

## Observations of Transport Variability in the Baltic Sea by Parasitic Use of a Fiber-Optic Cable

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### ABSTRACT

Transports between the Swedish mainland and the island of Gotland were studied by means of motionally induced voltages. The copper mantle of an existent fiber-optic telecommunications cable was grounded on Gotland, and the data acquisition system was installed on the mainland, whereby the bulk flow over the section could be observed. The magnetic field was simultaneously measured so as to permit a comparison with the induced voltage. It was found that geomagnetic fluctuations only weakly affected the observed voltage differences at subinertial frequencies, whereas in the superinertial range a considerable degree of geomagnetic influence was detected. The induced-voltage results were also compared to the geostrophic transports determined using tidal gauge data, analysis of which showed that the stratification of the western Gotland basin affected both types of calculations. Transport adjustments, based on taking into account the effects of stratification as well as the bedrock geological characteristics, were thus carried out. It was found that the best correspondence between the two independent estimates of the transport was obtained by locating the main halocline at a depth of 78 m, in good agreement with hydrographic results from the region.

### 1. Introduction

The Baltic is one of the largest semi-enclosed seas in the world; see the map in Fig. 1. It is characterized by a large freshwater excess due to its extensive drainage basin (Omstedt et al. 1997) and is, thus, strongly stratified with a brackish surface layer superimposed on a deep layer of higher salinity and density. This lower layer is intermittently renewed by high-saline inflows from the Kattegat and Skagerrak through the Danish Straits (Matthäus and Franck 1992).

Modeling of the Baltic has to a large extent focused on the vertical circulation, the study of which began more than a century ago (Knudsen 1900). The horizontal circulation of the brackish surface-water layer has, on the other hand, been the subject of much less inquiry, and only its gross features are known. The most prominent among these is a comparatively weak counter-clockwise circulation in the main basin of the Baltic, which, however, may be of considerable significance for the dispersion of particulate and dissolved matter and thus deserves further study.

An interesting possibility for systematically examining some aspects of the upper-layer circulation presented itself recently when the Swedish telecommunications authorities very generously made a submarine cable between Västervik on the Swedish mainland and Visby on the island of Gotland (see the map in Fig. 2) available for research purposes. By using this conductor to monitor the voltage induced by the motion of electrically conducting seawater through the earth's magnetic field, it ultimately proved possible to establish estimates of the integrated mass transport variability between the end points of the measuring system. This transect is located very strategically, since it runs across the main circulation gyre of the Baltic and hence may offer an almost unique possibility to examine the integral properties of the dominant surface circulation characterizing this inland sea.

In the next section the technical details of how the monitoring system was implemented are outlined, whereafter section 3 deals with the processing of the observational material. The analysis of the measurements is discussed in the subsequent section, whereafter some refinements of the data treatment are carried out in section 5. The study is concluded by not only a brief overview of the obtained results, but also some ideas

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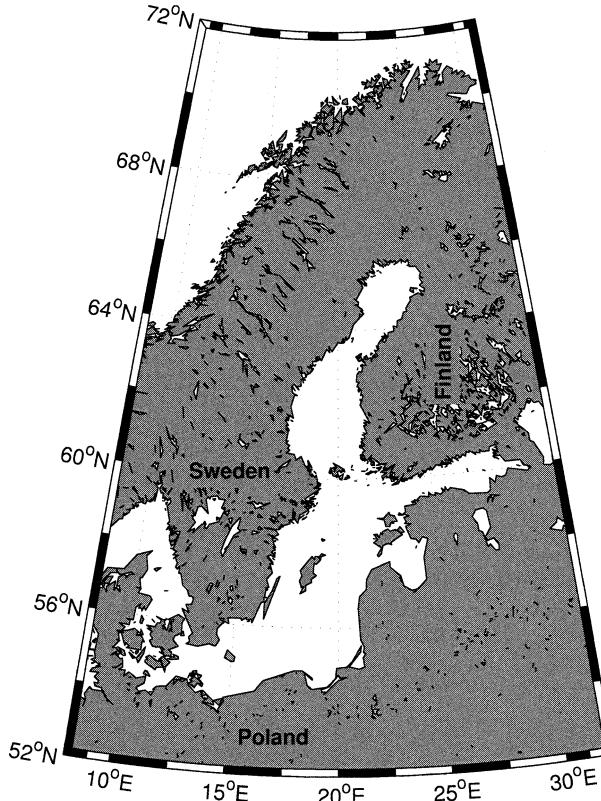


FIG. 1. Map of the entire Baltic, including the Danish Sounds leading to the Kattegat.

concerning future field observations with particular reference to the Baltic.

