-scale (~ 10 km) variability dominating over the fine-scale (~ 100 m) variability by an order of magnitude (KAHRU *et al.*, 1981).

On surveys 23/1 and 23/2, vertical profiles of chlorophyll *a* fluorescence were obtained by a Variosens *in situ* fluorometer attached to the CTD probe. As there were too few extracted chlorophyll measurements (kindly put at our disposal by K. Kremling, IfM, Kiel) to permit accurate conversion of fluorescence to concentration, the reported chlorophyll values may be slightly biased.

Several significant correlations between the horizontal chlorophyll distribution and the synoptic-scale thermohaline characteristics were observed. On survey 23/1, the center of the first mode eddy with fresh and cold water in the upper layer near Sta. G7 (Figs 5a and b) was prominent for its 2 to 3-fold reduced chlorophyll content (Fig. 5c). Hence, a good relationship with salinity, i.e., higher chlorophyll corresponding to saltier water and *vice versa*, was established on survey 23/1 (Fig. 12). The same tendency was observed on survey 23/2, although the survey area excluded the nucleus of the dominant first mode eddy. Correlations with the upper-layer temperatures were also statistically significant on both surveys but lower.

We may hypothesize that the freshwater anomaly was reduced in its nutrient content and, hence, limited the phytoplankton growth. This way, the chlorophyll concentration appears as an additional tracer together with salinity, giving evidence of advection of anomalous water by the eddy. In contrast with the 1980 surveys when the effects of the halocline and thermocline depths were dominant (KAHRU, 1982), here the correlations between the chlorophyll contents and the depths of isopycnals and isotherms were insignificant. A possible reason for that might be that due to much deeper mean halocline depth, the effects of the vertical nutrient flux (by vertical mixing, etc.) were unimportant compared to horizontal advection of water masses.

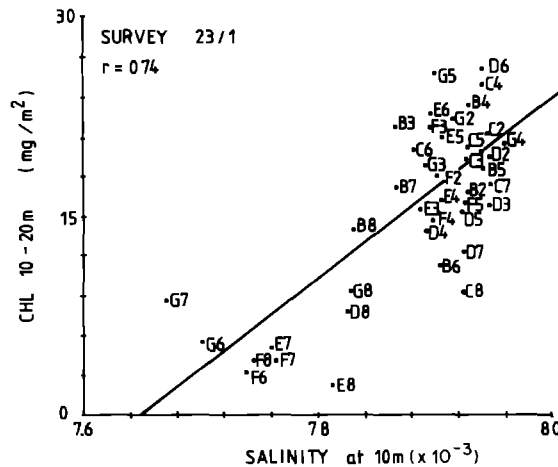


Fig. 12. Relation between chlorophyll *a* in the 10 to 20-m layer and the salinity at 10 m on survey 23/1. The two clusters correspond to different water masses. The correlation coefficient (*r*) is indicated.

Thermohaline structure of the upper layer

The upper layer of the Baltic Sea as well as of the ocean is considered 'quasihomogeneous' in several theoretical studies. However, measurements with a fine horizontal and vertical resolution (AITSAM and PAVELSON, 1982) show that the upper layer consists of patches with different *T,S*-composition, and of thermohaline fronts separating larger scale water masses. The patches have usually sharp boundaries and complicated structure, and range from a few

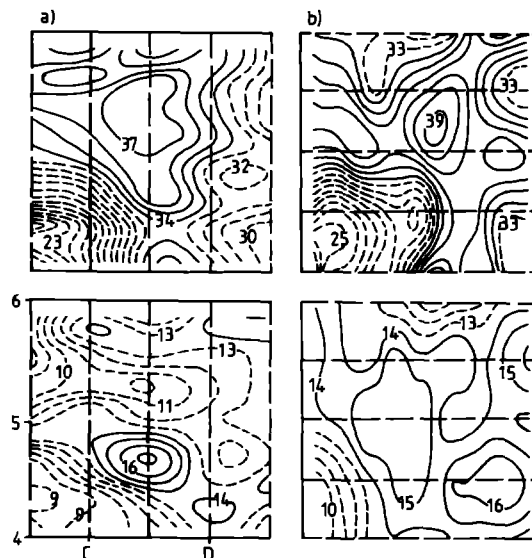


Fig. 13 Contour maps of the depth of isothermal surfaces 5°C (upper panels) and 9°C (lower panels) on the first (a) and second (b) survey with the undulating CTD. The contour interval is 1 m. Towing routes are indicated by straight dashed lines

