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Interannual and Seasonal Temperature and Salinity Variations in the Gulf of Riga and Corresponding Saline Water Inflow From the Baltic Proper

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Salinity and temperature data from the Gulf of Riga, a semi-enclosed sub-basin of the Baltic Sea, were analyzed with a focus on interannual and seasonal variability. The data were compiled from measurements taken from 1973 to 1995, a period which includes the stagnation period in the Baltic Sea. Interannual and seasonal variations in the net inflow of saline water from the Baltic Proper were estimated from volume and salt conservation equations for the period 1973-90.

The basic decreasing trend, superimposed interannual variations in salinity, and interannual and seasonal temperature variations in the Gulf of Riga coincided with corresponding changes above the halocline in the Baltic Proper. Seasonal salinity variations were notable in the Gulf of Riga as compared to the Baltic Proper, where variations were negligible. Estimated annual mean inflow varied between 2,000 and 5,000 m^3/s (average 3,200 m^3/s), with a notable increasing trend. A simultaneous increasing trend was extracted from annual mean river flow data. Short-term fluctuations (over 4-6 years) of annual mean inflow ran opposite to the fluctuations of the magnitude of river flow. The average salinity in the Gulf of Riga increased during strong inflow and weak river flow and decreased when inflow was weak and river flow was strong. Variations in the inflow of water salinity had a minor effect on salinity variations in the Gulf of Riga. Seasonal inflow was strongest in spring and autumn and weak in winter.

Introduction

The stagnation period in the Baltic Sea during the last quarter of the 20th century is well known. From 1977-93 there occurred no intense inflows of saline water from the North Sea via the Skagerrak and Kattegat into the Baltic Sea (Matthäus and Franck 1992). Major inflows feed permanent saline stratification in the cascade of sub-basins of the Baltic Proper as well as in parts of the Gulf of Finland. During the stagnation period, salinity in the Baltic Proper decreased by 1-1.5 psu in and below the halocline (Samuelsson 1996; Elken 1996). Salinity decline of the same magnitude was observed in the bottom layers of the Gulf of Finland (HELCOM 1996). Salinity also decreased in the northern part of the Baltic Sea and the Gulf of Bothnia. In the bottom layer of the Bothnian Sea, the maximum decrease was 1 psu; in the Bothnian Bay, the decrease was only 0.4 psu (Samuelsson 1996). In 1993 a major inflow of high saline water put an end to the stagnation period (Matthäus and Lass 1995). The result was a renewal of deep waters in the Baltic Proper and a corresponding salinity increase of 1-1.5 psu in 1994 (Elken 1996).

The Gulf of Riga, a relatively closed, almost circular eastern sub-basin of the Baltic Sea, receives its saline water from the upper portion of the Baltic Proper (Fig. 1). The gulf has a surface area of 14,000 km^2, a volume of 408 km^3 and a mean depth of 29 m (HELCOM 1990). The gulf is connected to the Baltic Proper by two straits. One is the Irbe Strait, which connects the gulf to the Eastern Gotland Basin and has a width of 27 km, a sill depth of 21 m, and a minimal cross-section area of 0.37 km^2. The second actually consists of a system of straits. The Virtsu Strait (Suur Strait) is the southernmost and narrowest (5 km) part of the system, with a sill depth of about 5 metres. The Gulf of Riga's salinity is heavily influenced by river runoff, with a complete turnover of the water column occurring every winter. The main rivers are located along the southern and eastern perimetres of the gulf. Average yearly river runoff is 32 km^3 (Bergström and Carlsson 1994).

This article will focus on temperature and salinity variations in the Gulf of Riga over time, concentrating on interannual and seasonal variations over a 23-year period. Because salinity in the Gulf of Riga is influenced by external factors such as freshwater supply, water and salt exchange with the surrounding sea, and meteorologically influenced local factors such as wind and convective mixing and circulation (plus the fact that water temperature is determined by air-sea heat exchange), co-variations of hydrography in the Gulf of Riga and Eastern Gotland Basin and their freshwater supply will be examined. Interannual and seasonal variations of water inflow, which are needed to explain observed salinity changes in the Gulf of Riga, will be calculated from salinity and volume conservation principles.

Variations in hydrographic conditions in the Gulf of Riga are important for the regional oceanography and ecology. Indeed the Gulf of Riga appears to be a source of nutrients – as well as pollutants – for the Baltic Proper (Yurkovskis *et al.* 1993; Mägi and Lips 1998). Previous studies on the hydrography of the Gulf of Riga have focused only on short-term snapshots of temperature and salinity distribution (Stipa *et al.* 1999; Kõuts 1995) and water exchange and hydrographic structures in the Irbe Strait (Lilover *et al.* 1998; Lilover *et al.* 1995; Lips *et al.* 1995).

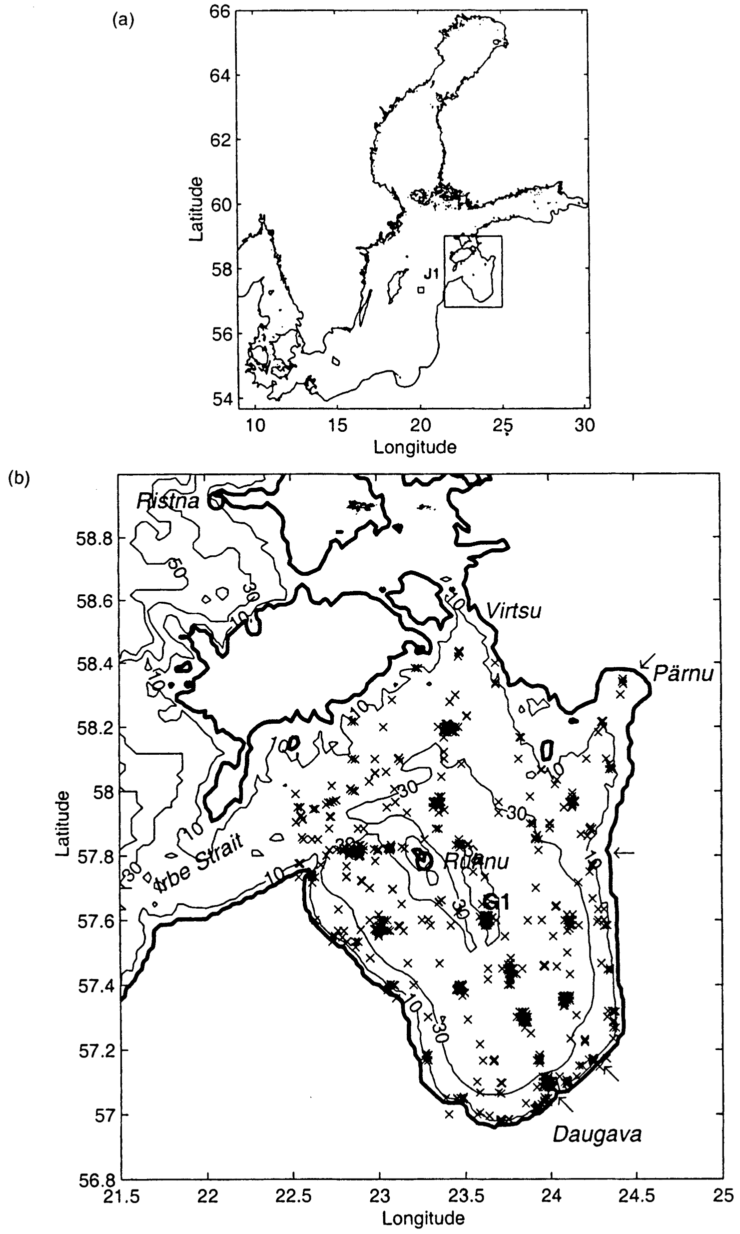

Fig. 1. Contour of the Baltic Sea with the location of the data area (J1) for the Baltic Proper hydrographic data (a). Bathymetry of the Gulf of Riga and the locations of the hydrographic data points (x). G1 is the most frequently visited monitoring station in the Gulf of Riga. Sea-level data are from Ruhnu, representing the sea-level of the Gulf of Riga. Arrows show the locations of the major rivers of the Gulf of Riga basin (b).

