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Background data to the exceptionally warm inflow
into the Baltic Sea in late summer of 2002

by

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C o n t e n t s

Abstract

An exceptional warm inflow from the Kattegat into the southern and central Baltic Sea in summer and autumn 2002 is documented in detail by observational data from the Danish Straits and the Darss Sill, from the Arkona, Bornholm, Gdańsk and eastern Gotland Basins, as well as by selected numerical model results. Comprehensive measurements are presented from permanent observation platforms, from occasional as well as regular ship-borne monitoring profiles, completed with various meteorological and gauge background records. The actual event is discussed within its climatological and historical context by various hydrographic long-term series.

The inflow described in this paper occurred during a long-lasting stagnation period of the Baltic Sea and caused, among other things, a ventilation of deep waters in the Gdańsk Deep and a reduction of hydrogen sulphide concentrations in the Gotland Deep. It was followed in January 2003 by a major Baltic inflow which terminated the stagnation period by a strong intrusion of cold and oxygen-rich Kattegat waters. The warm inflow was characterized by various unusual meteorological and hydrographic features which are thoroughly discussed.

Zusammenfassung

Ein außergewöhnlicher, warmer Einstrom vom Kattegat in die südliche und zentrale Ostsee im Sommer und Herbst 2002 wird in seinen Einzelheiten dokumentiert mit Beobachtungsdaten von Belt und Sund, von der Darßer Schwelle, vom Arkona-, Bornholm-, Danziger und dem östlichen Gotlandbecken sowie mit ausgewählten numerischen Modellergebnissen. Umfassende Messungen werden präsentiert von permanenten Beobachtungsplattformen, gelegentlichen und regelmäßigen Profilen von Forschungs- und Überwachungsfahrten, ergänzt durch diverse Hintergrunddaten zum Wetter und zum Pegelstand. Das aktuelle Ereignis wird mittels zahlreicher Langzeitreihen in seinem klimatologischen und historischen Umfeld erläutert.

Der in dieser Arbeit beschriebene Einstrom fand während einer lang andauernden Stagnationsperiode der Ostsee statt und verursachte unter anderem die Belüftung des Tiefenwassers im Danziger Tief sowie die Verringerung der Schwefelwasserstoffkonzentration im Gotlandtief. Er wurde im Januar 2003 gefolgt von einem großen Einstrom in die Ostsee, der die Stagnationsperiode durch einen starken Zufluss von kaltem und sauerstoffreichem Kattegatwasser beendete. Der warme Einstrom ist durch zahlreiche ungewöhnliche meteorologische und hydrographische Eigenheiten charakterisiert, die eingehend diskutiert werden.

1. Introduction

The summer monitoring cruise 2002 of the Baltic Sea Research Institute (IOW) ended in the first days of August (WASMUND 2002), confirming the lasting stagnation in the central Baltic, even with presence of hydrogen sulphide at depth levels below 70 m. The subsequent cruise at the end of October, however, found rather different conditions, especially in the Bornholm Sea (SCHMIDT 2002). More surprisingly, in November 2002, the Polish r/v 'Baltica' discovered the Gdańsk Basin to be suddenly oxygenated (ŁYSIAK-PASTUSZAK and DRGAS 2002). Abnormally high temperatures were recorded in the Gdańsk Deep and the south-eastern Gotland Basin, which virtually suggested sensor failures. At first sight, no relevant inflow event from the North Sea was observed in the mean time, just the opposite, outflow conditions had prevailed in the preceding months and the western Baltic including Kattegat had suffered from low winds, high surface temperatures and a severe shortage of dissolved oxygen (HELCOM 2003). Motivated by these unexpected hydrographic findings, a closer look at the details revealed that a long-lasting intrusion of Kattegat waters through the Great Belt into the Baltic had taken place in late summer 2002.

This unusual process had carried greater volumes of exceptionally warm waters into the deeper layers as far as up to the Gdańsk and eastern Gotland Basins where traces of oxygenated waters were found in thin warm layers at depths of about 200 m (FEISTEL 2003), long before the cold inflow waters of January 2003 (FEISTEL et al. 2003a). It lasted from August to October 2002 and was apparently caused by persistent calm weather conditions over central Europe between July and September 2002 (cf. NAUSCH et al. 2003), in contrast to the well-known major Baltic inflows (MBI) which are forced by heavy westerly gales.

Although summer inflows of highly saline bottom waters through the Great Belt and the Fehmarn Belt (THIEL 1938, WYRTKI 1953, 1954) and across the Darss Sill (MATTHÄUS and FRANCK 1979, MATTHÄUS et al. 1982, LASS et al. 1987) during calm outflow situations are known for a long time, they were believed to dissipate close behind the Darss Sill or to have only minor effects in the central Baltic. Deep water ventilation processes in major Baltic basins have never been described before as their immediate results. Thus, the study of summer inflows deserves more attention than they may have gained in the past because various details of their dynamic behaviour are still poorly known.

This late-summer inflow of 2002 into the Baltic Sea was an extraordinary process in various respects (FEISTEL et al. 2003a):

- according to the criteria of FRANCK et al. (1987), it is not even considered as a relevant major inflow for its low surface salinity at the Darss Sill; none the less, it left traces in various deep Baltic basins for several months;
- it was apparently not driven by westerly gales and the related sea level differences between the Kattegat and the south-western Baltic;
- its net salt inflow occurred in conjunction with a net volume outflow from the Baltic Sea;
- it significantly affected the deep water properties of all major basins in the Baltic proper, except the western Gotland Basin;
- it had an unexpected impact on the ecosystem (KRAUS et al. 2003, SCHMIDT et al. 2003);
- a comparable process has never been described before for the Baltic Sea.

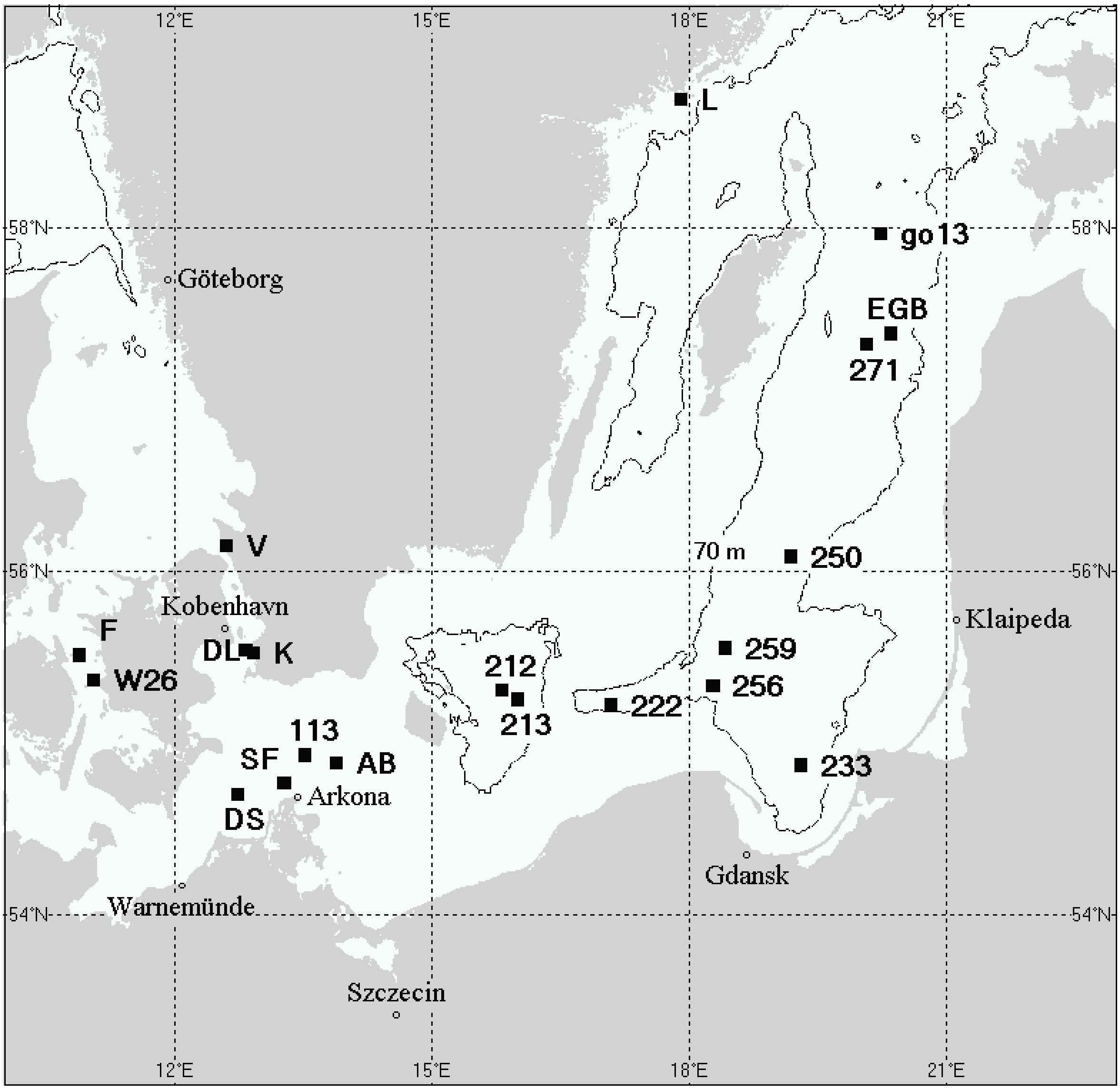


Fig. 1.1
Warm water observation positions in the western and central Baltic Sea, mostly labelled in IOW notation: W26 = Great Belt lighthouse, F = Fyn053 east of Kerteminde, DL = Drogden lighthouse, L = Landsort level gauge, V = Viken level gauge, K = Klagshamn level gauge, AB = Arkona Basin buoy, DS = Darss Sill mast, SF = a scanfish reading. The deep stations of the main basins are: Arkona Basin (AB) = 113, Bornholm Basin (BB) = 213 = BMP K2 and 212 = GLOBEC 023, Stolpe Channel (SC) = 222, Gdańsk Basin (DB) = 233 = P1, South-Eastern Gotland Basin (SEGB) = 259 = P140, Gotland Basin (GB) = 271, EGB = Gotland Basin mooring, Farö Deep (FD) = go13 = GOBEX 13

The general evolution of the summer inflow 2002 has already been characterized in an earlier paper (cf. FEISTEL et al. 2003a). Following the description given there, we distinguish between two different warm inflow periods. The first one, the exceptionally warm summer inflow, which we called "BB60" event, was recorded at the Darss Sill between 1st August and 10th October 2002. The second one, a regular warm water inflow frequent in fall (cf. e.g. Matthäus 1977), which we called "BB90" event with heavier so-called "BB90" waters, was observed from 23rd October to 1st

November 2002 (see section 4.4 of this paper). The two water masses BB60 and BB90 were named after the depth layers where the corresponding waters appeared in the Bornholm Basin. Both were very warm but differed significantly in oxygen content and density, and in the responsible inflow mechanism.

The present article describes the effects of the warm water inflows into the different Baltic deep basins – in particular those of the BB60 event - in much more detail in order to examine the propagation and exchange processes using as many available background data as possible. Therefore, we have divided the paper into sections belonging to important regions of the Belt Sea and the Baltic Proper, as displayed in the map (Fig 1.1). We present measurements and modelling results separately for each of them under the aspect of their rather different hydrographic properties. Moreover, we compare the recent event with long-term variations in the different regions. In the final discussion, we summarise the main features of the regions and briefly link them together.

2. Data Basis

Measurements presented in this paper cover mainly the time period between July 2002 and May 2003. In part they have been obtained by observations within the framework of the Baltic Monitoring Programme (COMBINE) of the Helsinki Commission (HELCOM) carried out by the Baltic Sea Research Institute (IOW) in Warnemünde, Germany, and the Institute of Meteorology and Water Management (IMGW) in Gdynia, Poland. The regular monitoring cruises comprise the months August (WASMUND 2002), October (ŁYSIAK-PASTUSZAK and DRGAS 2002, IMGW 2002, SCHMIDT 2002) and November 2002 (ŁYSIAK-PASTUSZAK and DRGAS 2002, IMGW 2002), and February (NAGEL 2003, IMGW 2003), March (FEISTEL 2003) and May 2003 (NAUSCH 2003b). Moreover, research cruises in the framework of GLOBEC, Germany, were undertaken in October (DUTZ 2002) and November 2002 (HERRMANN 2002). An inflow tracking cruise in January 2003 (NAUSCH 2003a) and several other cruises in August (SIEGEL 2002; ROEDER 2002a), September (VOSS 2002) and December 2002 (ROEDER 2002b) were carried out by the IOW.

The ship-borne investigations were supplemented by continuous records of temperature, salinity and partly oxygen at two permanent stations of the German *MAR*ine Environment Monitoring *NET*work (MARNET) of the Bundesamt für Seeschifffahrt und Hydrographie (BSH), the Darss Sill mast (DS) (KRÜGER et al. 2003), and the semi-diver buoy Arkona Basin (AB) (KRÜGER 2001), both operated by IOW. Additionally, current profiles were available from an Acoustic Doppler Current Profiler (ADCP) moored at Darss Sill, and from a mooring in the Eastern Gotland Basin (EGB), continuously recording currents and temperatures at the three depth levels 174 m, 204 m and 219 m (HAGEN and FEISTEL 2001).

Data from the Great Belt and the Sound were provided by Royal Danish Administration of Navigation and Hydrography, who operates real-time oceanographic observation platforms just north of the Great Belt Bridge (W26) and close to the Drogden Lighthouse. Both systems are equipped with temperature and salinity sensors and an Acoustic Doppler Current Profiler. Furthermore, the County of Funen has provided salinity profiling data from a station in the central Great Belt east of Kerteminde (F).

Data sources for investigation of the long-term development are the ICES and HELCOM data banks and the data collected within the German, Polish and Swedish National Marine Monitoring Programmes.

For the characterization of meteorological conditions, data from weather stations Warnemünde and Arkona of the German Weather Service (DWD) have been used. The filling stage of the Baltic Sea was estimated by means of the Landsort sea level, the level gradient between Kattegat and Baltic by the level gauges at Viken and Klagshamn (SMHI 2003). The wind and surface air pressure field data are obtained from the global model GME of DWD (SCHRODIN 2002). The IOW model runs were carried out using meteorological fields from the NCEP reanalysis electronic atlas (NCEP 2003). Throughout this paper, wind components are reported like marine currents in the physical and oceanographic way, i.e. counted positive where the transport is directed to, opposite to the common meteorological way. Thus, e. g., NW wind is described here by a positive SE wind component.

All hydrographic and chemical variables studied and the methods used were based on the standard guidelines for the COMBINE programme of HELCOM (HELCOM 2002). The positions of the stations of all cruises and the MARNET stations are shown in Fig. 1.1.

Two numerical models were used for interpretation of the summer inflow event. The simulation by the IOW model of the Baltic Sea relies on an adaptation of the MOM-3 code (PACANOWSKI and GRIFFIES 2000) to the Baltic Sea with a free sea surface and a tracer conserving fresh water input (GRIFFIES et al. 2001). Outputs from the operational 3D free-surface model MIKE 3 for the Belt Sea operated by DHI (DHI 2003a, b) has additionally been included in the analysis.

3. Meteorological Conditions

The summer of 2002 was the second warmest since 1890, at least for the southern Baltic Sea area, only that of 1997 was warmer. Positive deviations from the long-term mean air temperature continued until September, with very warm air masses from southern Europe causing unusually stable "subtropical" conditions in August and the first part of September. At Warnemünde, a positive temperature anomaly of about 2-3°C and peak values up to 6°C lasted from the end of July to the beginning of October (Fig. 3.1). The 16° heat sum (time integral of temperatures above 16°C) in August was exceptionally high with 128 Kd (Kd = Kelvin × days), compared to 50 ± 33 Kd of the long-term mean. Only the 1997 August value of 173 Kd was still higher.

Humidity was unusually high almost persistently between the middle of July and the end of August (Fig. 3.2). Unusually frequently, so-called Vb- or Adriatic Lows crossed the Alps northward and poured down torrential rains, locally at an amount not seen for a century or longer, causing substantial flooding, human tragedies and economic damage. Opposite to the usual west wind situations over Germany, the associated precipitation fronts remained spatially trapped for many hours, resulting in long-lasting strong local rainfalls with flash floods, like in Lower Saxony on 17th and 18th July by the cyclone 'Claudia'. The most striking event of this series, however, was the flood of several rivers in Czechia and Saxony in August. It started with heavy rains by the Vb cyclone 'Ilse' on 9th August, that caused the Elbe river overflowing the city of Dresden - among several other towns - from 12th to 21st August with a peak level of 9.40 m above normal on the 17th, exceeding even the 'century flood' level 8.77 m of 1845 (BIRGEL and BRAUN 2002).

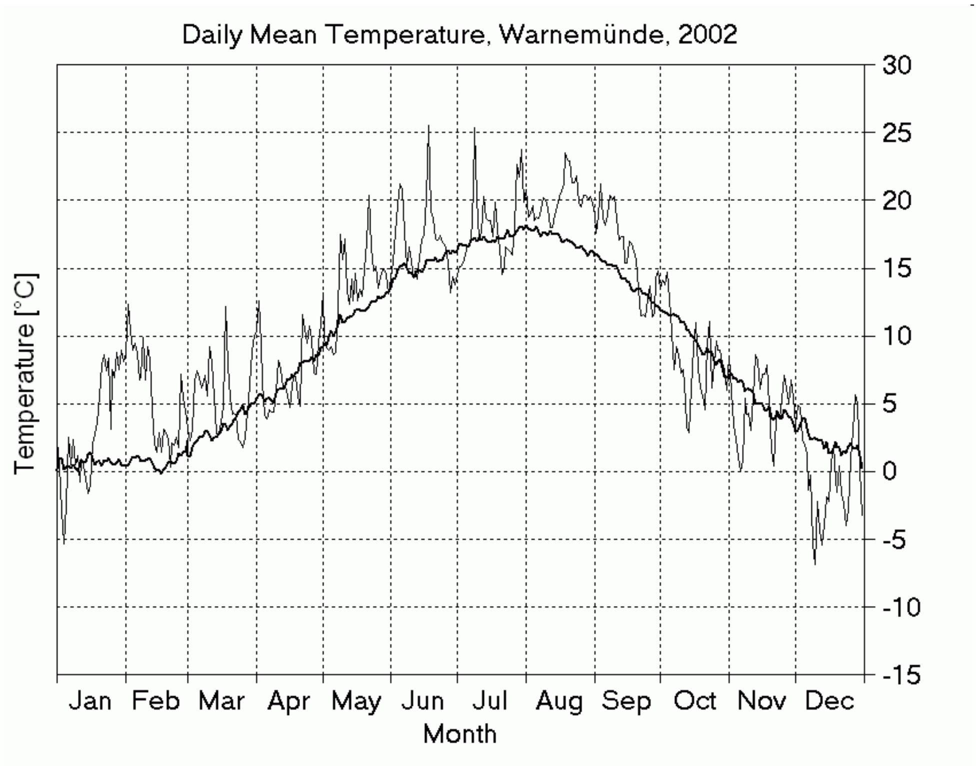


Fig. 3.1
Daily mean air temperature in °C at Warnemünde after DWD (2004). Bold curve: Daily temperatures averaged over 57 years from 1947 to 2003.

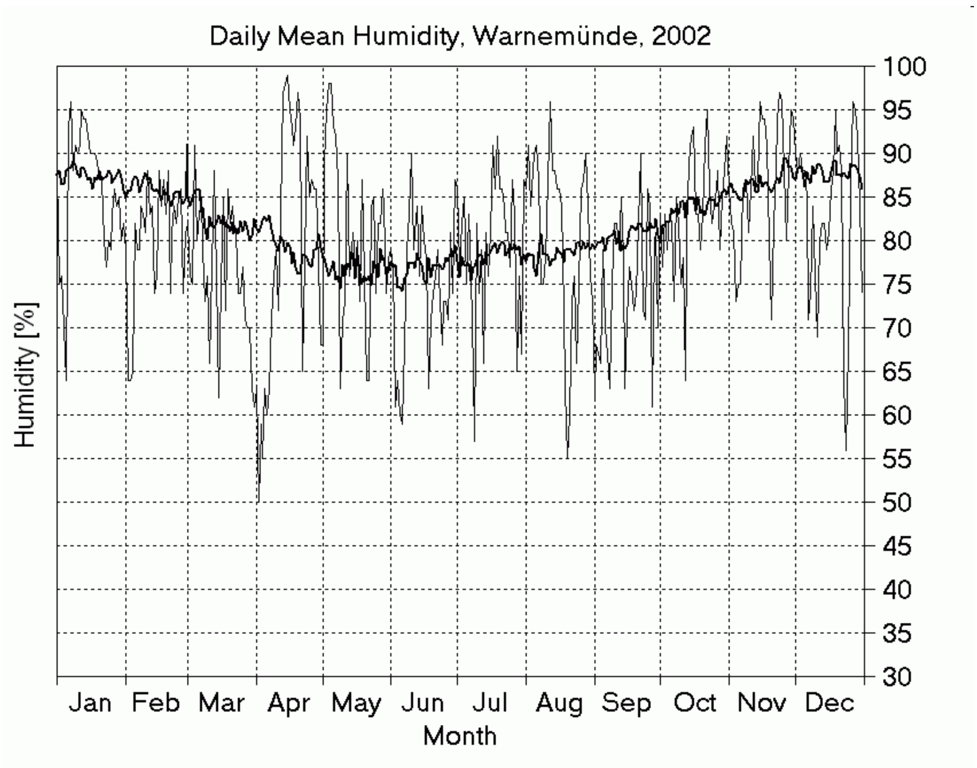


Fig. 3.2
Daily mean relative humidity in % at Warnemünde after DWD (2004). Bold curve: daily relative humidity averaged over 57 years from 1947 to 2003.

In Warnemünde, the corresponding fronts appeared as sudden rises of humidity above 90% (Fig. 3.2). The arrival of a cold front with westerly winds on 14th September removed the lingering warm and humid subtropical air masses over Germany (TIESEL 2002), indicated by dropping temperature in Fig. 3.1, but did not finally terminate the extended low-wind period (Fig. 3.3).

Water transport through the Danish Straits reacts to the driving forces like a low-pass filter with 10 days of memory, $f(t) = \exp(-t/10\mathrm{d})$ (LASS 1988, LASS and MATTHÄUS 1996, HAGEN and FEISTEL 2001). We have applied this filter to the wind at Arkona station, shown in bold in Fig. 3.3.

The north-west wind, i.e. the component blowing towards south-east (Fig 3.3a), dominates the barotropic, gale-forced inflow processes into the Baltic Sea. For the BB60 period, its filtered curve oscillates around zero with moderate amplitude. The north-east wind, however, drives outflow from the Baltic Sea (Fig. 3.3b). It showed a permanent value of about +2 m/s from the beginning of August to mid October, just the BB60 time interval. The exceptional duration of this wind situation caused, most probably, the observed unusual type of salt water intrusion. At the end of October, westerly storm winds started blowing and triggered the BB90 event with positive wind component in Fig 3.3a and negative in Fig. 3.3b.

During the extended BB60 inflow period, meteorological conditions underwent various natural fluctuations. However, instead of studying average values over this time interval, we prefer a ‘typical day’ scenario here, being more detailed in structure and thus more instructive. We have selected the 24th August as this representative day, shown in Figs. 3.4 and 3.5, and in the following passages we will consider certain details especially for this date.

Fig. 3.4 shows the European surface weather map for the 24th August 2002. An extended and complex low pressure system with embedded fronts spreads from Spain along the Alps up to Norway, approximately indicating the typical Vb-low track route. In conjunction with the high-pressure cell centred over Sweden, the wind field favoured outflow conditions from the Baltic. This is explicitly shown in the wind map (Fig. 3.5) of the 24th August, where the vector field displays north-eastern wind from Gotland, turning towards east-southern over the southern Baltic and Baltic Proper and changing to decidedly south-eastern over Kattegat (SCHRODIN 2002).

On 24th August, Warnemünde had a daily mean temperature of 21.8°C, 5 degrees above the long-term average of 16.5°C on this calendar day. Wind at Arkona was about 7 m/s from ENE, Landsort level reached 164 cm (see section 4.1).

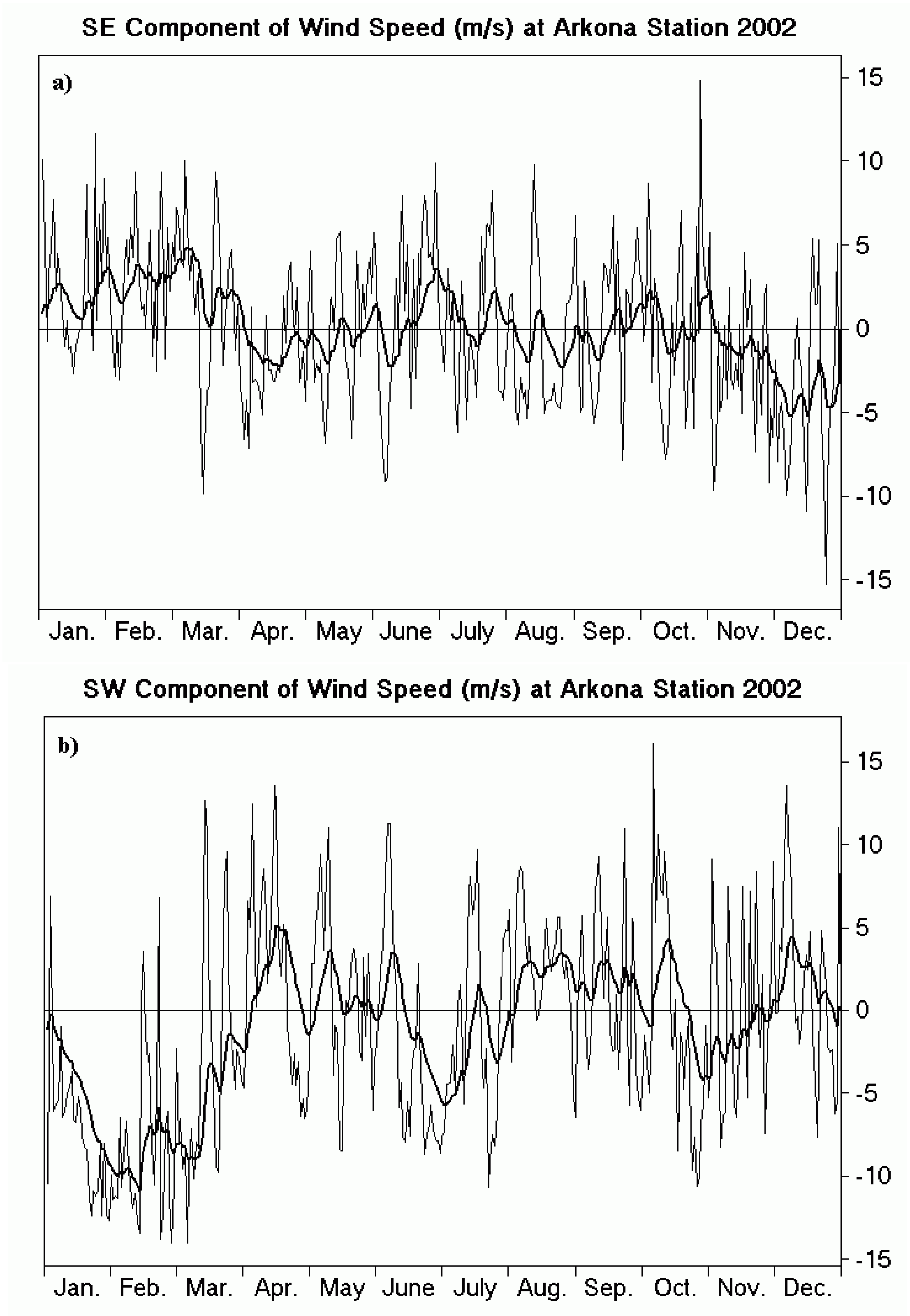


Fig. 3.3
Daily mean wind at Arkona station in m/s after DWD (2003); a) south-east component, positive if blowing from north-west, b) south-west component, positive if blowing from north-east. Bold curves are filtered with a 10-days exponential memory.

