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MAJOR INFLOWS OF HIGHLY SALINE WATER INTO THE BALTIC SEA - A REVIEW

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ABSTRACT

The water exchange between the North Sea and the Baltic is a natural process governed by meteorological and oceanographic factors. However, exchange is greatly restricted by the narrow and shallow transition area between the two seas. During "normal" inflows, the volume of water with a higher density crossing the sills into the Baltic is insufficient to displace the bottom water or significantly change the oceanographic conditions in the deep basins. This can only be done by major influxes of highly saline and oxygenated water which are typical, but relatively rare, phenomena in the Baltic Sea.

In the review paper, a brief summary of the present knowledge on major inflows of highly saline and oxygenated water into the Baltic Sea is given taking into consideration all identified events during this century. The recent inflow in January 1993 is classified by comparing with inflows in the past.

1. Introduction

The Baltic Sea is a landlocked sea area in the humid climatic zone. Its narrow and shallow transition area consisting of the Kattegat and Belt Sea greatly restricts the exchange of water with the North Sea. Moreover, circulation in the Baltic deep water is prevented horizontally by the bottom topography, and vertically by a permanent halocline. These factors cause periods of stagnation which are marked by increasing phosphate and nitrate concentrations and decreasing salinity and oxygen concentrations in the deep water, and sometimes culminate in the formation of considerable hydrogen sulphide concentrations in deep basins.

During "normal" inflows, the volume of water with a higher density crossing the sills is insufficient to displace the bottom water or significantly change oceanographic conditions in the Baltic deep basins. This can only be done by the strong influxes of highly saline and oxygenated water - termed major Baltic inflows - which are typical but relatively rare phenomena in the Baltic Sea.

Krümmel (1894, 1895) and Knudsen (1900) discussed the problem of Baltic deep water renewal as early as the end of the last century. Kalle's (1943) investigation of the major turnover in the Gotland Deep (see Fig. 1) in 1933/34 aroused increased interest in the causes and conditions for major Baltic inflows. Since the fifties, regular and frequent oceanographic observations and improvements in measuring techniques have permitted more detailed investigations to be carried out, and these have mostly been concerned with selected marked inflow events (e.g. Wyrtki 1954, Francke & Nehring 1971, Francke & Hupfer 1981, Lass & Schwabe 1990).

As to the causes, both meteorological and oceanographic preconditions are thought to be responsible for the occurrence of major Baltic inflows. Three basic approaches have been used to investigate the causes, conditions and progress in more detail:

1. Analysis of long-time series of relevant meteorological and oceanographic parameters recorded in the North Atlantic and the north western European shelf seas, including the Baltic. This approach was used, for instance, by Dickson (1971, 1973), Börngen (1978, 1983) and Börngen et al. (1990). Because of the basic importance of meteorological forcing for the occurrence of major inflows, further research in this field is necessary.

2. Identifying the major inflows by their typical effects in the Baltic deep basins. This approach has often been used in the past (Fonselius 1969, 1981, Fonselius & Rattanasen 1970, Fonselius et al. 1984, Nehring & Francke 1981). However, the method has a certain drawback due to the lack of sufficiently long-time series for the open Baltic deep water. Moreover, the number of inflow events that have been identified is relatively small because of the effects of major events depend on the density conditions in the deep basins at the time.

3. Identification of major events by characteristic levels of oceanographic parameters recorded in the entrance sill areas. This approach permits definite identification of all events regardless of their effects in the various deep basins on the condition that suitable long-time series are available. This method has recently been used by Wolf (1972), Franck et al. (1987, 1992b) and Matthäus & Franck (1992).

2. Characteristics of major inflows

Inflow processes culminating into major Baltic inflows consist of two fundamental parts: the *precursory* and the *inflow periods*. The *precursory period* covers the time from the minimum Baltic sea level preceding the major inflow to the start of that event. It is characterized by the inflow of water with relatively low salinity across the Darss Sill whereas highly saline water can already pass through the Drogden Sill. The *inflow period* is characterized by the influx of highly saline water across both sills up to the maximum Baltic sea level during this event.

