ICES STATUTORY MEETING 1993

ICES C.M.1993/C:51
Session V

THE MAJOR BALTIC INFLOW IN JANUARY 1993

by

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ABSTRACT

Inflow processes to the Baltic Sea culminating in strong inflows of highly saline and oxygenated water are typical but relatively rare phenomena. Since the mid-seventies, the frequency and intensity of major inflows have changed. Only a few events have occurred since then, and no inflow has been recorded between February 1983 and the end of 1992. That caused significant changes in the stratification and favoured both the drastic decrease in oxygen concentration and the extreme increase in hydrogen sulphide in the central Baltic Sea.

In January 1993, an effective major inflow occurred after 16 years of stagnation in the central Baltic deep water. The German Baltic Sea Research Institute in Warnemünde observed the overflow of the water in the Darss Sill area, and the propagation of the highly saline water into the central Baltic basins during spring and summer.

The meteorological conditions in the precursory and inflow periods are described, and the different steps of the overflow are discussed. The propagation of the penetrated water body is traced and the turnover in the Bornholm and eastern Gotland Basins is illustrated.

1. Introduction

Strong influxes of highly saline and oxygenated water into the Baltic Sea - termed major Baltic inflows - are attracting increasing attention during the past decade particularly because of both the absence of effective events since the mid-seventies and the drastic changes in the hydrographic conditions in the central Baltic deep waters (Matthäus, Franck 1992). They are attributed to the extreme exchange processes between North Sea and Baltic and they always represent the final stage of longer inflow events.

The water exchange between the North Sea and the Baltic is forced by both sea level and density differences between the Kattegat and the Arkona Basin (Hela 1944; Wyrtki 1954; Jacobsen 1980; Lass et al. 1987). Whereas the density difference is rather constant the sea level difference is strongly correlated with zonal winds (cf. e.g. Lass and Schwabe 1990). Hence, the exchange varies at the time scale of the atmospheric circulation over northern Europe. Moreover, the narrow and shallow transition area between the two seas (Fig. 1) prevents a continuous flow of salty North Sea water into the Baltic. Furthermore, circulation in the Baltic deep water is restricted horizontally by the bottom topography and vertically by permanent stratification. These factors cause periods of stagnation in the Baltic 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 (Fonselius 1981; Matthäus 1990).

The inflow of saline water through the Danish Straits and the Belt Sea occurs very intermittently. Mostly, inflowing water has a small volume or/and a low salinity. Mixing with the ambient water lowers its density along its path from the sills into the central basins. This implies the incoming water usually to be unable to displace the stagnant bottom water and to improve significantly the living conditions in the deep basins. This can only be done by major inflows consisting of large volumes of highly saline and oxygenated water originating from the North Sea.

Major inflows are typical, but relatively rare, phenomena in the Baltic Sea (Dickson 1973; Börngen et al. 1990; Matthäus and Franck 1992). A total of 92 events of various intensity have been identified during the present century which are observed more or less regularly up to the mid-seventies. The last inflow with considerable effect in the Baltic deep water occurred in December 1975/January 1976 (Lass, Schwabe 1990). Since the mid-seventies, the frequency and intensity of major inflows have changed. Only a few events have occurred since then and no inflows have been recorded between February 1983 and the end of 1992 (Franck, Matthäus 1992).

In January 1993, an effective major inflow took place after 16 years of stagnation in the central Baltic deep water. Oceanographers of the Baltic Sea Research Institute in Warnemünde/Germany observed the overflow by both current meters and temperature-conductivity recorders (SEACAT) moored at the Darss Sill (Stat 001 in Fig. 1). Moreover, a series of CTD casts was taken during the main inflow period along a section crossing the Darss Sill into the Arkona Basin. Later the propagation and the effects of the inflowed water has been recorded by several oceanographic cruises in the Baltic proper.

This intensive inflow of substantial quantities of highly saline and oxygenated water ended the most significant and serious stagnation period ever observed in the Baltic Sea (Matthäus 1990). A drastic decrease in temperature, salinity and oxygen concentration was recorded in the Baltic deep water of the eastern central basin during the 1977 to 1992-stagnation period. The period started with the highest temperatures (7.4 °C) and led to the formation of the highest concentrations of hydrogen sulphide (6 - 7 mg/dm^3) ever measured in the near bottom levels. The salinity and density values observed at the end of the period were the lowest ever recorded.

In the following, the meteorological conditions in the precursory and inflow periods caused the major Baltic inflow are analyzed, and the different steps of the overflow across the Darss Sill are discussed. Moreover, the propagation of the penetrated water body is traced, and the turnover in the Bornholm and eastern Gotland Basins is illustrated.

2. Meteorological conditions

At the end of December 1992, the circulation conditions were governed by a high pressure area passing through from the North Sea to the central part of Germany and resulting in weak, mostly westerly winds. This High moved towards Poland on the 31 December, joined to the strong High over northeastern Europe and moved to eastern Poland and Belorussia while strengthening. Between the 31 December and 5 January, the transition area between North Sea and Baltic was affected by winds of southerly to southeasterly directions (velocities 4 - 12 m/s, during squalls locally up to 20 m/s; cf. Fig. 2B) caused by the east European high pressure area and Atlantic low extensions moving from Great Britain to Norway.

During the 5th of January, the large scale weather situation changed in the 500 hPa level to a very strong west situation. According to the passing through of the first Atlantic low extension the ground wind shifted from SE to SW and increased to 12 m/s, during squalls to 20 m/s.