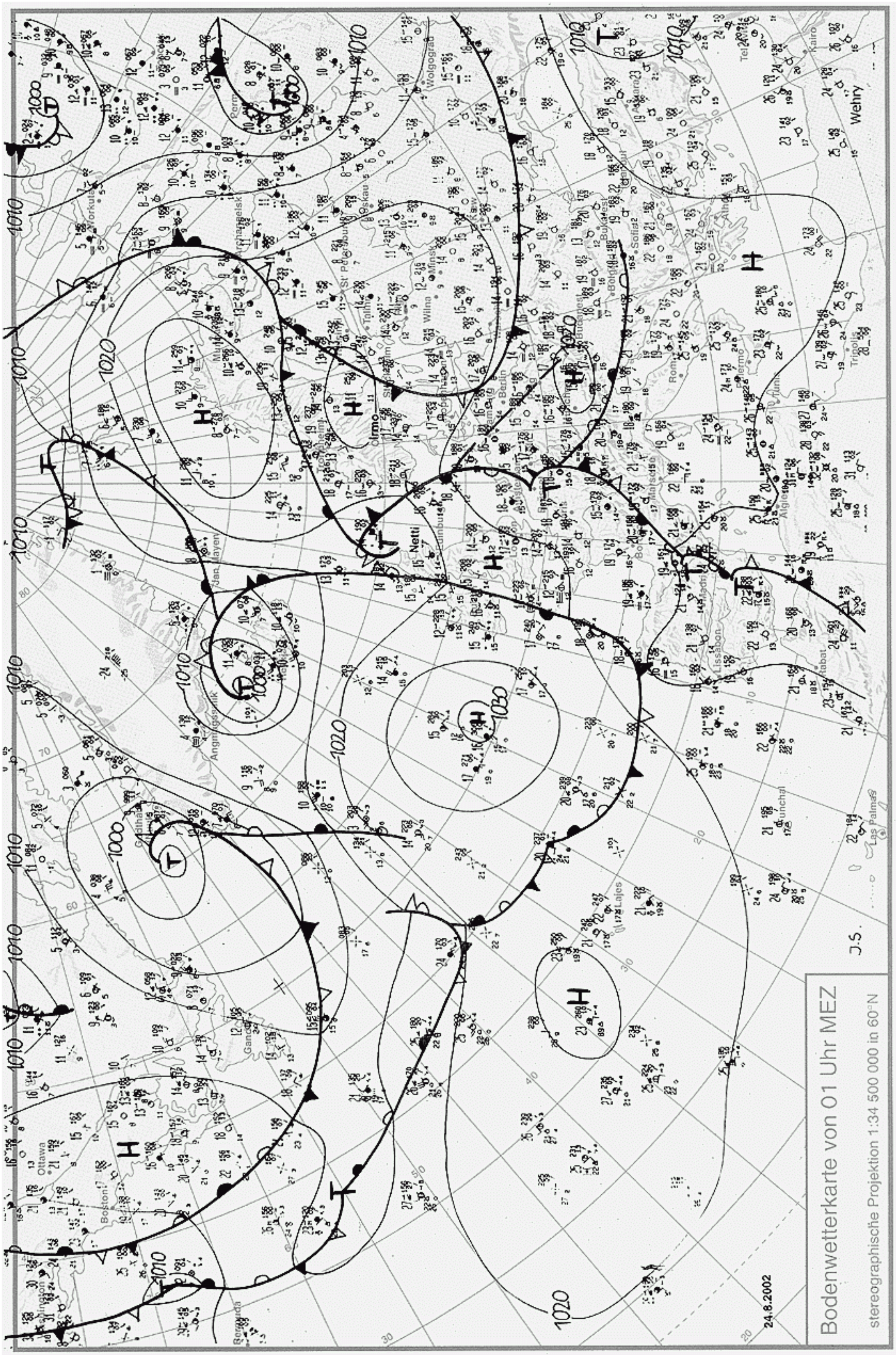


Fig. 3.4
Surface weather map of Europe and the North Atlantic for the ‚typical day', 24th August 2002 (reprinted with kind permission of "Berliner Wetterkarte e.V.")

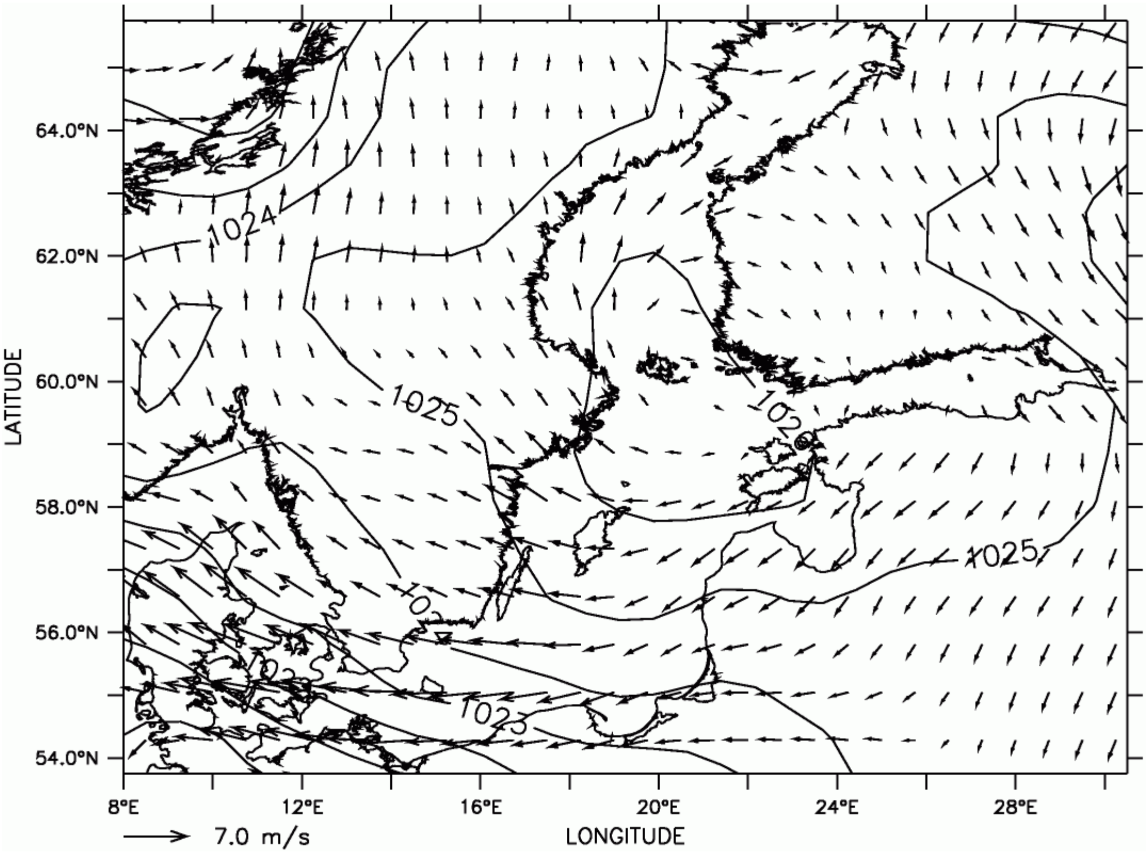


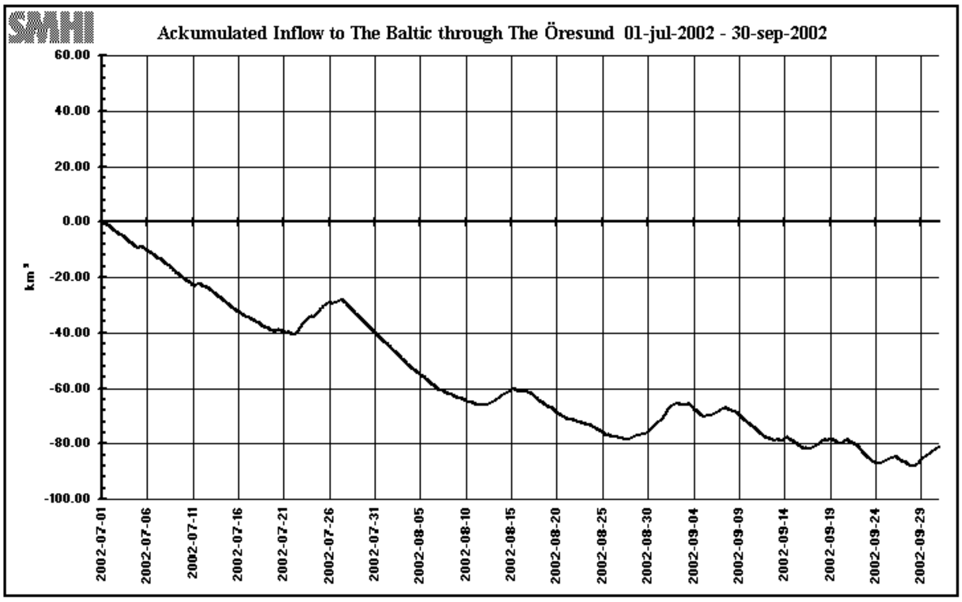
Fig. 3.5
Surface air pressure (hPa) and wind field (m/s) over the Baltic Sea area for the 24th August 2002 (after data from DWD 2002 global model GME, SCHRODIN 2002), showing calm outflow conditions with easterly wind directions prevailing over the central and western Baltic.

4. Regional Hydrographic Processes

The warm inflow showed very specific features along its propagation path from the Kattegat to the central Baltic basins. The BB60 inflow came almost exclusively through the Great Belt and crossed the Darss Sill in spatially rather inhomogeneous flow pattern, while the BB90 occurred through both the Sound and the Belt. In the Bornholm Basin, both BB60 and BB90 water masses appeared in different levels and, owing to this, they had different time histories afterwards. Even more distinct in effect, location and time of arrival, the waters appeared in the basins farther east. This behaviour is documented in dedicated sections below, beginning at the Danish Straits and ending in the eastern Gotland Basin.

4.1 Great Belt and Sound

The water volume transport through the Sound in the second half of 2002, based on current measurements, is shown in Fig 4.1.1 (SMHI 2002). During August an outflow from the Baltic of about 40 km³ was computed, but during September the net balance was almost zero. In the final phase of BB60 inflow, until 10th October, again an outflow of nearly 20 km³ was observed. However, for the subsequent, wind-driven BB90 inflow from 23rd October to 1st November, an inflow of about 25 km³ is clearly discernible.



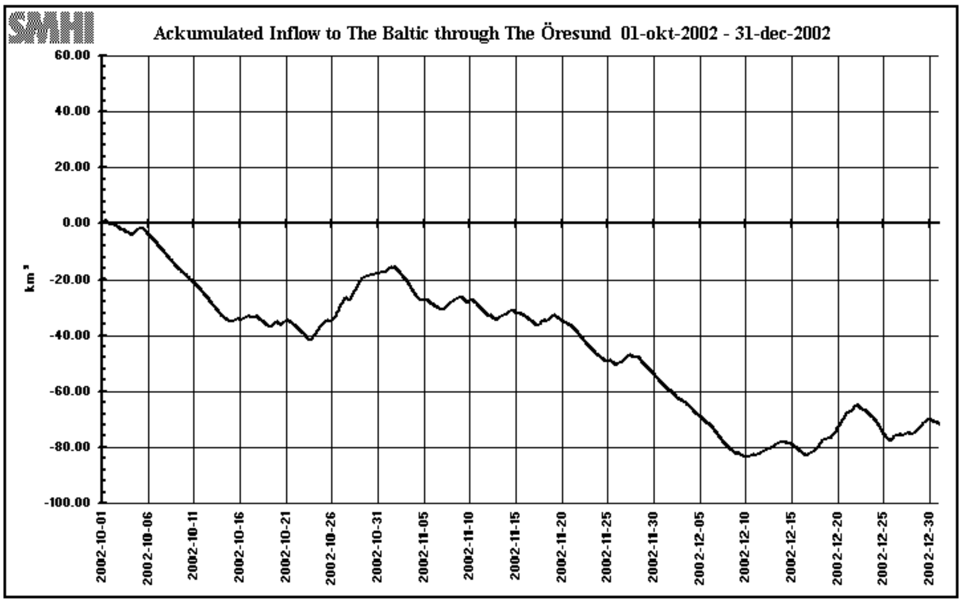


Fig 4.1.1
Time integral of volume outflow through the Sound in km³ as computed by SMHI (2002); top, from 1st July to 30th September 2002; bottom, from 1st October to 31st December 2002. Reference point is always the first day of the graph.

The outflow volume through the Great Belt in 2002 was computed by the DHI model (DHI 2003a) and is shown in Fig. 4.1.2. In August the outflow volume was 101 km³, in September 2 km³, and in the first 10 days of October 24 km³. During the BB90 period an inflow of 65 km³ occurred. These figures are qualitatively very similar to those from the Sound.

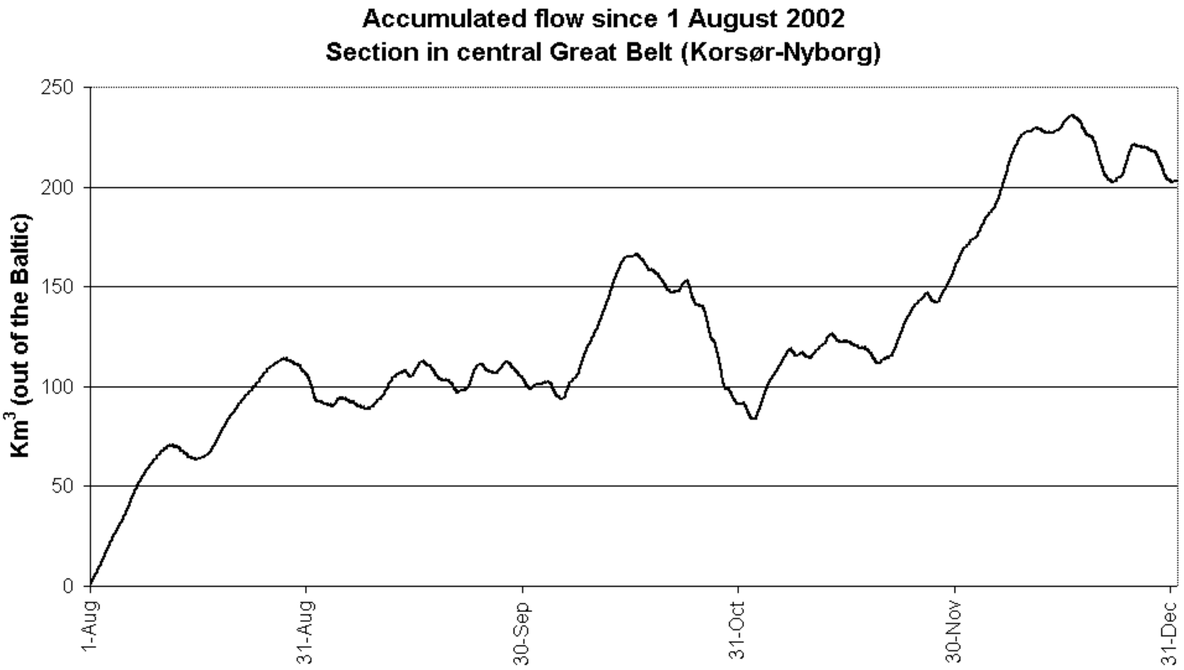


Fig. 4.1.2
Time-integrated outflow volume in km³ from the Baltic through the Great Belt into the Kattegat during last part of 2002 as computed by the DHI model (DHI 2003a).

Summing up both parts we have found an outflow in August of about 140 km³, no net transport in September, an outflow of 40 km³ until 10th October, and finally an inflow of 90 km³ after 23rd October.

The filling factor of the Baltic is well represented by the Landsort sea level, Fig. 4.1.3. Its time series is consistent with the wind conditions discussed in chapter 3. For the BB60 period, the level was almost permanently below average at about -10 cm, indicating permanent outflow. Later, at the end of October, a steep level increase exceeding 30 cm difference indicates the small BB90 inflow event, driven by the westerly gales, leaving the level at about zero for most of November.

From the Landsort data (Fig. 4.1.3) we can derive the water budget of the Baltic for these periods, based on a surface area of about 380,000 km² (HAGEN and FEISTEL 2001). In August the Baltic lost 61 km³, in September the water volume grew by 34 km³, until 10th October it again decreased by 57 km³, and during the BB90 inflow it increased by 84 km³. The differences between this balance and the transport data through the Danish Straits should be balanced by river discharge, precipitation and evaporation. The complete monthly water balance for 2002 based on climatological river data of MIKULSKI (1982) (Table 4.1.1) shows, however, that meteorological fluctuations and methodological uncertainties involve a monthly scatter of about ± 30 km³. We note that this error is only 5% on the annual scale, and that the Sound covers even 44% of the total annual outflow, but with very variable shares for each particular month. The error is somewhat bigger using the more recent river inflow data of CYBERSKI and WROBLEWSKI (2000). Interannual water balance fluctuations are typically about 50 km³/y (BERGSTRÖM and CARLSSON 1994).

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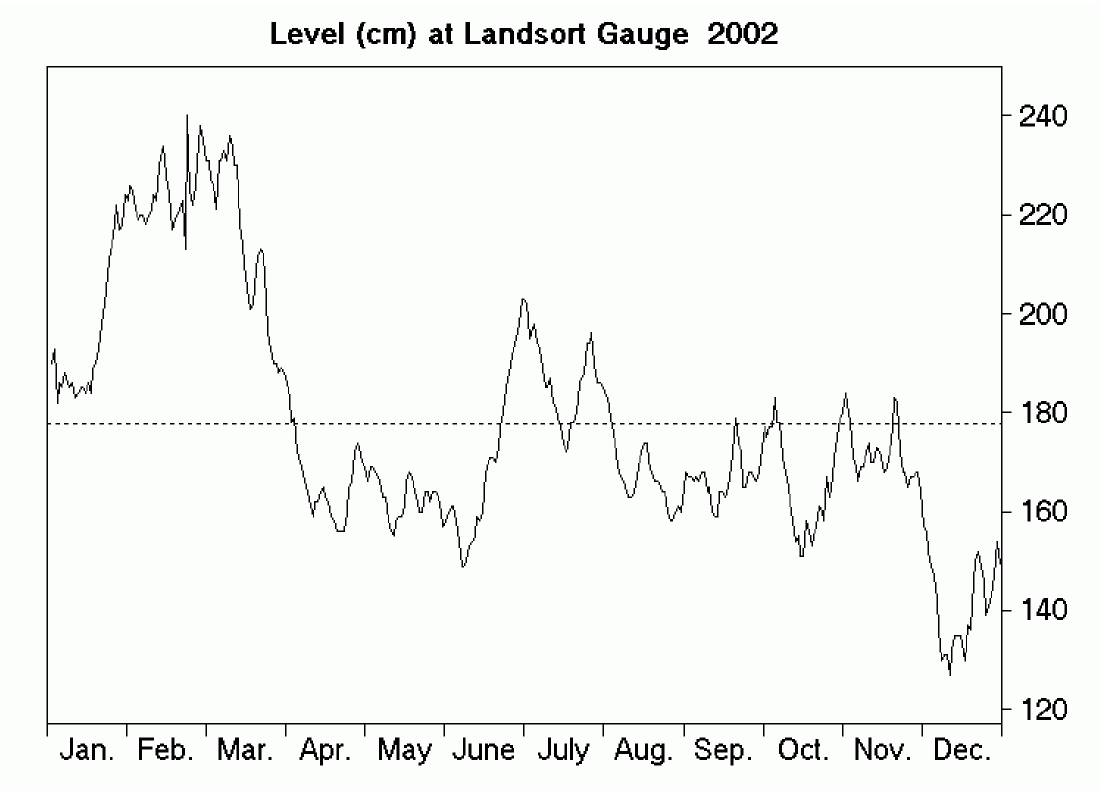

Fig. 4.1.3
Sea level at Landsort gauge in cm after SMHI (2003). The dotted line is the annual average.

Table 4.1.1
Baltic water balance of 2002, all quantities accumulated relative to 1st January 2002. Belt: Accumulated outflow through the Great Belt (DHI 2003b), Sound: accumulated outflow through the Sound (SMHI 2002), Outflow: total outflow Belt + Sound, LOrt: Landsort sea level (SMHI 2002), Baltic: Baltic water volume (= Landsort level × 3.8 km³/cm), Climatological monthly river discharge: M: MIKULSKI (1982), CW: CYBERSKI and WROBLEWSKI (2000), Error: imbalance Baltic + Outflow - Rivers

Date	Belt km³	Sound km³	Outflow km³	LOrt cm	Baltic km³	M km³	Error km³	CW km³	Error km³
1.1. 2002	0	0	0	0	0	0	0	0	0
1.2. 2002	-64	-16	-80	35	134	28	26	25	29
1.3. 2002	-97	0	-97	41	157	53	7	48	12
1.4. 2002	21	58	79	-4	-15	85	-21	78	-14
1.5. 2002	107	86	193	-21	-80	132	-19	123	-10
1.6. 2002	160	116	276	-32	-122	196	-42	184	-30
1.7. 2002	108	114	222	13	50	253	19	238	34
1.8. 2002	**158**	**156**	**314**	**-6**	**-23**	**296**	**-5**	**280**	**11**
1.9. 2002	**260**	**186**	**446**	**-22**	**-84**	**333**	**29**	**317**	**45**
1.10. 2002	**261**	**194**	**455**	**-13**	**-50**	**368**	**37**	**340**	**65**
1.11. 2002	**249**	**212**	**461**	**-6**	**-23**	**404**	**34**	**375**	**63**
1.12. 2002	320	268	588	-33	-127	439	22	407	54
31.12. 2002	361	282	643	-41	-157	471	15	427	59

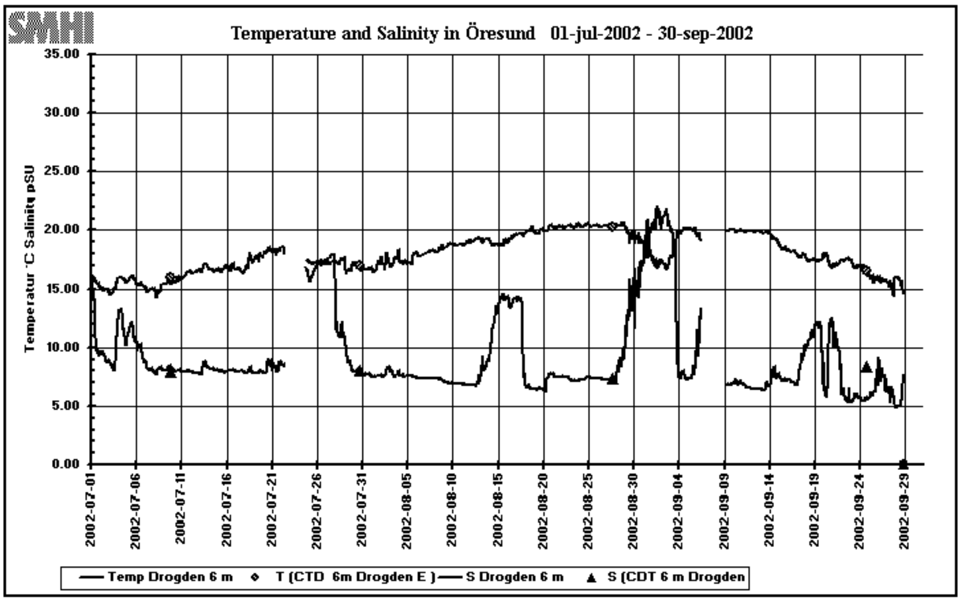

Fig. 4.1.4
Temperature (upper curve) and salinity (lower curve) at bottom level of the Drogden Sill in the Sound between 1st July and 30th September 2002, measured by the Royal Danish Administration of Navigation and Hydrography, analysed and published on the web by SMHI (2002). Note that some drift is present for the salinity sensor between sensor cleaning.

During the BB60 inflow period, there was only a short lasting period of highly saline water transport through the Sound (30 August – 3 September: inflow of about 10-15 km^3) (Fig. 4.1.4). For the typical day, the 24th August, salinity at the Drogden Sill was about 8 PSU. These are typical Baltic outflow properties, thus the Sound transport seems irrelevant for the warm summer inflow under study. Consequently, we have to focus our attention on the Great Belt as the responsible transport channel for the Kattegat water, even though it exhibits net outflow figures like the Sound.

The barotropic pressure gradient between the Kattegat and the western Baltic can be represented by the sea level difference between Viken (Kattegat) and Klagshamn (Baltic) along the Sound, shown as V and K in Fig. 1.1 (data kindly provided by SMHI). The rapid fluctuations are mostly tides (Fig. 4.1.5). The comparison with Darss Sill salinity (section 4.2) shows that the characteristic near-bottom salty layer at the Darss Sill grew thick mainly in those phases when the level difference was small (within about ±10 cm range) and the tides made the water oscillating back and forth in the channel. It disappeared at stronger gradients as well as during enhanced wind periods. On the selected 24th August, the level difference was negligible.