Ninety six major inflows of highly saline water into the Baltic Sea have been identified during the period from 1897 to 1993 excluding the two world wars (Franck et al. 1987, 1992b; Matthäus & Franck 1992). All inflows occurred between the end of August and the end of April (Fig. 2), so that we can call this period as "inflow season". The seasonal frequency distribution of the major inflows shows maximum occurrence between November and January and low frequencies in August/September and in March/April. Major events never occurred between May and middle of August.

Major inflows occur both as isolated events (6 cases) or in groups (17 cases) (Fig. 3). A group comprises all inflows separated by intervals of less than 1 year. Isolated events occurred in 1906, 1910/1911, 1936, 1973, 1979, 1993(?). Groups are found to extend mainly over two or three seasons, but never more than five consecutive inflow seasons. The largest groups were between 1948 and 1952 (12 events) and between 1968 and 1972 (10 events). The longest periods without inflow events lasted 9 (1983/1992) and 3 consecutive inflow seasons (1927/1930, 1956/1959) respectively. Inflows have never been observed in the second part of the inflow season, i.e. from January to April, during strong winters.

The different events can be characterized by means of the parameter Q representing an attempt to arrange major events according to their relative intensity. Q, called intensity index, is a function of the duration k of the inflow and the mean salinity S of the inflowing water:

$$Q = 50 \left(\frac{k - 5}{25} + \frac{S - 17}{7} \right)$$

Q ranged between 0 (k = 5 days, S = 17 PSU) and 100 (k = 30 days, S = 24 PSU).

Major inflows can be classified according to their intensity index into weak ($Q \leq 15$), moderate ($15 < Q \leq 30$), strong ($30 < Q \leq 45$) and very strong ($Q > 45$). Weak inflows, which account for about half of all inflow events, are never longer than eight days and have a maximum mean salinity of 18.6 PSU. Q has considerable seasonal variation with highest intensities from November to January.

Each major event is preceded by an inflow of less saline water. The duration of the precursory period varied between 4 and 58 days, but usually lasted for 5 to 25 days. The precursory and inflow periods last, on average, 22 and 10 days, respectively, i.e. two-thirds of the total inflow process is covered by the precursory period and one-third by the inflow period.

The characteristic properties of the inflowing water bodies like temperature, salinity and oxygen concentration have significant impacts on marine life and the oceanographic regime in the Baltic deep water. Temperature and oxygen concentration of the inflowing water are also important for the biochemical processes taking place in the deep water. Seasonal variations in temperature and oxygen concentration are considerable (Fig. 4). More intensive events between September and early December generally cause an increase in temperature whereas inflows between January and April lead to a distinct improvement of the oxygen conditions in the deep basins (Matthäus & Franck 1988).

Fig. 5 shows the frequency distribution of volumes of highly saline water V_d entering the Baltic Sea during all major inflows identified between 1897 and 1993. The volumes penetrating during the precursory period vary predominately between 80 and 160 km^3 (on average about 120 km^3). This water originated mainly from the Belt Sea entered the Baltic before the beginning of the actual inflow event. In general, volumes of highly saline water entering the Baltic during major inflows are >100 km^3 during very strong events and <100 km^3 during weak inflows (on average about 70 km^3) (Matthäus & Franck 1990).

During inflow processes culminating in major events the Baltic sea level can vary between -60 cm and +70 cm. Minimum sea levels which are always below the normal Baltic sea level precede each inflow of highly saline water, as a rule by between 5 and 40 days. However, negative Baltic sea levels during the last 15 days preceding an event are not a necessary precondition even for strong and very strong major inflows. During the total inflow process, the Baltic sea level increases by an average of 59 cm (i.e. 38 cm during the precursory period, 21 cm during the inflow period.

3. The event in January 1993

The recent major Baltic inflow is analyzed in detail by Matthäus et al. (1993). Compared with major events in the past the volume V penetrating during the complete inflow process was below the volumes entered during the inflows in 1913 and 1921, but achieved the volumes of the events in 1921/1922 and 1951 (cf. Table 1). However, both the volume of highly saline water crossing the sills V_d (cf. Fig. 5), the mean salinity S of the inflowing water and particularly the duration k (Table 1) were considerably lower. According to the parameters given in Table 1, there are similarities to the event in 1961.

