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THE FLOW OF WATER AND SALT IN THE SOUND DURING THE BALTIC MAJOR INFLOW EVENT IN JANUARY 1993

by

Bertil G. Håkansson, Barry Broman and Hans Dahlin

Swedish Meteorological and Hydrological Institute, S-60176 Norrköping (Sweden)

ABSTRACT

The volume and salt passing through the Sound, which is one of the two main channels (Great Belt and the Sound) connecting the Baltic with the North Sea, has been calculated since there are some uncertainty about the role of the Sound compared to the Great Belt regarding the saltflux. The volume flow model in the Sound is based on a balance between the along-channel sea surface slope and the bottom friction. This model approach was developed and tested with field measurements by Jacobsen (1980). In the present analysis hourly measurements of salinity and water levels were used to estimate the saltflux through the strait. During the latest major inflow event to the Baltic taking place in January 1993, we found that approximately 2.1×10^{12} kg salt intruded to the Baltic through the Sound. This corresponds to around 50 % of the total high-saline water flowing into the Baltic during this event and approximately 27 % of the total yearly volume of salt.

1. INTRODUCTION

One of the key processes to the water and salt balance in the Baltic Sea (see Figure 1.1) is the water exchange with the North Sea. The inflowing water with high salinity and rich in oxygen is influencing the environmental conditions and the natural resources (i.e. biological diversity, pollution status and Cod stock) of the Baltic Sea. Time series from the Baltic proper (cf. Matthäus, 1990, Andersson et.al., pp 69, 1992) reveal however that changes take place in the deep water salinity, temperature and oxygen from 1980 and onwards, probably coupled to changes in the forcing mechanisms of inflowing deep water and variations in the river runoff to the Baltic (Bergström and Carlsson, 1993). The stagnation of bottom water conditions and especially the persistent volumes of anoxic waters found in the deep Baltic Proper is probably also a result of the absence of any major inflow since 1976.

The shallow and narrow transition (see Figure 1.2) to the North Sea constitute the main reason for the Baltic to become a brackish water basin. These transition-areas are the Little Belt, the Great Belt and the Sound. The barotropic water transport is in general accepted to be dominated (≈ 2/3) by the Great Belt with a sill depth of 18 meters at Darrs in the southern part of the channel-like transition, whereas the Sound with a sill depth of 8 meters at Drogden take care of approximately 1/3 of the water exchange (cf. Jacobsen, 1980). However, the lenght of the Sound (≈ 90 km) is much shorter than that of the Great Belt (≈ 200 km), implicating that the advection-time is shorter in the former compared to the latter channel. In this case mixing between the ambient and the high-saline water will tend to lower the average salinity of the inflowing watermass to a greater extent in the Great Belt than in the Sound. Although it is more or less accepted that the volume flow is of different size in the two straits, we know much less about the saltflux in the channels. Therefore an attempt to quantify the salt flux in the Sound during a major inflow event such as the one in January 1993 is done in this investigation and compared with the corresponding estimate of salt flux through the Great Belt. Also a tentative salt and water budget of the Arkona basin are presented based on the achieved results from the Sound and other investigations.

The inflow events occur sporadic in time and are mainly driven by strong and persistent westerly winds over the North Sea and the Baltic. In January 1993 favourable conditions for a major inflow event prevailed during a time period of three weeks. On January 6 winds from SW started to blow with wind-speeds close to 10 m/s (at Kullen weather station shown in Figure 1.3). The wind direction changed slightly from southwest to northwest but always with a westerly wind-component up to January 26, whereafter the wind speed decreased and was directed more or less from the north. During the inflow period windspeeds exceeded 21 m/s for 7 days (2 days) and with 14 m/s for 17 days (10 days). Note that the average (1961 - 1990) figures for January are presented within brackets. These figures, are similar at neighbouring weather stations (i.e. Vinga and Falsterbo). According to windstatistics it is higher than average, but perhaps the most significant feature is that the wind came from almost the same direction during the whole period (21 days).

2. DATA DESCRIPTION

Tide gauge data from 7 stations in the Baltic and Kattegat (cf. Figure 1.1) are used to describe the evolution in time of water levels. The hourly data are presented in Figure 2.1 and 2.2, covering the time period from December 1 1992 to February 28 1993.

Time series of salinity from Oskarsgrundet located in the southern part of the Sound is shown in Figure 2.3. Salinity is recorded every hour at a depth of 5 meters, where the total depth is 7 meters. To avoid drift in the automatically recorded data in situ sampling are occasionally performed. Missing data are corrected by applying a lowpass filter to the raw data series. The missing data are exchanged with the corresponding lowpass filtered data. The layouts and missing data cover about 6 % of the time series more or less random in time. The investigated salinity time series runs from January 4 to February 28. Monthly salinity data from the Arkona basin are presented in Table 2.1, covering the time period from November 1992 to May 1993.

Table 2.1: Monthly salinity measurements in Arkona basin (BY 2).							
Depth/Date	18 Nov	16 Dec	28 Jan	6 Feb	12 Mar	22 Apr	24 May
(m)	(psu)	(psu)	(psu)	(psu)	(psu)	(psu)	(psu)
0.5	7.71	8.58	9.23	8.37	8.06	8.00	7.63
5.0	7.73	8.58	9.25	8.38	8.09	8.00	7.71
10.0	7.73	8.59	9.75	8.41	8.24	8.03	7.83
15.0	8.07	8.59	10.18	8.57	8.37	8.03	7.86
20.0	8.20	8.64	10.43	9.02	8.41	8.05	7.90
30.0	12.44	10.35	13.95	16.37	8.87	8.22	8.11
40.0	14.51	12.82	18.12	23.11	15.25	15.09	12.66
45.0	17.71	15.70	22.47	23.11	22.35	16.52	13.05

A Gaussian lowpass filter was used for correcting data gaps and in the analysis of the time series. The filter transform the time series X_i according to:

$Y_i = \Sigma (w_{ij} * X_i)/\Sigma w_{ij}$ where $w_{ij} = \exp(-(i-j)^2/(2*\sigma^2))$.

The standard deviation (σ) can be found by comparing the Gaussian distribution of the weight function with the corresponding rectangular distribution (i.e. normal running averages). Hence, it can be shown that the averaging period for each point in the transformed series is equal to approximately 3.4 times the standard deviation. For example, for time series based on hourly data the standard deviation; $\sigma = 7$ and 35.3 corresponds to an averaging time period of 24 and 120 hours, respectively. Note that the filter at the ends of the transformed time series include less data than at the inner parts, since the filter runs through the whole time series both in i and j for every Y_i.

3. WATER LEVEL CONDITIONS

Three tide gauges (Ratan, Stockholm and Visby) in the Baltic Sea are used to represent the evolution in time of the horizontal mean water level. At time-scales larger than a few days the water level in the Baltic behave coherent, whereas at shorter time-scales the water levels often show large horizontal variability. For example, the Visby and Ratan tide gauges are currently 180 degrees out of phase, according to Figure 2.1. The scatterplot in Figure 3.1a reveals this tendency as well as showing the in-phase component, although the scatter is large. The short time variability is mostly related to seiches in the Baltic, with periods between 22 to 53 hours (cf. Krauss, 1974). The span in the seiche periods depend on the interacting sub-basins, the longest period mentioned above represent the first harmonic of the whole Baltic Sea system.

In Kattegat north of the entrance area two tide gauges (Ringhals and Viken) are chosen as representative stations for the spatial mean water level. The time series shown in Figure 2.2 indicate high-frequency variability modulated by low-frequency variability. Since the stations are not far from each other both low and high frequency variability is correlated (cf. Figure 3.1b). A remarkable feature is that the amplitude of the high frequency variability increase when the amplitude of the low frequency varibility increase. In Table 3.1 standard deviation calculations demonstrate this tendency quantitatively. The inflow event took place during January 6 to 27 (corresponding to day 37 and 58 in Figure 2.2) when the water level in Kattegat rised approximately 0.50 - 0.60 meter on average. During this time period the oscillations in water levels are stronger than otherwise, creating trough to peak heights of around one meter. The typical period of the oscillations is close to 2 days. Hence, the inflow event is not only characterized by persistent and high mean water levels but also of large oscillations in the Kattegat area.

Table 3.1 Standard deviation of lowpassed (Gaussian) filtered tide gauge data from Ringhals (η_{Ri}), Ratan (η_{Ra}) and Visby (η_{Vi}), using an averaging period of 120 hours (5 days).

	Whole period 10 - 55 Julian days	Inflow period 10 - 25 Julian days
	(m)	(m)
η_{Ri}	0.15	0.21
η_{Ra}	0.13	0.11
η_{Vi}	0.06	0.07

3.1 Barotropic transports

The water budget of the Baltic may be described with a single box exchanging water with its surroundings. The conservation law of volume for this box is as follows:

$$A d\eta/dt = Q + Q_R + Q_P + Q_E \quad (3.1)$$

Here the Baltic surface area is A , $d\eta/dt$ is the time derivative of the spatial mean water level and Q_R, Q_P, Q_E are the inflow of water from river runoff, precipitation and outflow by evaporation. The water exchange with Kattegatt is given by Q which can be directed either as out- or as inflow. The yearly average magnitudes of the various components are shown in Table 3.2. On a monthly basis the average contribution from precipitation, evaporation and river runoff to the variation of the water level are on average less than 0.2 m, which is much lower than the short term water level variations of around one meter. During winter months the contribution from river runoff is also lower than average. A reasonable approximation to the water balance on time scales of a month and shorter is obtained by neglecting river runoff, precipitation and evaporation. Integration of Eq. (3.1) taking into account the above mentioned approximation and expressing it in discrete form, yields:

$$\Delta V + C = \Sigma Q_i * \delta t \quad (3.2)$$

Hence, the volume change ΔV is equal to $A*\eta$. It is balanced by the accumulated volume exchange taking place at the en trance area.

Table 3.2: Mean water budget components in the Baltic. Mean depth, surface area and volume of the Baltic sea are taken to be 54 m, $393*10^9$ m^2 and $21.2*10^{12}$ m^3, respectively. ([1]Dahlström B., 1986; [2]Stigebrandt A., 1985; [3]Bergström. S and B. Carlsson 1993; [4]Ehlin U., 1981; [5]Matthäus W. and H. Franck, 1990; [6]Henning D., 1988).

Components	In water level (m/year)	Transport ($x10^9$ m^3/year)	Volume ($x10^9$ m^3)
Precipitation[1]	~0.6	240	
Evaporation[2,6]	~0.5	200	
River runoff[3]	~1.2	473	
Outflow[4]	~2.4	943	
Inflow[4]	~1.2	470	
Inflow event 1951[5]	~0.8		320
Inflow event 1976[5]	~0.6		230
Inflow event 1993	~0.8		310

It was found by Jacobsen (1980) that the volume flow through the Sound (Q_{Oi}) is about 1/3 of the total flow (Q_i) through the connecting channels between the North Sea and the Baltic. The total volume flow may thus be estimated from the Sound volume-flow, which can be calculated using a barotropic and frictionally dominated model. It can be derived from the shallow water equations restricted to a balance between friction (quadratic bottom friction law parametrization) and sea surface slope (cf. Jacobsen 1980). This simple model suggests that the volume flow is proportional to the square root of the water level difference between the northern and southern Sound. This is here estimated by using the tide gauge data from Viken (η_V) and Klagshamn (η_K):

$$Q_{Oi} = C_1 *(\eta_V - \eta_K) / |\eta_V - \eta_K|^{1/2} \quad (3.3)$$

The constant of propotionality C_1 is taken to be $8.3*10^4$ $m^{5/2}/s$ (unpublished Håkansson (1987)), it can be compared with the value of $9.0*10^4$ obtained by Jacobsen (1980) using data from tide gauges at Copenhagen and Klagshamn. The volume flow calculated from Eq. (3.3) times the time step δt as well as the time integrated volume flow, corresponding to 1/3 of the volume changes of the Baltic, are presented in Figure 3.2 a,b. The instantenouos flow oscillates to a great extent, whereas the accumulated counterpart reveals a smooth evolution in time, reflecting the long-time changes usually found for the Baltic mean sea level (cf. Figure 2.1). The total volume passing the Sound during the inflow event is estimated to be 82.6×10^9 m³.