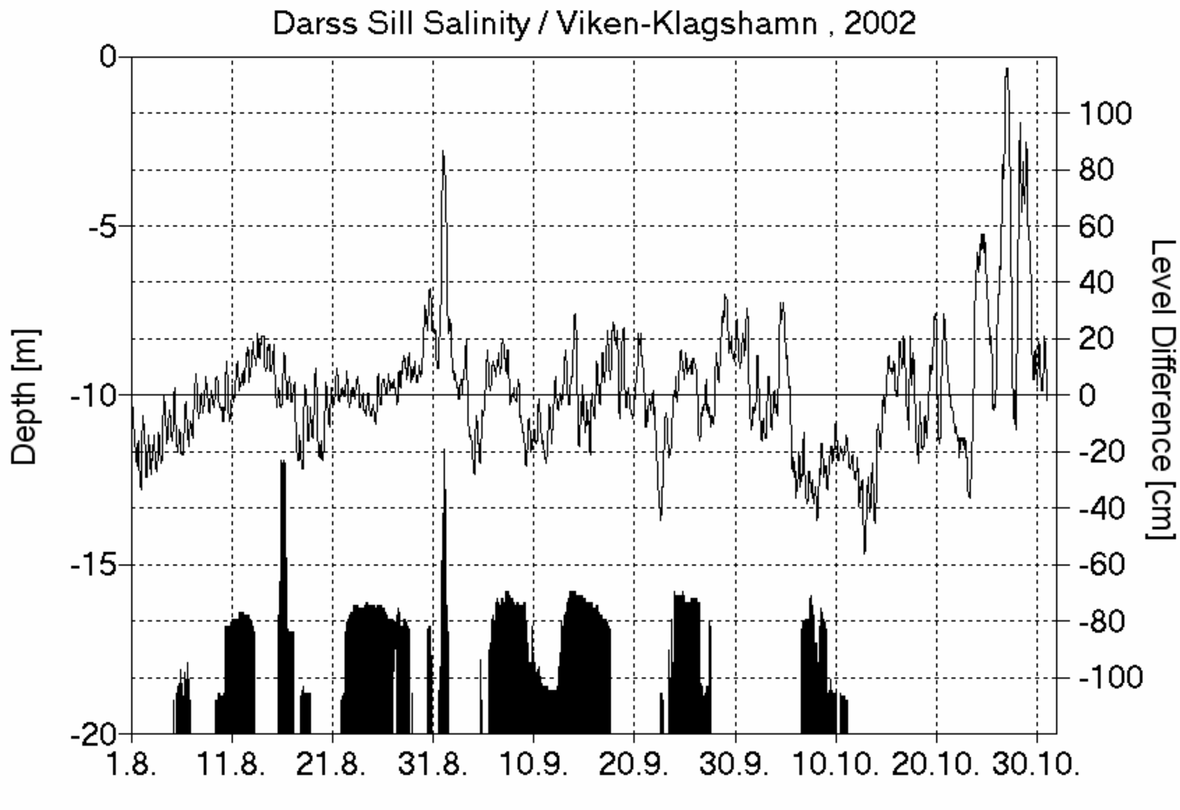

Fig. 4.1.5 Time series of sea level differences Viken – Klagshamn (curve) in comparison to the thickness of the high-salinity bottom layer (bars) with S ≥ 17 PSU at the Darss Sill mast, for the time from 1st August to 3rd November 2002.

For the main period of BB60 inflow in August/September the Great Belt water at station W26 showed strong salinity stratification, up to 28 PSU near the bottom but only about 8 PSU at the surface (Fig. 4.1.6). Especially striking are the extremely strong salinity fluctuations at about 10 m depths, the upper boundary of the bottom layer, suggesting the hypothesis that tides may periodically pump-in more saline and pump-out less saline water in a baroclinic counterflow through a constriction (STIGEBRANDT 1976, FEISTEL et al. 2003a). Salinity profiles at station Fyn053 (Fig. 4.1.7), central Great Belt about 20 km north of W26 are in much lower temporal resolution but with quality-controlled values. They show a high-salinity 30-PSU layer at 20 m depth during the BB60 inflow, almost coincident with the high-salinity phase at 15 m depth at W26 (Fig. 4.1.6).

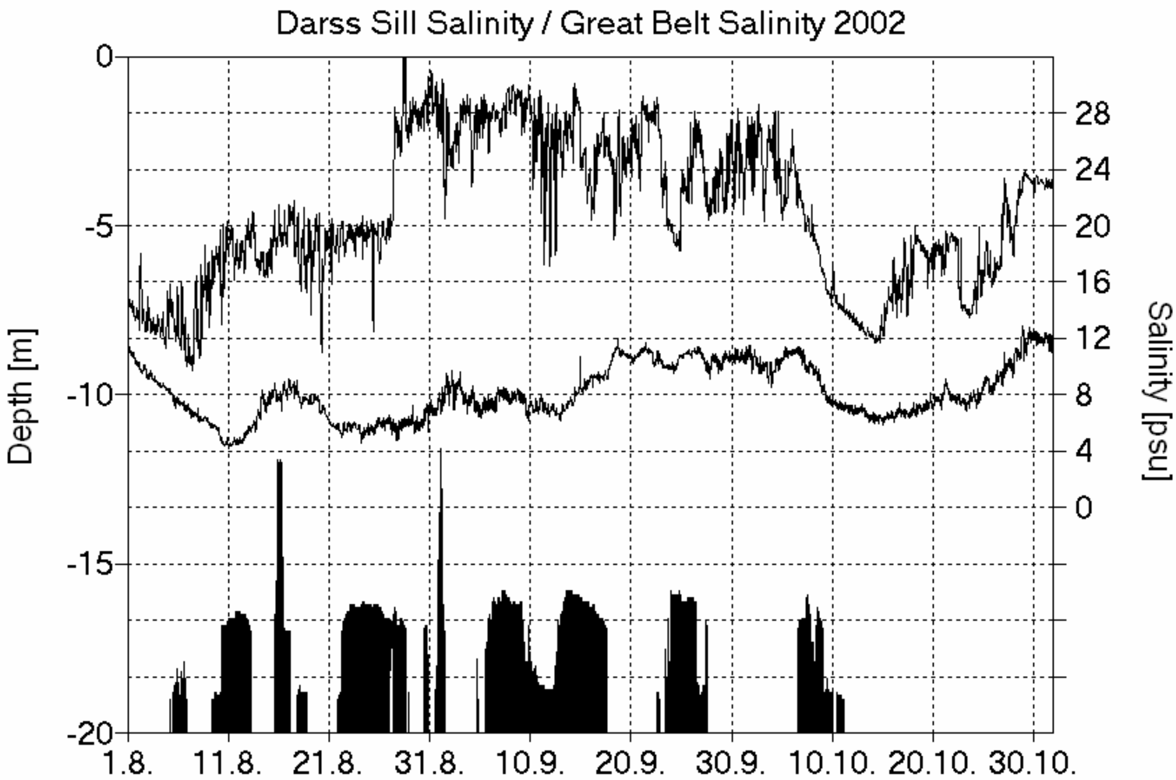

Fig. 4.1.6
Half-hourly time series of salinity (in PSU) recorded at levels 3.3 m (lower curve) and 14.9 m (upper curve) depth at the Danish station W26 in the Great Belt, in comparison with the $S \geq 17$ salinity near-bottom layer (bars) at the Darss Sill mast, for the time from 1st August to 3rd November 2002. Note that the absolute salinity data are raw data here including certain sensor drift.

The unusual situation of summer 2002 was especially obvious by the fact that while the Belt exported water volume from the Baltic to the Kattegat, it imported salt in opposite direction in the net balance, and both in significant amounts. Two hypotheses could serve as explanations to this virtual contradiction:

1) The “baroclinic counter current”: There is a two-layer baroclinic exchange with fresher water outflowing in the top layers and saltier water inflowing simultaneously in the bottom layer (KNUDSEN 1900, discussed in detail in JACOBSEN 1980, see also THIEL 1938, HELA 1944), as it is known from e.g. the Bosphorus (PITMAN and RYAN 1998) and other straits (WELANDER 1974, ASSAF and HECHT 1974). In such a process we expect to see volume and salt export in the top layer, but volume and salt import in the bottom layer at the same time.

2) The “tidal pump”: There is a correlation between salinity and flow direction, inflow is saltier than outflow. This way, alternating currents like tides could pump salt in and water out, similar to STIGEBRANDT’s (1976) model of the Oslo Fjord, without actually finding different flow directions at different depths at the same time. In such a process we expect to see net volume export in conjunction with net salt import in the same layer, for at least one depth ‘slice’ of the whole water column.

It is likely that a certain combination of both hypotheses is responsible for the summer 2002 inflow. We are going to inspect measured data of the W26 station in the Great Belt (cf. Fig. 1.1) in more detail now to shed some light on the problem.

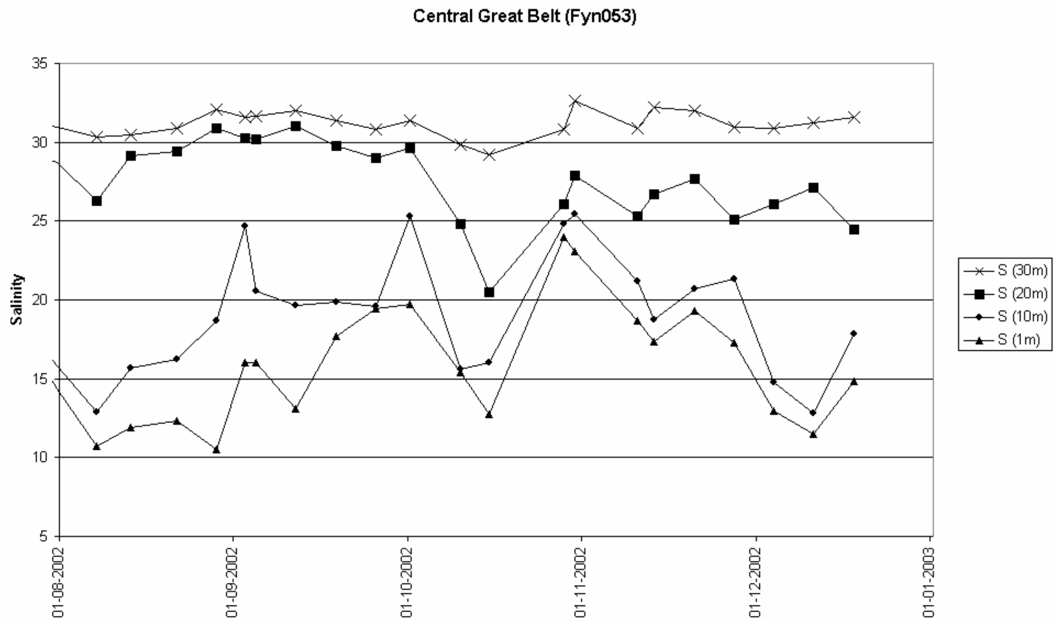

Fig. 4.1.7
10-daily time series of salinity (in PSU) at levels 1 m, 10 m, 20 m and 30 m depth from vertical profiling at the Danish station Fyn053 (F) in the Great Belt for the time from August to December 2002. Note the high salinity about 30 PSU at 20 m depths in the BB60 inflow period beginning in August and ending in October 2002

Fig 4.1.8a shows the volume transport, i.e. the time integral over the meridional current component, for different depth levels between 0 and 14.57 m as indicated at the curves. The general tendency is outflow, especially at the intermediate layers between 6 and 12 m depth. The bottom layer shows some outflow for August, and inflow in September which is compensated again in the first half of October. The alternating inflow and outflow periods can be identified over all layers, i.e. the vertical current profile is mostly barotropic-like. That argues against the baroclinic hypothesis 1).

Fig 4.1.8b shows the salt transport, i.e. the time integral over the meridional current component weighted with the momentary parcel salinity. Again, as with the volume transport, the main direction is salt export. The small salt import in the bottom layer in September is compensated by export until mid October. This is in favour of hypothesis 2) but only weakly.

On the other hand, especially in the September net balance, we see the upper layers exporting volume and salt, but the lower ones importing volume and salt, thus supporting thesis 1), but only weakly as well. In fact, the small salt transport derived this way from W26 data seems to contradict the massive salt import in summer 2002 as observed at various opportunities in the Baltic Proper. Our conclusion is that the W26 station record is probably insufficiently representative for the total Belt exchange in that period. W26 is located on the eastern bank of the Belt, and the main salt signal may have gone along the western flank, or in a deeper central furrow of the Belt, as suggested already by Fig. 4.1.7.

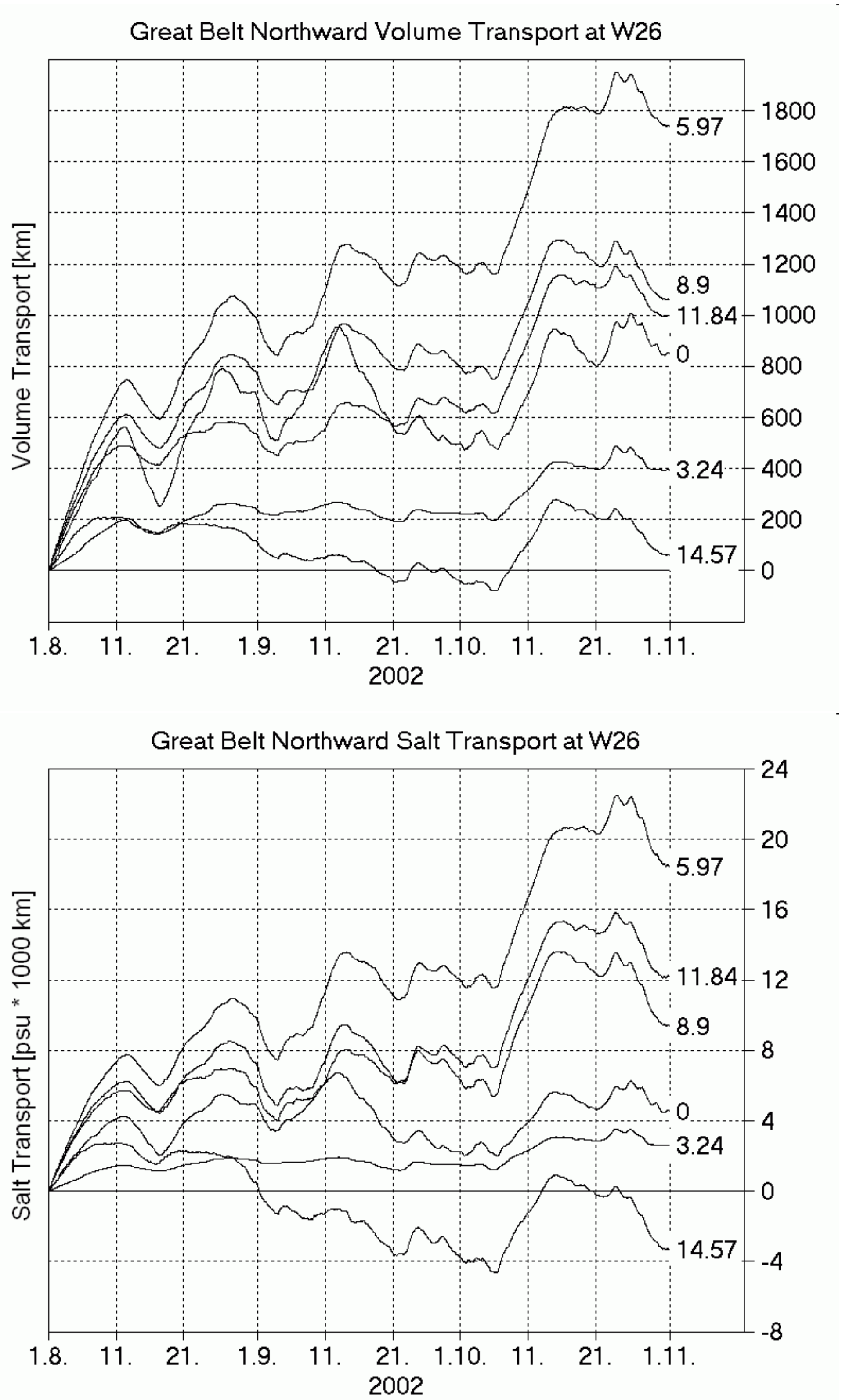

Fig. 4.1.8
Great Belt time-integrated volume (upper panel) and salt (lower panel) transport at W26 lighthouse position, relative to 1st August 2002. 6 depth levels are indicated at the curves (raw data)

4.2 Darss Sill Area

Between the end of June and mid September 2002, moderate winds with an easterly component prevailed over the western Baltic Sea (cf. chapter 3). For a period of about eight weeks, the IOW mast at the Darss Sill station (DS in Fig. 1.1) recorded bottom salinities of up to 20 PSU and temperatures up to 20°C (cf. NAUSCH et al. 2003), while the 14 PSU isohaline almost permanently enclosed a dense near-bottom layer with a mean thickness of about 5 m. The Baltic Sea filling factor as indicated by the Landsort sea level gauge (Fig. 4.1.3) was almost constantly below average from the end of July to the end of October, and showed only insignificant fluctuations, but no sudden rise in level as it is typical of 'usual' inflow events. Despite almost continuous surface outflow, substantial amounts of Kattegat waters were persistently flowing over a period of eight weeks along the sea floor in the opposite direction and accumulating in the adjacent deeper basins. As opposed to other warm, late-summer or autumnal inflows poor in oxygen, like those observed in September 1997 (MATTHÄUS et al. 1999, HAGEN and FEISTEL 2001) or in October 2001 (FEISTEL et al. 2003c), this particular current was characterised by strong stratification, the absence of wind mixing, and the separation of the dense water from the atmosphere already in the Belt Sea.

The Darss Sill salinity and current profiles (Fig. 4.2.1) of the late summer 2002 show a salty bottom layer of about 5 m thickness, with bottom salinities exceeding 17 PSU, almost continuously present over the entire period between 5th August and 11th October. The temperature of this layer was about 13°C on 5th August, rose to 15°C on 12th August after a gradual increase, reached a maximum of 18°C on 19th September and dropped back below 15°C on 11th October 2002, together with the salinity (cf. Fig. 4.2.2). Although most of the time the water column was strongly stratified, the alternating inflow/outflow phases recorded by the current profiler revealed an almost barotropic motion (Fig. 4.2.1). Thus, the during inflow phases, the whole water column including the low-salinity top layer was moving in a northeasterly direction. During the outflow intervals, the halocline appeared at greater depths. Only short periods at the turning points from outflow to inflow could be called baroclinic ones, with the surface layer flowing outwards over the bottom layer flowing into the Baltic Sea. However, in such calm situations the salt and current distribution over the Darss Sill cross section cannot be supposed to be strictly horizontally stratified, as revealed by dedicated investigations of the Water Exchange across the Darss Sill (WEDS) project in 1980 (Fig. 4.2.3). Thus, the local vertical profile of Darss Sill mast is not necessarily representative for the entire transect. The IOW numerical model shows the inhomogeneous salinity and current conditions at the Darss Sill for the 'typical day' 24th August 2002 (Fig. 4.2.4). Easterly wind prevailed until 14th September, when a cold front arrived and the wind direction turned to west and north (Fig. 4.2.2)

In general, similar conditions are frequently observed in the Darss Sill area. In the absence of wind stress, baroclinic pressure gradients force highly saline waters to enter the Baltic Sea from the Kattegat through the Great Belt against the net outflow. Coriolis force keeps the dense, salty current along the southern flank on its way from the Great Belt to the Darss Sill. On the northern side, off the island of Møn, less dense brackish waters are flowing in the opposite direction when crossing the Darss Sill. Fig. 4.2.3 shows such situation at the Darss Sill in August 1980. Very calm anticyclonic atmospheric conditions caused a typical outflow situation at the surface and a very strong halocline was formed near the bottom (B). Salinity gradients >12 PSU/m were measured in the central part of the Darss Sill. Below the halocline, highly saline water (22 – 24 PSU) flowed along the southern slope into the Arkona Basin (A).

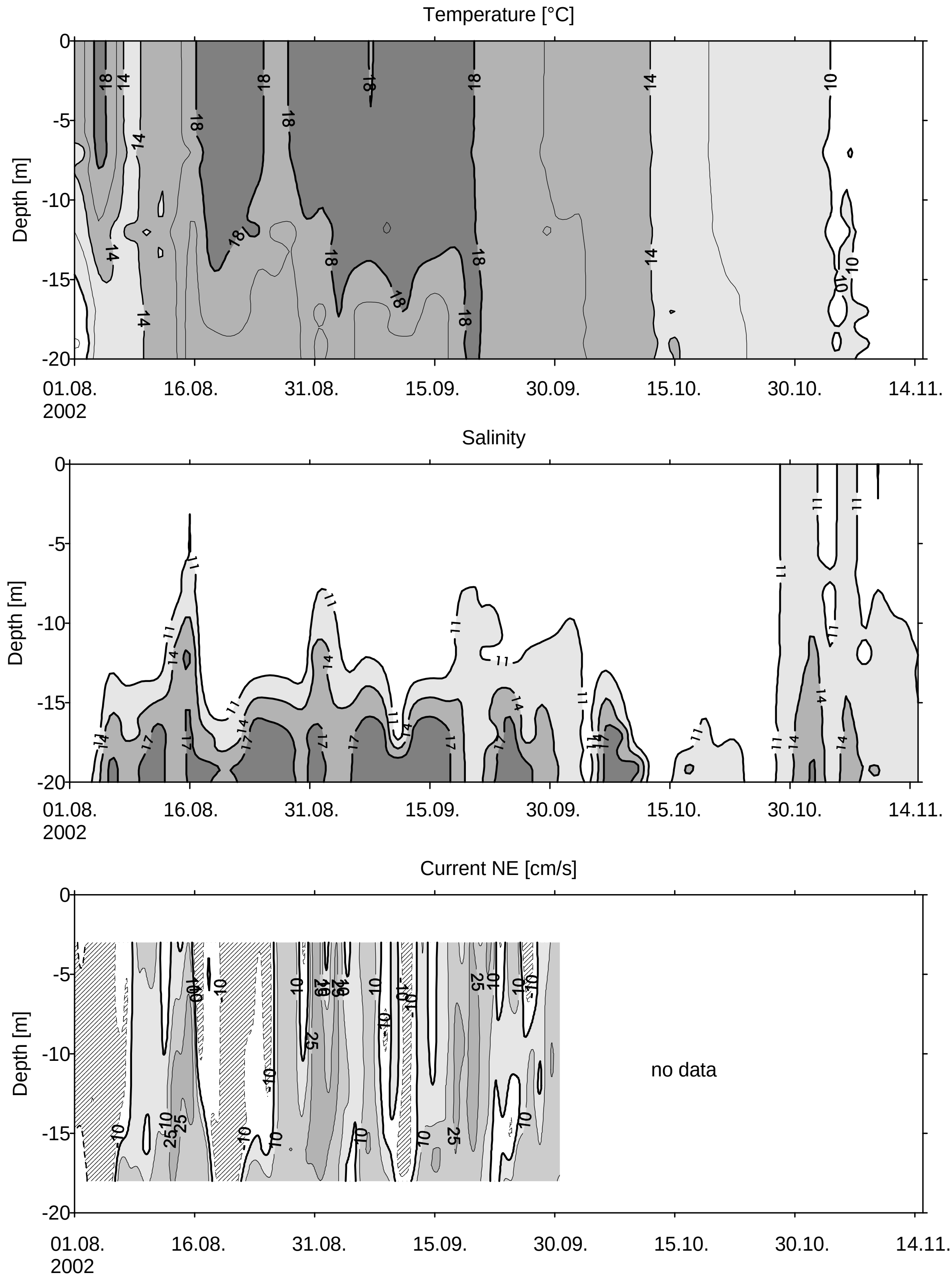

Fig. 4.2.1
Darss Sill mast temperature (top), salinity (middle) and NE current component (bottom) profiles from 1st August 2002 to 15th November 2002. Hatched current fields represent outflow.

