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The seasonal nature of major Baltic inflows

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Abstract

Major inflows of saline water into the Baltic Sea have a significant impact on the oceanological regime of the deep water in the central basins. Such events show seasonal characteristics, which are investigated here for the 80-year period from 1897 to 1976. The characteristic properties – i.e. salinity, temperature, density and oxygen concentration – of the water bodies entering the Baltic during major inflows are analyzed for the first time. The significance of the season of the inflow event for its effects on the oceanological conditions in the deep water is discussed.

Introduction

Major inflows of saline water into the Baltic Sea have a significant impact on living conditions in the deep water, and also affect the marine environment at the surface. Recent analyses of major inflows during the present century yielded statistical information on intensity, frequency, duration and other characteristic parameters of inflow events (MATTHÄUS et al. 1987, FRANCK et al. 1987a, b). The results indicated the seasonal nature of such events. Moreover, these analyses enabled us to calculate the fundamental properties of the inflowing water bodies. In the following, the basic features of major Baltic inflows are presented briefly and the seasonal characteristics of such inflow events are discussed.

Material and methods

The temperatures and salinities measured at the lightship "Gedser Rev" in the Darss Sill Area form the basis for the present study. The analysis covers the observation period between 1897 and 1976, with interruptions due to the world wars and to ice conditions.

The basic idea of the investigation is founded on the assumption that an effective increase in salinity (and oxygen concentration) in the Baltic deep water can be caused only by an overflow of highly saline water across the Darss Sill Area over its entire cross section for at least 5 consecutive days. These events, characterized as major Baltic inflows, occur under certain meteorological and oceanological conditions: strong westerly winds cause both the destruction of haline stratification and the formation of substantial positive sea level differences between Kattegat and Baltic. A previous reduction in water volume of the Baltic is favourable for inflow events. The presence of a positive anomaly of salinity in the deep water of the Kattegat (DICKSON 1971, 1973) can apparently increase the intensity of inflow events, but does not seem to be a necessary condition. A minimum duration of both strong westerly winds and positive sea level differences between Kattegat and Baltic is a necessary prerequisite for major inflows. If this condition is not fulfilled, westerly winds and positive sea level differences cause only average inflows, characterized by either low salinities or insufficient quantities of highly saline water.

In accordance with the above-mentioned assumptions and relevant studies of past observations (cf. also WOLF 1972), we used the following general conditions to identify major inflows at the Darss Sill Area (cf. Fig. 1):

i. The stratification coefficient $G = 1 - S_o/S_b$ (S_o = surface salinity) must be ≤ 0.2 for at least 5 consecutive days;
ii. The bottom salinity S_b must be $\geq 17 \times 10^{-3}$.

Further conditions have been specified, to decide whether or not a few days may be added to the inflow period before or after identified inflow events, and to determine in which case inflow periods shorter than 5 days, interrupted by a single day, may be counted as inflow events (FRANCK et al. 1987b).

To characterize the properties of the inflowing water bodies, the daily vertical means of the parameters averaged over the inflow period (Y_p) and the monthly means of Y_p related to the total number of inflow events in September, October, November etc. ($\bar{Y}_p$) were calculated. The major Baltic inflows have been categorized by means of an intensity index, Q, calculated from the duration, k, and mean vertical salinity, S_p, of the inflow period:

$$Q=50\left[\frac{k-5}{25}+\frac{10^3 S_p-17}{7}\right] \qquad (1)$$

The temperature, T, and salinity, S, of the inflowing water bodies are measured daily at the lightship "Gedser Rev". The density, σ, was calculated from the daily vertical means of temperature and salinity using KEALA's tables (1965). Assuming that the inflowing water was saturated with oxygen, the oxygen concentration, O_2, was ascertained from the temperature and salinity by means of the UNESCO tables (ANONYMOUS 1973).