The volume calculations are based on the sea level at Landsort (cf. Fig. 1) which represents the mean Baltic sea level fairly well (Lisitzin 1974; Jacobsen 1980; Franck & Matthäus 1992a). The inflow started at the Darss Sill not before the Baltic sea level reached 35 cm above normal (Fig. 6). At any rate, the Baltic sea level increase took only 19 days between the minimum of -17 cm and the maximum of +70 cm. That is very short compared with the other events (e.g. 1921/1922: 30 days; 1951: 26 days; 1975/1976: 51 days) and is characteristic for the recent inflow.

Table 1: Major Baltic inflows most effective in the Baltic deep water and the event in January 1993

Inflow period	Q	k	S	T		O_2	V_d	V
		(days)	PSU	°C		cm^3/dm^3	km^3	km^3
Nov/Dec 1913	76.6	29	21.0	7.7	16.4	7.3	157	351
Jan 1921	46.6	15	20.7	3.4	16.5	8.1	99	327
Dec 21/Jan 22	49.4	22	19.2	4.0	15.3	8.1	235	312
Jan/Feb 1938	27.3	14	18.3	3.1	14.6	8.3	175	275
Sep 1948	30.9	9	20.2	13.4	14.9	6.4	62	147
Nov/Dec 1951	79.1	25	22.5	7.5	17.6	7.3	218	317
Mar/Apr 1961	21.8	8	19.2	4.9	15.3	7.9	96	320
15-22 Nov 1964	17.5	8	18.6	8.4	14.3	7.3	104	181
24-30 Nov 1964	21.6	7	19.5	8.0	15.2	7.3	55	227
Feb 1969	24.8	5	20.5	3.3	16.3	8.1	39	142
Dec 1971	25.1	17	17.2	5.3	13.6	7.9	91	176
Dec 1975	28.2	15	18.1	5.2	14.5	7.9	25	138
Dec 75/Jan 76	60.0	24	20.1	4.1	16.0	8.0	115	232
Jan 1993	*21.2*	*9*	*18.7*	*3.5*	*15.2*	*8.2*	*125*	*310*

Compared with all identified events in the past (Matthäus & Franck 1992; Franck & Matthäus 1992b), the inflow in January 1993 must be classified as moderate one (cf. Figs. 2 and 3). According to the observations during this year the effects of the event in the central Baltic deep basins have been limited as it was feared after the recordings at the sills in January.

4. Outlook

The recent major inflow represents a unique opportunity for investigating the process of propagation of the salt and oxygen-rich water into the various Baltic basins. The huge amount of oceanographic data recorded by the marine scientific institutes around the Baltic allows detailed studies of the renewal and turnover of the Baltic deep water and the exchange processes between different deep basins. Major components for further investigations should be, for instance:

* The role of the Sound during salt water influxes
* The role of subsequent weather conditions, of river run-off, of the internal dynamics of the subbasins and of sill overflows between the subbasins, particularly the part of the Bornholm Basin as storage basin during the propagation of the salt water farther into the central Baltic
* What is going on with the heavily H_2S-contaminated deep water in the eastern Gotland Basin?
* How long will exist oxic conditions in the eastern Gotland Basin deep water without any major event in time?

Moreover, the oceanographic data set of the inflow in January represents a qualified basis for modelling of such events and should be a step to the development and validation of oceanographic models which can accurately describe and predict major inflow events. This also is, among others, a key issue of the scientific plan for the regional GEWEX-subprogramme BALTEX (**BALT**ic Sea **EX**periment).