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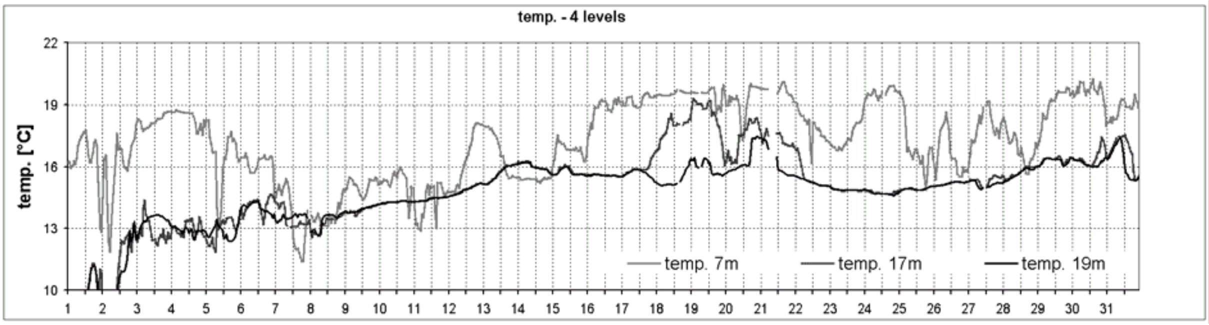

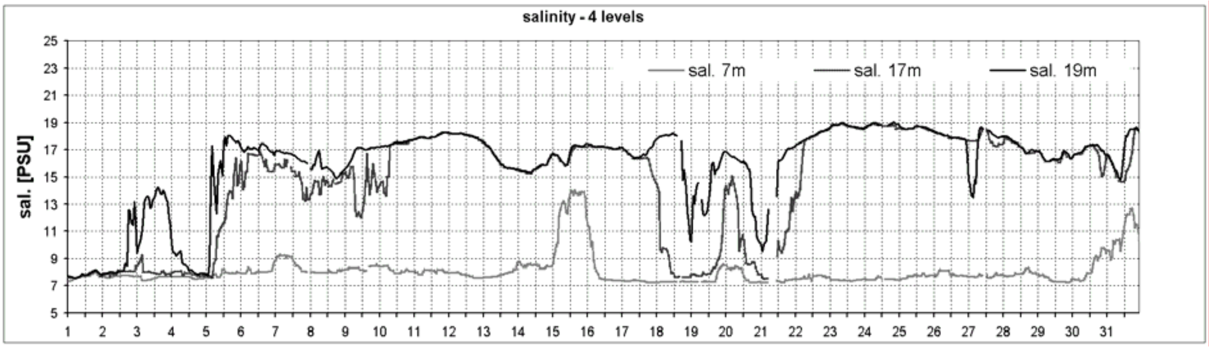

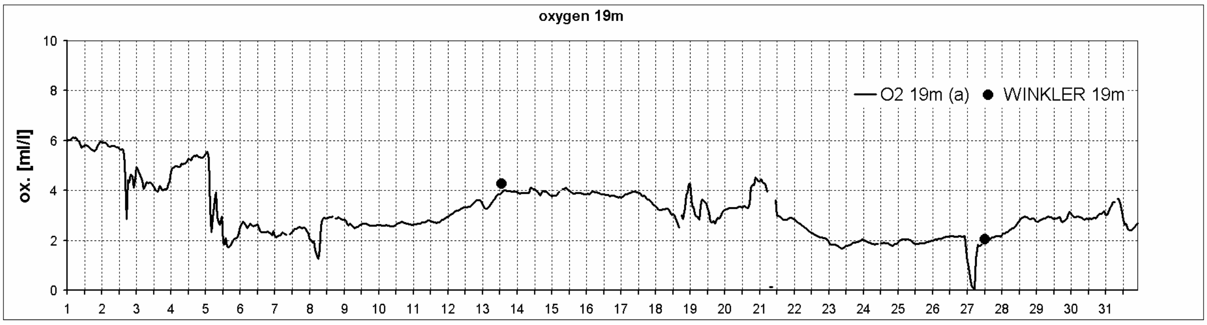

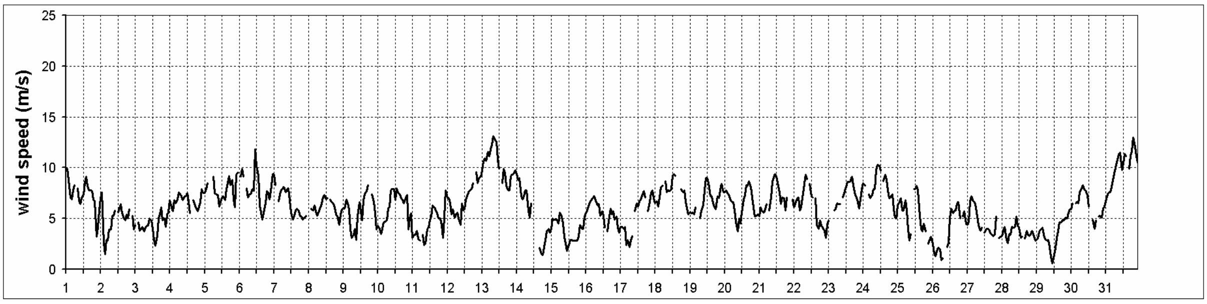

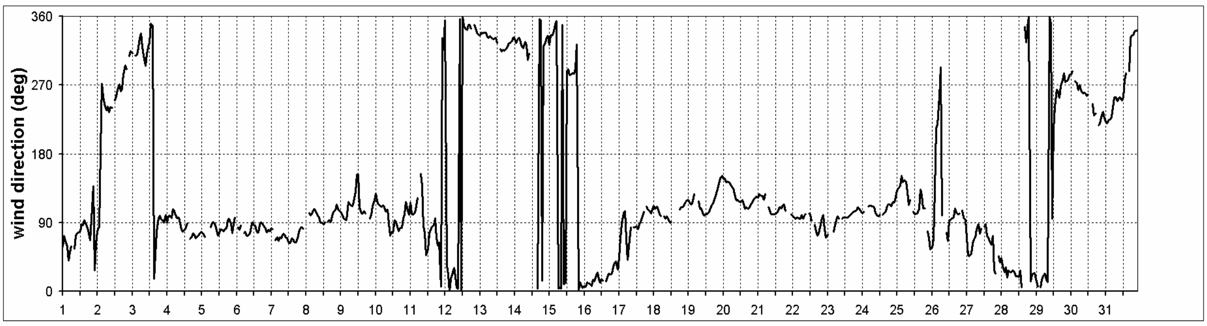

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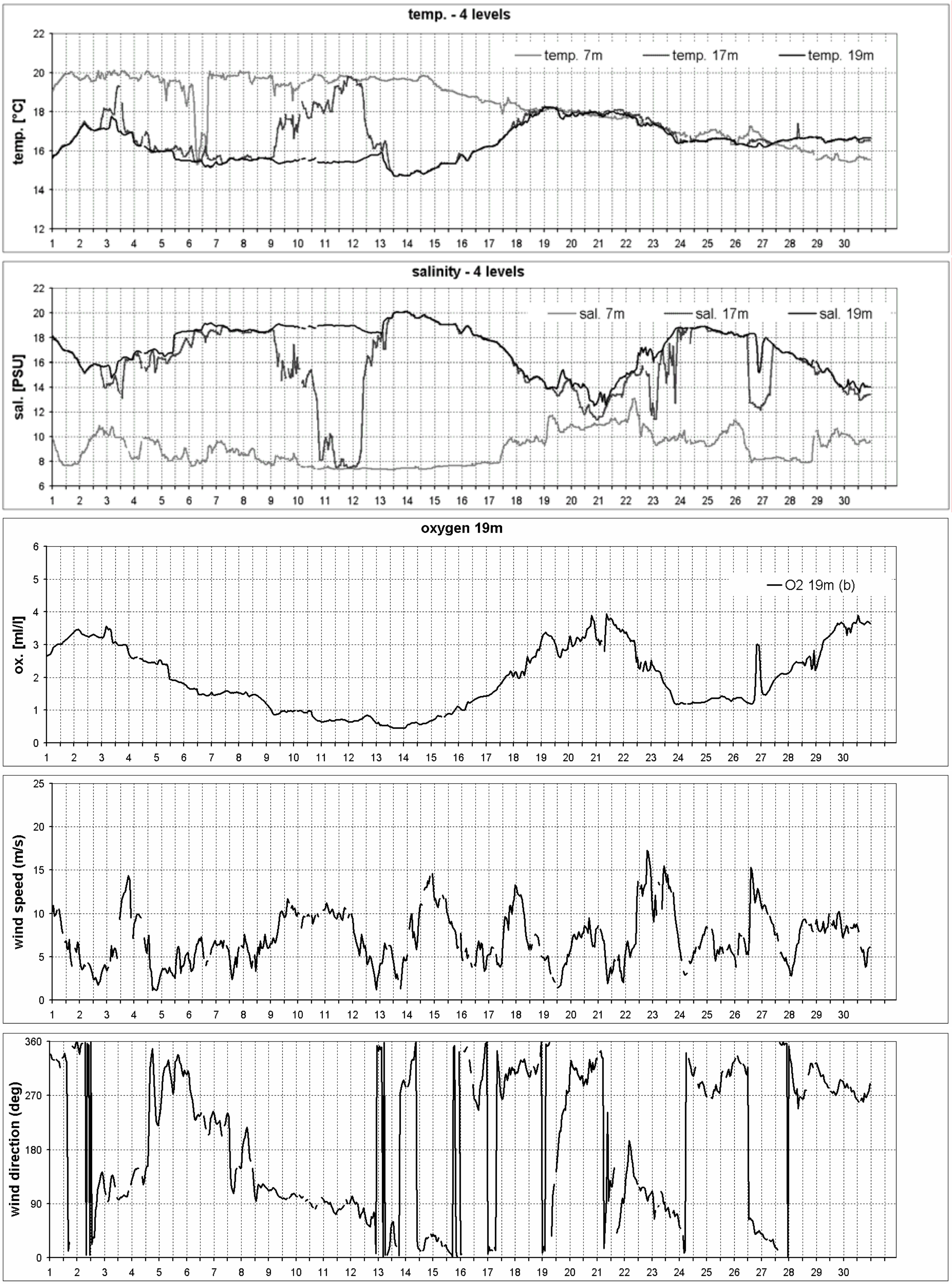

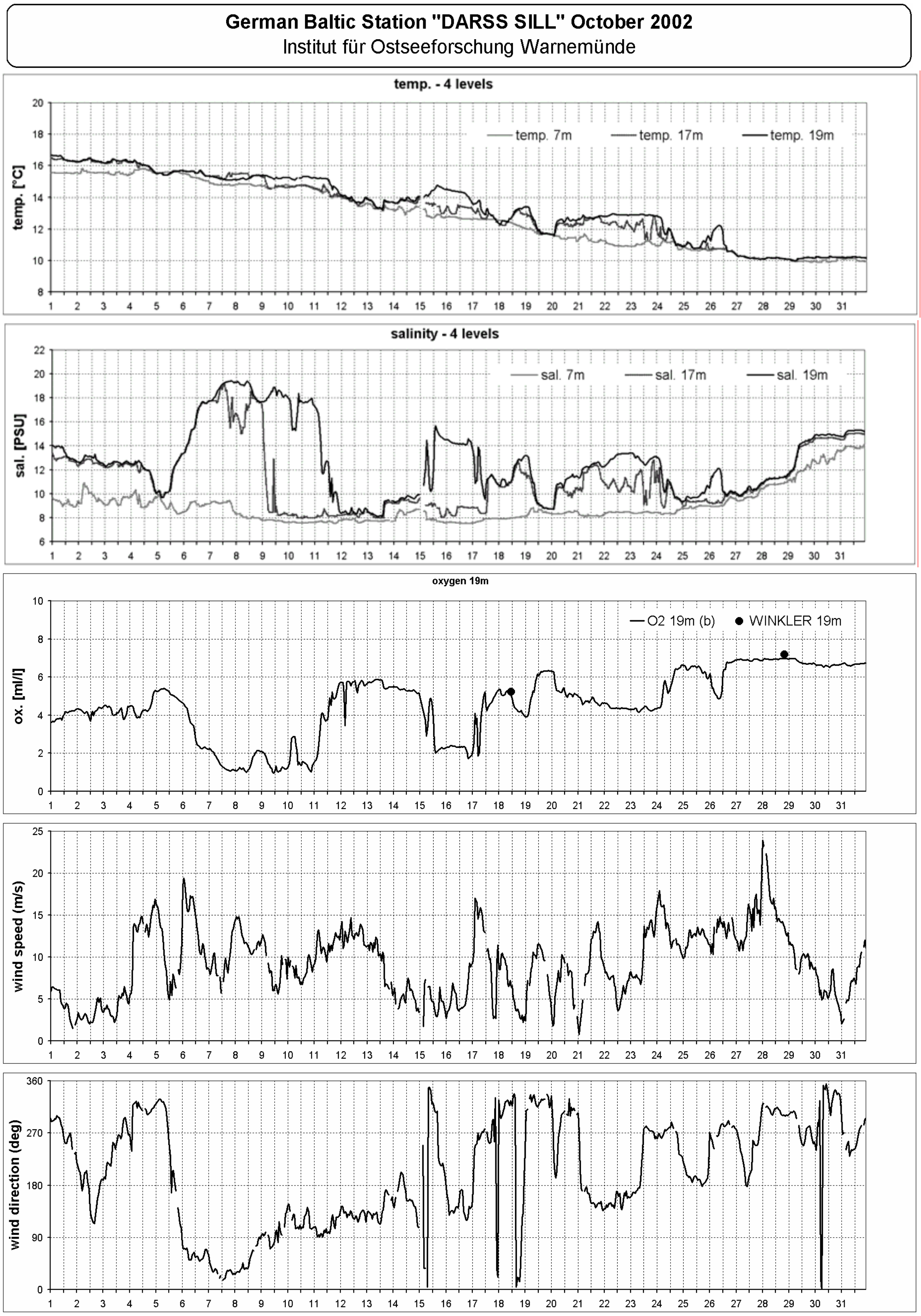

Fig. 4.2.2
Time series of temperature, salinity, oxygen concentration, wind speed and wind direction recorded at the Darss Sill mast for a) August, b) September, c) October 2002. The 12 m level is omitted for clarity. Temperature, salinity and oxygen concentration are quality controlled data with accuracies of ± 0.01°C, ± 0.01 PSU and ± 0.25 ml/l. The lowest temperature and highest salinity curves belong to the near-bottom level.

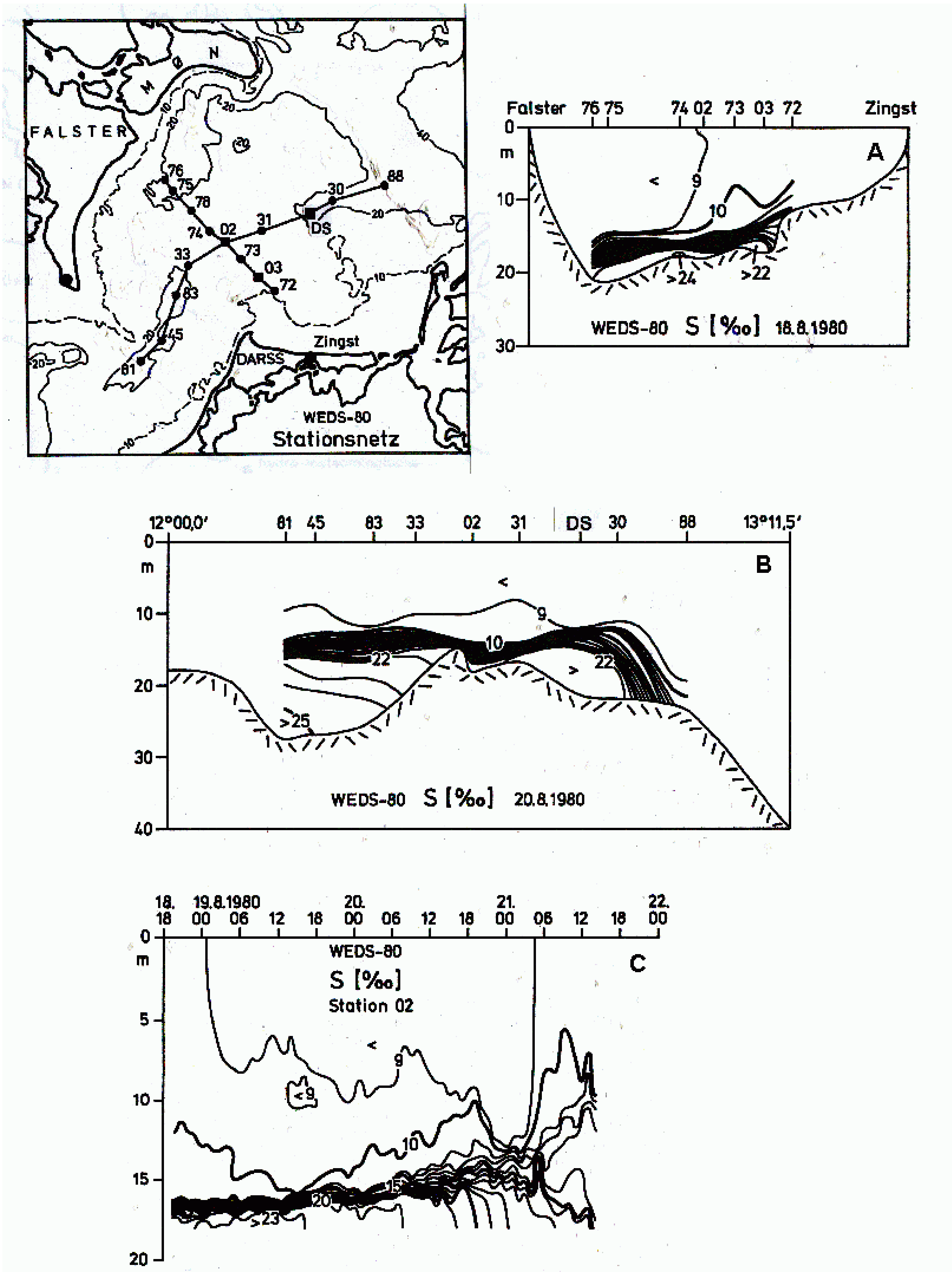

Fig. 4.2.3
Summer situation of near-bottom inflow in August 1980 demonstrated by the salinity distribution in NW–SE (A) and SW–NE direction (B) across the Darss Sill and the temporal development (C) (after MATTHÄUS et al., 1982).

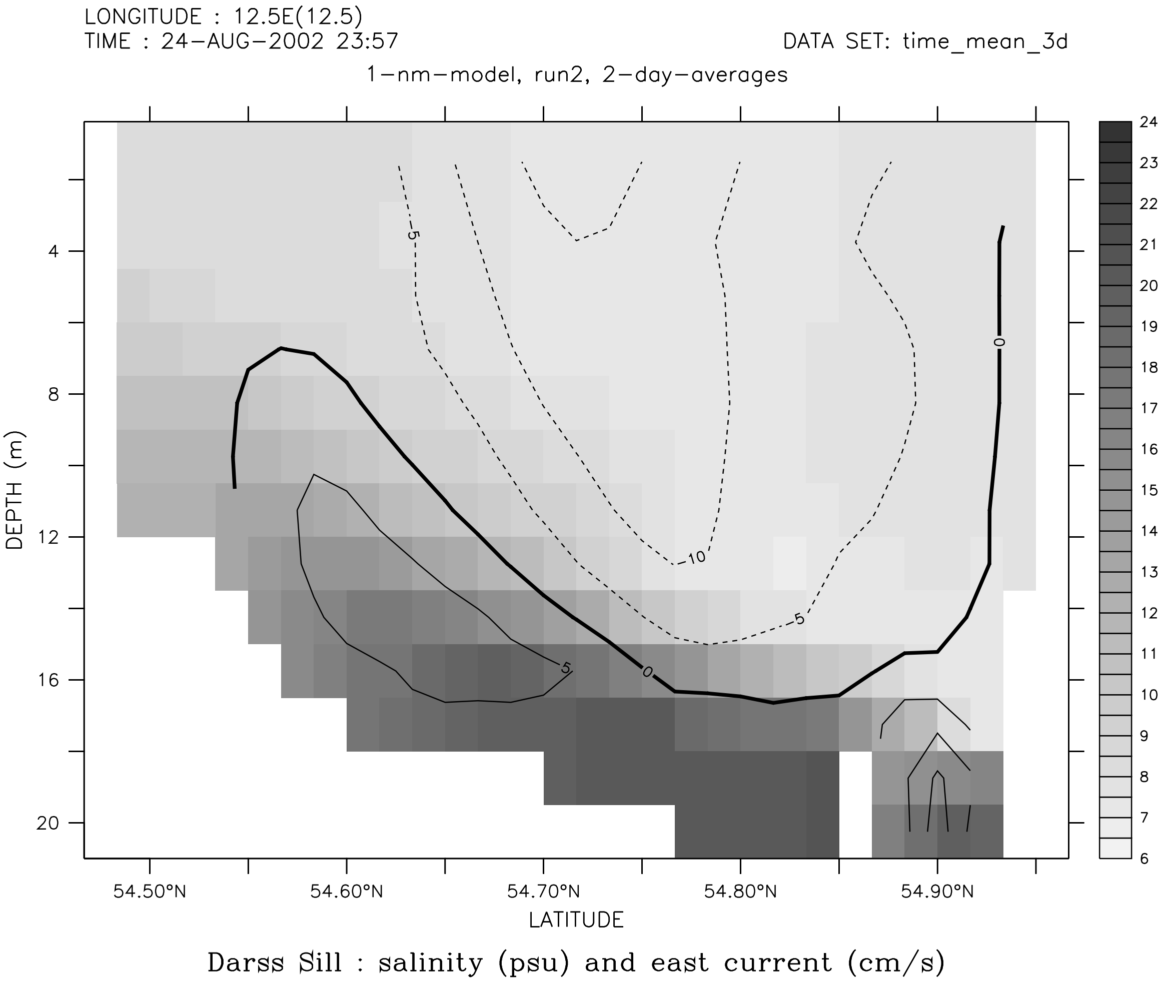

Fig. 4.2.4
Model simulation of salinity (grey scales, PSU) and eastward current (isolines, cm/s) across the Darss Sill for the ‘typical day’ 24th August 2002 (meridional section along 12°30' eastern longitude). Dotted lines enclose the outflow jet, solid ones the inflow jet. The IOW model has a local resolution of approx. 2 km and shows a typical inflow pattern along the southern slope.
For comparison, the Darss Sill mast (DS) is located at 54.70°N, but slightly farther east at 12°42’E.

Long lasting inflows like that in late summer 2002 carrying greater volumes of exceptionally warm waters into the central Baltic deep water are, however, very rare events. The inflow of BB60 water occurred in four periods interrupted only by short outflow periods. We identified the inflow periods by means of the salinity records at the 19 m level of the Darss Sill mast station. Inflow starts when the salinity exceeds 14 PSU for more than two days. The periods and the T-S-O_2 characteristics of the inflow water are shown in Table 4.2.1.

With the development of strong thermohaline stratification in the western Baltic Sea in June, oxygen concentrations in the near bottom waters of the Belt Sea began to decrease in general due to processes of mineralization of sedimenting organic matter. The long period of sunny, warm, and calm weather conditions in late summer of 2002 caused the oxygen situation in the near bottom waters to deteriorate rapidly. Oxygen levels fell to the limit of detection and there was even production of hydrogen sulphide.

Oxygen concentration in the near-bottom water at the Darss Sill (Fig. 4.2.2) fell to 2 ml/l on 5th August and continued to fluctuate between 1 and 4 ml/l for the entire period. These values correspond well to the pronounced oxygen deficiency observed simultaneously over wide areas of the Belt Sea (HELCOM 2003).

Table. 4.2.1
Periods of warm water inflow (BB60 water) across the Darss Sill and their mean *T-S-O_2* characteristics

Period 2002	**Mean temperature °C**	**Mean salinity PSU**	**Mean oxygen ml/l**
5 – 18 Aug.	14.68	16.92	3.04
21 Aug. – 20 Sep.	15.86	17.66	1.95
21 – 29 Sep.	16.74	17.09	2.08
6 – 11 Oct.	15.28	17.83	1.79

In late October 2002, a regular warm water inflow occurred, called BB90 event, which frequently can be observed in autumn (MATTHÄUS 1997). That part of the BB90 water which crossed the Darss Sill between 23rd October and 1st November had temperatures of 13 – 10 °C, salinities between 10 and 15 PSU and oxygen concentrations of 4 – 7 ml/l (cf. Fig. 4.2.2).

4.3 Arkona Basin

The new buoy - IOW/BSH MARNET Arkona Basin (AB in Fig. 1.1) - was first anchored at its working position in summer 2002 and began operating at the end of September, thus only in the wake of the main BB60 inflow phase. In Fig. 4.3.1, the time series from this semi-diver is supplemented by several CTD casts at neighbouring positions. The typical thermal summer stratification became significantly weakened in August and disappeared completely in October. In September, near bottom waters were warmer than 17°C. Salinities above the sea floor exceeded 17 PSU in August and September, accompanied by oxygen levels below 2 ml/l, marking the very warm summer inflow. The following small inflow of BB90 water in November is clearly visible by steeply rising isohalines, oxygen content higher than 5 ml/l and temperatures about 10°C. In January 2003, the strong, cold inflow is approaching with significant salinity increase.

Note that the continuously low oxygen concentrations in the near bottom layer start increasing rapidly in the first half of October (Fig. 4.3.1) and significantly exceed 4 ml/l at the end of October (Fig. 4.3.2). This change could already be seen at the Darss Sill mast (Fig. 4.2.2) but seems more pronounced in the Arkona Basin. As possible cause we can imagine a stronger mixing at the entrance to the Arkona Basin during the rapid downslope motion of the inflow water with surface water which is more oxygenated in autumn than it was in summer, see also Fig. 4.4.3 for a more detailed consideration. Probably, this process has contributed to the high oxygen content required to ventilate the entire Gdańsk Basin by November 2002 (see section 4.5).

The detailed time series at 7 m and 40 m depth of temperature and salinity, as well as oxygen concentrations at 40 m depth as recorded at the AB buoy is displayed in Fig. 4.3.2. In October, at the deepest level on record, the BB60 temperature is steadily decreasing from 17 to 12 °C, salinity from 18 to 10 PSU, and oxygen is rising from almost 0 to 6 ml/l. The BB90 inflow in November is evident with salinities up to 22 PSU and temperatures exceeding 10 °C, but oxygen data were not recorded.

