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Hydrographic-hydrochemical assessment of the Baltic Sea 2016

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Content

Kurzfassung

Die Arbeit beschreibt die hydrographisch-hydrochemischen Bedingungen in der westlichen und zentralen Ostsee für das Jahr 2016. Basierend auf den meteorologischen Verhältnissen werden die horizontalen und vertikalen Verteilungsmuster von Temperatur, Salzgehalt, Sauerstoff/Schwefelwasserstoff und Nährstoffen mit saisonaler Auflösung dargestellt.

Für den südlichen Ostseeraum ergab sich eine Kältesumme der Lufttemperatur an der Station Warnemünde von 63,5 Kd. Im Vergleich belegt der Winter 2015/16 den 27. Platz der wärmsten Winter seit Beginn der Aufzeichnungen im Jahr 1948 und wird als mild klassifiziert. Mit einer Wärmesumme von 267 Kd rangiert der Sommer in den „Top Ten“ der 69jährigen Datenreihe und reiht sich auf Platz 6 der wärmsten Sommer ein.

Die Situation in den Tiefenbecken der Ostsee war im Wesentlichen geprägt durch weitere Salzwassereinbrüche von mittlere Intensität (November 2015, Januar-Februar 2016), die dem großen Salzwassereinbruch vom Dezember 2014 folgten. Seit Mitte Januar wurde das östliche Gotland Becken erneut belüftet. Während der MBI November 2015 erneut den Boden erreichte, wurden vom nachfolgenden Ereignis nur Wassertiefen zwischen 100-200 m belüftet. Im Jahr 2016 wurden drei weitere kleinere Einströme mit Volumina zwischen 171 km³ und 184 km³ im Zeitraum Oktober bis Dezember registriert. Zusammenfassend kann gesagt werden, dass die seit 2014 beobachte Phase von verstärkten Wasseraustauschprozessen mit entsprechenden Konsequenzen für die biogeochemischen Kreisläufe weiterhin andauert.

Abstract

The article summarizes the hydrographic-hydrochemical conditions in the western and central Baltic Sea in 2015. Based on meteorological conditions, the horizontal and vertical distribution of temperature, salinity, oxygen/hydrogen sulphide and nutrients are described on a seasonal scale.

For the southern Baltic Sea area, the “cold sum” of the air temperature of 63.5 Kd in Warnemünde amounted to a mild winter in 2014/15 and ranks as 27th warmest winter since the beginning of the record in 1948. The summer “heat sum” of 267 Kd is ranked in the “top ten” over the past 69 years and ranks on place 6 of the warmest summers.

The situation in the deep basins of the Baltic Sea was mainly coined by ongoing inflow activity of moderate Major Baltic Inflows (November 2015, January-February 2016) following the Major Baltic Inflow of December 2014, which was the third largest ever observed. Since mid of January, the deep layer in the eastern Gotland Basin was ventilated again. The November 2015 MBI reached the bottom, whereas the following event only water depths between 100-200 m had ventilated. In 2016, furthermore three smaller inflow events with estimated volumes between 171 km³ and 184 km³ occurred in the timespan October to December. In conclusion, the observed phase of intensified water exchange processes with subsequent consequences for the biogeochemical cycles is going on since 2014.

1. Introduction

This assessment of hydrographic and hydrochemical conditions in the Baltic Sea in 2015 has partially been produced on the basis of the Baltic Sea Monitoring Programme that the Leibniz Institute for Baltic Sea Research Warnemünde (IOW) undertakes on behalf of the Federal Maritime and Hydrographic Agency, Hamburg and Rostock (BSH). Within the scope of an administrative agreement, the German contribution to the Helsinki Commission's (HELCOM) monitoring programme (COMBINE) for the protection of the marine environment of the Baltic Sea has been devolved to IOW. In 2008, the geographical study area was redefined: it now stretches from Kiel Bay to Bornholmsgat, and thus basically covers Germany's Exclusive Economic Zone. In order to safeguard long-term measurements and to ensure the description of conditions in the Baltic Sea's central basins, which play a decisive role in the overall health of the sea IOW has contributed financially towards the monitoring programme since 2008. Duties include the description of the water exchange between the North Sea and the Baltic Sea, the hydrographic and hydrochemical conditions in the study area, their temporal and spatial variations, as well as the identification and investigation of long-term trends.

Five routine monitoring cruises were undertaken in 2016 in all four seasons; additional observations were made in January. The data obtained during these cruises, as well as results from other research activities by IOW, form the basis of this assessment. Selected data from research institutions elsewhere in the region, especially the Swedish Meteorological and Hydrological Institute (SMHI) and the Maritime Office of the Polish Institute of Meteorology and Water Management (IMGW), are also included in the assessment. Fig. 1 gives the locations of the main monitoring stations evaluated; see NAUSCH et al. (2003) for a key to station nationality.

HELCOM guidelines for monitoring in the Baltic Sea form the basis of the routine hydrographical and hydrochemical monitoring programme within its COMBINE Programme (HELCOM, 2000). The five monitoring cruises in January/February, March, May, August and November were performed RV *Elisabeth Mann Borgese*. The additional winter cruise in January took place on RV *Solea* and was a joint cruise with the Thünen Institute of Baltic Sea Fisheries to observe the propagation of the MBI from November 2015 and following smaller inflows in the wintertime 2015/2016. Details about water sampling, investigated parameters, sampling techniques and their accuracy are given in NEHRING et al. (1993, 1995).

Ship-based investigations were supplemented by measurements at three autonomous stations within the German MARNET environmental monitoring network. Following a general maintenance, the ARKONA BASIN (AB) station has been in operation again since June 2012. DARSS SILL (DS) station was also overhauled, and went back into operation in August 2013. The ODER BANK (OB) station was in operation from mid-April to mid-December 2016; it was taken out of service for a break over the winter of 2016/2017. See chapters 3-5 for details.

Besides meteorological parameters at these stations, water temperature and salinity as well as oxygen concentrations were measured at different depths:

AB: 8 horizons T + S + 2 horizons O_2
DS: 6 horizons T + S + 2 horizons O_2
OB: 2 horizons T + S + 2 horizons O_2

All data are transmitted via METEOSAT to the BSH database as hourly means of six measurements (Krüger et al., 1998; Krüger, 2000a, b). An acoustic doppler current profiler (ADCP) at each station records current speeds and directions at AB and DS. Each of the ADCP arrays at AB and DS is located on the seabed some two hundred metres from the main station; they are protected by a trawl-resistant bottom mount mooring (designed in-house). They are operated in real time, i.e. via an hourly acoustic data link, they send their readings to the main station for storage and satellite transmission. For quality assurance and service purposes, data stored by the devices itself are read retrospectively during maintenance measures at the station once or twice a year.

Monitoring of Sea Surface Temperature across the entire Baltic Sea was carried out on the basis of individual scenes and mean monthly distributions determined using NOAA-AVHRR meteorological satellite data. All cloud-free and ice-free pixels (pixel = 1 × 1 km) from one month's satellite overflights were taken into account and composed to maps (Siegel et al., 1999, 2006). 2016 was assessed in relation to the mean values for 1990-2016 as the third warmest year after 2014 and 2015.

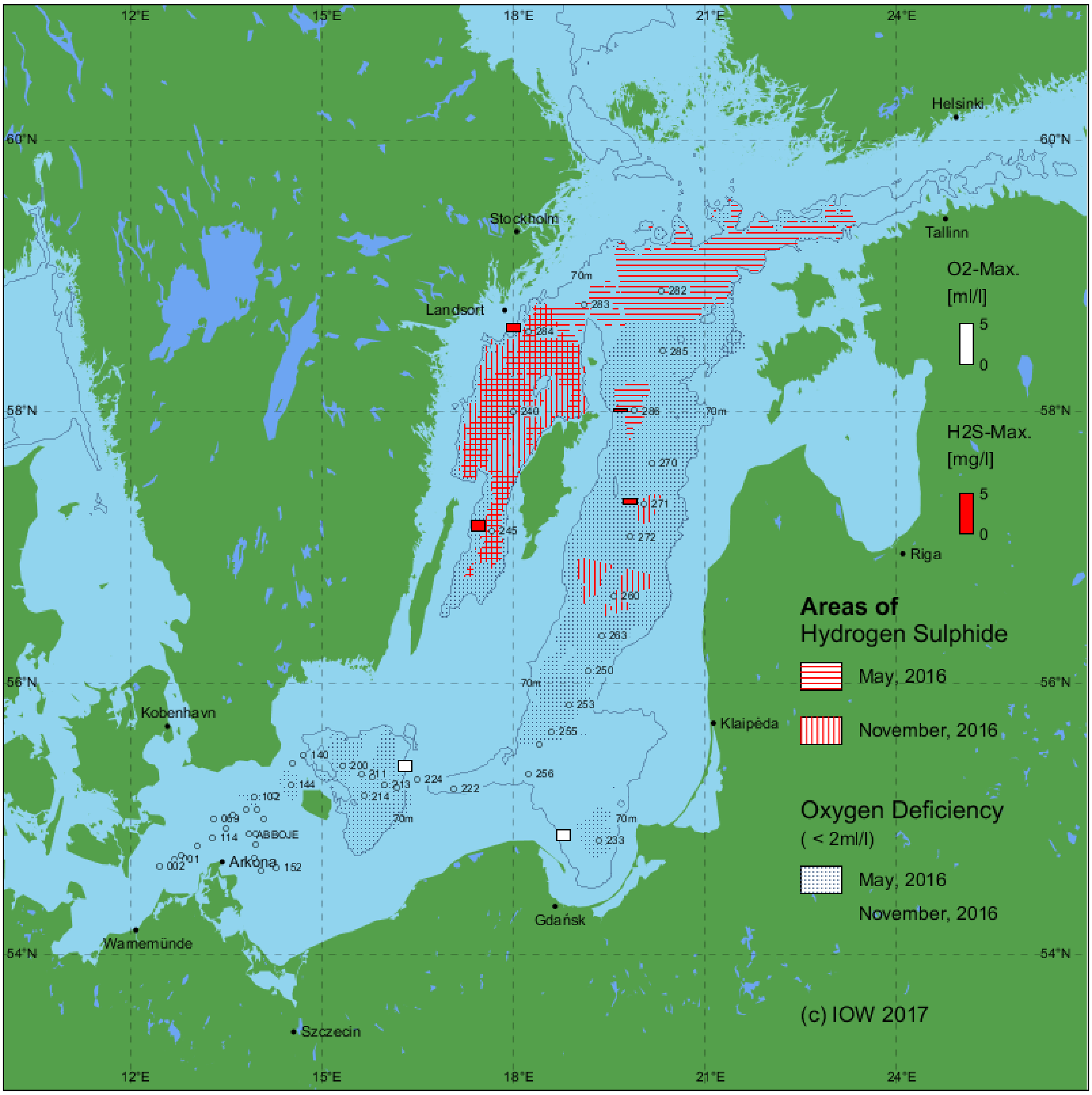

Fig. 1: Location of stations (■ MARNET- stations) and areas of oxygen deficiency and hydrogen sulphide in the near bottom layer of the Baltic Sea. Bars show the maximum oxygen and hydrogen sulphide concentrations of this layer in 2016; the figure additionally contains the 70 m -depth line

2. Meteorological Conditions

The following description of weather conditions in the southern Baltic Sea area is based on an evaluation of data from the Germany's National Meteorological Service (DWD), Federal Maritime and Hydrographic Agency (BSH), Swedish Meteorological and Hydrological Institute (SMHI), Institute of Meteorology and Water Management in Gdynia and Warsaw (IMGW), Freie Universität Berlin (FU) as well as IOW itself. Table 1 gives a general outline of the year's weather with monthly mean temperature, humidity, sunshine duration, precipitation as well as the number of days of frost and ice at Arkona weather station. Solar radiation at Gdynia weather station is given in addition. The warm and cold sums at Warnemünde weather station, and in comparison with Arkona, are listed in tables 2 and 3.

According to the analysis of DWD (DWD, 2016), 2016 was on global level even warmer than 2015 and again worldwide the warmest year since the beginning of extensive weather records in 1881, and for the German territory on eight position together with 6 other years (1934, 1989, 1990, 1999, 2006 and 2008). The mean annual temperature of 9.5 °C was about 0.6 K higher than the average for 1981-2010 and 0.4 K lower than the previous year 2015. The year began with cold temperatures in northern Germany and mild-humid winter weather in the southern part. Along Germany's Baltic coast the winter situation changed to warmer temperatures in the end of January and the months February, March and April each exceeded the thirty-year mean by 0.7-1.9 K. These warm temperatures continued during the course of the year. A long lasting late-summer phase in September pushed the monthly mean 3 K above the long-term average, only August and October showed balanced temperatures and November was slightly to cold (c.f. Table 1).

Across Germany, the amount of precipitation was 723 mm, 10 % below the average of 808 mm, but above 699 mm in 2015. In a regional comparison Schleswig-Holstein (735 mm) and Mecklenburg-Vorpommern (512 mm) showed values of 90 % and 83 % of their long term average for 1981-2010. The driest months at the coast were March and June. The longest periods without precipitation in the German territory happened from September 5th to 28th at the western Baltic Sea with 24 days at station Arkona and Barth, 23 days in Greifswald, and 22 days at the station Rostock-Warnemünde.

The average annual sum of 1,607 hours of sunshine exceeded slightly by 0.4 % (7 hours) the long-term average and was lower than in 2015 with 1,743 hours. The national ranking is led by the station Arkona (1,988 hours) at the isle of Rügen and followed by Fürstenzell (1,778 hours) in southern Germany. October was the least sunny month: with an average of 48 hours, it was 59 % below the long-term average. Surprisingly in December, the sun shone 53 % longer than usual (58 hours at station Arkona). The peak value belonged to June: 303 hours, 120 % respectively.

2.1 Ice Winter 2015/16

For the southern Baltic Sea area, the cold sum of 63.5 Kd at Warnemünde station amounted to a warm winter in 2015/16 (Table 2). This value plots below the long-term average of 102.4 Kd in comparative data from 1948 onwards and ranks as 16th warmest winter in this time series. In comparison, Arkona station at 36.1 Kd (Table 3) is markedly lower, and represents a relatively low value like the previous winters 2014/2015 (8.1 Kd) and 2013/2014 (42.1 Kd) compared to 87.5 Kd in winter 2012/2013. Given the exposed location of the north of the island of Rügen (it is surrounded by large masses of water), local air temperature developments are influenced even more strongly by the water temperature of the Baltic Sea (a maritime influence). In winter, milder values often occurred, depending on the temperature of the Arkona Sea, while in summer, the air was more strongly suppressed compared with more southerly coastal stations on the mainland. Except a cold spells from 2nd to 23rd January 2016, a very warm wintertime was recorded (Table 1). Overall, 37 days of slightly frost and 7 days of ice were recorded at Arkona compared to 34 days of frost and only 2 days of ice in the very mild winter of 2014/15 (NAUSCH et al., 2016). The winter's warm temperature profile was also reflected in icing rates.

According to SCHWEGMANN & HOLFORT (2016), this ice season in the Baltic Sea is classified as weak. Given warm weather conditions, the maximum extent of ice was reached at 22nd-23rd January 2016 with an area some 114 000 km². This ice coverage is ranked on 74th place since the year 1720, starting at the lowest value of 49 000 km² (year 2008) in this time series of 299 years. The maximum extent of ice corresponded to some 28 % of the Baltic Sea's area (415 266 km²), and was largely centred on the northern half of the Gulf of Bothnia, marginal areas of the northern and eastern Gulf of Finland (Newa Bight) as well as the Estonian coast between the mainland and the isles of Hiiumaa and Saaremaa. The south coast of the Baltic Sea remained free of ice, except sheltered areas in coastal lagoons. The value of 114 000 km² is twice as much than in the previous year 2015/2016 (51 000 km²) and recent years show the following maximum ice coverages: 95 000 km² in 2013/14, 187 000 km² in 2012/13 and 179 000 km² in 2011/12. By some 54 %, it fell short of the average of 213 000 km² in the time series from 1720 onwards (Figure 2). By way of comparison, it also fell short of the very low 30-year average of 149 000 km².

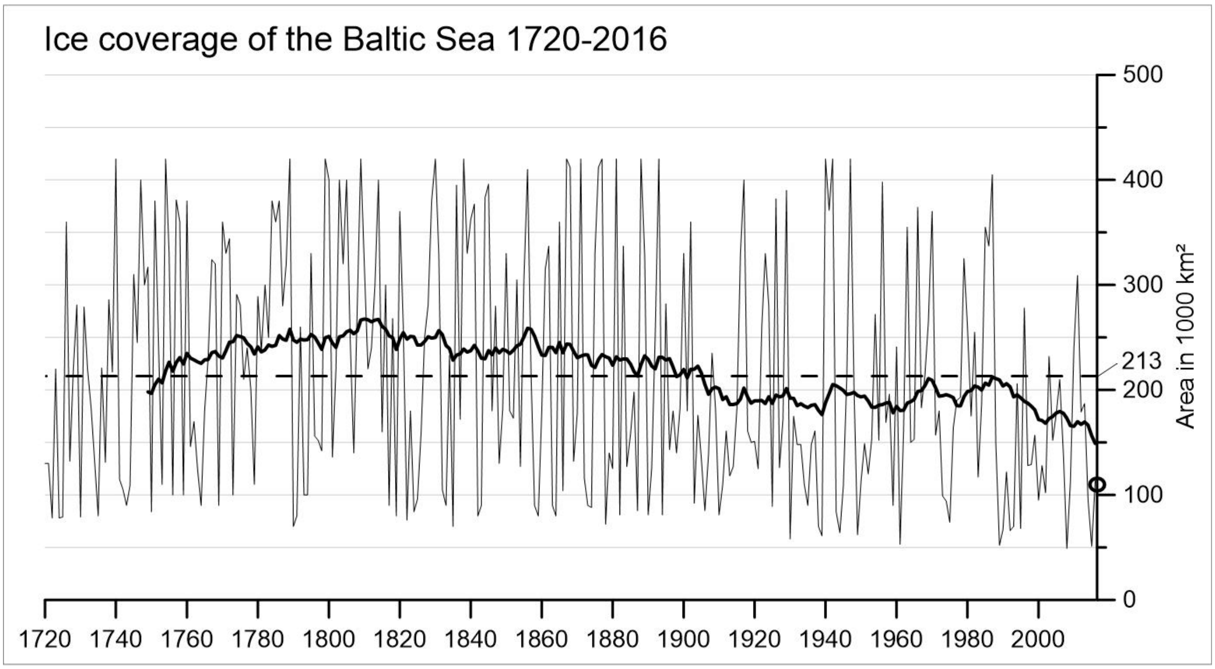

Fig. 2: Maximum ice covered area in 1000 km² of the Baltic Sea in the years 1720 to 2016 (from data of SCHMELZER et al., 2008, SCHWEGMANN & HOLFORT, 2016). The long-term average of 213 000 km² is shown as dashed line. The bold line is a running mean value over the past 30 years. The ice coverage in the winter 2015/2016 with 114 000 km² is encircled.

Along Germany's Baltic Sea coast, local conditions were assessed as a weak ice winter on the basis of an accumulated areal ice volume of 0.35 m (SCHWEGMANN & HOLFORT, 2016). After a very low value of 0.006 m in the previous year (SCHMELZER, 2015), it is the fifth weakest ice winter in a role. Besides various other indices, this index is used to describe the extent of icing, and was introduced in 1989 to allow assessment of ice conditions in German coastal waters (KOSLOWSKI, 1989, BSH, 2009). Besides the duration of icing, the extent of ice cover, and ice thickness are considered, so as to take better account of the frequent interruptions to icing during individual winters. The daily values from the 13 ice climatological stations along Germany's Baltic Sea coast are summed. The highest values yet recorded are as follows: 26.83 m in 1942; 26.71 m in 1940; 25.26 m in 1947; and 23.07 m in 1963. In all other winters, values were well below 20 m (KOSLOWSKI, 1989). At 0.35 m, the accumulated areal ice volume for winter 2015/16 is in line with low values of recent years: 0.009 m in 2014/15, 0.37 m in 2013/14, 0.38 m in 2012/13, 1.12 m in 2011/12 and 2.45 m in 2010/11. First icing was observed at 4th January in small harbours and sheltered areas and occurred up to the beginning of February. Along the Western Pomeranian lagoon chain icing of up to 32 days were registered in sheltered areas of the Greifswalder Bodden and Kleines Haff. At other areas the number of recorded ice days was thus as follows: 30 at Darss-Zingst lagoon chain and lagoon east of Rügen island (station Vierendehl), 17 days at Rostock harbour; 4 days at Lübeck harbour, 6 days in the Eckernförde Bight, 28 ice days at the mouth of the river Schlei and 10 days at the Flensburg Fjord. More open German sea areas all remained ice-free, according to the BSH maritime data portal and SCHWEGMANN & HOLFORT (2016). In the winter of 2015/16, an accumulated areal ice volume for the coast of Mecklenburg-Vorpommern of 0.45 m and Schleswig-Holstein of 0.23 m was calculated.

2.2 Weather Developments in 2016

Over the course of the year 2016, pressure systems and air currents were prevailing from westerly to south-westerly directions (cf. Figures 4a, 5b, 6). These wind directions account for about 50 % of the annual sum and the progressive wind vector curve of 2016 roughly follows the climatic mean situation (cf. 4a, b). The Institute of Meteorology at FU Berlin has given names to areas of high pressure and low pressure since 1954; a sponsorship deal ('Wetterpatenschaften') has also been in place since 2002 (FU-Berlin, 2016).