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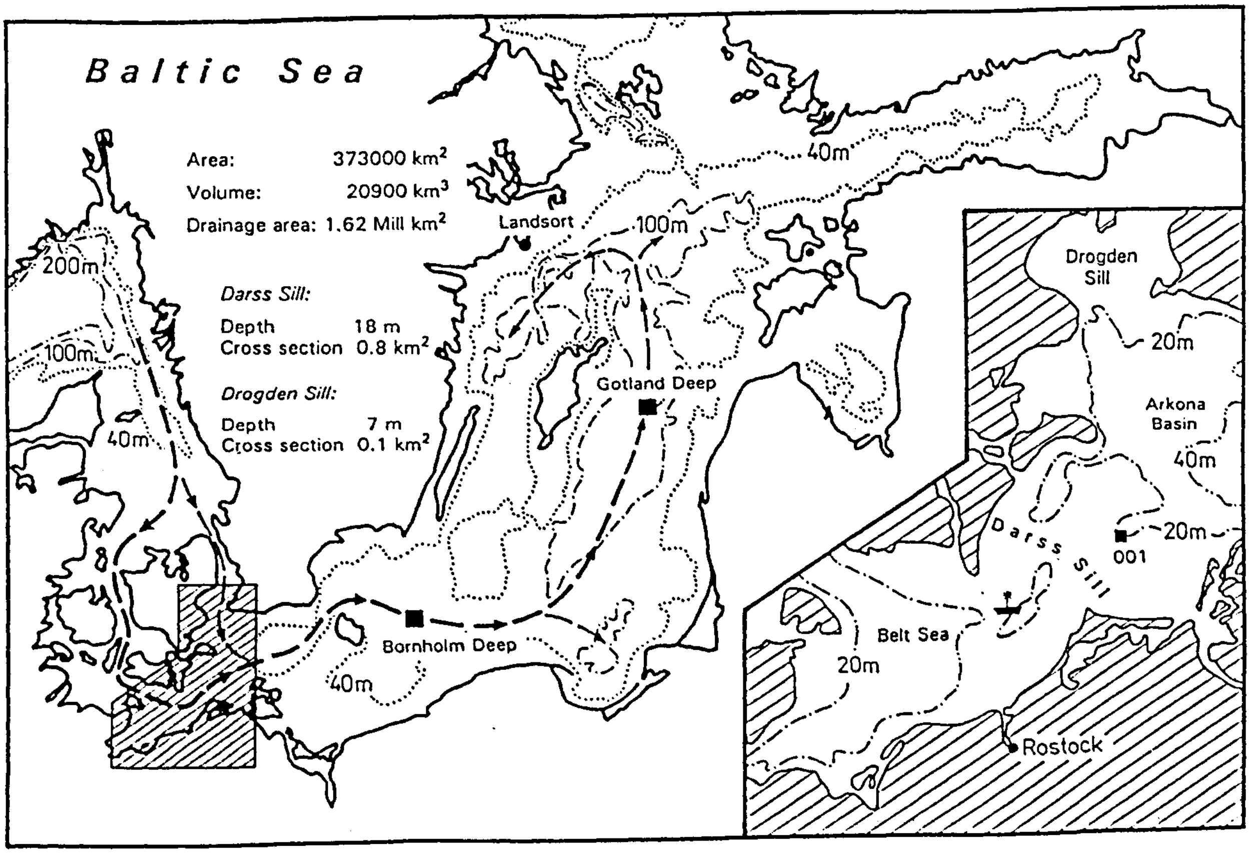

Fig. 1. The Baltic Sea and the situation of the sills in the transition area to the North Sea

