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VOLUMES OF WATER MASSES PENETRATING DURING MAJOR BALTIC INFLOWS AND THEIR CHARACTERISTIC PROPERTIES

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Based on 90 major Baltic inflows identified between 1897 and 1976, the volumes of water penetrating before and during these inflow events are calculated. Mean salinity, temperature, density, and oxygen concentration of the water masses flowing in during each inflow are analyzed. First order estimations of the duration of the transport and velocity of saline deep water are given for an area as far east as the Bornholm Basin.

INTRODUCTION

Major inflows of highly saline and oxygen-rich water into the Baltic Sea have significant impact on the physical, chemical, and biological conditions of the deep water in the central basins. Therefore the inflowing water volumes, estimated hitherto for a few marked inflow events only (e.g. Nov/Dec 1951: 201 or 220 km^3, Wyrtki 1954; Feb 1969: 30 km^3, Francke and Nehring 1971), and their properties are of great interest to biological questions.

METHODS

Using daily salinity measurements from the light vessel "Gedser Rev", a total of 90 major Baltic inflows have been found between 1897 and 1976 by definition of limiting values of salinity and of haline stratification at the Darss Sill (Franck et al. 1987).

The water volumes penetrating during these inflow events are estimated from the increase in the total Baltic water volume calculated from the Landsort sea level data which describe the Baltic mean sea level with sufficient accuracy (Hela 1944; Jacobsen

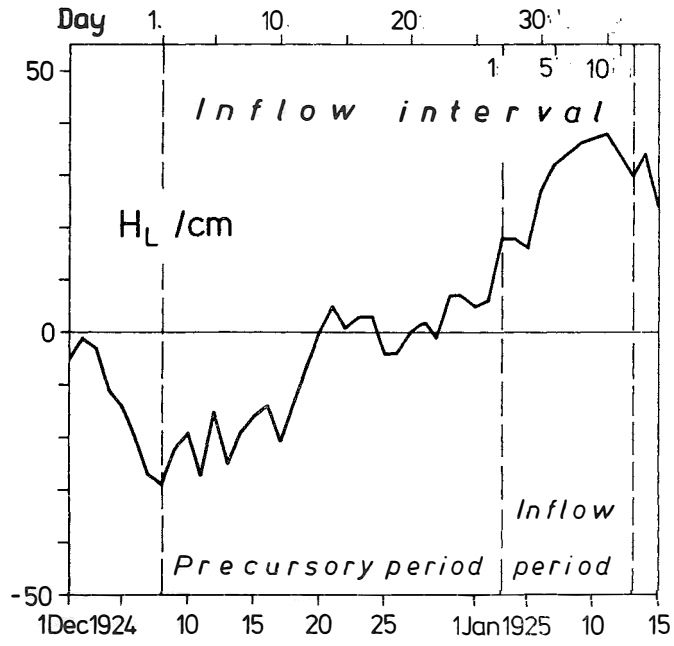

Fig. 1. Periods significant for major Baltic inflow as illustrated by sea level variations at Landsort (H_L)

1980). After eliminating the mean annual sea level variation (Anonymous 1954), both the total sea level increase during the precursory period (time interval between the appropriate minimum Baltic sea level and the start of the major inflow event, cf. Fig. 1) and the increase between the first day and the day of maximum sea level during the inflow period are calculated. The approximate volumes of inflowing water (precursory period: V_b; inflow period: V_d) are obtained by multiplying the increases by the area of the Baltic Sea (372 730 km ^{2}, Ehlin et al. 1974) and by subtracting the river run-off (Mikulski 1982).

In order to determine the properties of penetrating water volumes, salinity, temperature and density values, averaged over the inflow period (S_p,T_p, σ_p) are calculated from daily vertical means at the LV "Gedser Rev". Assuming that the inflowing water was saturated with oxygen, the oxygen content, O_{2p}, is ascertained from T_p and S_p. The salt quantities, q_s, penetrating into the Baltic Sea during inflow events are estimated by the product of $V_d \times S_p$.