## **2. Technical implementation of the observational system**

The communication link that we were given access to was of the fiber-optic variety and, hence, use was made of the copper sheathing employed to protect the fiber bundles from the deleterious effects of hydrogen diffusion (Runge and Trischitta 1986, chapter 17). Since the cable was comparatively short (viz., only around 100 km), no optical repeaters requiring a power supply through the sheathing were installed, and thus the conducting mantle could, with a minimum of practical complications, be used for direct measurements of the potential difference between the shore stations on the Swedish mainland and on Gotland, respectively. Concurrent measurements of the geomagnetic field were undertaken at Västervik on the mainland using a fluxgate magnetometer. After analog-to-digital (A/D) conversion and some data compression, all observations were transmitted on a daily basis to our home base in Stockholm for subsequent analysis and archiving (once the gross features of the geomagnetic dataset had been validated on the basis of results from the Swedish national reference station at Lovön in the vicinity of Stockholm).

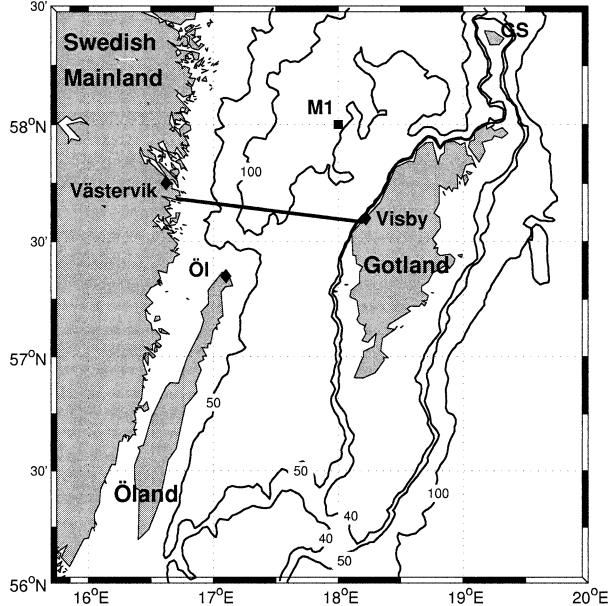


FIG. 2. Detailed map of the Öland–Gotland area showing the location of the fiber-optic cable between Västervik and Visby. The subsurface ridge providing a southern delimitation of the western Gotland basin is clearly visible in the lower part of the map. GS denotes the island Gotska Sandön. The tidal gauges were located at Visby and the northern cape of Öland, indicated by Öl. Hydrographic data were obtained from station M1.

A schematic drawing of the experimental arrangements is shown in Fig. 3. The most important component of the observational system is the submarine cable, which on both sides of the passage terminates in stations located in close proximity to the beach. Both stations were grounded locally with copper grids buried in the immediate neighborhood, hereby presumably ensuring good electrical contact with the sea. Prior to the in-

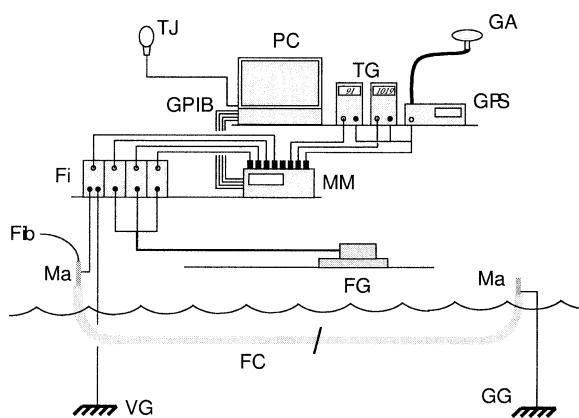


FIG. 3. Schematic diagram illustrating the experimental arrangements as well as the data acquisition system. The various components are denoted as follows: PC, computer; TG, time generators; GPS, global positioning system; GA, GPS antenna; GPIB, interface to multimeter; TJ, telephone socket; Fi, filters; MM, multimeter; FG, flux-gate sensor; Fib, fibers; Ma, mantle; FC, fiber-optic cable; VG, Västervik grounding; and GG, Gotland grounding.

stallation of the monitoring equipment, the mantle of the cable was found to be ungrounded at the Gotland station. As a necessary preparation, the mantle at one of the cable ends thus had to be grounded. The cable operator proved to be very tolerant and gave us permission to ground either of the ends. For practical reasons Gotland was selected for this purpose, and logistical consideration furthermore dictated that the data acquisition system be housed at Västervik. Here also the magnetic field variations were measured with a tri-axial fluxgate magnetometer (Bartington Mag-03) placed inside the Västervik station building. This sensitive piece of equipment was mounted on a concrete block so as to preclude inadvertent motion.

To verify whether the groundings in fact were in good electrical contact with the sea, the potential difference between the local ground and a sea-based Ag–AgCl electrode was recorded at both of the experimental sites. The voltage offset and variability between the Ag–AgCl electrode and the grids were found to be 0.4 V and 3 mV and 0.3 V and 10 mV at the Visby and Västervik stations, respectively. The higher variability at Västervik is most likely due to the Ag–AgCl electrode there being deployed in shallow water, making it more vulnerable to surface waves as well as to anthropogenic electrical contamination. These variabilities are, nevertheless, lower than that of the recorded induced voltage, and hence the grounding could be regarded as stable during the measurements reported here.