Table 1 – Distribution of salinity observations at 30 m in the Gulf of Riga.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Tot
1973	0	0	0	0	2	0	0	2	0	2	0	0	6
1974	0	3	0	4	3	4	3	4	4	3	3	3	34
1975	3	4	0	3	3	3	3	3	3	3	0	0	28
1976	0	0	0	6	11	6	5	6	5	5	0	0	44
1977	1	0	0	6	5	6	3	6	2	4	4	0	37
1978	7	0	0	0	18	9	9	9	4	5	0	0	61
1979	0	0	0	3	6	6	7	0	4	9	0	0	35
1980	3	0	0	5	17	9	7	8	0	9	1	0	59
1981	0	3	0	0	9	0	4	9	4	9	5	0	43
1982	0	0	0	0	9	0	0	9	0	9	0	0	27
1983	0	8	0	16	6	0	0	9	0	9	0	0	48
1984	1	0	0	0	9	0	0	14	0	7	2	0	33
1985	0	0	0	0	11	0	0	9	0	9	0	2	31
1986	1	0	0	0	13	1	0	10	0	13	3	2	43
1987	0	0	0	0	17	7	0	6	8	9	0	1	48
1988	5	8	0	16	16	0	0	7	0	0	9	2	63
1989	5	13	5	1	14	6	5	9	0	9	0	0	67
1990	0	9	0	0	9	3	0	9	0	9	0	0	39
1991	2	8	0	2	17	0	1	9	0	0	1	1	41
1992	1	12	3	1	12	3	13	2	2	11	6	3	69
1993	2	1	15	7	20	4	2	32	3	0	18	2	106
1994	4	0	0	20	24	20	20	16	17	11	14	13	159
1995	0	6	5	21	44	5	20	17	21	22	5	0	166
Tot	35	75	28	111	295	92	102	205	77	167	71	29	1287

Data

Available hydrographic data on the Gulf of Riga were assembled into a common database within the framework of the Gulf of Riga Project. The data cover the period 1973-95 and consist mainly of temperature and salinity values at standard depth. Data from the area of 22° 30'-24° 30'E and 56° 30'-58° 30'N were considered representative for the Gulf of Riga. (Spatial distribution of sampling locations is shown in Fig. 1b). Table 1 shows the distribution of salinity data at 30-m depth over time. On several occasions temperature and salinity casts do not coincide, but their differences are insignificant. The annual distribution of the samples gives a precise picture of the seasonal monitoring strategy: springtime conditions were normally recorded in May; summertime, in August; autumn, in October. Data coverage of other months is rather random. Winter conditions were recorded quite seldom because of frequent ice coverage.

One station, G1 (23° 37.5'E, 57° 36'N), was visited more frequently than the others. Approximately one order of magnitude fewer data is available for the G1 station than for the entire Gulf of Riga, but the temporal distribution of casts is similar to that of two data sets. Data from the single station capture pure temporal variations, while data averaged over a larger domain include mixed spatial and temporal variability. If one station is representative of gulf hydrography, then comparison of the analyses output of the two data sets allow for the distinction to be made between spatial and temporal variability. Long-term samples of mean temperature and salinity profiles calculated from both the G1 station data and from the entire Gulf of Riga data are compared in Fig. 2. Mean temperature profiles and their variability coincide well. A statistical T-test gave equal means within a 95% confidence level. This result indicates that air masses with spatial dimensions larger than the Gulf of Riga locally force thermal stratification in the gulf.

Mean salinity values are different at depths of 10 metres and 40 metres. Mean surface salinity is about 0.5 psu higher at G1, and variability is about half of that over the gulf. The spatial inhomogeneities of surface layer salinity over the Gulf of Riga include the effects of river runoff closer to the coast and migration of the surface salinity front in the Irbe Strait (Lips *et al.* 1995; Raudsepp and Elken 1995). At 40-m depth the gulf's average salinity is slightly higher than at G1. Inflowing saline water enters the gulf from the Irbe Strait and spreads along the deep western part. This water is continuously diluted with surrounding, less saline water until it reaches the bottom layer of the central gulf. Thus, there is some reduction of deep water salinity until it is measured at the G1 station (Kõuts 1995). Coinciding salinity values at the 50-m depth result from most of the data being taken from the G1 station. It therefore may be concluded that G1 station data are representative of the hydrography of the Gulf of Riga. Furthermore, the location of the G1 station is optimal for monitoring summertime temperature in the Gulf of Riga (Toompuu 1995). References to G1 station data are given where appropriate.

Hydrographic variations in the Baltic Proper are described using data from the monitoring station J1 (20° 05'E, 57° 20'N) (Fig. 1). The data were extracted from the HELCOM database and cover the time period 1970-98.

Land-based sources of fresh water consist of river and coastal runoff from areas downstream from the sampling sites and from typically small coastal segments situated between monitored basins and non-monitored rivers. The data were based on the database of a monthly time resolution for the period 1970-90, compiled by Per Stålnacke of Tema Vatten, Linköping University, Sweden. Annual mean and monthly mean values of freshwater supply of integrated contributions from all rivers and coastal freshwater sources were used.

Data from the Ruhnu sea-level station were used to ascertain sea-level variability in the Gulf of Riga (Station location is shown in Fig. 1).

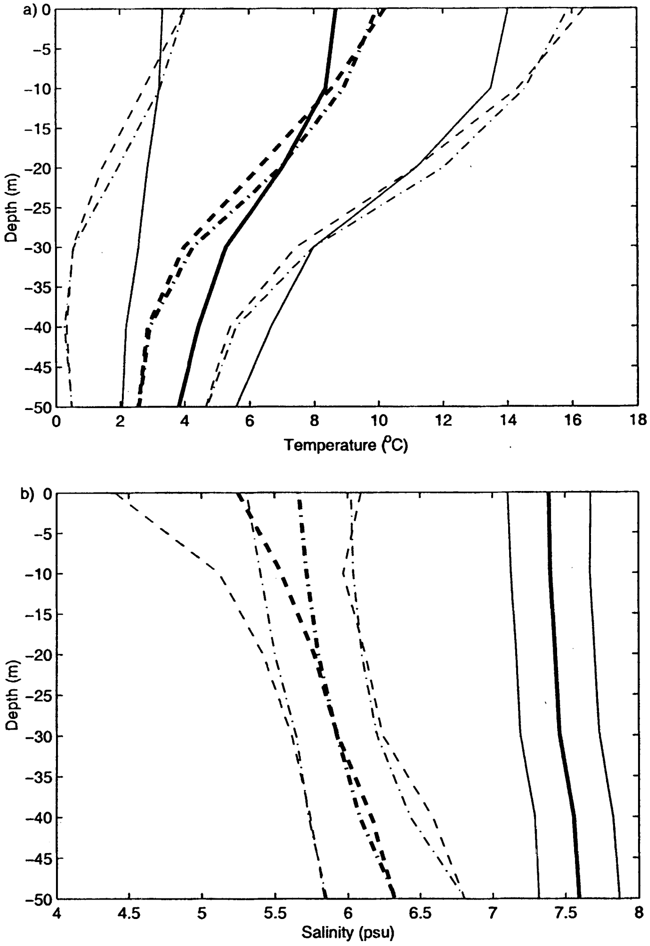

Fig. 2. Mean (bold) temperature (a) and salinity profiles (b) with standard deviations (thin) of the Baltic Proper upper layer (solid), the Gulf of Riga (dashed) and the G1 station (dash dotted).

Results

Two major water sources, river runoff and water exchange with the Baltic Proper, determine salinity in the Gulf of Riga. Net precipitation yields about 82 m^3/s, according to Omstedt *et al.* (1997). Salt supply to the Gulf of Riga is limited because of the shallowness of its connecting straits: a sill depth of 25 metres makes it difficult to believe that water from and below the halocline layer of the Baltic Proper (>60 m) can rise above sill in the Irbe Strait. Wind-induced, convective mixing and water circulation redistribute salinity and temperature in the Gulf of Riga.

