Papers

Coherent current oscillations and water exchange in the straits of the Gulf of Riga*

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Abstract

The water exchange processes through the Irbe and Virtsu (Suur) Straits were investigated in 1993–1997 within the framework of a five-year study programme – the Gulf of Riga Project. Simultaneous current measurement data from autonomous mooring stations in both straits were available for the analysis in two periods. In addition to the dominant signals – inertial oscillations in the Virtsu Strait and diurnal oscillations in the Irbe Strait – low-frequency oscillations were found in both straits.

During the experiment in July–August 1994, 12–14-day oscillations were observed in both straits: the maximum phase lag in the Virtsu Strait was 1 day. The other important low-frequency periodic component in both straits was 88 hours. In this case, the phase lag in the Virtsu Strait was about 20 hours.

In the 1995 experiment in the Irbe Strait, 42-hour oscillations were observed with a phase lag of 10–12 hours. The amplitude was about 30 cm s^{-1} in both

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straits. As in Lilover et al. (1998), where the flow regime in the Irbe Strait was observed, we can interpret these oscillations as being wind-generated. The present work shows the existence of these disturbances also in the Virtsu Strait.

The 88-hour oscillations observed in July–August 1994 can be interpreted as the first mode of the basin's eigenoscillations according to the concept of Otsmann et al. (1997) of a basin with two separate outlets. The lowest frequency oscillation with the period of 12–14 days seemed to propagate to the Gulf of Riga from the Baltic Proper, but the generating force could not be established because there was no noticeable variability between depressions and anticyclones during that period.

Based on the current measurements, two types of water exchange through the Irbe strait were established: the outflow over the whole cross-section of the strait, and a bidirectional flow with an inflow near the southern shore and increasing inflow in the near-bottom layers and an outflow in the northern part of the strait.

1. Introduction

The Gulf of Riga (also known as the Gulf of Liivi) is a basin of the Baltic Sea bordering Estonia (the southern parts of the islands of Saaremaa and Muhu) and Latvia. The Gulf is about 16 400 km^2 in area and about 425 km^3 in volume, which gives a mean depth of 25.9 m. A relatively shallow basin, the Gulf receives a heavy load from rivers (mainly from the Daugava). This was the circumstance that inspired the study of the influence of the Gulf of Riga as a source of pollution on the Baltic Proper. The Gulf is connected with the Baltic Proper through the Irbe Strait and with the entrance of the Gulf of Finland through the Moonsund straits, the southern part of which is the Virtsu Strait (also known as the Suur Strait). The cross-section area of the Irbe Strait is about 0.4 km^2, with a sill depth of 25 m and a width of about 30 km, and the narrowest cross-section of the Virtsu Strait is 0.04 km^2, with a depth of about 5 m. Both straits are important as regards water exchange between the Gulf of Riga and the Baltic Sea. To study the exchange of water and matter between the Gulf of Riga and the Baltic Sea, the Nordic Council of Ministers organized a five-year study programme in 1993–1997 called the Gulf of Riga Project. Within the framework of this Project, numerous measurements were carried out in both straits. In the present paper we concentrate on current measurements in the straits, particularly on the low-frequency periodic components of the currents. A knowledge of periodic variability helps to avoid mistakes in the interpretation of short-term or single measurements.

In a previous study, Pastors (1967) pointed out the two-layered character of currents in the Irbe Strait. Petrov (1979) observed the oscillating nature of the currents in the Irbe Strait, which he interpreted as being of tidal origin. The present investigations in the Irbe Strait focused on the meandering of the front separating the two different water masses described by Lips et al. (1995) and Lilover et al. (1998), and on the water exchange through the straits. The results of the current measurements carried out during the Gulf of Riga Project are reported in Talpsepp & Laanearu (1995). There are more current measurements in the Virtsu Strait, starting with those carried out by Mardiste (1964, 1975). Throughout the Gulf of Riga Project, current measurements in the Virtsu Strait were carried out every year, including winter measurements under ice-cover (Suursaar et al. 1995).

