Some results of research on internal waves in the Stolpe Sill area*

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Abstract

Current, temperature and salinity data obtained on the western slope of the Stolpe Sill in October 1998 were analysed to identify the processes responsible for the transport of dense, near-bottom water from the Bornholm Deep into the Stolpe Channel. Westward transport in the deep layer was opposed to the wind direction. The longitudinal current component was considerably smaller than the latitudinal one. Long waves (with periods $T > 10\,\mathrm{h}$) and short-period oscillations ($T < 2\,\mathrm{h}$) were recorded in the form of wave trains. The rotary-component spectral method revealed a dominant internal wave with a period close to the local inertial period ($T = 14.6\,\mathrm{h}$). High-frequency current fluctuations (time scales 2–30 min) were regarded as a quasi-horizontal turbulence caused by interaction between the long waves and the complicated bottom topography.

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1. Introduction

The transport of well-oxygenated, saline waters originating in the North Sea is of vital importance for the renewal of the deep layers of the Baltic Sea. The bottom topography of the Baltic, which consists of a number of deep basins linked by a system of channels, is one of the main factors influencing this flow of dense water. After passing through the Danish Straits, inflowing water carried by the near-bottom current enters the Arkona Basin where it is subject to strong mixing and dilution (Stigebrandt 1987). Its further transport through the Bornholm Channel into the Bornholm Basin has been investigated by direct measurement and modelling by many authors (Pedersen 1977, Lundberg 1983, Gidhagen & Hakansson 1992), who studied the significance of bottom friction, rotation and entrainment for the deep-water flow.

Exchange of inflowing saline water between Bornholm and the downstream Gdańsk and Gotland Basins occurs through the Stolpe Channel, which is separated from the upstream basin by a shallow sill. In the model by Kouts & Omstedt (1993), the depth of the Stolpe Sill was assumed to be the factor controlling the further transport of deep, dense water. The numerical simulations of Krauss & Brügge (1991) showed that northerly and easterly winds can increase downstream near-bottom flow in the Stolpe Channel. Jakobsen (1996) analysed deep flow in this area as the sum of different wind-induced and baroclinic currents and found the greatest correlation between the northern wind stress and discharge. At the same time the system was much influenced by seiches and internal waves.

During long periods of stagnation between major inflows, the deep water in the Bornholm Basin is not dense enough to lift the halocline over the threshold depth, thereby sustaining the direct advection of inflowing water into the Stolpe Channel. For this reason it is mainly water from intermediate layers that is expected to pass over the sill and move on to neighbouring basins. Detailed observations have revealed the existence of mechanisms responsible for forcing dense, saline water from the layer beneath the sill depth to overflow into the channel (Piechura *et al.* 1997). Analysis of high-resolution CTD transects performed across the sill has given rise to the hypothesis that long-period waves with amplitudes of several metres surge towards the sill and force the deep water over the sill. Nevertheless, the splash-like nature of this overflow, manifested by short-lived events when dense water rises above the sill and later falls back, suggests that the phenomenon is rather more complicated than was at first thought.

The generation and breaking of internal waves in the vicinity of a sill has been described by Stigebrandt (1976) for a sill fjord with a strong pycnocline. We suspect that similar events could be occurring at the Stolpe Sill.

The Institute of Oceanology PAS has been carrying out extensive investigations in the Stolpe Sill area during the last 5 years. Measurements made during transects across the sill have been repeated at short intervals and wave-like disturbances have often been found in the vertical distributions of temperature and salinity in the deep layers. But these results were deemed insufficient to explain the observed phenomena in detail. Time series of hydrological parameters would be required in addition to spatial measurement data in order to achieve some understanding of the motions dominating the deep layers in the neighbourhood of the sill.

The aim of this paper is to analyse the wave processes in the vicinity of the Stolpe Sill, and to evaluate and describe the part played by diverse temporal-spatial components in the dynamics and intermittence of overflow forcing.

2. Measurements and methods

During the research cruise of r/v 'Oceania' in October 1998, a series of high-resolution CTD transects covering part of the Bornholm Basin and the Stolpe Channel was carried out, together with mooring measurements on the western slope of the Stolpe Sill (Fig. 1). A Valeport 308 autonomous current meter was used to record the temperature, salinity, pressure and horizontal components of the current. The device was located at a depth of 62 m, 4 m above the bottom and a 94-hour data series was recorded. The rope connecting the underwater buoy with the surface float was correspondingly longer than the distance between the underwater unit and the sea surface, and was equipped with a number of floats. As a result, the underwater buoy was only minimally disturbed. The pressure sensor recorded the sum of the hydrostatic and atmospheric pressures.