At the beginning of **January** high pressure "Alf" across Scandinavia brought cold winter weather and easterly winds. A short interruption with southerly winds and warmer temperatures up to 6 °C occurred between January 8th-11th by low pressure cells "Britta", "Daniela" and "Carolina" crossing the area from the north Atlantic. A second cold spell followed up to January 23rd (Highs "Benno", "Claudius", "Dietrich" across central Europe), before warm winter weather continued with strong westerly winds. A succession of low pressures "Judith", "Karin", "Leonie" and "Marita" was crossing northern Europe, resulting in a rapid sea level rise to the end of the month after an outflow period with a lowstand of -23 cm MSL at tide gauge station Landsort Norra at January 17th (Figure 7a). The temperature profile for January varied regional with mild temperatures in central and southern Germany, but mainly cold temperatures in the northern part. Along Germany's Baltic Sea coast the temperature was -1.3 K to -0.6 K below the long-term average and showed a mean of 0.4 °C at station Arkona (Table 1). Sunshine duration in most areas of Germany was below average, for instance in Hamburg with 22 hours at 46 %. At Arkona station a positive sunshine duration of 118 % (53 hours) was recorded. The coast of Mecklenburg-Vorpommern was to dry (Arkona 69 %); in contrast Schleswig-Holstein registered an increased precipitation of 14 % above the average (station Schleswig).

February continued with the influence of low pressure cells crossing from the North Atlantic the Baltic Sea ("Norkys", "Pia", "Quirina", "Susanna"). Strong westerly winds with daily means of up to 16.1 m/s (February 2nd) caused a sea level rise to 46.5 cm at Landsort Norra (February 3rd) resulting in a next Major Baltic Inflow of moderate intensity. From January 30th to February 6th the sills in the western Baltic Sea were overflown by highly saline water changing immediately the hydrographic conditions in the Arkona Basin (Figure 3). Mid of the month high pressure "Friedhelm" crossed Central Europe as a through and low pressures "Ulrika", "Virginie" as well as "Walburga" circling around. Easterly winds caused outflow conditions to 4 cm MSL at Landsort Norra (Figure 7a). Since February 20th strong west winds occurred again by low pressure "Xin" across Scandinavia causing a slightly sea level rise. At the end of the month easterly winds occurred (through across Western Europe) and a long lasting outflow period began. Mostly mild and wet conditions dominated this month, with positive temperature anomalies of around 1.9 K along Germany's Baltic Sea coast, increased precipitation (Arkona station: 122 %), and low sunshine duration. An exception was the north-eastern part, where the sun was shining longer than in average (Arkona station: 146 %, 95 hours).

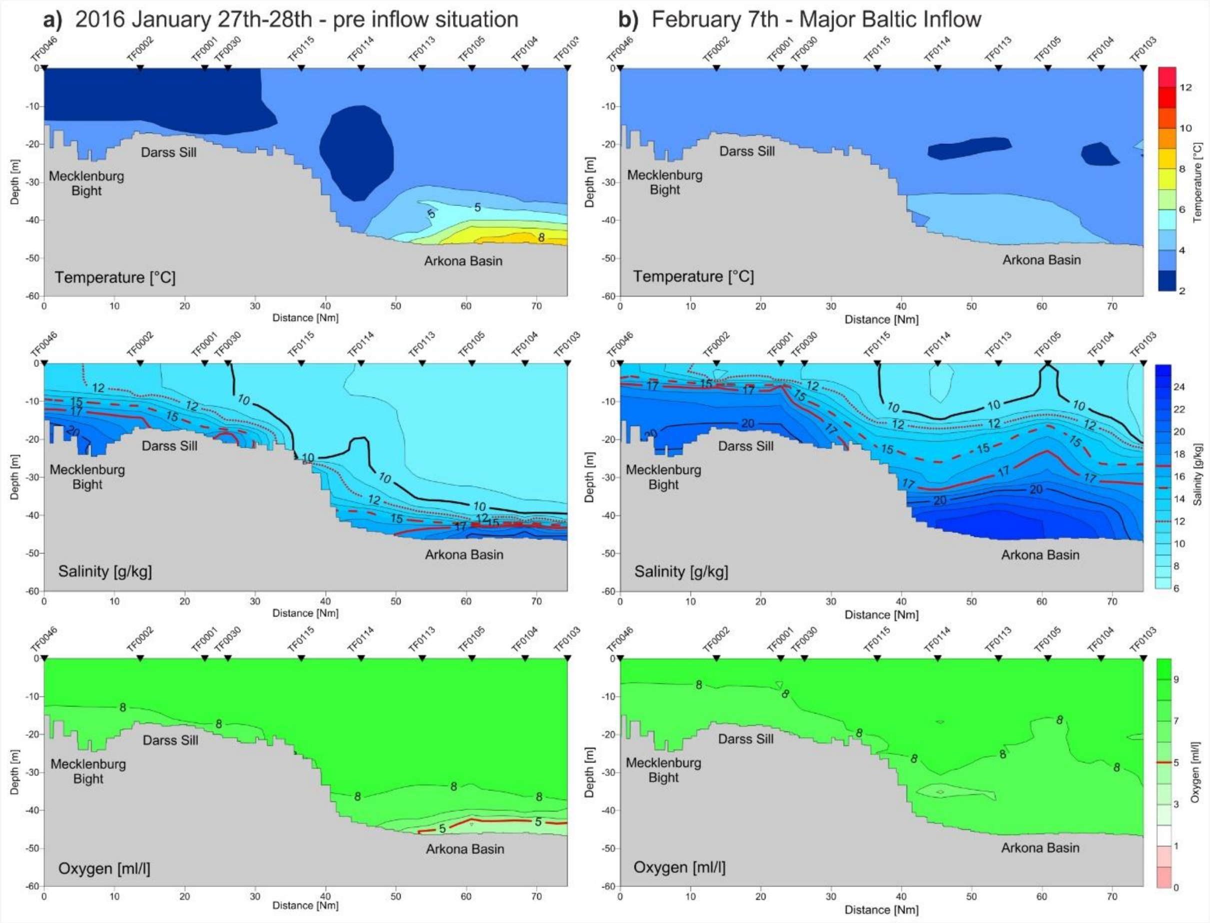

Abb. 3: Hydrographic changes in the Arkona Basin during January-February 2016 showing a next Major Baltic Inflow in a row occurring in the western Baltic Sea from 31st January to 06th February (cruise EMB-120). A) pre inflow situation showing high temperatures and low salinity in the deep water - halocline around 40 m depth, B) inflow situation – showing an uplifted halocline to 15 m depth, increased deep water salinity, lowered temperatures by inflow of cold winter water and increased bottom oxygen concentrations

In **March**, the through moved from Western to Central Europe and in the north low pressures “Bianca” and “Cordula” crossed the Baltic Sea region. High pressure “Joachim” controlled the weather situation up to March 17th inducing ongoing easterly winds (Figure 5b) and an outflow to a next lowstand of -26 cm MSL (station Landsort Norra) was reached to this time (Figure 7a). Afterwards low pressure cells “Frauke”, “Gaby”, “Hedi”, “Irmgard” and “Jeanne” dominated the weather situation with high pressure “Kurt” moving from Southern to Eastern Europe. Moderate westerly to southerly winds led only to slightly sea level rise of around 20 cm (Figure 5a, 7a). Along Germany’s Baltic Sea coast, monthly averages deviated by 0.5 K. At the station Arkona, a monthly mean of 3.7 °C (0.8 K deviation) was measured. Across northern Germany it was too dry, with amounts of precipitation between 30-50 % below the long-term average along the Baltic Sea coast. The average sunshine duration was 99 hours, 13 % lower than the long-term average of 114 hours. The station Arkona registered 105 hours of sunshine (81 %).

April showed the typical changeable weather with a dominance of low pressure cells crossing Northern Europe. Low Pressure “Quintana” crossed from April 17th to 19th the Baltic Sea with High “Norbert” across the British Isles inducing moderate to strong westerly winds of daily averages between 10.6 m/s to 12.2 m/s. During that time the sea level rose by 25 cm at Landsort Norra (Figure 7a). On all other days only light to moderate winds occurred and the sea level fluctuated during this month only slightly between -12 cm to +13 cm MSL. Temperatures along Germany’s Baltic Sea coast varied between -0.5 K (station Schleswig) and 0.7 K above the long-term average (station Arkona). Amounts of precipitation varied greatly from area to area: in Schleswig-Holstein, it was 62 % too wet in Schleswig; 60 % to wet in Rostock, but it was 35 % too dry at Arkona station and 53 % to dry in Ueckermünde on the Polish border. An average of 159 hours of sunshine across Germany was 7 % below the long-term average. In Northern Germany, the sun shone longer than in southern parts, for instance 196 hours as nation-wide maximum in Rostock-Warnemünde.

In **May**, the weather was mainly influenced high pressure cells “Oliver” and “Peter” across Central Europe and Scandinavia to the beginning of the months. Light to moderate easterly winds occurred causing slightly outflow to -25 cm MSL at Landsort Norra (Figure 5, 7a). Low pressure “Zoey” crossed from May 15th–17th the Baltic Sea and moderate west winds interrupted the outflow situation with a rapid sea level rise of 20 cm. Later on high “Quintus” and “Sören” induced easterly winds again and the sea level lowered to -15 cm MSL to the end of May. Along the German Baltic Sea coast, the air temperatures showed very warm values of 1.9 K above the long-term average. Arkona showed a monthly mean of 11.9 °C (+1.5 K). Amounts of precipitation were to dry and varied locally, for example Schleswig -44 % to dry, Rostock -81 % to dry, Arkona -42 % to dry and Ückermünde -62 % to dry compared to the long-term average. Nationwide only the south were to rainy and showed balanced to slightly to colt temperatures. The sunshine duration was with 220 hours in mean, 5 % above the long-term mean of 210 hours. Arkona registered 340 hours (125 %) as sunniest station.

The worldwide assessment of the NOAA (United States National Oceanic and Atmospheric Administration) classified the **June** 2016 with a mean temperature of 15.5 °C across continental and oceanic areas as “record warm” since the beginning of temperature measurements in the year 1880. It is the 14th month in a role, which showed worldwide a new temperature record and is 0.9 K above the mean of the 20th century. In Germany, the monthly mean of 17 °C was 1.3 K above the long-term average 1981-2010. The weather was dominated by low pressure cells crossing Northern Europe interrupted by high pressure “Volker” from 10th-15th June. Since June 18th up to the end of the month high pressure cells “Wolfgang” and “Xaver” moved as throughs from southwest to North-eastern Europe causing the first heatwave of the year (22th-25th June). The wind conditions during the month were calm with daily means up to 8.7 m/s (5 Bft), but mostly below 5.5 m/s (1-3 Bft) from westerly directions (Figure 5). The sea level fluctuated only slightly between -24 cm MSL to -5.8 cm MSL (Figure 7a). Along the German Baltic Sea coast the temperature was about 2 K warmer than the average 1981-2010, for instance Arkona of 16.1 °C (+ 1.9 K). Overall, June was too rainy with a mean of 115 mm precipitation compared to the long-term average of 77 mm (+33 %). This was caused by numerous thunderstorms mainly concentrated in Germany’s southern part. In contrast, the Northeast was mainly to dry, mirrored at Rostock (-35 %), Arkona (-53 %) and Ückermünde (-17 %). At 191 hours, sunshine duration was about 6 % slightly lower than the average of 204 hours. Arkona registered again the national top value of 303 hours (120 %).

The first half of **July** was influenced by low pressure cells crossing Scandinavia and Central Europe from the North Atlantic (lows “Oliane”, “Renate”, “Schekiba”, “Tiba”, “Ulrike” and “Vanessa”) and causing westerly winds (Figure 5b). At 6th July a summer storm (low “Renate”) occurred with a daily mean of 12.4 m/s (6 Bft) with gusts up to 23 m/s (9 Bft) registered at station Arkona (Figure 5a). The Sea level at Landsort Norra rose during this period around 27 cm from -5 cm MSL to 22 cm MSL (Figute 7a). Later on high “Burkhard” was located across the Baltic Sea region, bringing summer weather. Up to the end of the month calm easterly winds occurred, lowering the sea level around 20 cm to 0 cm MSL (July 31st). The monthly mean temperature accounts nationwide 18.6 °C (+0.6 K) and at the Baltic around 0.4 K above the long-term average. The precipitation was generally too low with 70 mm (-16 %), but varied along the Baltic Sea coast (Schleswig +7 %, Rostock -5 %, Arkona +65 % and Ückermünde -55 %). The sun shone 201 hours in average and was 10 % below the reference period 1981-2010. Longest sunshine duration was measured at station Rheinstetten (263 hours) in the southwestern part. Arkona recorded 245 hours (-12 %).

In **August,** the weather development was similar compared to July. Starting with dominance of low pressures crossing Scandinavia (lows “Arvenn”, “Christiane”, “Ella” and “Finni”) and high pressures “Carl”, “Daniel” and “Egbert” in Southern Europe, westerly winds occurred in combination with relatively low temperatures. At August 10th-11th a daily mean temperature of 13.3 °C was registered in Warnemünde and Arkona. At this time low pressure “Ella” crossed the Baltic Sea and daily means of wind exceeded 10 m/s (5-6 Bft) with gusts up to 20.5 m/s (8 Bft). The sea level rose around 30 cm up to mid-August. Later on classic summer weather returned under influence of highs “Faith” and “Gerd” since August 17th. Again easterly winds occurred and lowered the sea level (Figure 5, 7). Nationwide balanced mean temperatures occurred, the mean value of 17.7 °C was 0.2 K above the long-term average. At the German Baltic Sea, coastal values around the average were reached (0 K at Schleswig, 0.2 K at Rostock, 0 K at Arkona and -0.3 K at the station Ückermünde). The amount of precipitation was with 46 mm far below the average of 77 mm (-41 %). Along the Baltic Sea coast values varied from west to east (-13 % in Schleswig, -55 % in Rostock, -16 % in Arkona to -9 % in Ückermünde). Across Germany as a whole, sunshine duration was about 11 % (227 hours) above average at 206 hours. 240 hours were registered at Arkona (99 %), but the maximum of 272 hours showed the station Stuttgart-Schnarrenberg in Upper Rhine Rift at the southwestern part of Germany.

September was characterised by continuous widespread high pressure across Central Europe and Scandinavia (highs “Ian”, “Johannes”, “Karl”, “Lukas”, “Matthias”, “Nikolaus”, “Otto”). A long lasting very warm late summer period occurred. During the month, mainly light winds below 5.5 m/s (1-3 Bft) blew from eastern direction. Only at September 17th, stronger northeasterly winds with a daily mean of 10.7 m/s occurred. At the end of the month low pressures “ex-Karl” and “Walpurga” crossed Scandinavia between September 28th-30th, inducing strong westerly winds (>10 m/s). The sea level fluctuated between 17 cm MSL to -19 cm MSL. In the time series since 1881, the monthly temperature of 16.9 °C was far too warm by 3.4 K above the average 1981-2010 and September 2016 is on the same top level like the national record holder of 2006. At Arkona, a monthly temperature of 17.2 °C (+3.1 K) was reached. Rainfall of 39 mm was about 42 % below the average of 67 mm; at 215 hours of sunshine duration was 45 % above the long-term average 1981-2010. In the south-west of the Baltic Sea area, precipitation was as well far below the average (-48 % at Schleswig, -80 % at Rostock, -73 % at Arkona and -41 % at Ückermünde). In terms of sunshine duration, 233 hours (136 %)

was recorded at Arkona, but was overtaken by Berlin-Dahlem showing with 255 hours the nationwide maximum. Only September 1959 registered more sunshine!

The warm sunny September was followed by a cool cloudy **October**. The extensive high pressure “Peter” across Scandinavia was decisive for the weather in the Baltic Sea region up to October 26th. Central and Southern Europe were passed by low pressure cells from the North Atlantic (lows “Zofia”, “Andrea”, “Brigitte”, “Christa” and “Danielle”). Long lasting easterly winds caused an intensified outflow period resulting in a new lowstand of -44.5 cm MSL at October 19th (Figure 5, 7). During a storm from north-eastern direction, the highest daily average of the year 2016 with 18.7 m/s (8 Bft) was measured at October 6th. To the end of the month high “Peter” moved eastwards and the lows “Elisabeth II” as well as “Florentine” took the usual route across Northern Europe. Westerly winds caused an inflow of 53 cm sea level rise from October 19th to November 2nd comprising a total volume of 184 km³ (Figure 7a). Stations along the Baltic Sea coast recorded monthly temperatures that on average were in a range between 0 K at Arkona, -0.2 K at Schleswig, -0.5 K at Rostock and -0.6 K at Ückermünde. The nationwide average was 0.7 K (8.5 °C) too cold compared to the long-term mean of 1981-2010. With 56 mm, precipitation was 12 % below the average value of 63 mm; at 61 hours, sunshine duration was 43 % below average of 108 hours. Along the Baltic Sea coast, precipitation varied between 34 % at Schleswig and 4 % at Rostock too dry, in contrast to 42 % (Arkona) and 56 % (Ückermünde) too wet. The sun shone at Arkona station 48 hours (41 %). Only the years 1974 and 1998 were more cloudy.

At the beginning of **November**, the low pressure “Gisi” crossed the Baltic Sea region and the sea level at Landsort Norra reached a highstand of +8.8 cm MSL (November 2nd), pushed up from -44.5 cm MSL by strong westerly winds. Afterwards high “Siegfried” across Scandinavia controlled the situation to the middle of the months. In the south, the low pressures “Husch” and “Julia” crossed central Europe and easterly winds dropped the sea level to -23.4 cm MSL at November 14th. High “Siegfried” moved south-eastwards and a succession of the low pressures “Laura”, “Mirja”, “Nannette”, “Petrine” crossed Northern Europe up to November 23rd inducing moderate to strong south-westerly winds. Up to the end of the month, high “Thomas” across the British Isles and later on high “Uwe” in contrast to low pressures “Renate” as well as “Sanne” crossing northern Scandinavia were decisive for the weather. West to north-westerly winds occurred and the sea level rose stepwise (Figure 7). Cold and dry air masses dominated the weather pattern and the nationwide mean temperature was with 3.8 °C (-0.6 K) below the long-term average. With 56 mm of rainfall, conditions were clearly much too dry, and were 16 % below the thirty-year mean of 66 mm. The average sunshine duration of 60 hours was 13 % higher than the average of 54 hours. Along the coast, too, the negative temperature anomaly of in mean -0.6 K matched the Germanys nationwide assessment. Arkona recorded only 39 mm of rainfall, 81 % of what is usual in November. The sunshine duration there was 77 hours, 43 % above the average for 1981-2010.

After a cold previous month this situation changed in **December**, showing a positive anomaly of about 2.4 K along the southwestern Baltic Sea. Extensive high pressure cells (highs “Uwe”, “Wolfgang”, “Valentin”, “Xander” and “Yörn”) controlled the weather with cold and dry air masses across Central and Southern Europe. In contrast the low pressure cells from the North Atlantic crossed continuously Northern Europe (lows “Theresa”, “Ute”, “Vita”, “Waltraud” and “Xenia”). The sea level reached a new highstand of 30.6 cm MSL at December 11th (Figure 7a). At the middle of the month high “Wolfgang” and “Xander” spread as well across the Baltic Sea, lowering the sea level to -5.3 cm MSL (December 22nd). Around Christmas strong westerly to north-westerly winds occurred by low pressures “Zarina”, “Antje” and “Barbara” crossing quickly Northern Europe, inducing daily means of wind between 12.1 m/s to 15.2 m/s (6-7 Bft) and gusts up to 28.9 m/s (11 Bft) from December 24th t to 27th (Figure 5). The sea level at Landsort Norra rose rapidly to 44.3 cm MSL (Figure 7a). Cold temperatures in the south and mild ones in Northern Germany account to a mean temperature of 2.2 °C, which is 1 K above the long-term average. In contrast the station Arkona showed a mean temperature of 4.3 °C (+2 K) and Warnemünde of 4.7 °C (+2.4 K). At 27 mm, precipitation was far too low compared to the average of 72 mm (-62 %). The sunshine duration was nationwide at 65 hours (162 %) on the same record high level as 2015 and 1972. The German Baltic Sea coast followed this national trend of dry weather (-24 % at Schleswig, -4 % at Rostock, -16 % at Arkona and -10 % at Ückermünde). Arkona registered a sunshine duration of 58 hours (153 %), but in the south of Germany at the mountain Zugspitze in the Alpes the national maximum of 199 hours was measured.

2.3 Summary of Some of the Year’s Significant Parameters

An annual sum of 370943 J/m² of **solar radiation** was recorded at Gdynia. Lying in 36 place in the lower mid-range of a series of comparative data begun in 1956 (FEISTEL et al., 2008), this value is lower than the long-term average of 374 236 J/m². The sunniest months were June and May. At 64 107 J/m², June comes on 18th place in the first third in the long-term comparison (Table 1), but still fell well short of the peak value of 80 389 J/m² in July 1994, which represents the absolute maximum of the entire series. The year’s lowest value was 4126 J/m² in December, lying in 40th place below the long-term average of 4361 J/m².

With a **warm sum** of 267 Kd (Table 2), recorded at Warnemünde, the summer 2016 is ranked in the “top ten” over the past 69 years on 6th position and far above the previous year of 182.3 Kd on 22nd place. The 2016 value far exceeds the long-term average of 151.7 Kd, and exceeds the standard deviation, meaning that the year can be classified as a particularly warm one. Average monthly temperatures from May to September were above the long-term average, whereas the months April and October showed slightly colder temperatures. Especially May, June and September were far above the standard deviation. September is ranked as warmest in the time series since 1948 with 59.6 Kd, topping September 2006 by 1.5 Kd.

With a **cold sum** of 63.5 Kd in Warnemünde, the winter of 2015/16 is ranked in the upper midrange as 27th warmest winter in the long-term data series. A cold period in the first weeks of January led to a cold sum of 63 Kd which is far above the monthly long-term average on 16th place, but within the standard deviation (Table 2). All other winter months from November to April showed too warm values compared with the average.

Table 1: Monthly averaged weather data at Arkona station (Rügen island, 42 m MSL) from DWD (2016). t: air temperature, Δt: air temperature anomaly, h: humidity, s: sunshine duration, r: precipitation, Frost: days with minimum temperature below 0 °C, Ice: days with maximum temperature below 0 °C. Solar: Solar Radiation in J/m² at Gdynia station, 54°31‘ N, 18°33‘ O, 22 m MSL from IMGW (2017). Percentages are given with respect to the long-term mean. Maxima and minima are shown in bold.

