

The Baltic Inflow of Autumn 2001

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Dedicated to Wolfgang Matthäus

1. Introduction

In the middle of the previous century, the water exchange between the North and the Baltic Sea was assumed to possess an increasing trend, caused by intensified atmospheric circulation (SCHEMAINDA, 1956, MATTHÄUS, 1979). Commencing already in the 1920s, but especially due to the extensive inflow in 1951 - although followed by several years of stagnation - a severe change of the hydrographic conditions was marked by the dawn of the Baltic “Cod Age” (MEYER & KALLE, 1950, SCHEMAINDA, 1956, MATTHÄUS, 1979), when cod fish began to substitute plaice as the principal catch. A reversal of long-time salinity trends, however, was found by MATTHÄUS (1985) in the Arkona Basin for about the year 1970.

Since the mid-1970s both the frequency and intensity of extreme inflow events from the North Sea into the Baltic Sea have significantly decreased (SCHINKE & MATTHÄUS, 1998). This overall tendency continued during the 1990s (MATTHÄUS et al., 2001). Quite generally, the year 2001 did not particularly contrast to the typical climatic and meteorological conditions of the last two decades, which did not favour heavy water injections from the Kattegat into the Baltic Sea (MATTHÄUS & NAUSCH, 2002). On the other hand, however, they did not entirely exclude such processes either, as will be outlined in this paper.

In autumn 2001, a medium-size inflow of salty, oxygen-rich Kattegat waters into the western Baltic Sea has occurred. The effects of this event onto the Baltic deep basin waters are traced until summer 2002, although, with rapidly fading magnitude. In the following, a detailed time history of this process can be outlined, describing

- the meteorological and hydrographical situation in October/November 2001 in the western Baltic Sea
- the propagation pathway through several deep basins of the Baltic Sea
- anoxic/ oxic conditions before and after the inflow in the affected deep basins.

2. Inflow Conditions

Deep water renewal processes in the Baltic Sea depend on specific meteorological circumstances, which force substantial amounts of seawater, enriched with salt and oxygen, to propagate from the Kattegat through the Danish Straits into the western Baltic Sea (WYRTKI, 1954). From there, it slowly moves as a relatively thin bottom layer into the deeper central Baltic basins, replacing aged water masses there. To make this happen, easterly winds have to blow continuously for about 10 days to lower the Baltic fill factor, followed by a sudden turn to westerly gale winds, which again need to last for about 10 days in order to rising the fill factor to its maximum (MATTHÄUS & FRANCK, 1992).

Level (cm) at Landsort Gauge 2001

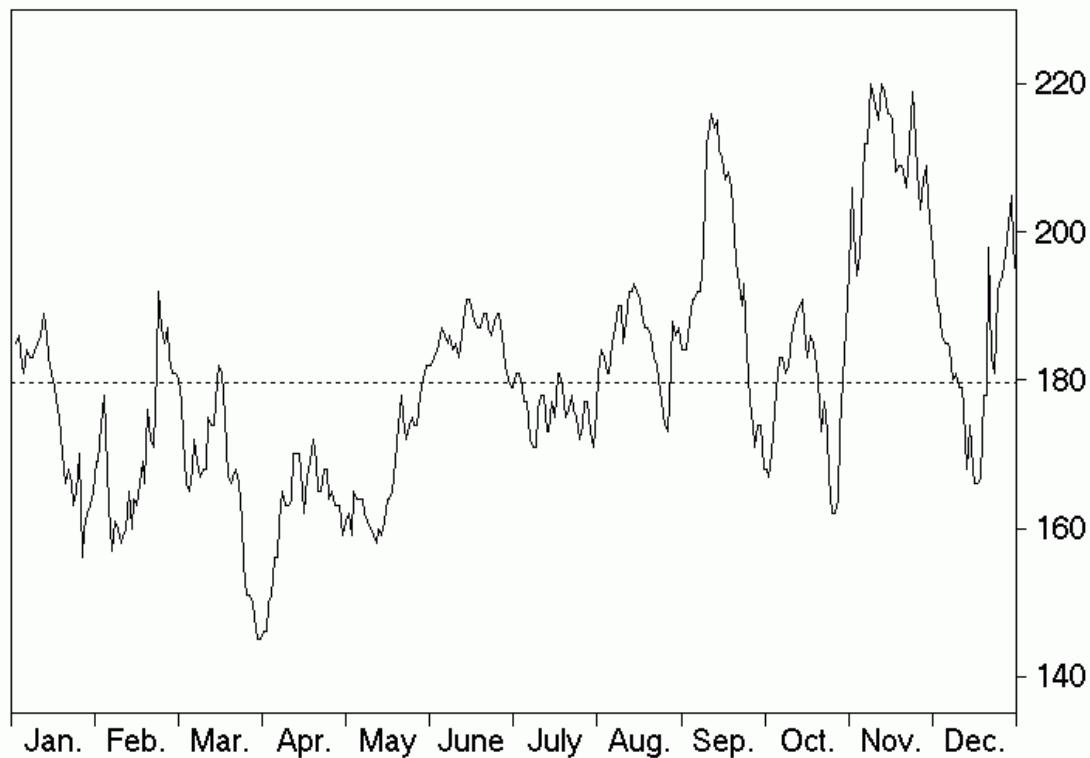


Fig. 1: Sea level at Landsort as a measure of the Baltic Sea fill factor (after data of SMHI); the dotted line marks the annual mean value.

The sea level at Swedish Landsort (Fig. 1) is considered an excellent indicator of the Baltic fill factor (MATTHÄUS & FRANCK, 1992; MATTHÄUS & BERGSTRÖM, 2001). With short exceptions, from end of January till end of May, this level was on average 10 cm above the annual mean; the lowest level of the whole year was observed on March 30th and 31st with 145 cm (35 cm below normal). During summer (June till August) the fill factor was balanced, and grew in autumn (September till December) heavily fluctuating up to about 20 cm above normal. The annual maximum was observed on November 8th and 12th with 220 cm (40 cm above normal).

Especially remarkable is the rapid and strong level rise end of October / beginning of November. From October 26th until November 8th, it went up by 58 cm, which corresponds to an increase of the water volume by about 223 km³ within 12 days due to an average transport of about 19 km³/day, if we assume the surface area of the Baltic Sea to be 384,000 km² (HAGEN & FEISTEL, 2001). This volume increase is comparable to that of the inflow during November/December 1951 (WYRTKI, 1951, SCHEMAINDA, 1956), and, reduced by the average river runoff of 1 km³/day in October/November, still slightly above the value of 193 km³ observed in the long-time mean (MATTHÄUS & FRANCK, 1990).

The event began on October 14th when at a Landsort level of 191 cm (high by 11 cm) an outflow dropped it to 162 cm (low by 18 cm), which together yields 29 cm or 111 km³ in 11 days. At the Rügen Island weather station Arkona, the wind turned to East on October 14th and remained in that direction until October 24th with a short pause on October 16th and 17th. About 14 m/s peak speed was measured on October 23rd. Then, the wind switched to West on October 25th, reaching a first maximum of 15 m/s on October 28th. Continuing westerly winds

showed a second maximum (19 m/s) on October 30th, a third (21 m/s) on October 31st, a fourth (17 m/s) on November 5th, a fifth (17 m/s) on November 6th, and, after a short break, a sixth (21 m/s) on November 15th. After the quick increase, this caused the sea level to remain high with 220 cm from November 18th till November 23rd with 219 cm, for 6 days without significant outflow, thus giving the salty waters piled up in the western Baltic Sea the opportunity to drift eastward before being washed out again.