Without any significant variation that very strong west weather situation continued during nearly 3 weeks between 6 and 25 January, 1993 (Figs. 2C and 3). During this period, the transition area was directly affected by an upper storm field and was partly also situated northerly of the jet stream. Caused by both the partly down to the ground acting upper storm fields, the strong meridional air temperature gradients and the cyclonality of the west wind field, hurricanes occurred and passed through on 14th, 22nd and 24th of January. At the meteorological station Arkona (northern Rügen Island) e.g. extreme squalls of 45 m/s from 250° on 14 January, of 39 m/s from 260° on 22 January and of 34 m/s from 250° on 24 January are recorded.

During 3 weeks, a calming down of the situation did not occur between the hurricane depressions due to other cyclonic eddies passing through (cf. Fig. 3). Westerly winds of 12 - 20 m/s (up to 30 m/s during squalls) predominated (mean velocity 14.5 m/s).

Starting on the 26 January, the strong west wind situation in the 500 hPa level changed to weaker northwesterly and northerly winds. A high pressure area moved from the North Sea towards the transition area up to the 29 January. The weakened wind shifted from westerly to northerly directions and weak winds between NE and E predominated on 29 January (Fig. 2D).

3. The Darss Sill overflow

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.

The barotropic current in the Great Belt (Fig. 4), at the Darss Sill (Fig. 5) and in the Sound changed immediately from outflow to inflow with the onset of the west wind and remained this direction except for short periods until 28 January. The corresponding mass flow through the Danish Straits together with the river discharge raised the sea level at Landsort by about 90 cm (cf. Matthäus 1993).

The inflow of highly saline water through the Sound across the Drogden Sill started immediately after the onset of current reversal and discharged water of high salinity into the Arkona Basin (H. Dahlin, pers. comm.). There it covered the bottom with a thin layer (cf. Fig. 6A). The inflow of saline water into the Arkona Basin via the Great Belt was delayed by one to two weeks. The salinity at the Darss Sill exeeded 15 PSU at the 13 January, remained constant for some days and increased to more than 17 PSU at the 18 January (Fig. 7). The climax of the inflow occurred at the Darss Sill between 26 and 28 January where water with temperatures of 3.6 °C and salinities of 22 PSU was observed to flow into the Arkona Basin. The salinity in 7 m depth decreased at the Darss Sill starting with the onset of the outflow within a week to 8 - 10 PSU whereas the salinity in the lower layers decreased to the same values within about two weeks. The salinity of 8 - 10 PSU is the characteristic range of the surface salinity in the Arkona Basin.

During the main inflow period, huge amounts of highly saline water crossed the Darss Sill into the Arkona Basin and accumulated there within a week. The 15 PSU isohaline was lifted from about 38 m depth to 10 m and the 20 PSU isohaline was displaced from 42 m to 32 m (Figs. 6B and C). In the bottom layer below 40 m depth, water with salinities between 22 - 24 PSU and temperatures of about 4 °C was observed (Fig. 8). This water originates from the Sound. The 15 PSU isohaline lowered until mid-February to a depth of 30 - 35 m indicating a flushing time scale of the Arkona Basin of about 2 - 3 weeks (cf. Fig. 9B).

4. The propagation into the central Baltic basins

The salt water discharged into the Arkona Basin was partly mixed into the surface water and flowed back into the Belt Sea and the

Sound during the following outflow phase. Another part was mixed southward into the water of the shallow areas east of Rügen Island. The remaining part flowed through the Bornholm Channel into the Bornholm Basin and replaced the old bottom water. The salinity in the bottom water increased from about 15 to 20 PSU and the oxygen concentration raised from about 1 to 7.5 cm^3/dm^3 between October 1992 and March 1993 (cf. Figs. 10A and D). The intermediate oxygen minimum became weaker and shallower between February and March indicating an ongoing mixing between the old bottom water and the inflowed salt water.

The Bornholm Basin below 60 m must be considered as storage basin for the inflowing highly saline water. The main quantity of the water entered in January 1993 was stored in that basin. The stagnant lower saline bottom water stored there before was lifted above the sill depth to the Stolpe Channel (60 m) by the inflow of saline water and moved under the action of gravity into the eastern Gotland Basin since the beginning of March (Figs. 10B and E). Water bodies with TS-properties of the Bornholm Basin intermediate water were observed in the Stolpe Channel in March to May. The maximum salinity of this water changed within a week in the Stolpe Channel indicating that the outflow of deep water from the Bornholm Basin is rather intermittent. The outflow became weaker in May.

In the beginning of April, first indications of the bottom water renewal in the eastern Gotland Basin were observed and the deep water of the Gotland Deep between 200 m and bottom was renewed in the middle of May (Figs. 10B, C, E, F). At the end of June, salinity and oxygen content increased to 11.7 PSU and 1.5 - 2 $cm^3 O_2/dm^3$ in the near-bottom layer of the Gotland Deep. The H_2S-containing water was lifted up and ranged between about 130 m and 195 m depth. Weak effects of the inflow could also be identified in the northern Gotland Basin.

As early as in May the decrease in salinity and oxygen concentration started again in the Bornholm Basin deep water. Recent cruises have shown that according to the intensity of the inflow at the sills the effects are limited in the central Baltic basins.

5. Conclusions

During the recent event, a total of about 310 km^3 and from it 125 km^3 of highly saline and oxygenated water entered the Baltic Sea. The highly saline water was characterized by a mean salinity of about 19 PSU, a mean temperature of 3.5 °C, a mean density anomaly of 15.2 kg/m^3 and a mean oxygen concentration of 8.2 cm^3/dm^3.