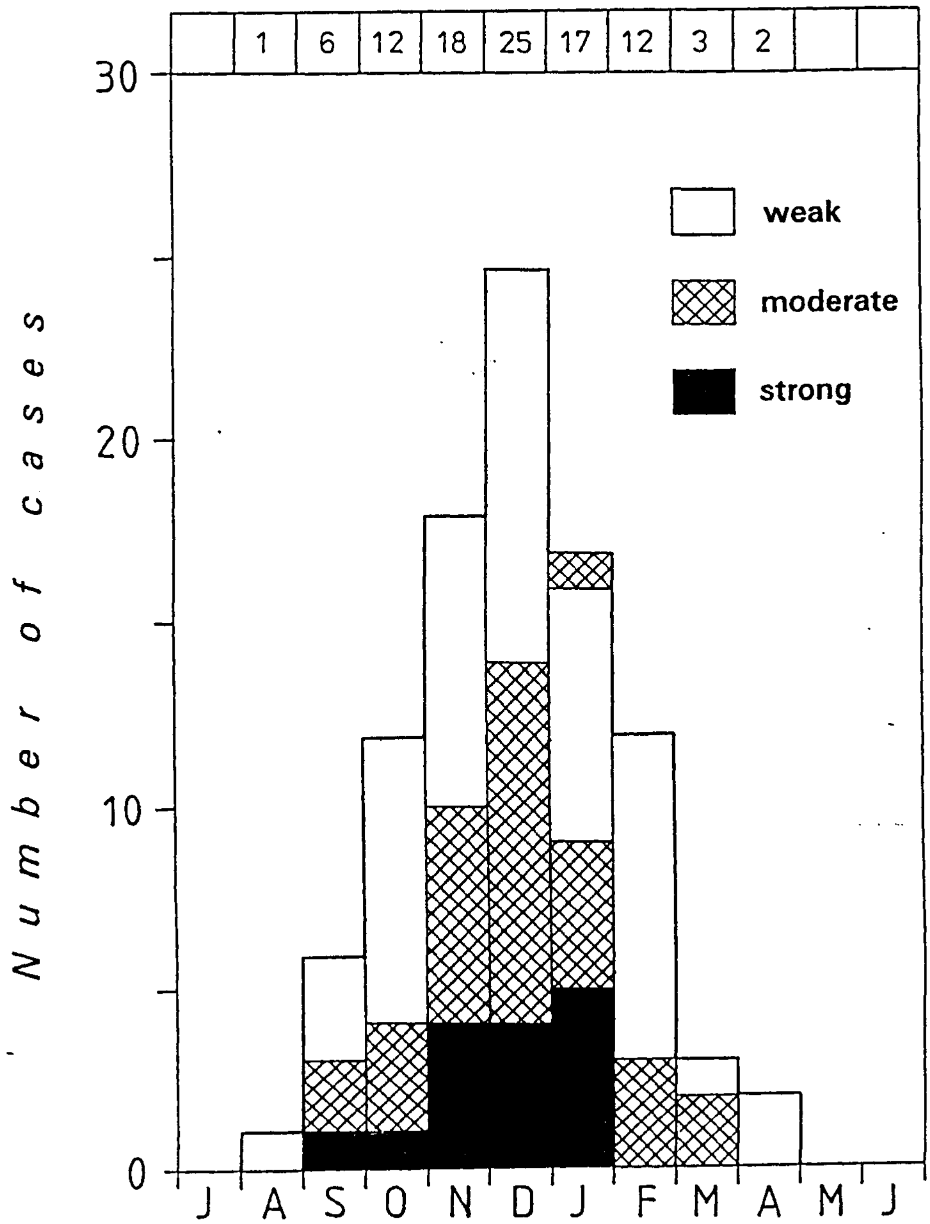

Fig. 2. Seasonal frequency distribution of major Baltic inflows during the present century for different intensity groups (January-1993-event: separated hatched box)