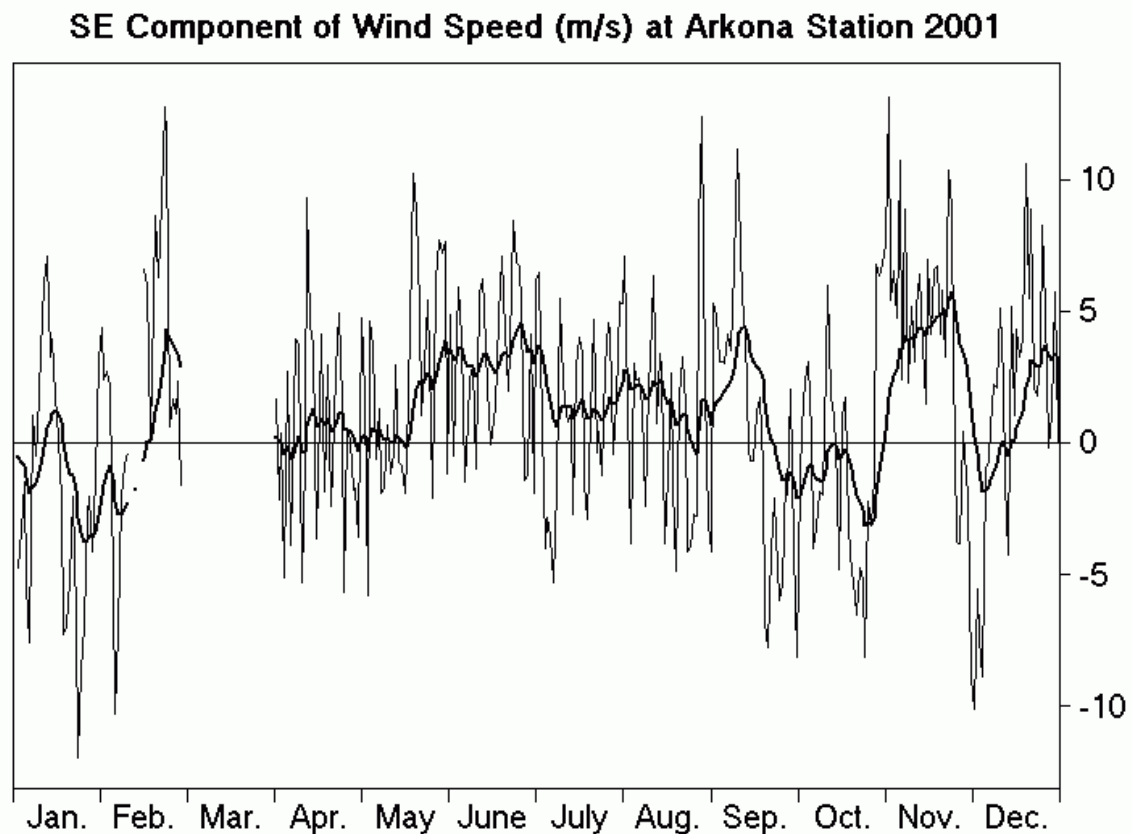


Fig. 2: Strength of the north-west wind (positive) at the weather station Arkona (after data of DWD). The bold curve appeared by filtering with an exponential 10-days memory.

The strength of north-easterly winds at the Arkona weather station can be used as a good indicator as well. After filtering south-east wind speed component at the Arkona weather station with a 10-days memory, the resulting time series exhibits a high correlation with the sea level measured at Landsort a few hours later. Fig. 2 shows this filtered curve together with the south-east component of the wind speed. The particular events of sudden level changes can well be assigned to related patterns in the filtered wind speed. For instance, the minimum of -3.1 m/s on October 26th followed by a maximum of +4.0 m/s on November 7th is in good agreement with the events derived from the Landsort level gauge (Fig. 1).