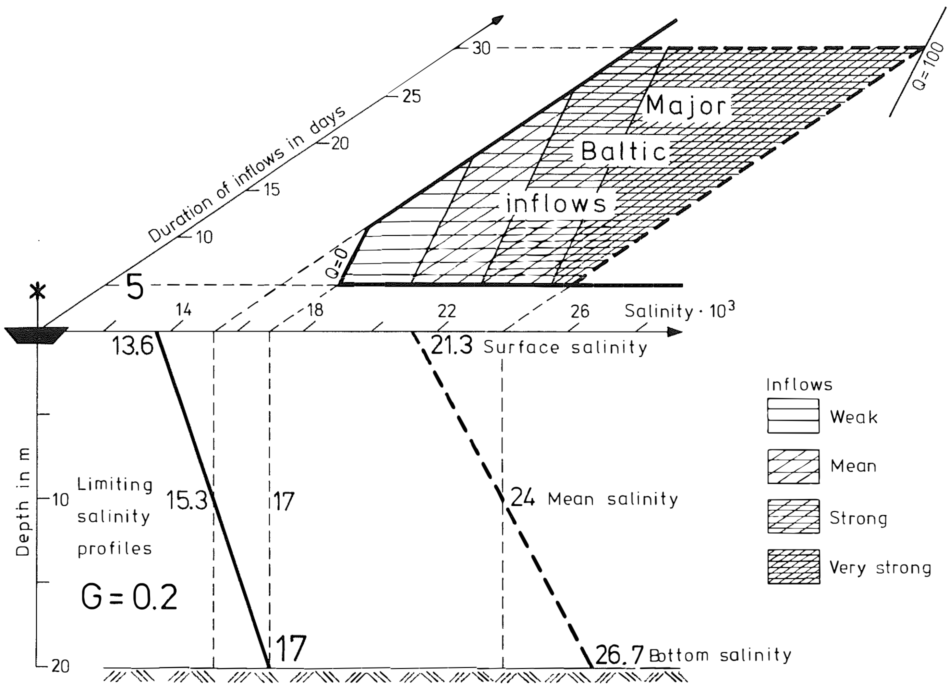

Figure 1

Definition of major Baltic inflows based on the haline stratification conditions at lightship "Gedser Rev"

The method used represents a first step towards identifying and assessing major Baltic inflows. The conditions specified earlier must be regarded as necessary for identifying, but inadequate for assessing, the complete datails of inflow events. The method permits all inflow events to be detected during the period investigated, and the determination of the exact date on which they started. However, variations are conceivable as to the calculated duration of the events, because short-term outflows could occur during an identified inflow event without the defined range of the stratification coefficient being exceeded. Such processes might possibly shorten the duration of an identified inflow event.

Basic characteristics of major Baltic inflows

On the basis of the above mentioned definitions (cf. Fig. 1), a total of 90 major inflows of highly saline water took place during the 80-year period from 1987 to 1976. All these inflows occurred during the months from August to April, which we shall term the "inflow season" (cf. also Fig. 4). The distribution of inflows throughout the whole period and their intensity indexes, Q, as calculated from equation (1) are shown in the lower part of Fig. 2.