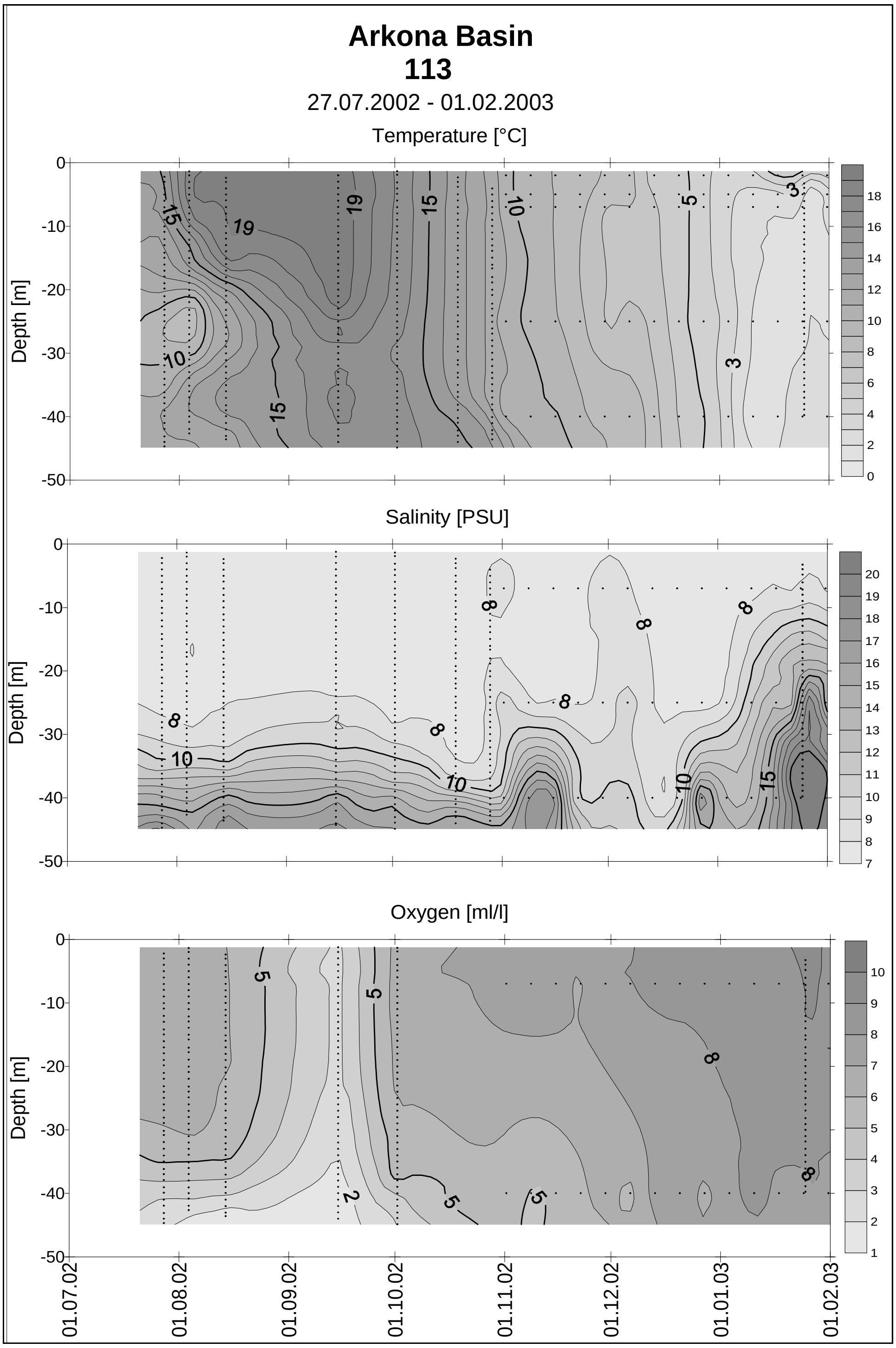

Fig. 4.3.1
Time series of temperature (top), salinity (middle) and oxygen concentration (bottom) between July 2002 and January 2003 in the central Arkona Basin (combined data from the Arkona Basin buoy, station 113 and adjacent positions)

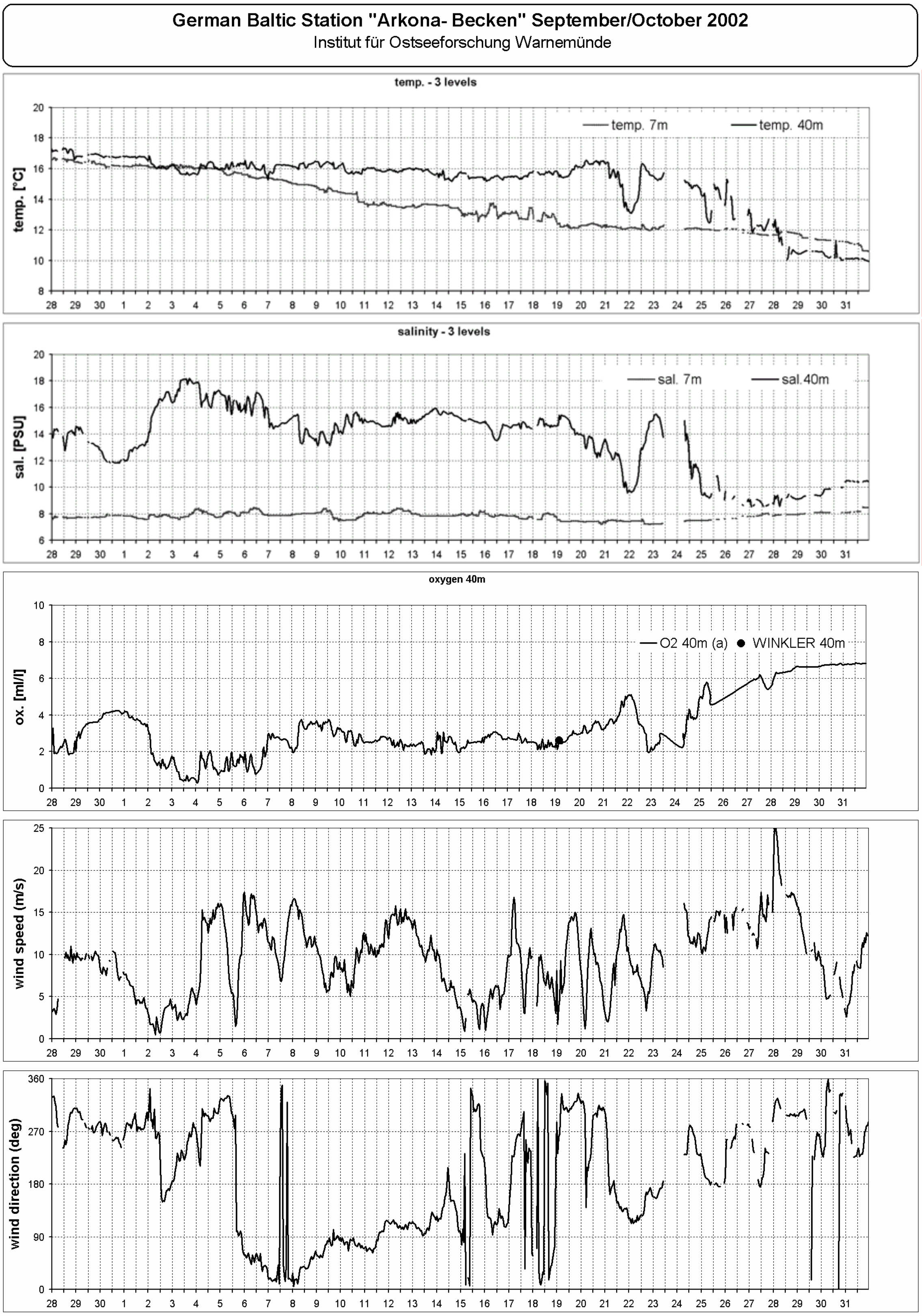

Fig. 4.3.2
Time series of temperature, salinity, oxygen concentration, wind speed and direction at the Arkona Basin buoy from the beginning of recording to the end of October 2002. The 25 m level is omitted for clarity. Temperature, salinity and oxygen concentration are quality controlled data with respective accuracies of ± 0.01°C, ± 0.01 PSU and ± 0.25 ml/l.

4.4 Bornholm Basin

The description of the inflow and spreading of BB60 and BB90 waters in the Bornholm Basin is based on observations obtained by the monthly GLOBEC cruises and on additional CTD casts from the HELCOM Monitoring Programme (COMBINE). During the GLOBEC cruises a regular grid of CTD stations was worked inside the 40 m isobath with a mean station-to-station distance of about 8 nautical miles. The COMBINE programme supplied the data for some stations in the central Bornholm Basin. From these data sets, time series and spatial distributions of temperature, salinity and oxygen concentration were compiled.

A small initial patch of inflowing saline water with temperatures above 10°C appeared in the halocline layer at the central Bornholm Basin around mid August 2002, whereas the main inflow of BB60 waters took place from the end of August onwards (Fig. 4.4.1). During the initial phase of the BB60 inflow, the waters spread along the western and southern rim of the Bornholm Basin in form of several mesoscale plumes in the halocline. The maximum temperature of 13.79°C in the halocline was observed on 5th October 2002 (Table 1 in FEISTEL et al. 2003a). At this time the layer affected by the BB60 waters reached its maximum thickness. It covered the entire halocline from 45 m down to 80 m depth. Due to the large volume of inflowing BB60 water the thickness of the halocline in the Bornholm Basin increased and the vertical salinity gradient was smoothed. The 11 PSU isohaline (center of the halocline layer) was lifted upwards from 63 m depth at the beginning of September to 48 m at the end of October 2002. However, the BB60 waters' contribution to the ventilation of the Bornholm Basin halocline seems to be negligible.

Between 27th October and 18th November the tip of the BB90 water entered the Bornholm Basin (cf. Fig. 4.4.1). Due to its high salinity the inflowing BB90 water partly replaced the old bottom water body. The inflow lifted up the BB60 water by about 10 m, so that further parts of the BB60 waters could leave the Bornholm Basin and spread eastward into the Stolpe Channel. High oxygen content of the BB90 water significantly increased the bottom layer oxygen concentration in the central Bornholm Basin (Fig. 4.4.1, lower panel).

The thermohaline stratification in the Bornholm Basin and in adjacent areas in mid November 2002 is depicted in Fig. 4.4.2. The warm waters of the BB60 inflow (indicated by A) were more or less uniformly distributed in the halocline of the Bornholm Basin. Parts of the BB60 waters had left the Bornholm Basin into the Stolpe Channel where they covered the water column from the bottom up to 55 m depth. First parts of BB90 waters (indicated by B; cf. Fig. 4.4.2, upper panel) had reached the central Bornholm Basin, but the BB90 inflow was not finished at this time. Large amounts of BB90 water were still covering the bottom layer of the Arkona Basin. Unfortunately, there is a larger gap in the Bornholm Basin data between 18th November 2002 and 18th Januar 2003, so that the later development of the BB90 inflow into the Bornholm Basin cannot be descibed here.

Based on changes in *T-S* properties of the inflowing water masses, some important mixing processes between the BB60 waters and the ambient water between the Darss Sill and the Bornholm Basin could be identified (Fig. 4.4.3). On its pathway through the Arkona Basin the inflowing BB60 waters (A) were mixed with the Arkona Basin surface water (O). This caused a rapidly decreasing salinity of the inflowing warm water and slightly increasing oxygen content from 1.5 to about 3 ml/l when BB60 water was passing the Bornholmsgat (B). The inflow into the Bornholm Basin seems to have occurred as a pulse-like flow, which formed mesoscale plumes of BB60 water in the halocline of the western Bornholm Basin. During the spreading through the Bornholm Basin a significant entrainment of the overlaying intermediate winter water (D) and of

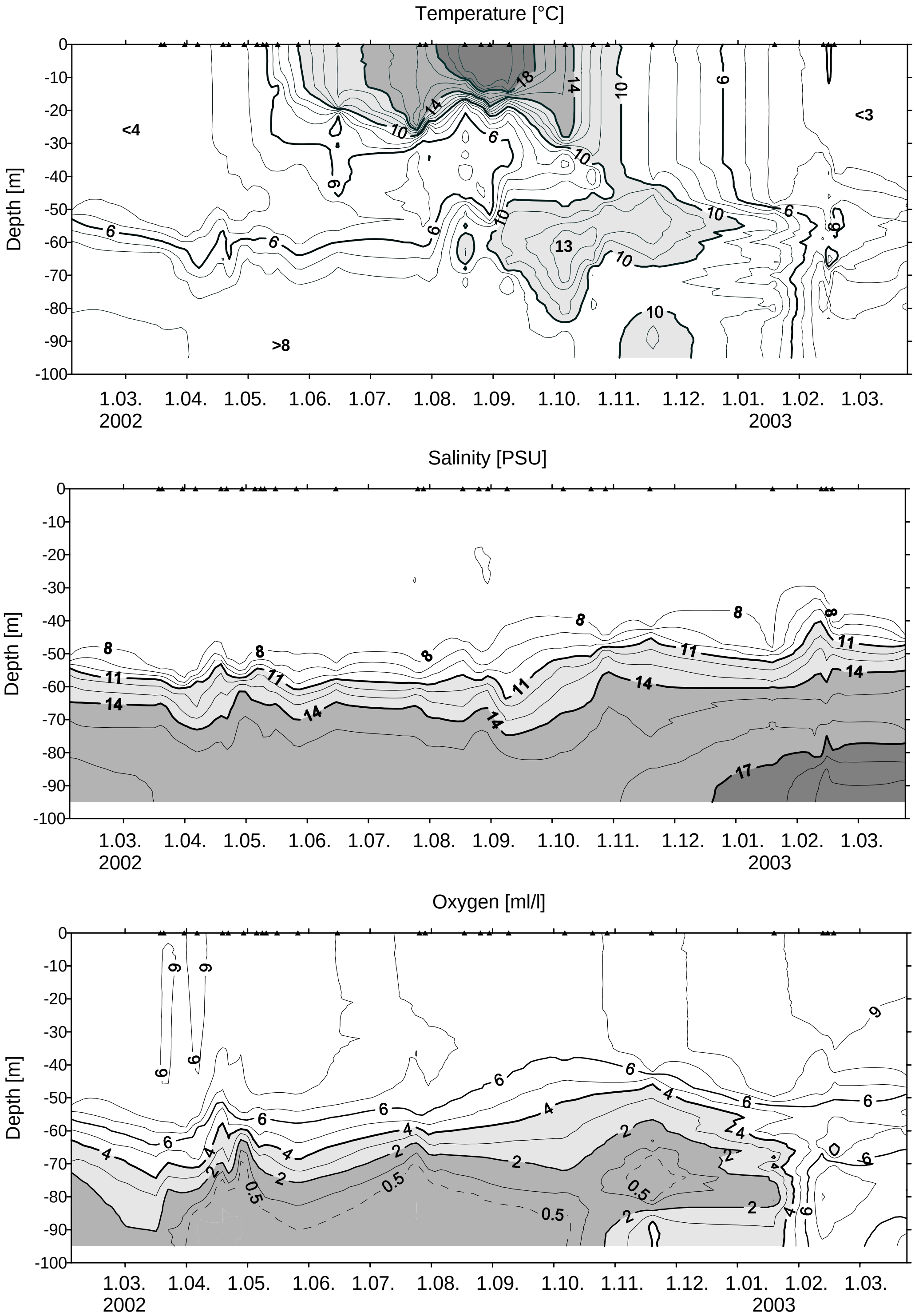

Fig. 4.4.1:
Time series of temperature (top), salinity (middle) and oxygen concentration (bottom) in the central Bornholm Basin (station 212, see Fig. 1.1) between February 2002 and March 2003.

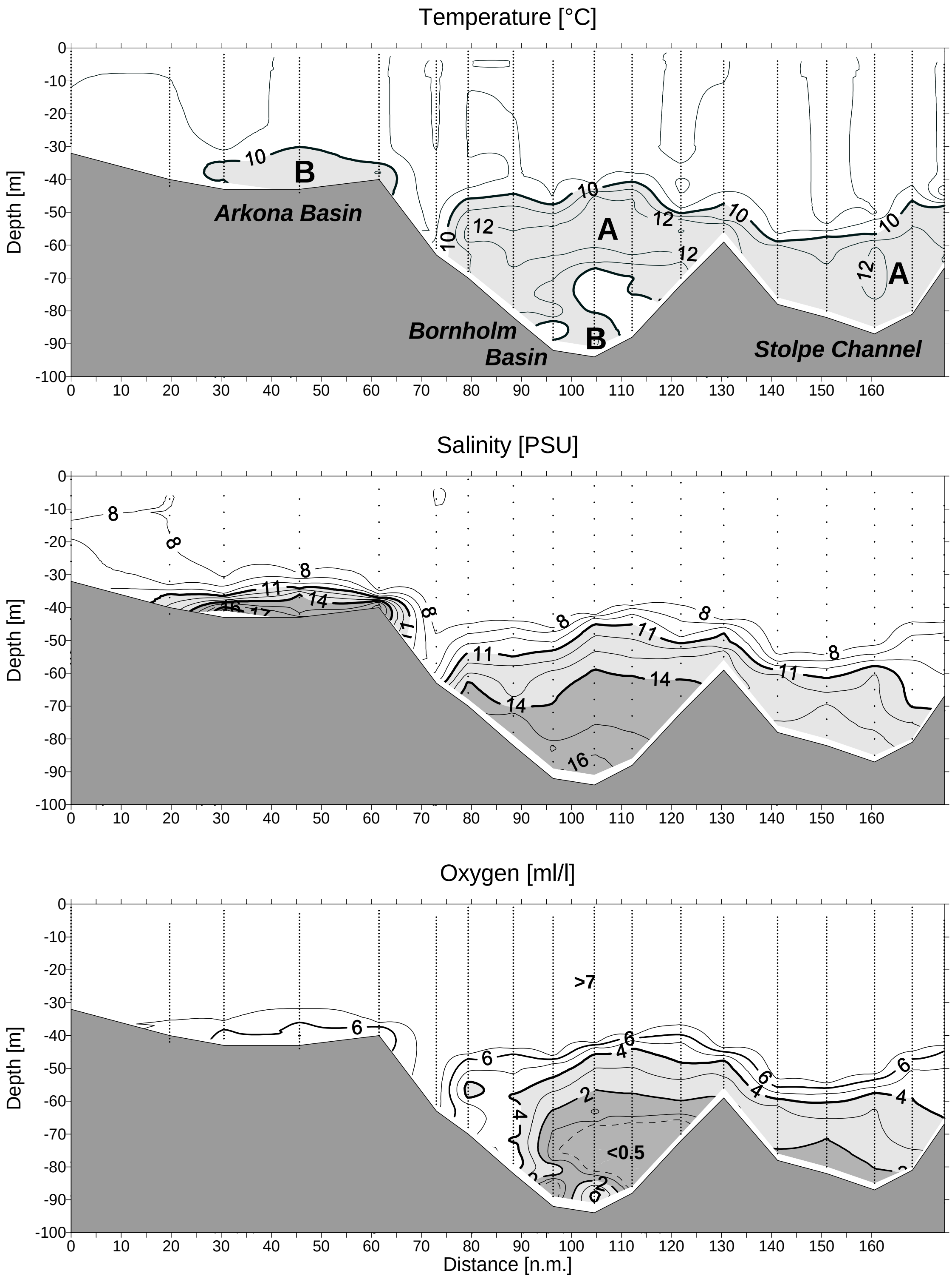

Fig. 4.4.2
Vertical distribution of temperature (top), salinity (middle) and oxygen concentration (bottom) in November 2002 at a transect from the western rim of the Arkona Basin (left) into the Stolpe Channel. In the temperature panel (top) the BB60 and BB90 waters are indicated by capital "A" and "B", respectively.

the old bottom water (F) into the BB60 water body was observed. Its temperature decreased from 15 to 12.5°C whereas the salinity and the oxygen content remained nearly unchanged (C).

Between November 2002 and January 2003 the mixing occurred mainly between the warm halocline water (C) and the bottom water (F). The temporal development of the composition of BB60 waters on their spreading through the Bornholm Basin is given in Table 4.4.1.

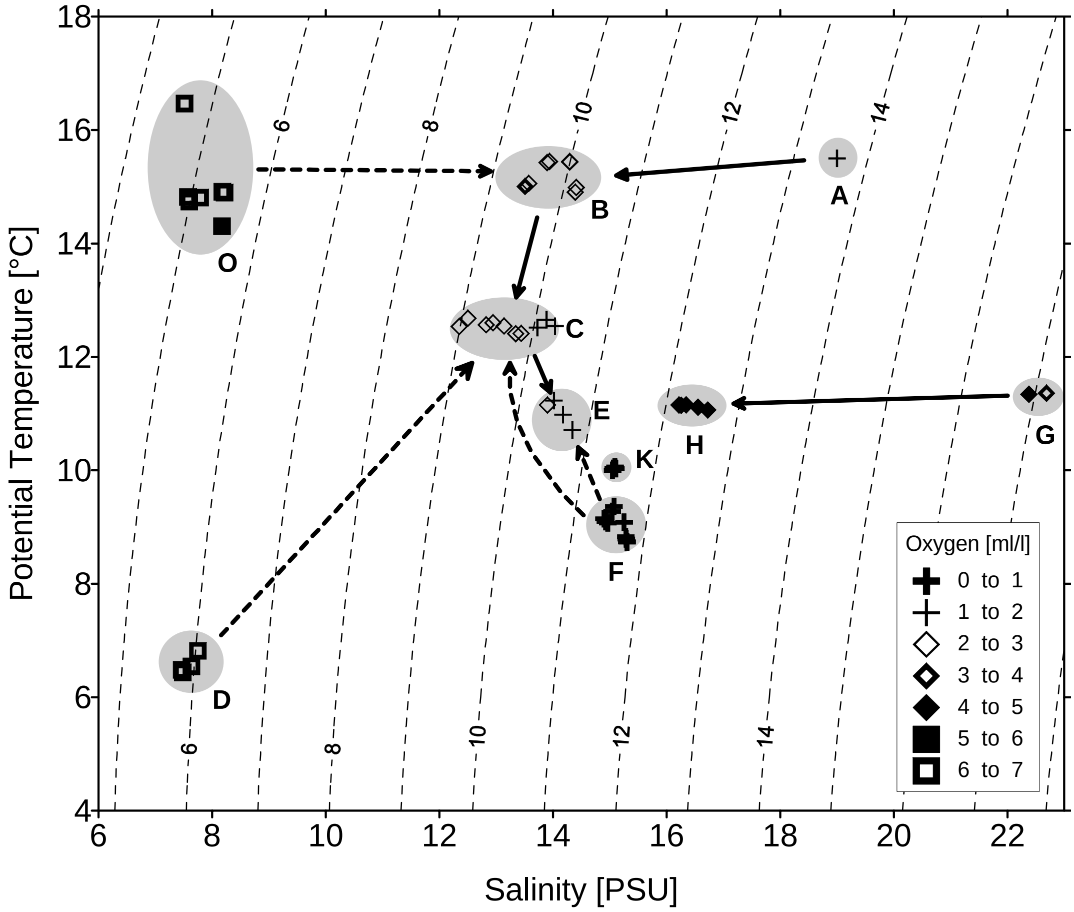

Fig. 4.4.3
T-S properties of selected water masses between the Darss Sill and the Bornholm Basin and their corresponding oxygen concentrations. The particular water bodies are marked as follows:

O – Arkona Basin surface water (August 2002)
A – inflowing BB60 waters at the Darss Sill
B – BB60 waters just after passing the Bornholmsgat (inflow into the Bornholm Basin)
C – BB60 waters one month after entering the Bornholm Basin (November 2002)
D – Intermediate winter water in the Bornholm Basin (IWW)
E – BB60 waters tree months after entering the Bornholm Basin (January 2003)
F – Old bottom water of the Bornholm Basin (BW, present until December 2002)
G – inflowing BB90 waters at the Darss Sill
H – BB90 waters just after passing the Bornholmsgat (inflow into the Bornholm Basin)
K – Old bottom water of the Bornholm Basin in January 2003

Table 4.4.1

Temporal development of BB60 water composition in the Bornholm Basin due to mixing with ambient water masses. Percentages of source water masses in the warm halocline layer, BB60 – B water overflowing the Bornholmsgat, Intermediate Winter Water (IWW) in the Bornholm Basin and old bottom water (BW) of the Bornholm Basin.

	BB60 (B)	IWW (D)	BW (F)
October 2002 BB60 (B)	100	0	0
November 2002 BB60 (C)	63	14	23
January 2003 BB60 (E)	37	8	55

4.5 Gdańsk Basin

A specific environmental situation was observed in the near bottom waters of the Gdańsk Deep (station 233 = P1 = BMP L1, Fig. 1.1) and in the SE Gotland Basin (station 259 = P140 = BMP K1, Fig. 1.1) in autumn 2002 and winter 2002/2003.

The relatively cold and extremely anoxic water present near the bottom of the Gdańsk Deep at the end of September 2002 was replaced by very warm water, referred to as summer BB60 water, some time before November (cf. Fig 4.5.1). The warm water contained enough oxygen to neutralise all hydrogen sulphide present and to rise the oxygen level to nearly 2 ml/l. The layer of warm water was quite thick and ranged between 80 m and the bottom (107 m). Between 70-60 m there was a layer of colder water (6.64 and 5.53ºC, respectively) and the upper water column was still warm after summer or from the sinking thermocline (ca. 7.5ºC). The effects of this BB60 summer water were strengthened in November and later by the subsequent inflow of BB90 water (note that water masses travel ca. 3 months from Kattegat to the Gdańsk Deep and SE Gotland Basin), resulting in warming up the near bottom water of the Gdańsk Deep up to 9.4°C (Fig. 4.5.1). This exceptionally warm water was still present in the base of the water column in the Gdańsk Deep in February 2003 (9.1°C) until it was finally removed in April 2003 by the major inflow of January 2003. The observed changes were more clearly marked in temperature and oxygen values while salinity revealed not so extensive differences.

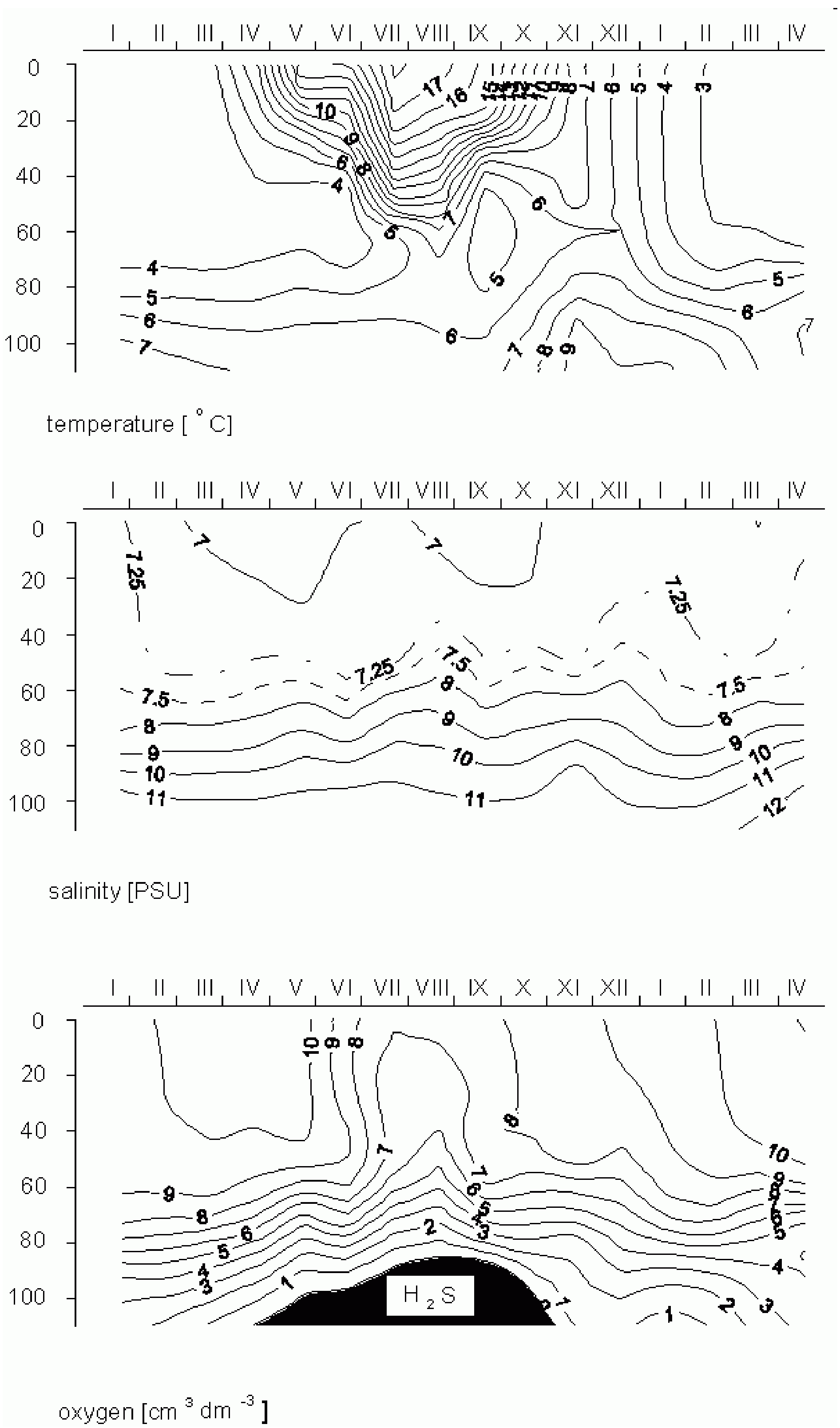

Fig. 4.5.1
Vertical profiles of temperature (top), salinity (middle) and oxygen concentration (bottom) at IMGW station P1 (BMP L1) in the Gdańsk Deep, as obtained from CTD casts between February 2002 and April 2003. Note the rise in near bottom temperature and vanishing of hydrogen sulphide in November 2002 marking the arrival of BB60 water masses with subsequent increment of oxygen concentration and water cooling due to January 2003 inflow.