Darss Sill - 2001

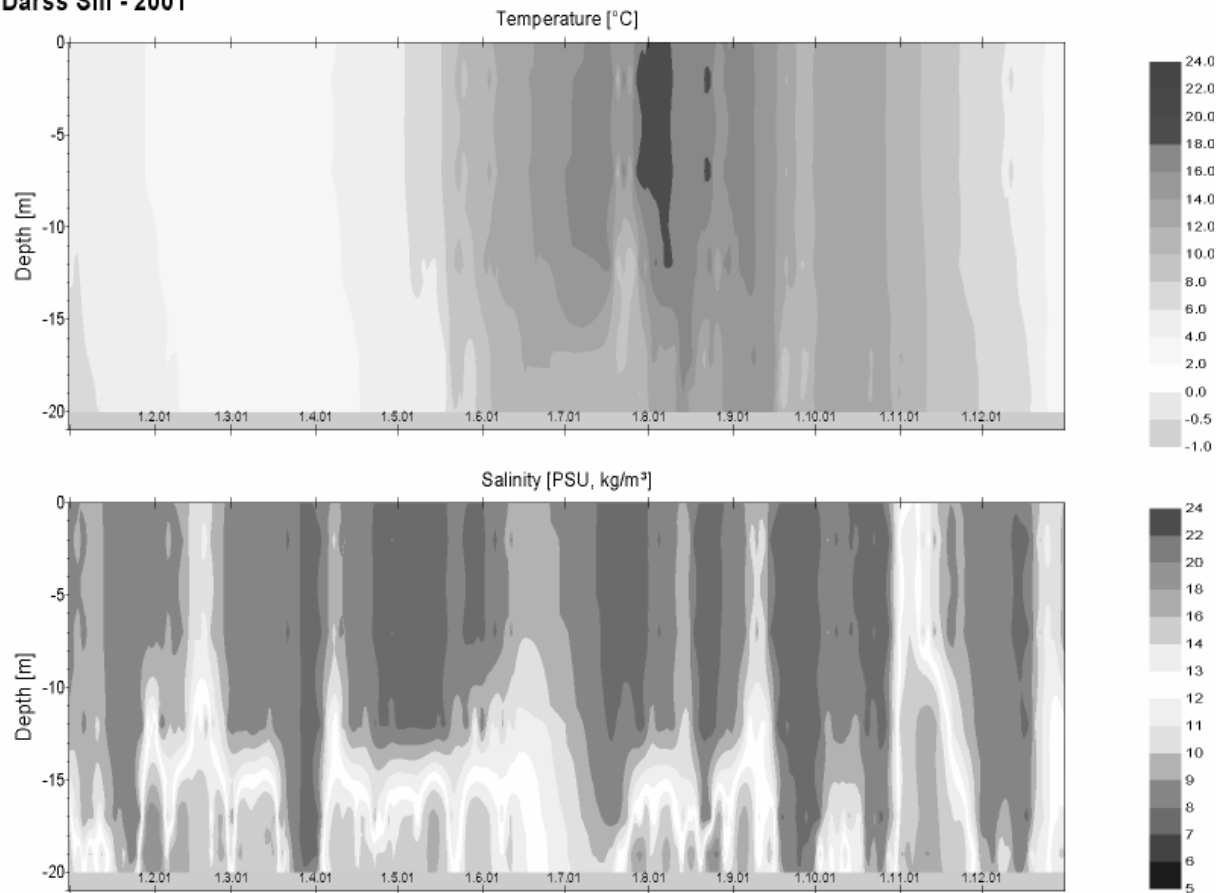


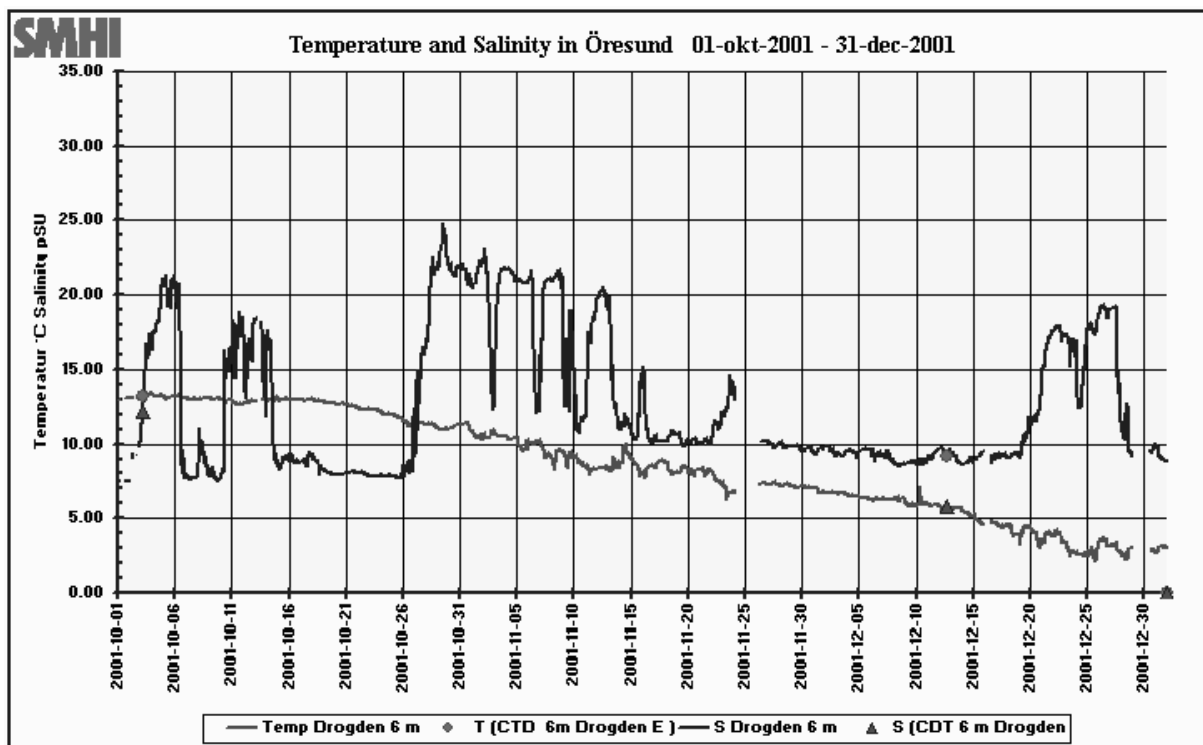
Fig. 3: Temperature and salinity recordings at the Darß Sill monitoring mast in 2001 (http://www.io-warnemuende.de/projects/monitoring/en_home.html).

The devices mounted at the Darß Sill monitoring mast, between Darß and Mön island, continuously recorded temperature, salinity, and the water current velocity at several depths (Fig.3). End of October, the sudden rise of salinity to the surface is clearly visible, shortly reaching a maximum there of 13 psu, followed by a slower relaxation back to normal conditions in November. Such a short and low surface salinity peak value is characteristic for minor inflow situations like that in August 1964, as described by MATTHÄUS & FRANCK (1979), and does not even count as a ‘weak inflow’ due to the classification scheme of MATTHÄUS & FRANCK (1988).

The graph shown in Fig. 3 displays rather smooth diurnal averages of the measurements. Although they are correctly reflecting the duration and intensity of the inflow, a closer look at the hourly resolved data reveals heavily fluctuating conditions at the mast, similar to the wind conditions at Arkona as discussed above. During the first few days of the inflow, salinity at 7 m depth increased only slowly from 7 to 10 psu. On October 31st, 18:00, the value started to quickly rise from 11 psu to a first maximum of 14.8 psu on the next morning, 6:00. It remained high at about 13 psu until a second maximum of 15.57 psu was reached on November 4th, 21:00. Again, the high salinity continued with values between 12 and 14 psu until November 8th, 4:00, when after a third maximum of 15.15 psu the level dropped to about 10 psu. The next high salinity front arrived on November, 11th, with a peak value of 16.98 psu at 7:00. The following maximum was 14.8 psu on November 12th, 11:00, after which only

salinities between 8 and 10 psu were observed. The final short peak up to 14.98 psu occurred for a couple of hours on the evening of November 15th.

The vertical average of the current speeds provides another measure for inflow duration and amount. Its time integral yields $L = 236 \text{ km}$ between October 26th and November 11th (NAUSCH et al., 2002). The comparison with Landsort sea level records results in an effective inflow cross section at the mast position of $A = V / L = (223 - 22) \text{ km}^3 / 236 \text{ km} = 0.85 \text{ km}^2$. Even though it effectively describes the inflow through both Belt and Öresund, this value is comparable with the actual underwater cross-section between Darß and Mön. Here, we had reduced the total volume of 223 km^3 by 22 km^3 as an estimate for the annual average fresh water excess within 16.5 days (MATTHÄUS, 1996). The accumulated inflow between October 25th and November 11th, by merely the Öresund, was found about 50 km^3 after data of SMHI (Fig. 4). Hence we can assume that three quarters of the inflow volume, namely about 150 km^3 , should have passed through the Danish Belts.