The measurement period was characterised by strong atmospheric disturbances caused by the passing of a deep low-pressure system. Prevailing wind directions varied between W and SW with speeds ranging from 5 to 20 $\mathrm{m\,s^{-1}}$. During the second part of the measurement period there were two stormy days with wind strengths of over 9°B. The time series obtained was about 4 days (93.6 hours) long, the time step Δt was 1 min. Maximum buoyancy frequency in the vicinity of the observation point was about 0.5 $\mathrm{min^{-1}}$ and this value coincided with the Nyquist frequency $1/2\Delta t$ (Bendat & Piersol 1986, Emery & Thomson 1997). This data thus described the whole internal wave frequency band from short waves with a period of about 2 minutes to quasi-inertial internal waves, the period of which at the point of observation was estimated at 14.6 hours. In this case, the

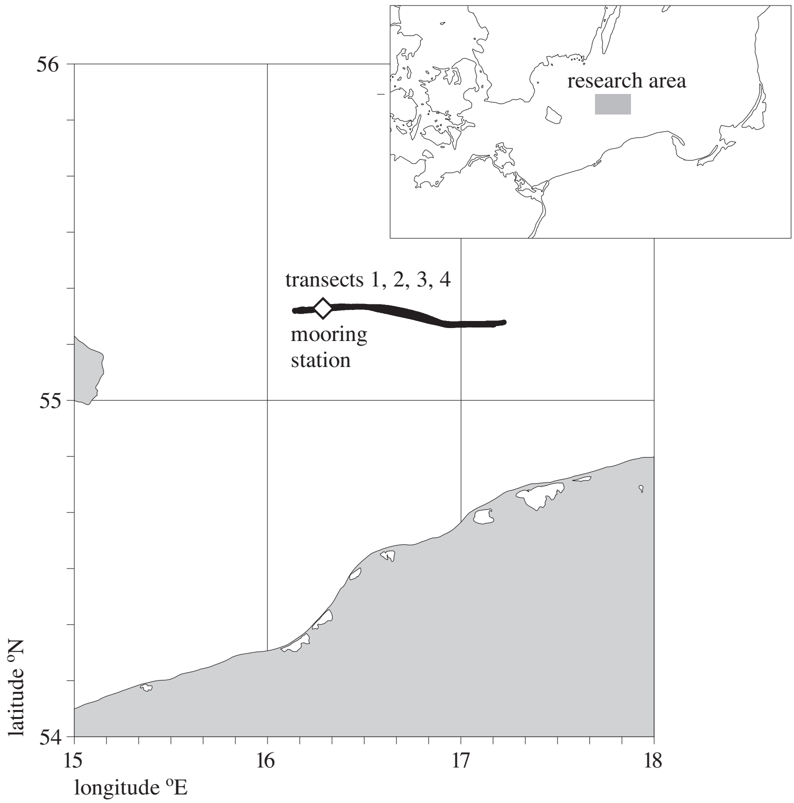

Fig. 1. Location of the high resolution CTD transects and mooring station in the Stolpe Sill area in October 1998

statistical reliability of the long-period spectral components will be low and, for example, the mean statistical regimes of inertial waves cannot be obtained. Only the variability of the observed parameters for the time interval examined will be considered.

3. Results

During the four consecutive high-resolution CTD transects across the Stolpe Sill (Fig. 2) a backward flow of deep water was recorded on the western slope. Initially water of salinity slightly higher than 10 PSU flowed over the sill and a lower salinity of about 9.0–9.2 PSU was recorded during the next two days. At the same time the halocline on the slope was pushed down by about 10 m with respect to the mean value. During the first stage of measurements, the isohalines in the deep layer were parallel to the bottom slope, suggesting that backward flow along the slope had just commenced. The later structures of the isolines then became more horizontal and a weak