An independent test of the assumptions behind the Sound model can be obtained by comparing directly the calculated volume changes from Eq. (3.3) with the observed ones, taking into account Eq. (3.2). The mean sea level and the corresponding volume change in the Baltic is estimated with data from Stockholm and Visby tide gauges. The integration constant in Eq. (3.2) is used to adjust the manipulated tide gauge data (ΔV+C) to the calculated volume change ($3*\Sigma Q_{oi}*\delta t$). The Stockholm and Visby time series are fitted by eye to the model results and presented in Figure 3.3, yielding C = 0 and 25 km³, respectively. The overall correspondence between modelled and estimated basin volume variation is good, whereas the short-time variabaility to a great extent is a result of local processes taking place within the basin.

4. SALT TRANSPORT IN THE SOUND

The time series of salinity from Oskarsgrundet in the southern part of the Sound and the calculated volume flow from Eq. (3.3) are presented in Figure 4.1. These time series will be used to estimate the volume flow and the saltflux taking place through the Sound. As indicated in Figure 4.1 both salinity and volume flux time series are influenced by a long- as well as short-time variability. We will study the interdaily (short-time) fluctuations separately from the long-time by applying the Gaussian lowpass filter, with an averaging period of 24 hours, to the time series. The short-time series are obtained by subtracting the lowpassed from the original series. The decomposed parts are presented in Figure 4.2 a and b. The standard deviation of interdaily fluctuations in flow rate and salinity are $\pm 1.78 \times 10^4$ m³/s ($\pm 2.04 \times 10^4$) and ± 1.56 psu (± 1.55 psu), where the figures within brackets are from the inflow period (10 to 25 Julian days).

Estimates of the saltflux are performed by taking the product of a reference density (ρ), the instantaneous flow rate (Q_{Oi}) and the salinity (S). The mean saltflux depend thus on the correlation of these variables. In Figure 4.3 a scatter plot of the highpassed filtered time series are shown. The interdaily salinity and volume flow fluctuations are not well correlated and thus we conclude that the saltflux on time scales shorter than 24 hours can be neglected. In fact it is almost impossible to see any difference between lowpassed filtered data and original data of saltflux (cf. Table 4.1). Average saltflux during the investigated period and during the inflow period is presented in the Table 4.1. The exact inflow period however is difficult to determine from the time series itself, which means that a certain amount of subjectivity is introduced later on in the analysis when we estimate the total inflow of water and salt content. Nevertheless, mean properties are here determined from the fully developed inflow period (i.e.Julian days 10 to 25), but this is rather heuristically chosen. Another way to estimate the inflowing salt volume, which is less critical to the lenght of the time period, can be done by using the method developed by Walin (1977). He introduced salinity as the independent variable instead of time and position. The transformation was applied to spatial data of velocity and hydrography, whereas here we are working with time series. Hence, each sample in time taken at one single spot represent an estimate of the spatial averaged transport of water and salt in the

Table 4.1: Averaged saltflux estimates for the investigated period (1339 hours) and for the inflow event period. Calculations based on both unfiltered ($\rho*Q_{Oi}*S$) and lowpassed filtered ($\rho*Q_{Oil}*S_l$) data are presented.

Saltflux	Whole period 10 - 55 Julian days (kg/s)	Inflow period 10 - 25 Julian days (kg/s)
$\rho*Q_{Oi}*S$	2.62×10^5	1.20×10^6
$\rho*Q_{Oil}*S_l$	2.60×10^5	1.20×10^6

Sound. From the time series we thus can estimate the volume of water and salt as function of salinity taking place during the time period of interest.

In this case the water volume in the salinity interval S to S+dS is added in a cumulative way from the time series of volume flow and salinity. Within each salinity interval the water volume (v(S)*dS) and the salt content (ρ*v(S)*S*dS) are obtained as functions of salinity (S). The integral or sum of these quantities are:

$$V(S_0) = \Sigma\, v(S) * dS\ ; \quad S_0 \leq S \leq 35 \text{ psu} \qquad (4.1)$$

$$VS(S_0) = \rho * \Sigma\, v(S) * S * dS\ ; \quad S_0 \leq S \leq 35 \text{ psu} \qquad (4.2)$$

Here the $VS(S_0)$ and $V(S_0)$ are the cumulative salt and water volume between 35 psu and S_0. If the lower integration limit (S_0) is put to zero the mean water and salt flux are obtained by dividing the integral (or sum) with the time series lenght.

In the calculation of these variables a salinity interval (dS) of 0.25 psu has been used. In Figure 4.4 both the water and salt volume as function of salinity are presented. It is shown that a change in the time interval only marginally change the water volume and salt content at salinities larger than 20 psu, which is characterizing the inflow event. The slope of $V(S_0)$ indicate a lower intensity of inflowing water volumes at salinities larger than 28 psu and between 15 and 25 psu compared to the intensity bewteen 25 and 28 psu. In this salinity range the water volume inflow intensity is 18.5×10^9 m^3/psu. Taking into account that this inflow occurred during 21 days the averaged volume flux in this salinity interval become 10.2×10^3 m^3/s,psu, which is a factor of 5 to 7 times larger than the long-time mean value obtained in the Bornholm Channel by Stigebrandt (1987) and Walin (1981), respectively.

The total high-saline water and salt content transported into the Baltic through the Sound during the inflow event are estimated from Figure 4.4 a and b, yielding V(20 psu) = 78.5×10^9 m^3 and VS(20 psu) = 2.1×10^{12} kg. The mean salinity of this inflowing water become 26.75 psu. Using conservation laws for salt and water (Knudsen, 1899) it can be shown that the yearly averaged inflow volume of water with a mean salinity of 17.4 psu is 450×10^9 m^3. Hence, during the 1993 inflow event approximately 17 % of the yearly high-saline water volume passed through the Sound into the Baltic, whereas the corresponding salt content was almost 27 % of the mean inflowing salt content.

5. DISCUSSION

In the estimation of water volume and salt content several processes were excluded, which may influence the magnitudes. For example, it is assumed that the station Oskarsgrundet is representative for the cross-sectional salinity distribution in the Sound. In near future however data can be available for testing this hypothesis using information from the extensive measurement programme initiated for monitoring eventual environmental hazards during the planning and construction of the Öresund bridge across the Sound. Models may also provide useful information on water exchange and transports of substancies like salinity. Another potential process influencing the salt flux is that the inflowing high-saline water may mix with the ambient Baltic water already in the Arkona basin (Kouts and Omstedt, 1993). This water mass may then be transported out to the North Sea as low-saline surface water without taking part in the deep water formation in the Baltic.

In order to shed some light on these uncertanties we have made a brief attempt to estimate the magnitudes of the components influencing the volume and salinity of dense bottom-water in the Arkona basin after the inflow event in late January 1993.

Information on the salinity and the time period of high-saline water crossing the Darrs sill in the southern Great Belt are estimated by Matthäus (1993). The volume entering across the Darrs sill is estimated by taking the fraction of days (230x8/20 km^3) with high-saline water inflow times the total volume of inflowing water. Brief estimates on volume (≈122x10^9 m^3) and averaged salinity (19.7 psu), based on hydrographic measurements of the water below the halocline in the Arkona during the end of the inflow period, are presented in the Table 5.1. It is also assumed that the deep water current on its way through the Arkona basin entrain water from the surface layer and that wind-entrainment lifts bottom water into the surface layer. The budget components are shown Table 5.1. Conservation of salt and water were used to calculate the outflow components taking into account that the surface layer in Arkona initially had a salinity of 1.1 psu lower than just after the inflow event (cf. Table 2.1) and a volume of approximately 340x10^9 m^3. The estimates in the table are by no means very accurate but should hopefully be of the right order of magnitude. For example, the figures in the table indicate that the volume flow through the Bornholm Channel should be close to 47 000 m^3/s which according to Stigebrandt (1987) is high but acceptable. This figure is also of relevant magnitude compared to the model results (using an upstream basin salinity difference between the surface and bottom layer of 10 psu and a bottom layer thickness of 20 meter) obtained by Gidhagen and Håkansson (1992). The high-saline bottom water in Arkona covers approximately a volume of 100 to 150x10^9 m^3 (corresponding to a pycnocline depth of 25 and 20 meters, respectively). It will take 20 to 35 days to spill this water mass through the Bornholm Channel with the above given flow rate.

For comparison and evaluation of the size of the 1993 major inflow event a data base has been used to calculate the total amount of salt in the Baltic Sea. This data base, consisting of interpolated values to a grid with a resolution of 20 km in the horizontal and with 10 vertical levels, has been developed at BSH (Bundesamt für Seeschiffart und Hydrographie in Hamburg). The total mean water volume was found to be 19x10^{12} m^3, which is slightly less than the 21x10^{12} m^3 found from the depth data base developed at SMHI (i.e. Ehlin et.al, 1974). In the BSH data base total salt content amounts to 130x10^{12} kg, yielding an averaged salinity of 6.84 psu. Here we will correct the estimate found from the BSH data base by considering the volume estimate by Ehlin et.al. to be the most accurate one. Hence, the total salt content is probably close to 144x10^{12} kg. The salt content entering to the Baltic during January 6 to 27 1993 amounts approximately to 1/36 (or 2.8 %) of the total content found in the Baltic on average.

Table 5.1: A tentative estimate of volume and salt contents below the halocline in the Arkona Basin during the inflow event January 6 to 27 1993 (G.B. - Great Belt, S. - the Sound, B. Ch. - Bornholm Channel). The data from the 1951 inflow event are taken from Wyrtki (1954).

Geographical area	Period (Date)	Mean Salinity (psu)	Volume (x10^9 m3)	Salt content (x10^{12} kg)
Initial content in Arkona (25 - 45 m)	Nov 18 - Dec 16 1992	13.0	103	1.3
Inflow through G.B. (Darrs)	Jan 18 - 26 1993	21.0	92	1.9
Inflow through S. (Oskarsgrundet)	Jan 6 - 27 1993	26.7	78	2.1
Entrainment from surface w. in Arkona	Jan 6 - 27 1993	8.5	58	0.5
Storage in Arkona	Jan 28 - Feb 6 1993	19.7	122	2.4
Detrainment to surface layer	Jan 6 - 27 1993	19.7	- 20	-0.4
Outflow through B. Ch.	Jan 6 - 27 1993	19.7	- 86	- 1.7
Inflow through G.B. (Darrs)	Nov 28 - Dec 16 1951	23.0	168	3.9
Inflow through S. (Drogden)	Nov 23 - Dec 10 1951	25.0	32	0.8

This inflow event should rise the averaged salinity in the Baltic with approximately 0.1 psu.