Mean

Mean salinity increases almost linearly with depth in the Gulf of Riga (Fig. 2). The salinity difference between surface and bottom is about 1 psu. The upper layer of the Baltic Proper is more homohaline, giving a salinity difference of about 0.2 psu between the surface and a 50-m depth. The linear increase of long-term mean salinity with depth in the layer above permanent halocline in the Baltic Sea is characteristic of inland sub-basins receiving a considerable amount of fresh water from rivers (Omstedt and Axell 1998). Upper layer salinity of the southern sub-basins is more homogenous. In the Arkona Basin, whose size and topography are comparable to those of the Gulf of Riga, a permanent saline water pool is observed below depths of 30 metres. The pool is due to continuous leakage of high saline water from the Kattegat (Omstedt and Axell 1998; Liljebladt and Stigebrandt 1996). Salinity in the Gulf of Riga is also regularly updated, but the salinity of inflowing water is not sufficiently high to form a vertical stratification able to resist convective and wind mixing.

Mean temperature stratification and variability in the Gulf of Riga are similar to those found in other sub-basins of the Baltic Sea (Omstedt and Axell 1998). The amplitude of the annual temperature cycle is strongest at the surface and decreases with depth. An intermediate layer of minimal temperature, typically observed below seasonal thermocline at 40-60-m depth, is absent, indicating that total turnover of the water column takes place almost every year. There is greater disparity between upper and lower layer temperature in the Gulf of Riga than in the Baltic Proper because shallow coastal areas warm up faster and reach higher temperatures than do open seas during summer. Winter cooling is an analogous process: the heat stored within and below the permanent halocline resists cooling because of upward thermal diffusion in the Baltic Proper.

Temperature and Salinity Time Series

Sample mean values of temperature and salinity were calculated for each depth and month, using available data, to get a general overview of the time scales of temperature and salinity changes in the Gulf of Riga. Missing monthly values were obtained using simple linear interpolation. Results are shown in Fig. 3. Similar figures (not shown) were calculated for the G1 station. Salinity variations were visually indistinguishable. On average, surface salinity was higher when data from G1 station alone were used. The thermal structure is better resolved in the shown data set than in that for the G1 station, especially for extreme temperatures.

Seasonal signal dominates temperature variability. Warm and cold summers can be seen in the interannual variability range. Maximal summer temperatures are well resolved because of good data coverage for August, which is the warmest month. Minimal winter temperatures are definitely overestimated, owing to lack of data on the cold period. Variability in the salinity field is composed of general decline in and several events of strong saline water inflow. Certain seasonality could be identified

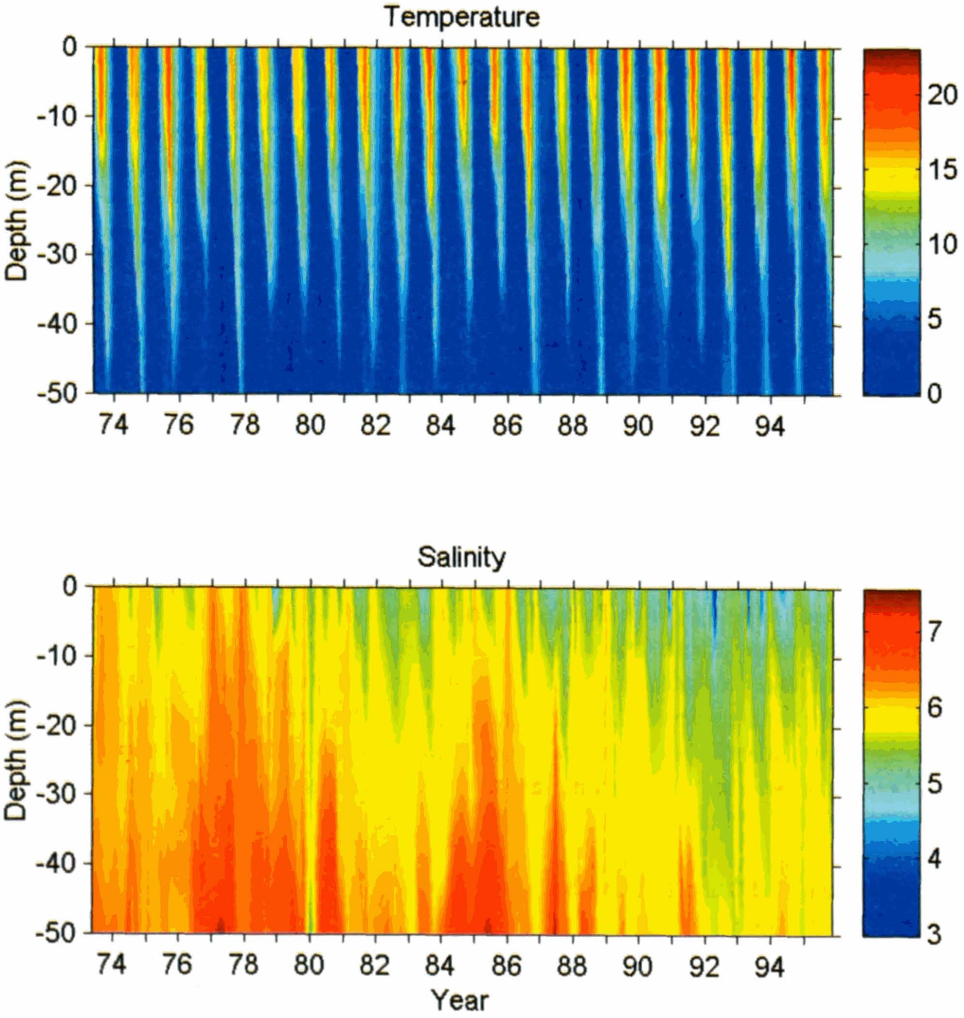

Fig. 3. Time-depth plots of temperature and salinity in the Gulf of Riga.

in the salinity time series. Deep layer salinity increase and concurrent salinity decrease in the surface layer occur during summer. The current data set does not allow investigation of variability beyond the seasonal time scale.

Table 2 – Linear trend of salinity.

Depth (m)	Gulf of Riga Slope (psu/yr)	Error (psu/yr)	Baltic Proper Slope (psu/yr)	Error (psu/yr)
0	-0.043	0.007	-0.028	0.005
10	-0.032	0.004	-0.026	0.005
20	-0.030	0.003	-0.028	0.005
30	-0.031	0.003	-0.030	0.005
40	-0.039	0.005	-0.033	0.004
50	-0.036	0.015	-0.034	0.004

Trend

There is a general freshening trend in the Gulf of Riga and the upper layer of the Baltic Proper (Fig. 4). Linear trend slope coefficients, with confidence intervals at 99.9% significance level and calculated over the time period 1973-95, are presented in Table 2. All negative trends are statistically significant. Salinity decrease is fastest in the surface layer of the Gulf of Riga, but it is not drastically different from that in other layers, remaining quite steady over a 23-year period. In the surface layer of the Baltic Proper, the trend is about 60% of that which occurs in the Gulf of Riga, while at other depths the trends overlap within error margins. A noticeable long-term increase in river runoff is consistent with the salinity decrease in the Gulf of Riga. Similar trends are observed in the Gulf of Bothnia and in the Gulf of Finland but not in the Baltic Proper (HELCOM 1996). Absence of a considerable positive trend explains the slower decrease of surface layer salinity in the Baltic Proper than in the Gulf of Riga. Continuous salinity decrease in the upper layer of the Baltic Proper shows that long-term salinity changes (due to an increase of river runoff) in the northern and eastern sub-basins of the Baltic Sea significantly affect upper layer salinity in the Baltic Proper. Renewal of halocline and deep water since 1993 did not stop the decrease of upper layer salinity until 1998. It takes much longer for saline bottom water to be vertically advected and diffused into the surface water than it takes for dense bottom water to fill the deeper parts of different sub-basins (Omstedt and Axell 1998; Axell 1998). Temperature trends were statistically insignificant, with 99.9% certainty, in both basins.