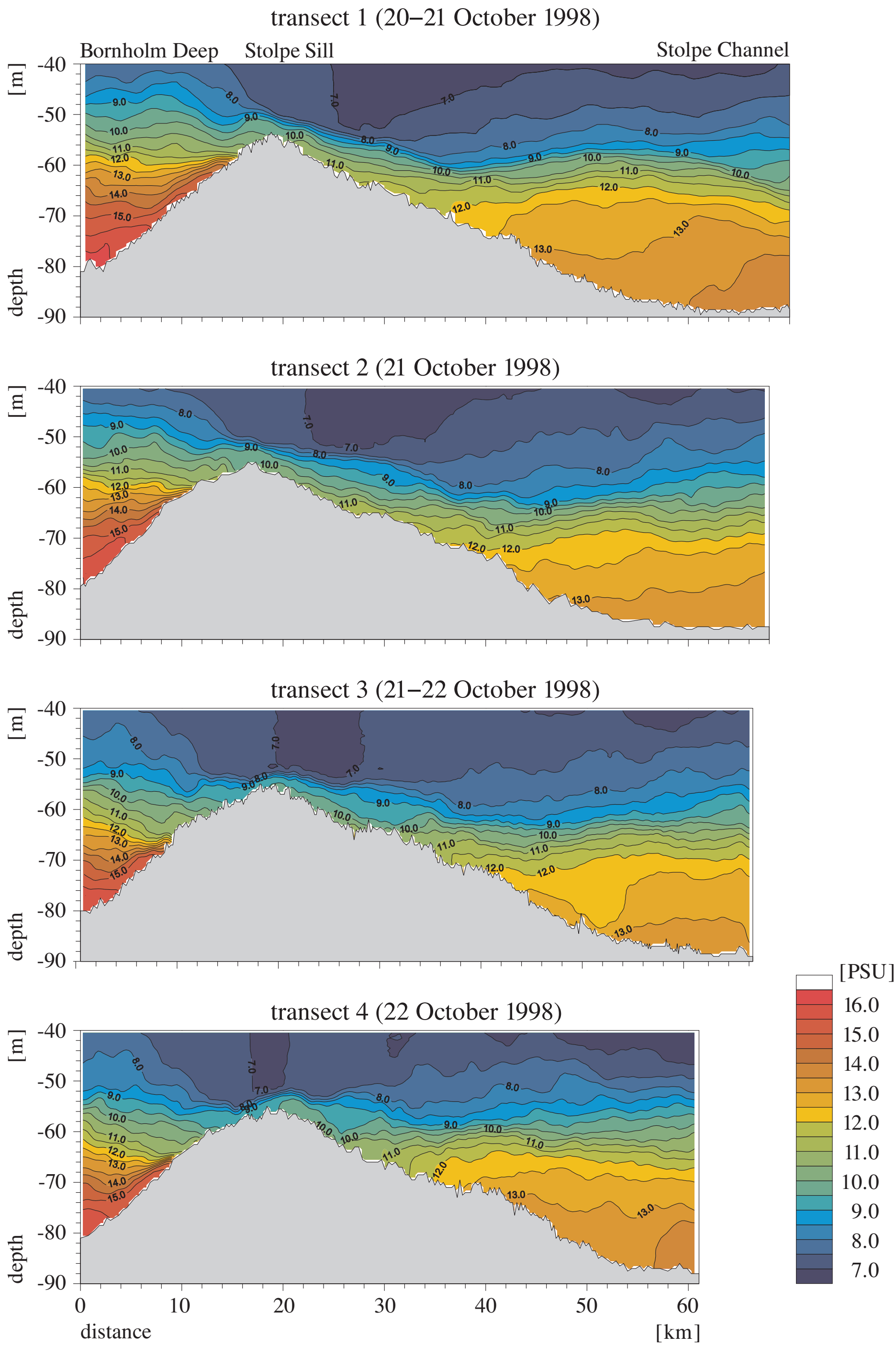

Fig. 2. Distribution of salinity [PSU] in the bottom layer during four consecutive transects across the Stolpe Sill in October 1998

anticyclonic disturbance developed within the lower part of the halocline. Transport of deep waters over the sill is strongly dependent on the halocline height on either side of the sill and every disturbance of the salinity field in the deep layer of the Bornholm Deep affects the intensity of transport.

The time series of horizontal current components u (positive East) and v (positive North), temperature T and salinity S are given in Fig. 3. It is immediately clear from the graphs that the parameters are of an oscillatory nature. Long-period oscillations with time scales greater than 10 hours and short-period oscillations with time scales from minutes to approximately 1 hour were recorded.

Long-period oscillations of current components can be analysed by means of the hodograph of motion (progressive vector diagram) shown in Fig. 4. During the whole observation period the current was dominated by the western component. Values of the northward longitudinal component were significantly lower. Midway through the observations, the southward component reversed direction.