Monat	t/°C	Δt/K	h/%	s/%	r/%	Frost	Eis	Solar
Jan	**0.4**	**-0.8**	87	118	69	**20**	**7**	5622
Feb	3	1.9	87	146	122	**10**	-	13281
Mrz	3.7	0.8	88	81	42	6	-	18208
Apr	6.7	0.7	80	95	65	1	-	44932
Mai	11.9	1.5	81	125	58	-	-	61543
Jun	16.1	1.9	80	120	47	-	-	**64107**
Jul	**17.7**	0.6	**79**	88	**165**	-	-	56035
Aug	17.3	0.0	no data	99	84	-	-	47943
Sep	17.2	**3.1**	**79**	136	**27**	-	-	37343
Okt	10	0.0	85	**41**	142	-	-	10490
Nov	5	-0.5	84	143	81	4	-	7313
Dez	4.3	2.0	**89**	**153**	84	6	-	**4126**

Table 2: Sums of daily mean air temperatures at the weather station Warnemünde. The ‘cold sum‘ (CS) is the time integral of air temperatures below the line $t = 0$ °C, in Kd, the ‘heat sum’ (HS) is the corresponding integral above the line $t = 16$ °C. For comparison, the corresponding mean values 1948–2015 are given.

Monat	KS 2015/16	Mittelwert	Monat	WS 2016	Mittelwert
Nov	0	2.5 ± 6.1	Apr	0	1.0 ± 2.4
Dez	0	21.4 ± 28.0	Mai	20.2	5.5 ± 6.8
Jan	63	38.9 ± 39.5	Jun	41.4	23.0 ± 14.5
Feb	0.5	31.0 ± 37.9	Jul	77.8	57.4 ± 36.1
Mrz	0	8.3 ± 12.0	Aug	68	53.0 ± 32.1
Apr	0	0 ± 0.2	Sep	59.6	11.5 ± 11.9
			Okt	0	0.4 ± 1.1
Σ 2015/2016	63.5	102.4 ± 85.5	Σ 2016	267	151.7 ± 68.5

Table 3: Sums of daily mean air temperatures at the weather station Arkona. The 'cold sum' (CS) is the time integral of air temperatures below the line *t* = 0 °C, in Kd, the 'heat sum' (HS) is the corresponding integral above the line *t* = 16 °C.

Monat	KS 2015/16	Monat	WS 2016
Nov	0	Apr	0
Dez	0	Mai	0.4
Jan	36.1	Jun	23.1
Feb	0	Jul	56.7
Mrz	0	Aug	49.6
Apr	0	Sep	40.4
		Okt	0
Σ 2015/2016	36.1	Σ 2016	170.2

Figures 4 to 6 illustrate the **wind conditions** at Arkona station throughout 2016. Figure 4 illustrates wind developments using progressive vector diagrams, in which the trajectory develops locally by means of the temporal integration of the wind vector. For comparison, the 2016 assessment (Figure 4a) and the long-term climatic wind curve derived from the 1951-2002 time series (Figure 4b) is shown. The 2016 curve (62 000 km eastwards, 24 000 km northwards) roughly follows the curve for the climatic mean (52 000 km eastwards, 25 000 km northwards), but showed in autumn a dominance of west-southwest to western directions instead the typical southwest winds. As a result of frequent changes in the direction of the wind and low intensity (Figure 5), the curve for 2016 shows strong wind vector compensation for the months April to June and September to October compared with the average for 1951-2002 (Figure 4a, b). The trend towards prevailing SW winds that began in 1981 and continues today (HAGEN & FEISTEL, 2008) is evident over the year. In January to March, May and September to October longer periods of easterly winds were occurring (Figure 5b). According to the wind-rose diagram (Figure 6), western to south-western directed winds account for about 50 % of the annual sum; easterly to north-easterly winds for a further 25 %. The mean wind speed of 6.5 m/s (Figure 5a) is lower than the long-term average of 7.1 m/s (HAGEN & FEISTEL, 2008). Comparing the east component of the wind (positive westwards) with an average of 2 m/s (Figure 5b) with the climatic mean of 1.7 m/s (HAGEN & FEISTEL, 2008), westerly winds were in 2016 only slightly stronger than the mean. With an average speed of 0.8 m/s, the north component of the wind (positive southwards) shows an equal value to the long-term average.

In line with expectations, the climatic wind curve in Figure 4b is smoother than the curves for individual years. It consists of a winter phase with a south-westerly wind that ends in May and picks up again slowly in September. In contrast, the summer phase has no meridional component, and therefore runs parallel to the x-axis. The most striking feature is the small peak that indicates the wind veering north and east, and marks the changeover from winter to summer. It occurs around 12 May and belongs to the phase known as the 'ice saints'. The unusually regular occurrence of this north-easterly wind with a return to a cold spell in Germany over many years has long been known, and can be explained physically by the position of the sun and land-sea distribution (BEZOLD, 1883).

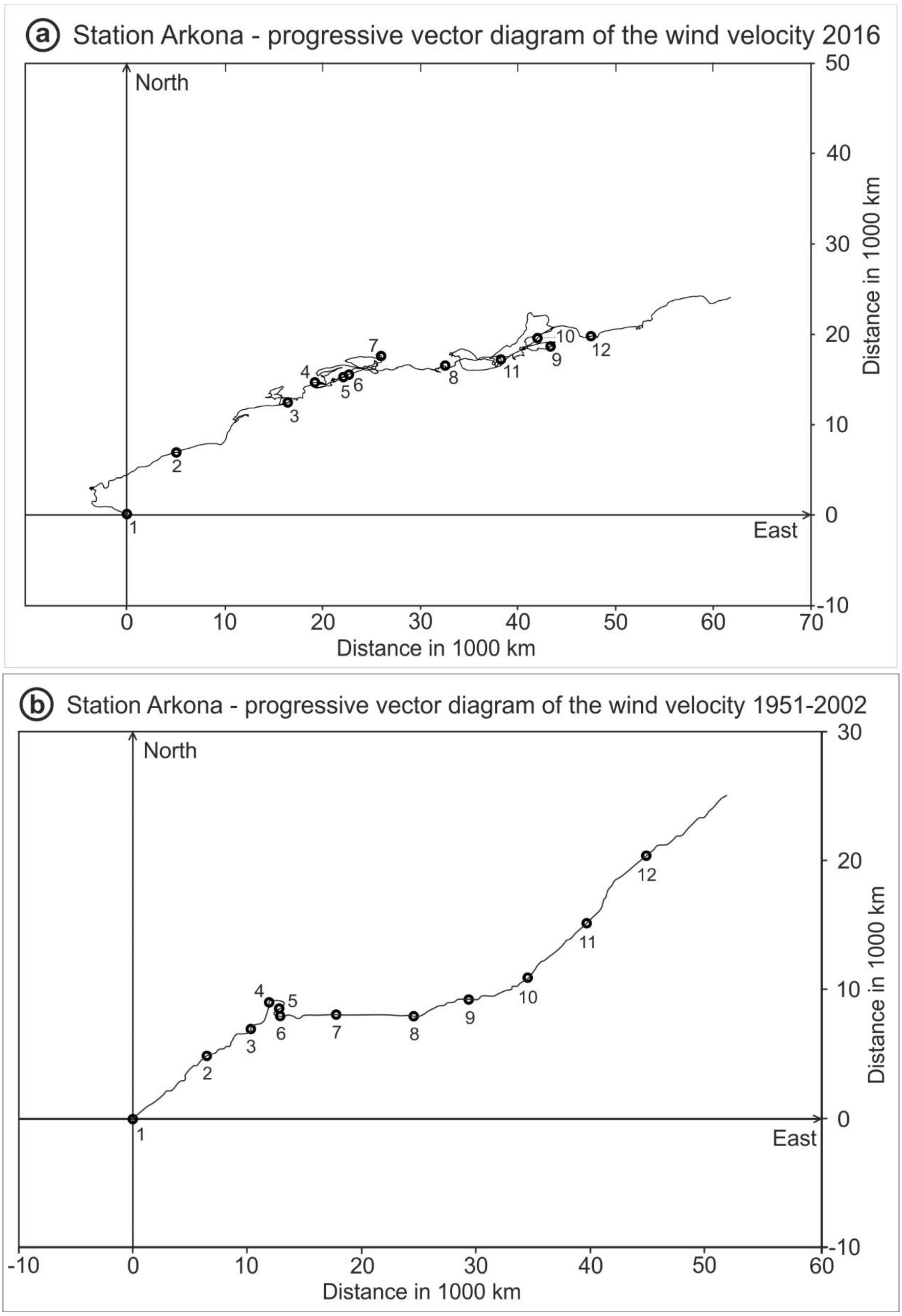

Fig. 4: Progressive vector diagram of the wind velocity at the weather station Arkona, distance in 1000 km, positive in northerly and easterly directions. The first day of each month is encircled. a) the year 2016 (from data of DWD, 2017) b) long-term average

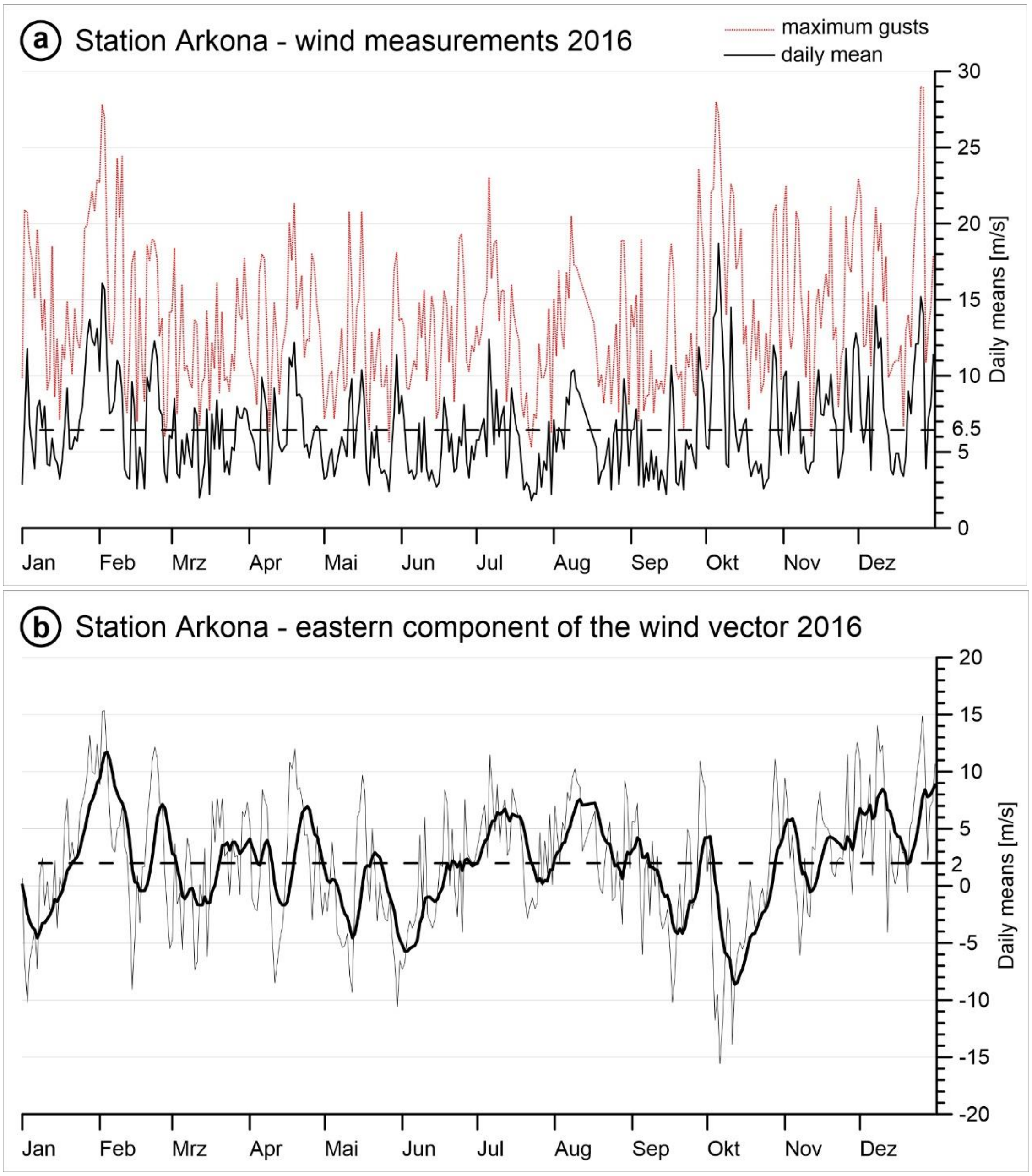

Fig. 5: Wind measurements at the weather station Arkona (from data of DWD, 2017). a) Daily means and maximum gusts of wind speed, in m/s, the dashed black line depicts the annual average of 6.5 m/s. b) Daily means of the eastern component (westerly wind positive), the dashed line depicts the annual average of 2 m/s. The line in bold is filtered with a 10-days exponential memory.

Wind development in the course of the year shows a typical distribution of stronger winds, as daily averages of more than 10 m/s (>5 Bft) were often exceeded in the winter half year (Figure 5a). From 5th–7th October a storm from north-eastern direction (low pressures “Zofia” and “Andrea” crossing central Europe) crossed the Baltic Sea as strongest wind event of the year, showing the highest daily average of 18.7 m/s and gusts up to 28 m/s (Figure 5a). Other storm events occurred from western direction at the beginning of February (low pressures “Norkys” and “Marita” across Scandinavia) with daily means of 16.1 m/s and gusts up to 27.8 m/s as well as on December 26th-27th (low pressure "Antje", daily mean of 15.2 m/s, gusts 29 m/s). The annual mean wind speed of 6.5 m/s is much lower than 2015's 7.2 m/s (NAUSCH et al., 2016) and the last recent years. Previous years showed following annual mean values of 6.7 m/s (2014), 7.0 m/s (2013), 7.1 m/s (2012) and 7.3 m/s in the year 2011 (NAUSCH et al., 2012, 2013, 2014, 2015). Maximum wind speeds in excess of 20 m/s (>8 Bft) were recorded as hourly means only at December 27th (21.3 m/s), February 3rd (20.2 m/s) and October 6th (20 m/s). In 2015 a similar maximum value of 21.9 m/s was reached on 10th January (NAUSCH et al., 2016). These recent values are far below previous peak values in hourly means of 30 m/s in 2000; 26.6 m/s in 2005; and 25.9 m/s (hurricane "Xaver") in December 2013. This is clearly illustrated by the wind-rose diagram (Figure 6) in which orange and red colour signatures indicating values greater than 20 m/s. They did only slightly occur in 2016.

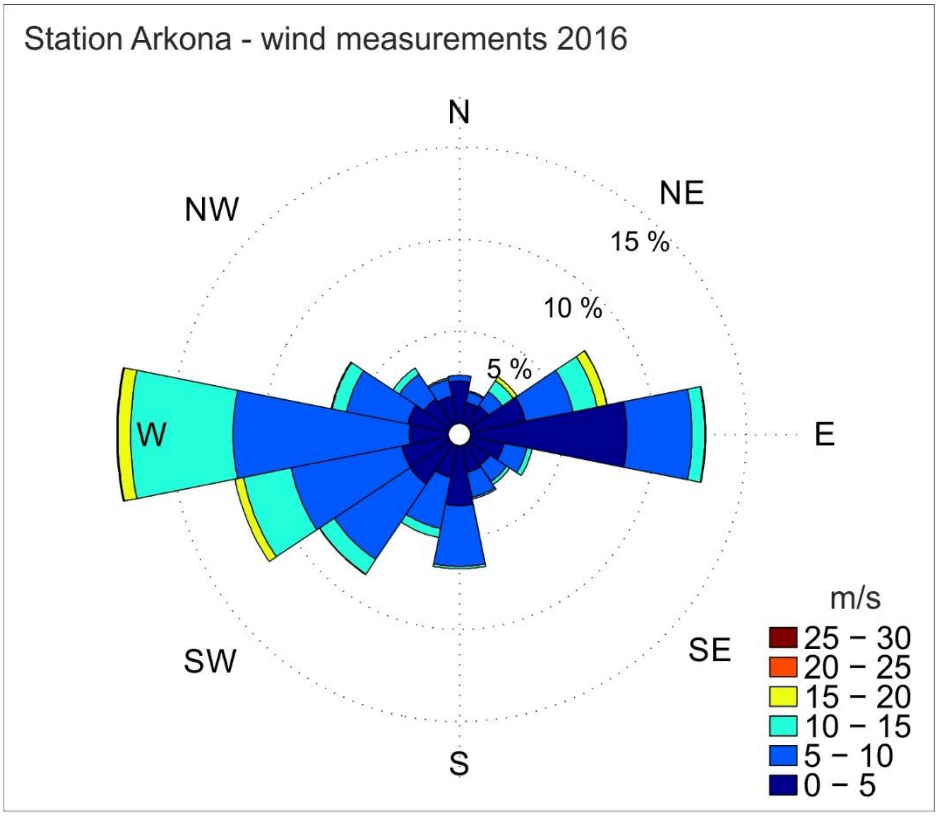

Fig. 6: Wind measurements at the weather station Arkona (from data of DWD, 2017) as windrose plot. Distribution of wind direction and strength based on hourly means of the year 2016

The Swedish tide gauge station at Landsort Norra provides a good description of the general water level in the Baltic Sea (Figure 7a). In contrast to previous years, after 2004 a new gauge went into operation at Landsort Norra (58°46’N, 17°52’E). Its predecessor at Landsort (58°45’N, 17°52’E) was decommissioned in September 2006 because its location in the lagoon meant that at low tide its connection with the open sea was threatened by post-glacial rebound (Feistel et al., 2008). Both gauges were operated in parallel for more than two years, and exhibited almost identical averages with natural deviations on short time scales (waves, seiches). Comparison of the 8760 hourly readings from Landsort (L) and Landsort Norra (L_N) in 2005 revealed a correlation coefficient of 98.88 % and a linear regression relation L + 500 cm = 0.99815 × L_N + 0.898 cm with a root mean square deviation (rms) of 3.0 cm and a maximum of 26 cm.

In the course of 2016, the Baltic Sea experienced four inflow phases with total volumes estimated between 171 km³ and 243 km³. Rapid increases in sea level that are usually only caused by an inflow of North Sea water through the Sound and Belts are of special interest for the ecological conditions of the deep-water in the Baltic Sea. Such rapid increases are produced by storms from westerly to north-westerly directions, as the clear correlation between the sea level at Landsort Norra and the filtered wind curves illustrates (Figures 5b, 7b). Filtering is performed according to the following formula:

$$\bar{v}(t)=\int_{0}^{\infty} \mathrm{d}\tau\, v(t-\tau)\exp(-\tau/10\,\mathrm{d})$$

in which the decay time of 10 days describes the low-pass effect of the Sund and Belts (well-documented both theoretically and through observations) in relation to fluctuations of the sea level at Landsort Norra in comparison with those in the Kattegat (Lass & Matthäus, 2008; Feistel et al., 2008).

Early in the year on January 17th, the gauge at Landsort Norra recorded a lowstand of -23 cm MSL (Figure 7a) as a result of preceding long lasting easterly winds. A system shift to strong westerly winds caused a sea level rise to 46.5 cm (February 3rd) and a resulting total volume of 243 km³ was calculated. With the empirical approximation formula:

$$\Delta V/km^3 = 3.8 \times \Delta L/cm - 1.3 \times \Delta t/d$$

(Nausch et al., 2002; Feistel et al., 2008), it is possible using the values of the difference in gauge level ΔL in cm and the inflow duration Δt in days to estimate the inflow volume ΔV. For this event a salt transport of 1.6 Gt and highly saline volume transport of 82 km³ was calculated at the sills and by CTD data in the Arkona Basin for the timespan January 31st and February 6th, which is classified as Major Baltic Inflow of moderate intensity. After the MBI of November 2015 (Nausch et al., 2016) this is a next salt water intrusion, but of cold winter water of 3.9 °C in mean and a high oxygen concentration of 7.5 ml/l in mean (Naumann, 2016). A long lasting outflow period occurred in the timespan February to March and a new lowstand of -26 cm MSL was reached. During springtime, the sea level fluctuated between 10 cm and -20 cm

MSL without large inflow volumes. From June to mid of August, the sea level increased stepwise from -30 cm MSL to 30 cm MSL. The warm late summer weather in September of low winds induced a baroclinic overflow of bottom salinity values up to 24 g/kg at the Darss Sill (see Chapter 3.3). In October, a next outflow period occurred by strong easterly winds (Figure 5) resulting in the lowest sea level of the year 2016 with a mark of -44.5 cm MSL at October 19th. In the following days up to November 2nd, the sea level rose to +8.8 cm MSL and a water volume of 184 km³ entered the Baltic Sea. After a short regression to -23 cm MSL (November 14th), the sea level rose stepwise within a month by single wind events to a mark of 31 cm MSL (December 11th) which presents a volume of 171 km³. Again outflow conditions occurred and a gauge level of -5 cm MSL was reached at December 22nd. During Christmas time strong westerly to north-westerly winds occurred and the sea level showed a mark of 44 cm MSL at December 27th which correlates to a volume of 182 km³.