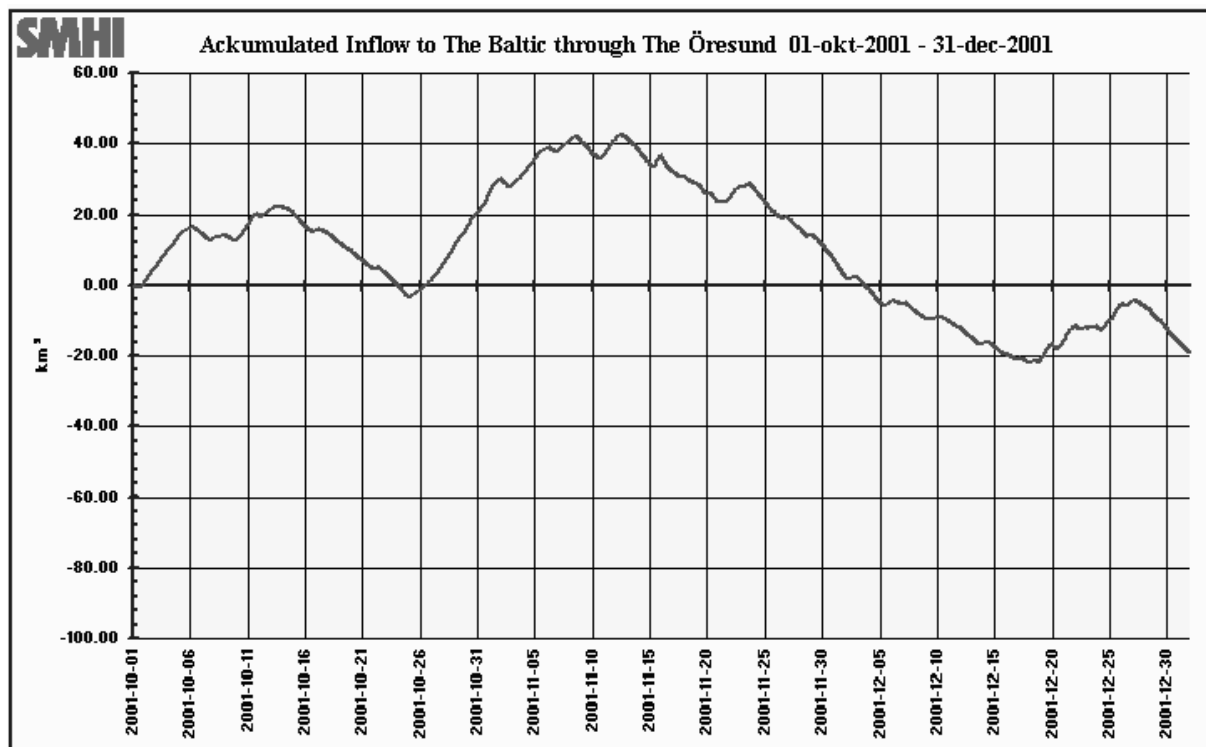


Fig. 4: Above: Temperature and salinity in Öresund between October 1st and December 31st 2001. Below: Accumulated inflow into the Baltic Sea through Öresund for the same period. (courtesy to SMHI - www.smhi.se/hfa_coord/BOOS/y2001/inflow2001_4.html).

3. Deep Water Observations

Due to several German and Swedish monitoring and other cruises between October 2001 and May 2002, a detailed history of the continuation of this inflow event into deeper water layers can be described. The start of an inflow process was occasionally noticed during the IOW monitoring cruise from October 25th till November 8th, 2001. At the end of the cruise, on November 7th, an intensive inflow of highly saline water with up to 19.4 psu in the whole water column was measured in the western Baltic Sea. However, this inflow was considered not having passed the Darss sill yet.

Four repeated transects (Fig. 5) between the western Baltic Sea and the Bornholm Basin on October, 26/28th, November 6/7th, 12th, and 16th show the stages of successive progression of the high salinity waters, first covering the whole water column in the shallow regions, then propagating eastward, later sliding down to deeper layers into the Arkona Basin and relaxing to lower salinities at the surface. Note that surface salinities of 16-17 psu were found at the Darß Sill which correspond to extrema measured at the nearby monitoring mast for few hours on November 11th only; they clearly exceed the maximum of daily means recorded at there (13 psu). Such observations provide a hint on the strong horizontal gradients and temporal fluctuations existing in this area during the actual inflow process.

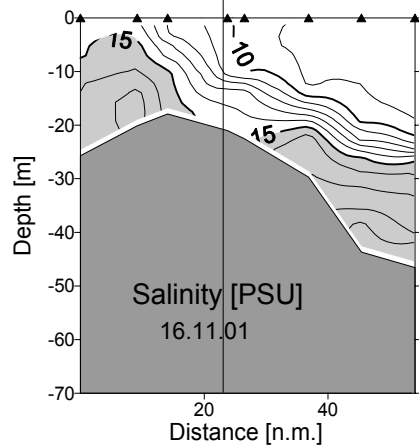
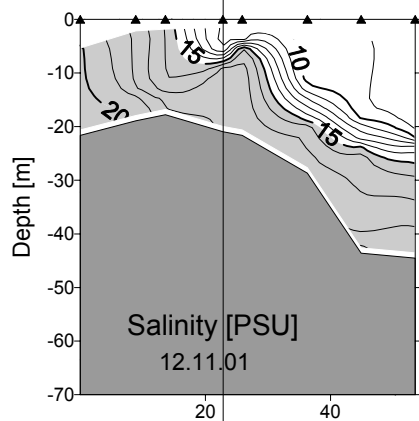
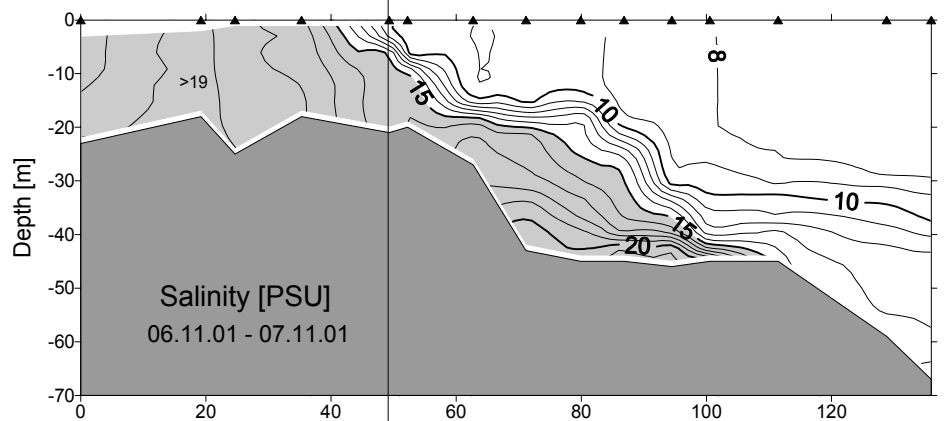
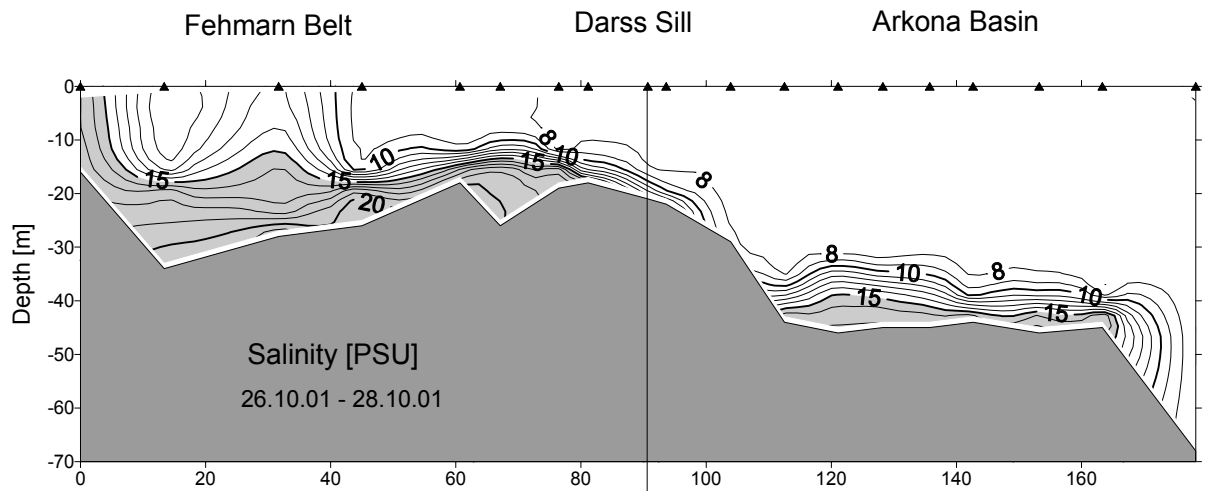


Fig. 5: Salinity distributions along a zonal transect in the western Baltic Sea between Fehmarn and Arkona Basin. Salinities exceeding 15 psu are shown greyed. From top to bottom: October 26/28th, November 6/7th, November 12th, November 16th, 2001 (Data from IOW cruises); the vertical line is drawn at the same position at the Darß Sill for easier comparison.