The mantle and the local ground as well as the signals of the fluxgate magnetometer were connected to 6 dB octave<sup>-1</sup> low-pass filters, all with a designed cutoff frequency of 20 mHz. The filters were deliberately made out of passive electrical components so as to avoid unnecessary grounding between the signal sources and the final A/D conversion. After filtering, the signals were fed into a high-resolution digital multimeter (Keithley Instruments, Model K2000) with the capacity to record 10 independent channels. The scanning rate was set to 0.1 Hz, well above the cutoff frequency of the filter, and with an 0.2-s time delay between the channels. Finally, an ordinary portable computer, with the prime task of storing data, was used to communicate with the multimeter through a general-purpose interface bus (GPIB). The built-in modem of the computer was used for data transfer to our home institute (thus making evaluation in near-real time possible), and moreover served as an invaluable tool for checking the status of the system.

A requisite property of a long-time monitoring system is the ability to generate accurately time-stamped data, hereby facilitating postevaluation. For this purpose we employed an ordinary GPS clock, programmed to give a 1-min pulse at 1200 UTC. To further improve the time resolution, two step generators (with different rise times) were restarted once every day by the same pulse. The GPS clock and the two step generators were directly connected to the digital multimeter without passing any

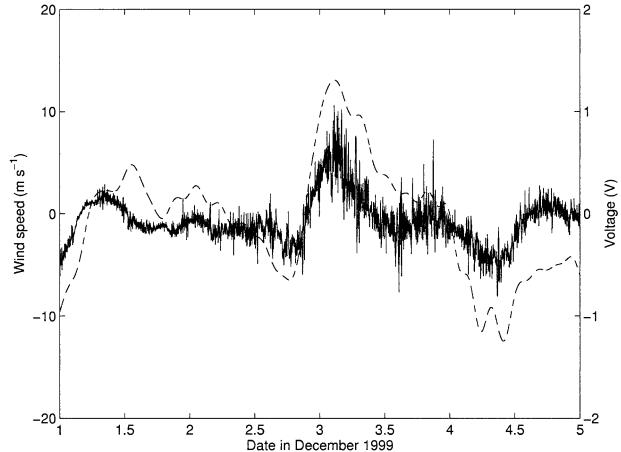


FIG. 4. Diagram showing the recorded wind speed at Gotska Sandön (north of Gotland; cf. the map in Fig. 2) as well as the measured voltage Västervik–Visby during the first four days of December 1999. The dashed line shows the wind, whereas the solid line shows the recorded voltage.

filters, and thus an unambiguous reading of time was achieved.

The technical installation became operational during the fall months of 1999. The forthcoming investigation will limit itself to December 1999, when the overall hydrographic situation remained comparatively stable after the autumnal convection (which above the main halocline resulted in a more-or-less homogeneous surface-water layer of salinity around 7 PSU). This month-long period was also characterized by extreme contrasts in the magnitude of the wind forcing, as borne out by the initial results summarized in Fig. 4. The diagram, encompassing 1–4 December, shows the “raw” voltage signal from the Västervik–Visby cable graphed together with the north–south component of the observed wind at the meteorological station on Gotska Sandön, north of Gotland, during 1–5 December. These first results indicated a high degree of covariability between the two independently observed variables, which strengthened our general conviction that it would prove feasible to utilize the voltage measurements for examining the larger-scale properties of the Baltic circulation between Gotland and the Swedish mainland. The observational system moreover functioned smoothly during this month, a state of affairs that did not always prove to hold. As an illuminating example of an a priori unexpected system malfunction, it deserves mention that around a year later, namely, the last week of December 2000, a degraded voltage signal with no geophysical information whatsoever was recorded. After considerable inquiry it was recognized that a high-voltage power cable adjacent to the fiber-optic link was in use during this time for testing emergency procedures by running the power transmission in a monopolar dc mode, thereby contaminating the ambient electric field to such an extent that only noise was recorded by our observational system.

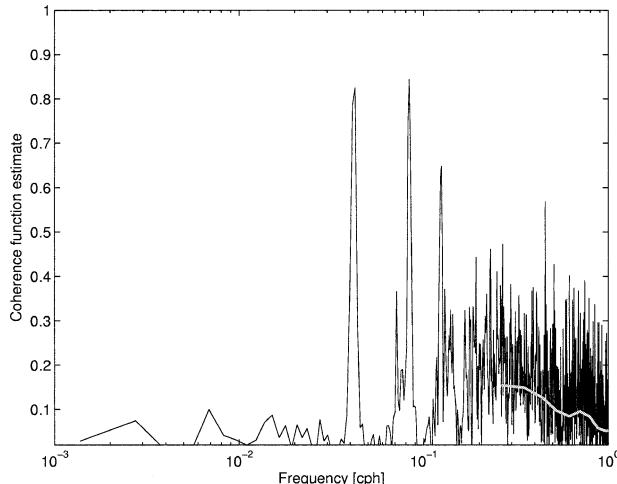


FIG. 5. Estimate of the coherence between the north-south component of the local magnetic field, measured at Västervik, and the potential difference between Västervik and Visby. A high degree of coherence is found for superinertial frequencies, whereas in the sub-inertial range the coherence is low except at the tidal frequencies. The solid line represents the yearly average of spectra based on monthly datasets, whereas the gray curve shows the yearly average of the spectral results for the corresponding half-day time series.