It is interesting to note that the mean direction of the deep current was opposite to that of the prevailing wind. The opposed directions of wind and current in the near-bottom layer, which seems strange at first glance, may be the result of a strong compensation process involving the near-bottom waters. A similar two-layer flow structure, when deep-layer flow increases in the direction opposite to that of the wind-driven current, was described on the basis of numerical model results and field measurements by Krauss & Brügge (1991). In the observation area, which included our location on the western slope of the Stolpe Sill, their model produced a significant near-bottom westward current for the main forcing due to strong westerly winds. Another cause of such a flow structure could be the anticyclonic eddy passing through the measurement point from west to east and extending over the deep layer. Such mesoscale disturbances in the Bornholm Basin were described by Krauss & Brügge (1991). Elken (1996) also demonstrated that saline water entering the Bornholm Basin can form baroclinic eddies, either on top of the halocline or over deep anticyclonic lenses. An interesting peculiarity, related to long-period variability, was noted in the temperature, salinity and pressure time series. The time scale of this variability was about 30 hours. A salinity increase from 9.2–9.4 PSU to about 14–14.4 PSU was recorded at the wave-crests. The temperature also rose from 5.5–5.6 to 7.2°C. The considerable wave-like disturbances had a double amplitude of about 10 m, which was estimated on the basis of a vertical salinity gradient taken to be $0.5\,\mathrm{PSU\,m^{-1}}$. A sharp intensification in the short-period oscillations was noted in the vicinity of the crests. It is clear that a more powerful wave train corresponded to the second crest.

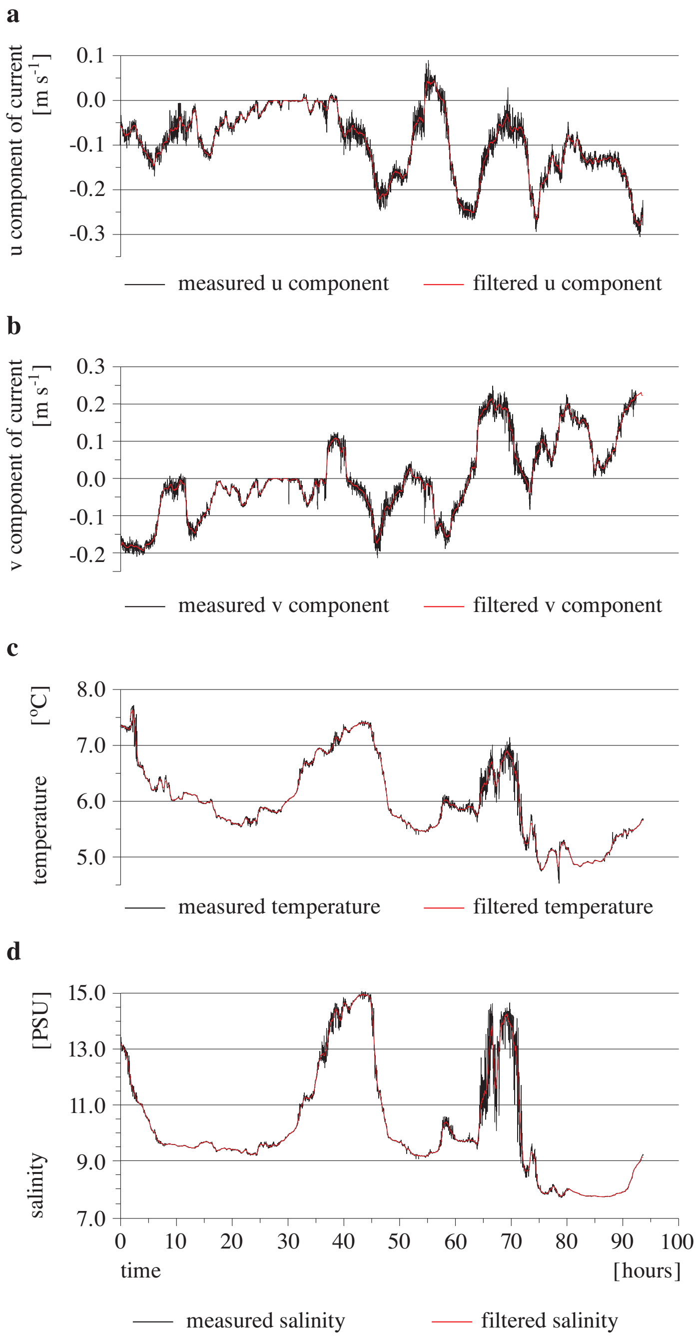

Fig. 3. Time series of current velocity components u and v (a) and (b), temperature T (c) and salinity S (d), measured over the western slope of the Stolpe Sill 4 m above the bottom between 23 October (08:00) and 27 October (06:00) 1998. Low-pass filtered data are superposed on the diagrams