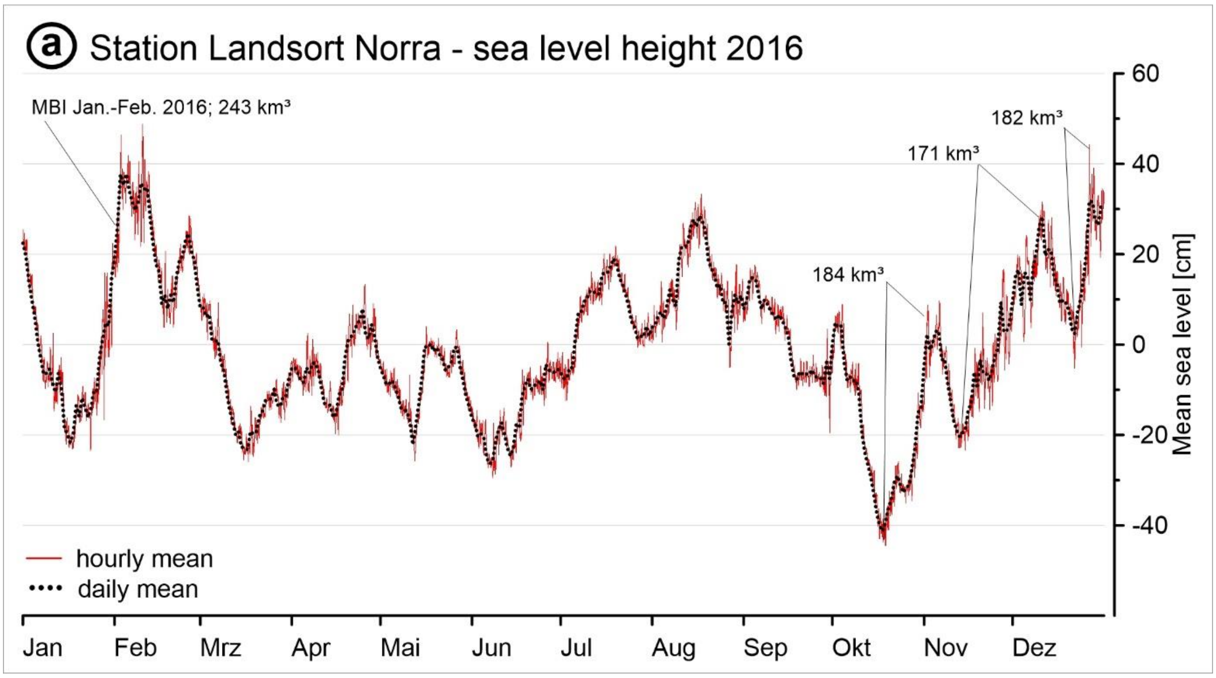

Fig. 7a: Sea level at Landsort as a measure of the Baltic Sea fill factor (from data of SMHI, 2017).

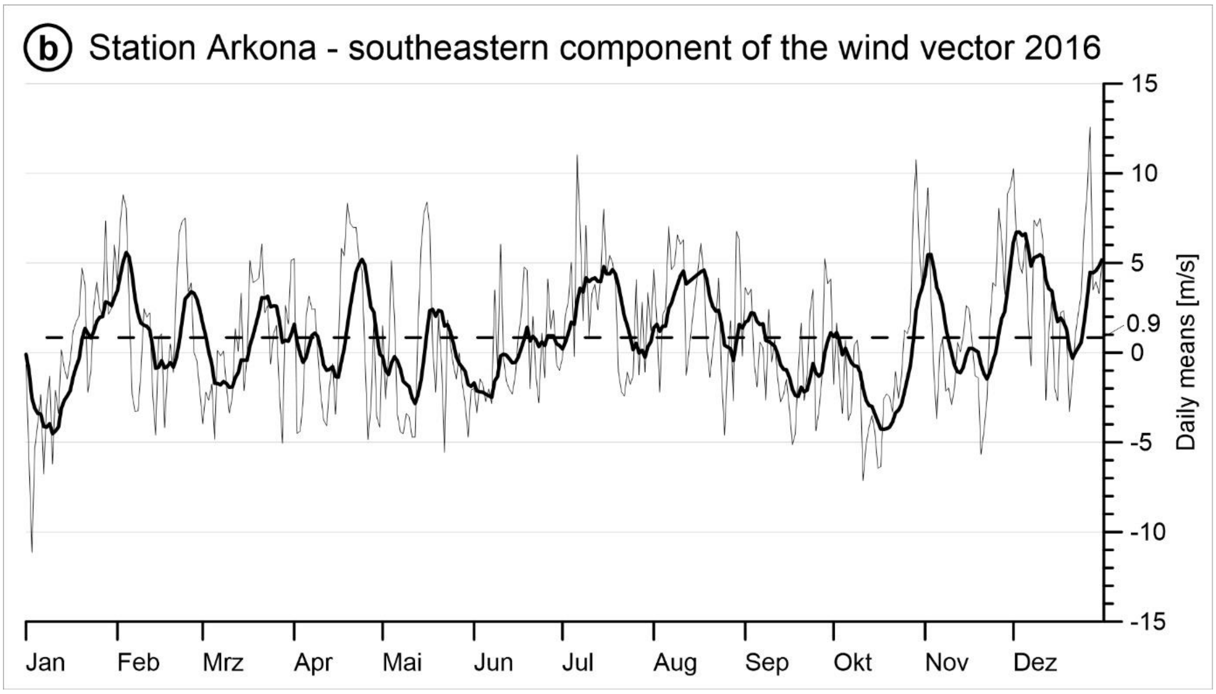

Fig. 7b: Strength of the southeastern component of the wind vector (north-westerly wind positive) at the weather station Arkona (from data of DWD, 2017). The bold curve appeared by filtering with an exponential 10-days memory and the dashed line depicts the annual average of 0.9 m/s.

3. Water Exchange through the Straits / Observations at the Monitoring Platform "Darss Sill"

The monitoring station at the Darss Sill supplied nearly complete records during the year 2016, except for a few occasional data gaps due to hardware problems. A corrupted memory card in one of the controlling computers led to a short data gap in all parameters (except for the ADCP data) between 10 and 22 February. Oxygen measurements at the deepest sensor were affected by cable damage, resulting in a few multi-week data gaps during the months of May and June. The ADCP provided full data records throughout the observation period. As usual, in addition to the automatic oxygen readings taken on the observation mast, discrete comparative measurements of oxygen concentrations were taken at the depths of the station's sensors using the Winkler method (cf. GRASSHOFF et al., 1983) during the regular maintenance cruises. Oxygen readings were corrected accordingly.

3.1 Statistical Evaluation

The bulk parameters determining the water mass properties at the Darss Sill were determined from a statistical analysis based on the temperature and salinity time series at different depths. The small data gap between 10 and 22 February (see above) was filled by interpolation. Sensitivity studies showed that this had no significant effect on the statistics.

The yearly mean temperatures (Table 4, Figure 8) show that the year 2016 belonged to one of the warmest years of the last 25 years. Surface layer temperatures were the second highest during this period, only slightly colder than the record-setting year 2014. This is consistent with the analysis of atmospheric data presented in chapter 2.3, where 2016 was shown to be the 6th warmest of the past 69 years. The standard deviation of the water temperature, also shown in Table 4 and Figure 8, largely mirrors the annual cycle. The values for 2016 are slightly above the multi-year average but otherwise unspectacular. It is likely that the relatively high surface temperatures in summer (see below) were partly compensated by the relatively mild winter temperatures, leading to an overall shallower annual cycle, and thus to a smaller standard deviation. Also this is consistent with the atmospheric data discussed in section 2.3, which revealed that the winter was significantly warmer than the long-term average.

Table 4: Annual mean values and standard deviations of temperature (T) and salinity (S) at the Darss Sill. Maxima in bold face

	7 m Depth		**17 m Depth**		**19 m Depth**	
	T	**S**	**T**	**S**	**T**	**S**
Year	**°C**	**g/kg**	**°C**	**g/kg**	**°C**	**g/kg**
1992	9,41 ± 5,46	9,58 ± 1,52	9,01 ± 5,04	11,01 ± 2,27	8,90 ± 4,91	11,77 ± 2,63
1993	8,05 ± 4,66	9,58 ± **2,32**	7,70 ± 4,32	11,88 ± 3,14	7,71 ± 4,27	13,36 ± 3,08
1994	8,95 ± 5,76	9,55 ± 2,01	7,94 ± 4,79	13,05 ± 3,48	7,87 ± 4,64	14,16 ± 3,36
1995	9,01 ± 5,57	9,21 ± 1,15	8,50 ± 4,78	10,71 ± 2,27	–	–
1996	7,44 ± 5,44	8,93 ± 1,85	6,86 ± 5,06	13,00 ± 3,28	6,90 ± 5,01	14,50 ± 3,14
1997	9,39 ± 6,23	9,05 ± 1,78	–	12,90 ± 2,96	8,20 ± 4,73	13,87 ± 3,26
1998	8,61 ± 4,63	9,14 ± 1,93	7,99 ± 4,07	11,90 ± 3,01	8,10 ± 3,83	12,80 ± 3,22
1999	8,83 ± 5,28	8,50 ± 1,52	7,96 ± 4,39	12,08 ± **3,97**	7,72 ± 4,22	13,64 ± **4,39**
2000	9,21 ± 4,27	9,40 ± 1,33	8,49 ± 3,82	11,87 ± 2,56	8,44 ± 3,81	13,16 ± 2,58
2001	9,06 ± 5,16	8,62 ± 1,29	8,27 ± 4,06	12,14 ± 3,10	8,22 ± 3,86	13,46 ± 3,06
2002	9,72 ± 5,69	8,93 ± 1,44	9,06 ± 5,08	11,76 ± 3,12	8,89 ± 5,04	13,11 ± 3,05
2003	9,27 ± 5,84	9,21 ± 2,00	7,46 ± 4,96	**14,71** ± 3,80	8,72 ± **5,20**	15,74 ± 3,27
2004	8,95 ± 5,05	9,17 ± 1,50	8,36 ± 4,52	12,13 ± 2,92	8,37 ± 4,44	12,90 ± 2,97
2005	9,13 ± 5,01	9,20 ± 1,59	8,60 ± 4,49	12,06 ± 3,06	8,65 ± 4,50	13,21± 3,31
2006	9,47 ± **6,34**	8,99 ± 1,54	8,40 ± 5,06	14,26 ± 3,92	9,42 ± 4,71	**16,05** ± 3,75
2007	9,99 ± 4,39	9,30 ± 1,28	9,66 ± 4,10	10,94 ± 1,97	9,63 ± 4,08	11,39 ± 2,00
2008	9,85 ± 5,00	9,53 ± 1,74	9,30 ± 4,60	-	9,19 ± 4,48	-
2009	9,65 ±5,43	9,39 ±1,67	9,38 ±5,09	11,82 ±2,47	9,35 ±5,04	12,77 ±2,52
2010	8,16 ± 5,98	8,61 ± 1,58	7,14 ± 4,82	11,48 ± 3,21	6,92 ± 4,56	13,20 ± 3,31
2011	8,46 ± 5,62	-	7,76 ± **5,18**	-	7,69 ± 5,17	-
2012	-	-	-	-	-	-
2013	-	-	-	-	-	-
2014	**10,58** ± 5,58	**9,71** ± 2,27	**10,01** ± 4,96	13,75 ± 3,53	**9,99** ± 4,90	14,91 ± 3,40
2015	-	-	-	-	-	-
2016	10,23 ± 5,63	9,69 ± 1,98	9,27 ± 4,59	14,07 ± 3,53	9,11 ± 4,43	15,56 ± 3,45

Table 5: Amplitude (K) and phase (converted into months) of the yearly cycle of temperature measured at the Darss Sill in different depths. Phase corresponds to the time lag between temperature maximum in summer and the end of the year. Maxima in bold face

	7 m Depth		17 m Depth		19 m Depth	
	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase
Year	K	Month	K	Month	K	Month
1992	7,43	4,65	6,84	4,44	6,66	4,37
1993	6,48	4,79	5,88	**4,54**	5,84	**4,41**
1994	7,87	4,42	6,55	4,06	6,32	4,00
1995	7,46	4,36	6,36	4,12	–	–
1996	7,54	4,17	6,97	3,89	6,96	3,85
1997	8,60	**4,83**	–	–	6,42	3,95
1998	6,39	4,79	5,52	4,46	–	–
1999	7,19	4,52	5,93	4,00	5,70	3,83
2000	5,72	4,50	5,02	4,11	5,09	4,01
2001	6,96	4,46	5,35	4,01	5,11	3,94
2002	7,87	4,53	6,91	4,32	6,80	4,27
2003	8,09	4,56	7,06	4,30	**7,24**	4,19
2004	7,11	4,48	6,01	4,21	5,90	4,18
2005	6,94	4,40	6,23	4,03	6,21	3,93
2006	**8,92**	4,32	7,02	3,80	6,75	3,72
2007	6,01	4,69	5,53	4,40	5,51	4,36
2008	6,84	4,60	6,23	4,31	6,08	4,24
2009	7,55	4,57	**7,09**	4,37	7,03	4,32
2010	8,20	4,52	6,54	4,20	6,19	4,08
2011	7,70	4,64	6,98	4,21	7,04	4,14
2012	–	–	–	–	–	–
2013	–	–	–	–	–	–
2014	7,72	4,43	6,86	4,17	6,77	4,13
2015	–	–	–	–	–	–
2016	7,79	4.65	6,33	4,33	6,11	4,23

The mean salinities and their standard deviations at the station Darss Sill are shown in Table 4 and Figure 9. In particular the values for the lowermost two sensors are a sensitive measure for the overall inflow activity. Figure 9 shows that both mean salinity and standard deviation computed from these near-bottom records are comparable to the year 2014, which was characterized by a particularly strong inflow event end of the December. Both 2014 and 2016 rank among the 3-4 years with the highest average salinities and standard deviations of the entire record. As discussed in detail below, strong inflow activity was also observed in 2016, which may explain the similarity between both years.

The amplitude and phase shift of the annual cycle were determined from a Fourier analysis of the temperature time series at 7 m depth (surface layer) and at the two lowermost sensors (17 m and 19 m depth). This method finds the optimal fit of a single Fourier mode (a sinusoidal function) to the data, from which amplitude and phase can then easily be inferred as the characteristic parameters of the annual cycle. The results are compiled in Table 5. Similar to the standard variations discussed above, Table 5 shows that also the amplitudes of the annual cycle at different depths are, although somewhat above the long-term average, far from the record-setting years (for example, the year 2006) that were characterized by particularly warm summers and cold winters. Interesting is the pronounced phase lag of approximately 0.3 – 0.4 months between the surface and near-bottom temperatures that is also evident from Table 5. As density stratification usually isolates the lower layers from direct atmospheric forcing, this phase lag mirrors the delayed arrival of surface waters from the Kattegat that propagate as dense bottom currents through the Great Belt before they arrive, with the above-mentioned delay, at the Darss Sill. The phase shift observed in 2016 was similar to previous years, and also the other phase parameters are well inside the typical range, suggesting that 2016 was, with respect to the timing of the thermal forcing, not an exceptional year.

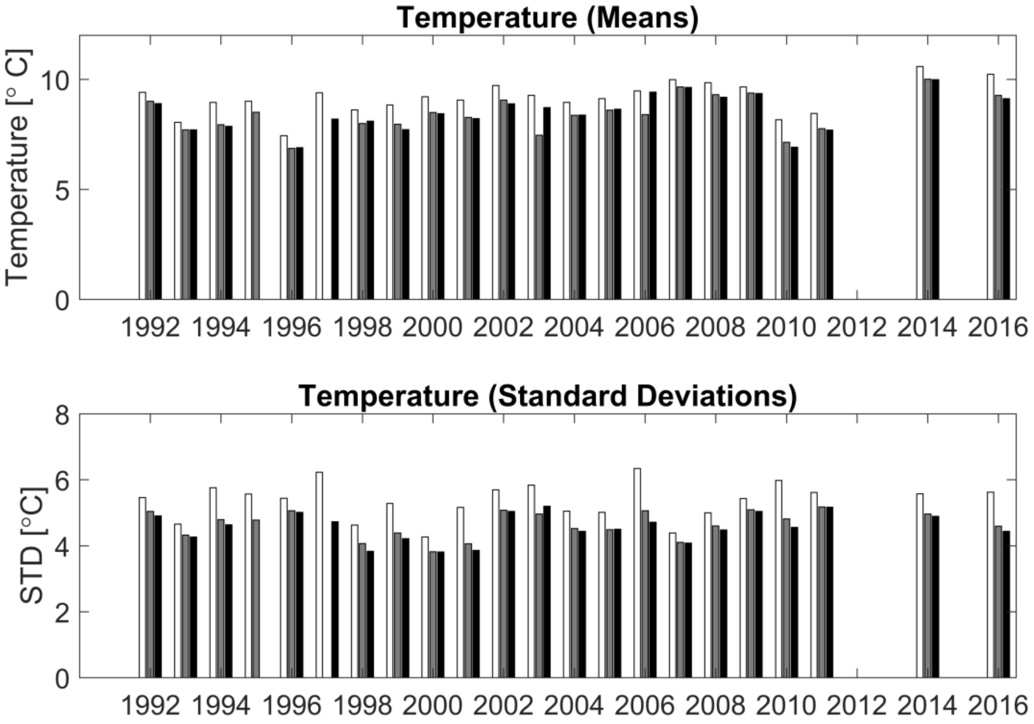

Fig. 8: Mean and standard deviation of water temperature taken over one year in the surface layer (7 m, white bars) and the bottom layer (17 m, grey bars and 19, black bars) at the Darss Sill

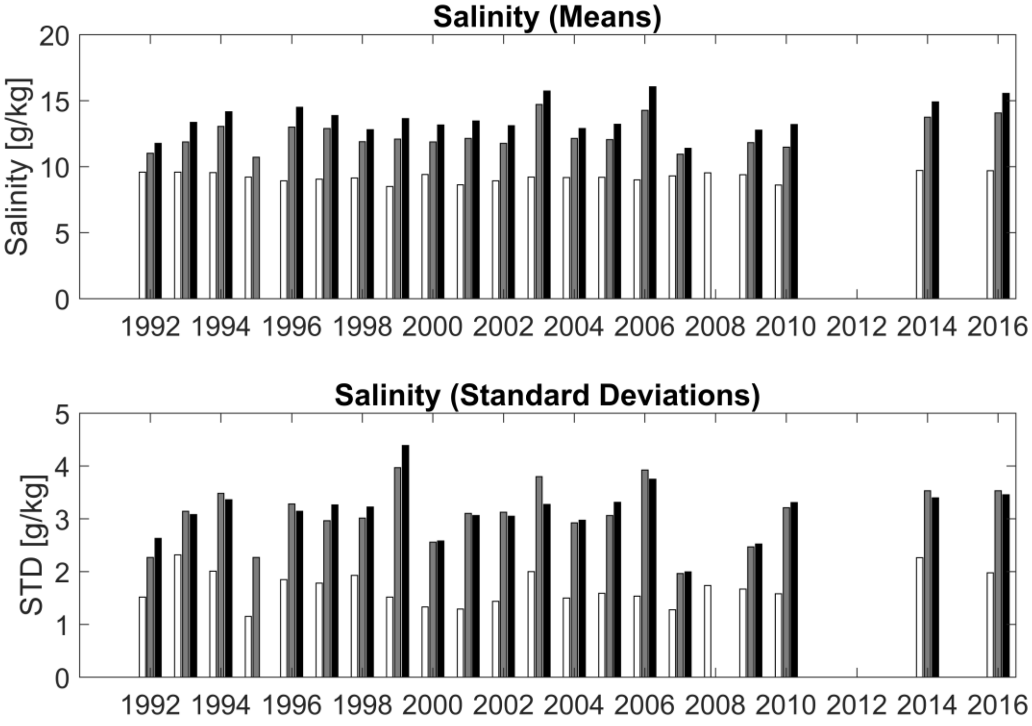

Fig. 9: Mean and standard deviation of salinity taken over one year in the surface layer (7 m, white bars) and the bottom layer (17 m, grey bars and 19, black bars) at the Darss Sill

3.2 Warming Phase with Major Baltic Inflow in January/February

Figure 10 shows the development of water temperature and salinity in 2016 in the surface layer (7 m depth) and the near-bottom region (19 m depth). As in the previous years, the currents observed by the bottom-mounted ADCP in the surface and bottom layers were integrated in time, respectively, in order to emphasize the low-frequency baroclinic (depth-variable) component, plotted in Figure 11 as a ‘progressive vector diagram’ (pseudo-trajectory). This integrated view of the velocity data filters short-term fluctuations, and allows long-term phenomena such as inflow and outflow events to be identified more clearly. According to this definition, the current velocity corresponds to the slope of the curves shown in Figure 11, using the convention that positive slopes reflect inflow events.

The first weeks of the year 2016 were characterized by outflow conditions, driven by persistent easterly winds (see Figures 5 and 7b), which finally resulted in gauge levels as low as -23 cm at Landsort Norra (Figure 7a). These low water levels set the scene for the most important inflow event of the year 2016, which was triggered by a gradual turning of the winds to westerly directions mid of January (Figures 5 and 7b). On 17 January, also the currents at the Darss Sill turned from outflow to inflow conditions (Figure 11), and bottom salinities rapidly increased (Figure 10). The strong salinity contrast between the surface and bottom layers might be interpreted as a strong baroclinic component during the initial phase of the inflow but this is not supported by the velocity data shown in Figure 11. Salinities exceeded the value of 21 g/kg in the first week of February in the near-bottom region, and the salinities in the surface layer were only slightly smaller. On 05 February, inflow velocities gradually decreased, and finally, on the evening of the same day, changed to persistent outflow directions (Figure 11). This day terminated the Major Baltic Inflow 2016, and set the starting point for an extended period of outflow conditions lasting until mid of March with a few short interruptions.

As discussed in chapter 2.3, approximately 243 km^3 of water and 1.6 Gt of salt were imported during this event, which therefore can be classified as an MBI of intermediate intensity. Current measurements at the Öresund, conducted by SMHI, indicate that this second inflow pathway contributed approximately 40 km^3 (or 16%) (http://www.smhi.se/hfa_coord/BOOS/Oresund.html). The temperatures of the intruding waters varied between approximately 2 °C and 4.5 °C. The densest near-bottom waters (salinities near 21 g/kg), observed in the first week of February, were, however, characterized by a much narrower temperature range of 3.5-3.8 °C, which should facilitate their identification in the downstream basins. Oxygen concentrations (Figure 12) were close to the saturation point. The MBI 2016 was therefore a typical example for a barotropic winter inflow event with high oxygen concentrations.