The optimism over the encouraging initial results shown in Fig. 4 was, however, tempered by the insight that a good deal of effort remained to be undertaken before the observational system could be regarded as a viable tool for oceanographic investigations. As will be evident from what follows, this work to a considerable extent pertained to calibration matters.

### 3. Initial treatment of the data

The relationship between the volume transport of seawater and the observed voltages due to electromagnetic induction was already a subject of discussion by Faraday in the 1830s, although the formal theory describing the process was only established in its present-day form at the end of the 1940s (e.g., Malkus and Stern 1952; Longuet-Higgins et al. 1954). A straightforward summary of the most important results, pertinent for the applications to be dealt with in the present study, has been given by Fristedt et al. (2002).

Before this theoretical framework can be applied, it is, however, essential to ascertain to which degree the directly measured voltage signal is “contaminated” by variations of the earth’s geomagnetic field. During the field experiment the fluxgate sensor on the Swedish mainland was installed with precisely this purpose in mind. In Fig. 5 the results from a coherency analysis between the observed voltage over the Västervik–Visby cable and the recorded north-south horizontal component of the geomagnetic field are shown. (This specific component has been selected for closer investigation since it gave rise to the largest contamination of the measured voltage signal.) From the diagram it is rec-

ognized that for higher frequencies (with a lower bound approximately corresponding to the inertial period) the two signals covary in a significant manner, whereas for lower frequencies the coherence is in general weak (with the interesting exception of the diurnal and semidiurnal spikes caused by the cooscillating geomagnetic and oceanic tides). This set of circumstances must be regarded as highly providential in view of the fact that we shall focus on examining quasi-stationary processes so as to permit use of the geostrophic approximation when calibrating and interpreting the observational results. It was found that in practice low-pass filtering of the voltage signal sufficed to remove the effects of variations of the earth’s magnetic field, thereby obviating a possible need to take recourse to a remote reference for this purpose. (The digital filter that was employed was of the Butterworth variety, based on the use of six poles and with a cutoff at 14 h approximately corresponding to the inertial period.) The drawback associated with applying this simplified procedure is that the tidal components of the flow may be somewhat contaminated by geomagnetic noise, but since these tidal velocities are known to be exceedingly small in the Baltic (cf. Witting 1911), the error induced can be regarded as negligible.

It is furthermore noteworthy that December 1999 was characterized by an overall very low planetary geomagnetic  $k_p$  index, a situation that facilitated our investigation. That this does not always prove to be the case was demonstrated around 5 months later when a magnetic storm raged, giving rise to an induced voltage several orders of magnitude larger than that of the signal associated with the uncommonly severe atmospheric storm shown in Fig. 4. (Note, however, that this magnetic storm in April 2000 was exceptionally strong, as manifested by it being associated with an aurora borealis visible even in northern France where this is a very rare occurrence indeed.)

### 4. Data analysis

Once the effects of the variations of the geomagnetic field have been filtered out using the procedure described in the preceding section, the stage is set for further exploitation of the recorded voltage for oceanographic purposes. As previously mentioned, we shall in the present study focus on investigating slowly varying flows, since we can for this class of motion make use of available water-level records for establishing geostrophic estimates of the barotropic transport.

The sea level records, yielding the deviation of the free surface from its equilibrium position, were obtained from two tidal gauges in the Swedish network, one located at Visby on Gotland and the other at the northern extremity of the island of Öland (cf. the map in Fig. 2). The volume flux across the transect defined by these two tidal stations can be expected to closely agree with that between Visby and Västervik, since the strait between Öland and the mainland is a narrow and shallow

passage only permitting a minuscule flow. The two sections are furthermore located in such close proximity that we do not expect any significant time lags between the transport records.

The Öland–Gotland transect of length 65 km has a maximum depth of around 110 m and an average depth of 64.5 m. For a lack of supplemental information we now posit that the sea level changes in a linear fashion between the tidal gauges, and thus the following result for the barotropic transport  $Q_{\text{geo}}$  is obtained:

$$Q_{\text{geo}} = -\frac{g}{f} \Delta \eta \bar{h}, \quad (1)$$

where  $\Delta \eta$  is the sea level height difference between the end points of a section of average depth  $\bar{h}$ . The Coriolis acceleration is given by  $f$  and the acceleration of gravity by  $g$ . Note that although this estimate must be regarded as a lowest-order result in view of the assumption that the free surface behaves strictly monotonically, it is insensitive to the vagaries of the bottom topography since the total transport only depends on the average depth (which may be determined to a high degree of accuracy). On the basis of this relationship it is a straightforward matter to calculate the transports during December 1999 from the low-pass filtered sea level data at our disposal.