For comparison with earlier major inflows we have put estimates of water and salinity during the 1951 event in Table 5.1. This information was taken from Wyrtki (1954). Note the difference in the distribution of salt and water passing through the two straits during these two events. The salinity measurements during the 1951 (1993) case indicate that high-saline water crossed the Darrs sill during 19 to 20 days (8 days) and the Drodgen sill during 17 days (15 days). Wyrtki used the method given by Jacobsen (1925), which transform the visually observed current velocity and direction at the lightship Drogden located downhill of the Drogden sill to total flow rate of the Sound. This linear relationship was later criticized by Jacobsen (1980), who demonstrated that this formula underestimates the flow rate severely and that the coeffecient linking the flow rate with the velocity drift with time, most likely due to errors in the observation technique. In fact he also suggested that the estimates of volume and salinity of the high-saline inflowing water during the 1951 case should be reevaluated taking into account a simple model like the one given by Eq. (3.3), where the slope of the water level is balanced by bottom friction determines the flow rate. It is our intention to continue the work on salt transports in the Sound with an extension of previous work to the 1951 and 1975/76 inflow events.

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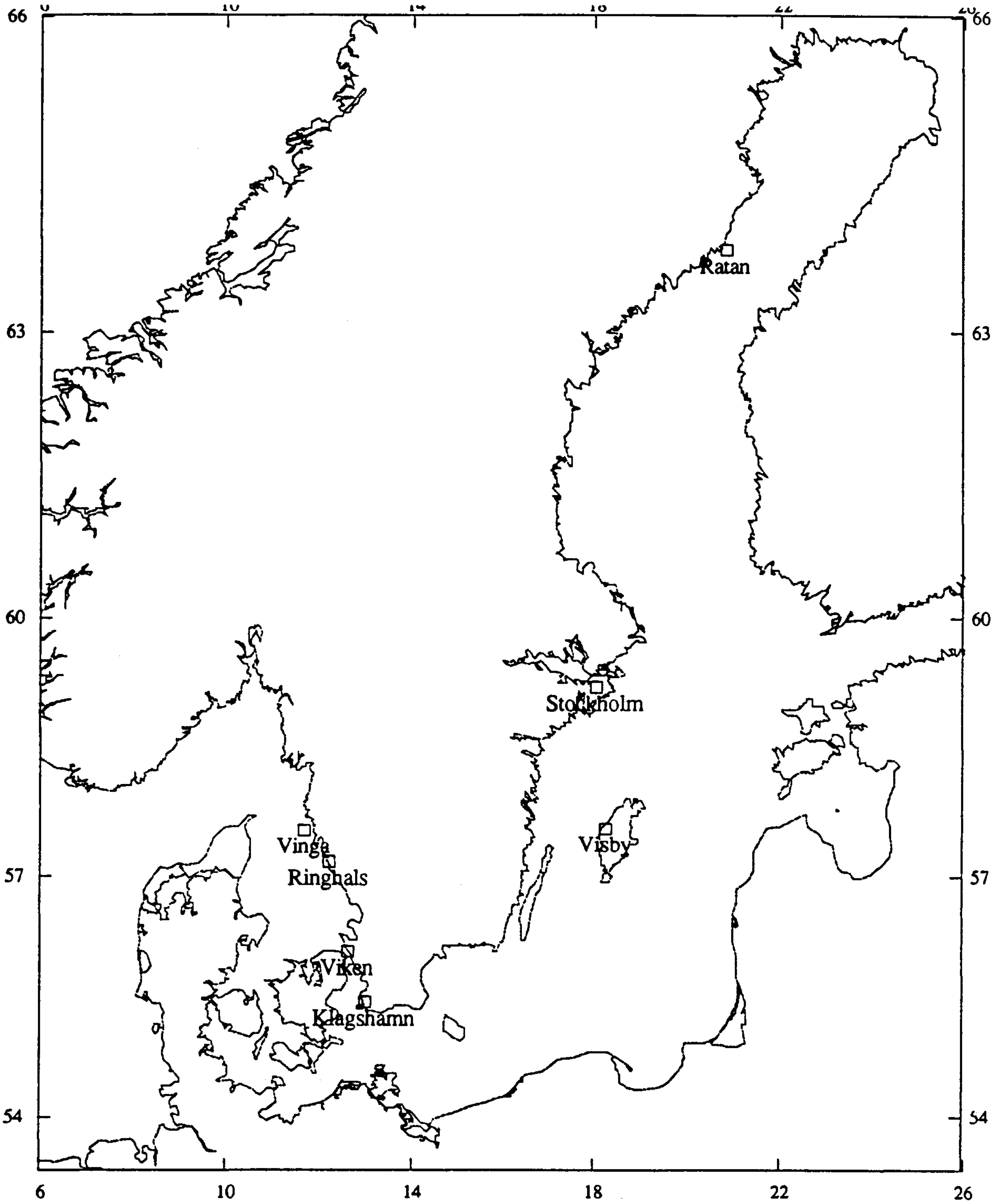

Figure 1.1. *Map of the Baltic Sea area, including tide gauge and Vinga weather stations.*

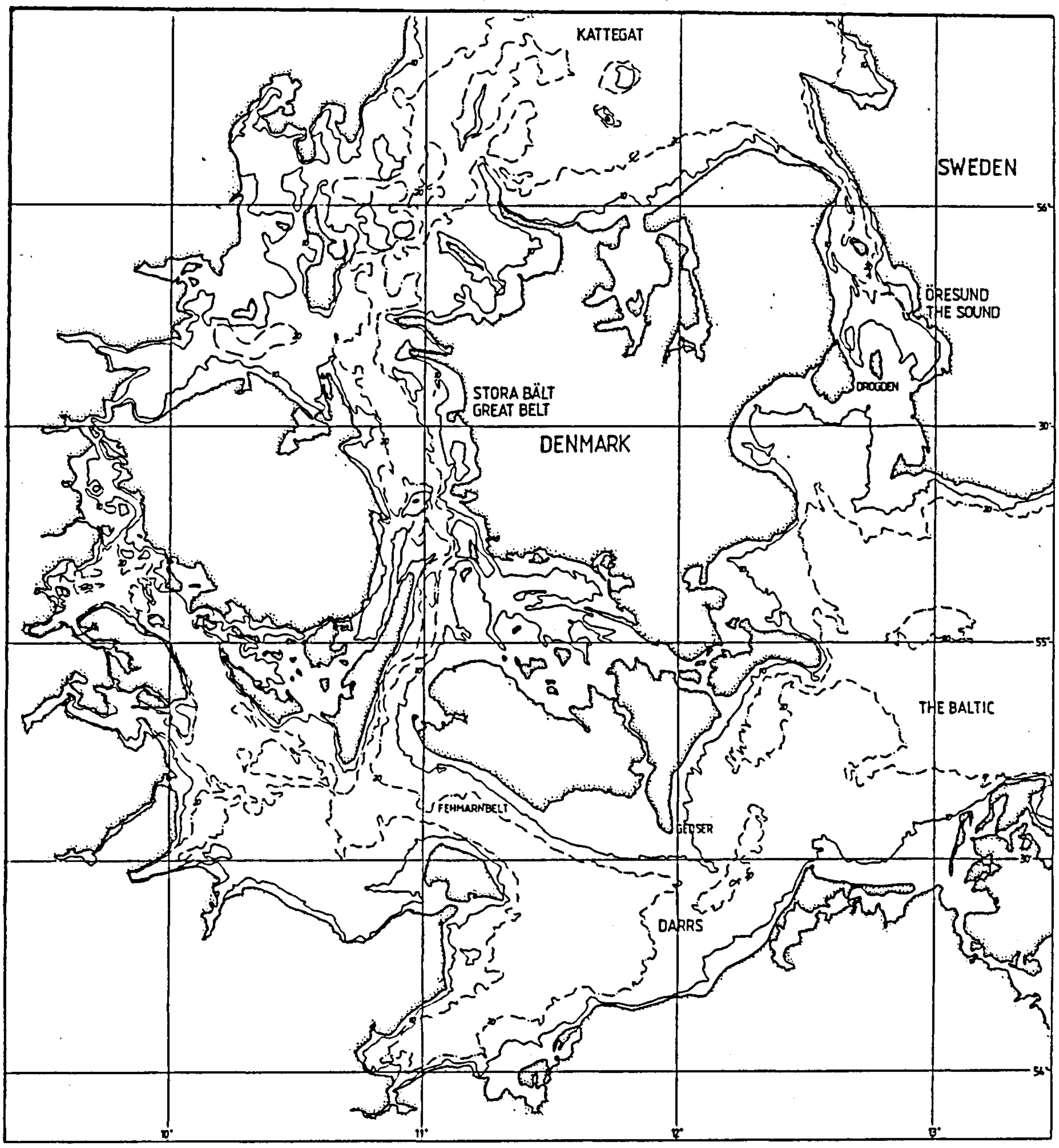

Figure 1.2.	*Bathymetric map of the transition area between the North Sea and the Baltic.*

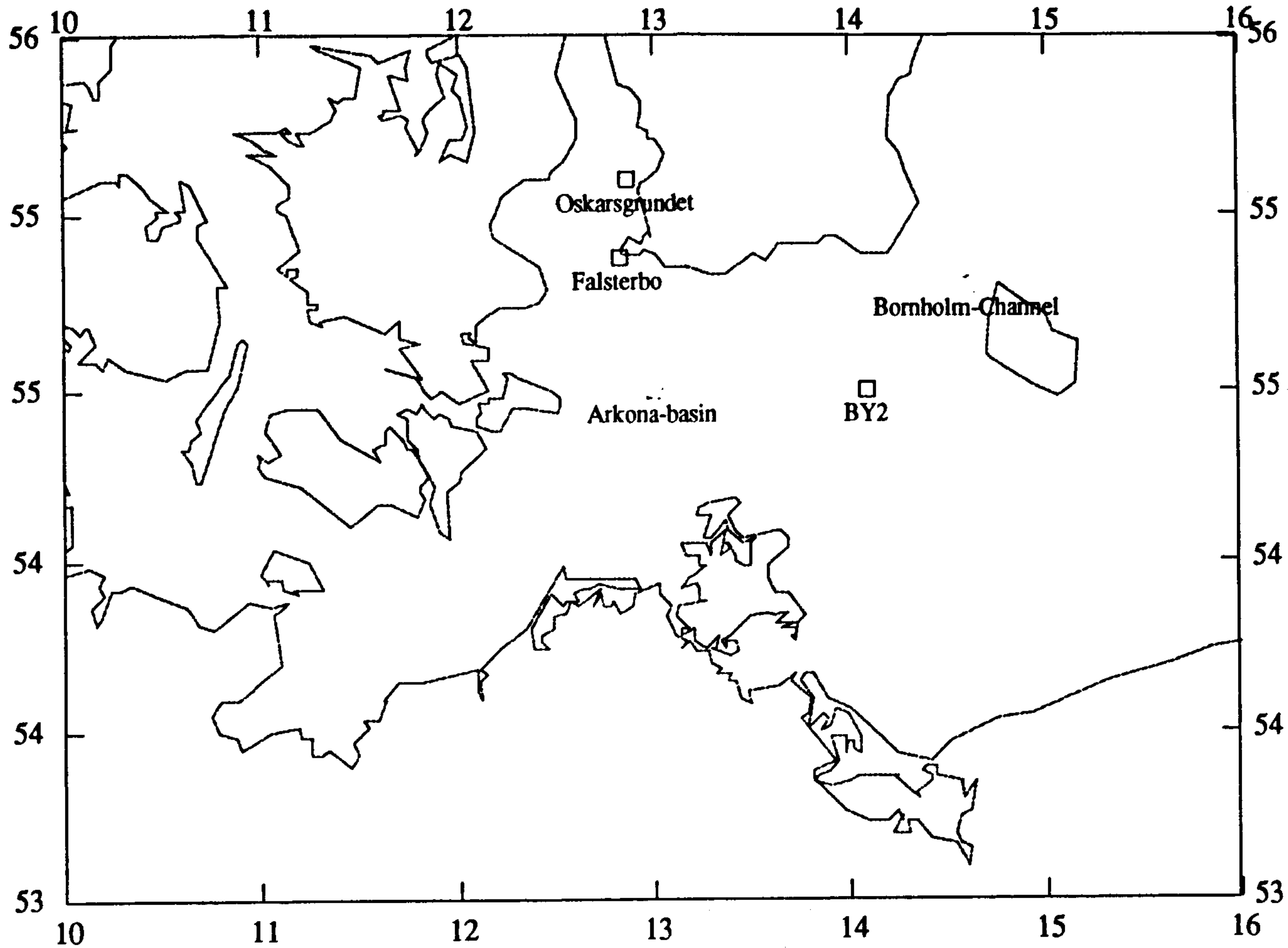

Figure 1.3. *Geographical location of stations and the Arkona basin with the Bornholm Channel.*