Compared to all inflows identified during the present century (Matthäus, Franck 1992; Franck, Matthäus 1992), the recent inflow must be considered as a moderate one. According to the measurements since May, we must state that the effects of the inflow in the central Baltic basins seem to be limited. Nevertheless, the inflow led hitherto both to a certain increase in salinity and, at least temporarily, to oxic conditions in the central Baltic deep water. This will improve the living conditions of fish and benthic organisms and positively influence the spawning behaviour and larval development of cod in the Baltic Sea, at least in the Bornholm and Gdansk Basins.

Acknowledgements
The authors would like to thank the Monitoring Group of the Baltic Sea Research Institute Warnemünde and the crews of the research vessels "A. v. Humboldt" and "Prof. Albrecht Penck" for the assistence in the field works. Acknowlegement is given to the Federal Maritime and Hydrographic Agency Hamburg for supporting our work by the outputs from the operational model running in the Agency, and to the Swedish Meteorological and Hydrological Institute Norrköping (SMHI) for information exchange concerning the start and progress of the recent event. We

are also grateful to Barry Broman (SMHI) for providing with the Landsort sea level data and to the Great Belt Link Company Copenhagen for making available current and salinity observations in the Great Belt area.

References

Börngen, M., P. Hupfer, and M. Olberg, 1990: Occurrence and absence of strong salt influxes into the Baltic Sea. *Beitr. Meereskunde Berlin*, **61**, 11 - 19.

Dickson, R. R., 1973: The prediction of major Baltic inflows. *Dt. Hydrogr. Z.*, **26**, 97 - 105.

Fonselius, S., 1981: Oxygen and hydrogen sulphide conditions in the Baltic Sea. *Mar. Poll. Bull.*, **12**, 187 - 194.

Franck, H., and W. Matthäus, 1992: The absence of effective major inflows and the present changes in the hydrographic conditions of the central Baltic deep water. *Proc. 12th Symp. Baltic Marine Biologists, Helsingør 1991*. In: Intern. Symp. Series, Olsen & Olsen, Fredensborg, 53 - 60.

Hela, I., 1944: Über die Schwankungen des Wasserstandes in der Ostsee. *Merentutk. Julk.*, **134**, 108 pp.

Lass, H. U., R. Schwabe, W. Matthäus, and E. Francke, 1987: On the dynamics of water exchange between Baltic and North Sea. *Beitr. Meereskunde Berlin*, **56**, 27 - 49.

Lass, H. U., and R. Schwabe, 1990: An analysis of the salt water inflow into the Baltic in 1975 to 1976. *Dt. Hydrogr. Z.*, **43**, 97 - 125.

Matthäus, W., 1993: Major inflows of highly saline water into the Baltic Sea - a review. *ICES Statutory Meeting 1993*, Paper ICES C.M. 1993/C:52.

Matthäus, W., and H. Franck, 1992: Characteristics of major Baltic inflows - a statistical analysis. *Cont. Shelf Res.*, **12**, 1375 - 1400.

Matthäus, W., 1990: Langzeittrends und Veränderungen ozeanologischer Parameter während der gegenwärtigen Stagnationsperiode im Tiefenwasser der zentralen Ostsee. *Fischerei-Forsch. Rostock*, **28**, 3, 25 - 34.

Wyrtki, K., 1954: Der große Salzeinbruch in die Ostsee im November und Dezember 1951. *Kieler Meeresforsch.*, **10**, 19 - 25.