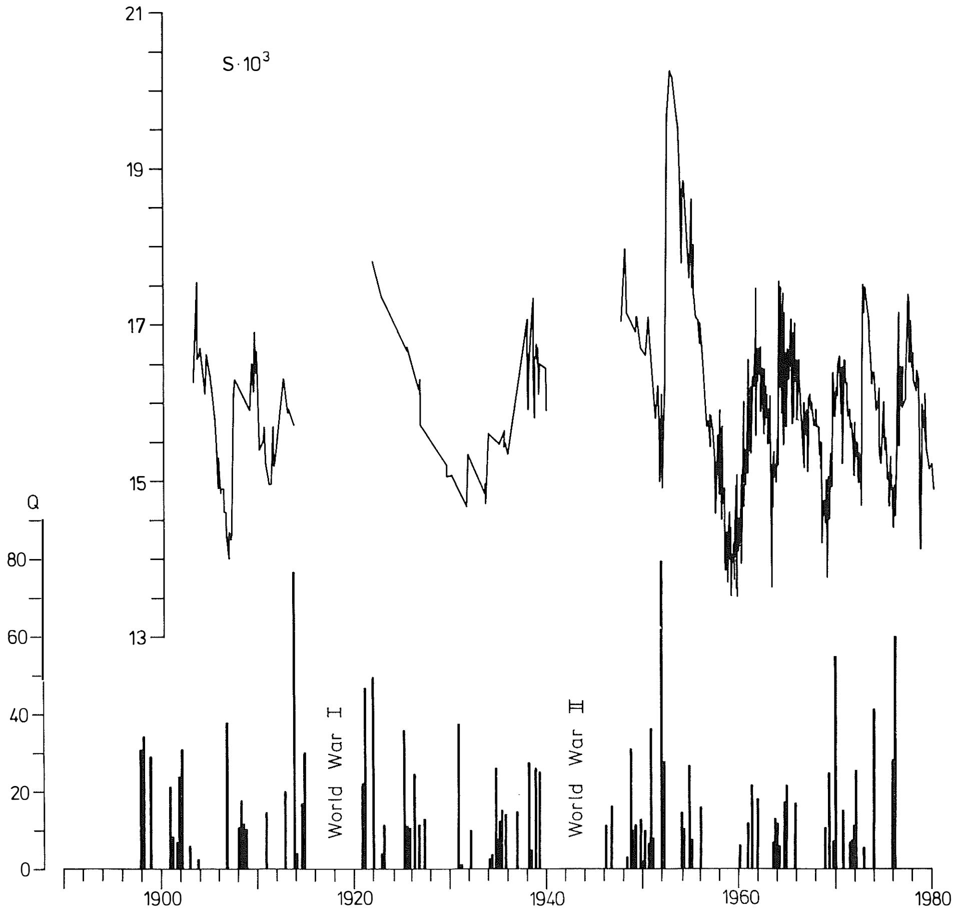

Figure 2

Major inflows of saline water into the Baltic Sea between 1897 and 1976 as characterized by the intensity index (Q, bottom), and their effects on salinity (S) at the 80 m level of the Bornholm Deep (BY 5) (top)

Major inflows occur both as isolated events (4 cases) or in groups (16 cases); a group comprises all inflows separated by intervals of less than one year. Isolated events occurred in 1906, 1910/1911, 1936 and 1973. The largest groups were between 1948 and 1952 and between 1968 and 1972 (12 and 10 inflow events, respectively). The longest periods without inflow events lasted 3 consecutive inflow seasons (1927/1930, 1956/1959). In Table 1, the most intensive groups of major Baltic inflows, classified by sums of Q, are listed together with the number of inflow seasons and inflows per group, as well as the most intensive event of each group.

Table 1

The most intensive groups of major Baltic inflows between 1897 and 1976

No.	Period	Number of		Σ Q	The most intensive event of the group		
		inflow seasons	in-flows		Period	Q	No.
1	Mar 1948–Jan 1952	5	12	236.5	25.11.–19.12.52	79.1	1
2	Oct 1968–Nov 1972	5	10	169.2	29.10.–25.11.69	54.8	4
3	Dec 1912–Dec 1914	3	5	147.9	18.11.–16.12.13	76.6	2
4	Nov 1920–Jan 1923	3	5	133.2	16.12.21–6.1.22	49.4	5
5	Jan 1925–Apr 1927	3	6	106.6	3.–13.1.25	35.7	11
6	Dec 1900–Nov 1903	4	7	100.2	7.–22.1.02	31.1	13
7	Nov 1897–Dec 1898	2	3	94.3	7.–22.12.98	34.4	17
8	Oct 1963–Nov 1965	3	7	93.6	24.–30.11.64	21.6	31
9	Dec 1975–Jan 1976	1	2	88.2	22.12.–14.1.76	60.0	3
10	Jan 1938–Feb 1939	2	4	82.8	24.1–6.2.38	27.3	20

Concerning the end of the current stagnation period in the eastern Gotland Basin deep water (MATTHÄUS 1987), we assume from our results that the probability of individual events with high intensity is only small. For the near future we can expect a group of inflow events covering possibly several consecutive inflow seasons. This group can also be expected to include strong or very strong inflows.