Already on December 11th, 2001, r/v “Argos” measured 4.68 ml/l oxygen at 80 m depth in the Bornholm Deep, BY 5, where hydrogen sulphide (-0.98 ml/l oxygen equivalent) still was found one month earlier. In the same period of time, temperature has changed from 6.9 to 10.0 °C, and salinity from 15.2 to 16.2 psu.

These dense oxidic warm waters reached deployed recording devices in the eastern Gotland Basin at position 57°23’N, 20°20’E in 174 and 204 m depth on January 3rd, 2002 (Fig. 6). The initial impulse exceeded 0.5 K in temperature rise; it was followed by decaying pulsations until end of March, 2002, and eventually led to a persistent warming of about 0.1 K compared to December 2001.

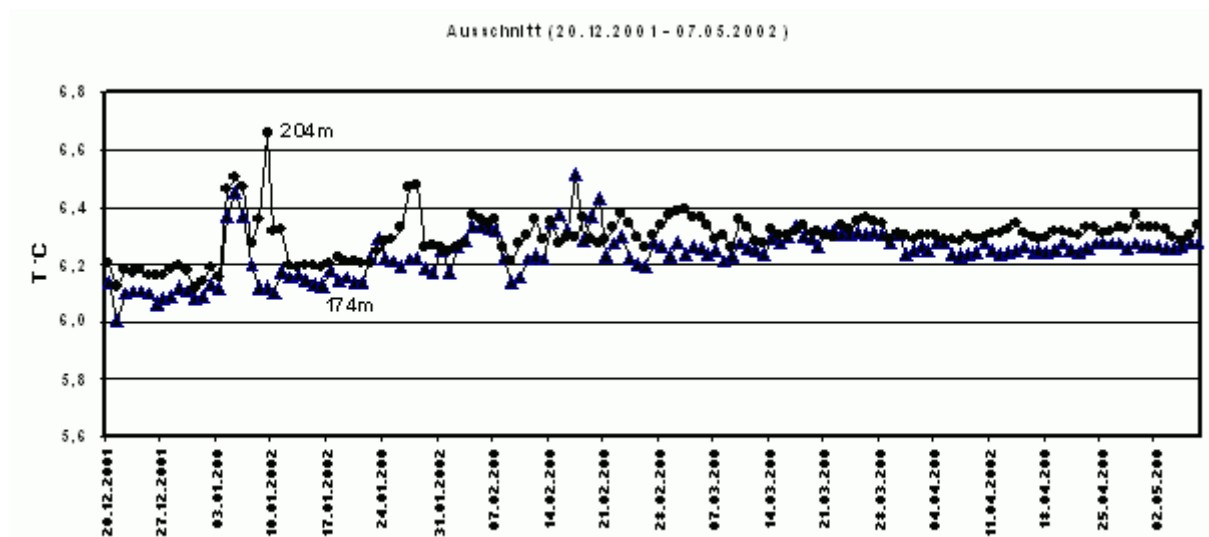


Fig. 6: Temperature records (°C) at 174 and 204 m depths in the eastern Gotland Basin (57°23’N, 20°20’E) between December, 20th, 2001, and May, 5th, 2002.

The rapid propagation of the intense inflow event continued and reached the central station in the eastern Gotland Basin, BY 15, latest on January 14th. In the bottom near layer r/v “Argos” measured 0.80 ml/l oxygen (Fig. 7). The hydrogen sulphide containing layer was lifted up and covered the range between 150 m and 195 m only. The northern and western Gotland Basin remained unaffected at that time.

Already 14 days later the pulse of oxygen was used up, probably by mineralization processes, and the system turned back to anoxic conditions. From 125 m down to the bottom hydrogen sulphide was measured by r/v “Aranda” (pers. comm.). However, the detected concentrations were lower compared to the situation before the inflow. Measurements in February 2002 supported these findings. Hydrogens sulphide concentrations were present between 125 m and 240 m, however, decreased in comparison with the situation in November 2001 by 75% in the near bottom layer. Hydrogen sulphide concentrations between 125 m and the 200 m layer were not affected by these inflows and did not change significantly. This development was accompanied by an increase in salinity by about 0.3 psu in the same period (Tab. 1).