2. Material and methods

The present work focuses on the coherence of water oscillations in both straits of the Gulf, based on current measurements. As mentioned before, numerous current measurements were carried out within the framework of the Gulf of Riga Project, especially in the Virtsu Strait. The current measurements from two periods – July–August 1994 and June 1995 – suited our purposes perfectly. The locations of the mooring stations in the Irbe Strait is shown in Fig. 1: 1994 – station P0 (57°49.9′N, 22°09.1′E) – the

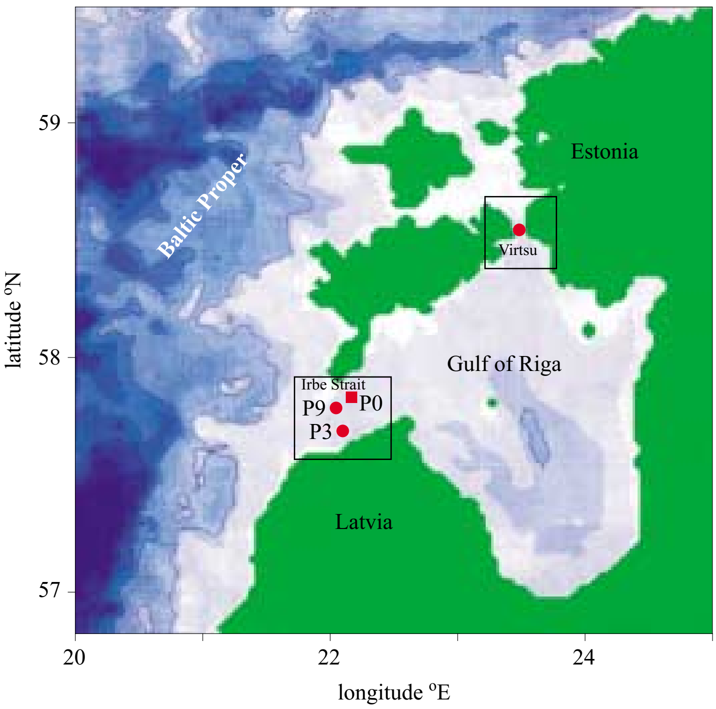


Fig. 1. The location of mooring stations in the Irbe and Virtsu Straits. The circles in the Irbe Strait denote the location of stations P3 and P9 in 1995, and the square shows the location of station P0 in 1994. The circle in the Virtsu Strait denotes the mooring station in 1994 and 1995

square in Fig. 1, with one current meter at a depth of 12 m in water 26 m deep; 1995 – stations P3 (57°41.6′N, 22°06.0′E) and P9 (57°47.3′N, 22°02.9′E) – the circles in Fig. 1, with two meters deployed at respective depths of 5 and 17 m in waters 23 m deep. Time series of current measurements, i.e. velocity, direction and temperature, were recorded on Aanderaa RCM4 and RCM7 instruments at these autonomous mooring stations every 10 or 15 minutes.

Wind data for 1994 were available from the Ruhnu and Vilsandi weather stations. The wind speed was rather low, exceeding 8 m s^{-1} only twice during a period of nearly two months. In spite of the considerable distance between these stations, wind speeds were similar at both, indicating that local winds are of lesser importance. In June 1995, three depressions passed through the region at two-day intervals; the wind variability also reflected this pattern.

3. Results

The current measurements carried out in 1994 in the northern part of the Irbe Strait (Fig. 1) showed outflow from the Gulf of Riga to be dominant, but in 1995 a bidirectional current structure was observed. Fig. 2 shows progressive vector diagrams for the southern and northern parts of the Gulf. North is oriented upwards, and the velocity scale in the panels varies in each one. The measurements were started on 9 June 1995, and circles were drawn every 24 hours. As Fig. 2 and the measurements of temperature, salinity and current measurements with ADCP (Lilover et al. 1998) show, the inflow of water to the Gulf of Riga near its southern coast was dominant (bottom layer, station P3). At the same time, the outflow observed in the upper layer and in the northern part of the strait (Fig. 2) was oriented along the strait at about 230° with respect to north. The maximum inflow velocity was 31 cm s^{-1}, the outflow 10 cm s^{-1}, and the mean inflow 6 cm s^{-1}. Independently of the direction of the mean flow at the two stations, there was a slight decrease in the periodic low-frequency variability with depth.

We next compared the periodic components in the currents in the Virtsu and Irbe Straits in July–August 1994. Variability with inertial and diurnal frequency was always present in the currents, but because we regard this variability as a local phenomenon, we have concentrated on low-frequency variability. To compare low-frequency variability in the two straits it seemed reasonable to use the along-channel oriented inflow component in the Irbe Strait and the along-channel oriented outflow component in the Virtsu Strait. Therefore, we used differently oriented coordinate systems in the straits (see Fig. 1 for channel orientation).