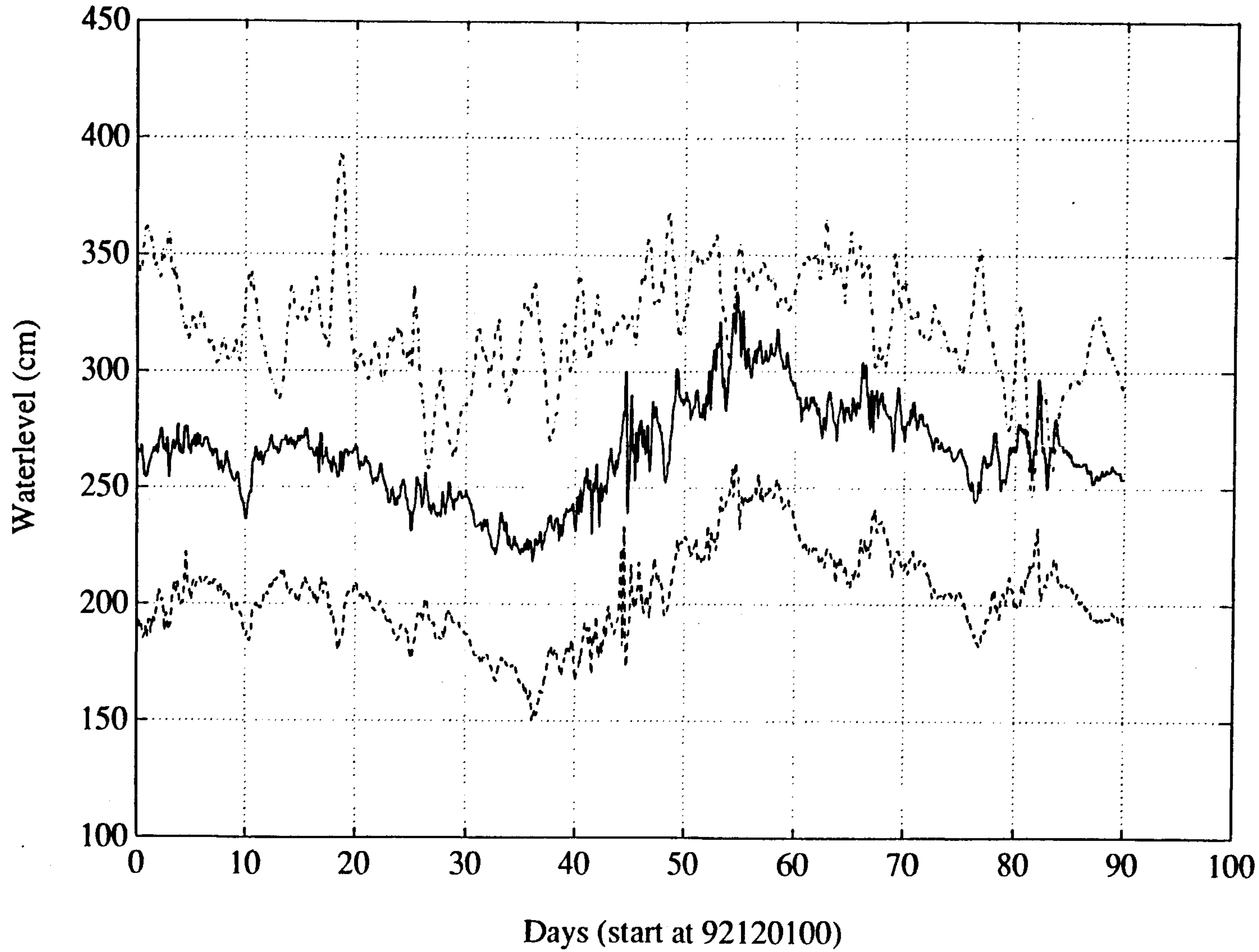

Figure 2.1. ***Hourly data of water levels during December 1, 1992, to February 28, 1993, taken from tide gauges at Ratan (dashdot), Stockholm (solid) and Visby (dashed).***

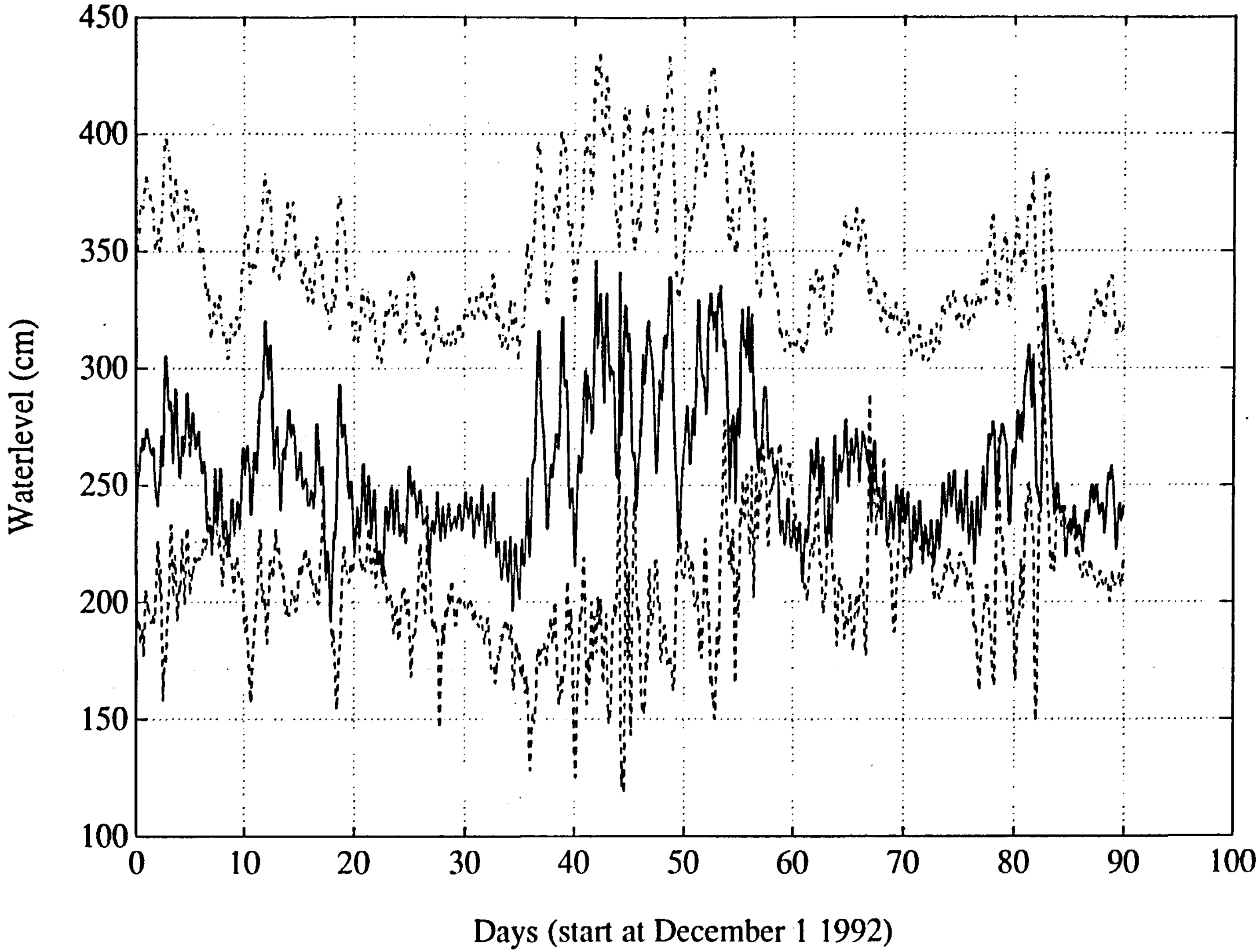

Figure 2.2. ***Hourly data of water levels during December 1, 1992, to february 28, 1992, taken from tide gauges at Ringhals (dashdot), Viken (solid) and Klagshamn (dashed).***