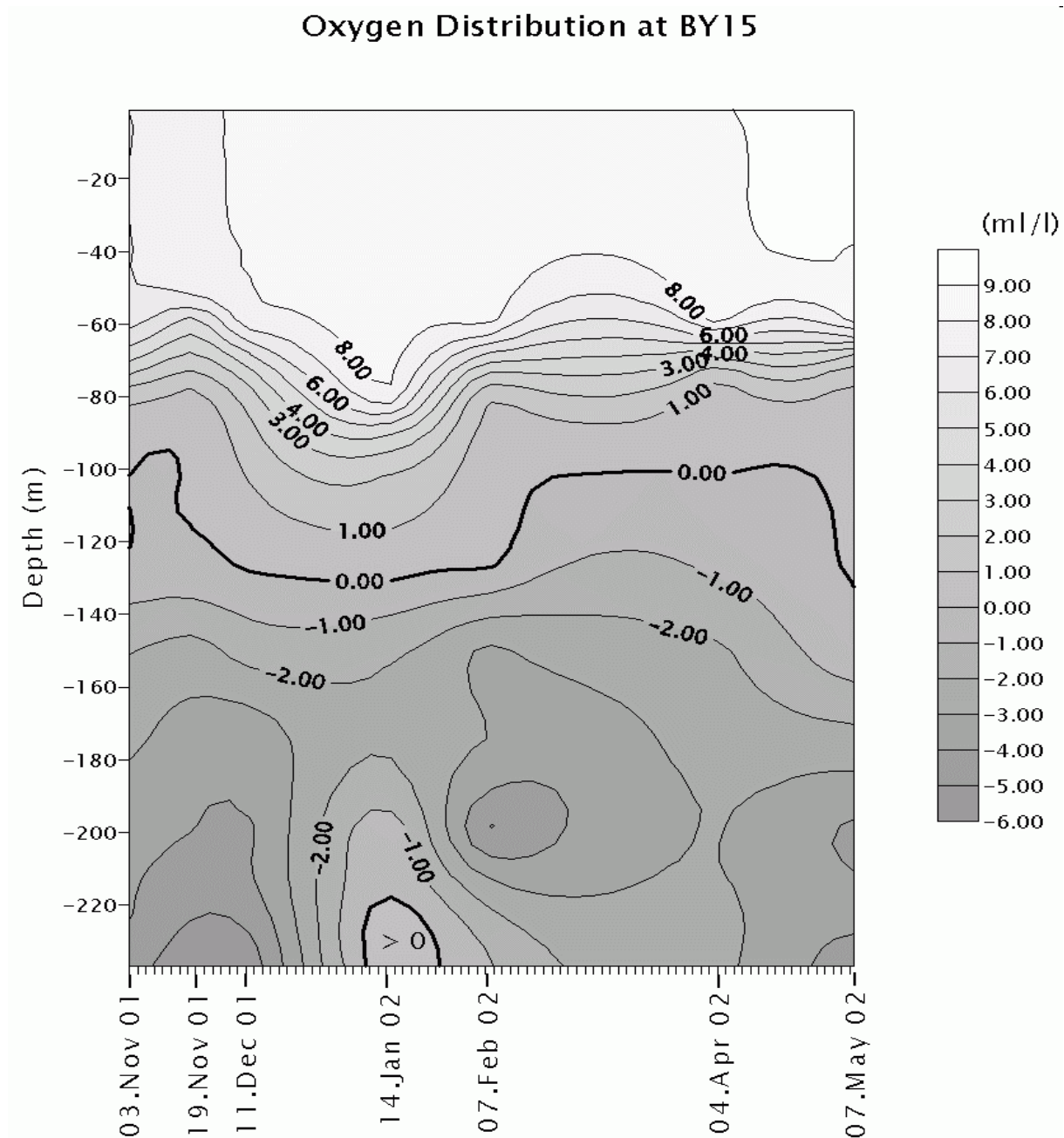


Fig. 7: Oxygen distribution in the eastern Gotland Basin (BY 15) between November 3rd, 2001, and May 7th, 2002. Note that the graph is interpolated between subsequent measurements and does not reflect, for example, the steep gradient to be actually expected on January, 3rd.

In the further course of the year, the stagnation period became completely recovered in the eastern Gotland Basin. In May 2002 the distribution patterns of hydrogen sulphide are comparable to the situation in November 2001 (Fig. 7). The salinity remains still slightly higher (Tab. 1).

Tab. 1: Development of salinities (psu) in the near bottom layer of the three main deeps in the eastern and northern Gotland Basins between November 2001 and May 2002.

	November 2001	February 2002	April 2002	May 2002
Gotland Deep	12.03	12.33	12.22	12.19
Farö Deep	11.53	11.31	11.48	11.45
Landsort Deep	10.42	10.23	10.16	10.16

As can be seen from the salinity distribution as well (Tab. 1), effects of the inflow could be detected in the Farö Deep area not before the end of March / beginning April. Also, the rather constant bottom temperature of about 5.9 °C between October 2001 and February 2002 has now risen to 6.16 °C. The oxidation capacity of the inflowing water was, however, too low to replace hydrogen sulphide in that depth. Only a minor decrease in hydrogen sulphide content was observed.

In the western Gotland Basin the slowly decreasing salinity indicates an uninterrupted continuation of the stagnation period (Tab. 1). This development is supported by the measured redox conditions. In the Landsort Deep the hydrogen sulphide content is continuously increasing in the near bottom layer from -0.95 ml O₂/l in November 2001 to -1.29 ml O₂/l in May 2002.

Tab. 2: Time development of temperature, salinity, and oxygen conditions at the 80 m level of the Bornholm Deep (BY 5) between October, 2001, and May, 2002.

	28.10.2001	11.12.2001	02.02.2002	30.03.2002	05.05.2002
Temperature (°C)	6.99	9.98	9.22	8.35	8.65
Salinity (psu)	15.53	16.20	16.05	14.91	15.27
Oxygen (ml/l)	-0.37	4.68	1.55	1.54	0.71

Coming back to the Bornholm Basin, where the effects of the recent inflow were seen most clearly. The extreme signal with the sudden rise by > 2 °C in temperature, almost 1 psu in salinity and nearly 5 ml/l in oxygen in December in the bottom-near waters is fading rapidly (Tab. 2). In May 2002, directly above the bottom only 0.1 ml/l were measured and it can be expected that again anoxic conditions prevail now. Due to the warmth of that inflow, the bottom water temperature is persistently high by still almost 2 °C above the long-time average of 6.62 °C between 1971 and 1990, which itself appeared at the end of a warming trend found after 1900 (MATTHÄUS, 1979).

4. Ventilation Status Changes

Before about 1980, inflow events were relatively frequent and could be observed on average once a year. A total of 111 so-called Major Baltic Inflows have been identified between 1880 and 2000, whereby data were unavailable during World War I and II (MATTHÄUS & NAUSCH, 2002). In the last two decades, however, they became rather scarce; the currently last such major inflow took place in 1993. Since then, the oxygen level of Baltic deep waters has dramatically decreased and is still in what is called 'stagnation'. There was another inflow starting in September 1997 with rather warm waters but low oxygen levels (MATTHÄUS et al., 1999, HAGEN & FEISTEL, 2001). It could not significantly improve the anoxic conditions in the deep layers, but its exceptional warmth is still measured today.

The Baltic inflow of autumn 2001 propagated rapidly into the deeper basins of the Baltic Sea, as described above. Effects could be observed in the Bornholm Basin already in December 2001 where the oxygen content in the deep water increased up to 4.68 ml/l. In Fig. 8a-d one can trace the time evolution of deep water oxygen deficiency between October 2001 and May 2002 by data observed on regular IOW monitoring cruises. We note the significant improvement of the conditions in the Bornholm Sea and in the eastern Gotland Basin between October 2001 and February 2002, while the Farö conditions still get worse first and respond delayed by March 2002.

However, these effects were without long-lasting duration. The system has already returned to anoxic conditions in spring/summer 2002. The inflow event can be evaluated only as a short interruption of the present stagnation period which lasts since 1995 (NEHRING et al., 1995). It ranges among the strong inflows with respect to its total water volume of $> 200 \text{ km}^3$, but only among the weak ones with respect to its duration and salinities in the classification scheme of MATTHÄUS & FRANCK (1988).

Finally, we may conclude that extended and long-lasting stagnation periods can only be sporadically interrupted by minor inflow events like the one described here, while a general improvement of Baltic deep water conditions seems to require altered general atmospheric circulation patterns like those observed rather regularly during winter seasons in the 1950s and the 1960s.