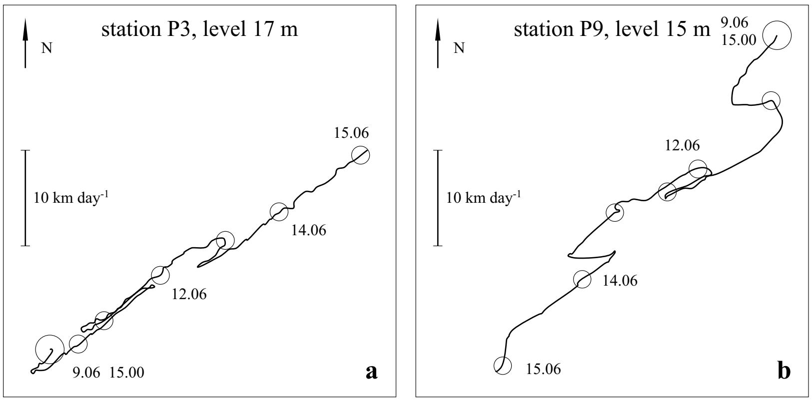


Fig. 2. The progressive vector diagrams in the southern (station P3, level 17 m) and northern (station P9, level 5 m) parts of the Irbe Strait in June 1995. North is oriented upwards, and the velocity scale is given differently for each panel

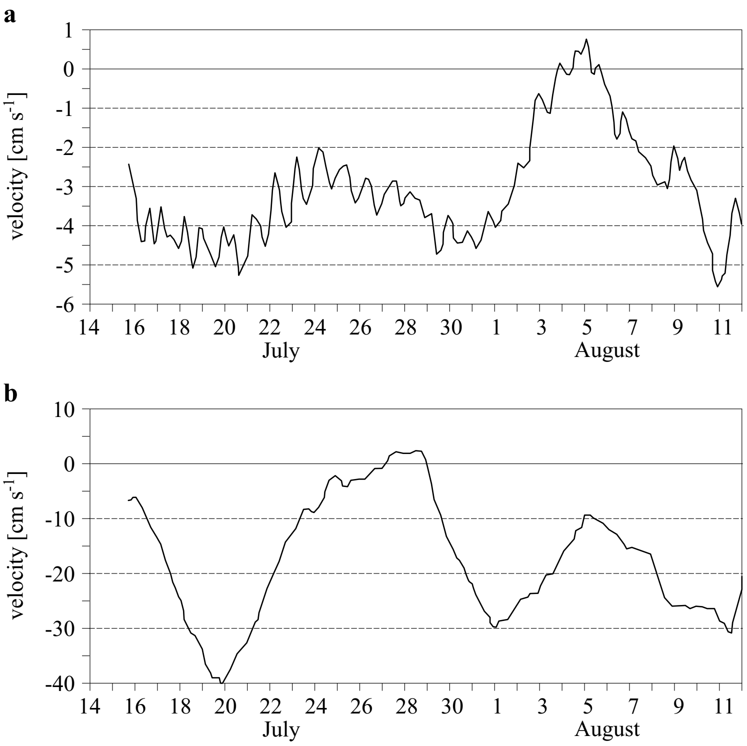


Fig. 3. The current oscillations in the Irbe and Virtsu Straits in July–August 1994, where the period of 88 hours has been filtered out. Panel (a) – filtered along-channel oriented component (T > 88 hrs) of the inflowing current at 10 m depth at station P0 in the Irbe Strait, panel (b) – filtered along-channel oriented component (T > 88 hrs) of the outflowing current at 5 m depth in the Virtsu Strait

Low-pass filtering and spectral analysis were used to find the dominant periods in the longitudinal channel components of the current velocity. The results of filtering were less dependent on the type of low-pass filter. In the present case, a Hanning filter with cut-off periods of 24 and 88 hours was used. The power spectral density of the along-channel oriented current in straits was computed using the Welch averaged periodogram method. With this method, the data row is divided into overlapping sections which are then detrended and windowed by the Hanning filter. The Welch method was used to increase the number of degrees of freedom and through that, to improve the reliability of the spectral calculations.