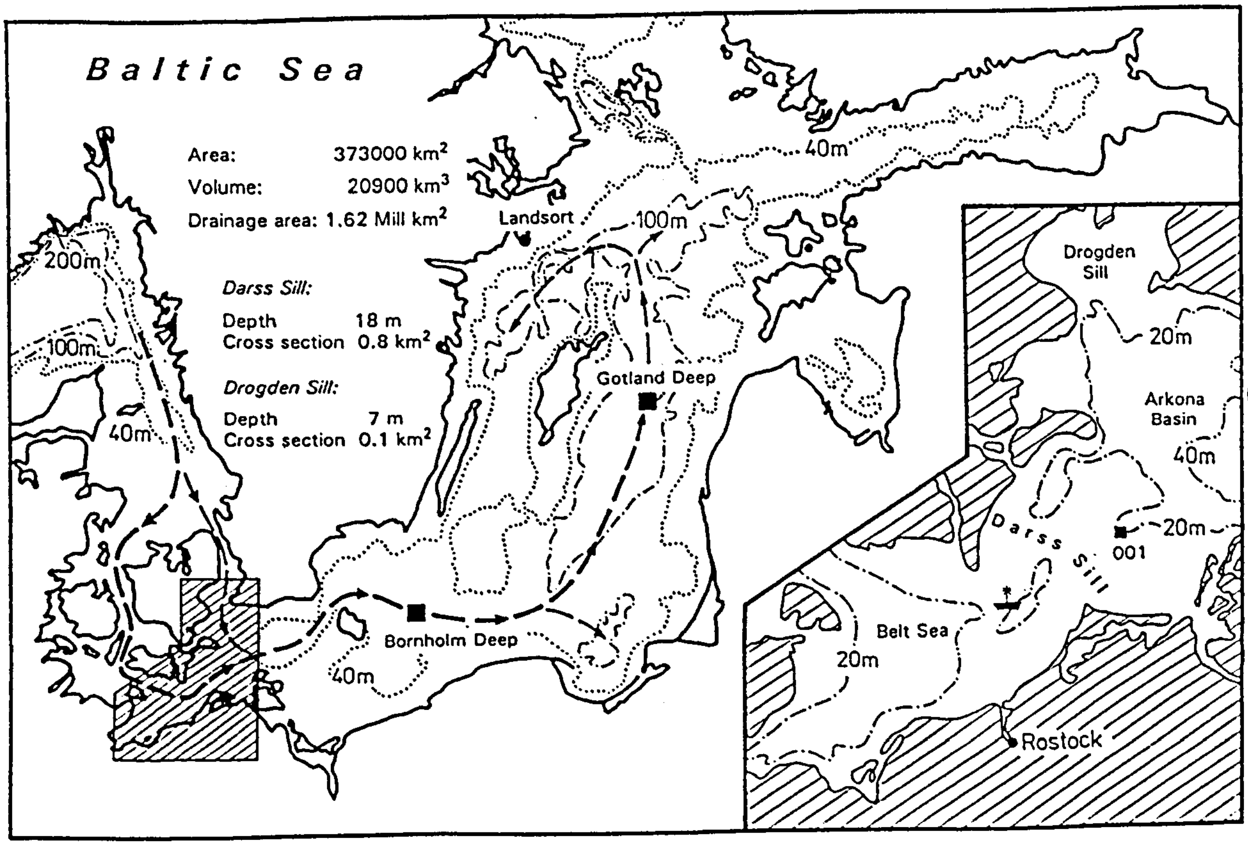


Fig. 1. The Baltic Sea and the situation of the sills in the transition area to the North Sea

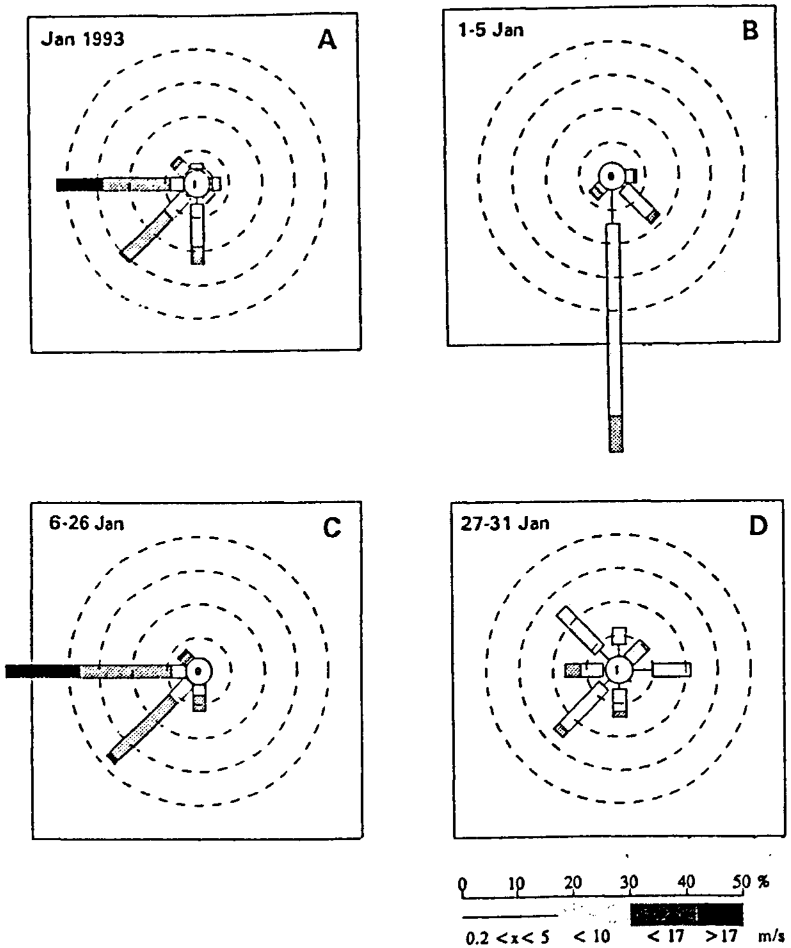


Fig. 2. Wind characteristics at the meteorological station Arkona (Rügen Island) during different periods in January 1993