Once these geostrophic estimates for the section between Öland and Gotland are available for comparative purposes, we direct our attention to the induced-voltage record from the Västervik–Visby transect for the same period. We retain the assumption already made above that the water is in barotropic motion (although this need not be horizontally homogeneous). Following von Arx (1950) and Longuet-Higgins et al. (1954), as well as Malkus and Stern (1952), we furthermore, as a first approximation, neglect the seabed conductivity. Hence the following expression for the transport determined on the basis of the observed potential difference is obtained:

$$Q_{\text{miv}} = \frac{\Delta U}{F_z} \bar{h}'. \quad (2)$$

Here  $\Delta U$  is the measured voltage,  $F_z = 49 \mu\text{T}$  is the vertical component of the earth's magnetic field, and  $\bar{h}' = 76 \text{ m}$  is the average depth between Visby and Västervik. When applying this transport formula to the low-passed voltage record from December 1999, note must be taken that it is the variations that primarily concern us here, since the potential cannot be measured in absolute terms. Similarly, the geostrophic calculations using formula (1) are, by necessity, based on the observed deviations from the averaged sea levels at Öland and Gotland rather than on a geodetically leveled set of tidal gauge data. Hence a comparison between the two independent sets of transport estimates is most conveniently accomplished by examining the ratio between the standard deviations  $r = \sigma(Q_{\text{geo}})/\sigma(Q_{\text{miv}})$ . For the month-long period presently under consideration this

quotient proved to be 1.6, which clearly indicates that the estimated transports do not match each other at all times. Note, however, that the correlation between the time series was determined to be 0.88.

The oceanographic significance of the observed transports will be touched upon in the concluding section of this study, but here we focus on the discrepancies between the estimates of the transport variability. These can have several possible sources, and in what follows we shall subject the observational data to a more thorough analysis in order to possibly draw some conclusions as regards the likely mechanisms.

## 5. Refined analysis of the observational data

One of the main results from the initial analysis, reported upon in the previous section, was that the two transport records were not in complete agreement; in an overall sense the variation of  $Q_{\text{miv}}$  was a factor 1.6 weaker than that of  $Q_{\text{geo}}$ . Since the transports associated with the pure wind current have been neglected in the analysis, these could presumably be invoked to explain the discrepancy. (The longer-term effects of these Ekman transports are in fact mirrored in the sea level data, but the direct contribution to the mass flux across the section has been disregarded when calculating the transports.) However, a closer analysis reveals that the wind current transports are several orders of magnitude too small to accomplish this task.

A crude, but straightforward, method to correct the inconsistency would be by introducing an ad hoc scaling factor, amplifying  $Q_{\text{miv}}$  to the same level as  $Q_{\text{geo}}$ . An adjustment of this type would, however, depend on positing that the tidal gauge data do full justice to the true transport. In addition to the previously discussed leveling problems, this assumption must, on several further counts, be regarded as somewhat questionable. First, when calculating the transport, the vertical structure of the velocity field must be known. [In formula (1) this was taken to be vertically homogeneous, which in fact rarely is the case.] Second, it is not immediately given that the sea levels at all times reflect a velocity field in geostrophic balance. Third, and perhaps most important, the use of an empirically determined scaling factor would not clarify the underlying physical mechanisms, hereby precluding the possibility of gaining added insights concerning the internal structure of the flow.

It is of considerable importance to emphasize that not only  $Q_{\text{geo}}$  must be corrected:  $Q_{\text{miv}}$  must also be subjected to adjustments, since effects related to variations of topography and conductivity variations may influence the conversion from measured voltage to transport. Extensive methodological investigations concerning the calibration of cable-derived transport estimates have been undertaken by, for example, Sanford (1971) and Sanford and Flick (1975), as well as Chave and Luther (1990). A recurring conclusion from these as well as other studies is that variations in the conductivity of the water

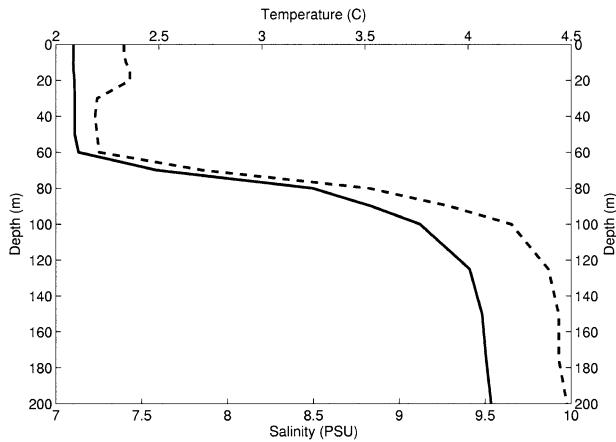


FIG. 6. Observed wintertime hydrographic situation from station M1 in the western Gotland basin (temperature, dashed; salinity, solid). The permanent halocline as well as the almost uniform upper layer (thermally homogenized by autumnal convection) are clearly in evidence.