The duration and velocity of transport of the inflowing highly saline water from the Darss Sill to the Bornholm Basin are estimated from sporadic salinity and oxygen measurements available from about 15 major Baltic inflows.

RESULTS

Major Baltic inflows always represent the final stage of longer lasting inflow processes. Therefore, both the inflow period of highly saline water and the precursory period, which is characterized by the inflow of less saline water, are of importance (Fig. 1).

The precursory period starting at the time of appropriate minimum sea level and volume of the Baltic has an average duration of 22 days; in extreme cases it can continue for nearly two months. The water volumes penetrating during this period, V_b, vary mainly from 80 to 160 km^3 (Fig. 2). The volumes V_b do not correlate with the intensity of major Baltic inflows, Q; for instance, strong inflows of highly saline water can be preceded by both small and large volumes of inflowing less saline water (cf. Table 1).

Table 1

Characteristic properties of the inflowing water masses during the ten most intensive Baltic inflows between 1897 and 1976

No.	Inflow period	Q	V_b (km^3)	V_d (km^3)	T_p (°C)	S_p ($Sx10^3$)	q_s (10^9 t)	O_{2p} (cm^3/dm^3)
1	25 Nov – 19 Dec '51	79.1	99	218	7.5	22.5	4.9	7.3
2	18 Nov – 16 Dec '13	76.6	194	157	7.7	21.0	3.3	7.3
3	22 Dec '75 – 14 Jan '76	60.0	117	115	4.1	20.1	2.3	8.0
4	29 Oct – 25 Nov '69	54.8	78	151	9.4	18.2	2.7	7.1
5	16 Dec '21 – 6 Jan '22	49.4	77	235	4.0	19.2	4.5	8.1
6	17 Jan – 31 Jan '21	46.6	228	99	3.4	20.7	2.0	8.1
7	13 Nov – 29 Nov '73	41.4	95	112	6.6	19.4	2.2	7.6
8	26 Nov – 13 Dec '06	38.0	125	120	6.8	18.7	2.2	7.6
9	10 Nov – 20 Nov '30	37.3	144	107	8.4	20.5	2.2	7.2
10	28 Sep – 15 Oct '50	35.9	153	31	13.3	18.4	0.6	6.5

The water entering the Baltic Sea during the precursory period originates mainly from the Belt Sea. Comparing the mean inflow volume V_b = 121.2 km^3 with the total Belt Sea volume of 290.6 km^3 (Ehlin et al. 1974), it can be seen that, on the average, 42% of the Belt Sea volume enters the Baltic Sea before the beginning of the actual inflow event. That means that the highly saline water from the southern Kattegat does not fill up all parts of the strongly structured Belt Sea area before the inflow event starts at the Darss Sill. Probably the highly saline water passes this area as a stream-like phenomenon of varying extent.

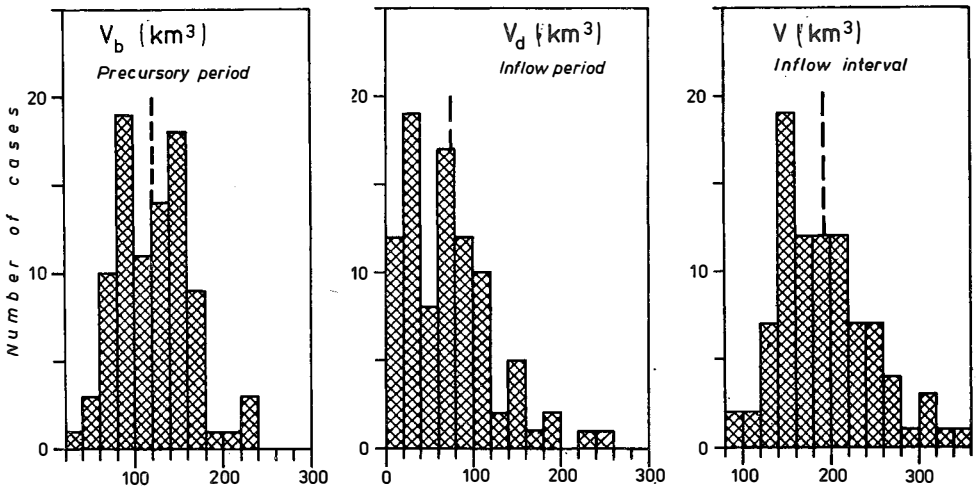

Fig. 2. Frequency distribution of the water volumes penetrating before the beginning of major events at the Darss Sill (V_b), during the inflow event (V_d) and during the complete inflow interval (V)