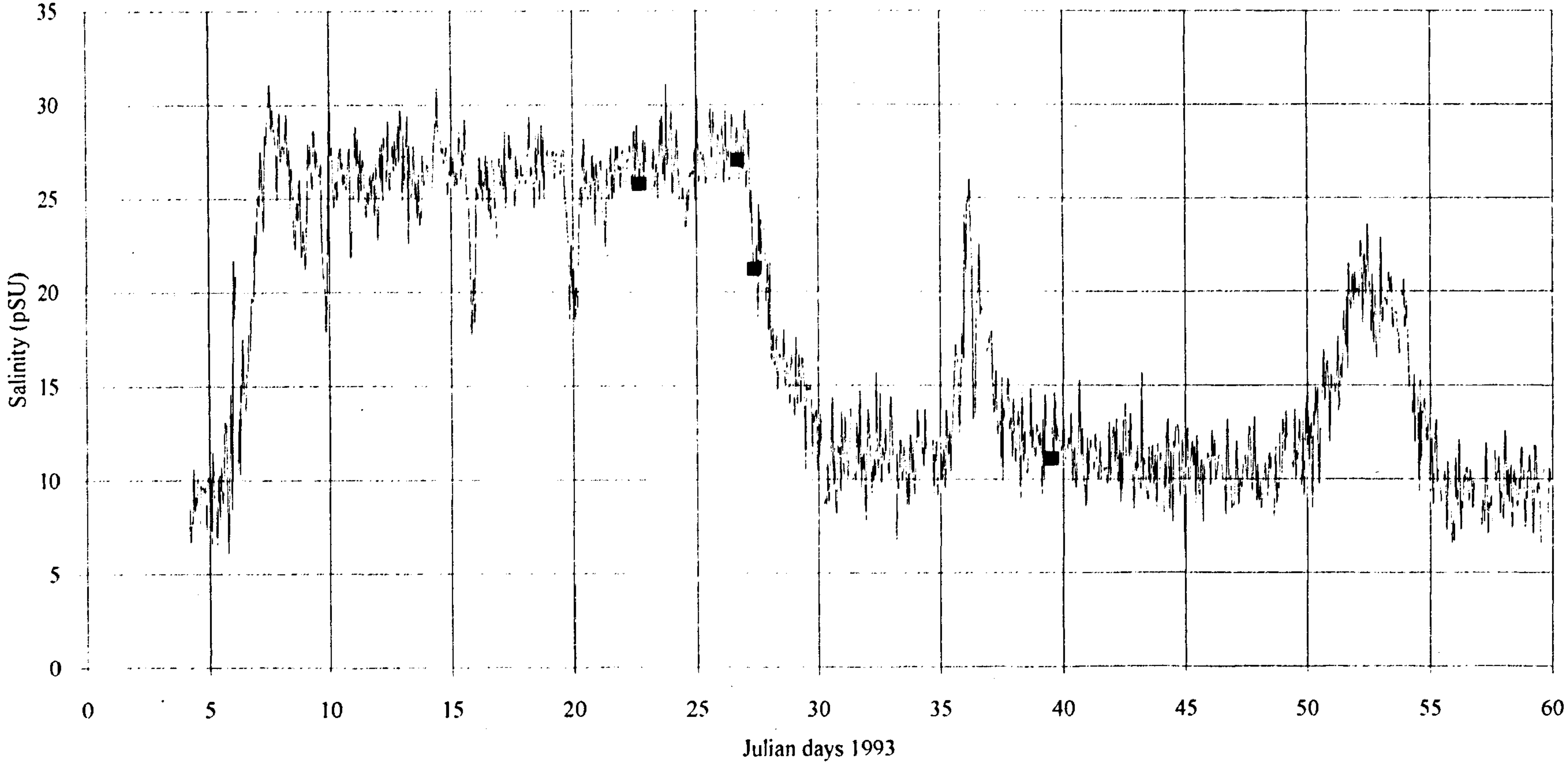

Figure 2.3. *Time series of salinity at Oskarsgrundet with in situ samples (*).*

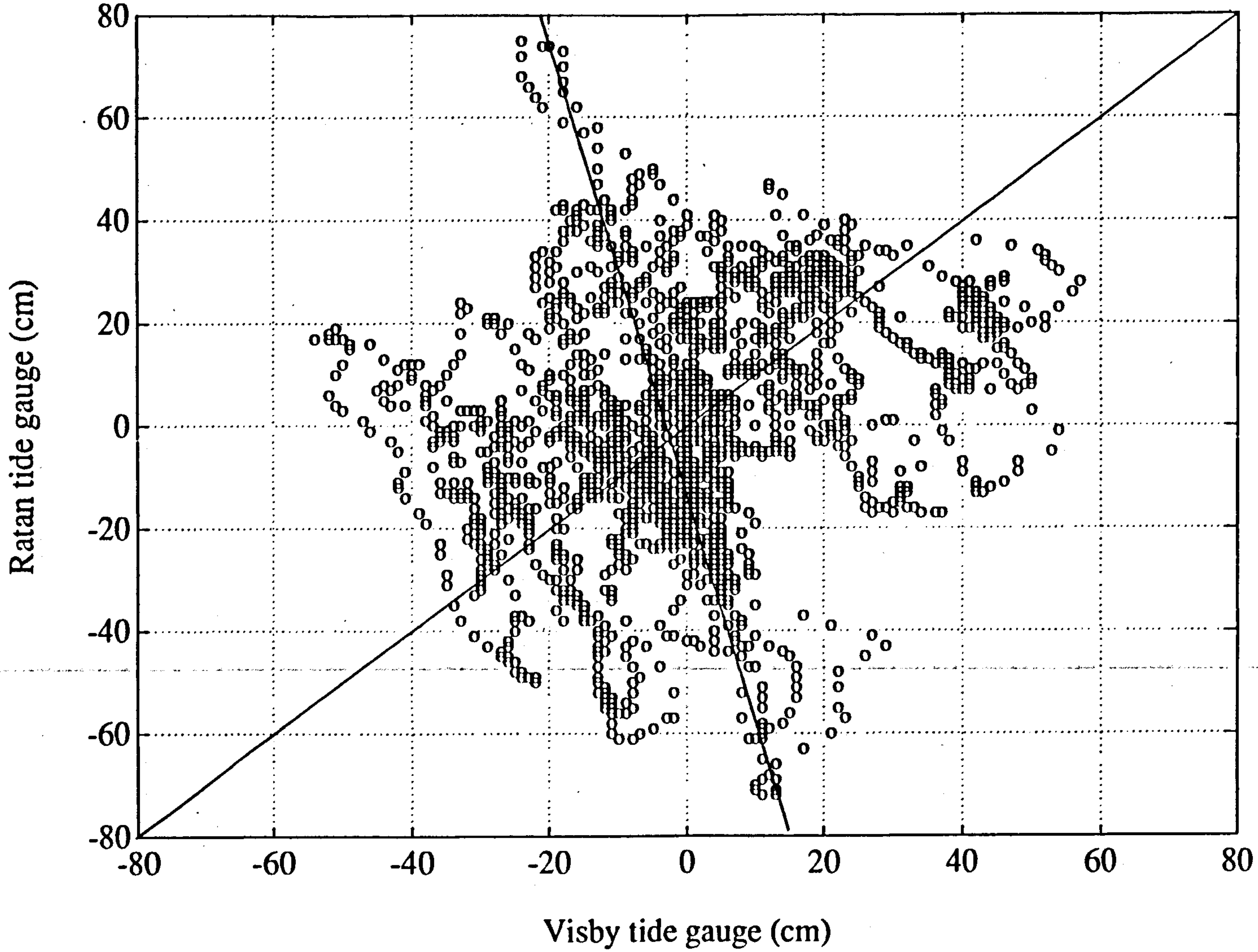

Figure 3.1a. *Scatter plot of water levels from Visby and Ratan; tide gauges based on hourly data.*

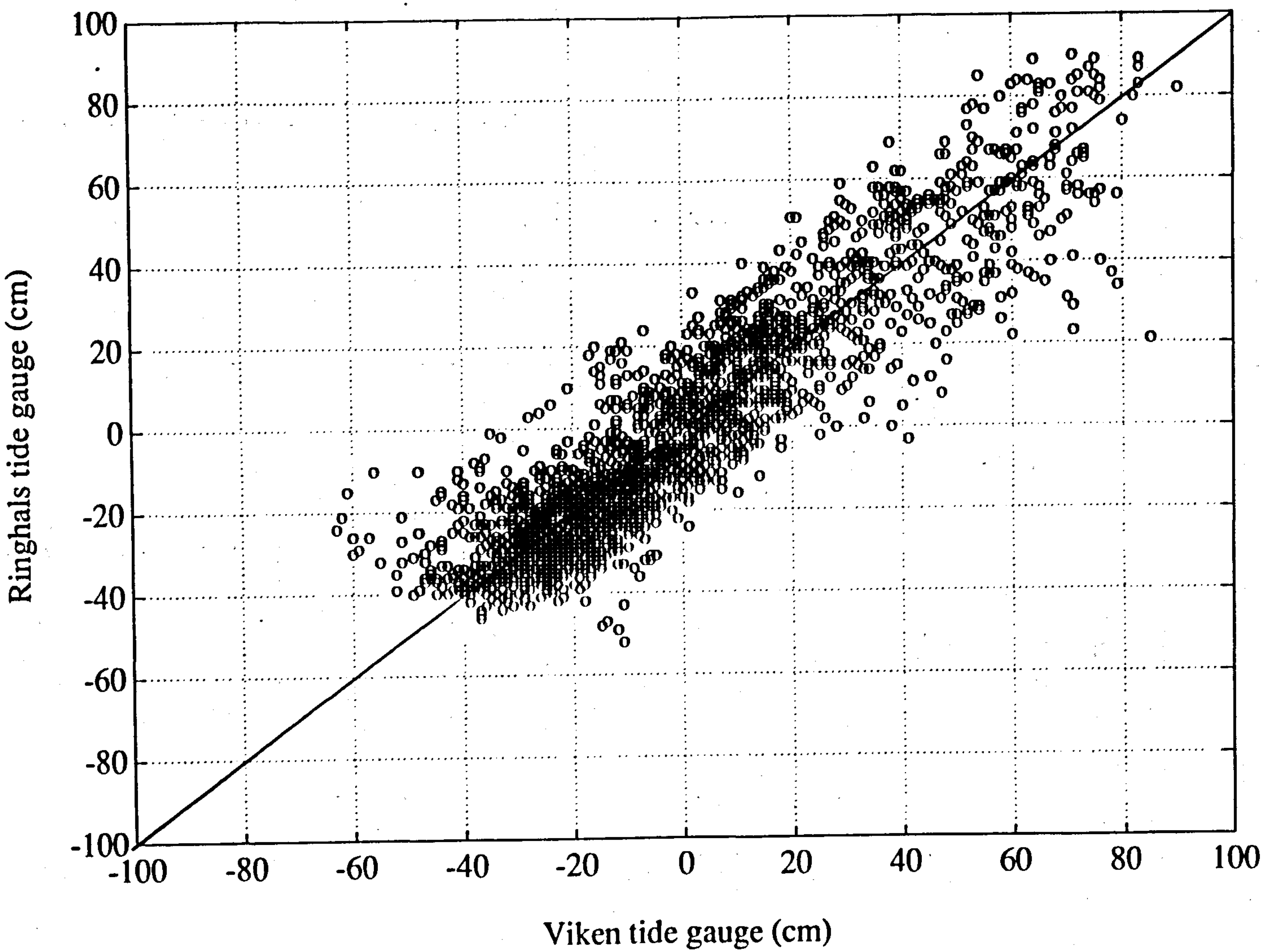

Figure 3.1b. Scatter plot of water levels from Viken and Ringhals; tide gauges based on hourly data.