Interannual Variations

Interannual salinity variations are superimposed on the general decreasing trend in Fig. 4. Saline water inflows from the Baltic Proper cause a salinity increase in the Gulf of Riga. Two of the most pronounced events (extending over the entire water column) of salinity increase in the Gulf of Riga during the periods 1975-77 and 1983-85 coincide with similar events in the Baltic Proper. River runoff to both basins was low during these years. Opposite salinity changes were seen in the upper

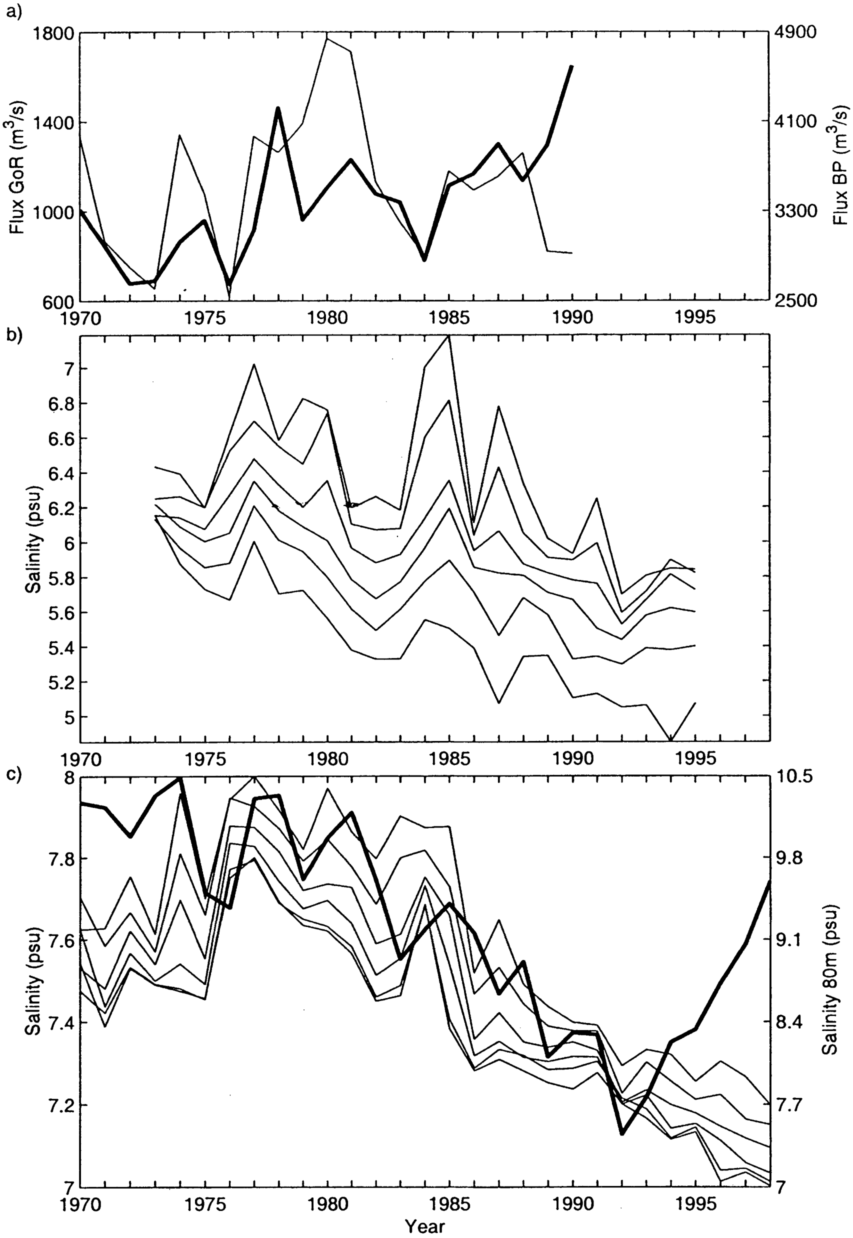

Fig. 4. Time series of annual mean freshwater supply by rivers and other coastal sources to the Gulf of Riga (bold) and the Baltic Proper (thin) (a). Time series of annual mean salinity in the Gulf of Riga at 0, 10, 20, 30, 40, and 50 m. Salinity increases with depth (b). Time series of annual mean salinity in the Baltic Proper at 0, 10, 20, 30, 40, and 50 m (thin) and at 80 m (bold) (c).

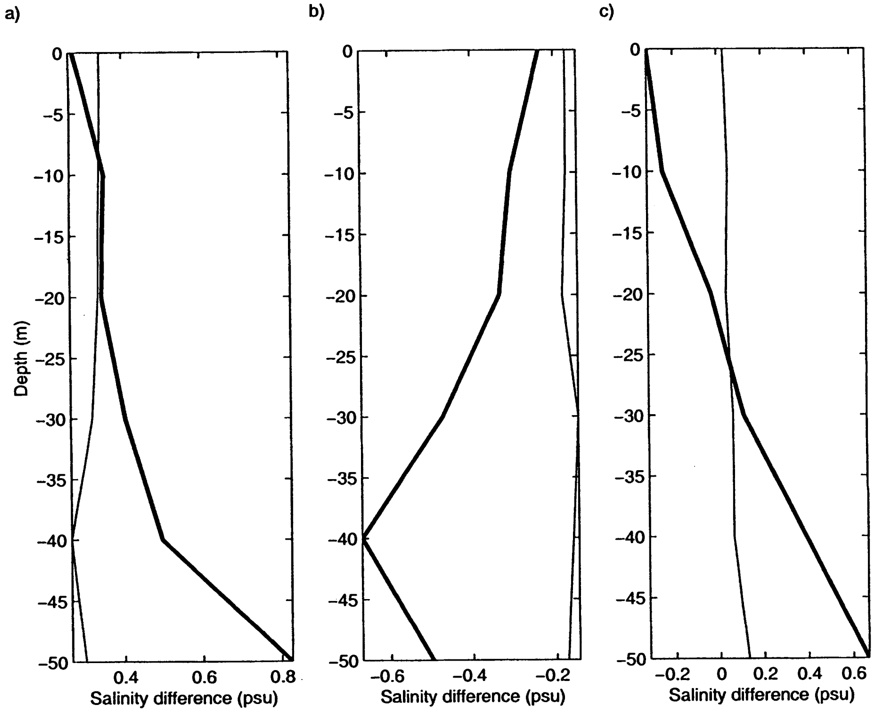

Fig. 5. Three types of salinity co-changes in the Gulf of Riga (bold) and in the upper layer of the Baltic Proper (thin) for 1977-1975 (a); 1982-1980 (b) and 1987-1986 (c).

and lower layers of the Gulf of Riga during the periods 1979-80 and 1986-87. In the Baltic Proper, salinity increase starting from the halocline was gradually suppressed or changed into salinity decrease moving towards the surface layer during these years. Salinity decrease in 1974-75, 1980-82, and 1985-86 was simultaneous in the two basins. The first two of these events were accompanied by high river runoff into both basins. Time shifts for the mentioned changes between the basins and depth intervals are not properly resolved using annual mean values. The available data set is too sparse and irregular for reasonable monthly resolution over the studied period. Three different types of interannual salinity changes are summarized in Fig. 5. High river runoff in 1978 and 1990 was not supported by high freshwater supply to the Baltic Proper. Occurrence of a singular peak of river flow in 1978 is questionable and will be discussed in the context of co-variations with other variables in the Discussion section. Recently Laznik *et al.* (1999) documented the annual riverine input of fresh water into the Gulf of Riga for the period 1977-1995. (Their database is essentially the same as ours for the period up to 1990). Their figures show that the high value in 1990 is supported by relatively strong river flow in 1989 and 1991 and is therefore more reliable.

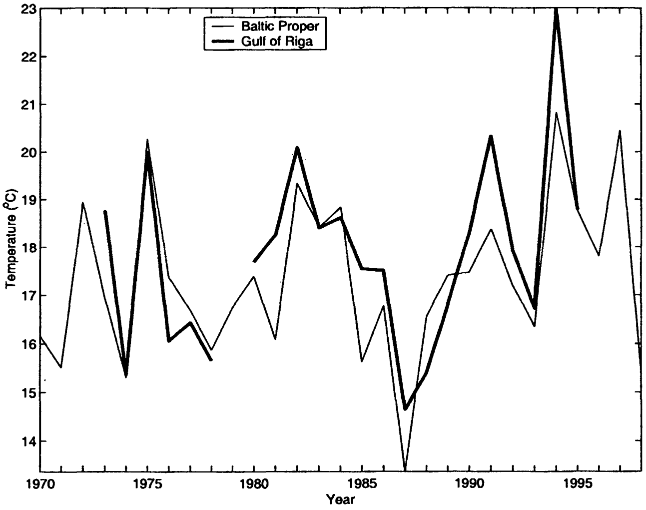

Fig. 6. Time series of the sea surface temperature in the Gulf of Riga (bold) and the Baltic Proper (thin) in August.