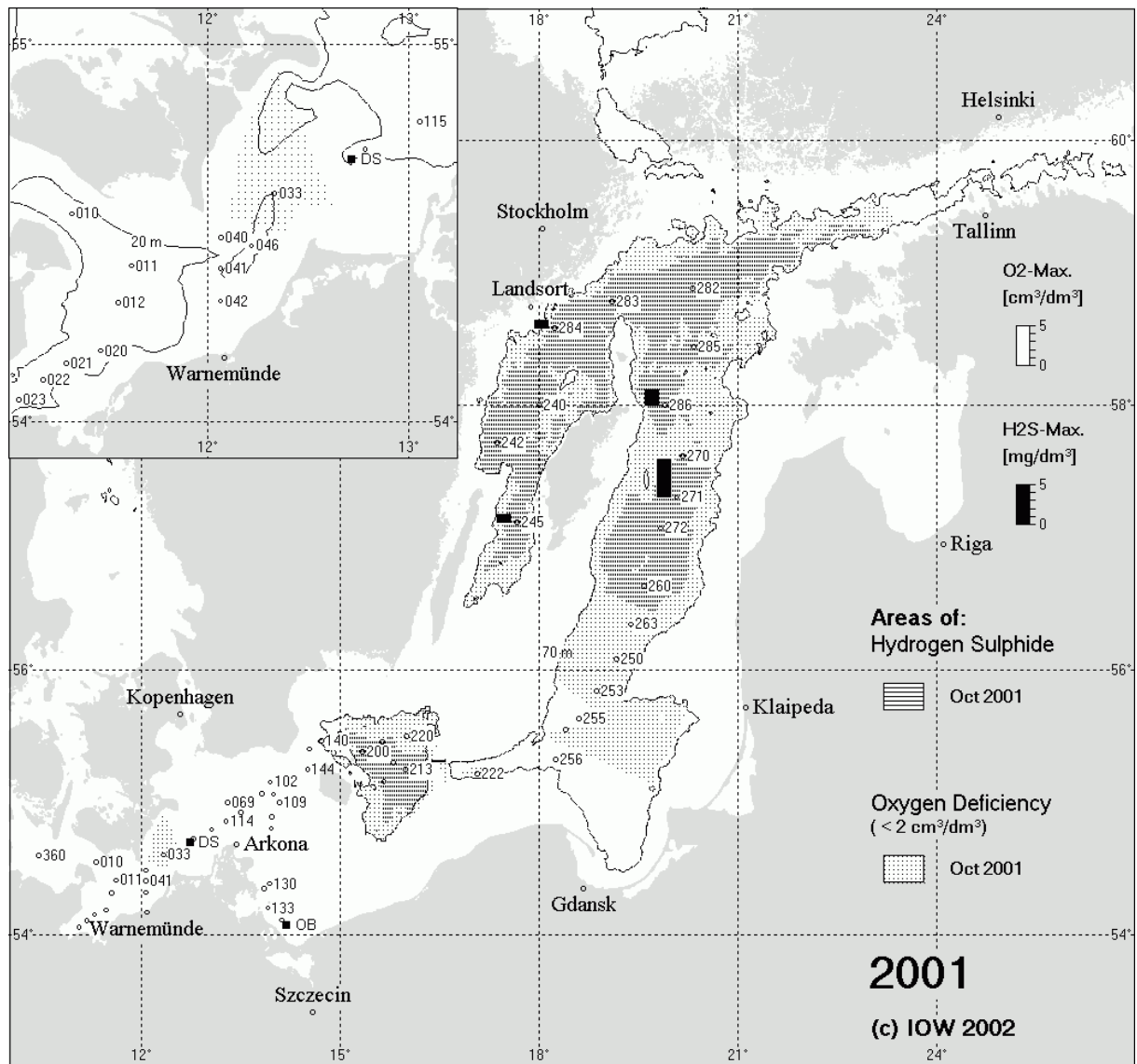


Fig. 8a: Areas of oxygen deficiency and hydrogen sulphide in the near bottom layer of the Baltic Sea in October 2001 (histograms show the maximum hydrogen sulphide concentrations of this layer).

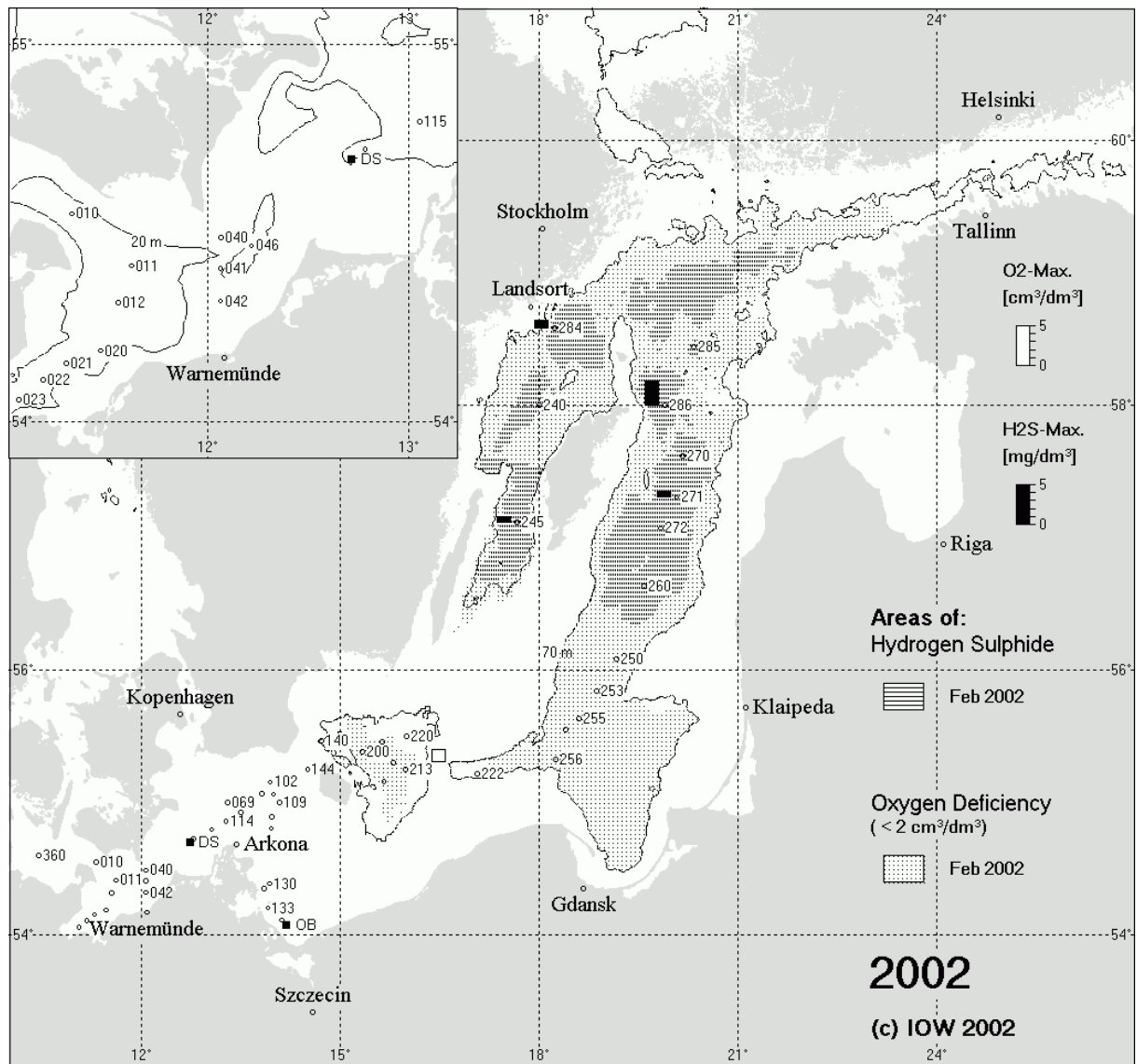


Fig. 8b: Areas of oxygen deficiency and hydrogen sulphide in the near bottom layer of the Baltic Sea in October 2001 (histograms show the maximum oxygen and hydrogen sulphide concentrations of this layer).