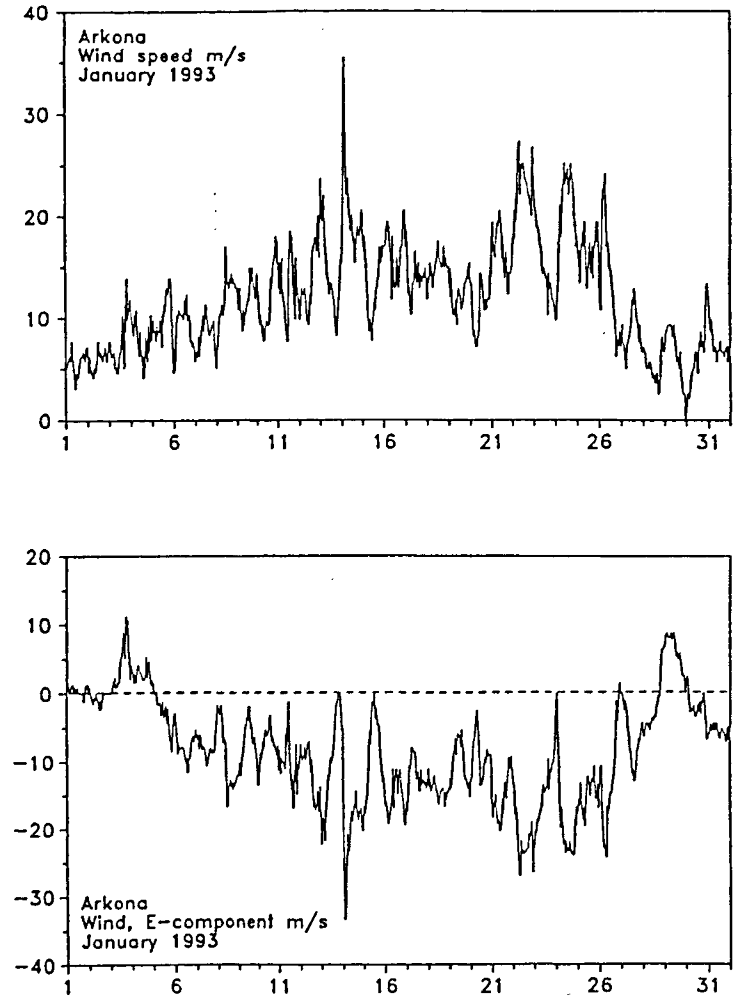
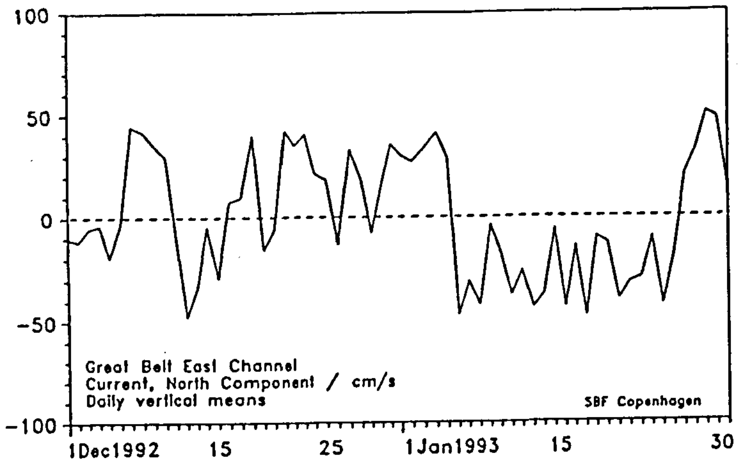


Fig. 3. Wind speed and E-component (negative values correspond to wind from west) at the meteorological station Arkona (Rügen Island) in January 1993



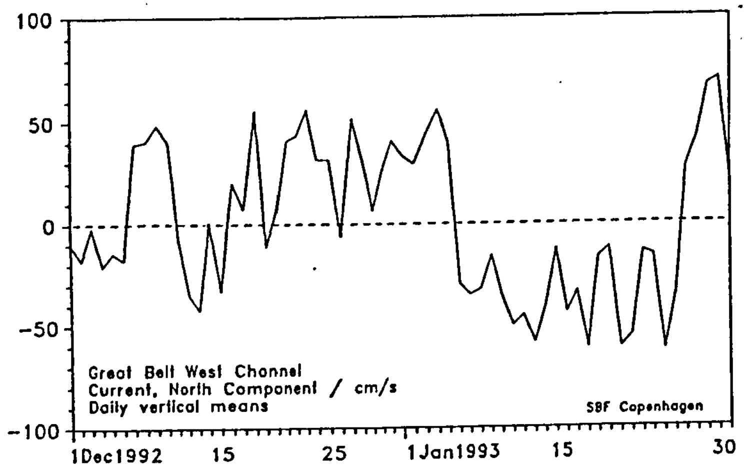


Fig. 4. N-component of the currents in the Great Belt West and East Channels (data from SBF Copenhagen)