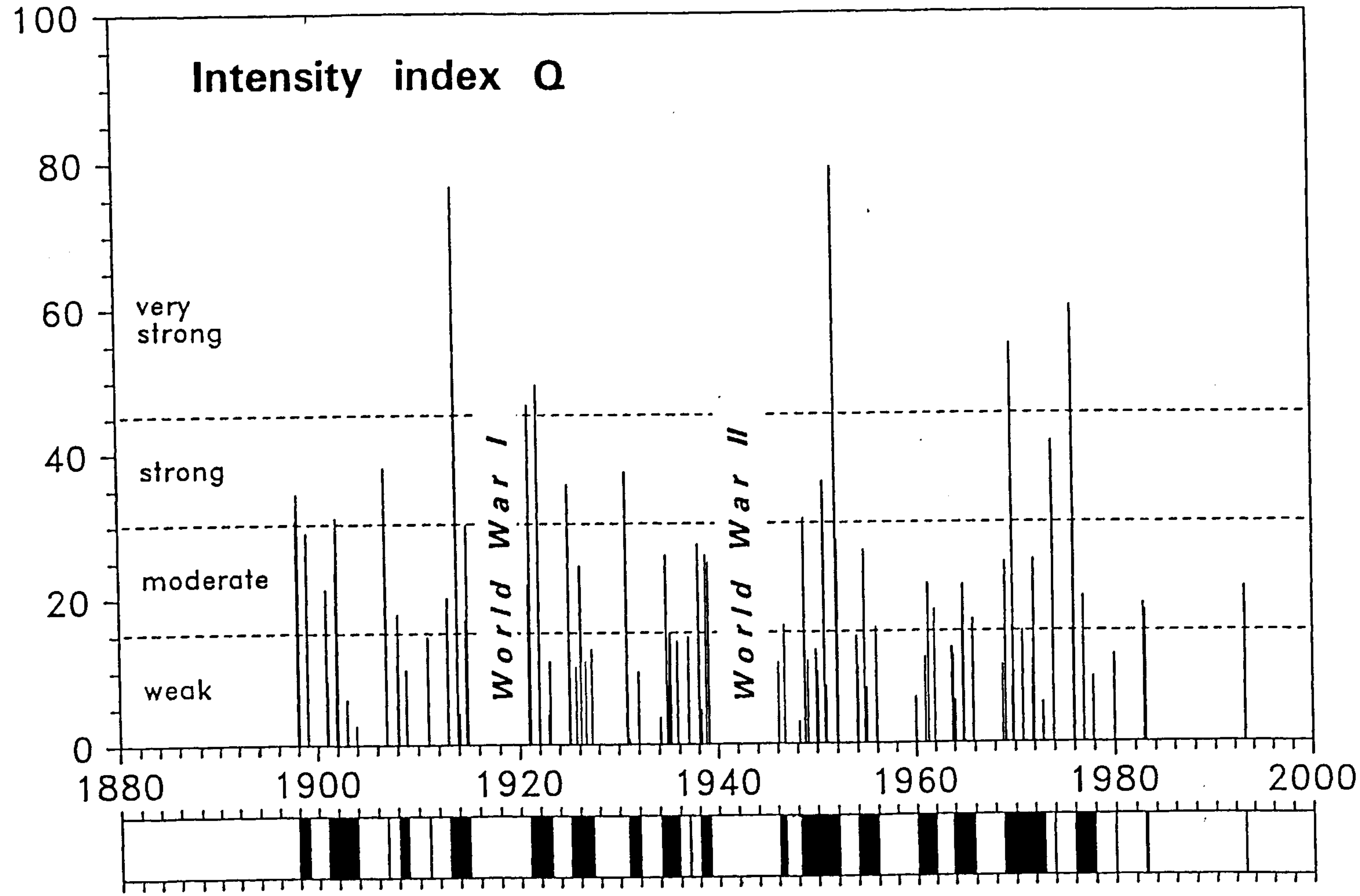

Fig. 3. Major inflows of highly saline water into the Baltic Sea, characterized by an intensity index Q (above) and the inflow groups (below)