mass as well the sediment affect the recorded signal to a significant extent. This conclusion also was given recent support from a similar shallow-water field experiment conducted in Öresund (Fristedt et al. 2002), where it was demonstrated that the induced voltage was strongly influenced by conductivity variations caused by the stratification. These qualitative deliberations may contribute toward understanding the observed discrepancy between  $Q_{\text{miv}}$  and  $Q_{\text{geo}}$ , and indeed it becomes clear from the CTD profile shown in Fig. 6 that the hydrography is more reminiscent of a two-layer situation than the initially postulated single-layer idealization. Under this gross simplification, adhered to in the analysis of section 4, the presence of the Baltic main halocline was evidently disregarded, thereby, among other things, leading to the omission of the conductivity variations associated with the stratification.

In the previous analysis it has furthermore been assumed that the sea level records reflect a transport that is in geostrophic balance and that this state of affairs holds true during the entire measurement period. As already hinted at, this may not have been the case at all times. Thus an extremely high southward transport across the Västervik–Visby transect from 13 to 16 December, as deduced from the tidal gauge records, was not corroborated by the induced voltages. A closer examination of the sea level data revealed exceptionally high water levels at the Öland tidal station during this period. This anomaly was absent in the Visby record, leading to the high geostrophic transport estimates. An analysis of the meteorological conditions showed that during precisely this period a strong shear characterized the wind field between Visby and northern Öland, a rare occurrence in view of the large horizontal length scales typical of the weather systems over Scandinavia. On this occasion a northerly gale raged over Öland, whereas the Gotland weather was much more peaceful. This led

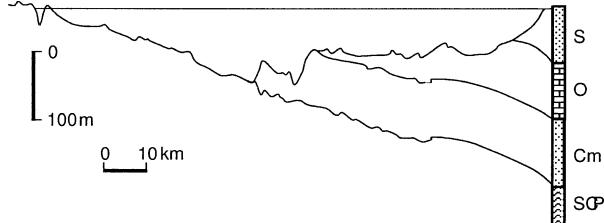


FIG. 7. Geological section between Västervik (to the left in the diagram) and Visby. The various strata are denoted as follows: S, Silurian; O, Ordovician; Cm, Cambrian; and SCP, sub-Cambrian pebbleplain.

to local *windstau* effects over the shallow western part of the section, hereby invalidating the geostrophic calculations and leading to overestimates of the transports. As a consequence, this period will not be used for comparative purposes in the subsequent analysis.

In a basic treatment of cable-derived voltage data, the effects of variations of topography and conductivity must be compensated for, or, as a minimum requirement, their influence on the recorded voltage must be estimated. Including the effects of a vertically nonuniform velocity structure and water-column conductivity variations on the horizontal electric fields results in the well-known formula for the conductivity-weighted horizontal velocity field (Spain and Sanford 1987). Similarly, taking into account the seabed conductivity gives rise to the  $k$  factor introduced by von Arx (1950). The measured voltage is, however, not only affected by the vertical structure of the conductivity, but also by its horizontal distribution, which may give rise to nonlocal currents. Following Sanford and Flick (1975), the latter type of effect can, in the present case, be disregarded by taking into account that the bathymetry does not manifest any large variations within distances of around 50 km from the Västervik–Visby transect.

From Fig. 6 as well as Fig. 7, showing the various geological strata between Västervik and Visby, it may be recognized that not only the two-layer stratification but also the seabed can be expected to play a significant role when calculating the voltage-derived transport  $Q_{\text{miv}}$ . The presence of a lower (most likely passive) layer of salinity around 9.5 psu as well as a conducting bottom introduces a short-circuiting of the induced voltage, hereby leading to underestimates of the transports. The single-layer geostrophic transport formula (1), on the other hand, yields transport overestimates if the water mass is not in vertically homogeneous motion, a situation that cannot be ruled out in view of the pronounced stratification visible in Fig. 6. It thus proves necessary to estimate the effects of a conductive seabed and a vertically stratified flow with a lower layer in weak, if any, motion.

With respect to our knowledge of the geological characteristics of the seabed, the first core boring in the region was made in 1911–12 near Visby (Hedström 1923). A more detailed study based on seismic profiling