Comparing the salinities at the 80 m level of the Bornholm Deep (BY 5) with the intensity indexes, it can be seen that the magnitude of Q does not always correlate with the magnitude of the effects in the near-bottom water of the Bornholm Basin (cf. Fig. 2). Some events with high salinities like those in 1921/1922, 1951, and 1969 were followed by marked increases in salinity. In contrast to the 1951 event, fairly intensive inflows like those of 1906, 1930, and 1973 hardly caused variations in the salinity of the Bornholm Basin deep water. The effect of inflow events is therefore not only subject to the intensity of the inflow but also to the density conditions existing in the Baltic deep basins.

Table 2 shows the mean properties of the inflowing water bodies calculated for the ten most intensive Baltic inflows between 1897 and 1976. The magnitudes of the properties are given by their frequency distributions in Fig. 3.

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. The mean salinity is most commonly between 17.5 and 18×10^{-3}. Inflows with salinities

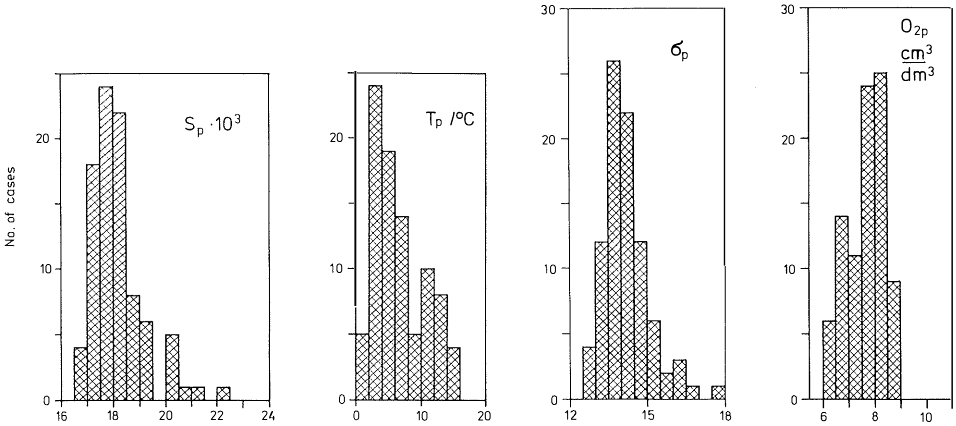

Figure 3

Frequency distributions of major Baltic inflows referring to the mean vertical salinity (S_p), temperature (T_p), density (σ_p), and oxygen concentration (O_{2p}) of the inflow period

higher than 20.5 x 10^{-3} are very rare. The highest mean salinity of 22.5 x 10^{-3} was observed during the 1951 event.

Table 2

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

No.	Period	Q	S_px10^3	T_p °C	σ_p	O_{2p} cm^3/dm^3
1	25 Nov – 19 Dec, 1951	79.1	22.5	7.5	17.574	7.25
2	18 Nov – 16 Dec, 1913	76.6	21.0	7.7	16.396	7.29
3	22 Dec, 1975 – 14 Jan, 1976	60.0	20.1	4.1	15.976	8.01
4	29 Oct – 25 Nov, 1969	54.8	18.2	9.4	14.014	7.13
5	16 Dec, 1921 – 6 Jan, 1922	49.4	19.2	4.0	15.251	8.07
6	17 – 31 Jan, 1921	46.6	20.7	3.4	16.533	8.13
7	13 –29 Nov, 1973	41.4	19.4	6.6	15.281	7.55
8	26 Nov – 13 Dec, 1906	38.0	18.7	6.8	14.663	7.55
9	10 – 20 Nov, 1930	37.3	20.5	8.4	15.939	7.19
10	28 Sept – 15 Oct, 1950	35.9	18.4	13.3	13.544	6.52