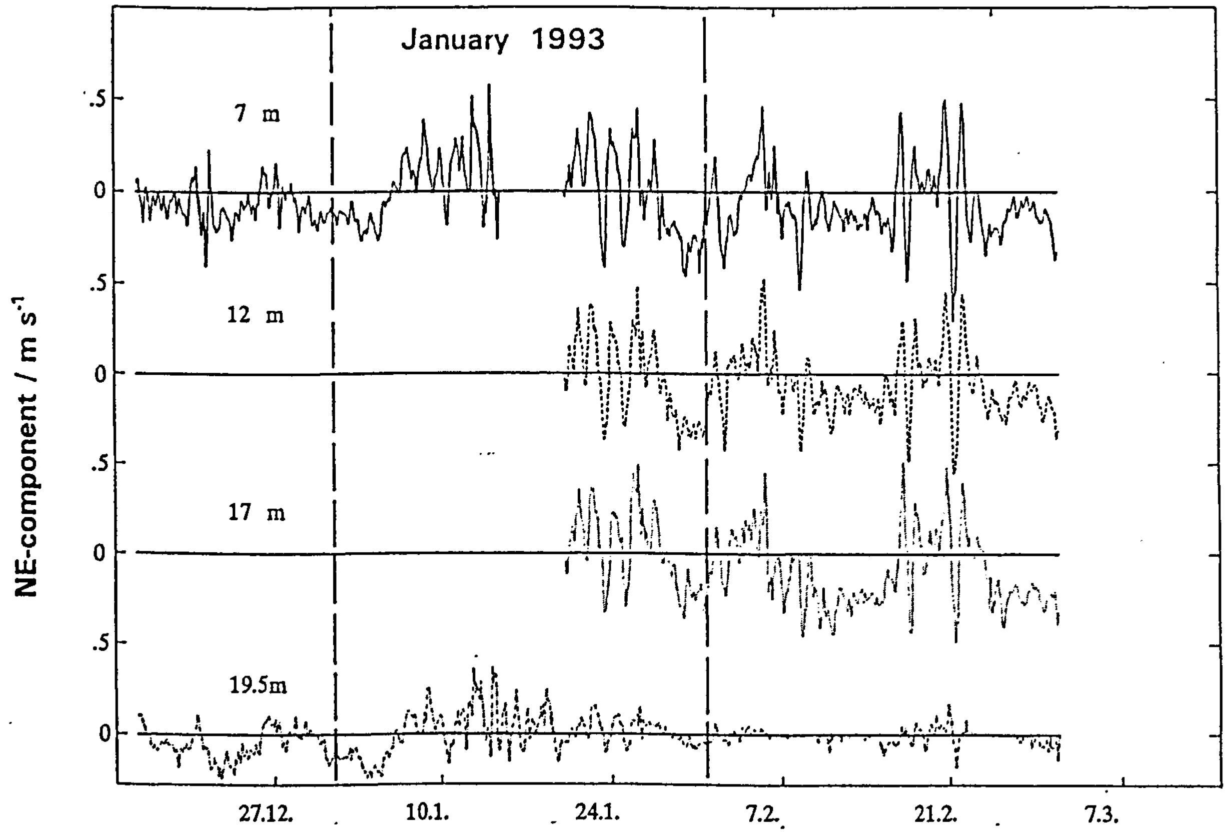


Fig. 5. NE-component of the currents in different depths at the Darss Sill (Pos. 001, cf. Fig. 1)

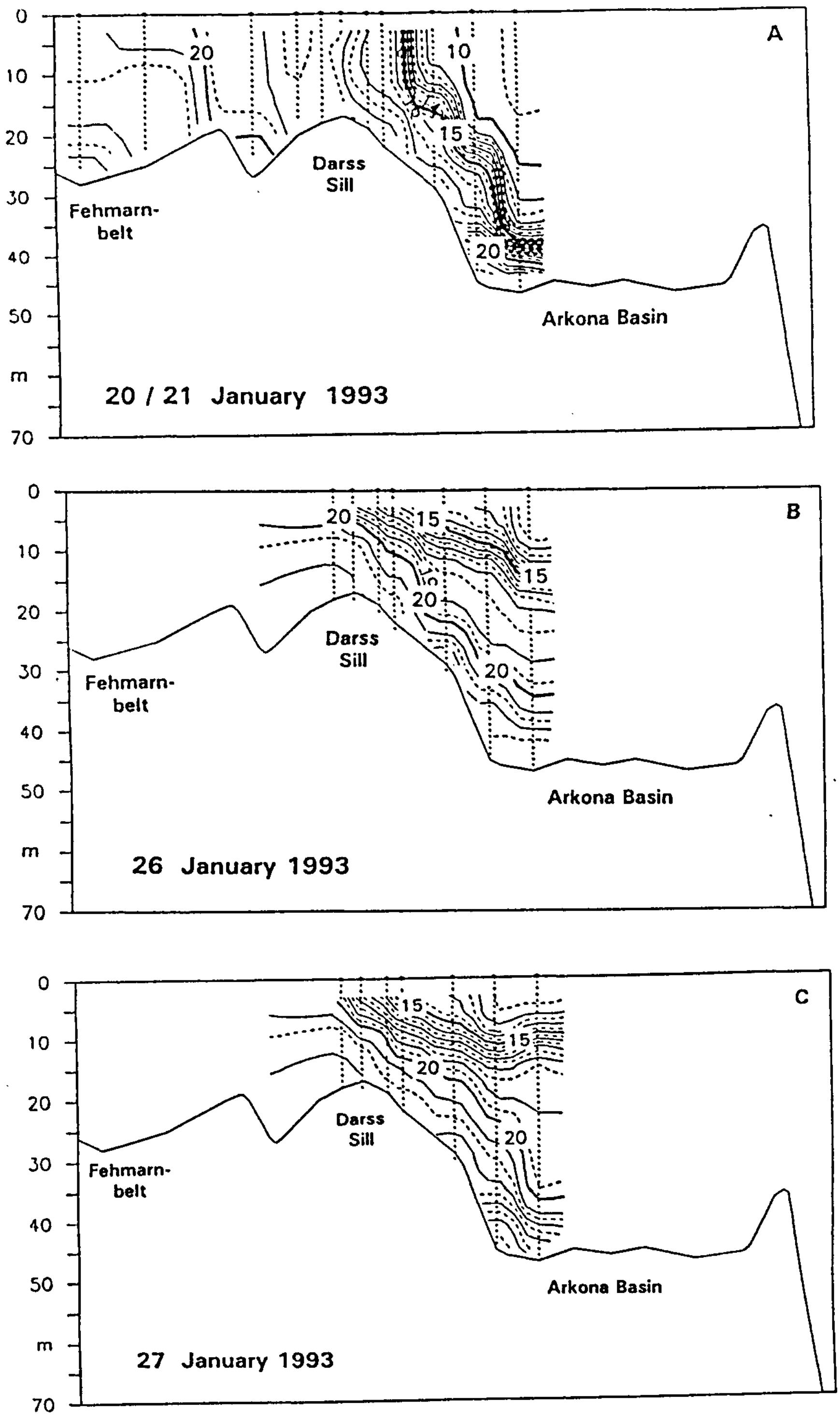


Fig. 6. Longitudinal transects of salinity (in PSU) crossing the Darss Sill into the Arkona Basin during the inflow event in January 1993