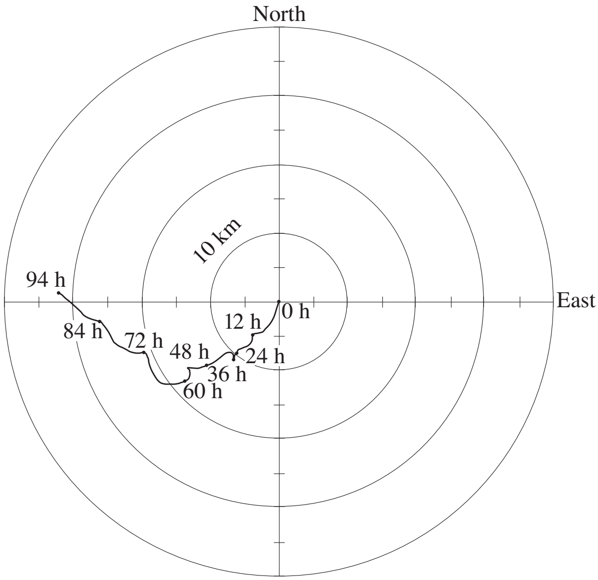

Fig. 4. Progressive vector diagram of current at a depth of 61 m on the western slope of the Stolpe Sill (the Bornholm Deep side), r/v 'Oceania', 23–27 October 1998

These strong oscillations have a variety of causes: internal seiches in the Bornholm Basin could be one of them. These may interact with the bottom topography of the slope and generate short-period waves in the same way as in the ocean, where long tidal oscillations generate short-period waves on the shelf break (Gill 1982). However, the corroboration of this hypothesis will need more accurate data on seiches. Detailed investigations based on high-resolution thermohaline data from transects across the sill are required in order to investigate the generation of wave packets.

The pressure also varied within a range of 0.4 dbar. The amplitudes of these oscillations were in agreement with pressure variations within the strong cyclone, the centre of which, during the observation period, passed some 100 km to the North of the mooring point.

The temporal variations in the velocity components u and v showed that quasi-inertial oscillations were present mainly during the second half of the measurement period. The periods of these oscillations were close to the local inertial period (14.6 h) and the phase shift between u and v was *ca* 90°. The length of the quasi-inertial wave train was approximately 2 oscillations and the profiles of these waves differed to some extent from the ideal harmonic form. These irregularities probably resulted from the breaking and dispersion of the internal waves at the sloping bottom.

4. Spectral analysis of mooring data

Quantitative estimations of the periods and phase shifts for the observed disturbances were calculated by spectral methods, including the rotary component spectra technique (Gonella 1972). Here, the spectral density of the current velocity vector is split into horizontal rotary components – clockwise and counter-clockwise spectral densities S_+ and S_-. The components of the rotary spectra are illustrated in Fig. 5a. This shows that the clockwise component S_+ exceeds the counter-clockwise one by about one order of magnitude. The maximum of the clockwise component S_+ is close to the local inertial frequency $f = 1/14.6\,\mathrm{h}^{-1}$. It is known from the linear internal wave theory (Calman 1978) that at the inertial frequency the whole wave energy is determined by the clockwise rotary component. The observed data are in good agreement with this theoretical statement.

Short-term disturbances lasting from several minutes to one hour occur against a background of long-term variability. These oscillations reach a maximum in the salinity and temperature spectra (Fig. 5b), but no similar maximum is detected in the current velocity spectrum. The coherence between the fluctuations in the salinity S' and the current velocity V' was rather low (Fig. 5d).

Extracting low-frequency components from original data provided a series of high-frequency disturbances for further analysis. A 'purpose-built' low-pass filter was used with an algorithm based on a linear approximation over the intervals surrounding each point of the time series under consideration. The length of this interval determined the cut-off frequency. The filter effect on time series of u, v, T, S is shown in Figs. 3 and 6. This filter allows the low-frequency spectral component to be reduced by four orders of magnitude. At the same time the spectral components with periods from approximately 0.5 hour and longer are not distorted, which is evident when spectra of the original and filtered data are compared (Figs. 5b and 5c).

Figure 6 illustrates time series of high-frequency components of velocity u', v', temperature T', salinity S', and special density ratio $R'_\rho = -\alpha\, T'/\beta\, S'$. The values $\alpha = -\rho^{-1}\,(\delta\rho/\delta T)_{p,\,S}$ and $\beta = -\rho^{-1}\,(\delta\rho/\delta S)_{p,\,T}$ are the thermal expansion coefficient and salinity contraction coefficients respectively. They were calculated from the smoothed temperature $<T>$ and salinity $<S>$ values obtained after low-pass filtering. They demonstrate clearly that the statistical realisation of the currents and thermohaline fields differ significantly, whereas the variations in the fluctuations of the thermohaline parameters T' and S' are quite similar. Fluctuations of the density ratio R'_ρ at a depth of about 61 m, where the current meter was installed, were estimated at 0.02–0.05. The classical density ratio $R_\rho = -\alpha\ <T>_z\ /\beta <S>_z$, based on evaluations of the mean vertical gradients $<T>_z$ and $<S>_z$