The unusually cold air temperatures in January (chapter 2.3) resulted in a rapid decrease of the mixed-layer temperatures at the station Darss Sill during the first weeks of January (Figure 10). The lowest hourly mean temperatures of the year were observed on 23 January, when values as low as 1.9 °C were observed 2 m below the surface. The temperature minimum in the near-bottom region was reached with a slight delay due to the time required to advect the cold surface waters from the Kattegat as a dense bottom current through the Danish straits. Temperatures during the outflow period following the MBI 2016 stagnated around 3-4 °C until mid of March.

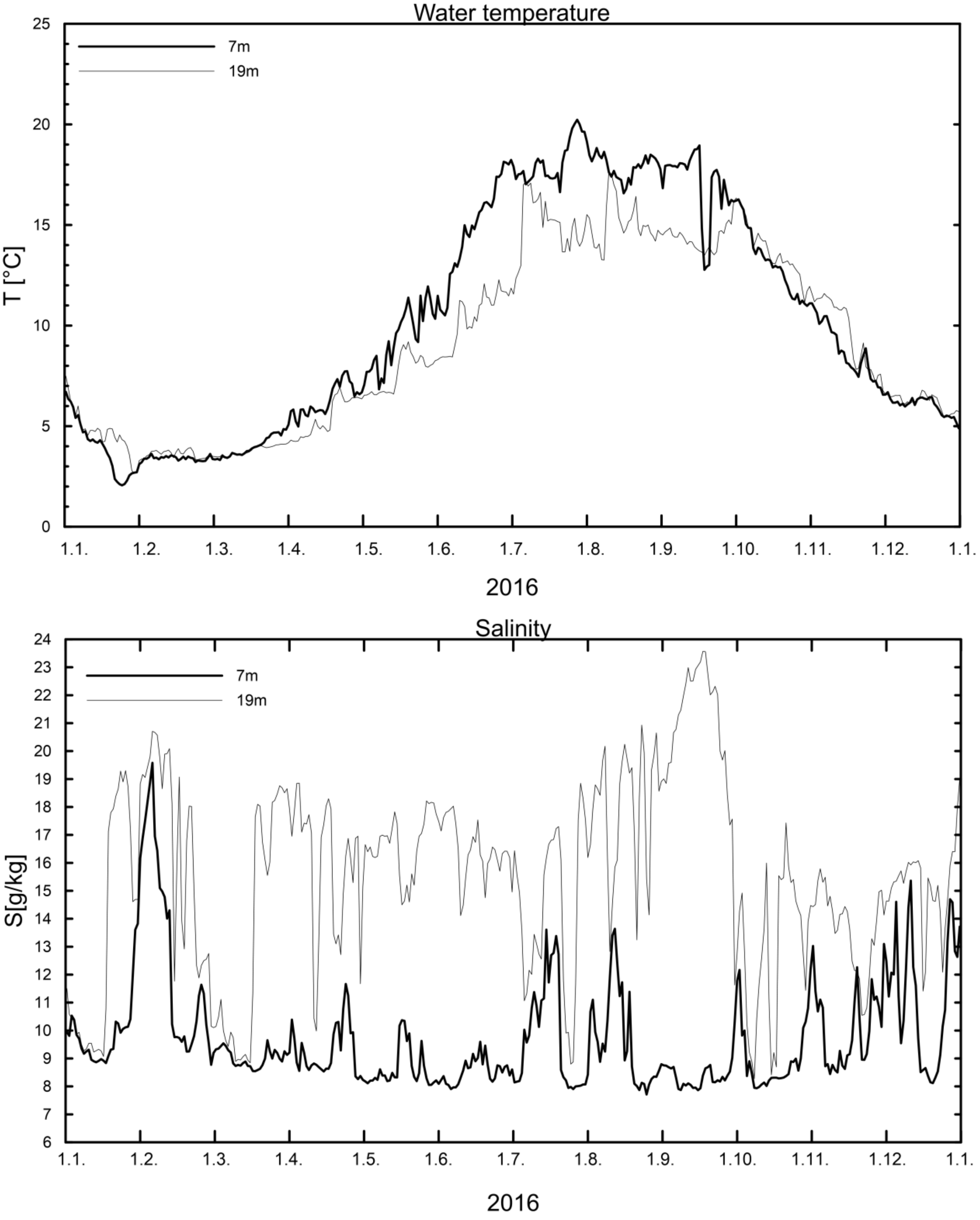

Fig. 10: Water temperature (above) and salinity (below) measured in the surface layer and the near bottom layer at Darss Sill in 2016

The following warming period until beginning of June was characterized by a series of smaller inflow events, the first of which was initiated by a pulse of high-salinity waters in the bottom layer on 17 March. Water levels during this period (Figure 7a) fluctuated only weakly around slightly negative values, and the velocity records (Figure 11) suggest a long-term baroclinic tendency with near-surface outflow and near-bottom inflow. This baroclinic trend is also mirrored in the salinity data shown in Figure 10, indicating that the intruding salty waters only occasionally affected the surface layers. Due to the persistent density stratification, temperatures in the bottom layer evolved in a step-like pattern, where short stagnation periods during outflow conditions alternated with rapid temperature increases induced by the arrival of new inflow pulses. Due to the cable problems mentioned at the beginning of this chapter, oxygen data during this period are sparse but the continued moderate inflow activity suggests that the development of pronounced oxygen minima is unlikely (Figure 12).

The current measurements in Figure 11 show that the baroclinic trend was terminated by a reversal of the velocities in the near-bottom layer in the second week of June, inducing a 6-week period with only occasionally interrupted barotropic inflow. Water levels (Figure 7a) increased during this period by approximately 40 cm. With the intensification of the inflow beginning of July, waters with higher salinities started to affect the entire water column (Figure 10), and oxygen levels remained above the threshold of 80 % saturation (Figure 12). Mid of July, the inflow became weaker, and on 20 July the currents across the Darss Sill switched to outflow conditions (Figure 11). As a consequence, water levels at Landsort started to decrease (Figure 7a), salinities collapsed (Figure 10), and oxygen concentrations started sinking (Figure 12). The most pronounced decrease in oxygen was observed on 27 July, when saturations dropped from 80 % to less than 44 % percent saturation within a few hours. A rapid increase in salinity at the same time, combined with outflow velocities, indicates that the upwelled oxygen-depleted bottom waters from the Arkona Basin arrived at the station.

During the following 2-week inflow period between beginning and mid of August, water levels at Landsort increased to the highest value since the end of the MBI in February (Figure 7a). This pronounced event terminated the inflow trend that characterized the entire summer period. It was strong enough to leave a clear imprint on the surface salinities (Figure 10), and resulted in a recovery of the oxygen concentrations up to full saturation (Figure 12). Also the temperatures of the bottom waters imported with this inflow event reached, although only for a short period, those of the surface waters. The highest temperatures of the year were observed a few days before the beginning of the inflow period, on 26 July, when an hourly mean value of approximately 20.5 °C was reached in the surface layer. This is more than 2 °C warmer compared to the previous year, underlining the exceptionally warm summer of 2016.

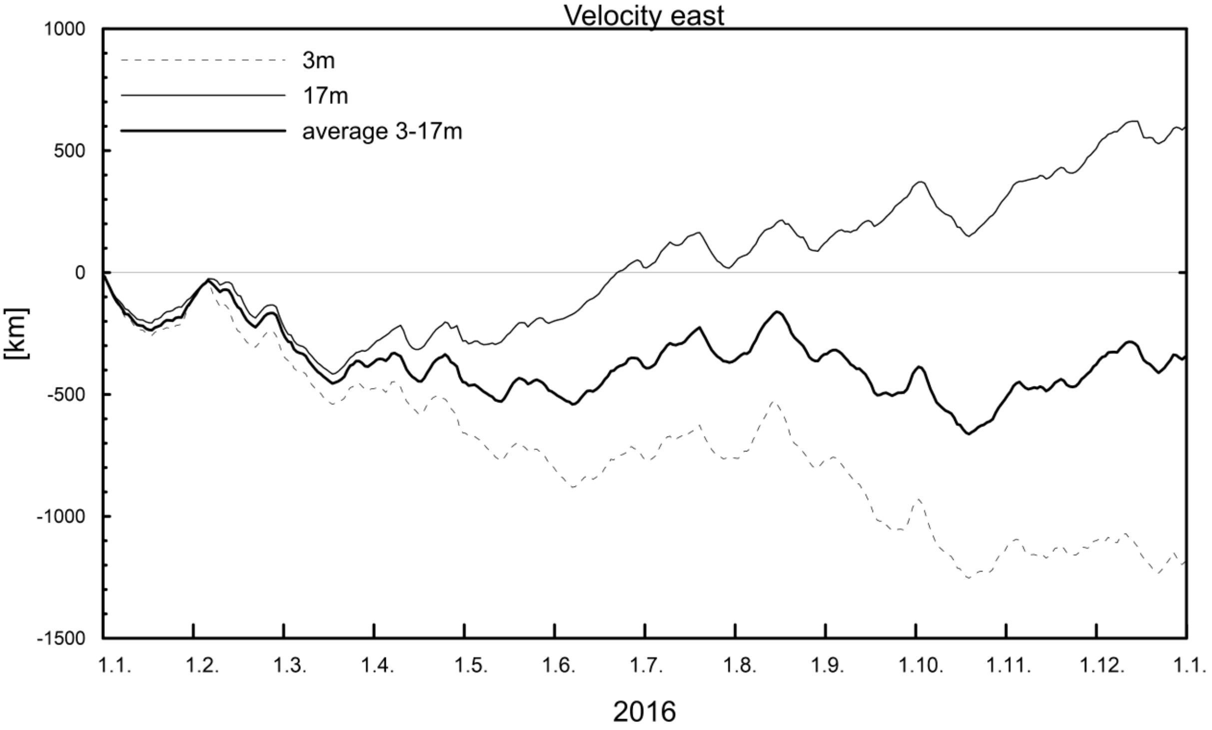

Fig 11: East component of the progressive vector diagrams of the current in 3 m depth (solid line), the vertical averaged current (thick line) and the current in 17 m depth (dashed line) at the Darss Sill in 2016

3.3 Cooling Phase with inflows events of intermediate strength

Decaying easterly winds terminated the last of the summer inflow pulses around mid of August, thus triggering a quick relaxation of the sea level to near-neutral values (Figure 7a). On 29 August, winds reversed to easterly directions again, and a short episode of barotropic inflow was established at the Darss Sill. The following month of September was characterized by relatively low wind speeds (Figure 7b), and, accordingly, small vertical mixing that permitted the evolution of stratification inside the shallow Danish Straits. As a consequence, an extended period with baroclinic inflow activity developed, as most directly evident in the velocity data shown in Figure 11. While almost the entire month of September was characterized by near-bottom baroclinic inflow, brackish surface waters left the Baltic Sea at the same time. The Landsort gauge showed no clear indications for falling or rising water levels, suggesting an approximately balance between inflow and outflow (Figure 7a). Remarkable are the high salinities observed in the bottom layer during this period: values of up to 24 g/kg by far exceeded those of the MBI in February, and therefore constituted the highest values of the year. Interestingly, despite the high salinities and continued inflow activity, the effect of the baroclinic near-bottom inflow on the oxygen concentrations was detrimental (Figure 12). The inflow waters were characterized by exceptionally low oxygen concentrations, at least 40 % below the saturation level, which most likely reflected enhanced oxygen consumption in the Danish Straits. The still relatively high bottom water temperatures might have increased microbial turnover and respiration rates in this area. However, as the intruding waters only affected the lowest meters of the water column (not shown), it seems unlikely that large amounts of oxygen-depleted waters entered the Arkona Basin during this period.

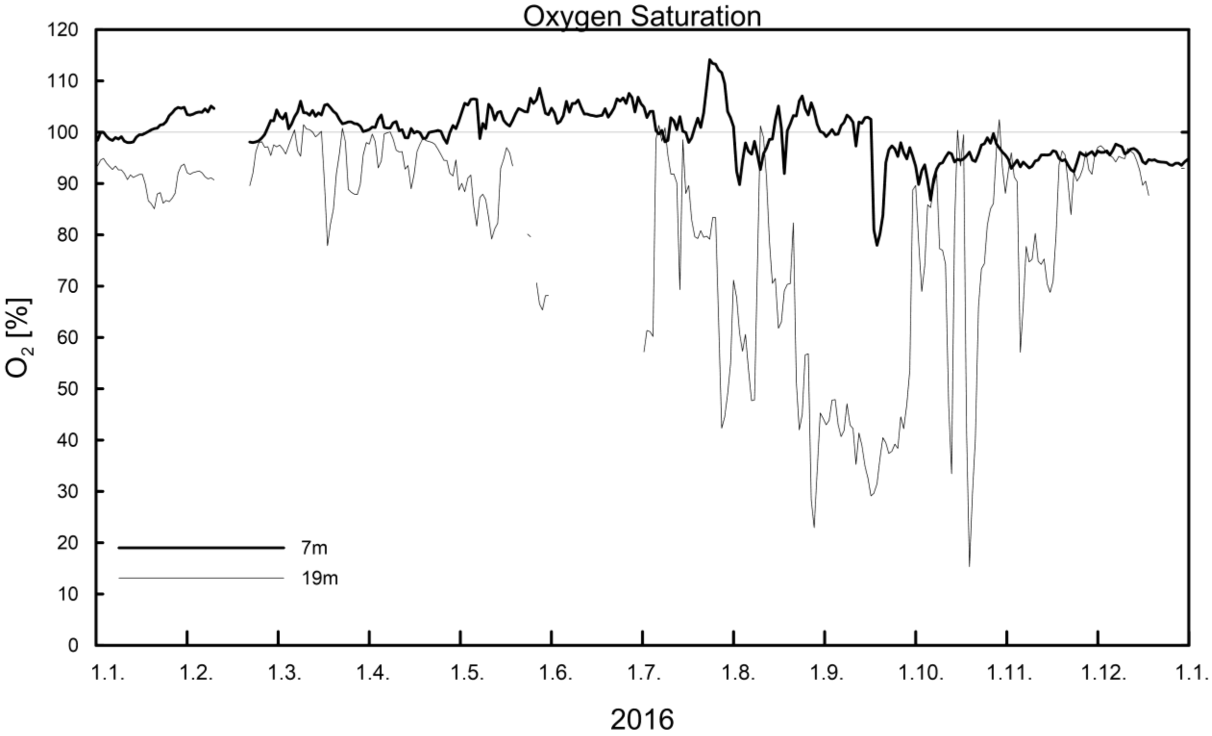

Abb. 12: Oxygen saturation measured in the surface and bottom layer at the Darss Sill in 2016

More relevant than the baroclinic inflow period in September were, however, two intermediate-strength inflow events occurring in October and in the second half of November. Both are clearly visible in the sea level variations shown in Figure 7a. The first of these events was prepared by a vigorous outflow period during the first half of October that followed a short and therefore inconsequential inflow peak at the beginning of the same month. Around 15 October, water levels at Landsort had reached a value close to -40 cm, which formed the absolute minimum of the year 2016. The resulting sea level difference across the Danish straits was strong enough to overcome the effect of the initially still opposing winds, triggering weak inflow activity on 18 October. Comparing the velocity records from the surface and bottom layers (Figure 11) shows that the inflow had a clear baroclinic component, and was enhanced in the last week of October during a period with strong westerlies (Figure 7b). On 04 November, the inflow in the surface layer ceased and water levels at Landsort were close to neutral values (Figure 7a) but the baroclinic pressure gradients were still sufficient to support weak near-bottom inflow. This inflow event left a clear signature in the surface salinities at the station, and resulted in an increase of the bottom oxygen concentration up to saturation levels (Figure 12). Maximum salinities, observed in the first week of November, were around 15 g/kg at temperatures slightly above 11 °C. As discussed in chapter 2.3, with a total import of 184 km^3 of water, this event was the second strongest of the year 2016. The velocity records of SMHI suggest that only a small fraction of this the overall inflow volume (approximately 20 km^3) entered the Baltic Sea through the Öresund (http://www.smhi.se/hfa_coord/BOOS/Oresund.html).

The processes occurring during the first half of November, after the end of inflow phase described above, present a somewhat puzzling behaviour. While the velocity records at the Darss Sill suggest only little water exchange near the surface, and even a tendency for weak inflow at the bottom, the water levels at Landsort indicate strong outflow conditions (Figures 7a and 11). This contradiction can, at least partly, be resolved by the velocity measurements of SMHI in the Örseund (http://www.smhi.se/hfa_coord/BOOS/Oresund.html), which indicate outflow conditions until mid of November, thus partly compensating the inflow across the Darss Sill. This is a rather exceptional situation, in which small-scale water level differences in the region of the Danish Straits seem to have resulted in opposing transports across the Great Belt and Öresund, respectively.

The following period until approximately mid of November was characterized by unusually low winds and sinking sea levels at Landsort (Figure 7). Outflow during this period is supported by the current measurements of SMHI in the Öresund, whereas the velocity record at the Darss Sill indicates negligible net transports near the surface and even weak inflow in the near-bottom region (Figure 11). In the last week of November, this near-bottom inflow strengthens and extends to higher level before it collapses mid of December due to changing wind directions. Water levels at Landsort had increased by nearly 50 cm during the entire period between mid of November to mid of December, which, as computed in chapter 2.3, corresponds to an overall important of 171 km^3 of water. Oxygen concentrations of the imported waters were close to saturation throughout the water column (Figure 12) but maximum salinities remained below 16 g/kg at temperatures around 6.5 °C (Figure 10). It is therefore unlikely that these oxygen-rich waters have the potential to significantly contribute to the ventilation of the deep layers of the downstream basins. However, as discussed in more detail in the following chapter, waters with higher salinities might have passed through the Öresund during this and the preceding inflow event in October.

The last important event of the year was triggered by strong westerly winds (with the highest wind speeds of the year) in the second half of December (Figure 7b). After the water levels at Landsort had decreased to near-neutral levels, they rapidly increased again as a result of this wind event, indicating a short but intense inflow period (Figure 7a). Also the velocity records shown in Figure 11 suggest a 5-day barotropic inflow pulse between 22 and 27 December. This event is also reflected in a rapid increase in near-surface salinities (Figure 10). Oxygen concentrations are close to saturation. Water temperatures at the end of the year were around 5 °C, approximately 2 °C warmer compared to the previous year.

4. Observations at the Buoy “Arkona Basin”

The dynamics of saline bottom currents in the Arkona Basin was investigated in detail some years ago in the framework of the projects “QuantAS-Nat” and “QuantAS-Off” (Quantification of water mass transformation in the Arkona Sea), funded by the German Research Foundation (DFG) and the Federal Ministry for the Environment (BMU). Data from these projects included the first detailed and synoptic turbulence and velocity transects across bottom gravity currents passing through a channel north of Kriegers Flak during a number of medium-strength inflow events (Arneborg et al., 2007; Umlauf et al., 2007; Sellschopp et al., 2006). In a pilot study, Burchard et al. (2009) investigated the pathways of these haline intrusions into the Arkona Basin in 2003 and 2004. They identified the channels north of Kriegers Flak and the Bornholm Channel as zones of greatly intensified mixing, and validated their model results using data from the MARNET monitoring network as published in this report series every year. The theoretical analysis of these data revealed a surprisingly strong influence of Earth’s rotation on turbulent entrainment in dense bottom currents, leading to the development of new theoretical model that take rotation into account (Umlauf & Arneborg, 2009a, b, Umlauf et al., 2010). The correct representation of the turbulent entrainment rates in numerical models of the Baltic Sea is known to be essential to predict the final interleaving depth and ecosystem impact of the inflowing bottom gravity currents in the deeper basins of the central Baltic Sea. Recently, a comparison of MARNET data with the results of new generation of three-dimensional models with adaptive, topography-following numerical grids has shown that the model was able to provide an excellent representation of the processes in the Western Baltic Sea also during MBIs, taking the record-setting MBI 2014 as an example (Gräwe et al., 2015).

The Arkona Basin monitoring station described in this chapter is located almost 20 nm north-east of Arkona in 46 m water depth. As in the previous years, the station again provided complete temperature and salinity records. Oxygen measurements from the period between 20 October and 13 December are, however, lacking due a malfunctioning of the optical oxygen sensor. A system reboot during one of the maintenance cruises solved the problem; the reasons for the failure could not be reconstructed. As described in chapter 3, the optode-based oxygen measurements at the monitoring station were corrected with the help of the Winkler method, using water samples collected and analysed during the regular MARNET maintenance cruises. Figure 13 shows the time series of water temperature and salinity at depths of 7 m and 40 m, representing the surface and bottom layer properties. Occasionally, also data from the uppermost (2m depth) and the deepest sensor (43 m depth), both not shown in the figure, will be discussed. Corresponding oxygen concentrations, plotted here as saturation values, are shown in Figure 14.

During the first weeks of the year, the surface layer at the Arkona station still showed a gradual cooling trend with temperatures decreasing from 6.5 °C at the beginning of January down to approximately 3.2 °C one month later (Figure 13). In February, daily mean temperatures fluctuated between 2.7 °C and 4.2 °C, where the lower value, reached on 19 February, marked the minimum temperature of the year 2016. This minimum temperature was slightly smaller than the value of 3.4 °C recorded in the previous year but substantially larger than the minimum temperature of 0.9 °C observed in 2013. The mirrors the relatively mild conditions of the winter 2015/2016.