In August, surface temperature was used instead of annual mean temperatures to describe interannual variations. Data coverage is not uniform over the year, which may bias annual mean temperatures towards higher values. Surface temperature varied between 15-23°C in the Gulf of Riga in August (Fig. 6). The hottest summer was in 1994, and the coldest was in 1987. Sea surface temperatures are up to 2°C lower in the Baltic Proper, while still representing similar variations. August heat content in the Baltic Proper above 60-m depth, calculated by optimal interpolation method (Toompuu 1998), annual mean air temperatures in Tallinn (Jaagus 1998), and Götska Sandön (HELCOM 1996), is in concert with the above variability.

Seasonal Variations

Seasonal variability was calculated as a sample mean for each month after the estimated linear trend was removed from original salinity data on the Gulf of Riga. The trend was retained, however, in temperature data and salinity data on the Baltic Proper. Seasonal changes in thermal stratification are consistent with the annual cycle of air-sea heat exchange (Fig. 7). In the Gulf of Riga, the water column is thermally well mixed during winter (December-March), with seasonal thermocline beginning to develop in April. Strongest thermal stratification is observed in August and starts to erode in September because of winds and heat loss to the atmosphere. Part of the heat stored in the upper layer of the Gulf of Riga during summer is continuously mixed deeper into the water column and reaches the bottom in November. Winter temperature is lower in the Gulf of Riga than in the upper layer of the Baltic Proper. Variability of monthly temperature variance shows an almost similar season-

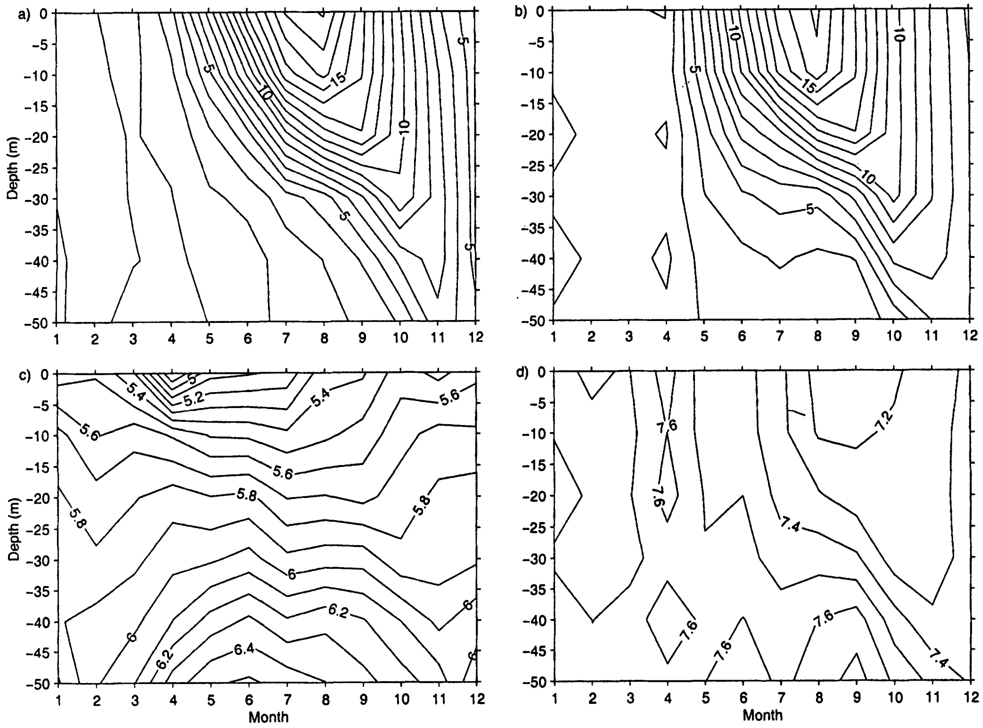

Fig.7. Climatological monthly temperature distribution in the Gulf of Riga (a) and in the upper layer of the Baltic Proper (b). Climatological monthly salinity distribution in the Gulf of Riga (c) and in the upper layer of the Baltic Proper (d).

al pattern. Maximum variance is observed in the thermocline, owing mainly to interannual variations in thermocline depth and absolute temperatures.

Salinity distribution in the Gulf of Riga indicates clear seasonality. In the summer, strong stratification develops by salinity decrease in the surface layer and salinity increase below 20 metres, indicating that an estuarine circulation scheme likely prevails. In April surface layer salinity drops because of the high rate of river runoff (Fig. 8). Effects of the runoff extend into May but are rather weak at the G1 station. The accumulated effect of the high springtime river runoff reaches the central Baltic Proper only in September, while salinity increase at 50-m depth is negligible. Thus, seasonal salinity variations are rather weak in the Baltic Proper as compared to those in the Gulf of Riga. Salinity stratification is partly retained during winter, and there is slight salinity increase above 40-m depth from November to December, perhaps indicating saline water inflow to the Gulf of Riga through the Irbe Strait.

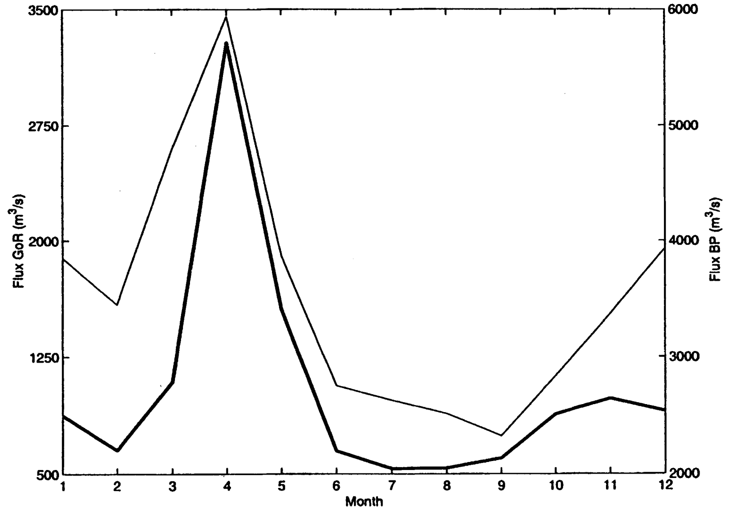

Fig. 8. Climatological monthly freshwater supply by rivers and other coastal sources to the Gulf of Riga (solid) and to the Baltic Proper (thin).

Discussion

Water exchange values in the straits and related salt flux are needed to explain the described salinity variations. No long-term current measurements with reasonable spatial resolution are available. Continuous current measurements in the Irbe Strait usually cover periods of up to several month (Lips *et al.* 1995; Lilover *et al.* 1995). Complicated spatial structure of the currents due to prevailing frontal circulation (Lilover *et al.* 1998) makes it difficult to estimate water exchange from the measurements performed in one or even two locations. (This is also pointed out by Otsmann *et al.* 1997.) Current measurements for the Virtsu Strait cover longer periods, especially in 1993-1995 (Suursaar *et al.* 1996a; 1996b). Flow structure is less variable in space and data from a single location was able to be extrapolated over the strait's cross-section with only minor uncertainties (Otsmann *et al.* 1997). Indirect estimations are either based mainly on different strait models applied to the varying periods of up to two years (Võsumaa *et al.* 1995; Otsmann *et al.* 1997) or are highly theoretical (Laanearu *et al.* 2000). All referenced studies reflect that setup of a reasonable strait model is a complicated task that is yet to be completed. Therefore, a reverse approach, characterized by calculating volume exchange from described salinity variations, is implemented here.