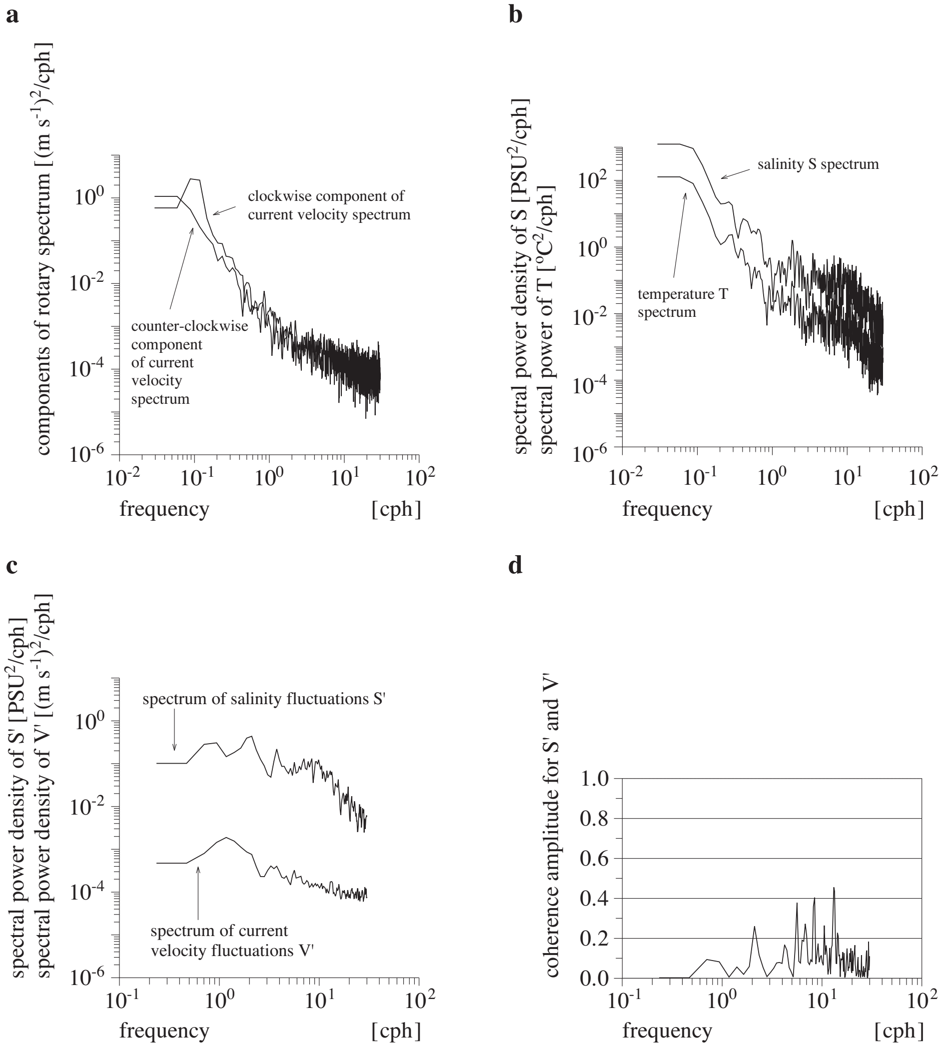

Fig. 5. Rotary and power spectra for time series of temperature, salinity and current velocity: rotary spectra of current velocity V (a), spectral power density of temperature T and salinity S (b), spectral power density of salinity S' and current velocity V' fluctuations (c), coherence between salinity S' and current velocity V' fluctuations (d)

of the temperature and salinity fields (Gill 1982) has approximately the same values. Owing to the small temperature contribution to the density variations, the temperature field did not adequately represent the wave disturbances. By contrast, the salinity practically follows the density and can therefore be regarded as a suitable representation of the internal wave field.

In the temperature-time series, and especially in the salinity series, it is obvious that short-period waves have an intermittent structure. The recorded wave trains lasted from approximately 1 to 5 hours, and the observed wave train contained from 2–3 single oscillations to several tens of them. Moreover, the time intervals between wave trains varied from parts of an hour to ten or more hours. The wave train intensity was very variable; two consecutive powerful trains were recorded between the 60th and 70th hours of measurement (Fig. 6). The amplitudes of these oscillations fluctuated within quite a wide range – from 0.2 to 1.5 PSU for salinities and from 0.04 to 0.3°C in the temperature field. Taking into account the fact that the maximum value of the vertical salinity gradient in the deep layer was about $0.5\,\mathrm{PSU\,m^{-1}}$, the amplitudes of short-period waves can attain values of 0.4–3 m.