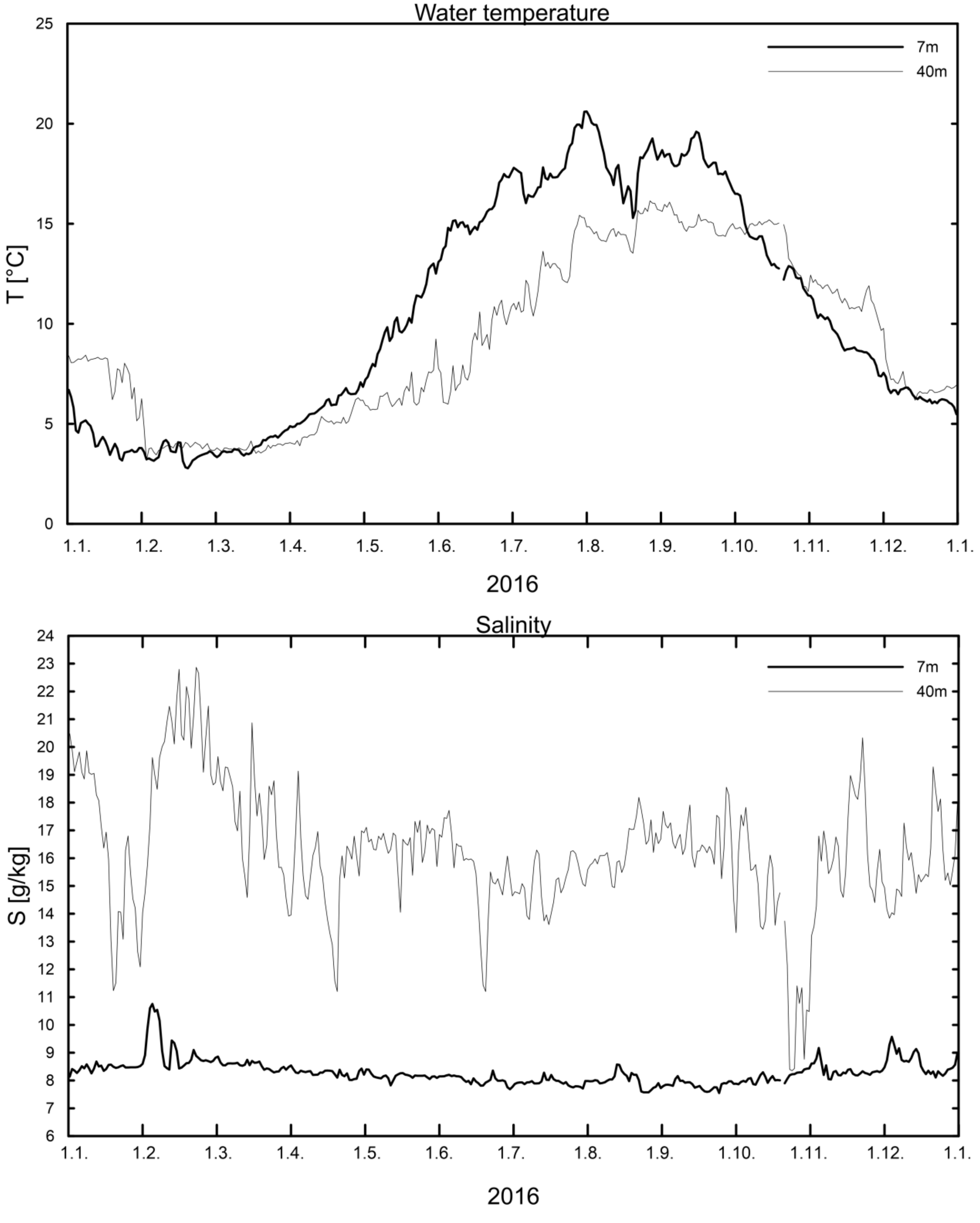

Fig. 13: Water temperature (above) and salinity (below) measured in the surface layer and near bottom layer at the station AB in the Arkona Basin in 2016

The bottom waters, usually decoupled from direct atmospheric forcing by the presence of a strong halocline, exhibited a similarly strong temperature drop from 8.4 °C at the beginning of January down to values comparable to those in the surface layer during the first weeks of February. Remarkable is in particular the abrupt decrease between end of January and the first week of February that indicates the arrival of the cold and salty inflow waters of the MBI 2016 described in the previous chapter (Figure 13). The presence of this new water mass became evident on 02 February, when salinities at the deepest sensor (43 m depth, not shown) exceeded 16 g/kg and water temperatures decreased to less than 4.5 °C, remaining below this threshold for the following two weeks. On the same day, salinities at 16 m exceeded the value of 10 g/kg for the first time in the new year, and further increased up to almost 14 g/kg on 06 February before decaying again, which illustrates the large volume of saline waters imported by the MBI 2016. Even in the surface layer, values above 10 g/kg were observed for a few days in the first week of February. The densest inflow waters of slightly below 23 g/kg were found mid of February in the near-bottom region, with corresponding water temperatures in the range 3.5-4.0 °C. The latter are perfectly consistent with temperatures in the range 3.5-3.8 °C of the densest inflow waters crossing the Darss Sill (see previous chapter), which will be helpful to identify the inflow waters during their descent into the neighbouring Bornholm Basin. For comparison, it is worth noting that the maximum salinity found at the bottom of the Arkona Basin (sensor in 43 m depth) after the record-breaking MBI 2014 that crossed the Darss Sill in December 2014 was 23.7 g/kg (see NAUSCH et al. 2016).

Note that waters with high salinities of up to 20 g/kg were observed in the bottom layer of the Arkona Basin already at the beginning of January as a result of a series of inflow events of intermediate strength in November and December as well as the moderate MBI of November 2015 (see NAUSCH et al. 2016). These water masses are easily distinguished from the MBI 2016 by their higher temperatures of more than 8 °C (Figure 13). The same is also true for the short salinity peak around 25 January, which represents the intermittent appearance of waters from the smaller inflows in 2015 rather than the early arrival of waters from the MBI 2016. As a result of these 2015's inflow events, bottom oxygen concentrations were already high (around 80 % saturation) at the beginning of 2016 but further increased to more than 90 % after the arrival of the cold inflow waters associated with the MBI 2016 (Figure 14).

As described in chapter 3, the MBI 2016 was followed by an extended outflow period until approximately mid of March. As a consequence, both the thickness of the salt water pool and the bottom salinities in the Arkona Basin decayed, and the bottom temperatures stagnated at low temperatures in the range 3-4 °C (Figure 13). Bottom oxygen concentrations fluctuated around values slightly below the saturation level but showed no clear indications for a decay, despite the lack of any deep-water ventilation. This may be explained by the small consumptions rate in waters that are only a few degrees above the freezing point.

A clear long-term trend for surface-layer warming can be discerned in Figure 13 after the first week of March with particularly high warming rates in May, which was characterized by exceptionally warm and dry weather conditions (see chapter 2). The maximum surface-layer temperatures of the year (hourly mean value at 2 m depth: 20.7 °C) were reached on 31 July, which is comparable to the year 2014 (21 °C) but considerably warmer than maximum temperatures of only 18 °C reached in 2015. However, immediately after the temperature maximum end of July, surface-layer temperatures started to collapse during a 3-week period with unusually cold summer weather as pointed out in chapter 2. On 20 August, temperatures at 7 m depth fell below 16 °C. Quickly improving weather conditions in the last third of August, and in particular in the following month of September, rated as the warmest September since the beginning of the records of the German Weather Service, are clearly mirrored in the unusually high surface-layer temperatures. Figure 13 shows values close to 20 °C mid of September, and still more than 16.5 °C by end of the month, both of which is rather exceptional.

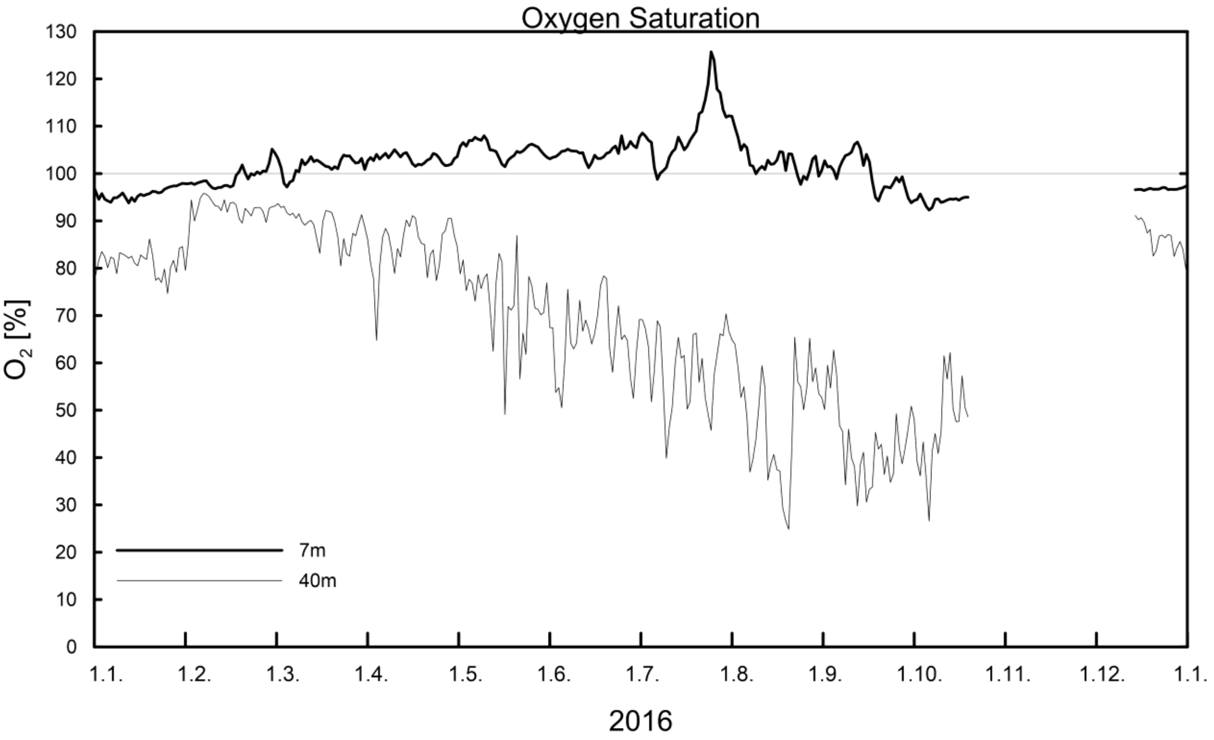

Fig. 14: Oxygen saturation measured in the surface and bottom layer at the station AB in the Arkona Basin in 2016

The temperatures in the near-bottom region followed those in the surface layer with smaller amplitude and a significant delay, which reflects the time scale for the transport of waters across the Great Belt during a series of smaller inflow events characterizing the summer period until approximately mid of August (see chapter 3). The cumulative effect of these events was sufficient to keep the near-bottom salinities in the range 14-18 g/kg, except for a few stronger short-term fluctuations. However, the near-bottom oxygen concentrations exhibited a nearly linear decay between April and mid of August, suggesting that the oxygen import due to these inflows could not fully balance the local oxygen consumption. The lowest oxygen concentrations of the year (daily average less than 25 % saturation, hourly average less than 11 %) were observed on 20 August just before the arrival of the intermediate-strength inflow event passing the Darss Sill in the first two weeks of August (Figure 14). These waters resulted in a temporary recovery of the oxygen concentrations to values around 60 % saturation in the following weeks. Note that the effect of primary production during the particularly warm and sunny period in the second half of July is evident in the exceptionally high surface-layer oxygen concentrations (29 % above the saturation level on 25 July), just a few days before the maximum temperature of the year was reached.

The temporary recovery of the oxygen concentrations resulting from the small inflow event in August was, however, not of long duration. With the arrival of low-oxygen waters intruding via the Darss Sill during the baroclinic September inflow (see previous chapter), oxygen concentrations started decaying again during the first week of September, and reached minimum values around 30 % saturation (daily means) in the second week of this month (Figure 14). Despite the high salinities of the inflow waters at the Darss Sill (more than 23 g/kg, see chapter 3), however, no significant increase in salinity can be identified at the bottom of the Arkona Basin. As pointed out in chapter 3, the baroclinic inflow in September 2016 was confined to a thin near-bottom layer, and it is therefore likely that the intruding waters were mixed and diluted during their descent into the Arkona Basin. This suggests that the September 2016 inflow will not have any significant impact on the water mass properties of the deeper down-stream basins like the Bornholm Basin.

After 04 October, the thickness of the near-bottom pool of high-salinity waters in the Arkona Basin gradually shrank, and bottom salinities decreased until end of the month, when unusually small values around 9 g/kg were reached (Figure 13). As discussed in chapter 3, weak inflow activity started at the Darss Sill on 18 October, and considerably gained in strength during the last week of the same month. The first signatures of these inflow waters could be detected in the deepest layers of the Arkona Basin on 30 October, when the two lowermost sensors showed a reversal of the decreasing salinity trend. From this point on, deep-water salinities gradually increased until, on 21 November, a maximum value of 20.9 g/kg at a temperature of 10.5 °C was reached at 43 m depth. This inflow affected the bottom waters up to a depth of 33 m, were maximum salinities of 12.8 g/kg were found on the same day. Surprising are the large maximum salinities near the bottom, which by far exceed those of less than 16 g/kg found at Darss Sill (see Figure 10 above). It is therefore likely that the bottom waters in the Arkona Basin are mainly composed of waters that entered the western Baltic Sea via the Öresund rather than through the Great Belt.

Also the following inflow period, observed at the Darss Sill between mid of November and mid of December, left a clear imprint on the bottom water properties in the Arkona Basin. After a two-week period with decaying salinities, starting in 23 November, the first waters of this inflow arrived at the Arkona Buoy around 06 December. From this date on, near-bottom salinities exhibited a generally increasing trend, reaching maximum values of 21.1 g/kg (43 m depth) on 21 December (Figure 13). Already on 20 December, salinities above 20 g/kg were found. Again, these salinities are too large to be explained by the import of waters via the Darss Sill, where maximum salinities during this event did not exceed 16 g/kg (Figure 10). Measurements of SMHI in the Öresund suggest that the inflow via this second pathway had started approximately at the same time (after a longer outflow period), leaving the question about the origin of the densest waters at the bottom of the Arkona Basin somewhat unclear.

As pointed out at the beginning of this chapter, for technical reasons oxygen measurements are not available for the period between 20 October and 13 December. The impact of the fall/winter inflows on the deep-water oxygen budget is therefore hard to quantify in detail. However, oxygen readings obtained during the last 10 days of December, when the sensors were functional again, indicate that the cumulative effect of these inflows was reflected in high oxygen concentrations up to 80 % - 90 % of the saturation level.

The final event of the year was an inflow of intermediate strength that passed the Darss Sill between 22 and 27 December (see chapter 3). First signs of the arrival of waters from this event at the Arkona station became evident on 28 December, when near-bottom salinities started increasing, and finally, on the last day of the year, exceed the threshold of 20 g/kg at 43 m depth (Figure 13). It is likely that this event will also have an impact on the first days of the following year 2017. The year ends with mixed-layer temperatures of 5.5 °C, about 1 °C colder than those of the previous year.

5. Observations at the Buoy "Oder Bank"

The water mass distribution and circulation in the Pomeranian Bight have been investigated in the past as part of the TRUMP project (*TR*ansport und *UM*satzprozesse in der *P*ommerschen Bucht) (v. BODUNGEN et al., 1995; TRUMP, 1998), and were described in detail by SIEGEL et al. (1996), MOHRHOLZ (1998) and LASS, MOHRHOLZ & SEIFERT (2001). For westerly winds, well-mixed water is observed in the Pomeranian Bight with a small amount of surface water from the Arkona Basin is admixed to it. For easterly winds, water from the Oder Lagoon flows via the rivers Świna and Peenestrom into the Pomeranian Bight, where it stratifies on top of the bay water off the coast of Usedom. As shown below, these processes have an important influence on primary production and vertical oxygen structure in the Pomeranian Bight.

The Oder Bank monitoring station (OB) is located approximately 5 nm north-east of Koserow/Usedom at a water depth of 15 m, recording temperature, salinity, and oxygen at depths of 3 m and 12 m. Following the gradual replacement of the oxygen sensors at the other MARNET stations, optode sensors from Aanderaa (Norway) are in use also at station OB since 2010. These optical oxygen measurements were validated with the help of water samples taken during the regular maintenance cruises using the Winkler method. After the winter break, the monitoring station OB was brought back to service on 15 April 2016, approximately one month later compared to the previous year. Starting from that date, the station provided continuous time series of all parameters until 13 December, when it was again demobilized to avoid damage from floating ice.

Temperatures and salinity levels at OB are plotted in Figure 15; associated oxygen readings are shown in Figure 16. Similar to the other MARNET stations, the maximum temperatures that were reached during the summer period were slightly larger compared to the previous (relatively cold) year but still considerably smaller compared to the record-setting years 2010, 2013, and 2014, when temperatures of up to 23 °C were observed at station OB. In 2016, the maximum daily mean temperatures in the surface layer exceeded the threshold of 20 °C only for three short periods: in the last weeks of July and August, respectively, and for a few days during an exceptionally warm period mid of September. The maximum hourly mean temperature, reached on 26 July, was 21.7 °C. As in the previous years, surface temperatures at the monitoring station OB were significantly larger compared to those at the deeper and more energetic stations in the Arkona Basin and the Darss Sill (see Figures 10 and 13), which reflects the shallower and more protected location of this station.

The dynamical reason for the stronger warming of the surface layer at station OB is the suppression of mixed-layer deepening due to stable stratification caused by the transport of less saline (i.e. less dense) mixed waters from the Oder Lagoon on top of the more salty bottom waters. During the summer months, such stratification events correlate excellently with short phases of enhanced temperature differences between the bottom and surface layers, and with increasing surface-layer temperatures. In 2007 and 2010, extended stratification events of this type also led to a sharp drop in near-bottom oxygen concentrations as discussed in more detail below.

Distinct events of this type were observed in 2016 in May, June, and July (Figure 15). The month of May was characterized by a particularly long-lasting and strong event that started on 18 May, just after a previous strong wind event had destroyed any pre-existing stratification. Starting from this date, surface and bottom salinities strongly deviated from each other, reaching a peak difference of more than 3 g/kg. This resulted in a stabilization of the water column, and thus in a suppression of mixing of water between the upper and lower layers. As a result, the surface layer rapidly heated up, reaching maximum temperature of nearly 20 °C during a short period in the first week of June, while in the insulated lower layer temperatures stagnated. A strong wind event with daily mean wind speeds exceeding 11 m/s on 10 June induced a rapid mixing of the water column, and therefore set the endpoint of this stratification event. Similar stratification episodes lead to the generation of the surface-salinity minima, and associated temperature maxima, throughout the warm season (Figure 15).

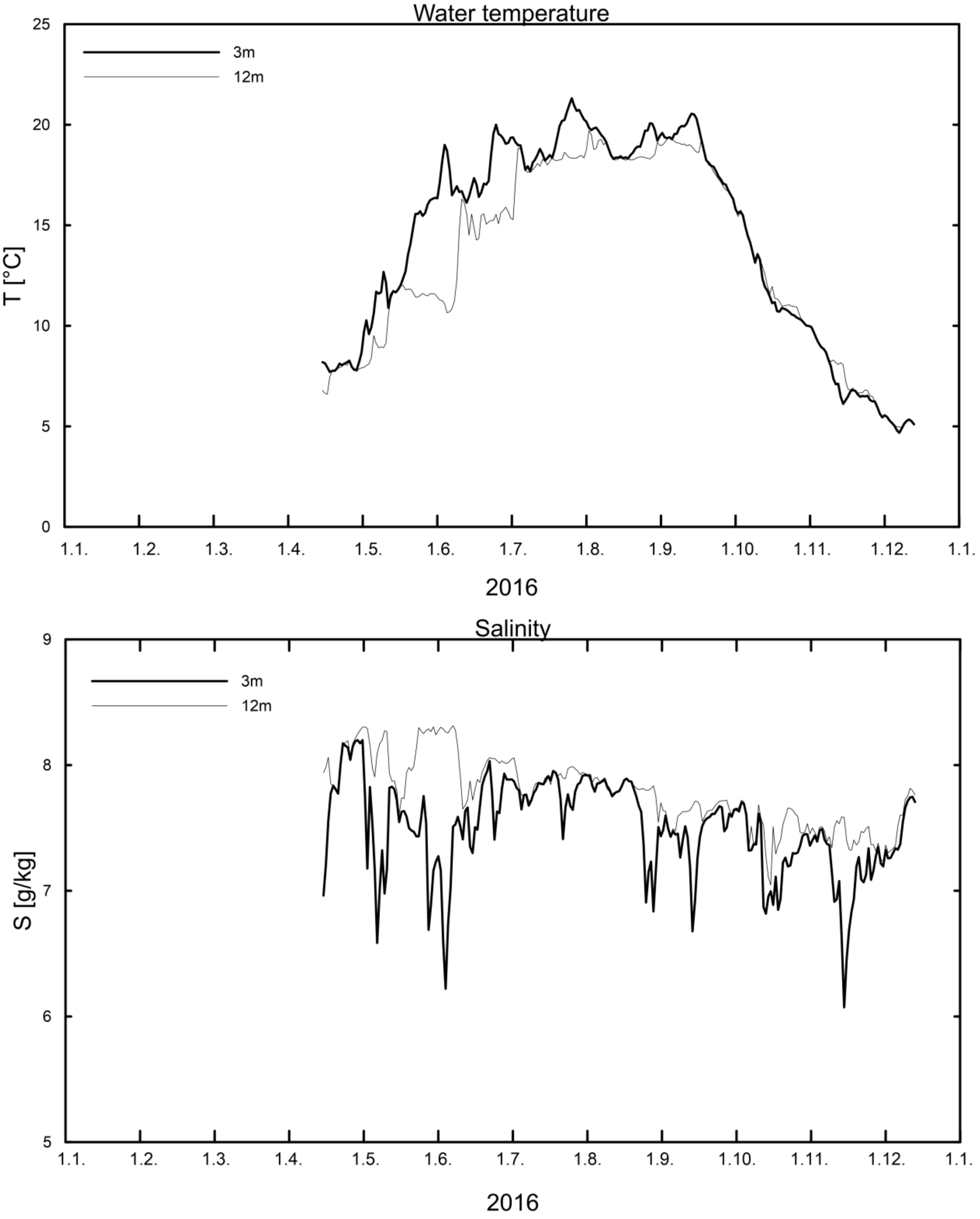

Fig. 15: Water temperature (above) and salinity (below) measured in the surface layer and near bottom layer at the station OB in the Pomeranian Bight in 2016