The temperature of the inflowing saline water hardly differs from the average seasonal temperature. The mean vertical temperature, T_p, of inflows therefore ranges from 2 to 8 °C, because most inflows take place between November and February. Since the inflow season starts in August/September, the mean temperature of the inflowing water bodies can occasionally be higher than 13 °C; the lowest mean temperature of an inflow was calculated to be 1.4 °C.

The most common mean vertical densities, σ_p, of the inflowing water bodies range between 13.5 and 14.5 σ units. Mean densities of more than 16 σ units are very rare. The 1951 event shows the highest mean density of about 17.6.

The mean oxygen content of the inflowing water, O_{2p}, is generally between 7.5 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. Events with oxygen concentrations of the inflowing water bodies below 6 cm^3/dm^3 were not observed.

Seasonal characteristics of major Baltic inflows

The seasonal variations are related to the total number of inflow events in each month. Inflow events were assigned to that month which contained most days of the respective inflow period. The number of months observed varies between 59 (February) and 70 (September). Because of the small number of events in August, March, and April (cf. Fig 4) the analysis of seasonal variations might not be significant for these months.

Fig. 4 shows the frequency distribution of the major Baltic inflows related to the months during which observations were made. The number of inflow events per month is shown in the upper part. Inflow events are most frequent in December (32 % of all observed Decembers). In November and January the frequency is about 21 %. The probability of