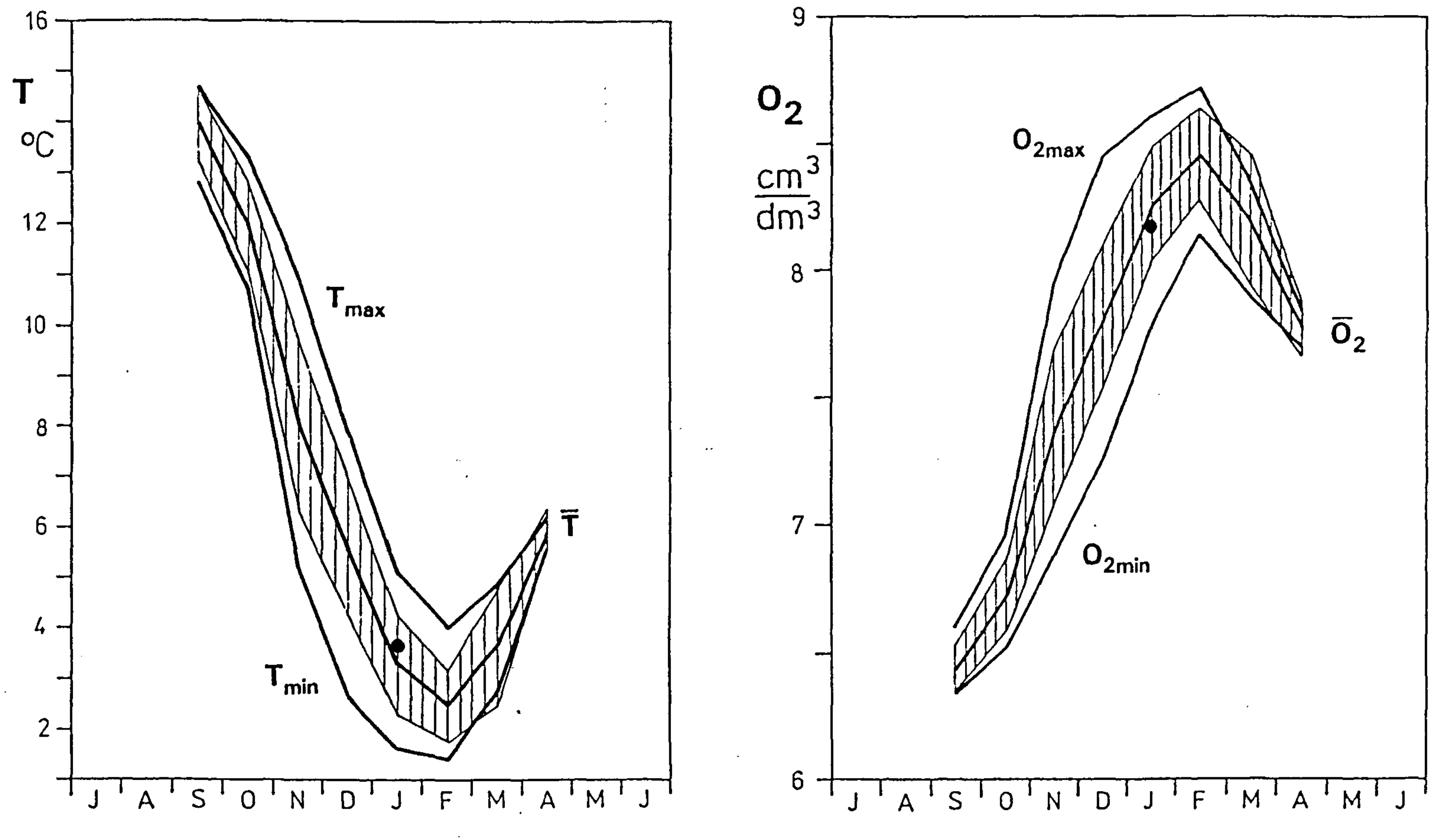

Fig. 4. Seasonal variations of temperature T and oxygen concentration O_2 (monthly means T, O_2 and extreme values) of the water penetrating during major Baltic inflows (hatched areas correspond to the standard deviation; dots indicate the 1993-event)