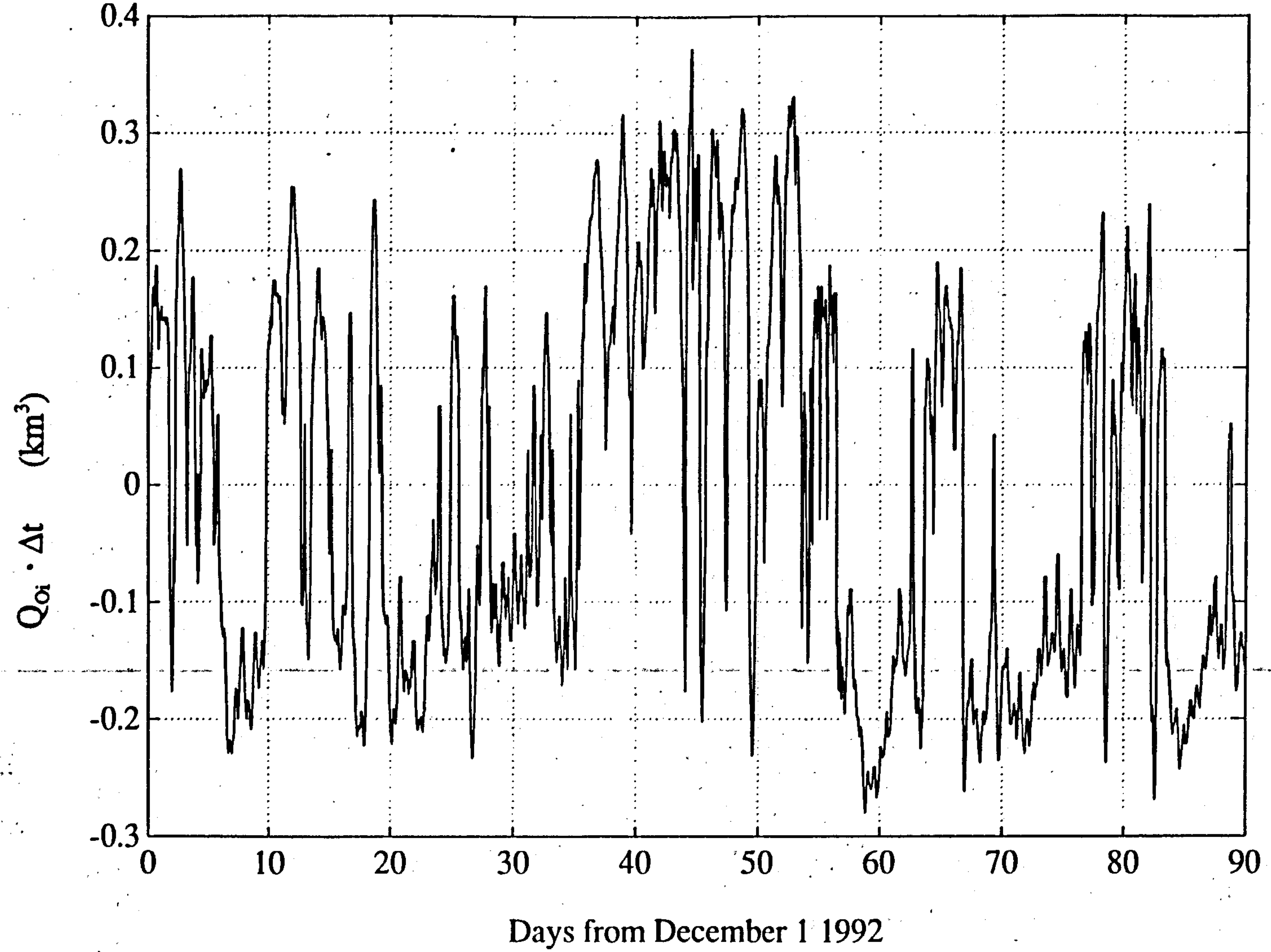

Figure 3.2a. *Calculated volume flow in the Sound using Eq. (3.3).*

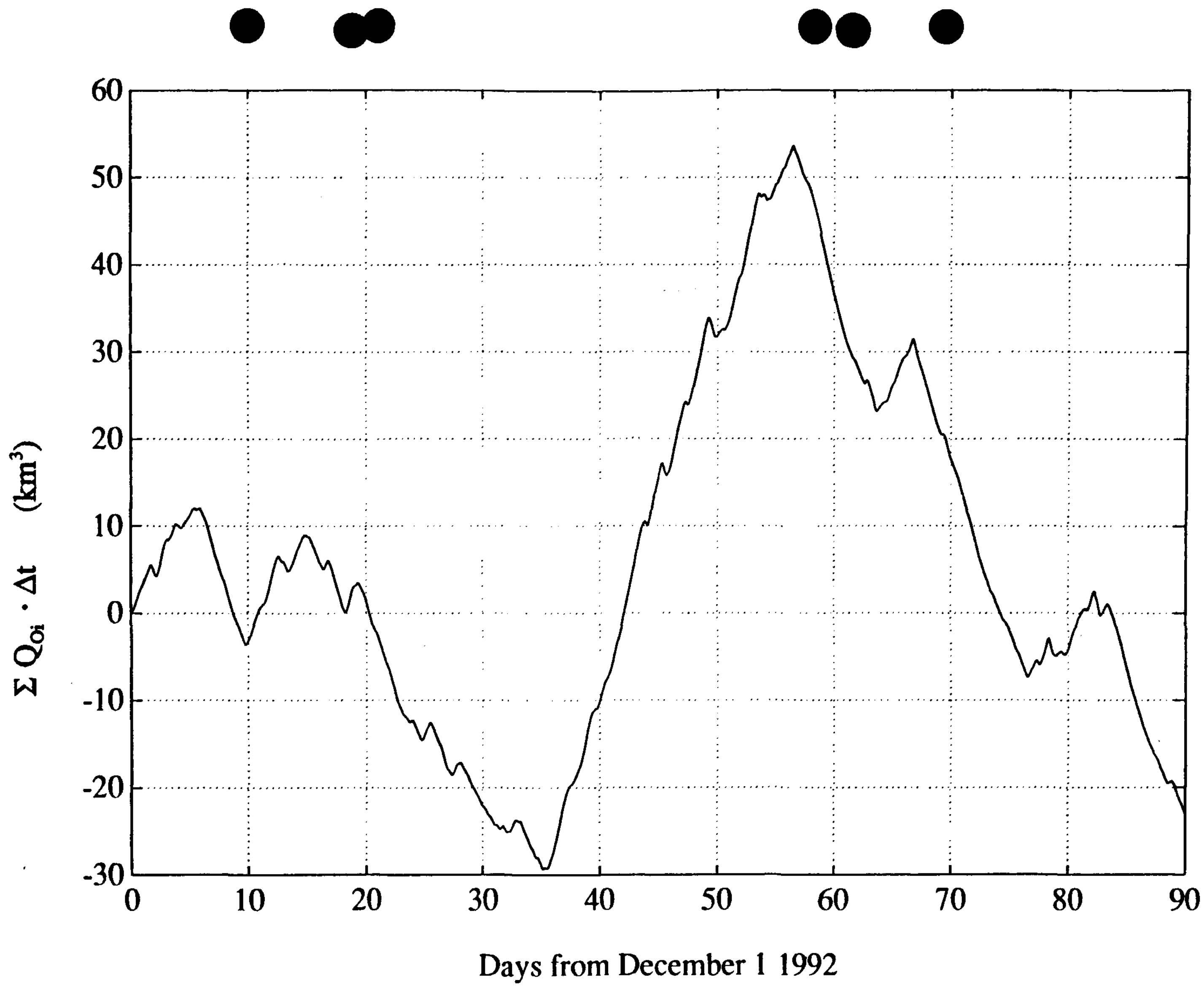

Figure 3.2b. *Accumulated volume flow in the Sound using Eq. (3.3).*

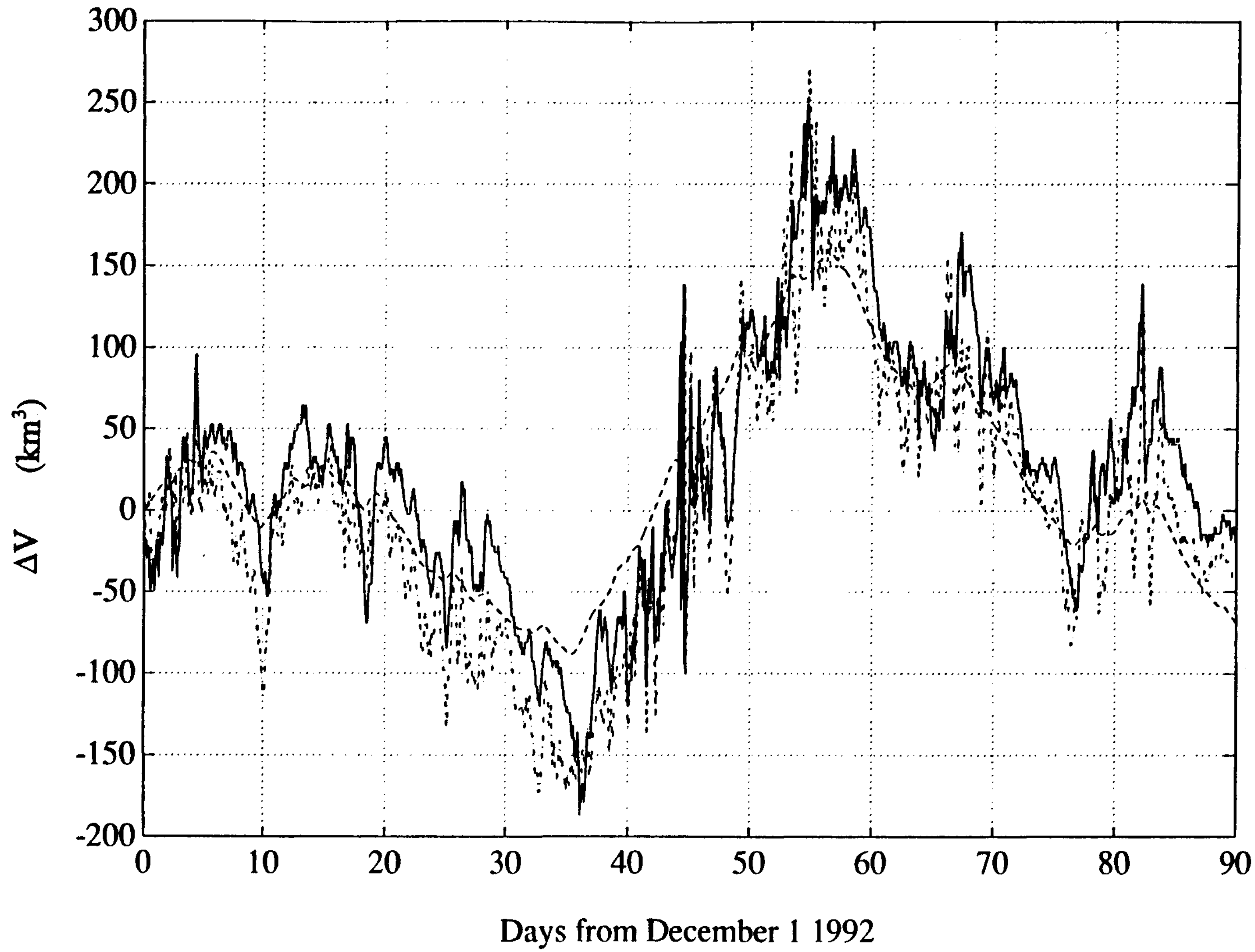

Figure 3.3. ***Estimated and modelled (dashed) water volume change in the Baltic using Stockholm (dashdot) and Visby (solid) tide gauge data.***