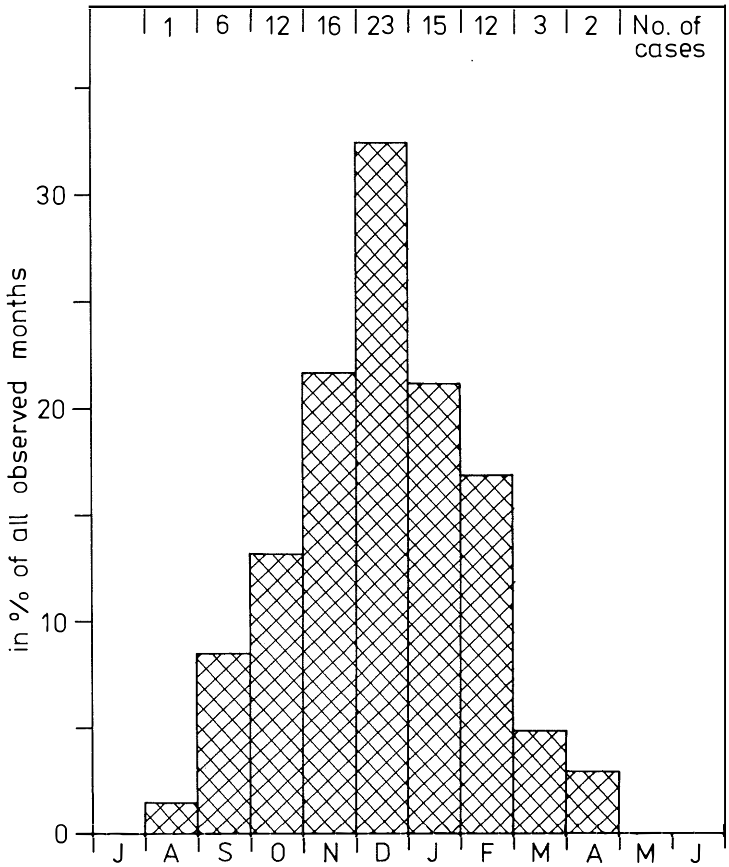

Figure 4

Seasonal frequency distribution of the major Baltic inflows

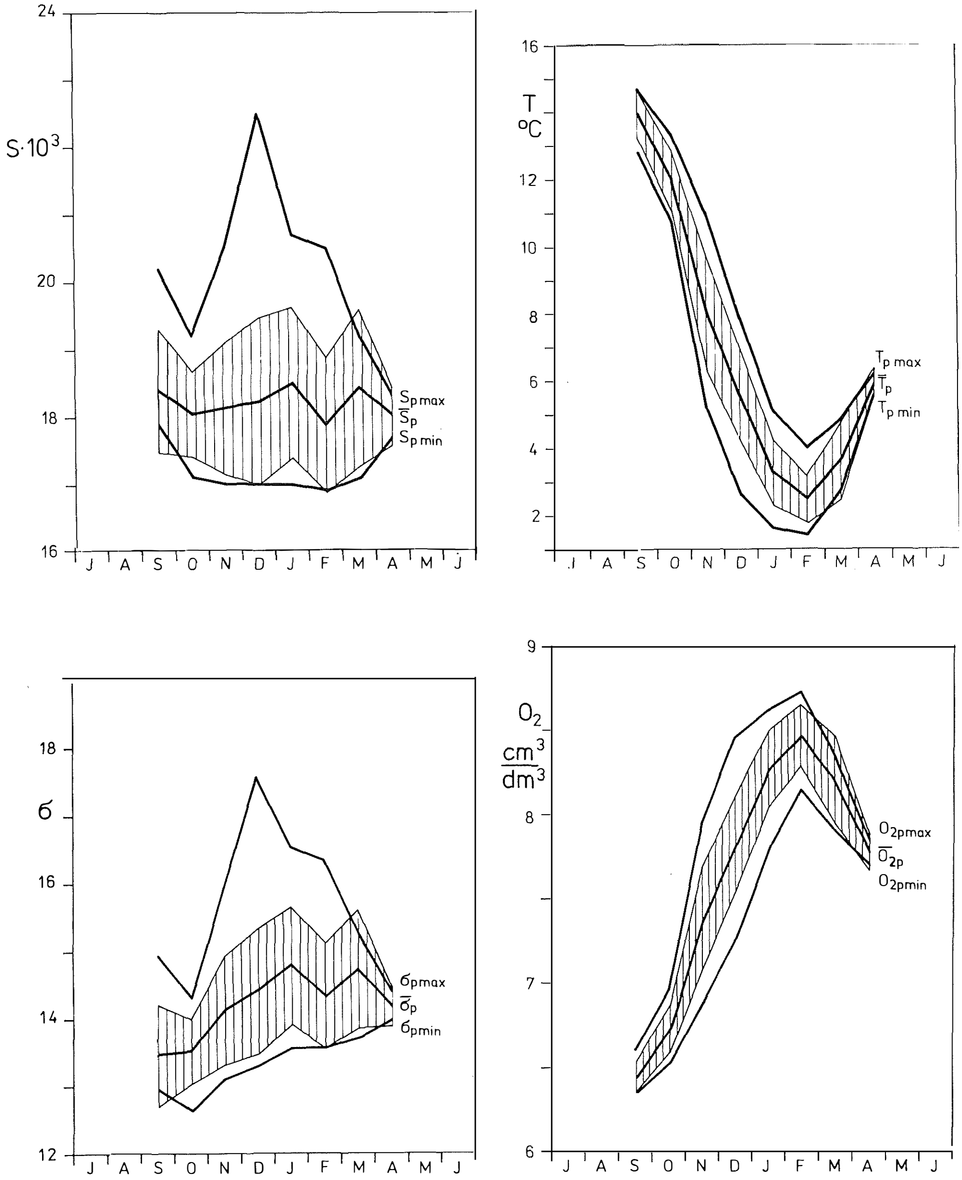

Figure 5

Seasonal variations in monthly means and extreme values of salinity ($\overline{S}_p$), temperature ($\overline{T}_p$), density ($\overline{\sigma}_p$), and oxygen concentration ($\overline{O}_{2p}$) during inflow periods (hatched areas correspond to the standard deviation range)

such events in August/September and in March/April is only small. Major inflows never occurred between May and July during the 80-year period considered.