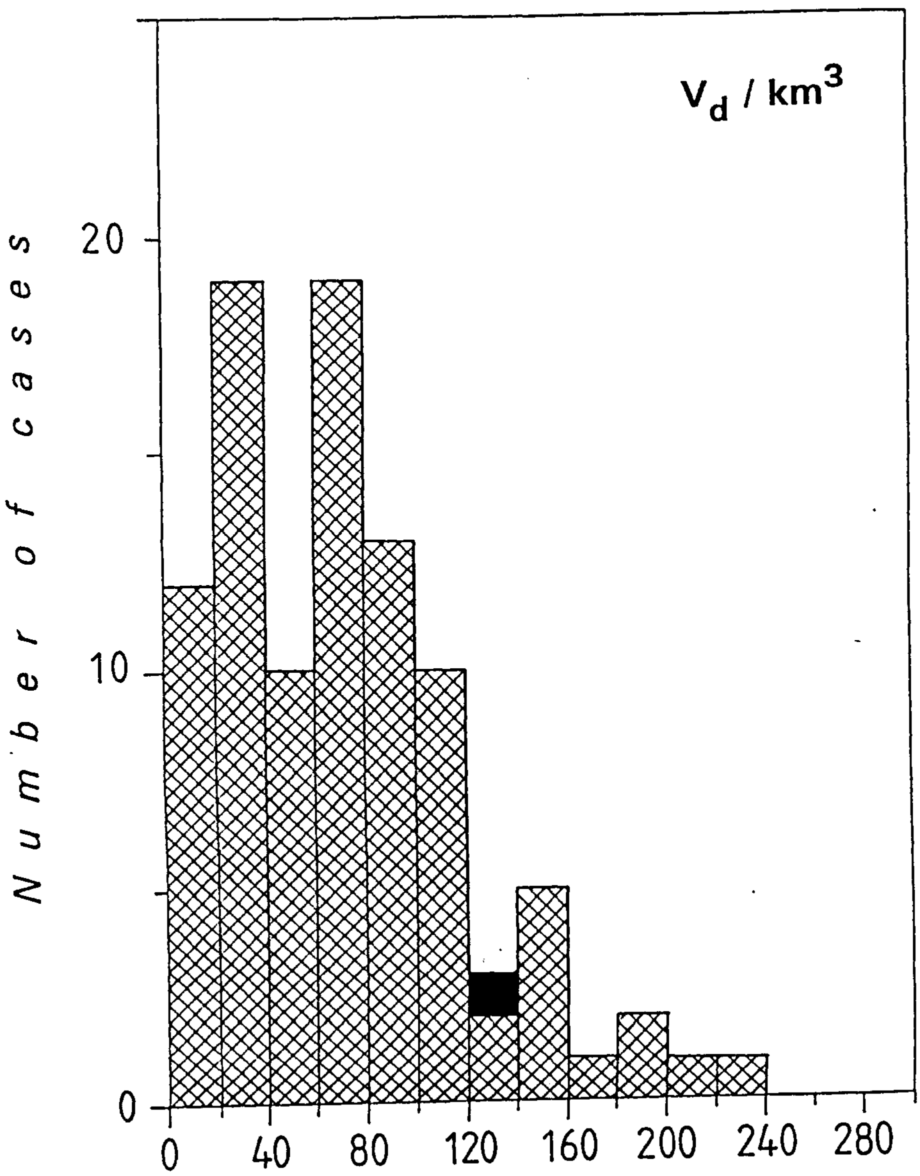

Fig. 5. Frequency distribution of the water volumes V_d penetrating during major Baltic inflows (black box: January-1993-event)

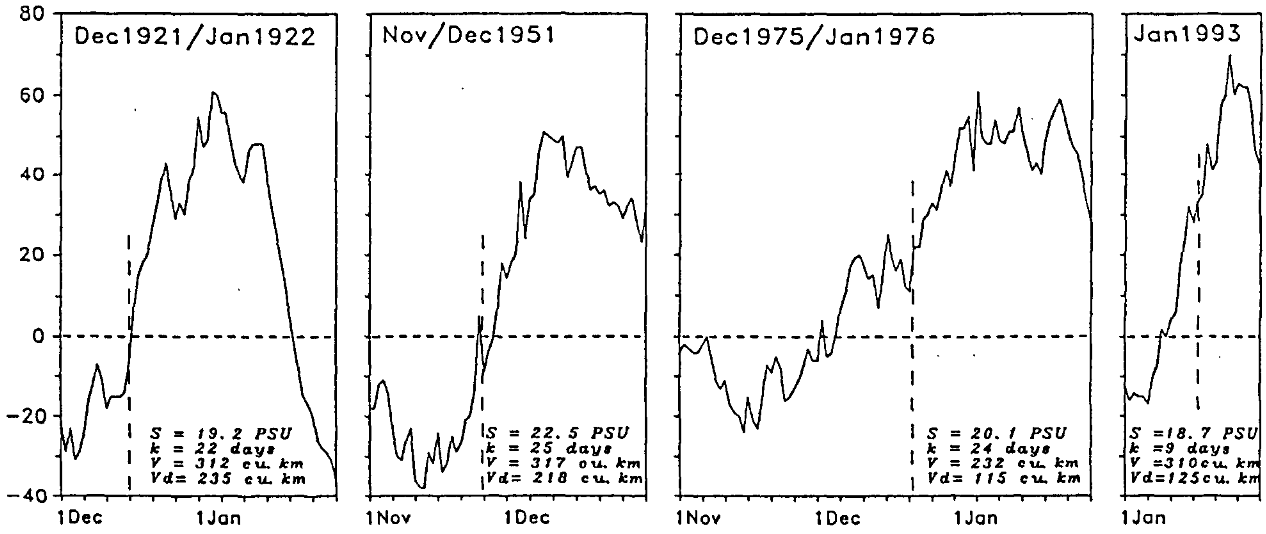

Fig. 6. Variations of the daily mean sea level of the Baltic Sea (Landsort) during the January-1993-event compared with other strong inflows in the past