4.6 Gotland Basin

In the central Gotland Deep, the clearest indicators of inflow waters are the signals of oxygen (or hydrogen sulphide) concentrations and temperature (Fig. 4.6.1). The first splash of the BB60 water inflow, so-called BB60a, appeared below the halocline at the beginning of December 2002 with a maximum between 90 and 100 m depth (Table 4.6.1, Fig. 4.6.2). It lifted the water column, and, apparently in conjunction with the beginning of winter convection from the surface it even destroyed the cold (< 4°C) intermediate layer above the halocline and raised surface salinity above 7 PSU. Until mid January 2003, the very warm BB60 waters occurred in the Gotland Basin at levels between 100 and 120 m depths, still with temperatures above 7°C. The two temperature maxima visible in Fig. 4.6.1 at different densities and with a delay of one month suggest that the second batch of BB60 waters, BB60b in Fig. 4.6.2, arrived only after its uplift and release in the Bornholm Basin by BB90 waters in November 2002. Their thin but pronounced warm layers were still observed in CTD profiles until March 2003 all over the Gotland Basin area (FEISTEL 2003).

A coincident signal arrived in the bottom layer at the beginning of December 2002, reducing the hydrogen sulphide concentration there. The signal can be set in relation to the enhanced current in the near bottom layers measured by the Gotland Basin mooring EGB (position shown in Fig. 1.1), where peak velocities up to 9 cm/s were recorded at the end of November 2002 (see Fig. 4.6.3, bottom). The question for its possible cause is raised by this sudden decrease of hydrogen sulfide concentration in December 2002 at 225 m depth (Table 4.6.1), accompanied by a pronounced deep current acceleration. Was another fraction of the summer inflow responsible for this event, perhaps in conjunction with the ventilation of the Gdańsk Basin by November? In fact there is no quantitative change visible in salinity and density at this level and time, not even in temperature, the ‘passive tracer’ (Table 4.6.1). The required properties of depth and density do not match those found in adjacent basins, therefore an external inflow appears unlikely. The hypothesis is formulated that surface wind conditions altered the deep current structure, as indicated by the temporary flow reversal in Fig. 4.6.3, and carried different water bodies of the Gotland Basin itself to the central station. Thus, there is no satisfying explanation for the lowering of H_2S concentration immediately above the sea floor in December 2002 beside changes in basin-internal circulation processes.

The BB90 inflow waters of November 2002 arrived in the bottom layer of the Gotland Basin in March 2003 (Table 4.6.1, Fig. 4.6.2). They passed the EGB mooring in two pulses over a period of about 20 days (Fig. 4.6.3) with pronounced signals especially in temperature. They are clearly discernible as well in all three plots of Fig. 4.6.1. The inflow continued with heavy fluctuations in April 2003 until the arrival of much colder water masses from the major inflow of January 2003 (Fig. 4.6.4). The BB90 waters were capable of ventilating most of the water below 200 m before the arrival of the much more intense January inflow, at the end of April 2003 (Table 4.6.1, Fig. 4.6.2).

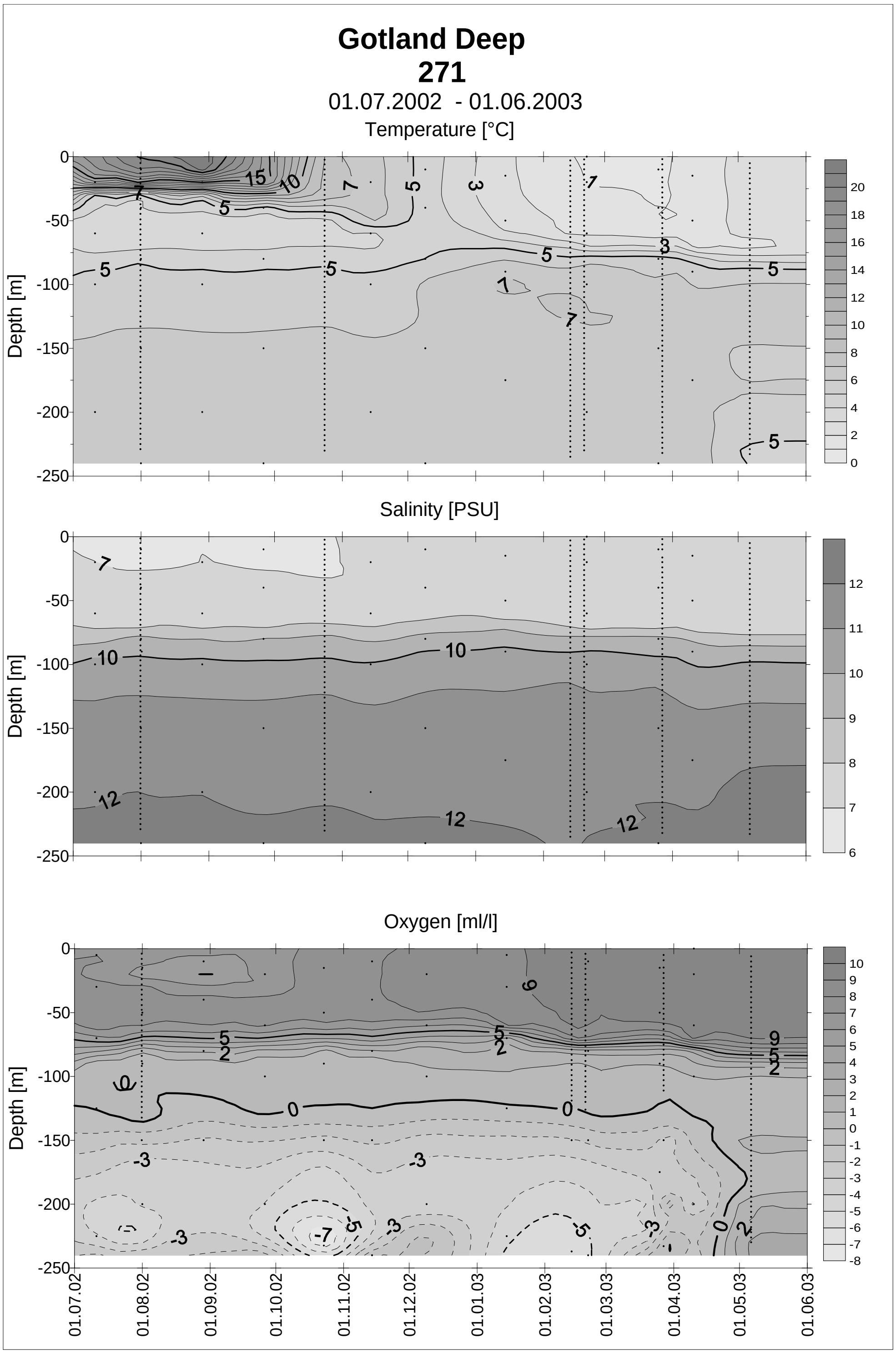

Fig. 4.6.1
Vertical profiles of temperature (top), salinity (middle) and oxygen concentration (bottom) at IOW station 271 in the central Gotland Basin, as obtained from CTD casts between July 2002 and May 2003. Note the vanishing 4°C isotherm at 60 m depth in the mid of November 2002, while the surface water was still warm, 6°C. Another warm signal (>7°C) arrived in January 2003 at 100 m depth, and in January/February 2003 at 120 m depth. At the bottom, hydrogen sulphide was already oxidised at the end of March 2003, before the cold January 2003 inflow arrived there at the end of April. Bottle data kindly provided by SMHI (2003) are included in the diagram.

Table 4.6.1
Detailed records of salinity *S*, temperature *T*, oxygen concentration O_2 and density anomaly σ_t at depth levels 240 m, 225 m and 100 m at the Gotland Basin central station 271 between May 2002 and May 2003, data by SMHI (2003). H_2S is given as negative O_2 equivalent. The inflow signals of BB60 and BB90 waters and the cold major Baltic inflow MBI of January 2003 are marked bold.

Date	Depth m	*S* PSU	*T* °C	O_2 ml/l	σ_t kg/m³	Inflow
16 May 02	100	10.38	5.68	+0.61	8.65	
13 Jun. 02	100	10.41	5.56	+0.24	8.68	
11 Jul. 02	100	10.25	5.45	+0.17	8.56	
01 Aug. 02	100	10.24	5.44	-	8.56	
29 Aug. 02	100	10.20	5.40	+0.57	8.53	
26 Sep. 02	100	10.13	5.30	+0.35	8.48	
14 Nov. 02	100	10.05	5.30	+0.22	8.41	
09 Dec. 02	**100**	**10.48**	**6.11**	**+0.86**	**8.70**	**BB60a**
16 Jan. 03	**100**	**10.65**	**7.27**	**+0.95**	**8.75**	**BB60b**
20 Feb. 03	100	10.44	7.05	+1.11	8.60	
25 Mar. 03	100	10.16	6.07	+0.68	8.45	
10 Apr. 03	100	9.86	5.89	+1.01	8.23	
08 May 03	100	10.10	6.06	+0.68	8.41	
16 May 02	225	12.03	6.39	-3.76	10.50	
13 Jun. 02	225	12.08	6.53	-3.58	10.52	
11 Jul. 02	225	12.06	6.47	-4.03	10.51	
01 Aug. 02	225	12.10	6.50	-4.21	10.54	
29 Aug. 02	225	12.09	6.50	-1.25	10.54	
26 Sep. 02	225	12.04	6.40	-4.43	10.50	
14 Nov. 02	225	12.01	6.37	-4.03	10.48	
09 Dec. 02	225	12.02	6.37	-0.49	10.49	
16 Jan. 03	225	11.99	6.36	-0.67	10.47	
20 Feb. 03	225	11.97	6.36	-0.67	10.45	
25 Mar. 03	225	11.95	6.34	-4.39	10.44	
10 Apr. 03	225	11.98	6.47	-1.75	10.45	
08 May 03	**225**	**12.34**	**5.01**	**+3.11**	**10.84**	**MBI 03**
16 May 02	240	12.19	6.60	-4.34	10.68	
13 Jun. 02	240	12.18	6.59	-1.43	10.67	
11 Jul. 02	240	12.17	6.57	-1.84	10.66	
01 Aug. 02	240	12.16	6.54	-2.15	10.66	
29 Aug. 02	240	12.14	6.55	-1.93	10.64	
26 Sep. 02	240	12.10	6.44	-1.21	10.62	
14 Nov. 02	240	12.09	6.44	-1.21	10.61	
09 Dec. 02	240	12.08	6.43	-0.98	10.60	
16 Jan. 03	240	12.05	6.42	-1.43	10.58	
20 Feb. 03	240	12.02	6.36	-1.34	10.56	
25 Mar. 03	**240**	**12.20**	**6.69**	**+0.22**	**10.68**	**BB90**
10 Apr. 03	240	12.06	6.53	-1.57	10.58	
08 May 03	**240**	**12.45**	**4.89**	**+3.33**	**11.00**	**MBI 03**

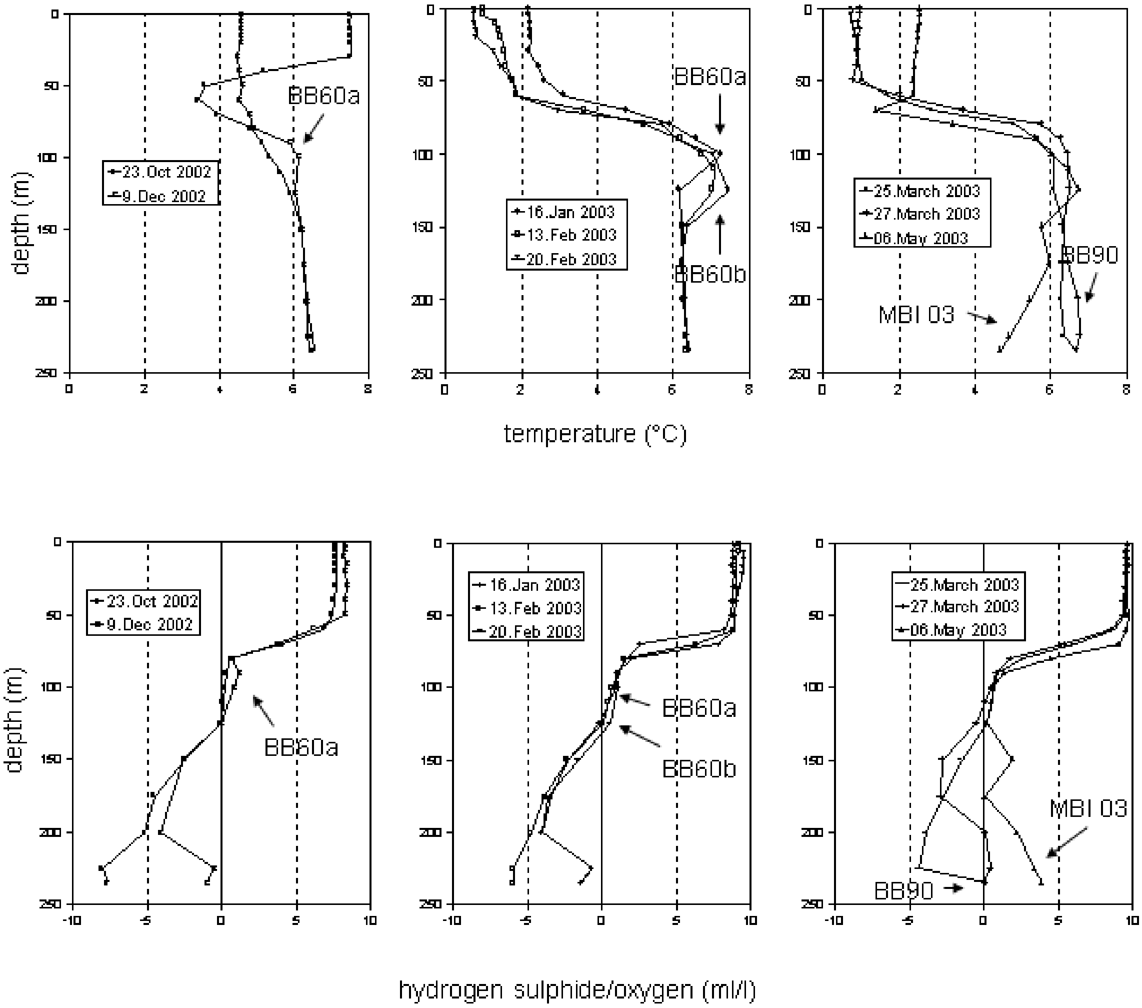

Fig. 4.6.2
Time evolution of the vertical profiles of temperature (top) and oxygen concentration (bottom) at the central Gotland Basin station 271 (position see Fig. 1.1) between October 2002 and May 2003

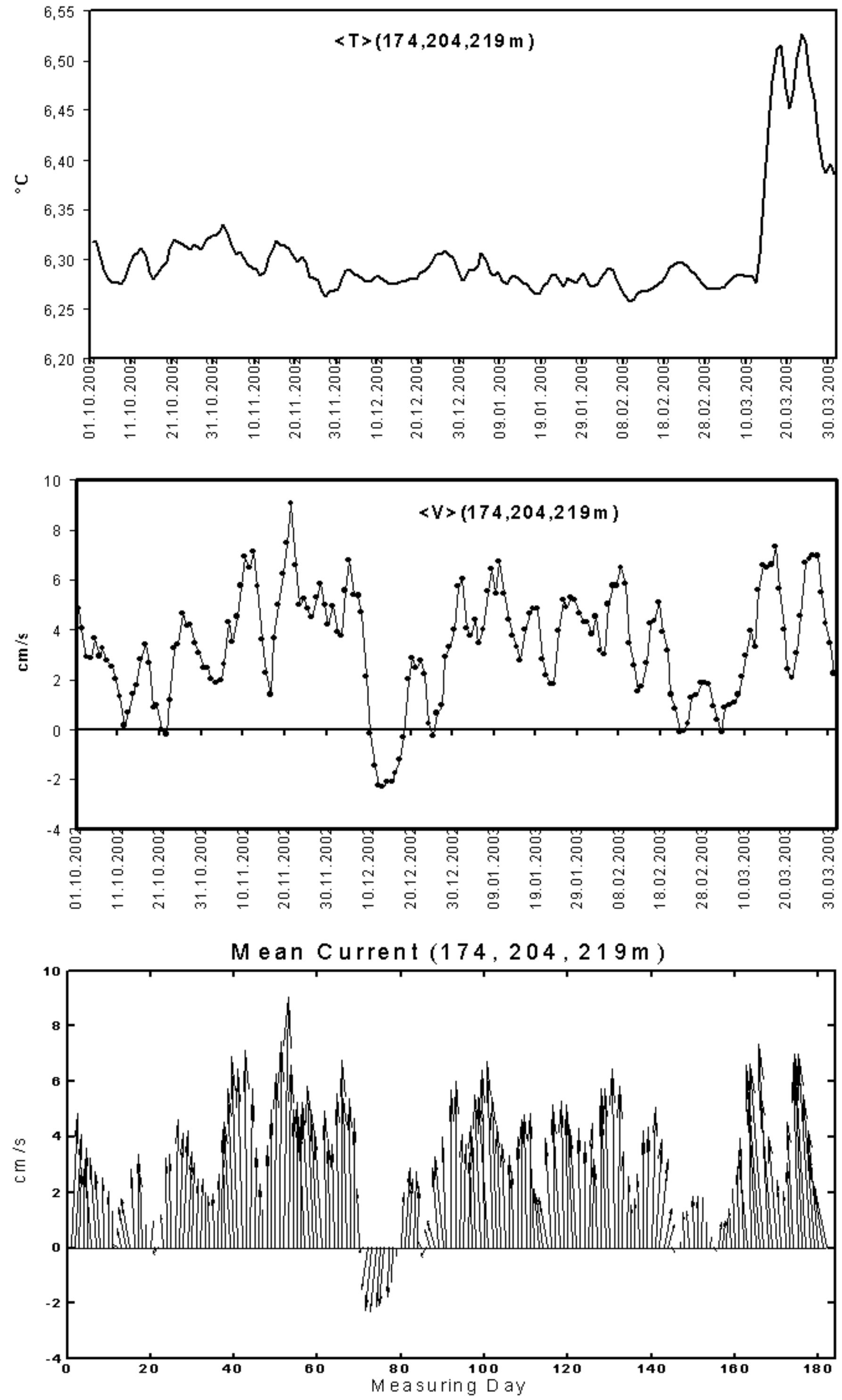

Fig. 4.6.3
Average records over depth levels 174, 204 and 219 m of temperature (top), along slope current speed (middle) and current vector (bottom) at the mooring position EGB in the Gotland Basin between 1st October 2002 and 30th March 2003. The inflow of BB90 waters in March 2003 is clearly marked in temperature and current signals. BB60 waters did not reach the recording depth of the mooring.

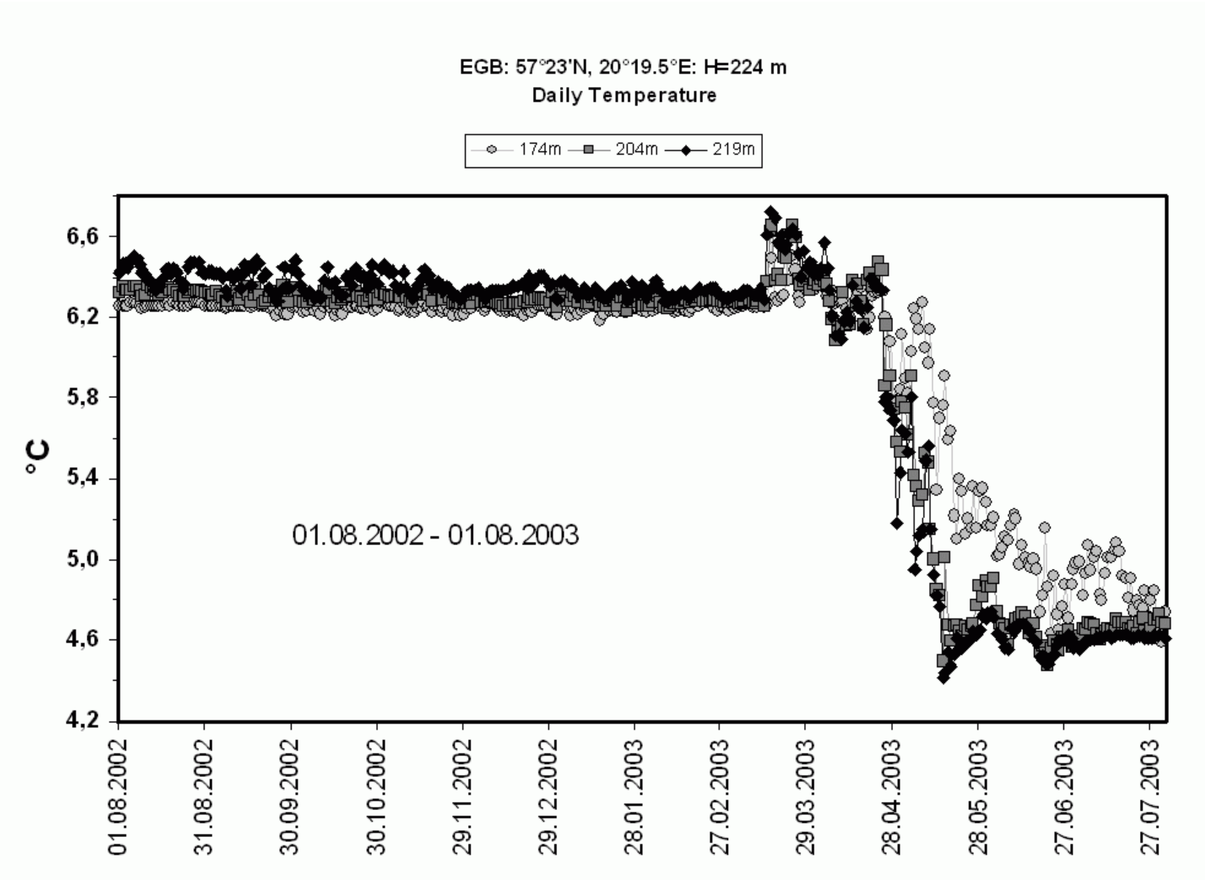

Fig. 4.6.4
Temperature records at depth levels 174, 204 and 219 m at the mooring position EGB in the Gotland Basin over one year between 1st August 2002 and 30th July 2003. The inflow of warm BB90 water in March/April 2003 is followed by the cold major Baltic inflow in May.

There is some observational evidence for persistent along-slope currents which cyclonically rotate along the isobaths within layers of several decametres above the sea bed of the Gotland Basin (HAGEN and FEISTEL 2004). Towards the centre of the basin, sporadically occurring inflow events of saline/ dense deep water produce gradients in density. They accelerate this deep circulation roughly by a factor of 3 to form a dome-shaped halocline over the centre of the basin as described in more detail by HAGEN and FEISTEL (2001). For this case, it became evident that dynamics in near-bottom layers is largely decoupled from that of shallower layers and that the resulting deep circulation occupies the whole deep basin. Its strength and duration strictly depend on the time history of the corresponding inflow event.

Usually, motions of upper and lower layers are forced by winds at the sea surface and resulting current speeds decrease with increasing water depth. On the climatic scale, the dominating westerly winds drive related surface currents in the entire Baltic Proper. The elliptic bathymetry of the eastern Gotland Basin represents its largest basin with north-south orientation of the main basin axis. For simplification, we like to follow CSANADY (1982) and consider a closed, large, homogeneously stratified, circular basin. The wind conditions mentioned should result in two oppositely rotating circulation cells (Fig. 4.6.5). The line of vanishing motion is expected to be perpendicular to the prevailing westerlies and should roughly be orientated in north-south direction, separating an anticyclonic cell in the west from a cyclonic cell in the east. It could be speculated that long lasting west or east wind situations establish persistent circulation cells with reduced exchange processes of passive tracers between them. For this case, enhanced easterly (westerly) winds decelerate (accelerate) the deep cyclonic circulation cell over the eastern topographic flank while the opposite situation occurs over the western flank of this basin. When, however, wind directions switch from westerly to easterly sectors due to eastward travelling atmospheric cyclones, the rotation of both circulation patterns will adjust immediately to such changed forcing conditions. Released instabilities of currents may favour exchange processes of passive tracers between the eastern and the western cell via turbulent mixing. Former differences of passive tracers between both circulation cells, such as hydrogen sulphide within near-bottom layers, are smoothed out spatially. Therefore, we expect that a long lasting situation of west or east winds maintains differences in passive tracers due to reduced exchange processes between the circulation cells above the eastern and western topographic flanks of this basin while frequent changes in zonal wind directions account for a tendency of spatial homogeneity in the entire deep basin.

A comparable situation was observed in the Gotland Basin during autumn/early winter 2002. At the Arkona weather station, which can be considered to be representative for the central Baltic (MOHRHOLZ 1998), the wind changed from westerly to easterly directions during the end of October and reached peak values in December (Fig.3.3a, b). The filling factor of the Baltic Sea, which is sufficiently described by sea level records at the coastal station Landsort, dropped drastically due to the westward driven outflow. As a result, both circulation cells changed their rotation directions. This clearly follows from recorded deep currents (174m, 219m, 224m) over the eastern topographic flank at the NE-position (224m water depth) (Fig. 4.6.3). Subsequently triggered mixing processes weakened the overall concentration of hydrogen sulphide in central parts of the deep basin for about two months (see section 4.6).