During an inflow period (mean duration 10 days), the penetrating water volume, V_d, varies mainly from 10 to 120 km³ (cf. also Fig. 4). The frequency distribution of V_d differs clearly from that of V_b (cf. Fig. 2). Small volumes of 20–40 km³ occur most frequently. The frequency diminishes as the volume increases, especially above the mean value $V_d = 71.4$ km³.

There is a distinct correlation between the penetrating water volume during the inflow period, V_d, and the intensity of major inflows, Q (based upon haline conditions) (Fig. 3). The correlation ($r = +0.68$) is significant at the 99.9% level. The correlogram includes the fluctuation limits referring to the intensity classes of inflow events. In spite of a small number of the very strong events, the variation range of V_d is similar to that of moderate and strong inflows. Both very high (235 km³) and low values of V_d (99 km³) occur (cf. Table 1). Generally, the penetrating volume of highly saline water, V_d, is > 100 km³ during very strong events and < 100 km³ during weak inflows.

The frequency distribution of the total water volume $V = V_b + V_d$ flowing in during the complete inflow interval is given in the right histogram of Fig. 2. In 61% of the events the volumes vary between 140 and 220 km³. On the average, 193 km³ of water enter the Baltic during a complete inflow process, the largest inflow bringing 351 km³. The mean value of the ratio V_d/V is 35%.

Based upon salinity and oxygen observations (Christiansø Deep, near station BY 4; central Bornholm Basin, station BY 5) available from about 15 major Baltic inflows,