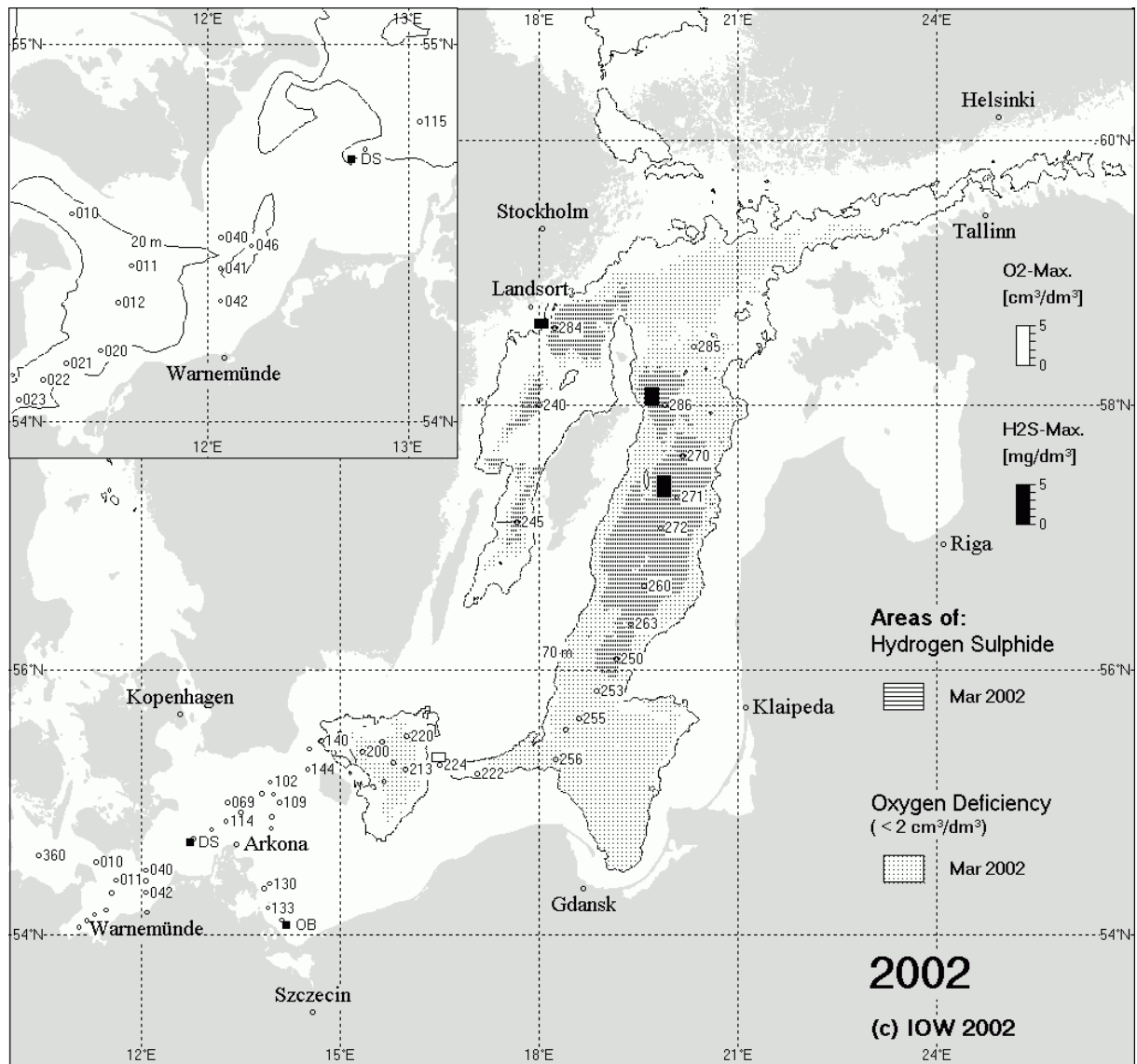


Fig. 8c: Areas of oxygen deficiency and hydrogen sulphide in the near bottom layer of the Baltic Sea in March 2002 (histograms show the maximum oxygen and hydrogen sulphide concentrations of this layer).

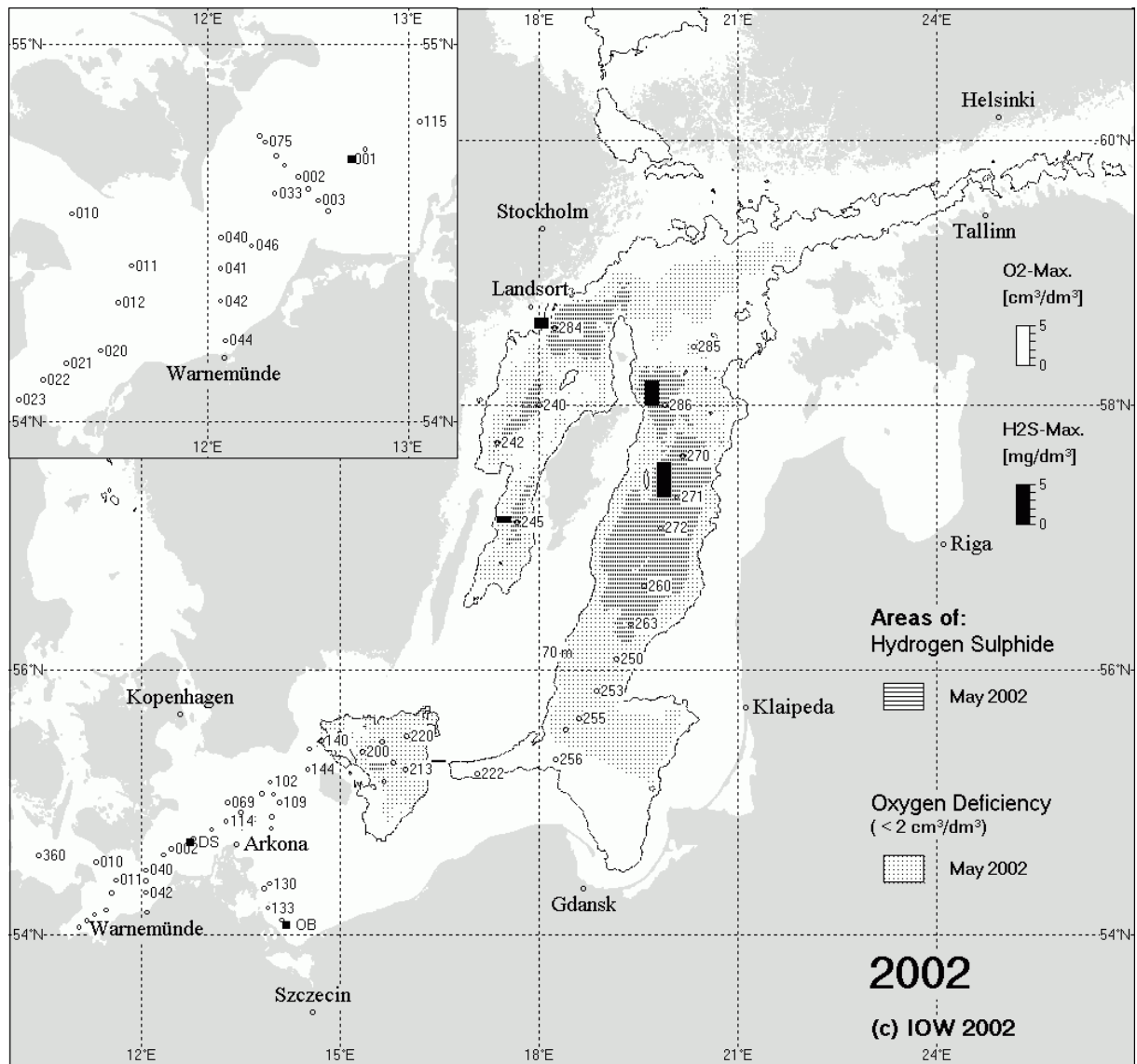


Fig. 8d: Areas of oxygen deficiency and hydrogen sulphide in the near bottom layer of the Baltic Sea in May 2002 (histograms show the maximum oxygen and hydrogen sulphide concentrations of this layer).

5. References

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Acknowledgments

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