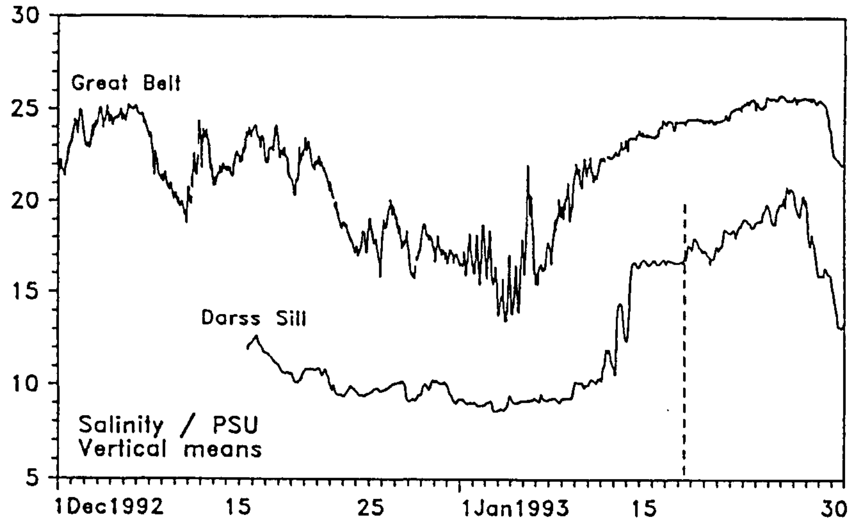


Fig. 7. Vertical means of the salinity in the Great Belt (data from SBF Copenhagen) and the Darss Sill (Pos. 001, cf. Fig. 1)