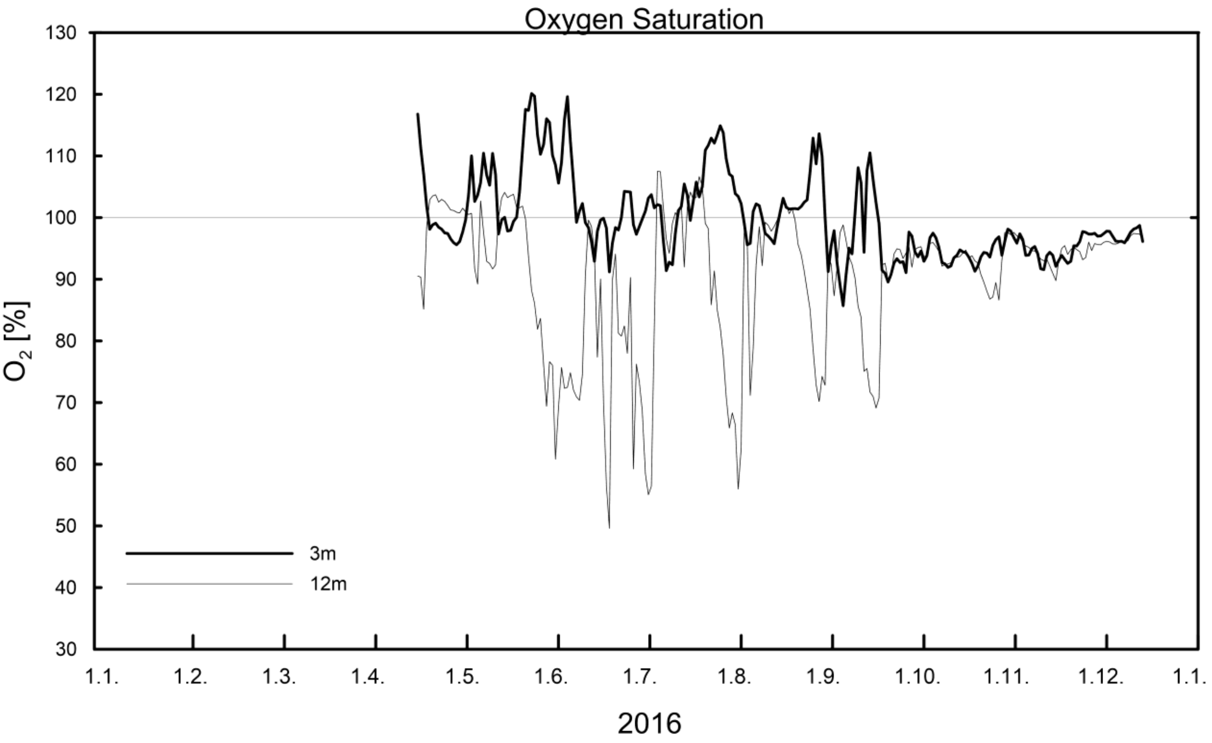

Fig. 16: Oxygen saturation measured in the surface and bottom layer at the station OB in the Pomeranian Bight in 2016

From an ecological perspective, the most important consequence of the suppression of turbulent mixing during these events is the decrease in near-bottom oxygen concentrations due to the de-coupling of the bottom layer from direct atmospheric ventilation. The impact of these events on the oxygen budget of the Pomeranian Bight becomes evident from Figure 16, showing oxygen concentrations at depths of 3 m and 12 m. For all stratification events, a distinct negative correlation can be identified between increasing oxygen saturation in the surface layer and a decrease in the near-bottom layer, reflecting the effects of primary production and sedimentary oxygen demand, respectively. Examples of such events include the stratification periods in Mai and June, when hourly mean oxygen concentrations dropped down to 53 % (31 May), 36 % (18 June), and 26 % (26 June), respectively – in each case, however, only for a few hours. Somewhat longer events took place from 30 June until 2 July (concentrations stayed below 60 % throughout this period), and for a few days at the end of June, when minimum hourly concentrations of 45 % where reached. Pronounced events were also observed in late August and mid of September, however, without reaching oxygen saturations below 60 %. Despite the fact that minima in salinity may also be observed during the cold season (a particularly strong event of this type took place in November, see Figure 15), these occurrences do not leave any important imprint on the near-bottom oxygen concentrations. It is likely that this points at reduced microbial respiration rates due to the already low water temperatures at this time of the year. All in all, the minimum near-bottom oxygen concentrations during the summer months were somewhat more pronounced compared to the previous year, but again far above the anoxic conditions observed during the record-breaking year 2010 (NAUSCH et al. 2011a).

The increase in primary production of biomass in the Oder Lagoon, induced by the lateral transport of lagoon water to station OB, is likely to have resulted in the super-saturated oxygen concentrations that were observed in the surface-layer during all of the above events (Figure 16). In addition, lagoon water also exports high nutrient concentrations from the lagoon. At OB, this may have resulted in locally increased production rates, which in turn may explain the increased oxygen concentrations in the surface layer. The correlation between the oxygen increase in the surface layer and the decrease in the near-bottom layer may point at increased oxygen consumption rates induced by the decay of freshly deposited biomass ("fluff").

6. Hydrographic and Hydrochemical Conditions

6.1 Water Temperature

6.1.1 The Sea Surface Temperature of the Baltic in 2016 derived from Satellite Data

The development of Sea Surface Temperature (SST) of the Baltic Sea in 2016 was investigated using data of the American NOAA and European MetOp weather satellites. The Federal Maritime and Hydrographic Agency (BSH) Hamburg provided up to eight daily satellite scenes. Evaluation methods and methodological aspects are discussed in SIEGEL ET AL. (2008). The annual assessment of the development of SST in the Baltic Sea is summarised in NAUSCH et al. 2016 and in HELCOM Environment Fact Sheets (SIEGEL & GERTH, 2016). Reflections on long-term development of SST since 1990 are presented in SIEGEL et al. (1999, 2006, 2008) and SIEGEL & GERTH (2010). The heat and cold sums of air temperature in Warnemünde (Chapter 2, Table 2) as well as data from MARNET stations (BSH/IOW) were included for the interpretation of the detailed SST development.

The year 2016 was the third warmest year since 1990. February to July and September contributed by positive anomalies of up to +5 K in May, which was the warmest May since 1990. August and November were characterised by negative anomalies of up to -3 K along the west and east coast of the central Baltic induced by upwelling due to abnormal westerly and easterly winds in those months. June and September belonged to the warmest months in the southern Baltic and October in the Gulf of Bothnia. A strong cooling beginning of 2016 already led to ice in the German inner coastal waters on 6 January and continued until 23 January. This was also the time of maximum ice coverage in the entire Baltic Sea. The week, 09-15 March, was the coldest week in the entire open Baltic Sea. The SST increase in late spring was more pronounced as usual, leading to positive anomalies in May and June and to an early development of cyanobacteria. A warming phase in the second half of July made 26 July to the warmest day of 2016. After SST decrease beginning of August particularly in the northern Baltic, a stable situation lasted until mid-September with SST's of 18-20 °C in the southern and western Baltic. This led not only to the high anomalies in September but also to a long cyanobacteria season.

Cold and heat sums of air temperature of Warnemünde (Table 2, Chapter 2) give information about the severity of winter and the course of summer. The winter 2015/16 was with a cold sum of 63.5 Kd below the long term average (102.4 Kd) since 1948. January contributed with 63 Kd mainly to this value (Average 38.9 Kd). The heat sum for summer (267 K d) exceeded the long-term average (151.7 Kd) and was the sixth warmest summer since 1948. All summer months from May to September exceeded by far the long-term means (Chapter 2).

Anomalies of monthly mean SST for the entire Baltic Sea in Fig. 17 are the basis for the discussion of overall thermal development in 2016. The seasonal development of monthly mean temperatures in the central areas of the Arkona, Gotland and Bothnian Seas are presented in Fig. 18 in comparison to the long-term monthly means (1990-2016). Daily and weekly mean SSTs were the basis for the detailed description of temperature development.

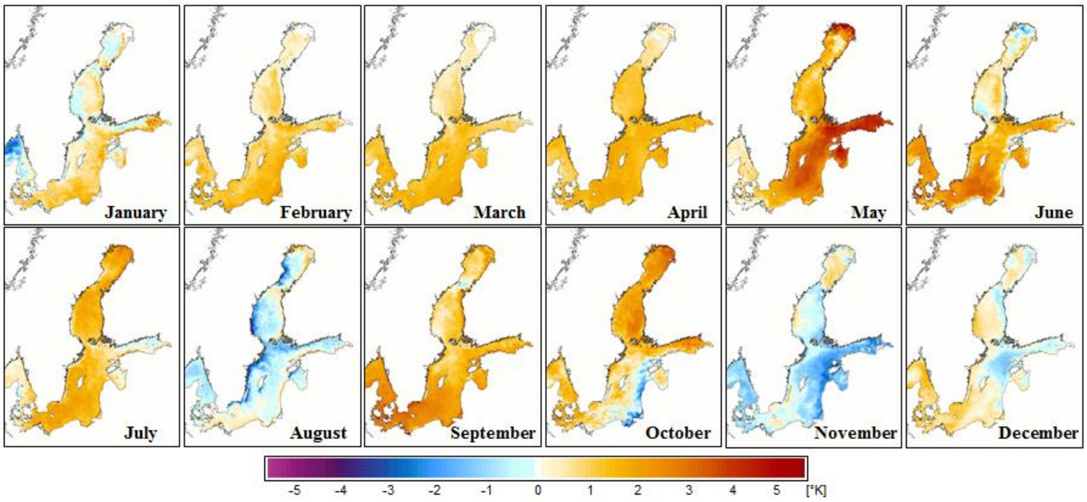

Fig. 17: SST- Anomalies of the monthly mean temperature of the Baltic Sea in 2016 referring to the long-term means (1990-2016)

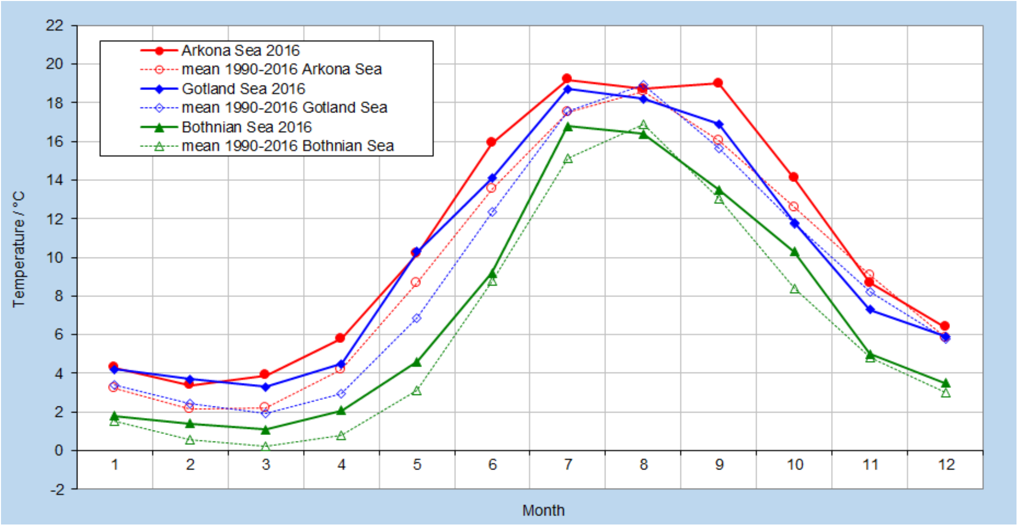

Fig. 18: Seasonal cycle of SST in the central Arkona-, Gotland- and Bothnian Sea in 2016 in comparison to the mean values (1990-2016)

After rather high positive anomalies in November and December 2015, the SST in January 2016 approached the long-term mean values leading to only slight positive anomalies in the southern Baltic. From February to April, the anomalies increased to about +2 K before a strong warming led to high anomalies of +3 K to +5 K in the most eastern and northern as well as in the central parts, that May 2016 became the warmest May since 1990. With anomalies between +2 K and +3 K, June belonged also to the warmest in the southern Baltic Sea. The northern Baltic varied around the average. The anomalies in July are mainly between +1 K and +2 K except in the eastern and western parts, where slight negative values occurred. Deep pressure systems in August brought an abnormal high number of west-wind situations in the northern and central Baltic leading to intense upwelling of cold water along the Swedish coast and to negative SST anomalies of up to -4 K, there. September was particularly in the southern and western part warmer than the long-term mean values and belonged to the warmest since 1990 in these regions. October and particularly November were characterised by abnormal high frequencies of easterly winds in the central Baltic leading to upwelling of cold water along the coast of the Baltic countries and anomalies of -2 K to -3 K. In the Gulf of Bothnia, the October 2016 belonged to the warmest since 1990. December was in the range of long-term mean values.

The annual cycles of the Arkona Sea (AS), Gotland Sea (GS) and Bothnian Sea (BoS) in Fig. 18 show that February was the coldest month in AS but March was coldest in the GS and BoS, as in the long-term averages. The yearly cycle of BoS follows the averages except the July, which is the warmest month in the three regions in contrast to the averages. Further particularities occurred especially in May in the GS, in September in AS and in October in BoS. In the AS the monthly mean SST of September was higher than in August.

Beginning of 2016, a strong cooling took place leading to ice in the German inner coastal waters already on 6 January (Fig. 19, left image). A further cooling continued until 22 January (Fig. 19, right image) which led to SST between 0 and 3 °C along the German coast. This was also the period of maximum ice coverage in the entire Baltic Sea (Fig. 20, right image).

Fig. 19: MODIS Terra and MODIS Aqua true colour images from 6 Jan and 22 Jan 2016 showing the maximum ice coverage along the German coast 2016 (data: NASA- MODIS Rapid Response System)

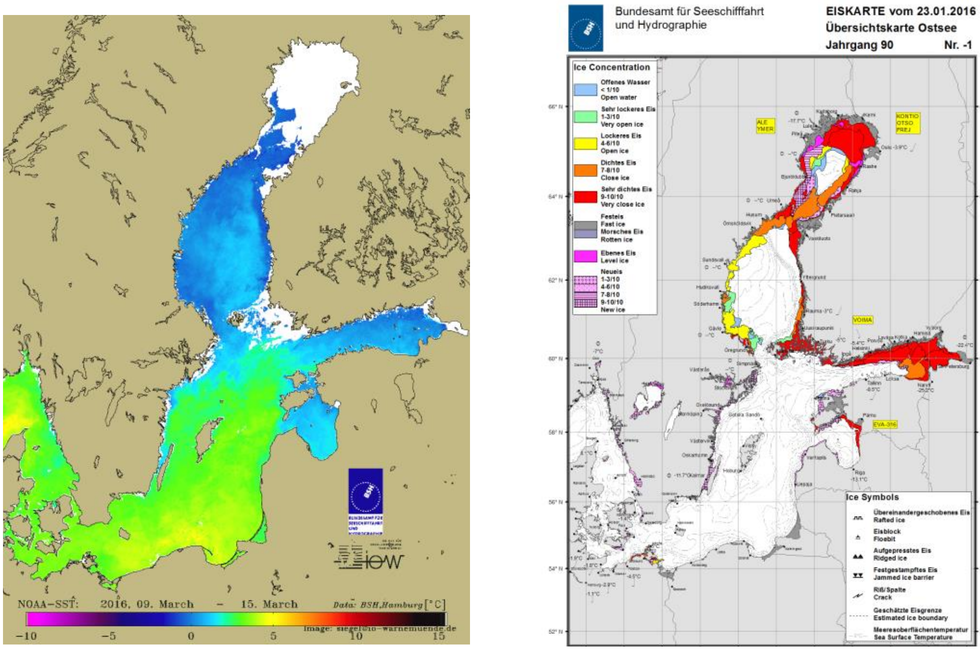

Fig. 20: Weekly mean SST of the Baltic Sea for 09 - 15 March (coldest week) and maximum ice coverage of the year 2016 on 23 January (SCHWEGMANN & HOLFORT, 2016)

The ice developed in the shallower coastal regions and not yet in the central parts. Until 28 January, the SST increased again and the ice did not longer exist in the German waters. As mentioned before the minimum SST in GS and BoS was reached in March that March, 09 – 15, was the coldest week in the entire Baltic (Fig. 20, left image). This was associated with a second maximum in ice coverage particularly in the northern Baltic. After 20 March, a slight SST increase started and reached 5-6 °C in the western Baltic and 0-2 °C in the BoS. The transect of mean SST through the entire Baltic in the coldest month, March, is presented in relation to long-term average (1990-2016), previous year, and range of variation in Figure 21 reflecting the impression from Figure 17. SST of entire Baltic is higher than the long-term mean values and reached partly in the area between the Bornholm and Gotland Sea the upper limit of the variation range.

In April, the SST increase continued with only short and slight interruptions that end of the month SST reached 6-8 °C in the western and southern Baltic (WB, SB) and about 3 °C in the BoS.

May was very special in the SST development as described on the basis of the monthly anomalies and the yearly cycle. A first strong warming took place until 10 May with maximum SST of 15 °C. Deep pressure system until about 20 May induce cooling by cloudy conditions and wind mixing.

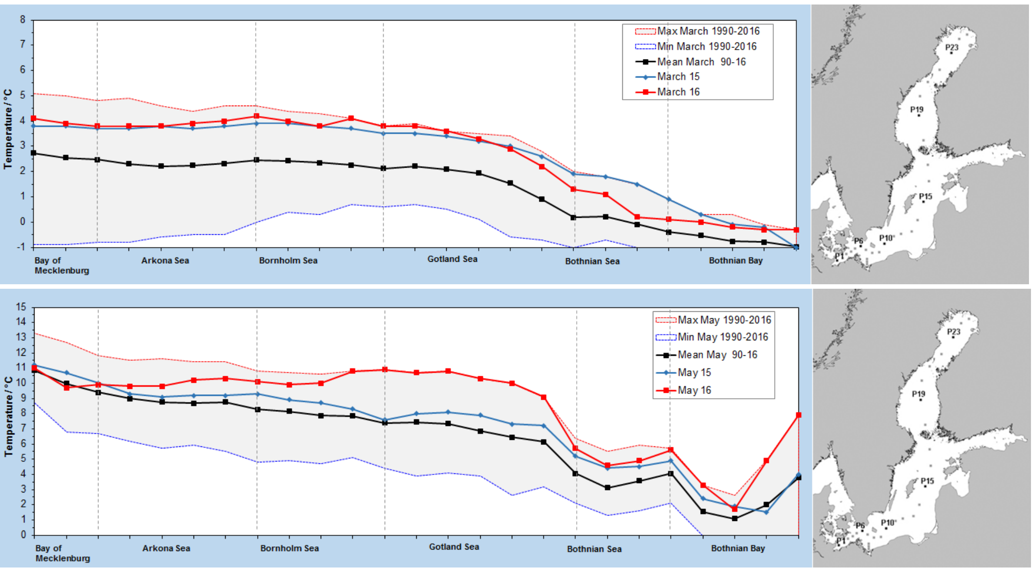

Fig. 21: Temperature distribution along the transect through the central basins of the Baltic Sea in March and in May 2016 in comparison to the previous year, the long-term mean value of 1990-2016 and the variation range

After that, a further warming from the coast led to temperatures of 13-16 °C in the central parts of WB and SB outside of upwelling influence leading to this relatively warm month. These high surface temperatures und calm conditions supported the early development of cyanobacteria as derived from MODIS data and confirmed during the monitoring cruise in the third decade of May. In Figure 21 (lower panel), the transect of mean SST through the entire Baltic in this special May is presented in relation to long-term average (1990-2016), previous year, and range of variation. Particularly, in the GS the SST is up to 3 K higher than the long-term averages and determined the upper limit of the variation range.

In the first decade of June, a further warming took place leading to 18 °C in south- eastern Baltic before a wind mixing reduced the SST again to 13-16 °C. After 20 June, a low wind period supported a strong heating until 25 June with SSTs of 16-19 °C in the central and western Baltic and cyanobacteria developed again. A stagnation period followed until the end of the month.

After a short period of 5 days of calm weather conditions, deep pressure systems passed the Baltic Sea area partly with wind speeds of up to 17 ms^{-1}, which reduced the maximum SST from 18-19 °C to around 16 °C. This situation lasted until the next warming in the third decade of July, which made 26 July to the warmest day of the year (Fig. 22).

After a slow SST decrease beginning of August, a stronger one followed between 10 and 15 August particularly in the northern Baltic. This resulting situation was more or less stable until mid of September with SST maximum of 18-20 °C in the southern and western Baltic.

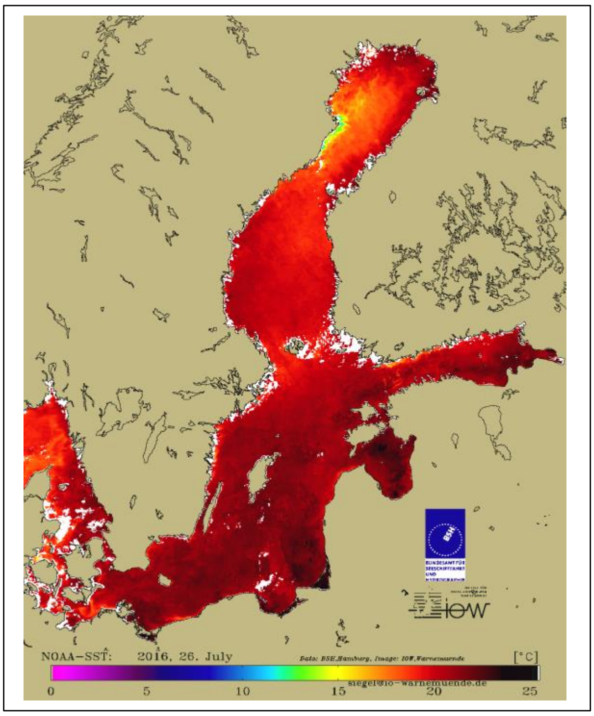

Fig. 22: SST distribution of the Baltic Sea on July 26, the warmest day of year 2016.