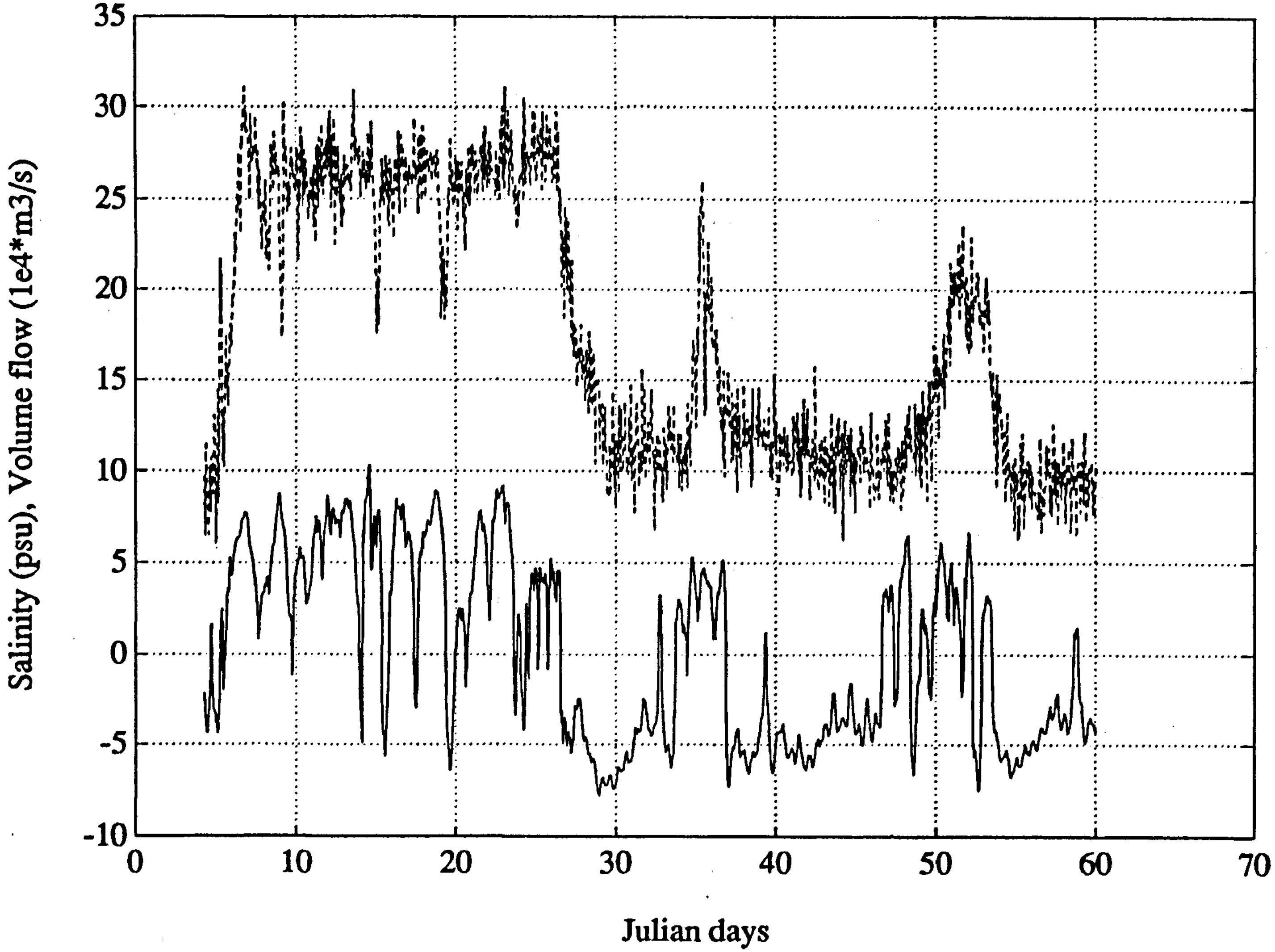

Figure 4.1. *Time series of hourly calculated volume flow ($Q_{Oi}(t)$, solid) and measured salinity ($S(t)$, dashed) in the Sound.*

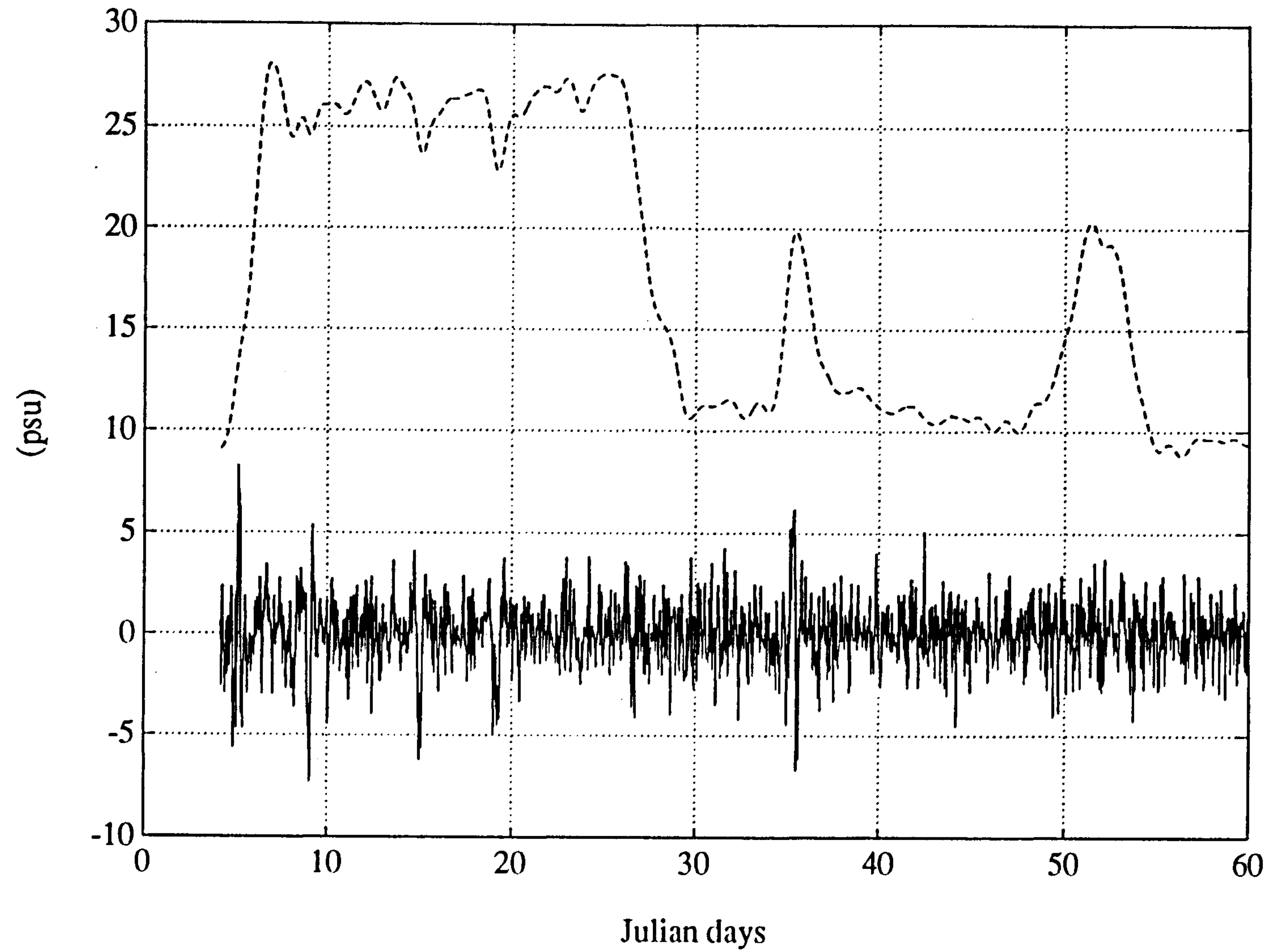

Figure 4.2a. Time series of lowpassed filtered (dotted) and highpassed filtered (solid) data of salinity (S).

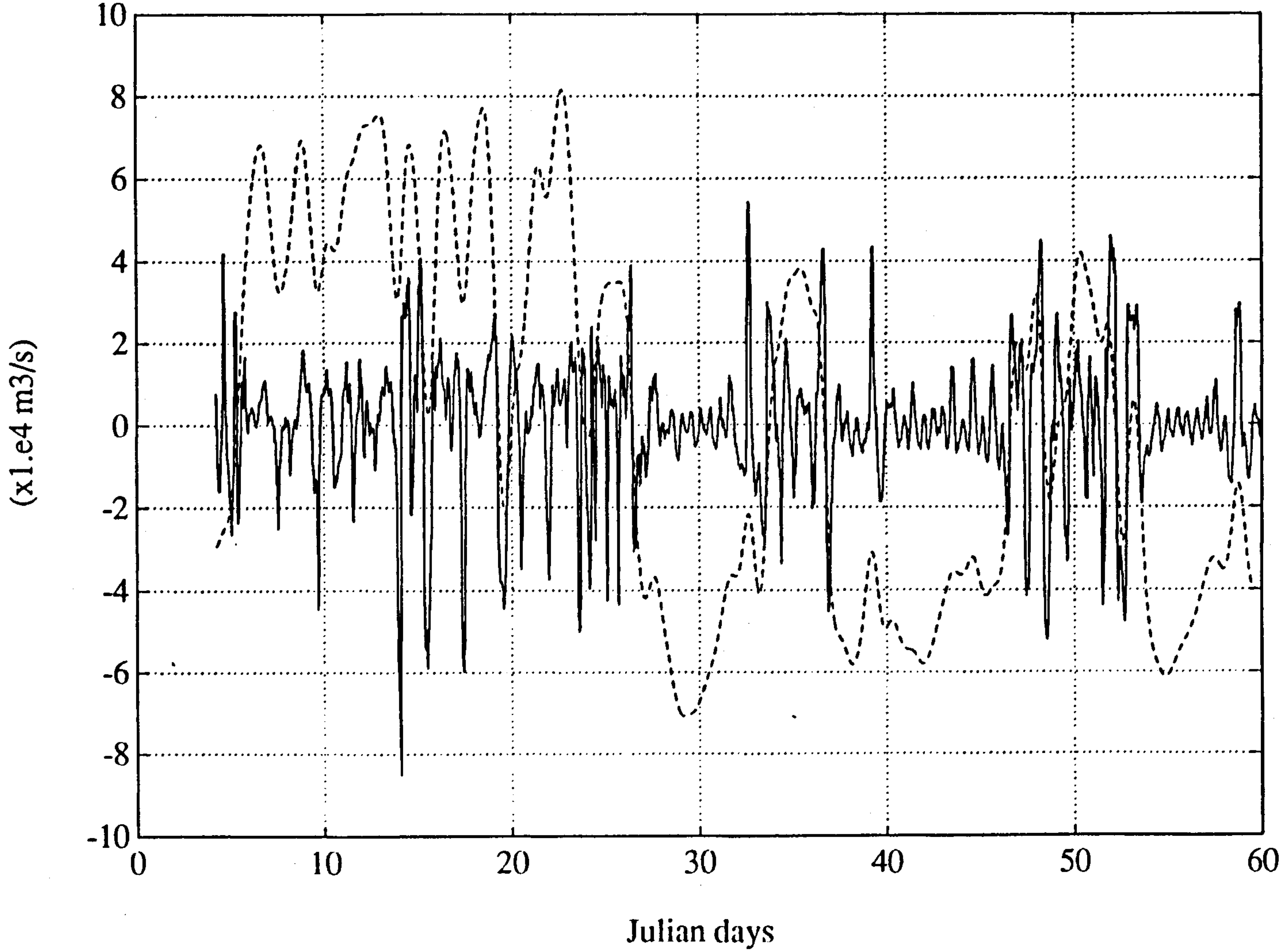

Figure 4.2b. Time series of lowpassed filtered (dotted) and highpassed filtered (solid) data of volume flow (Q_{Oi}).