was undertaken in the Baltic proper by Flodén (1980). During this investigation it was established that the seabed between the Swedish mainland and Gotland is dominated by two types of bedrock, to the west it is of the crystalline variety, and to the east it is sedimentary rock. The sub-Cambrian peneplain slopes from the mainland with an almost constant angle of  $0.2^\circ$  in an east-southeasterly direction (cf. Fig. 7). At around 50 km from the coast a sandstone structure, deposited during the Cambrian era, outcrops between the crystalline bedrock and a limestone stratum. The latter layer, deposited mainly during the Ordovician era, commences at around 60 km from the mainland, leaving only a 2–12-km-wide zone of direct contact between the sandstone and the seawater. The cumulative effects of the sedimentary bedrocks are to flatten out the bathymetry, which eventually rises so as to form the island of Gotland at the eastern limit of the transect (Flodén 1980). Unfortunately, regional data concerning porosity are scarce. The only available information (to our knowledge) originates from a geothermal energy project (VIAK 1981), in the course of which the porosities of the various strata were investigated. The western part of the seabed, constituted by crystalline bedrock, is known to be a good electrical insulator and hence does not affect the recorded voltages. The sedimentary types of bedrock are known to be porous and, as a consequence, are conductive. The porosities of the sandstone and the limestone were found to be 20% and 5%, respectively (VIAK 1981). Furthermore, the Ordovician limestone is known to be calcareous and is associated with a comparatively high sound velocity (Flodén 1980), which agrees well with a low degree of porosity. The continuously thickening strata in the east-southeasterly direction, as well as the fact that three different types of bedrock are present, complicate the determination of the seabed conductance. An estimate can be obtained by assuming that the strata are evenly distributed over the transect and by furthermore neglecting the presence of the thinner limestone layer of low conductance. The relation between porosity and conductivity is given by Archie's law:

$$\sigma_{\text{bulk}} = (\sigma_{\text{fluid}})P^2, \quad (3)$$

where  $P$  is the fractional porosity,  $\sigma_{\text{bulk}}$  is the bulk conductivity of the stone, and  $\sigma_{\text{fluid}}$  is the seawater conductivity. Here,  $P$  was taken to be 20%,  $\sigma_{\text{fluid}} = 1.2 \text{ S m}^{-1}$ , and the average thickness of the sandstone layer was taken to be 50 m. These values yielded a conductance of 2.4 S. This very conservative estimate must be regarded as an upper bound, since effects of the Ordovician stratum have been neglected. It should furthermore be noted that the short-circuiting is limited to the eastern third of the transect, thereby limiting the influence of the sedimentary rock even more. Although the internal structure of the water column has not yet been subjected to closer scrutiny, it is instructive to examine the influence of the sedimentary rock in relation to an

equivalent layer of seawater. It may thus easily be shown that a conductance of 2.4 S is obtained by "replacing" the sandstone with a 2-m-thick layer of seawater. Having recognized this, it is evidently necessary to introduce an electrical model taking the combined effect of the conductivities and velocities into account.

The hydrographic situation in this part of the Baltic is dominated by the permanent salinity stratification (cf. Voipio 1981). The brackish surface-water layer is separated from the deep water proper by a 10–20-m-thick primary halocline, the depth of which ranges from 60 to 80 m. The deep-water layer, which (as will be further expanded upon in the concluding section of this study) for the present purposes can be regarded as stagnant, as well as the sedimentary bedrock act as a short circuit, thereby lowering the recorded voltage. Consequently, this can be expected to decrease the "single layer" calculated magnitude of the variability compared to the transport results obtained from the sea level records, namely, precisely what has been observed in the initial data analysis reported in section 4. In order to deal with this effect, a simple electrical model will be employed. Using the same formalism as in a recent study of the stratified flow through Öresund (Fristedt et al. 2002), the following relationship (for a section of length  $L$ ) between induced voltage, conductivity, and layer thicknesses is obtained:

$$\Delta U = L F_z \left( \frac{\nu_1 h_1 \sigma_1}{\sigma_1 h_1 + \sigma_2 h_2 + \sigma_3 h_3} \right). \quad (4)$$

Here  $\nu_1$ ,  $\sigma_1$ , and  $h_1$  denote the upper-layer conductivity and thickness, respectively;  $\sigma_2$  and  $h_2$  the corresponding lower-layer characteristics. The third layer (with index 3) has been introduced to handle the conducting sedimentary bedrock. The relative thinness of the transition layer between the two water masses justifies the approach of using the halocline depth as a measure of the level of the interface between the two layers. The formula shows that in order to calculate the corrected transport,  $Q_{\text{min}}^{\text{corr}}$ , it is necessary to multiply the measured voltage with a scaling factor (which under the prevailing circumstances proves to amplify the calculated transport). It is worth underlining that in spite of using a simple model, it is possible to not only calculate the transport but also to determine the upper- and lower-layer thicknesses. Furthermore, note that in formula (4) the denominator includes both the lower-layer and the sedimentary bedrock conductances. This latter quantity was previously estimated to be 2.4 S, to be compared to the lower-layer conductance of 29 S (based on a conductivity of  $1.2 \text{ S m}^{-1}$  and a thickness of 24 m). The influence of the sandstone seabed is thus of minor importance and will henceforth be neglected.