The monthly means of the intensity index, $\overline{Q}$, show considerable seasonal variation, with the highest values of between 20 and 24.2 occurring from November to January. The maximum values of $Q_{max} > 50$ were calculated for the same months. As far as the duration of the inflow events are concerned, the monthly means, $\bar{k}$, show a clear seasonal characteristic, with 12.7 days in December and 6 days in April. The maximum values observed between November and January vary from 24 to 29 days.

The properties of the inflowing water bodies are important for the oceanological conditions in the Baltic deep water. Salinity, temperature, density, and oxygen concentration show considerable seasonal variations in the surface water of the transition area. Seasonal variations in the monthly means of salinity, $\bar{S}_p$, and density, $\bar{\sigma}_p$, of the inflowing water bodies, however, are small (cf. Fig. 5).

The monthly means $\bar{S}_p$ vary only between 17.9 and 18.5 x 10^{-3}. Seasonal variations are therefore hardly noticeable. As far as the maximum mean vertical salinities, $S_{p\,max}$, of the inflowing water are concerned, values $\geq 20.5 \times 10^{-3}$ were found only between November and February.

The density of the inflowing water is important for the final interleaving of the water body in the basins of the Baltic Sea. As a result of the relatively high temperatures during the first part of the inflow season, the monthly means $\bar{\sigma}_p$ increase from 13.5 in September to a maximum of 14.8 in January and decrease to about 14.2 σ units in April. The maximum values $\sigma_{p\,max}$ vary between 15.9 and 17.6 σ units from November to February.

Temperature and oxygen concentration of the inflowing water bodies are important for the biochemical processes taking place in the Baltic deep water. Seasonal variations in the monthly means $\bar{T}_p$ and $\bar{O}_{2p}$ are considerable (cf. Fig. 5), and they are similar to those of the near-surface water between September and April, with a temperature minimum of 2.5 °C and an oxygen maximum of 8.5 cm^3/dm^3 in February. Hence, the more intensive events between September and early December generally cause an increase in the temperature of the Baltic deep basins (cf. Table 2, inflows in November/December 1951, October/November 1969), whereas inflows in January to April lead to a decrease (e. g. inflows in March/April 1961, February 1969, December 1971). For the effects on the Gotland Basin deep water see FONSELIUS/RATTANASEN (1970), FONSELIUS (1977) and MATTHÄUS (1985).

As far as the oxygen content of the inflowing water bodies is concerned (cf. Fig. 5), the situation is reversed. More intensive inflows in the first part of the inflow season generally do not have such marked effects on the oxygen conditions of the Baltic deep water (cf. inflow in November 1973) as inflow events between January and April (e. g. inflows in January 1954, March/April 1961, February 1969).

Conclusions

1. The probability of individual events with a high intensity is only small.
2. Concerning the end of the current stagnation period in the Baltic deep water, we may expect a group of inflow events possibly covering several consecutive inflow seasons. Strong to very strong inflows may also be expected within this group.
3. Inflow events take place only during the inflow season from August to April.
4. Major inflow events show a distinct seasonal characteristic, occurring most frequently from November to January with maximum intensities and durations.
5. The seasonal variations in the mean salinity and density of the water bodies entering during major Baltic inflows are small. The mean temperatures and oxygen concentrations of the inflowing water show pronounced seasonal characteristics.

6. More intensive events between September and early December generally cause an temperature increase in the Baltic deep basins, whereas the inflows in January to April lead to a temperature decrease.
7. Concerning the improvement of the oxygen conditions in the Baltic deep water, more intensive inflow events generally show clear effects between January and April. The present environmental conditions in the deeper part of the eastern Gotland Basin will be improved only by a group of inflow events.

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