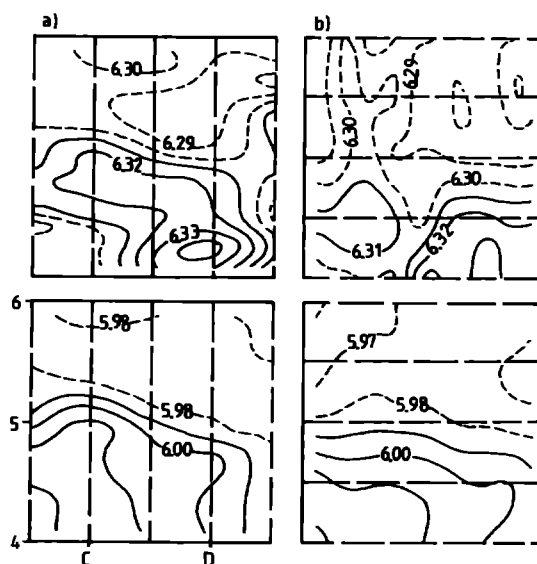


Fig. 14. Contour maps of density at the isothermal surfaces 5°C (upper panels) and 9°C (lower panels) on the first (a) and second (b) survey with the undulating CTD. The contour interval is 0.01 σ_t units.

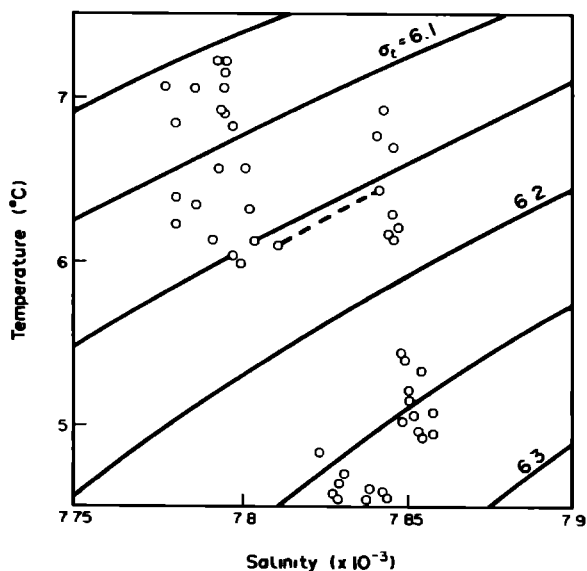


Fig. 15. Horizontal T, S -diagram on 20-m depth for the second leg (C4–C6) of the first survey with the undulating CTD. Neighbouring points at the boundary of the water masses are connected with a dashed line.