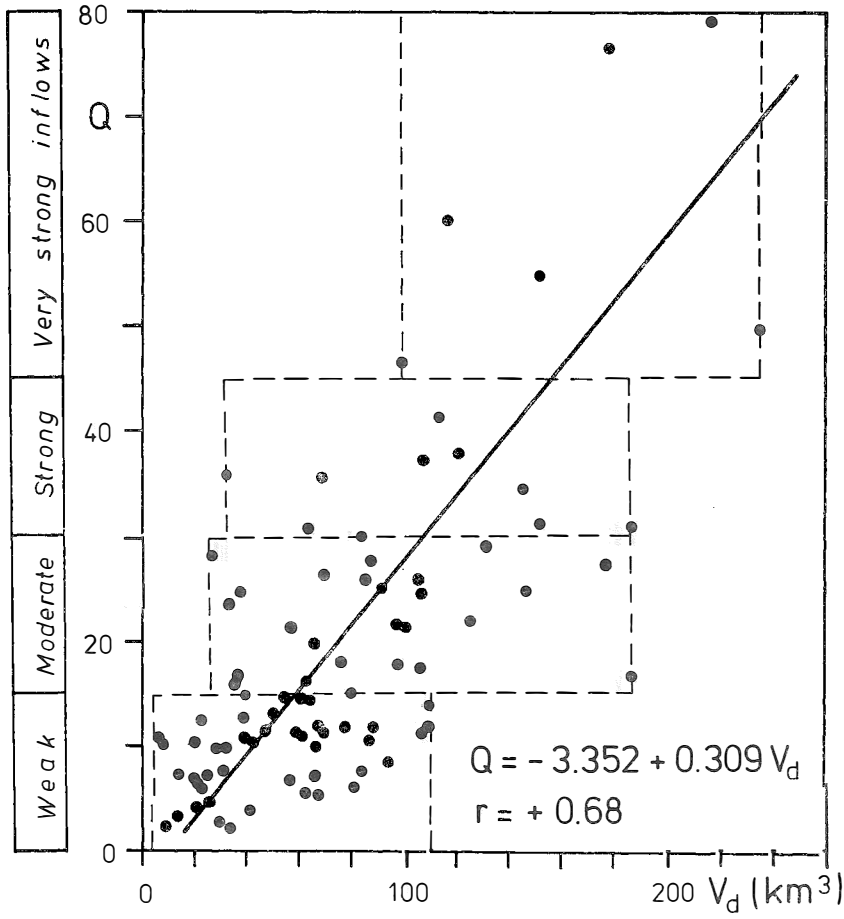

Fig. 3. Correlation between the intensity (Q) of major events and the inflowing water volume (V_d) during the inflow periods

Table 2

Duration and velocity of propagation of highly saline water between the Darss Sill and the Bornholm Basin

Area		Duration (days)	Velocity (cm/s)
Christiansø Deep (near BY 4)	Mean value	22	11
	Range of variation	15–35	7–16
Central Bornholm Basin (BY 5)	Mean value	41	8
	Range of variation	16–59	5–18

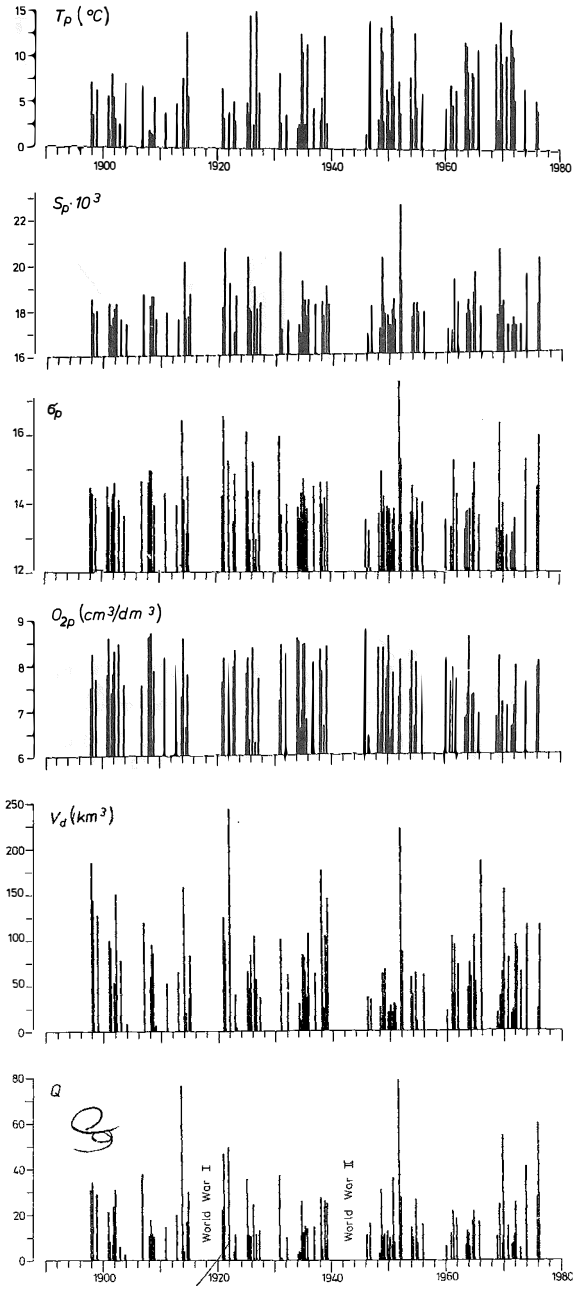

Fig. 4. Characteristic values of all major Baltic inflows between 1897 and 1976 (Q: intensity index; V_d: water volume penetrating during the inflow period; T_p, S_p, σ_p, O_{2p}: temperature, salinity, density and oxygen content respectively, averaged over the inflow period)

first order estimations are obtained of the duration and velocity of water propagation between the Darss Sill and the above-mentioned areas (Table 2). Due to the different intervals between the available observations, it is believed that the mean values and the upper limits of duration are somewhat too high, whereas the mean values and the lower limits of velocity are somewhat too low.