In the low-frequency band, current oscillations with periods of 88 hours and 12–13 days occurred in both straits. Fig. 3 shows the current oscillations in the Irbe and Virtsu Straits where the variability with the period of

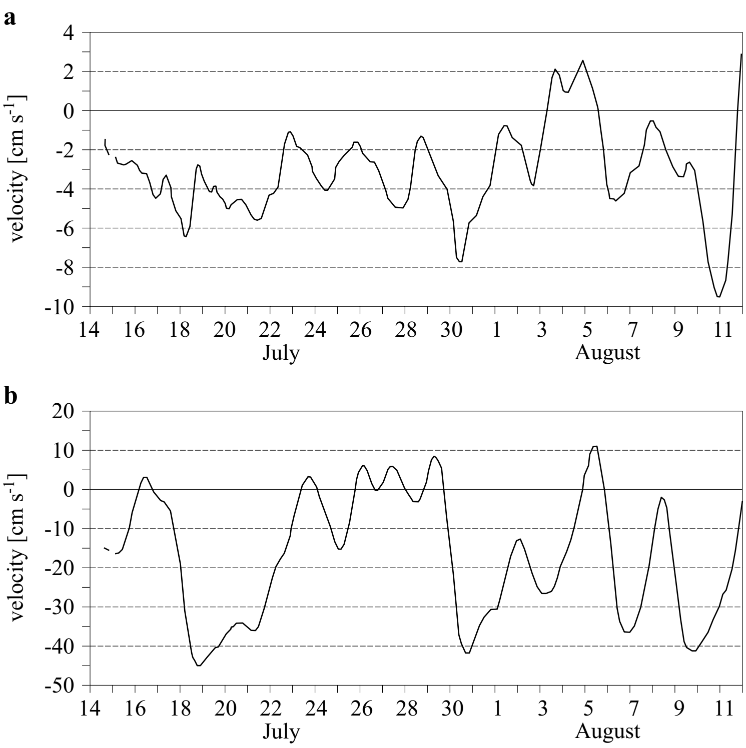


Fig. 4. The current oscillations in the Irbe and Virtsu Straits in July–August 1994 with the inertial and diurnal components filtered out, demonstrating the dominant 88-hour period in both series. Panel (a) – filtered ($T > 24$ hrs) along-channel oriented component of the inflowing current at 10 m depth at station P0 in the Irbe Strait, panel (b) – filtered along-channel oriented component ($T > 24$ hrs) of the outflowing current at 5 m depth in the Virtsu Strait

88 hours has been filtered out. In the Irbe Strait the amplitude of oscillations was 2–3 cm, whereas in the Virtsu Strait it was about 20 cm, i.e. 10 times higher. Fig. 3 also shows signs of dominant diurnal oscillations: these were not completely removed by the filter length we used. We established that the cross-section of the Irbe Strait is ten times larger than that of the Virtsu Strait, so we can conclude that the oscillating water mass in both straits is nearly equal. The phase lag in the Virtsu Strait is about one day or oscillations are even in the same phase, that is, they have zero phase shift. Because only a few oscillations occurred during the measurement period, it was not possible to detect the phase shift with greater accuracy.

Fig. 4 shows the same current components with the diurnal and inertial oscillations filtered out. We found the dominant period of 88 hours to be the mean value of local extremes in the low-pass filtered series. The 88-hour oscillations were dominant in both current series with a phase lag of about 20 hours in the Virtsu Strait. With regard to the 12–13 day oscillations, the amplitudes of oscillations also differed by one order of magnitude (2–3 cm s^{-1} in the Irbe Strait and 10–25 cm s^{-1} in the Virtsu Strait).

During the period of intensive measurements in 1995 (Lips et al. 1995), the period of dominant current oscillations (30 cm s^{-1}) was 42 hours in both straits (Fig. 5) with a phase lag of 10–12 hours in the Virtsu Strait. The oscillations were recorded in the upper layer (5 m) at the northern station