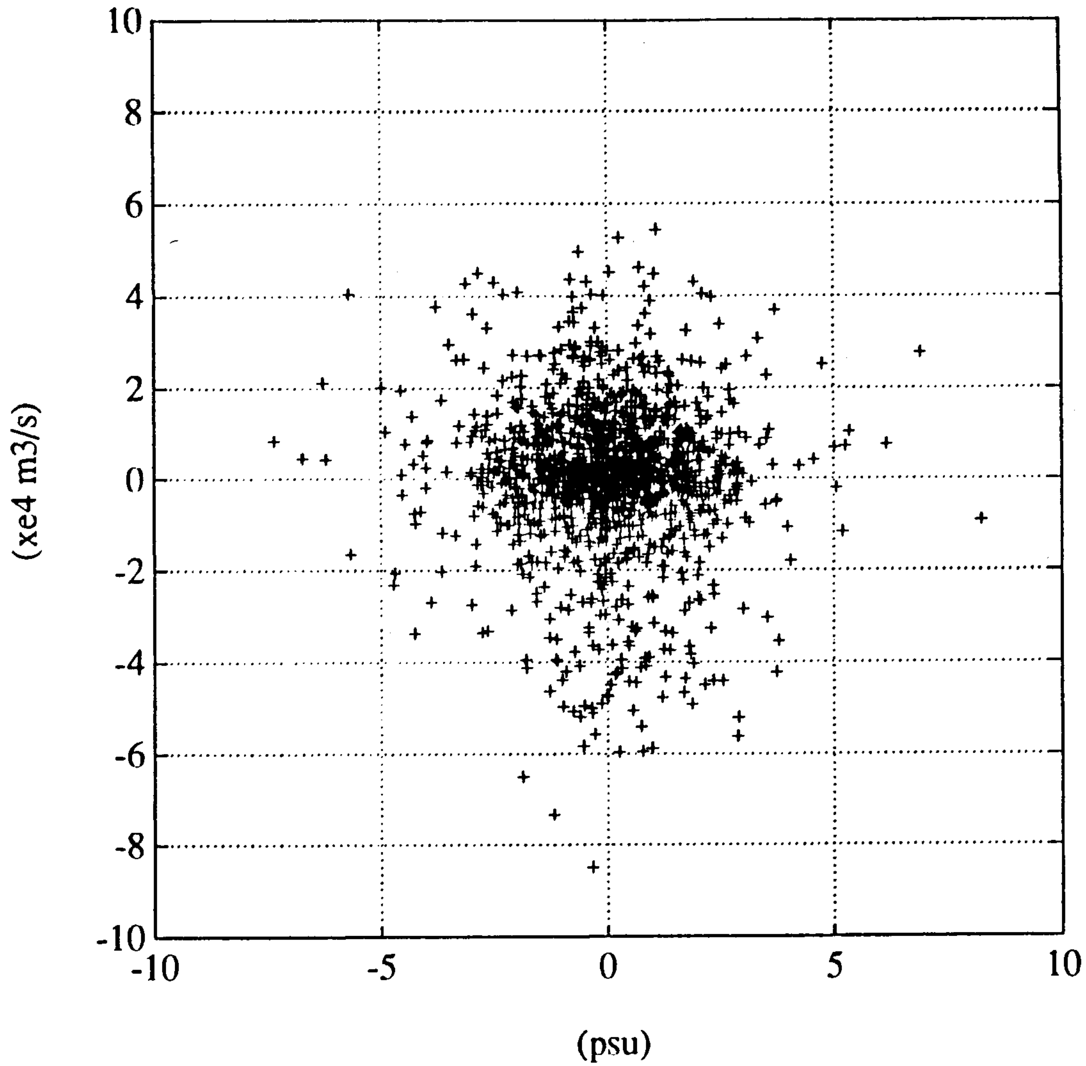

Figure 4.3. Scatter plot of residual (highpassed) salinity (S) and volume flow (Q_{Oi}).

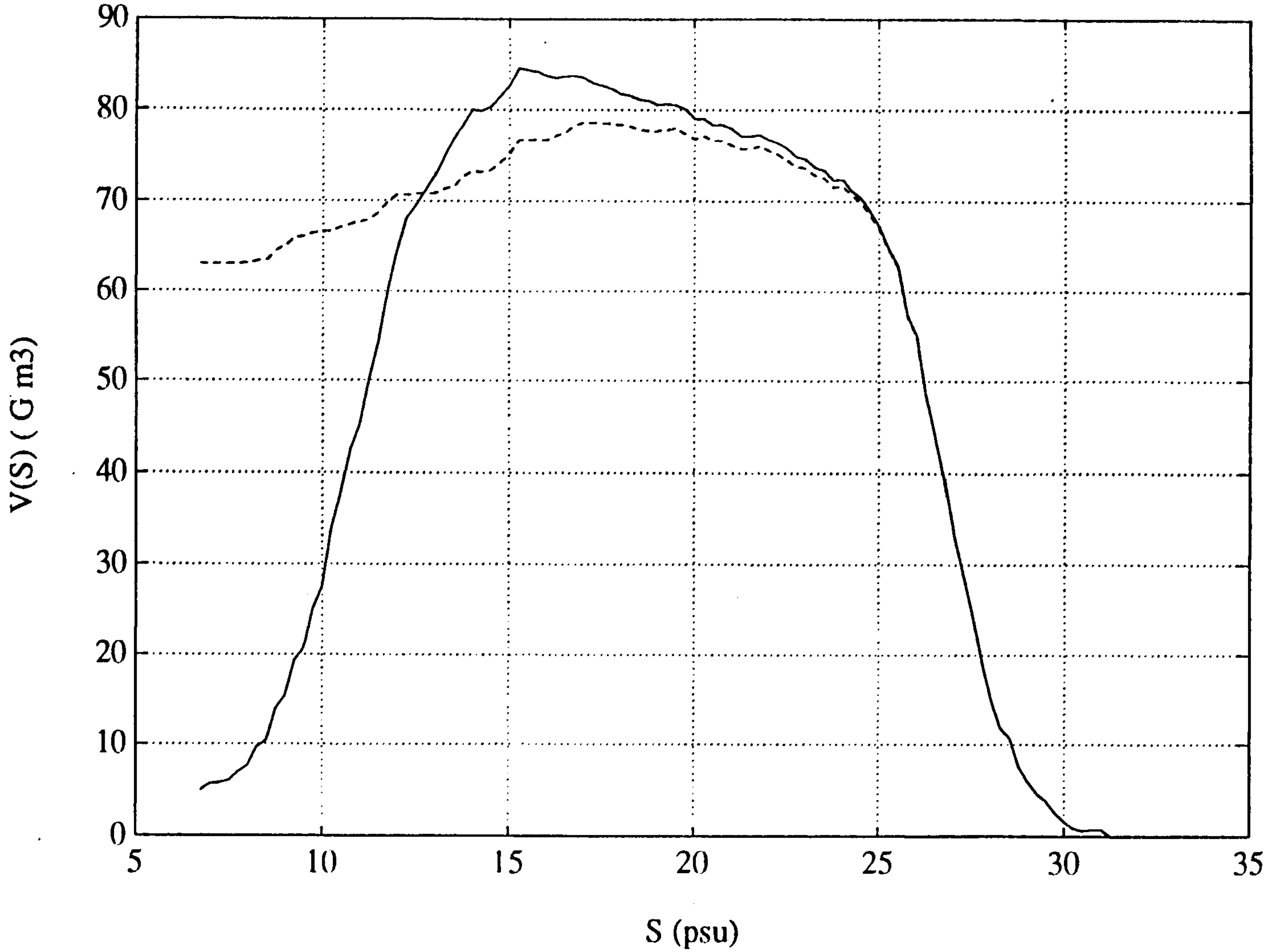

Figure 4.4a. ***Water volume as function of salinity during a) the whole period January 4 to February 28 (solid) and b) during the inflow event January 4 to 30 (dashed), passing through the Sound.***

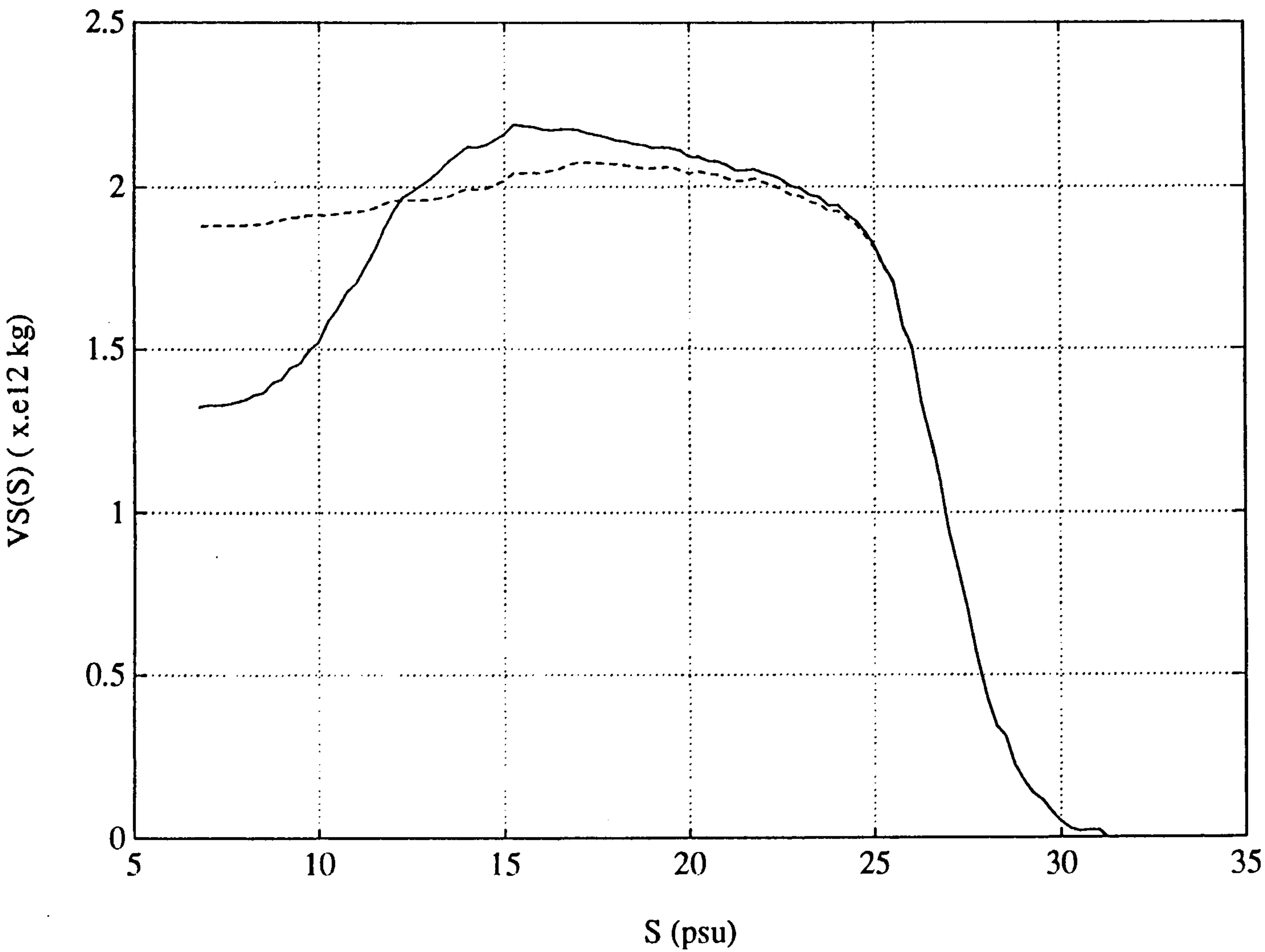

Figure 4.4b. *Salt content as function of salinity during a) the whole period January 4 to February 28 (solid) and b) during the inflow event January 4 to 30 (dashed), passing through the Sound.*