Spatially integrated equations of volume and salinity conservation were used for the Gulf of Riga

$$A^0 \frac{d}{dt}\eta(t) = Q_{\mathrm{in}}(t) - Q_{\mathrm{out}}(t) + R(t) \qquad (1)$$

$$\frac{d}{dt}\int_{-H}^{\eta} A(z)S(z,t)dz = Q_{\mathrm{in}}(t)S_{\mathrm{in}}(t) - Q_{\mathrm{out}}(t)S_{\mathrm{out}}(t) \qquad (2)$$

where, Q_{in} is inflow, Q_{out} is outflow, R is river flow, $A(z)$ is the area of the horizontal cross-section as a function of depth (hypsographic function), $A^0 = A(0) = 14150$ km^2 is surface area of undisturbed volume, S_{in} and S_{out} are salinity of inflow and outflow water, η is sea level and H is maximum depth of the gulf. Water exchange through the different straits and prevailing bi-directional flow in the Irbe Strait (Lilover *et al.* 1998; Laanearu *et al.* 2000) are not explicitly resolved. Expressing outflow rate from Eq. (1), substituting it into Eq. (2), and introducing undisturbed volume of the gulf as $V_0 = 385$ km^3 yields the equation for the calculation of the net inflow rate

$$Q_{\mathrm{in}}(t) = (S_{\mathrm{in}}(t)-S_{\mathrm{out}}(t))^{-1}$$

$$\left\{\frac{d}{dt}\left[(V_0+A^0\eta(t))\bar{S}(t)\right] + R(t)S_{\mathrm{out}}(t) - A^0\frac{d\eta(t)}{dt}S_{\mathrm{out}}(t)\right\} \qquad (3)$$

where $\bar{S}$ is the mean salinity of the gulf.

Interannual variations of the annual mean inflow are calculated for the period 1973-1990. This period captures the most prominent salinity variations in the Gulf of Riga (decreasing trend, shorter periods of remarkable salinity increase and decrease). Inflow and outflow salinity, mean salinity of the gulf, and river flow are estimated from the measurements for that period. The range of interannual variations of the sea level (volume of the gulf) of ±10 cm (Raudsepp 1998b, from the sea level record at Ristna, eastern Baltic Proper) is assumed to make an insignificant contribution to the annual mean water exchange and is therefore neglected.

Inflow salinity is determined from annual mean salinity values for the Baltic Proper. A dominating signal of temporal variability, consistent in the upper 50-m layer of the Baltic Proper, was extracted from the salinity time series using the method of principal component analyses (Preisendorfer 1988). This method reduces the influence of single salinity disturbance at a specific depth. The first principal component accounted for 95% of the total variance. The remaining 5% had an additional variability in the range of ±0.1 psu and is neglected. The vertical mean of reconstructed salinity from the upper 35-m layer was used for inflow salinity.

Outflow salinity was determined by the same approach, taking into account two factors. First, water masses from the top layers are primarily transported out of the gulf. Second, the hypsographic function of the Gulf of Riga is significant. The time series for the principal component analyses were formed as volume-weighted mean salinity of top k layers

$$\overline{S_k}(t) = \frac{\sum_{i=1}^{k} S_i(t) V_i}{\sum_{i=1}^{k} V_i}, \quad k = 1, 2, \ldots, 6 \tag{4}$$

The S_i and V_i are salinity and corresponding volume of the ith layer of the Gulf of Riga. The Gulf of Riga was divided vertically into 6 layers (0-5; 5-15; 15-25; 25-35; 35-45; 45-bottom). Thus, $\bar{S}_6(t)$ is mean salinity of the Gulf of Riga (or, by multiplying it with gulf volume, gives total salt content). The first principal component of the Gulf of Riga's volume-weighted salinity explains 97% of the overall variance. Residual salinity varies in the range of ±0.1 psu. The mean salinity of water masses from the upper layer of 35-m, $S_4(t)$ was used for the outflow salinity. Outflow salinity constitutes about 99% of the mean salinity of the Gulf of Riga. Salinity in the near-bottom layer contributes to the total salinity of the Gulf of Riga only marginally, as a relatively small volume is occupied by this water mass.

Strong freshwater inflow in 1978 created some doubt, as it represented a peak unsupported by any of the other variables. Inspection of the salinity time series in both basins, total salt content in the Gulf of Riga, and variations of river flow to the Baltic Proper suggests that the value should be close to the river flow of neighboring years. The principal component analyses method was applied to check the consistency of river flow in 1978 against inflow and outflow salinity as well as total salt content in the Gulf of Riga. The first principal component explained about 70% of the total variance, while the 1978 peak freshwater inflow was cut off in reproduced time series. A river runoff value comprising the average of river runoff in 1977 and 1979 was therefore used in the calculations.

The time series (which were used to calculate the inflow rate) of inflow and outflow salinity, mean salinity in the gulf, and river flow are depicted in Fig. 9.

The annual mean values of inflow rates were calculated using a discrete form of Eq. (3)

$$Q^{n+\frac{1}{2}} = \left(S_{\mathrm{in}}^{n+\frac{1}{2}} - S_{\mathrm{out}}^{n+\frac{1}{2}}\right)^{-1} \left(V_0 \frac{\bar{S}^{n+1} - \bar{S}^{n}}{\Delta t} + R^{n+\frac{1}{2}} S_{\mathrm{out}}^{n+\frac{1}{2}}\right) \tag{5}$$

where n is year number and the variables at timestep $n + 1/2$ are defined thus

$$\psi^{n+\frac{1}{2}} = \frac{\psi^{n+1} + \psi^{n}}{2}$$

The resultant inflow rate, inflow salinity, river flow, and outflow salinity are the averages of two consecutive years, with the average salinity of the gulf belonging to the corresponding year.

Estimated annual mean inflow varies between 2,000 and 5,000 m^3/s (Fig. 9), with the average registering at 3,200 m^3/s. A stationary inflow corresponding to both

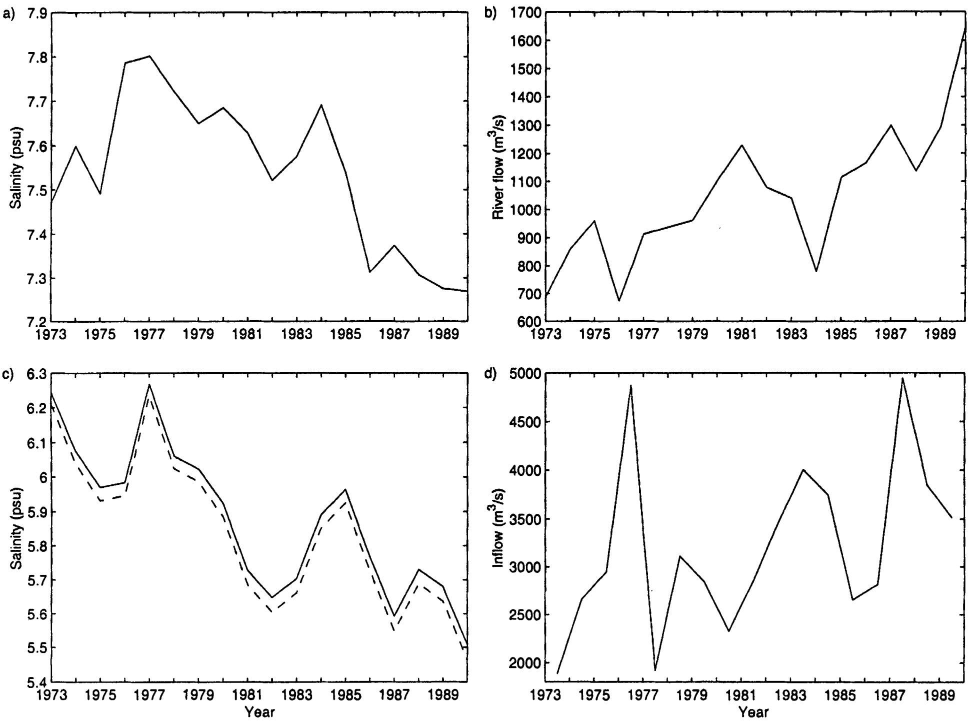

Fig. 9. Time series of annual mean inflow water salinity (a), river flow (b), outflow water salinity (dashed), and average salinity (solid) in the gulf (c), used in the calculation of annual inflow (d) from Eq. (5).

mean values of inflow and outflow salinity (7.54 and 5.84 psu, respectively) and river flow (1,050 m^3/s) for the period 1973-90 should therefore be 3,600 m^3/s (113 km^3/yr). Recent estimates of annual water exchange are between 60-200 km^3/yr (1,900-6,300 m^3/s) (HELCOM 1996). An increasing trend is obviously sub-imposed on the interannual variations. Thus there is decreasing trend in inflow salinity, outflow salinity, and mean salinity of the Gulf of Riga accompanied by an increasing trend in river flow and inflow. Coefficients of the linear trends are presented in Table 3. Salinity of inflowing water has decreased, while salinity flux to the Gulf of Riga has increased steadily because of the increased inflow.