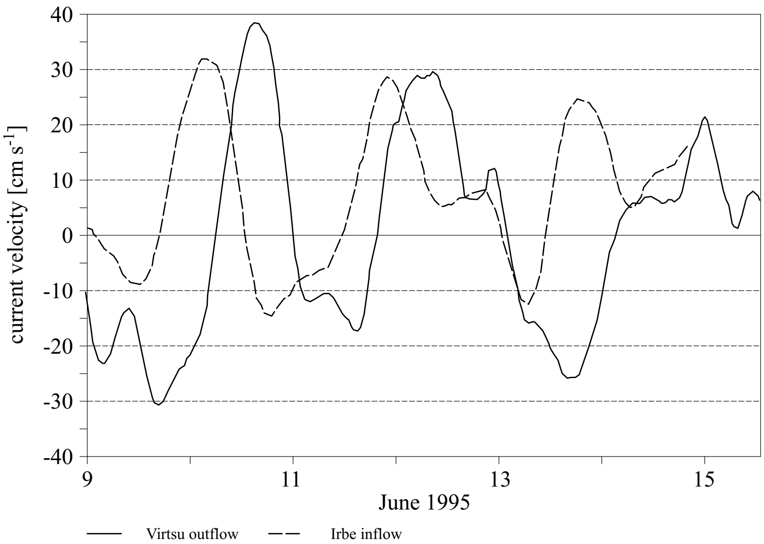
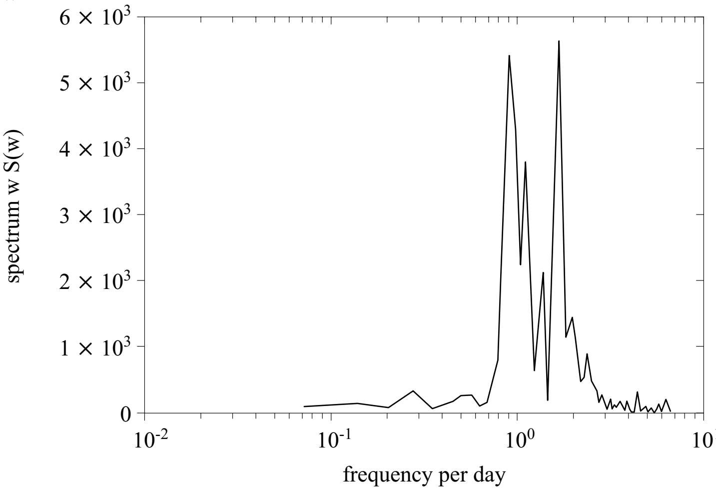


Fig. 5. The along-channel oriented current components (T > 24 hrs) in the Irbe and Virtsu Straits in 1995 with the diurnal oscillations filtered out. The dominant 42-hour oscillations in both series with a phase lag of about 10–12 hours can be observed in the Virtsu Strait

(Fig. 1) and in the near-bottom layer (17 m) at the southern station with a phase-lag of some hours near the bottom. To compare the data from the Irbe Strait with those from the Virtsu Strait, we used the data from the upper layer at the northern station. Different from the measurements in 1994, the amplitude of the longitudinal current speed was of the same magnitude in both straits.

a



b

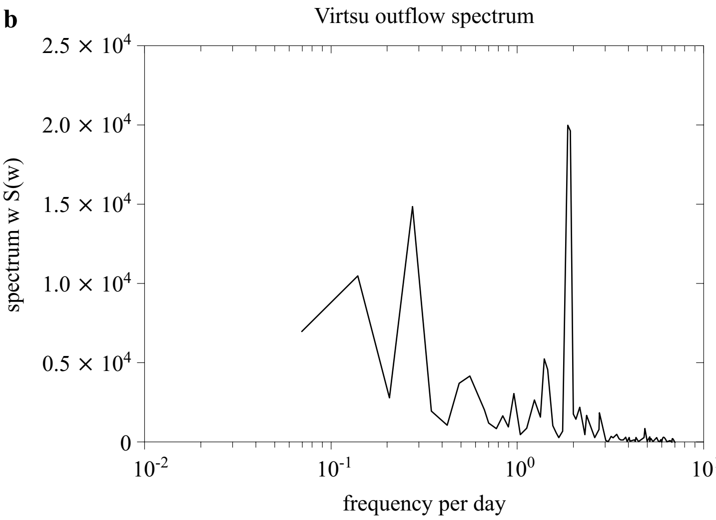


Fig. 6. The spectral densities of the along-channel oriented inflow current component in the Irbe Strait at 10 m depth at station P0 (a) and of the outflow current component at 5 m depth in the Virtsu Strait (b) of the measurements carried out in July–August 1994. The Welch averaged periodogram method with the Hanning window is used

Figs 6a and 6b present the respective spectral densities of the along-channel oriented inflow current component in the Irbe Strait and of the outflow current component in the Virtsu Strait. The spectral density presented in the coordinate w S(w) enables us to compare the energy in different frequency bands, because the energy is proportional to the area under the spectral density line in Fig. 6. The spectra confirm the results observed in Figs 3–5 in both straits during the period of measurements, namely, that inertial oscillations were well developed, and that the diurnal oscillations with the highest energy in the Irbe Strait contained less energy than those in the Virtsu Strait, but were still distinguishable. The energy of the low-frequency oscillations, i.e. 42 hours, 88 hours and 12–13 days was highest in the Virtsu Strait. These periods could also be observed in the Irbe Strait, where their contribution to the whole energy of oscillations was smaller.