The sources of the observed short-period waves are not yet fully understood. The most intensive short-period oscillations were found at the crests of long waves with a 30 h period. This confirms the hypothesis about the generation of short-period waves by instabilities due to the interaction of long waves with the bottom topography. This scenario seems plausible owing to the considerable amplitudes of the long-period waves and their non-linearity. The ratio of the wave amplitudes to the halocline depth ranged from 5 m to 30 m. According to Stigebrandt (1976) and the laboratory experiments of Southward & Cacchione (1972), when interfacial internal waves begin to flow over a sloping bottom, the amplitude increases, the wavelength shortens and the wave profile becomes asymmetric with a steeper frontal slope. Eventually, the wave nature is completely lost and vigorous turbulence is generated. In general, internal waves are dissipated on the sloping bottom and their energy is thought to be converted to turbulent energy in the lower layer. The effects of the mixing processes in the boundary layer are transferred to the interior of the water volume, where there is essentially no small-scale turbulence, and a horizontal turbulence field develops. Laanemets *et al.* (1996) also considered near-inertial waves a possible source of energy for small-scale turbulence in the halocline in the Bornholm Basin. A numerical model for the generation of these waves was described with external forcing represented by the moving wind front. The wind-induced drift current was modulated by a horizontally propagating wave with inertial frequency, as a result of which internal gravity waves were forced. These waves can carry energy from the subsurface layer into the deep stratified layers, thereby giving rise to shear instability.