Interannual variations of inflow and river flow and their consistency with interannual variations of annual mean salinity in the gulf are analyzed by using standardized time series of the variables $\psi_i = (\psi_i - \bar{\psi})/\sigma_\psi$, where $\bar{\psi}$ is the mean and σ_ψ is the standard deviation of the variable, after the linear trends are removed from their respective time series. The standard deviations are presented in Table 3. The means are zero in the present case because of the removed linear trends. Changes in river flow and inflow run opposite to one another (Fig. 10). The highest correlation (in absolute

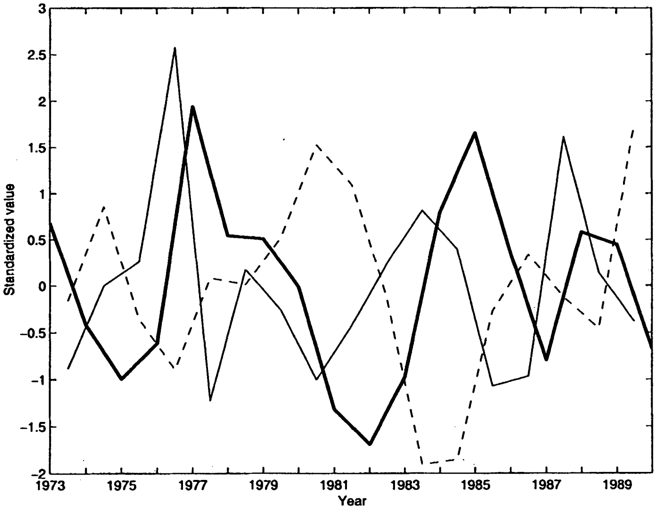

Fig. 10. Standardized time series of inflow (thin), river flow (dashed), and mean salinity in the gulf (bold). The linear trends were removed from the corresponding time series before standardizing.

Table 3 – The linear trends of river flow, inflow, outflow water salinity, inflow water salinity, $\psi^{n+1/2} = a(n+1/2) + b$, and of average salinity in the Gulf of Riga, $\psi^n = an + b$. The n is year number with $n = 0 \equiv 1973$. Standard deviations (Std) of corresponding residual time series.

Variable (ψ)	Slope (a)	Intercept (b)	Std
River flow	31.4 (m^3/s)/yr	774 m^3/s	102 m^3/s
Inflow	76.7 (m^3/s)/yr	2551 m^3/s	796 m^3/s
Inflow salinity	-0.0237 psu/yr	7.75 psu	0.108 psu
Outflow salinity	-0.0321 psu/yr	6.109 psu	0.1035 psu
Average salinity	-0.0334 psu/yr	6.160 psu	0.124 psu

values) between river flow and inflow (of -0.5) belongs to a zero lag. This indicates that the river flow has certain effect on the inflow to the Gulf of Riga.

The salinity in the Gulf of Riga increases when inflow is large and river runoff is small. Salinity decreases when inflow is small and river runoff is large. The salinity changes, $\Delta s^{n+1/2} = s^{n+1} - s^n$, were plotted against corresponding differences between inflow and river flow, $\Delta q_r = q^{n+1/2} - r^{n+1/2}$, in Fig. 11. A rather strong linear relationship exists between Δs and Δq_r.

$$\Delta s = 0.65\Delta q_r - 0.08 \qquad (6)$$

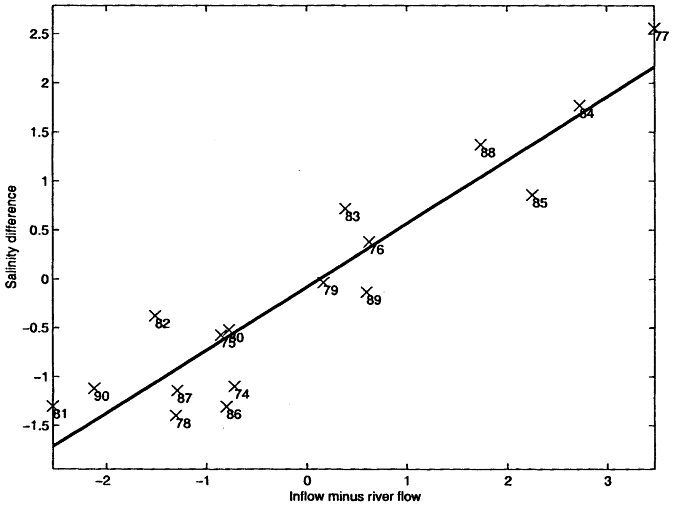

Fig. 11. Difference of standardized salinity, versus difference between standardized inflow and river flow, together with regression line. The numbers at the crosses correspond to the year *n+1*.

(correlation coefficient, *r=0.93*). The most prominent salinity changes occur when the difference between inflow and river flow is at its greatest (i.e., the salinity increase in 1976-77 and 1983-84 and the salinity decrease in 1980-81 and 1989-90) (Fig. 11). At these times salinity increases or decreases in the entire water column (Fig. 4). Two situations with moderate differences between inflow and river flow are worth mentioning. In 1986-87 salinity in the Gulf of Riga decreased in the upper 15-m layer but increased below the 25-m depth. The difference between inflow and river flow is negative for that period. In 1987-88 salinity changes in the gulf are opposite to those of the previous case. Correspondingly, the difference between inflow and river flow is positive.

The same procedure, taking into account see-level variations, was used to calculate monthly inflow rates. Sea-level records at Ruhnu were used to determine the Gulf of Riga water level. The Ruhnu station is located in the center of the gulf, thereby reducing the effects of various occurrences at coastal stations. The annual harmonic of sea-level changes was extracted from monthly mean sea-level data for the period 1978-82 using the method of principal component analyses for stationary time series (Preisendorfer 1988). (Application of the method is described in detail in Raudsepp *et al.* (1999)). Inflow salinity was taken equal to the top layer salinity of the Baltic Proper. Outflow salinity was taken equal to the volume-weighted mean salinity of the upper 15-m layer of the Gulf of Riga (Fig. 12). Average salinity of the gulf is highest during fall and drops fast during winter and early spring.

Using a discrete form of Eq. (3)

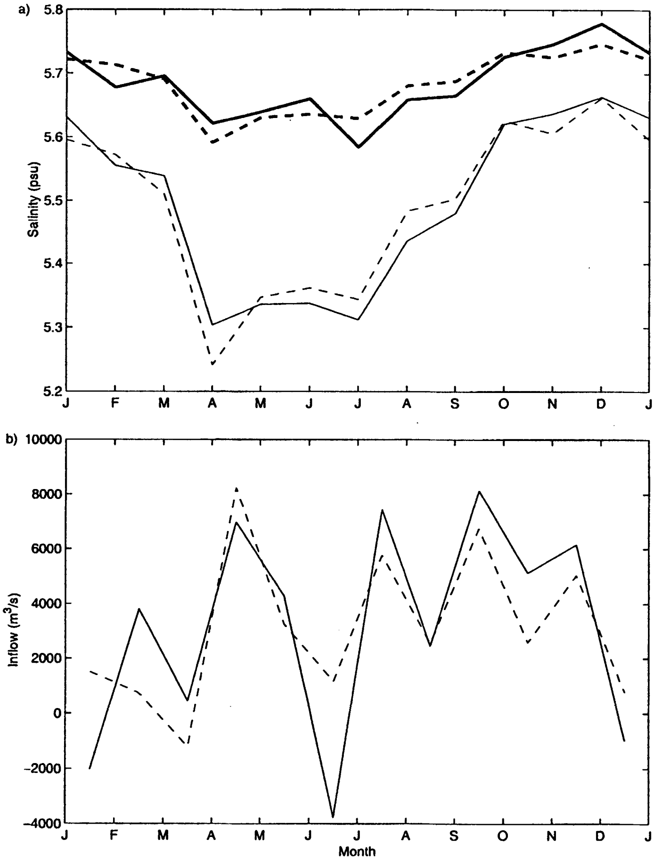

Fig. 12. Monthly values of outflow water salinity (thin) and mean salinity (bold) in the Gulf of Riga (a) calculated from data (solid) and approximated by the first principal component (dashed). (b) Estimated monthly mean inflow to the Gulf of Riga from salinity data (thin) and from salinity approximated by the first principal component (dashed).