Fig. 7 shows the coherence between the inflowing current in the Irbe Strait and the outflowing current in the Virtsu Strait. The straight line in Fig. 7 denotes the 95% confidence limit of zero coherence; thus, there is a 95% probability that values exceeding this level are coherent. Although the number of points in the low-frequency band is small in the graph in Fig. 7, we can see that all periods in the low-frequency band exceed the line of zero coherence. Thus, we can conclude that low-frequency oscillations in both straits are statistically coherent. We can also notice the confident coherence of current components at local inertial and diurnal frequencies, which exceeded the 95% confidence level. Thus, although the

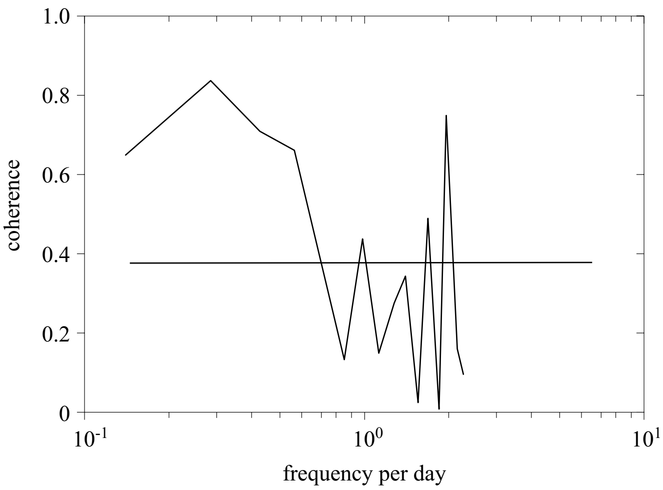


Fig. 7. The coherence between the inflow current in the Irbe Strait and the outflow current in the Virtsu Strait. The confidence level of zero coherence is 95%

inertial oscillations were dominant in the Virtsu Strait, these oscillations also existed in the Irbe Strait and correspondingly, the diurnal oscillations that were dominant in the Irbe Strait also existed in the Virtsu Straits, thereby displaying a statistical coherence of currents in both straits at these frequencies.

4. Discussion and conclusions

Otsmann et al. (1997) used a integrated barotropic model of the Gulf of Riga with channels connecting the Gulf of Riga with the Baltic Proper based on equations of motions describing the water balance of the system. The model was constructed by Otsmann et al. (1997) to study the water exchange between the Baltic Proper and Gulf of Riga as a result of periodic processes, diurnal oscillations in particular. The input parameters of the model are the water level outside the Gulf, the wind stress τ in the channels, and the river inflow into the Gulf; the model outputs include the flow volumes $Q_1(t)$ and $Q_2(t)$ in the straits.

The procedure of solving the main equations leads to the classic problem in mechanics of forced oscillations, introduced, for example, by Landau & Lifschitz (1973), where the assumption of the existence of a nontrivial periodic solution enables us to obtain the eigenfrequencies of the system. In our case the eigenfrequency in the mesoscale range giving the periodic solution is of interest. The period in the mesoscale range of interest is longer than the diurnal period but shorter than several weeks.

When checking the model assumptions, we found that during the experiment in 1994 the volume fluctuations in both straits were of the same order; we were therefore able to use the two-channel basin model of Otsmann et al. (1997) for the interpreting the measurements during this experiment.