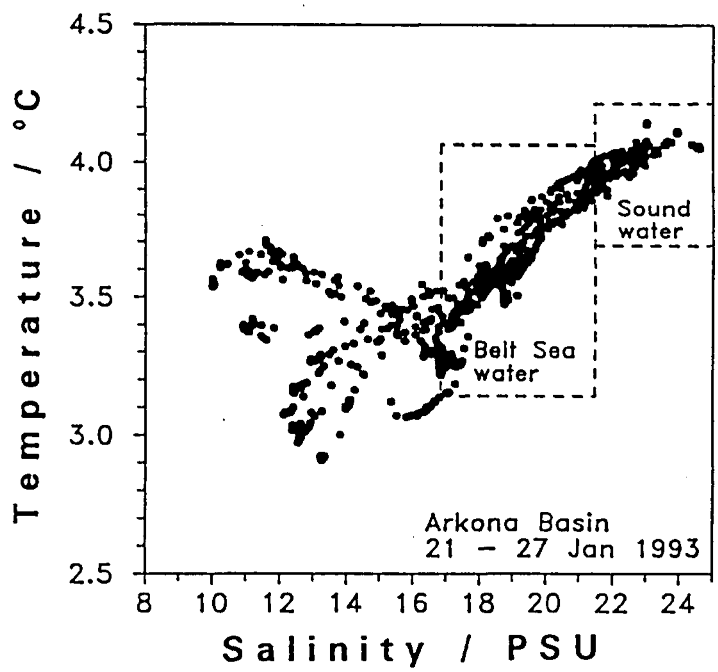


Fig. 8. TS-diagram of the observations in the central Arkona Basin

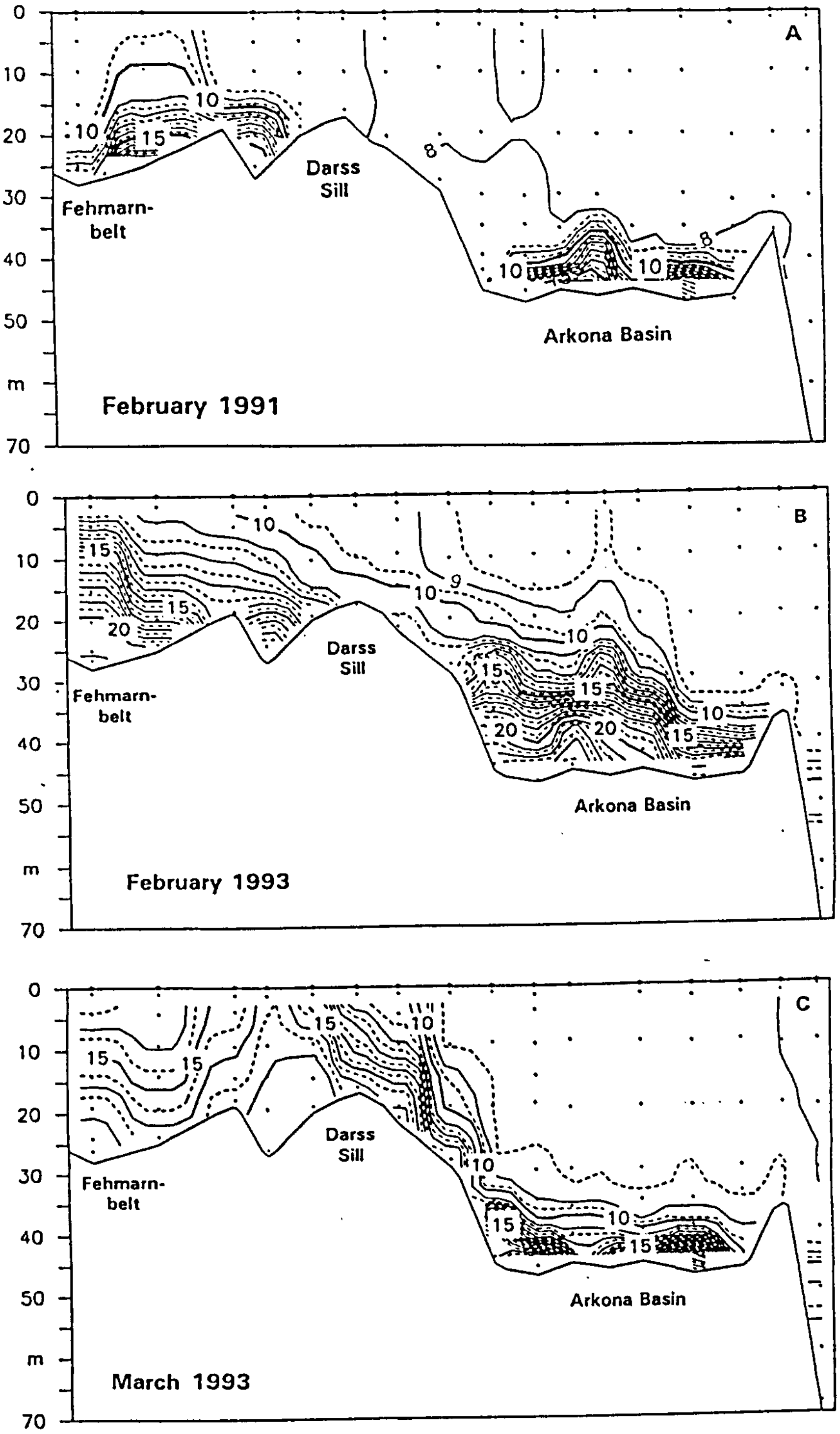


Fig. 9. **Longitudinal transects of salinity (in PSU) between Fehmarnbelt and Arkona Basin during a year without major inflow (A), in February (B) and March 1993 (C)**

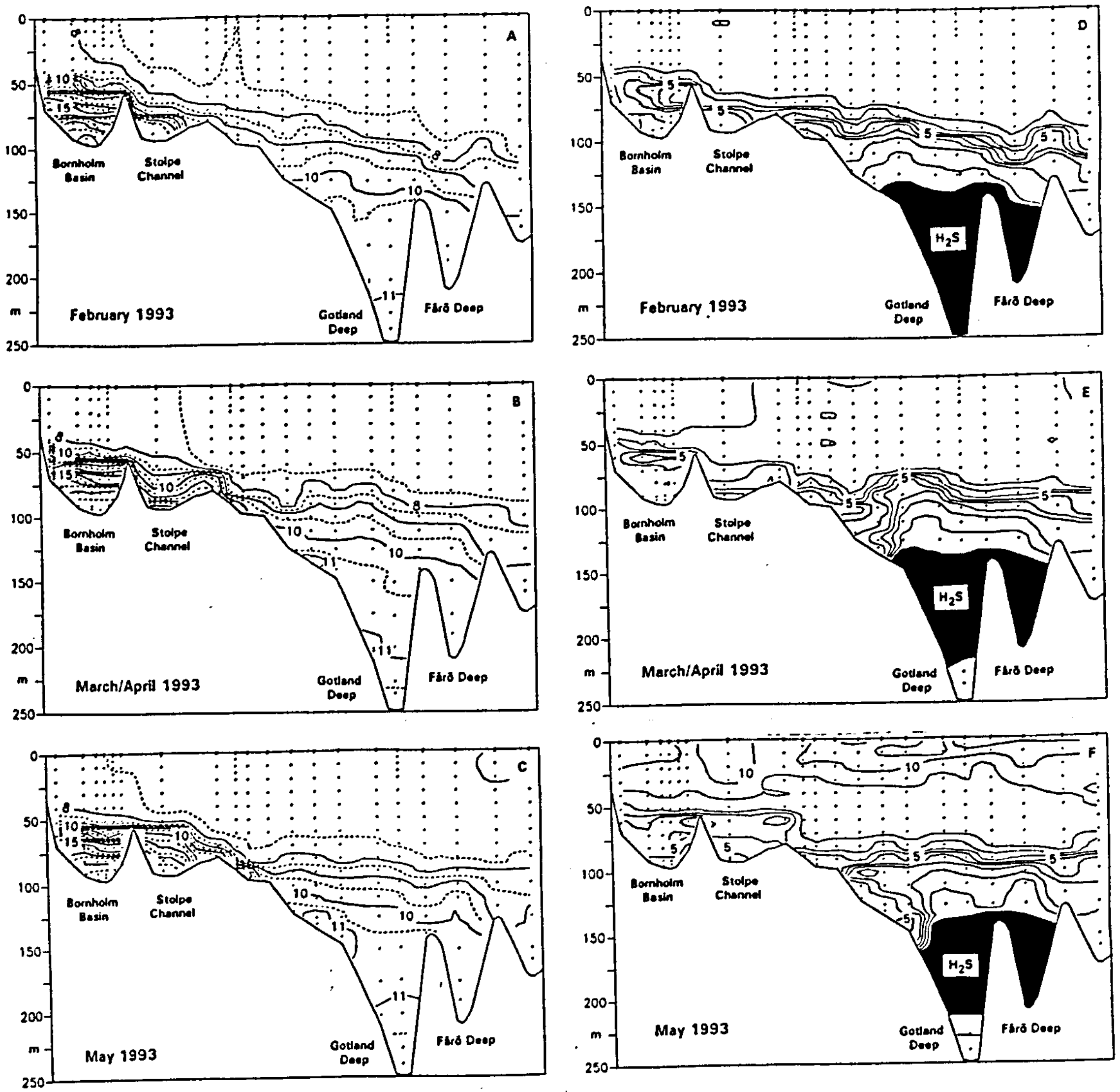


Fig. 10. Propagation of saline water into the central Baltic illustrated by salinity (A - C, in PSU) and oxygen distributions (D - F, in cm^3/dm^3) along a transect between Bornholm Basin and Fårö Deep