The duration of propagation to the central Bornholm Basin is twice as long as that to the Christiansø Deep (cf. Table 2). Although there is a natural reduction in the velocity of the inflowing deep water, the results seem to give some evidence that the inflowing water does not always follow the shortest route from the western edge into the central Bornholm Basin.

Besides the intensity index, Q, and the inflowing water volume, V_d, the mean values of characteristic properties of water masses penetrated into the Baltic Sea during the inflow periods are shown in Fig. 4 for each major Baltic inflow between 1897 and 1976 (cf. also Table 1).

The temperature of highly saline water hardly differs from the average seasonal temperature. Therefore, the mean vertical temperature, T_p, of inflows ranges mainly from 2 to 8 °C, because most inflows take place between November and February. The temperature can occasionally be higher than 13 °C; the lowest mean value was calculated to be 1.4 °C.

The mean vertical salinity, S_p, of the inflows is seldom lower than 17×10^{-3} because this concentration is defined as the lower limit for the bottom salinity during an inflow at the Darss Sill. The mean salinity is most commonly between 17.5 and 18×10^{-3}. Inflows with values higher than 20.5×10^{-3} are very rare. The highest mean salinity of 22.5×10^{-3} was observed during the 1951 event.

The mean vertical densities, σ_p, of the inflowing water masses range predominantly between 13.0 and 15.0 σ-units. Mean densities of more than 16 σ-units are rare. The 1951 event shows the highest mean density (17.6 σ-units).

The mean oxygen content of the inflowing water, O_{2p}, is generally between 6.5 and 8.5 cm^3/dm^3. The highest mean oxygen content of an inflow was calculated to be 8.7 cm^3/dm^3 (Feb. 1946). Events with oxygen concentrations of the penetrating water below 6 cm^3/dm^3 were not observed.

The quantities of salt, q_s, transported into the Baltic Sea ranged between 1.8 and 4.9×10^9 tons of salt during 23 inflow events with volumes $V_d \geq 100\ km^3$, i.e., stronger inflows can transport about 10–20% of the total salt content of the deep water of the Baltic proper across the sills. The quantities of salt entered the Baltic Sea during the ten most intensive inflows are included in Table 2.

CONCLUSIONS

Major inflows of highly saline water into the Baltic Sea – the final stages of longer lasting inflow processes – are characterized by two periods: the precursory period

covering inflows of less saline water and the true inflow period. The water volumes penetrating during the different periods are estimated from the Baltic sea level increase; the characteristic properties of water masses of the inflow period are investigated from data measured at the Light ship "Gedser Rev". The following conclusions can be drawn:

1. The precursory period and the inflow period last, on the average, 22 and 10 days, respectively.
2. The water volume crossing the sills during the precursory period ranges between nearly 20 and 230 km^3 (an average of 121 km^3). In about 70% of events the volumes varied from 80 to 160 km^3.
3. On the average, about 42% of the water volume of the Belt Sea passes the sills before the beginning of a major event.
4. The volumes of highly saline water entering the Baltic Sea during major inflows range between nearly 3 and 235 km^3 (an average of 71 km^3). In about 80% of all cases identified, the volume was 10–120 km^3. The inflowing water volume is always $> 100\ km^3$ during very strong events.
5. First order estimation of duration and velocity of propagation of highly saline water between the Darss Sill and the Bornholm Basin yield mean values of 22 days and 11 cm/s, respectively (as far as Christiansø Deep) and 41 days and 8 cm/s, respectively (as far as central Bornholm Basin).
6. Mean vertical temperature, salinity, density and oxygen content of water bodies penetrating during the inflow periods predominantly amount to 2–8 °C, 17.0–18.5 x $x\ 10^{-3}$, 13.0–15.0 σ-units and 6.5–8.5 cm^3/dm^3 respectively. Seasonal variations in mean salinity and density are small, whereas distinct seasonal changes are found in mean temperature and oxygen content of the inflowing highly saline water.
7. The water entering during the inflow period transports 2 to 5 $x\ 10^9$ tons salt into the Baltic Sea during stronger events.

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