Neglecting friction, the model equations can be expressed as follows:

$$\frac{dQ_1(t)}{dt} + \frac{gF_1}{L_1}h(t) = f_1(t), \tag{1}$$

$$\frac{dQ_2(t)}{dt} + \frac{gF_2}{L_2}h(t) = f_2(t), \tag{2}$$

$$F\frac{dh(t)}{dt} = Q_1(t) + Q_2(t) + Q_j(t), \tag{3}$$

$$f_i(t) = F_i\left[\frac{g}{L_i}H_i(t) + \frac{\tau_i(t)}{d_i}\right],\ i = 1, 2, \tag{4}$$

where $H_i(t)$ and $h(t)$ are the horizontally averaged water levels in the Baltic Proper and in the Gulf of Riga, $Q_1(t)$ and $Q_2(t)$ are the volume fluctuations in the Virtsu and Irbe Straits respectively, and τ_1 and τ_2 are the wind-stress projections to the directions of channels (Fig. 1). The parameters appearing in the model were as follows: g – acceleration due to gravity, F – area of the Gulf (1.63×10^{10} m^2), F_1 – cross-section of the Virtsu Strait (4.5×10^4 m^2), F_2 – cross-section of the Irbe Strait (4×10^5 m^2), L_1 – length of the Virtsu Strait (7.5×10^4 m), L_2 – length of the Irbe Strait (4.8×10^4 m), d_1 – depth of the Virtsu Strait (10.5 m), d_2 – depth of the Irbe Strait (19 m).

Combining eqs. (1)–(3) for forced oscillations, we can find eigenfrequencies of 23.6 hours, 92 hours and 24.4 hours for the Gulf of Riga (Otsmann et al. 1997). In both straits well-developed diurnal oscillations were observed that are close to the corresponding eigenfrequencies of the model. We can also see that one of the dominant periods observed in the measurements (88 hours) is very close to the model's eigenfrequency, corresponding to a period of 92 hours. In view of the fact that the model input parameters are given approximately, we can conclude that the coincidence of the observed and model periods is satisfactory. The phase speed corresponding to the 88-hour oscillations is 1.7 m s^{-1} (120 km in 20 hours).

The 12-13-day oscillations were also volume-consuming – the oscillating water volume (not the water level) in both straits was of the same order of magnitude. We exclude the local wind force as the generating mechanism of these long-period oscillations, because on the basis of data from the nearby weather stations at Ruhnu and Vilsandi, the wind did not exceed 6 m s^{-1} during the experimental period and no variability with close to a 12-13-day period was observed. We set up the hypothesis that the large-scale air pressure variation in the Baltic Sea area may be a possible generating force and that these low-frequency oscillations come from the Baltic Proper. In earlier work concentrating on mesoscale variability in the Baltic Sea, the topographic wave mode was found to be dominant (Talpsepp 1983, Raudsepp et al. 2003). In the present case the oscillations propagate with the shallower water to their left from the Irbe Strait to the Virtsu Strait, in contrast to the theory of topographic low-frequency waves, which can propagate only with the shallower water to their right (Mysak 1980).

Next, we considered the generating mechanism of the 42-hour oscillations during the experiment in 1995. During the two-week period in that year, the wind was found to be the generating force. During the experiment, 42-hour oscillations were found in both straits. Lilover et al. (1998) refers to the passing of low pressure patterns over the Irbe Strait area with wind speeds up to 10 m s^{-1}. Depressions passed through the region three times during the measurement period, at intervals of two days. As a result, the intermittence of westerly and easterly winds over the Irbe Strait was found to be highly correlated with the current oscillations in the Irbe Strait. As we can see in Fig. 5, the current oscillations are similar in both straits and we can conclude that the 42-hour oscillations in both straits are wind-generated with a phase lag in the Virtsu Strait, as mentioned above.

The whole spectrum of oscillations is of importance in the exchange of water and matter between the Gulf of Riga and the Baltic Proper. If during inertial oscillations water circulates around an ellipse with diameters up to 1–1.5 km (the current speed in that period ranges from 10 to 15 cm s^{-1}), then under the influence of the low-frequency oscillations, the diameter of the water circulation will already have increased to 25–50 km in the strait area. This kind of oscillating movement in the strait area has a substantial influence on the water exchange, because the water that is temporarily carried out into the Baltic Proper from the strait area (into the Gulf) will mix with the water in the Baltic Proper (inside the Gulf). Thus, regardless of the generating force, the observed low-frequency variability will create a water exchange mechanism in the straits of the Gulf of Riga, and in the Irbe Strait in particular, owing to the longer space scales.

River inflow is of great importance in the water exchange in the long term because this and precipitation exceed evaporation in the Gulf of Riga and in the Baltic Proper. Thus, water outflow from the Gulf of Riga to the Baltic Proper is dominant, according to the calculations of annual values or mean values over many years. On the other hand, we cannot see any reason why water inflows from rivers will contribute to the mesoscale periodicity of the water level or currents in the straits.

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