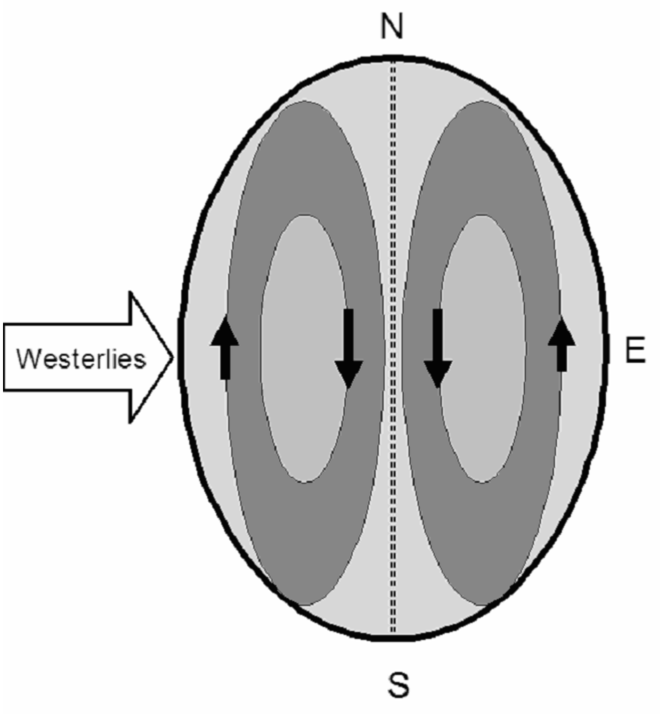

Fig. 4.6.5
Idealised deep circulation according to CSANADY (1982) within a large, closed, north-south oriented, elliptic basin like that of the eastern Gotland Basin; westerly winds generate an anticyclonic cell in the west and a cyclonic cell in the east with persistent northward currents above its eastern topographic flank.

5. Long-Term Evolution

The deep waters of the Arkona, the Bornholm and the Gdańsk Basin show characteristic annual temperature cycles which amount to a mean annual variation of 11 – 12°C (Arkona Basin: >35 m depth), to 5.7°C (Bornholm Basin: 60 m) and to 0.9°C (Gdańsk Basin: 100 m) (cf. MATTHÄUS 1977). These variations are caused by different inflow activities during the year and from year to year. In contrast to the upstream basins, the deep water of the eastern Gotland Basin displays no significant annual variations.

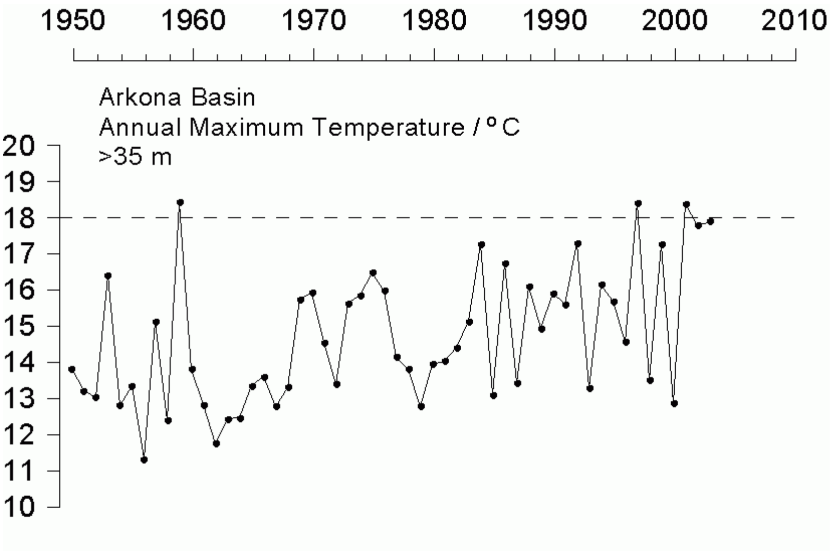

Fig. 5.1
Annual temperature maxima in the Arkona Basin at depths greater than 35 m

In historical retrospect, deep water temperatures as high as those described in this paper have only rarely been encountered. The annual maximum temperatures of about 63000 samples measured in the Arkona Basin at depths >35 m are shown in Fig. 5.1. Only three times between 1950 and 2003, values exceeding 18°C have been recorded: on 19th August 1959 (18.41°C), 8th September 1997 (18.39°C) and 25th July 2001 (18.37°C). This time, on 14th September 2002, the highest recorded value was 17.78°C, i.e. the 1959 "record" still remains valid. As far as the 50 – 70 m level of the Bornholm Basin is concerned, annual maximum temperatures exceeding 17°C have only been recorded on 5th October 2002 (cf. Fig. 5.2), values selected from a data set of almost 115000 single readings within this depth interval.

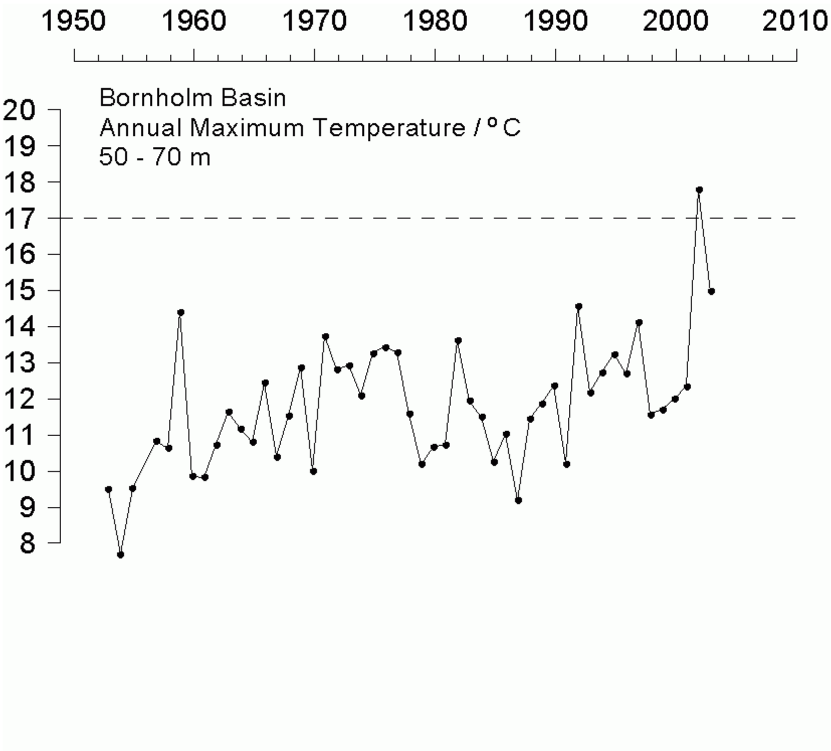

Fig. 5.2
Annual temperature maxima in the Bornholm Basin at depths between 50 and 70 m

Inflows of lower volumes of saline (in summer also warm) water frequently penetrate across the Darss and Drogden Sills into the Arkona Basin during each baroclinic or weak barotropic inflow event. Within or immediately below the halocline, this water passes relatively quickly the Arkona Basin and is trapped in the Bornholm Basin, renewing the ambient water to a certain extent. Such regular inflows in summer and early fall cause a mean annual temperature maximum >12°C in September/October at depths >35 m in the Arkona Basin and >8°C in November/December at depths between 55 and 70 m in the Bornholm Basin (MATTHÄUS 1977).

The filling stage of the Bornholm Basin with saline water below the permanent halocline is a measure for the estimation of the impact of smaller inflows on the central Baltic deep water. Depending on the inflowing volume of saline water, smaller but even major inflows fill up only that basin and the water does not pass to a greater extent over the Stolpe Sill and further downstream through the Stolpe Channel into the Gdańsk Basin and the central Baltic (cf. MATTHÄUS et al. 2001). When the buffering capacity of the Bornholm Basin is exceeded or there are longer lasting inflow periods of saline water crossing the sills into the Arkona Basin within or immediately below the halocline, this penetrating water can pass the Bornholm Basin in 50 – 60 m depth, crossing the 60 m deep Stolpe Sill in easterly direction, propagate downstream relatively quickly and cause significant effects in the intermediate levels of the central Baltic deep water.

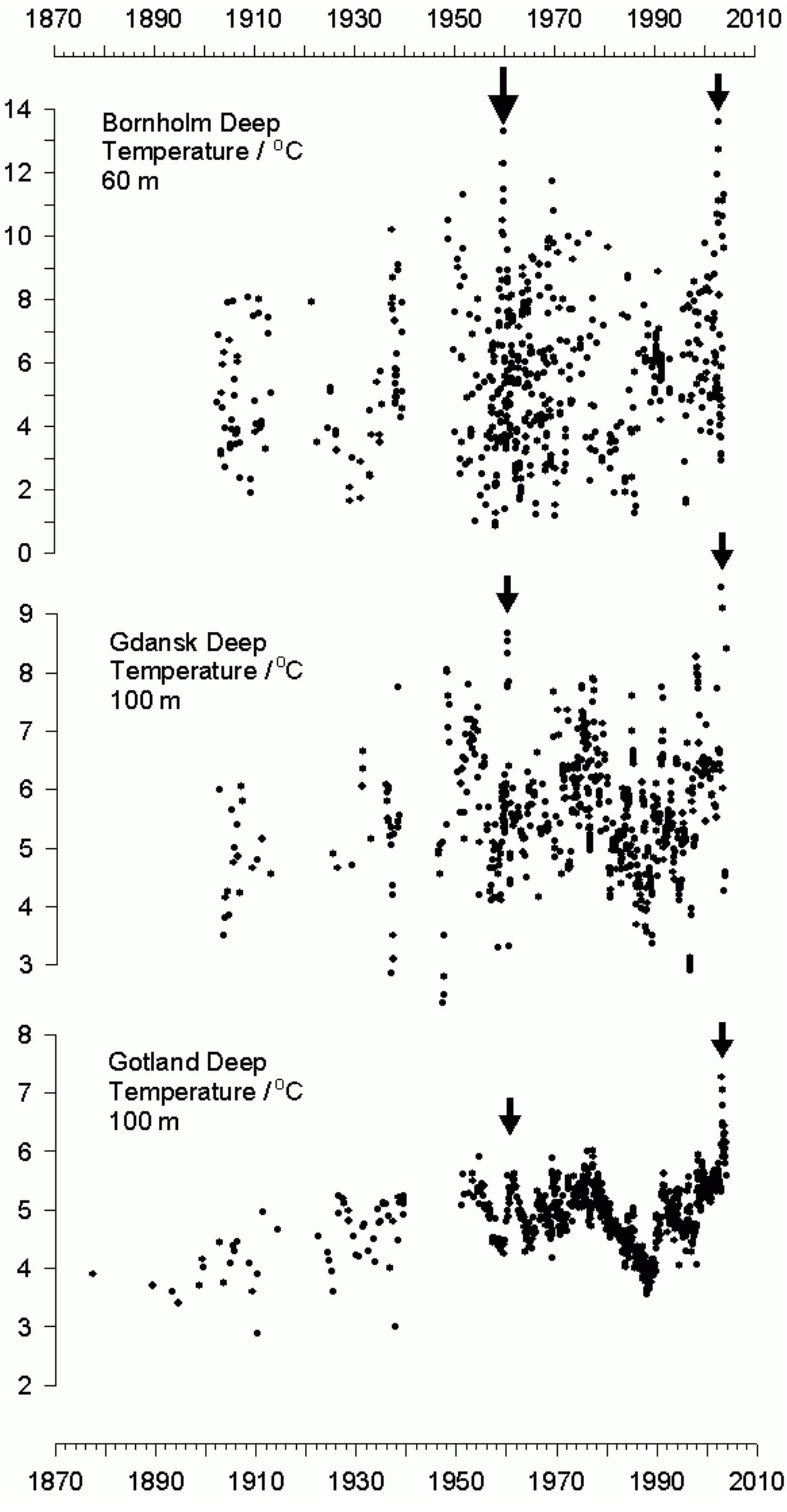

Fig. 5.3
Temperatures recorded at the Bornholm Deep at 60 m, the Gdańsk Deep at 100 m and the Gotland Deep at 100 m depth. The exceptional warm signals of 1959 and 2002 are marked with arrows.

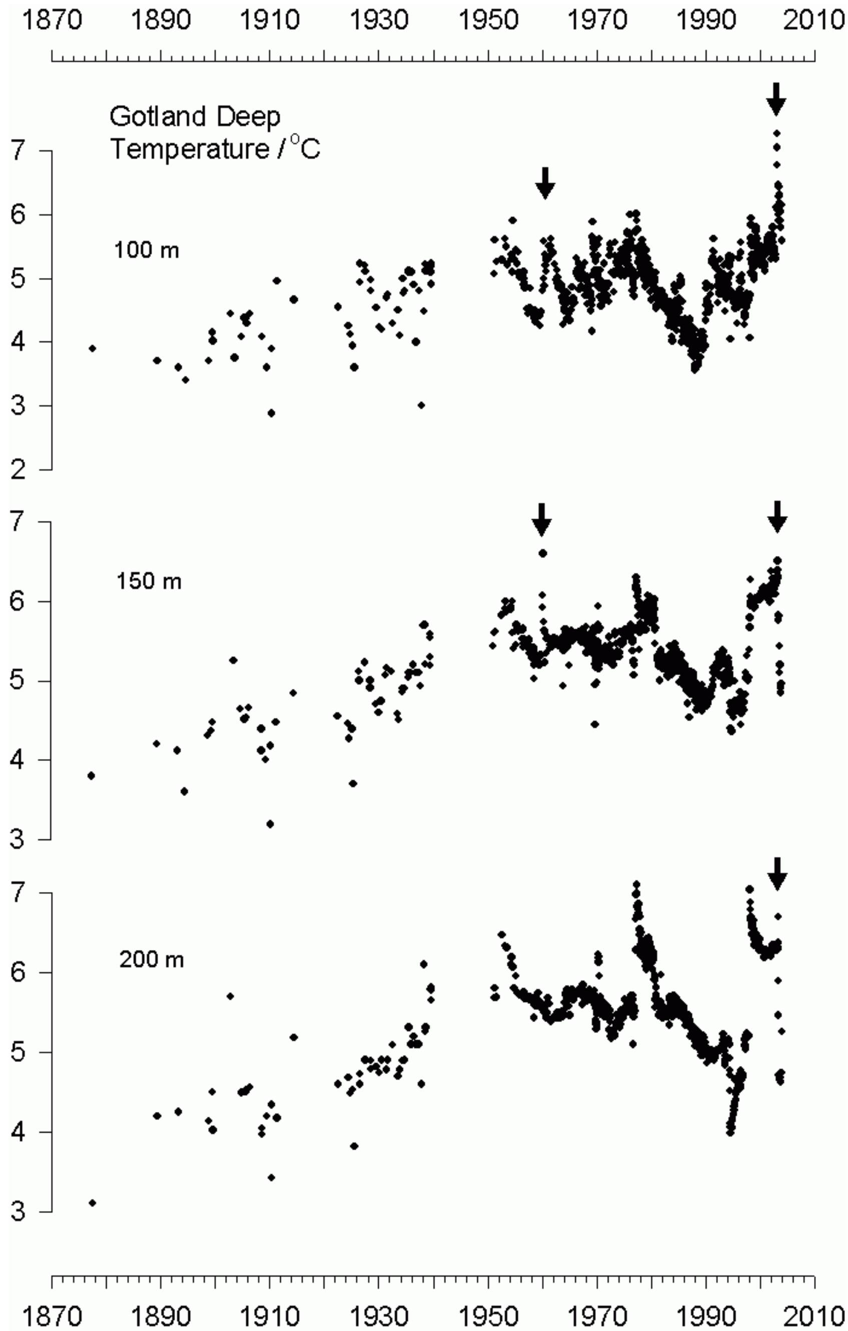

Fig. 5.4
Gotland Deep temperatures at depth levels 100, 150 and 200 m. The warm signals caused by the 1959 and 2002 inflows are indicated by arrows.

Thus, the unusually warm water which penetrated into the Baltic Sea in August/September 2002 caused, in autumn 2002, the highest temperatures on record at the 60 m level of the Bornholm Basin (13.79 °C) and at the bottom of the Gdańsk Basin (9.45 °C, cf. Fig. 5.3). In these two basins, similarly warm water has only be recorded in October/November 1959 with temperatures of 13.3 °C (Bornholm Basin: 60 m) and 8.67 °C (Gdańsk Basin: 100 m). In spring 2003, the inflowing warm waters also brought about the highest temperatures ever observed in the 100 m level of the Gotland Deep (7.27°C) but the 1959 event had not such marked effect (5.58 °C) at least in the 100 m level (Fig. 5.3).

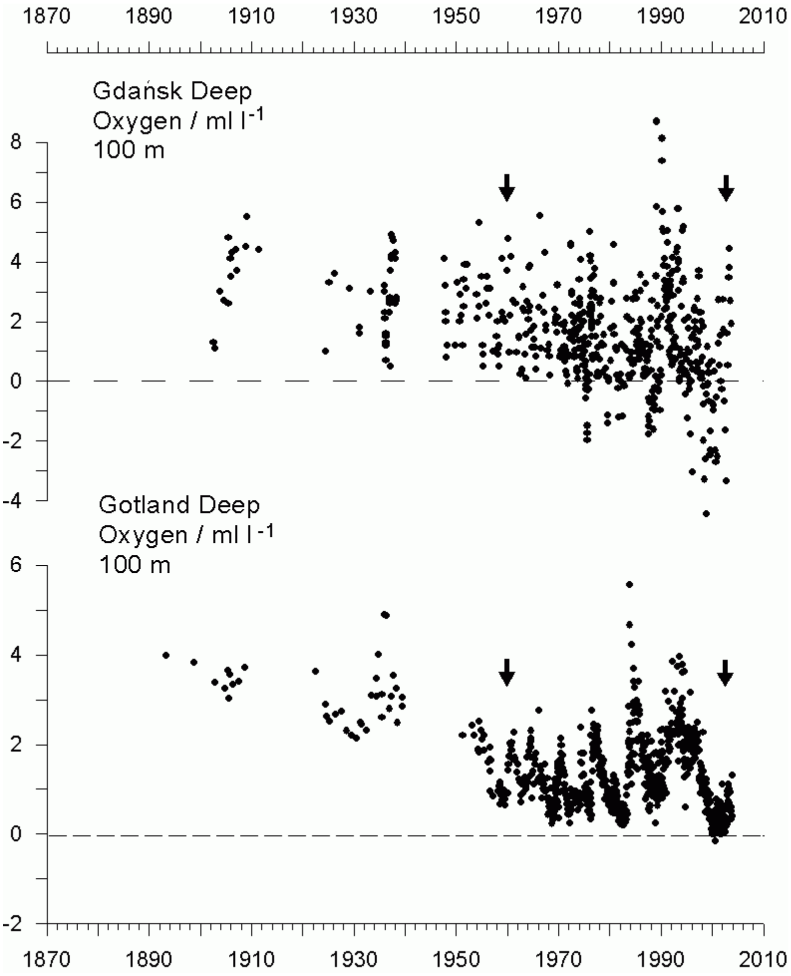

Fig. 5.5
Oxygen concentrations at the 100 m levels of the Gdańsk and Gotland Deeps. Arrows mark the warm inflows of 1959 and 2002

In 2002, the Bornholm Basin was filled with highly saline water (near-bottom salinity 15.5 – 16 PSU) and the 15-PSU-isoline was located at about 75 m depth throughout the year. The lower-density fraction of the inflowing BB60 warm water, i.e. BB60a, could pass relatively quickly the deeper parts of the Bornholm Basin and propagated into the Gdańsk and Gotland Basins. The effect is visible in the Gotland Deep at levels between 100 and 200 m (cf. Fig. 5.4). BB60b and BB90 waters were temporarily trapped in the Bornholm Basin and their propagation was delayed by the Stolpe Sill.

The effects of the 2002 warm water event are only slightly distinct in the oxygen regime in the long-term variation of the 100 m levels of the Gdańsk Deep or the Gotland Deep (cf. Figs. 4.6.2 and 5.5). The dominant signal in oxygen is the major inflow in January 2003 (FEISTEL et al. 2003b), at least at the 100 m level of the Gdańsk Deep.

In the southern Baltic, the summer of 1959 is also classified among the very warm summers of the past century. According to TIESEL (2003) it belongs to the top ten warmest, at least since 1947. July and August 1959 were very warm with air temperature anomalies of +1.9 K and +2.5 K at the Arkona weather station. Even September and October showed positive anomalies of +1.4 K and +1.6 K, too (MHD 1959). The Arkona SE wind component indicated that the inflow across the

Dass Sill occurred from the second half of August to the end of September 1959 and was obviously more or less continuous (cf. Fig. 5.6). The Landsort sea level showed a rapid increase only in August (Fig. 5.7). Salinity measurements at l/v “Gedser Rev” did not indicate any significant barotropic inflows in August/September. The exceptionally warm waters found later in deep water of the Bornholm and Gdańsk Basins (Fig. 5.3) are likely due to the inflow during the maximum sea surface temperatures in the western Baltic.

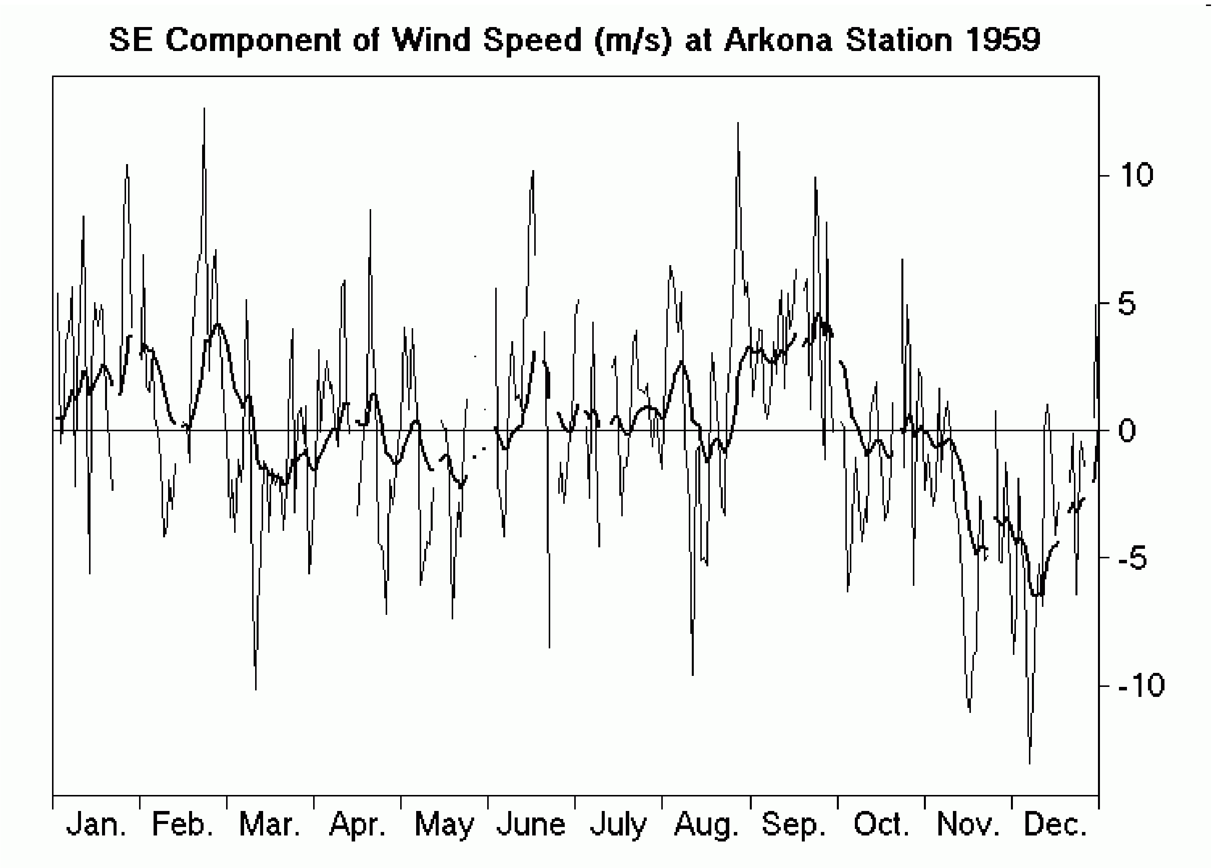

Fig. 5.6
SE component of the wind at Arkona station in 1959 (NW winds positive). The bold line is computed with 10-days exponential memory, showing high correlation with Landsort sea level (cf. Fig. 5.7)

After the very strong major Baltic inflow in 1951, the near-bottom salinity of 20.8 PSU in the Bornholm Basin decreased to only 15 PSU in late 1959 (cf. MATTHÄUS and NAUSCH 2003). Between 1955 and 1960, the Bornholm Basin deep water stagnated, the salinity at depths > 60 m was low in 1959, and in October/November 1959 the 15 PSU isoline was located between 80 and 90 m depth. While the maximum temperatures recorded in 1959 in the Arkona Basin at depths >35 m reached more than 18 °C (cf. Fig. 5.1), the warm water inflow led to temperatures between 10.5 °C (19th October) and 13.3 °C (23th November) in the 60 m level of the Bornholm Basin (cf. Fig. 5.3). The main inflow of warm water of about 13 – 13.4 °C occurred in 70 – 80 m. Due to reduced salinity of the water resident in the basin, part of the inflowing warm water was trapped in the Bornholm Basin and only a fraction propagated further downstream. The warm water penetrating into the Gotland Basin led to the highest temperatures on record (6.6 °C) in the 150 m level of the Gotland Deep in March 1960 (cf. Fig. 5.4). In 1969, another warm water inflow occurred which had a distinct signal at the 60 m level at least of the Bornholm Deep (cf. Fig. 5.3).