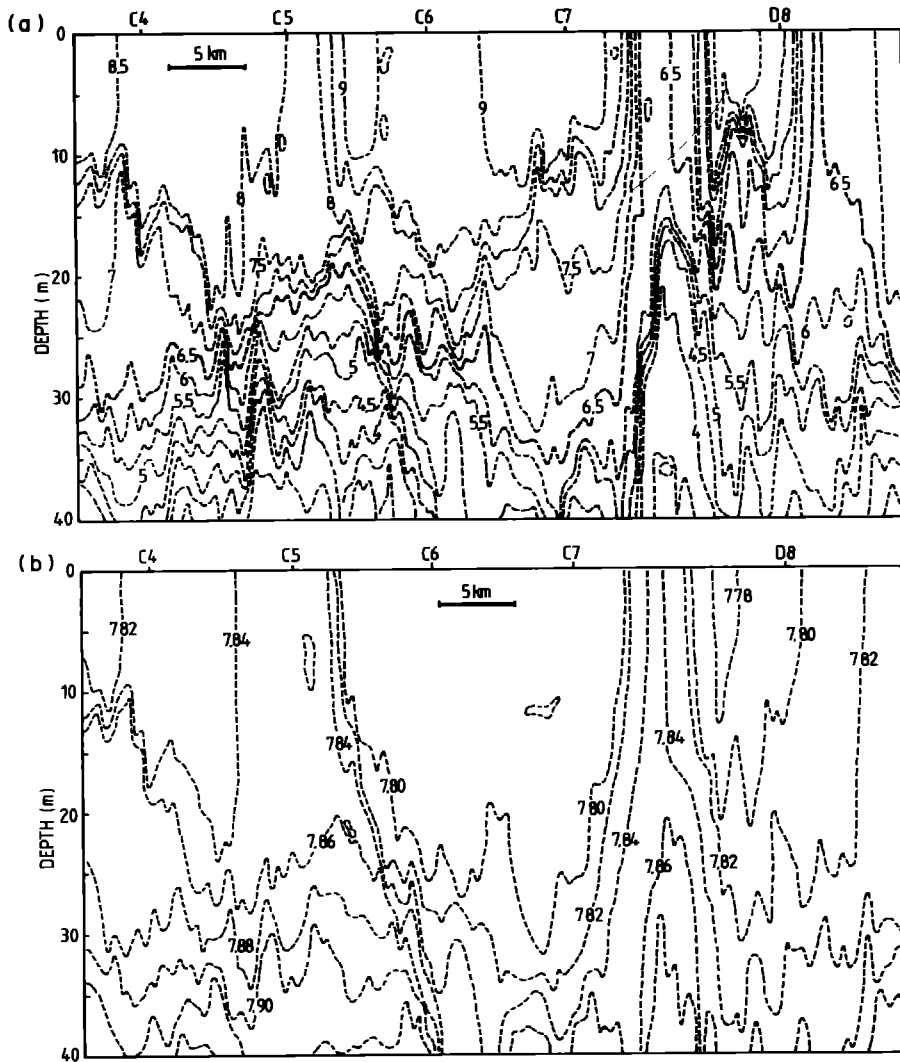


Fig. 16. Temperature (a) and salinity (b) at the section on 16 June with the undulating CTD.

to a few tens of kilometers. Some of the observed patches are not compensated by density, i.e., temperature and salinity anomalies are accompanied by isopycnal displacements. Elevations and lowerings of isopycnals are induced mainly by short-period internal and inertial waves but, in some cases, low-frequency displacements of isopycnals, compensated by vertical geostrophic current shears, prevail.

Two surveys performed with the undulating CTD in the area BC4–DE6 (hatched area of Fig. 1) provided maps of the structure of the upper 40-m layer. In the southwestern part of the area the isotherms and isopycnals were lifted up—from 3 to 4 m in the subsurface layer (Fig. 13, lower panels) to 15 m in the lower part of the thermocline (Fig. 13, upper panels). This thermocline elevation remained nearly at the same place for both of the surveys performed from 23 to 24 June. The relatively stationary structure of this thermocline elevation

gives some proof to its long time scale, at least of a few days. Unfortunately, the area of our undulating CTD surveys is too small to map the whole region of the isothermal and isopycnal elevation.

The maps of density on the isothermal surfaces of 9 and 5°C (this representation removes the kinematic effect of internal waves) clearly distinguish between two water masses with different temperature and salinity (Fig. 14a and b). Since the spline interpolation was used to construct the maps, the east–west boundary between the ‘northern’ and ‘southern’ water masses has been oversmoothed. The real width of this front did not exceed 1 km. On the horizontal T,S -representation (Fig. 15) we recognize that there is no change in the density while crossing the front from one water mass to the other.

An inspection of the towed section on 16 June (Fig. 16) suggests that the same system of water masses was present on the area a week ago. Actually, a thermohaline front was observed 3 km to the north of Sta. C5 as shown in Fig. 16b. Both of the fronts (on 16 and 23 to 24 June) were density compensated and revealed similar T,S -characteristics. It is very likely that we observed fragments of the same frontal system. Hence the lifetime of density-compensated thermohaline fronts in the open Baltic is comparable to the lifetime of density fronts which is more than a week (AITSAM *et al.*, 1982).