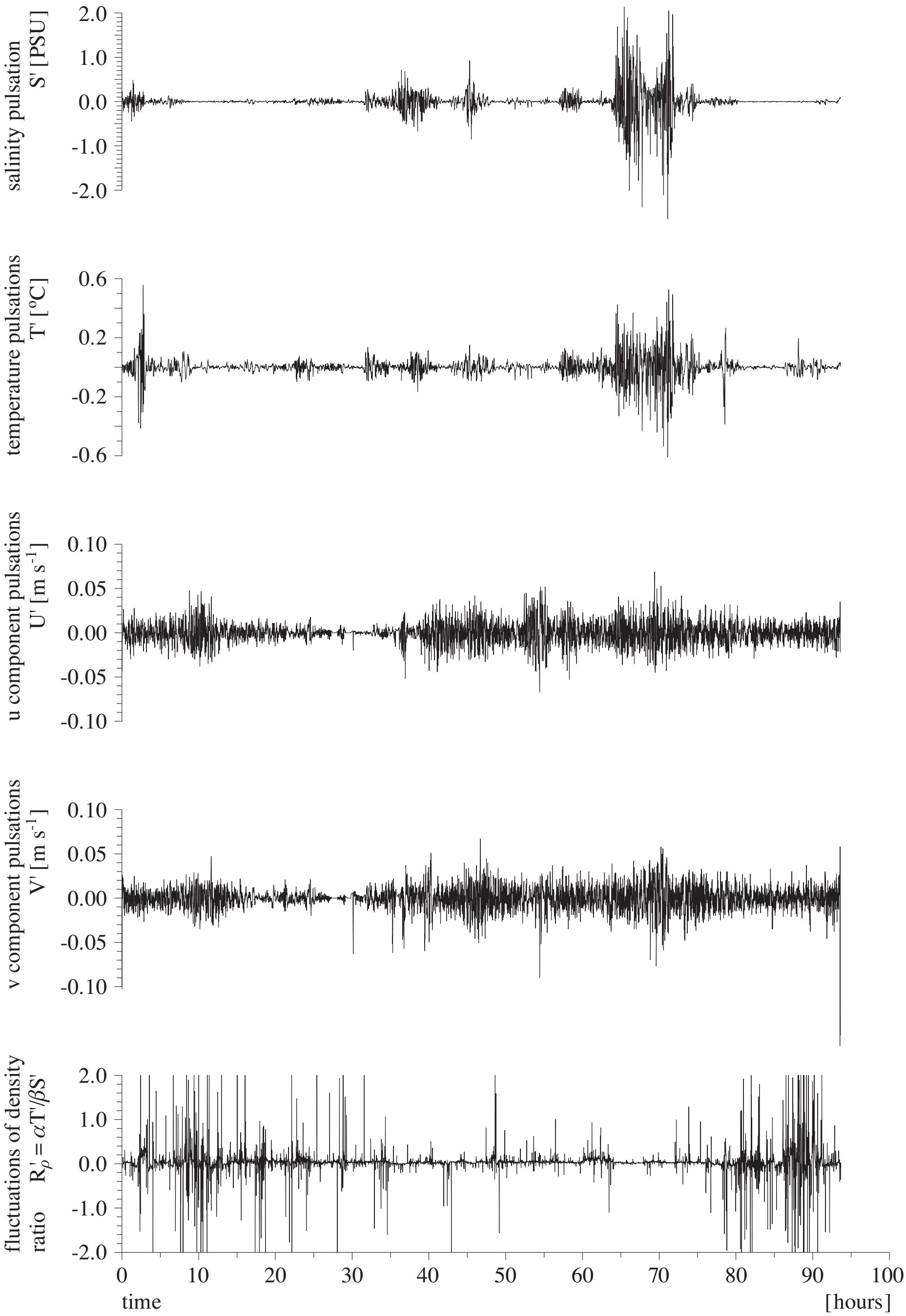

Fig. 6. Time series of pulsations of salinity S', temperature T', current components u' and v' and density ratio R'_ρ on the western slope of the Stolpe Sill in October 1998

Although the current velocity fluctuations varied considerably with time, the intermittence of these variations was of a different nature from that of the salinity, density or temperature variations. For example, wave packets were not characteristic of the current velocity fluctuations. Typical values of the velocity oscillations were about 1–3 $\mathrm{cm\,s^{-1}}$. It can be assumed that the observed short-period velocity fluctuations are due to quasi-horizontal turbulence, because firstly, the coherence with salinity fluctuations was very low and secondly, the observed amplitudes were quite high and exceed the sensitivity of the device (sometimes the fluctuations fell to zero). The obtained magnitudes of the velocity fluctuations can therefore be regarded as evaluations of the dynamic turbulence for scales from 2 minutes to approximately 0.5 h generated on the Stolpe Sill. The nature of the instability generating turbulence has not been found with certainty. The velocity and salinity/density fluctuations compared in Fig. 6 indicate that packets with velocity fluctuations were of longer duration than the wave train lengths. This indicates that turbulence generation is related to an existing force of longer duration than is the case with the generation of short-period wave packets. Interactions between long period waves such as seiches and inertial waves and the non-homogeneous bottom slope may be an important cause of turbulence generation.

5. Summary

The intention of the measurements in the Stolpe Sill area was to evaluate parameters of the temporal variability of the horizontal current velocity vector and thermohaline fields in a key region of the Baltic Sea, where superposition and interaction of complicated dynamical processes on various scales take place.

The occurrence of salinity and density oscillations with periods of about 30 h was an interesting phenomenon disclosed by the time series of hydrological parameters. The salinity fluctuation due to these motions varied between 9.2 and 14.4 PSU and the double amplitude of the observed wave was estimated at 10 m. Vertical amplitudes of the oscillations were significant in comparison with the vertical extent of the layer with the strongest density gradient. The ratio of the wave amplitudes to the vertical scale of this layer was approximately 0.2, thus giving some indication of the non-linear nature of the oscillatory movements. At the crests of the oscillations with a 30 h period, where upward distortion of isopycnal surfaces occurred, short-period wave trains were registered with amplitudes of up to 3 m. The short-period fluctuations vanished from these domains. The current velocity due to inertial waves did not exceed 25 $\mathrm{cm\,s^{-1}}$.

The short-period waves demonstrated a prominent wave train structure. The intensity of the oscillations varied considerably, with a typical wave amplitude ranging from 0.4 to 3 m. Fluctuations in the short-period current velocity components, corresponding to the 2–30 min time-scale band, were estimated at approximately 1–3 $\mathrm{cm\,s^{-1}}$. These values can be regarded as a preliminary evaluation of the turbulent fluctuations that should be prevalent in such a dynamically active region as the Stolpe Sill.

Two-layer flow, with the direction of the deep current opposite to that of the prevailing wind vector, was observed during the entire measurement period. The dominant westward component of the near-bottom flow due to westerly winds was suspected to be an effect of a compensatory deep current or mesoscale baroclinic disturbance developed in the halocline layer.

These features confirm the complicated non-linear nature of the dynamical processes in the Stolpe Sill area. One of the principal questions remaining to be answered is the role of these processes in the transport of dense, inflowing water over the sill into the Stolpe Channel. Future research should include a detailed analysis of longer time series of thermohaline and current properties under different forcing conditions representative of the Bornholm Basin, Stolpe Sill and Stolpe Channel areas. Studies of the interactions between long- and short-period motions should be carried out, with special attention paid to the seiches and their role in the generation of high-frequency oscillations. The problem of small-scale turbulence generated by internal waves at the sloping bottom is of crucial importance. The theory of the generation and breaking of internal waves in the vicinity of the sill should be adapted to the Stolpe Sill geometry and the thermohaline conditions obtaining there.

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