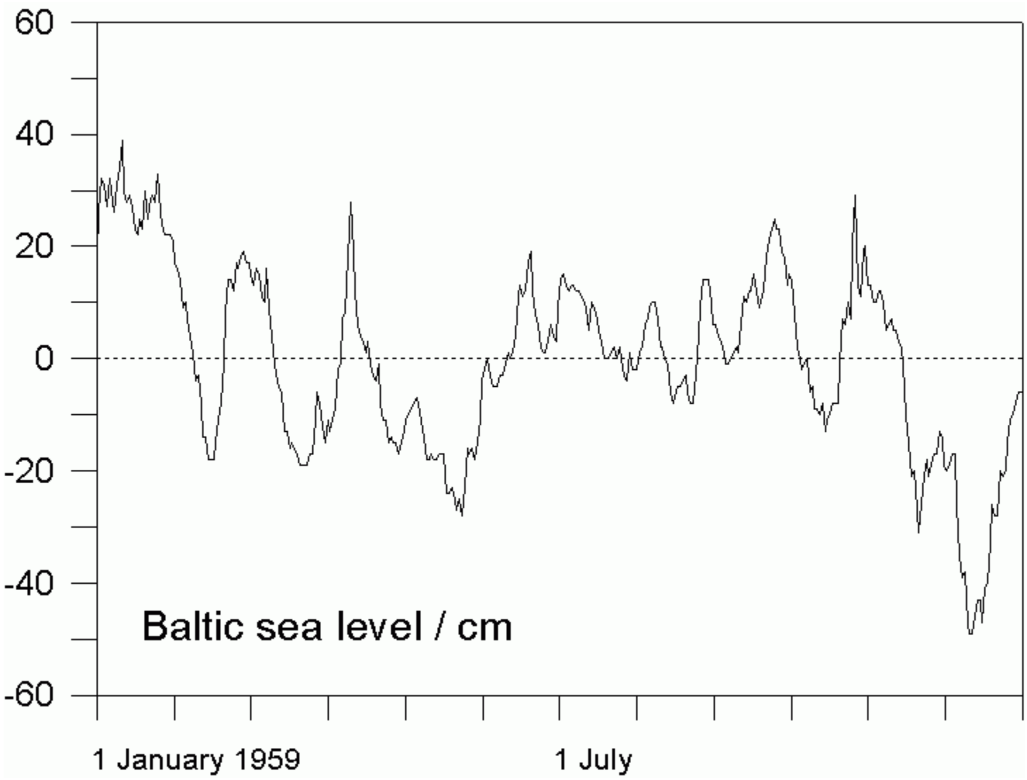

Fig. 5.7
Daily Landsort sea level data of 1959. Note the steep increase at the end of August.

The evaluation of long-term temperature data in the near-bottom layer of the Gdańsk Deep showed an increasing number of elevated temperature values in the 1950s, the 1970s and since 1990. About 20 cases of temperature $t > 7.0$ºC in the period 1959-2002 and less than 10 in the south eastern Gotland Basin (1986-2002) have been recorded. The values measured at the end of 1959 and in November 2002, however, are the highest in the recorded data series (Fig. 5.3).

Past 1989, the correlation coefficient in the near bottom layer of the Gdańsk Deep is $R = 0.48$ for the computed trend of 0.12 °C/yr. It shows that most of the inflows into the Gdańsk Basin, taking place in the last decade of the 20th century, were of warm autumnal water. That seems to indicate a shift in inflow intensity from winter to autumn in this period in comparison to the preceding period. The linear regression analysis of temperature in the near-bottom water of the south-eastern Gotland Basin also showed a positive trend between 1986 and 2002.

As far as long-term variations are concerned, temperature in the 100 m level of the Gdańsk Deep (cf. Fig. 5.3) and the deep water of the Gotland Deep (cf. Fig. 5.3) show a mean increase from the beginning of the measurements to the late 1970s (cf. also MATTHÄUS 1979, 1983, 1990). From then on, to the end of the 1980s and beginning of the 1990s, a mean negative trend is dominant. Starting in the early 1990s, temperature increased again significantly, at least in the 100 m levels (cf. Fig. 5.3). The mean long-term oxygen trends in the 100 m levels of the Gdańsk and Gotland Deeps (cf. Fig. 5.5) show a decrease up to the late 1970s (cf. MATTHÄUS 1979) followed by an weak increase during the stagnation period 1976-1992. However, a drastic decrease has been observed during the last stagnation period 1994-2002 (Fig. 5.5).

Summary

The late-summer BB60 inflow of 2002 into the Baltic Sea was an extraordinary process in various respects (FEISTEL et al. 2003a):

• it displayed strong salinity stratification while passing the Darss Sill mast, absence of wind mixing, and separation of the dense water from the atmosphere already in the Belt Sea;
• it was almost exclusively fed in by the Great Belt with extremely small contributions from the Sound;
• its dynamic details, especially inside the Great Belt, have not yet been properly reflected by measurements nor by numerical models;
• it coincided with the appearance of a very pronounced, permanent thermocline in the Belt Sea and widespread, severe oxygen deficiency conditions beneath it;
• although it carried mainly oxygen-poor water over the Darss Sill, it did ventilate the previously anoxic Gdańsk Basin soon afterwards;
• it brought exceptionally warm water into deep basins, for example, the warmest water on record at 100 m depth in the Gdańsk and Gotland Basins;
• its warm signals contrast in a remarkable way to the subsequent cold inflow of January 2003 (FEISTEL et al. 2003b)

Chapter 3 describes the specific meteorological situation in central Europe in summer 2002 as the likely cause of the extraordinary dynamic processes observed in the Baltic Sea. Calm outflow conditions prevailed over many weeks, causing strong thermal as well as salinity stratifications in the Belt Sea. The significant BB60 inflow of highly saline waters through the Great Belt and over the Darss Sill appeared in 4 successive periods of time from August to October 2002 (Table 4.2.1), flowing almost exclusively through the Great Belt, followed by a gale-forced, but still very warm BB90 inflow at the turn of October/November 2002, and the contrasting cold major Baltic inflow in January 2003. The BB60 inflow dynamics in the Danish Straits and Darss Sill area is described in sections 4.1 and 4.2, but it could not yet be completely clarified in very detail, neither by observational data nor by numerical model results. Although the MARNET Darss Sill mast data provide a complete time series over the period under study, its local character prevents an accurate quantitative knowledge of the total inflow and outflow masses of water and salt due to the inhomogeneity of the Darss Sill hydrographic cross section. The BB60 inflow passed the Arkona Basin relatively quickly, its later fraction could be documented by the first records of the new MARNET Arkona Basin buoy. The lighter BB60 waters crossed the Bornholm Basin above the Stolpe Sill threshold depth and immediately propagated through the Stolpe Channel and ventilated the entire Gdańsk Basin by November 2002. The required oxygen content was still missing in the inflow water masses when passing the Darss Sill but was later gained by exchange with colder ambient waters from the layers above in the Arkona and Bornholm Basins. The heavier BB60 fraction was interleaved below 60 m depth and became trapped in the Bornholm Basin behind the Stolpe Sill until it was released by the later BB90 inflow. The latter, warm BB90 water again was buffered there until the cold January inflow arrived. Thus, the warm inflows left the Bornholm Basin in 3 successive pulses with different properties. The corresponding signals could be traced as far as the Gotland Deep in spring 2003 in separate deep water layers. BB60 and BB90 water signatures became transformed along their propagation as shown in Fig. 6.1.

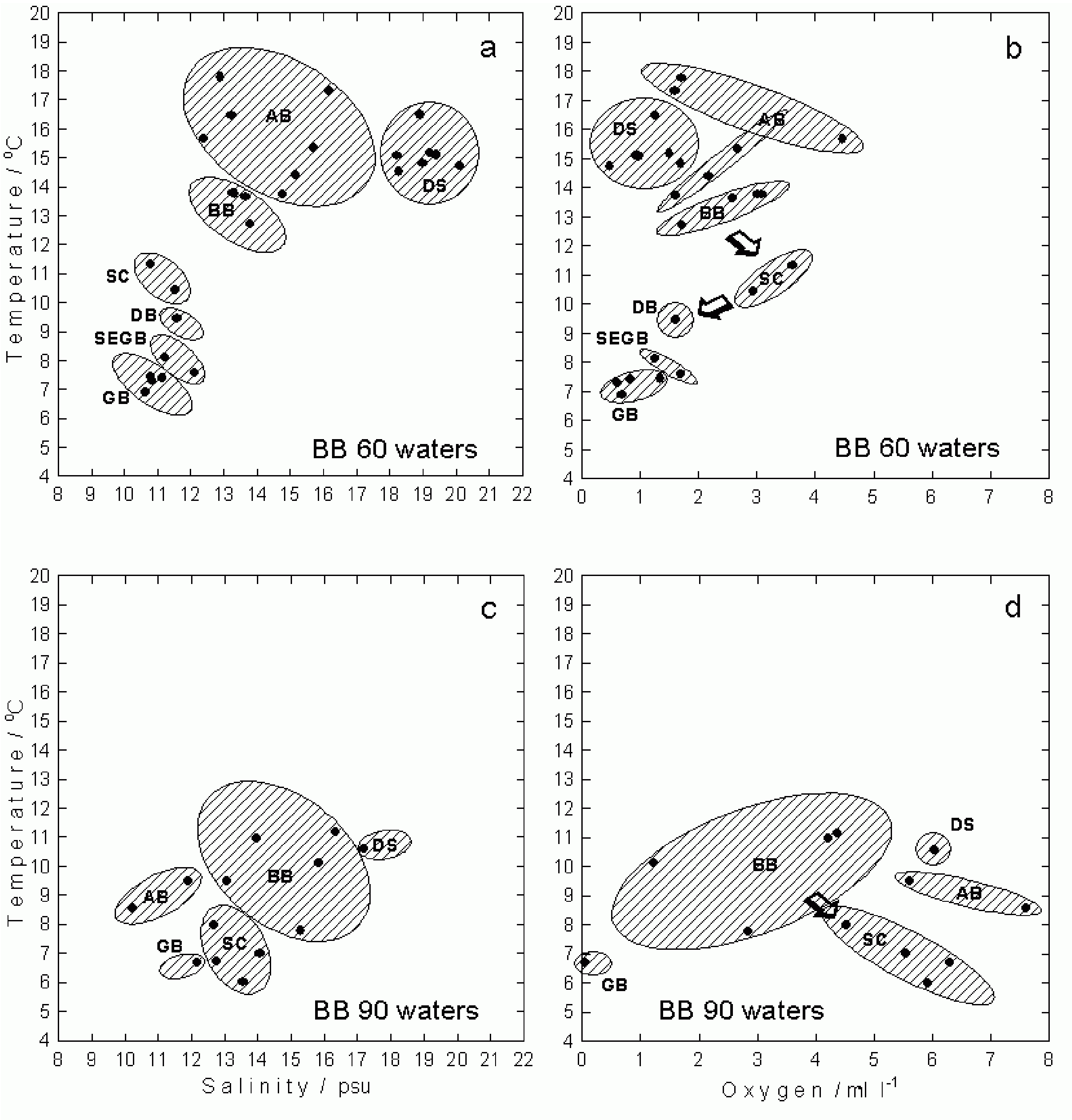

Fig. 6.1
T-S (left) and *T-O*$_2$ (right) properties of water samples found in various basins belonging to the inflow waters BB60 (top) and BB90 (bottom) between August 2002 and March 2003. Basins are DS: Darss Sill, AB: Arkona Basin, BB: Bornholm Basin, SC: Stolpe Channel, DB: Gdańsk Basin, SEGB: South-Eastern Gotland Basin, GB: Gotland Basin. Arrows indicate transformations of water properties along the propagation path.

Fig 6.1 provides an overview of *T-S-O*$_2$ properties of the warm inflow waters encountered in the different Baltic basins, based on the data reported in FEISTEL et al. (2003a). Samples were collected from various cruises, bottle samples, CTD casts and local time series, always selecting the maximum temperature specimen in that record, except for the Darss Sill (DS), where maximum salinity was the criterion, because highest temperatures there are always found in the outflowing, low-salinity surface layer. This is the cause for DS data found in the T-S diagrams at highest salinities but not highest temperatures.

The general tendency in these graphs is that during the eastward propagation the inflow waters lose salt, heat and oxygen due to exchange with ambient water bodies present there, and due to internal oxygen depletion. A remarkable exception is seen in the transformation from the Bornholm Basin (BB) to the Stolpe Channel (SC), where against the general scheme oxygen appears enriched (Fig 6.1 b, d). A similar, additional, and perhaps even more effective process apparently happened already in the Arkona Basin, as demonstrated in Fig. 4.4.3 in the Bornholm Basin section. We believe these to be essential observations for the capability of the warm and oxygen-poor inflow to entirely ventilate the Gdańsk Basin. We have discussed this point in the related sections in more detail.

The warm summer inflow of 2002 decribed in this paper was followed by a similar inflow in summer 2003, although under slightly different meteorological circumstances (FEISTEL et al. 2003a, 2004). This inflow is considered responsible for e.g. the dramatic warming again of the Gotland Deep water observed after the cold major Baltic inflow of January 2003 (FEISTEL 2004, NAUSCH 2004). Moreover, at the time this article is formulated (May 2004), a Vb low “Erika” had brought heavy rainfall to Germany, at some places exceeding the long-term monthly precipitation already within a few days, while calm outflow conditions are prevailing since mid April 2004, suggesting a possible beginning summer inflow in 2004 again. As our historical retrospective chapter 5 demonstrates, warm inflows occasionally happened already in earlier years, but were mostly considered to be of little relevance. However, similar processes of this extention, strength and frequency have never been described before for the Baltic Sea. Its faint hydrographic coupling to the world ocean by the narrow Danish Straits and its sensitivity to fluctuations of the meteorological/climatologic regime over central Europe indicate the enhanced warm summer inflows to manifest a specific Baltic response to gradual global change and warming.

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References

ASSAF, G. and HECHT, A. (1974): Sea straits: a dynamical model. Deep-Sea Research **21**, 947-958.

BERGSTRÖM, S. and CARLSSON, B. (1994): River Runoff to the Baltic Sea: 1950-1990. Ambio **23**, 280-287.

BIRGEL, D. and BRAUN, D. (2002): Die Jahrhundertflut. Bilder einer Katastrophe. Dresdner Nachrichten GmbH und Co. KG, Dresden. 26 pp.

CSANADY, G. T. (1982): Circulation in the coastal ocean. Dordrecht, Boston, London, D. Reidel Publishing Company. 284 pp.

CYBERSKI, J. and WROBLEWSKI, A. (2000): Riverine water inflows and the Baltic Sea water volume 1901-1990. Hydrology and Earth System Sciences **4**, 1-11.

DHI (2003a): What is MIKE 3?
http://www.dhisoftware.com/mike3/Description/index.htm

DHI (2003b): The Waterforecast.
http://www.waterforecast.com

DUTZ, J. (2002): GLOBEC cruise report 44/01/11, October 2002.
http://www.ifm.uni-hamburg.de/globec/cruises/gg02_13program.pdf

DWD (2003): unpublished data.

DWD (2004): Klimadaten im KL-Standardformat.
http://www.dwd.de/de/FundE/Klima/KLIS/daten/online/nat/index_standardformat.htm

FEISTEL, R. (2003): IOW Cruise Report 11/03/02, March 2003.
http://www.io-warnemuende.de/projects/monitoring/documents/cr110302.pdf

FEISTEL, R. (2004): IOW Cruise Report 11/04/03, March 2004.
http://www.io-warnemuende.de/projects/monitoring/documents/cr110403.pdf

FEISTEL, R., NAUSCH, G., HEENE, T., PIECHURA, J. AND HAGEN, E. (2004): Evidence for a warm water inflow in summer 2003. Oceanologia, in preparation.

FEISTEL, R., NAUSCH, G., MOHRHOLZ, V., LYSIAK-PASTUSZAK, E., SEIFERT, T., MATTHÄUS, W., KRÜGER, S. and SEHESTED HANSEN, I. (2003a): Warm waters of summer 2002 in the deep Baltic Proper. Oceanologia **45** (4), 571-592.
http://www.iopan.gda.pl/oceanologia/454feis1.pdf

FEISTEL, R., NAUSCH, G., MATTHÄUS, W. and HAGEN, E. (2003b): Temporal and spatial evolution of the Baltic deep water renewal in spring 2003. Oceanologia **45** (4), 623-642.
http://www.iopan.gda.pl/oceanologia/454feis2.pdf

FEISTEL, R., NAUSCH, G. and HAGEN, E. (2003c): The Baltic Inflow of Autumn 2001. Meereswissenschaftliche Berichte, Warnemünde, **54**, 55-68.
http://www.io-warnemuende.de/documents/mebe54_inflow01.pdf

FRANCK, H., MATTHÄUS, W. and SAMMLER, R. (1987): Major inflows of saline water into the Baltic Sea during the present century. Gerlands Beiträge zur Geophysik **96**, 517-531.

GRIFFIES, S. M., PACANOWSKI, R. C., SCHMIDT, M. and BALAJI, V. (2001): Tracer conservation with an explicit free surface method for z-coordinate ocean models. Monthly Weather Review **129**, 1081-1098.

HAGEN, E. and FEISTEL, R. (2001): Spreading of Baltic deep water: A case study for the winter 1997-1998. Meereswissenschaftliche Berichte, Warnemünde, **45**, 99-133. http://www.io-warnemuende.de/research/mebe.html

HAGEN, E. and FEISTEL, R. (2004): Observations of low-frequency current fluctuations in depp water of the Eastern Gotland Basin/Baltic Sea. Journal of Geophysical Research **109**(C0344): doi: 10.1029/2003JC002017 (1-15).

HELA, I. (1944): Über die Schwankungen des Wasserstandes in der Ostsee mit besonderer Berücksichtigung des Wasseraustausches durch die dänischen Gewässer. Annales Academiae Scientiarium Fennicae **28**, 1-108.

HELCOM (2002): Manual of marine monitoring in the COMBINE programme of HELCOM. Baltic Marine Environment Protection Commission, Helsinki. Updated 2001/2002. http://www.helcom.fi/mons/combinemanual2/combinehome.htm

HELCOM (2003): The 2002 oxygen depletion event in the Kattegat, Belt Sea and Western Baltic. Baltic Sea Environment Proceedings, **90**, 1-59.

HERRMANN, J. P. (2002): GLOBEC Cruise Report, IHF Hamburg, 11.11.-29.11.2002.

IMGW (2002): Monitoring Cruise Reports of r/v “Baltica” No. 05(81) and 06(82). http://baltyk.imgw.gdynia.pl

IMGW (2003): Monitoring Cruise Reports of r/v “Baltica” No. 01(83). http://baltyk.imgw.gdynia.pl

JACOBSEN, T. S. (1980): Sea water exchange of the Baltic – measurements and methods. The Belt Project. National Agency of Environmental Protection, Denmark, 106 pp.

KNUDSEN, M. (1900): Ein hydrographischer Lehrsatz. Annalen der Hydrographie und Maritimen Meteorologie, **28**, 316-320.

KRAUS, G., MÖLLMANN, C., HINRICHSEN, H.-H., LEHMANN, A. and SCHNACK, D. (2003): Unusual water mass advection affected Central Baltic key species 1: Sprat and the summer inflow. GLOBEC International Newsletter, **9**(2), 27-28. http://www.pml.ac.uk/globec/Publications/Newsletter/Newsletter.htm

KRÜGER, S. (2001): Baltic Station – Arkona Sea. In El-Hawary, F. (Ed): Basic Shipboard Instrumentation and Fixed Automatic Stations for Monitoring in the Baltic Sea. The Ocean Engineering Handbook, pp. 1-52 to 1-61, CRC PRESS LLC, Boca Raton, USA.

KRÜGER, S., ROEDER, W. and WLOST, K.-P. (2003): Baltic Stations Darss Sill and Oder Bank. ICES Cooperative Research Report, **257**, 198-203.

LASS, H. U., SCHWABE, R., MATTHÄUS, W. and FRANCKE, E. (1987): On the dynamics of water exchange between Baltic and North Sea. Beiträge zur Meereskunde, **56**, 27-49.

LASS, H. U. (1988): A theoretical study of the water exchange between the North Sea and the Baltic and sea level variations of the Baltic. Beiträge zur Meereskunde, **58**, 19-33.

LASS, H. U. and MATTHÄUS, W. (1996): On temporal wind variations forcing salt water inflows into the Baltic Sea. Tellus, **48A**, 663-671.

ŁYSIAK-PASTUSZAK, E. and DRGAS, N. (2002): Warunki tlenowe (Oxygen conditions), in: Environmental conditions in the Polish zone of the southern Baltic Sea in 2002, W. KRZYMINSKI, E. ŁYSIAK-PASTUSZAK and M. MIĘTUS (eds.), Mater. Oddz. Mor. Inst. Meteor. i Gosp. Wod., Gdynia, (in press).

MATTHÄUS, W. (1977): Zur mittleren jahreszeitlichen Veränderlichkeit der Temperatur in der offenen Ostsee. Beiträge zur Meereskunde, **40**, 117-155.

MATTHÄUS, W. (1979): Langzeitvariationen von Temperatur, Salzgehalt und Sauerstoffgehalt im Tiefenwasser der zentralen Ostsee. Beiträge zur Meereskunde, **42**, 41-93.

MATTHÄUS, W. (1983): Aktuelle Trends in der Entwicklung des Temperatur-, Salzgehalts- und Sauerstoffregimes im Tiefenwasser der Ostsee. Beiträge zur Meereskunde, **49**, 47-64.

MATTHÄUS, W. (1990): Langzeittrends und Veränderungen ozeanologischer Parameter während der gegenwärtigen Stagnationsperiode im Tiefenwasser der zentralen Ostsee. Fischerei-Forschung, **28**(3), 25-34.

MATTHÄUS, W. and FRANCK, H. (1979): Zur kurzzeitigen Veränderlichkeit der Schichtungsverhältnisse im Seegebiet der Darßer Schwelle. Beiträge zur Meereskunde, **42**, 95-110.

MATTHÄUS, W., FRANCKE, E., LASS, H. U. and SCHWABE, R. (1982): Untersuchungen der Wasseraustauschprozesse im Bereich der Darßer Schwelle. Beiträge zur Meereskunde, **47**, 31-50.

MATTHÄUS, W. and NAUSCH, G. (2003): Hydrographic-hydrochemical variability in the Baltic Sea during the 1990s in relation to changes during the 20th century. ICES Marine Science Symposia **219**, 132-143.

MATTHÄUS, W., NAUSCH, G., LASS, H. U., NAGEL, K. and SIEGEL, H. (1999): The Baltic Sea in 1998 – Characteristic features of the current stagnation period, nutrient conditions in the surface layer and exceptionally high deep water temperatures. Deutsche Hydrographische Zeitschrift, **51**, 67-84.

MATTHÄUS, W., NAUSCH, G., LASS, H. U., NAGEL, K. and SIEGEL, H. (2001): The Baltic Sea in 1999 – Stabilization of nutrient cencentrations in the surface water and increasing extent of oxygen deficiency in the central Baltic deep water. Meereswissenschaftliche Berichte, Warnemünde, **45**, 3-25.

MHD (1959): Täglicher Wetterbericht des Meteorologischen und Hydrologischen Dienstes der DDR, Leipzig, **13**.

MIKULSKI, Z. (1982): River inflow to the Baltic Sea. Polish Academy of Sciences, Polish National Committee of the IHP, University of Warsaw, Faculty of Geography and Regional Studies.

MOHRHOLZ, V. (1998): Transport- und Vermischungsprozesse in der Pommerschen Bucht. Meereswissenschaftliche Berichte, Warnemünde, **33**, 1-106.

NAGEL, K. (2003): IOW Cruise Report 11/03/01, February 2003.
http://www.io-warnemuende.de/projects/monitoring/documents/cr110301.pdf

NAUSCH, G. (2003a): IOW Cruise Report 40/03/22, January 2003.
http://www.io-warnemuende.de/projects/monitoring/documents/cr400322.pdf

NAUSCH, G. (2003b): IOW Cruise Report 44/03/03, May 2003.
http://www.io-warnemuende.de/projects/monitoring/documents/cr440303.pdf

NAUSCH, G. (2004): IOW Cruise Report 40/04/11, May 2004.
http://www.io-warnemuende.de/projects/monitoring/documents/cr400411.pdf

NAUSCH, G., FEISTEL, R., LASS, H. U., NAGEL, K. and SIEGEL, H. (2003): Hydrographisch-chemische Zustandseinschätzung der Ostsee 2002. Meereswissenschaftliche Berichte, Warnemünde, **55**, 1-71.

NCEP (2003): NCEP Reanalysis Electronic Atlas. NOAA-CIRES Climate Diagnostics Center. http://www.cdc.noaa.gov/ncep_reanalysis/index.html

PACANOWSKI, R. C. and GRIFFIES, S. M. (2000): MOM 3.0 Manual, Tech. Rep., GFDL, Princeton, 671 pp.

PITMAN III, W. C. and RYAN, W. B. F. (1998): Noah's Flood. The New Scientific Discoveries About the Event That Changed History. Simon & Schuster, New York.

ROEDER, W. (2002a): IOW Cruise Report 40/02/19, August 2002.

ROEDER, W. (2002b): IOW Cruise Report 40/02/26, December 2002.

SCHMIDT, J., MÖLLMANN, C., TEMMING, A., HERRMANN, J.-P., FLOETER, J., SELL, A. and ST. JOHN, M. A. (2003): Unusual water mass advection affected Central Baltic key species 2: Pseudocalanus and the winter inflow. GLOBEC International Newsletter, **9**(2), 28-29.
http://www.pml.ac.uk/globec/Publications/Newsletter/Newsletter.htm

SCHMIDT, M. (2002): IOW Cruise Report 11/02/03, October 2002.
http://www.io-warnemuende.de/projects/monitoring/documents/cr110203.pdf

SCHRODIN, R. (2002): Quarterly Report of the Operational NWP-Models of the Deutscher Wetterdienst, No. 28, Deutscher Wetterdienst, Offenbach, Deutschland, pp. 67.

SIEGEL, H. (2002): IOW Cruise Report 40/02/09, August 2002.

SMHI (2002): Flow through the Sound 2002.
http://www.smhi.se/hfa_coord/BOOS/y2002/inflow2002_3.html

http://www.smhi.se/hfa_coord/BOOS/y2002/inflow2002_4.html

SMHI (2003): unpublished data.

STIGEBRANDT, A. (1976): On the effect of barotropic current fluctuations on the two-layer transport capacity of a constriction. Journal of Physical Oceanography, **7**, 118–122.

THIEL, G. (1938): Strombeobachtungen in der westlichen Ostsee im Juli 1936. Aus dem Archiv der Deutschen Seewarte und des Marineobservatoriums, **58**, 1-28.

TIESEL, R. (2002): Sommer 2002 - der zweitheißeste Sommer seit wenigstens 1890. http://www.tiesel.de/klima1.html

TIESEL, R. (2003): Temperatursummen der Lufttemperaturen an der Wetterstation Warnemünde 1946 – 2002. Unveröffentlichte Daten.

VOSS, M. (2002): IOW Cruise Report 40/02/21, September 2002.

WASMUND, N. (2002): IOW Cruise Report 40/02/18, August 2002. http://www.io-warnemuende.de/projects/monitoring/documents/cr400218.pdf

WELANDER, P. (1974): Two-layer exchange in an estuary basin with special reference to the Baltic Sea. Journal of Physical Oceanography **4**, 542-556.

WYRTKI, K. (1953): Die Dynamik der Wasserbewegungen im Fehmarnbelt I. Kieler Meeresforschungen **9**, 155-170.

WYRTKI, K. (1954): Die Dynamik der Wasserbewegungen im Fehmarnbelt II. Kieler Meeresforschungen **10**, 162-181.