$$Q^{n+\frac{1}{2}} = (S_{\mathrm{in}}^{n+\frac{1}{2}} - S_{\mathrm{out}}^{n+\frac{1}{2}})^{-1} \times$$

$$\left[\frac{(V_0 + A^0 \eta^{n+1})\bar{S}^{n+1} - (V_0 + A^0 \eta^{n})\bar{S}^{n}}{\Delta t} + R^{n+\frac{1}{2}} S_{\mathrm{out}}^{n+\frac{1}{2}} + A^0 \frac{\eta^{n+1} - \eta^{n}}{\Delta t} S_{\mathrm{out}}^{n+\frac{1}{2}} \right] \quad (7)$$

on a monthly basis (including terms with sea-level determined from Eq. (3), negative inflows were obtained for December-January, January-February, and June-July

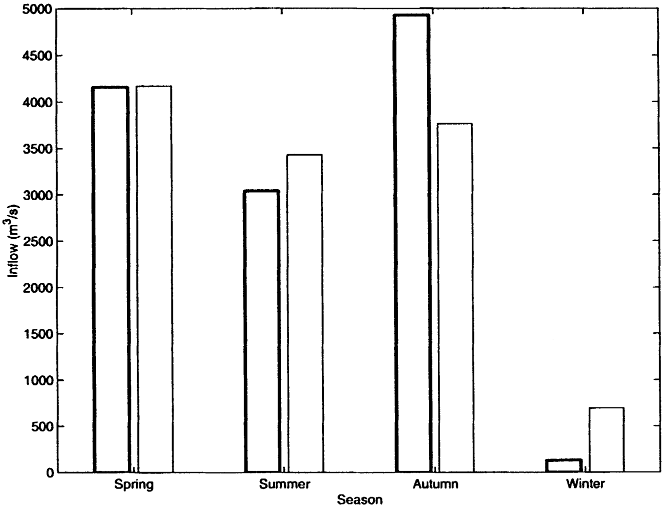

Fig. 13. Estimated seasonal inflow to the Gulf of Riga from salinity data (bold) and from salinity approximated by the first principal component (thin).

(Fig. 12). The results were slightly improved when the salt content (and the outflow salinity) was approximated by the first principal component (Fig. 12), which explains 92% of total variance. (The salinity time series for principal component analyses were formed according to Eq. (4), taking into account monthly sea-level). This approach gave a negative inflow between March and April (Fig. 12). The March salt content contains the largest error margin, as the number of measurements is smallest (see Table 1). Inflow is greatly affected by small uncertainties in salt content determination. Uncertainties in inflow salinity are not so crucial because inflow salinity affects the magnitude of the inflow but not the sign. Inclusion of sea-level changes reduced contributions from the last two terms in Eq. (7) considerably for summer, while the sum of the terms remained positive.

A conclusion that can be made from the calculated monthly inflows is that during seasonal peak in river flow, inflow is suppressed. Immediately after the river flow weakens, inflow from the Baltic Proper increases.

To reduce the dependence of total salt content on small changes, inflow was estimated on a seasonal basis. Salt content and sea-level were calculated for December, March, June, and September. River flow and salinity inflow/outflow were calculated as three-month averages for January, April, July and October. The estimated inflow was expected to represent the inflows in winter (December, January, February), spring (March, April, May), summer (June, July, August), and autumn (September, October, November). Cases using both raw data and an approximation made by the first principal component were recalculated (Fig. 13). Even when using a seasonal time-scale instead of a monthly one, uncertainties in total salt content may influence the results significantly. Nonetheless, both these calculations show that strong inflow occurs in spring and autumn. The inflow is at its lowest in winter and at an intermediate value in summer. The lowest winter inflow has not been reported thus far. A possible explanation for low inflow could be ice coverage on the gulf. In winters when ice covers the Virtsu Strait, the water exchange scheme changes significantly as compared to an ice-free period (Otsmann *et al.* 1997). Water exchange through the straits – especially through the Irbe Strait – during periods of partial ice coverage on the Gulf of Riga (which occurs during most winters (Berzins 1995)). has not been investigated thus far. Applying the strait models with a horizontally integrated gulf model (*e.g.* Võsumaa *et al.* 1995) does not necessarily give an accurate description of water exchange during periods of partial ice coverage on the gulf. The strong salinity stratification during late spring and summer is retained because of reduced mixing. In autumn convective mixing destroys stratification even though the inflow of saline water is at its highest value.

Conclusions

Salinity and temperature data taken from the Gulf of Riga and from the upper layer of the Baltic Proper over a 21-year period (1973-95) were analyzed. The focus was on interannual and seasonal variation of temperature, mean salinity, and salinity stratification in the Gulf of Riga. An interannual and seasonal variation of the saline water inflow from the Baltic Proper was estimated from volume and salt conservation equations. The calculation of the inflow rate from volume and salt conservation over a short period (less than a year) is very sensitive to possible uncertainties in the determination of total salt content. In particular, quantitative values of the given estimates should be taken with some precaution.

Interannual and seasonal temperature variations are similar in the Gulf of Riga and upper layer of the Baltic Proper. There was no significant trend in either series. The 20-year period is too short to detect the local effect of global warming. Thermal variability is caused by local heat exchange with the atmosphere; heat transport from other areas of the Baltic Sea has only a minor effect. The shallowness of the Gulf of Riga, by contrast to the depth of the Baltic Proper, explains the Gulf of Riga's higher surface temperature in summer. This difference is reflected in the mean temperature profile, which shows about a two-degree higher upper layer in the gulf and a lower temperature at 50-meter depth of the same magnitude as the Baltic Proper.

Salinity in the Gulf of Riga and above the halocline in the Baltic Proper has steadily decreased. This decrease has been rather uniform across the entire water column and has not considerably changed vertical salinity stratification. Freshening of the surface layer with a fixed temperature in the Gulf of Riga affects ice formation, as the ice formation temperature of saline water is comparably greater. The strongest interannual changes (increases and decreases) in salinity in both basins were similar to one another and were supported by strong and weak river runoff into each basin. Consistency of salinity changes above the halocline in the Baltic Proper and in the Gulf of Riga reflects general processes characteristic for the entire Baltic Sea.

Changes of the salt content in the Gulf of Riga are influenced mainly by changes in river runoff and inflow of saline water from the Baltic Proper. The direct effect of inflow water salinity to the mean salinity in the gulf seems to be minor. Water and salt exchange between the Gulf of Riga and the Baltic Proper increased steadily from the beginning of 1970s to the end of the 1980s. Long-term trends in river flow and inflow are positive, while interannual variations of 4-6 year periods are negative.

Interannual variations of average salinity (or total salt content) of the Gulf of Riga, river flow, and inflow can be decomposed into two components of different time-scale – "mean fields" and fluctuations,

$$\begin{aligned}\bar{S}(t) &= \bar{S}(\tau) + S'(t)\\ R(t) &= R(\tau) + R'(t)\\ Q_{in}(t) &= Q_{in}(\tau) + Q'(t)\end{aligned} \tag{8}$$

where τ is time. The first terms on righthand side of Eq. (8) represents a "mean field", which may be either constant or slowly variable according to time (in this case it is a linear function of time). The second term represents year-to-year fluctuations. A non-dimensional linear regression relationship in the form of Eq. (6) approximates year-to-year variations.

Seasonal variations of salinity stratification are notable in the Gulf of Riga but considerably weaker in the Baltic Proper. In April surface layer salinity decreases as a result of strong river flooding. Right after a flood, strong inflow feeds the lower layer with saline water. Strong stratification is maintained by low mixing and continuous inflow during summer. Nonetheless, salt content in the gulf remains at an annual minimum. The seasonal salinity cycle points to enhanced estuarine circulation in spring and summer. The seaward transport of river water in the upper layer and the compensating landward transport of saline water in the lower layer cause the observed formation of seasonal halocline (Stipa *et al.* 1999). This pattern seems to be similar to the formation of seasonal halocline and prevailing summertime estuarine circulation in the southern Gulf of Finland (Raudsepp 1998). Wind-induced and convective mixing destroy stratification in autumn, when saline water inflow from the Baltic Proper is strong. The salt content is at a maximum in December and decreases thereafter. The low winter inflow may be caused by ice cover on the Gulf of Riga. The effects of ice coverage on water exchange through the straits merit further investigation.

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