Consequently, instead of the averaged transect bottom depth, the upper-layer thickness (as defined by the halocline depth) was used for both the "tidal gauge" and the "voltage monitored" transport-variability calcula-

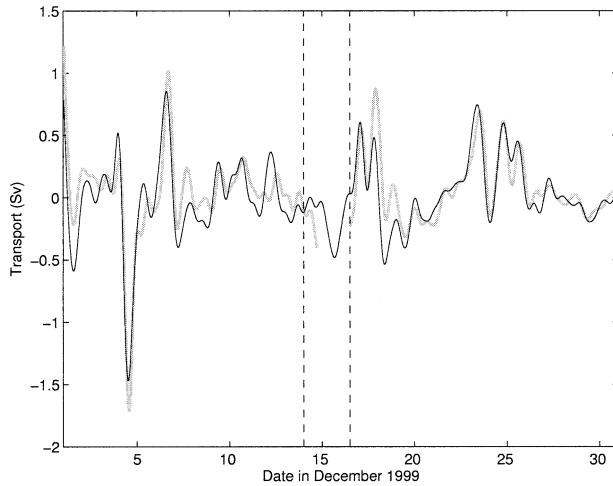


FIG. 8. Overall results from the refined analysis showing  $Q_{\text{geo}}$  (gray line) and  $Q_{\text{mv}}$  (solid line), the corrected transport variabilities from the geostrophic and voltage calculations, respectively. The period 14–16 December was characterized by an exceptionally pronounced local *windstau* effects at the Öland tidal station. This is possibly why the geostrophic results for this period deviate strongly from the transports deduced from the cable measurements.

tions, under the auxiliary assumption that the deep-water layer was stagnant. Figure 8 shows the corrected transports, which are seen to match each other very closely. In this analysis the layer thicknesses were determined by minimizing the difference in variability between the two transports. An optimal result was achieved for an interface depth of 78 m, consonant with the hydrographic results shown in Fig. 6 as well as with climatological data (Voipio 1981).

Despite the overall good agreement between the two sets of independently determined transport results, there remain some minor discrepancies. Their source is far from self-evident in view of possible lower-layer motion. The fact that the measurements were performed over two slightly different transects may also have played a role, and it must further be kept in mind that it is not given a priori that the transport at all times is in a perfect geostrophic balance; compare the previously discussed anomalous period 14–16 December.

## 6. Discussion and outlook

From the obvious mutual coherence shown by the initial estimates, it is clear already that the first transport values calculated from the voltage record in section 4 were not altogether off the mark, particularly with respect to the variability. It was, however, recognized that these estimates could be further improved, and in section 5 a somewhat more subtle analysis was undertaken, leading to considerable improvements and an ultimately very satisfactory set of results as summarized in Fig. 8. This more detailed treatment of the dataset used the large-scale vertical features of the Baltic hydrography as a vantage point, in particular the fact that between

Gotland and the Swedish mainland the deep-water layer may be regarded as essentially stagnant. In order to justify this premise, we shall here expand somewhat on the oceanographic basis for what de facto represents a decomposition of the motion into a barotropic as well as a compensating baroclinic mode (where the latter serves the purpose of yielding a more-or-less quiescent deep water).

As noted already in the introduction, the Baltic is a strongly stratified sea, with dense, high-saline deep water entering through the Danish Straits and proceeding gradually along a series of deep basins in a counter-clockwise direction around Gotland until it finally has been entrained into the surface layer. The western Gotland basin, across which our two sections stretched, represents the “end of the line” as regards this process, since to the south it is separated from deeper regions by a pronounced ridge with a threshold depth of around 50 m stretching between the southern headlands of Öland and Gotland (cf. the map in Fig 2). Hence the tongue of deep water extending southward through the western Gotland basin is arrested, which implies a very weak southward flow corresponding to the entrainment flux into the surface layer. In view of the barotropic forcing prevalent in the area, it appears likely that this state of affairs is maintained by baroclinically compensating lower-layer motion maintained by adjustments of the permanent halocline. A mechanism of this type is consistent with the more or less stagnant deep-water conditions known to characterize the two sections made use of in the analysis.

To conclude this study it may be noted that the monitoring system for the transport between Gotland and the Swedish mainland shows encouraging signs of being in reasonable working order. An important use envisaged for the installation is to provide volume fluxes over a section for assimilation in the operational numerical models of the Baltic currently being run. Note, however, that data assimilation with respect to an integrated property such as that presently considered (viz., the entire transport over half a circulation gyre) will undoubtedly pose new and challenging formal problems, since assimilation techniques primarily have been developed within the framework of meteorological forecasting and for other types of datasets.

Further use of the observational records is contemplated when examining the high-frequency variability of the flow, that is, precisely the signal component that in the present investigation was extirpated by applying a low-pass filter. (In a sense processes over longer time scales can already, as shown here, be dealt with satisfactorily solely on the basis of the water-level records, which, for this spectral range makes the voltage record somewhat redundant.) This nongeostrophic superinertial motion is, in integrated form, immediately available from the Västervik–Visby record. It is foreseen that this information will prove useful, especially when judging if the three-dimensional models presently becoming op-

erational do justice to the rapid, transient processes that, as a result of the meteorological forcing, are such a typical oceanographic feature of the Baltic.

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