In the background of large-scale water masses, some smaller scale thermohaline anomalies, not compensated in density, were detected. An anomaly where the colder and saltier water had been lifted up from the deeper layers was found between Stas C7 and D8 of the towed section of 16 June (Fig. 16). The mean ascent of the isotherms and isohalines was about 20 m, while the shape of the anomaly looked like a cone with a diameter varying from 3 km in the subsurface layer to 7 km on the 40-m depth level. At the sea surface the anomaly was reflected in the differences of 2.5°C and 0.05×10^{-3} of temperature and salinity, respectively.

CONCLUSIONS AND DISCUSSION OF THE MONITORING SCHEMES

The joint experiment proved the existence of considerable physical and chemical variability in the area of 25×30 nmi located in the Gotland Basin. In this study, most attention was focused on the synoptic eddies and their influence on the distributions of chemical parameters, chlorophyll *a*, and the intensity of the physical fine-structure. As in previous experiments, first and second mode eddies were detected from the hydrographic data, and this was supported by direct current measurements. A first mode eddy represented a freshwater anomaly with reduced chlorophyll content in the upper 60-m layer. Chemical measurements demonstrated a drop in the nitrate concentration in the deep nucleus of a second mode eddy. These facts can be interpreted by advection of isolated waterbodies by the eddies, i.e., the eddy nuclei contain anomalous water advected by the eddies from the places of their formation. Measurements with fine horizontal resolution confirmed that the Baltic upper layer ‘homogeneous’ water consists of a number of patches with different T,S -composition, and of thermohaline fronts, separating larger scale water masses. A relatively sharp internal front was observed. As an example of the interrelation between larger and smaller scale processes, we found an increased intrusive fine-structure activity in the second mode eddy. According to the observations, the eddies, fronts, low-frequency waves, and the fine-structure, are all linked in the Baltic as in the ocean. We hope that our observations encourage future theoretical studies.

Besides detailed descriptions of variability, an application of our study is related to the problem of distinguishing between the signal and noise in the long-term estimations of natural and man-made trends in the Baltic environment. Optimal sampling frequency and spacing of the monitoring stations can be easily determined, if spatio-temporal statistics of the measured parameters is well known. Unfortunately, there are no such estimates over a broad range of spectra.

MATTHAUS (1979) reported that between the years of 1900 to 1980, the general increase in the Baltic salinity resulted in a lift of the average halocline by 5 to 6 m in the Gotland Deep. The r.m.s. deviations of the depths of the isohalines of 9 and 10×10^{-3} for the period of 1877 to 1978 were 7 and 8 m, respectively. Our measurements in limited areas gave the r.m.s. isopycnal displacements within the halocline from 3 to 8 m, depending on the 'eddy' activity. Thus, single measurements, with the synoptic-scale variability not filtered out, fail to give adequate information on the year-to-year trends. For the estimation of long-term trends in the physical parameters we propose to have a set of monitoring polygons with a proper spacing (~5 to 10 km) between the stations in each polygon, instead of spatially sparse monitoring stations. At the present stage of technology, it is possible to furnish the monitoring ships with automated CTD probes and possibly with other on-line measurement devices to meet the requirements at reasonable expenses.

Since devices for automated chemical and biological measurements are not yet widely available, routine time- and labour-consuming chemical sampling might be done at a few stations only. We have found it reasonable to take a limited number of chemical monitoring samples from levels of constant density, instead of constant depths. This treatment removes the kinematic deformations of stratification which are due to internal wave-like motions and do not represent irreversible changes in the environment. In the Baltic halocline layers, salinity (which mainly determines the density) can also be the 'natural coordinate' (SHAFFER, 1979). Measurements with the chemical profiler suggest that patchiness of nutrients at the isopycnal surfaces is of considerably smaller amplitudes than the kinematic deformations of the nutrient stratification as observed along constant depths (except for the fronts and nuclei of strong eddies). The physical background provided by the CTD measurements, covering the area around the chemical station, enables classification of the chemical samples, i.e., if the temperature distribution at isopycnals lacks striking anomalies (which is the 'normal' situation), we may hope that a single sample is representative not only of the water in the sampling bottle but also of the isopycnal surface around the station.

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