A slight cooling to the end of the month reduced the temperatures to up to 16-17 °C. These high temperatures led not only to the high anomalies in September but also to a long cyanobacteria season. The transect of mean SST through the entire Baltic in the months August and September are presented in relation to long-term average (1990-2016), previous year, and range of variation. In August (Fig. 23, upper panel), the SST is in the central parts in the range of the long-term mean values. In September (Fig. 23, lower panel), the SST is in the entire Baltic above the long term mean values and particularly in the southern and western parts with values of up to +2.5 K above the averages. End of September strong westerly winds induced upwelling of cold water along the Swedish coast in the northern and central Baltic and in the southern and eastern central Baltic SSTs of 15-17 °C still exist.

From 5 October, passages of low-pressure systems with changing wind and cloud conditions accelerated the cooling. End of October SSTs of 7-9 °C characterises the northern Baltic and 10-12 °C the southern part.

The cooling continued in November particularly in the northern Baltic that end of the month temperatures of 0-5 °C occurred in GoBo and 7-10 °C from WB to GS. In the first decade of November, the first ice developed in the northern Bothnian Bay.

In December, the SST decreased very slowly that there were 0-3 °C in GoBo and 3-6 °C in the southern Baltic. After the comparatively warm September in the southern and October in the northern Baltic, the strong cooling in November led to monthly mean temperatures of November and December in the range of the long-term mean values.

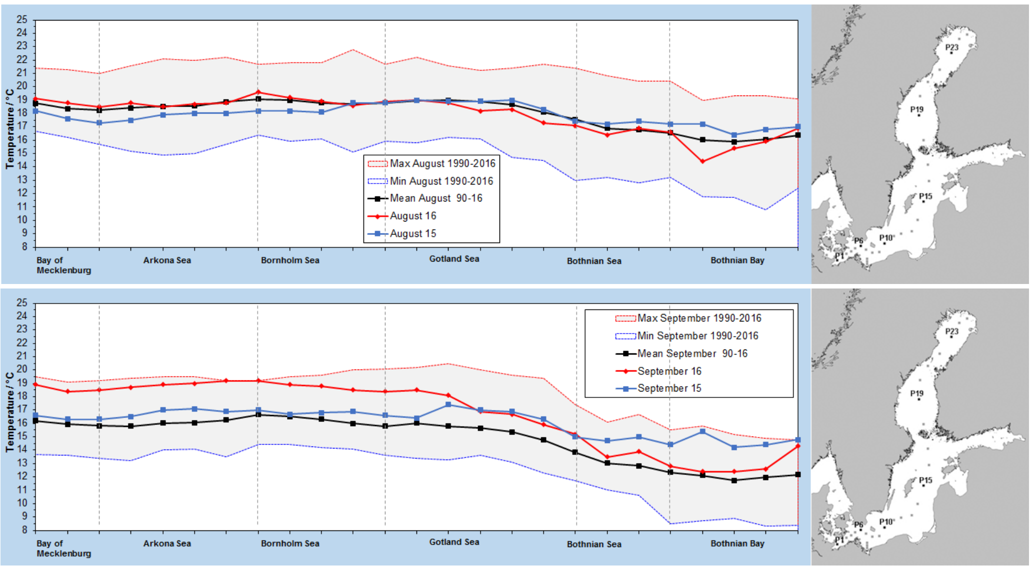

Fig. 23: Temperature distribution along the transect through the central basins of the Baltic Sea in August and September 2016 in comparison to the previous year, the long-term mean value of 1990-2016 and the variation range

Overall, 2016 was after 2014 and 2015 the third warmest year since 1990 (Fig. 24). The annual temperature average throughout the Baltic Sea was about 0.8 K higher than the long-term average, and only 0.3 K below the warmest year 2014. February to July and September contributed by their positive anomalies. With up to +5 K May was the warmest since 1990. June and September belonged to the warmest months in the southern Baltic and October in the Gulf of Bothnia. The resulting temperature trend was 0.6 K per decade.

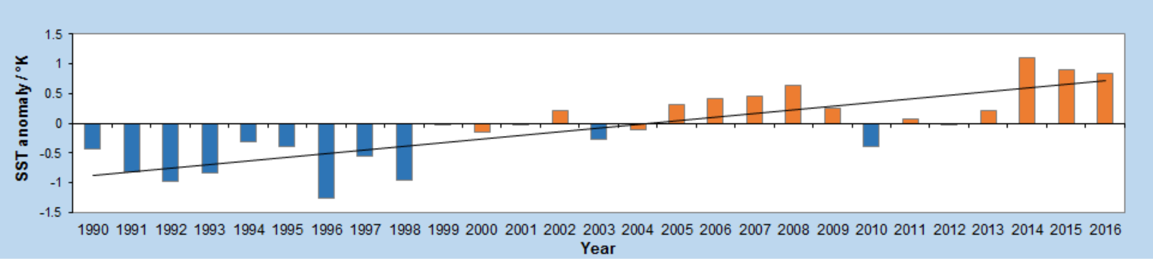

Fig. 24: Anomalies of the annual mean sea surface temperature of the entire Baltic Sea during the last 27 years (1990-2016)

6.1.2 Vertical Distribution of Water Temperature

The routine monitoring cruises carried out by IOW provide the basic data for the assessment of hydrographic conditions in the western and central Baltic Sea. In 2016, monitoring cruises were performed in January/February, March, May, August and November. Snapshots of the temperature distribution along the Baltic talweg transect obtained during each cruise are depicted in Figure 25. This data set is complemented by monthly observations at central stations in each of the Baltic basins carried out by the Swedish Meteorological and Hydrological Institute (SMHI). Additionally, continuous time series data are collected in the eastern Gotland Basin. Here the IOW operates two long-term moorings that monitor the hydrographic conditions in the deep water layer. The results of these observations are given in Figures 26 and 28.

The surface temperature (SST) of the Baltic Sea is mainly determined by local heat flux between the sea surface and the atmosphere. In contrast, the temperature signal below the halocline is detached from the surface and the intermediate winter water layer and reflects the lateral heat flows due to salt-water inflows from the North Sea and diapycnal mixing. The temperature of the intermediate winter water layer conserves the late winter surface conditions of the Baltic till the early autumn, when the surface cooling leeds to deeper mixing of the upper layer.

In the central Baltic, the development of vertical temperature distribution above the halocline followed with some delay the annual cycle of atmospheric temperature (cf. chapter 2). The winter of 2015/2016 was unusually mild, except the January. This is reflected by the very small ice coverage of only 114 000 km^2. From February to April 2016, temperatures clearly exceeded the long-term means (cf. Chapter 2). Thus, the cooling of sea surface during winter time was significantly reduced in the western and central parts of the Baltic. The spring started with SST well above the long term mean. Warmer than average temperatures continued until July 2016. However, in August the temperatures were near the long term mean and remained higher than the climatological mean till end of the year 2015.

The deep water conditions in the central Baltic in 2016 were mainly controlled by the extreme Christmas MBI of December 2014 Baltic (Mohrholz et al., 2015), and the subsequent inflow events in January and November 2015, and January/February 2016. A fraction of saline water of these inflows also reached the deep water layer of the Baltic's central basins, and prolonged the ventilation process that started with the 2014 Christmas MBI.

At the beginning of February 2016 the temperature distribution along the Baltic talweg revealed the typical winter cooling in the surface layer. As a result of the cooler than average January, surface temperatures decreased in the shallow areas of the Mecklenburg Bight to values about 1.8 °C to 2.2 °C. However, only west of the Darss Sill surface temperatures below 3 °C were observed. Surface temperatures in the adjacent Arkona Sea were still around 3.6 °C. This value was well above the density maximum with the result that further cooling forced temperature driven mixing. In the central Baltic, the deep convection associated with cooling largely homogenized the surface layer and the former winter water layer. The thermocline at station TF271 in the eastern Gotland Sea was found at a depth of 65 m, and reached the permanent halocline starting at the same depth. With 4.35 °C, the upper layer temperature at station TF271 exceeded the temperature of the density maximum by 1.5 K. Further cooling thus preserved the deep vertical convection, and contributed to further homogenization of the surface layer. Generally, the surface temperatures in the central Baltic of 4.3 °C reflected extremely high winter values in February 2016. It exceeded the value of 3.5 °C from February 2015, which was also well above the average temperature. In contrast, in February 2014 the SST in was close to 1 °C.

The temperature distribution below the halocline reflects the impact of the inflow events of saline water from the North Sea. The moderate inflow during January 2016 dominated the bottom temperature distribution in the Arkona Basin and the Danish straits. Waters of the inflow constituted a 20 m thick bottom layer in the Arkona basin. Baroclinic late summer inflows and the moderate inflow in November 2015 have flushed the halocline of the Bornholm Basin with warm water. Till February 2016 this water was mixed up with ambient cooler water of the Bornholm Basin. The mixed water body depicted the highest temperatures in the entire Baltic. It filled the eastern part of the halocline in the Bornholm Basin and the bottom layer of the Slupsk Furrow. It was characterised by temperature above 8 °C, with maximum value of about 9.4 °C in the eastern Bornholm Basin. The deep layers of the Bornholm Basin were still covered by the warm and high saline waters from the inflow series in 2014 and March 2015. Here the bottom temperature was 8.1 °C. Between the eastern outlet of the Slupsk Furrow and the entrance of the eastern Gotland Basin some warm water plumes were observed in the bottom layer. These plumes spread eastward and were originated from pulse like overflows of the eastern sill of Slupsk Furrow. The deep water in the Gotland Basin was still covered by the warm water of the Christmas inflow 2014. In the bottom layer water with higher temperature from the November inflow 2015 just arrived. Here the bottom temperature at station TF 0271 was at 7.8 °C. Due to bad weather conditions during the cruise in January 2016 the Farö Deep was not covered by the CTD measurements.

In normal years, relatively low surface temperatures are still observed during the monitoring cruise in March. As a result of the abnormally warm air temperatures in winter 2015/2016, the surface temperature of the western Baltic was well above the February temperatures. In the central Baltic Sea the SST remained close to the level of early February. Only in the northern part of the Baltic transect the SST had decreased by about 1 K since the previous cruise. The maximum temperature of 5.3 °C was observed at the Kadet Trench (station TF041). Other areas of the western and central Baltic Sea depicted also comparatively warm surface temperatures of 4.3 °C in the Arkona Basin, 4.0 °C in the Bornholm Basin, and 3.6 °C in the eastern Gotland

Basin. The minimum SST of 2.8 °C was observed at station TF0282 in the northern Gotland Basin. Surface temperatures in the western and central Baltic clearly exceeded those of the density maximum. The onset of seasonal warming has already established weak temperature stratification in the western Baltic, with a thermocline depth of about 15 m.

The small MBI in January 2016 imported about 98 km³ of cold, saline water into the Baltic. The bottom of the Arkona Sea was covered by a 15 m thick layer of inflow water. The temperature of this water body was about 4.5 °C. Partly the saline water of this inflow event has passed the Bornholm Gat and was spreading along the halocline in the north-western Bornholm Basin. The temperature distribution in the deep-water of the Bornholm Basin depict a patchy structure. The warm water body at the halocline, observed in February, was mixed up with cooler water from the recent inflow. Maximum temperature in the halocline has decreased from 9.4 °C in February to 7.1 °C in March. The bottom water in the Bornholm basin was replaced by a small cool water body with a temperature of about 5.7 °C. Also the warm water in the deep water layer of the Slupsk Furrow has cooled due to further mixing with cool inflow water from November 2015. Partly the former deep waters from the Bornholm Basin and the Slupsk Furrow have reached the eastern Gotland basin. Due to its high density the water filled up the warm bottom water pool, which led to a rising of the 7.5 °C isotherm from 226m to 220m between February and March 2015. The bottom temperature at station TF 0271 (Gotland Deep) and in the Farö Deep was at 7.6 °C and 6.5 °C respectively. The eastward tilt of the 6 °C isotherm and temperature stratification in deep water of the eastern Gotland basin indicates the active inflow process.

Between March and May, the surface water of the Baltic warmed noticeably caused by increasing air temperatures and solar radiation, respectively. Surface temperatures ranged between 11.6 °C in the Kiel Bight, 9.7 °C in the Arkona Basin, 8.9 °C in the Bornholm Basin, and 8.4 °C in the eastern Gotland Basin. Generally, the SST was about 1.0 to 1.5 K higher than in May 2015. In the entire western and central Baltic the seasonal thermal stratification was well pronounced, and blocked the direct interaction between the atmosphere and the layer of winter water at 30-70 m depth. Compared to the climatological value, also the intermediate layer was extremely warm in 2016. Usual winter water temperatures are about 2 °C, controlled by the temperature of maximum density of surface water. In the eastern Gotland Sea, the minimum temperature of intermediate winter water was 3.81 °C in May 2016. It was slightly lower (-0.25 K) than in the previous year. Similar conditions were observed throughout the central Baltic. Due to the mild winter 2015/2016 the surface water never fell below the temperature of density maximum. And thus, the usual convective mixing in spring was not observed in 2016.

Below the permanent halocline in the Bornholm Basin the deep water body was mixed partially with the cool inflow water from the January 2016 inflow. The bottom water temperature in the Bornholm Basin increased slightly to 6.2 °C. In the Slupsk Furrow the former deep water was replaced by a mixture of former deep-water from the Bornholm Basin and cool water from the January inflow. Compared to March the bottom temperature was decreased by 1.9 K to 5.9 °C in the Slupsk Furrow. The tip of the cool water has passed the eastern sill of the Slupsk Furrow and spreads northward. The major part of the warm November 2015 inflow had reached the eastern Gotland basin. Here it caused a rise of the 7 °C isotherm from 192 m in March to 186 m in May 2016. The former deep water of the eastern Gotland basin was pushed further to the

Farö Deep, where the 6.5 °C isotherm changed rapidly from 182m in March to 137 m in May.
By the beginning of August 2016, typical summer thermal stratification had become established throughout the Baltic Sea. The seasonal thermocline lay at depths between 20m and 30m, and separated the strongly warmed layer of surface water from the cool winter intermediate water. In the basins of the central Baltic Sea, minimum temperatures in the intermediate water were around 4.1 °C, which was nearly the same value as in 2014. In the Bornholm Basin the winter water had almost vanished. Only in the eastern part few remains of the winter water were identifiable by its temperature of about 6.0 °C.
The surface temperatures in spring were well above the long term mean, and also the May, June and July 2016 were warmer than average. Thus, surface temperatures in the western and central Baltic Sea were about 19 °C and above. At station TF213 in the Bornholm Basin, 19.2°C was recorded on 05 August, and 18.5 °C was recorded at station TF271 in the eastern Gotland Basin.
A calm period in the end of July caused a baroclinic inflow of warm water at the Darss Sill. It formed a 15 to 20m thick warm bottom layer in the western Arkona Basin. Here, bottom temperatures up to 15° C were observed. A part of this water body has already passed the Bornholmgat. The warm water is interleaved in the halocline of the western Bornholm Basin at depth of 50 to 60m. The core temperature of this layer was about 11.7 °C.
No significant changes were observed in the deep layer of the Bornholm Basin and the central Baltic. Local diapycnal mixing caused minor changes and flattening of temperature gradients. The bottom temperatures of the Bornholm Basin and the Slupsk Furrow were at 6.55 °C and 5.99 °C, respectively. The bottom temperature in the eastern Gotland basin remains nearly constant at 7.5 °C since May 2016.

The temperature distribution in early November 2016 revealed autumnal erosion of the surface layer thermocline. Unusual high temperatures were observed during late summer and autumn 2016 in the western Baltic region. Thus, the temperature in the upper layer was higher than usual. The temperature in the surface layer, extending to a depth of 35 m to 45 m was well above 10 °C up to the Slupsk Furrow. In the Arkona Basin a surface temperature of 10.6 °C was observed. Towards the Bornholm Basin it increased slightly to 10.8 °C (station TF213). In the Slupsk Furrow an SST of 11.0 °C was detected. Further to the eastern Gotland Basin and the Farö deep decreasing surface temperatures were found, which were 7.9 °C and 6.5 °C on stations TF271 and TF286, respectively. The deepening of the thermocline reduced the vertical extent of the intermediate winter water layer in the central Baltic to 20-35 m thickness, with minimum temperatures of 4.7 °C (station TF271). No layer of winter intermediate water was present in the Bornholm Basin and the Slupsk Furrow.

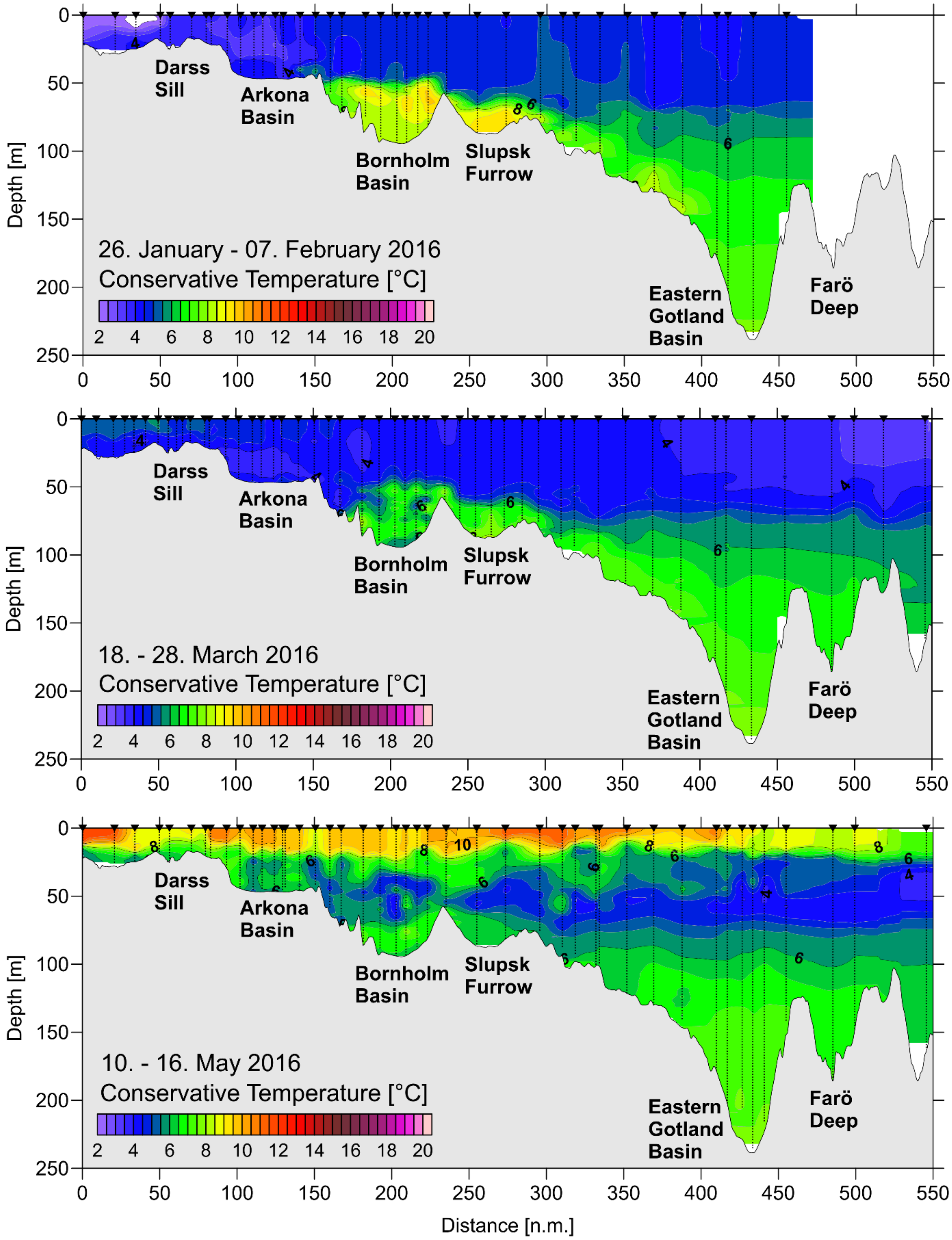

Fig. 25a: Temperature distribution along the talweg transect through the Baltic Sea between Darss Sill and northern Gotland Basin

Baroclinic inflow events in the late summer and autumn brought some warm saline water into the western Baltic. This water spread along the bottom of the Arkona basin eastward. Maximum temperature in this water body of 14 °C was observed at the bottom near the Bornholmgat. The major part of the water from baroclinic summer inflows has already passed the Bornholmgat and is sandwiched between the upper layer and the deep water in the Bornholm Basin. Here it formed a 20 m to 30 m thick layer. The density of the inflowing water was too low to replace the cooler bottom water in the Bornholm basin, which was formed in spring. At the time of the cruise the tip of the warm summer inflow has already passed the Slupsk Sill. It replaced the former bottom water in the western and central part of the Slupsk Furrow. Due to partial entrainment of ambient water into the inflow water body, its temperature decreased eastwards. At the bottom of the Slupsk Furrow the temperature was about 9.5 °C (station TF222). Between the eastern Sill of Slupsk Furrow and the eastern Gotland Basin a further warm plume was detected near the bottom. The density of this water was not mighty enough to reach the deep layers of the eastern Gotland Basin. It likely will be sandwiched at about 100 m depth.

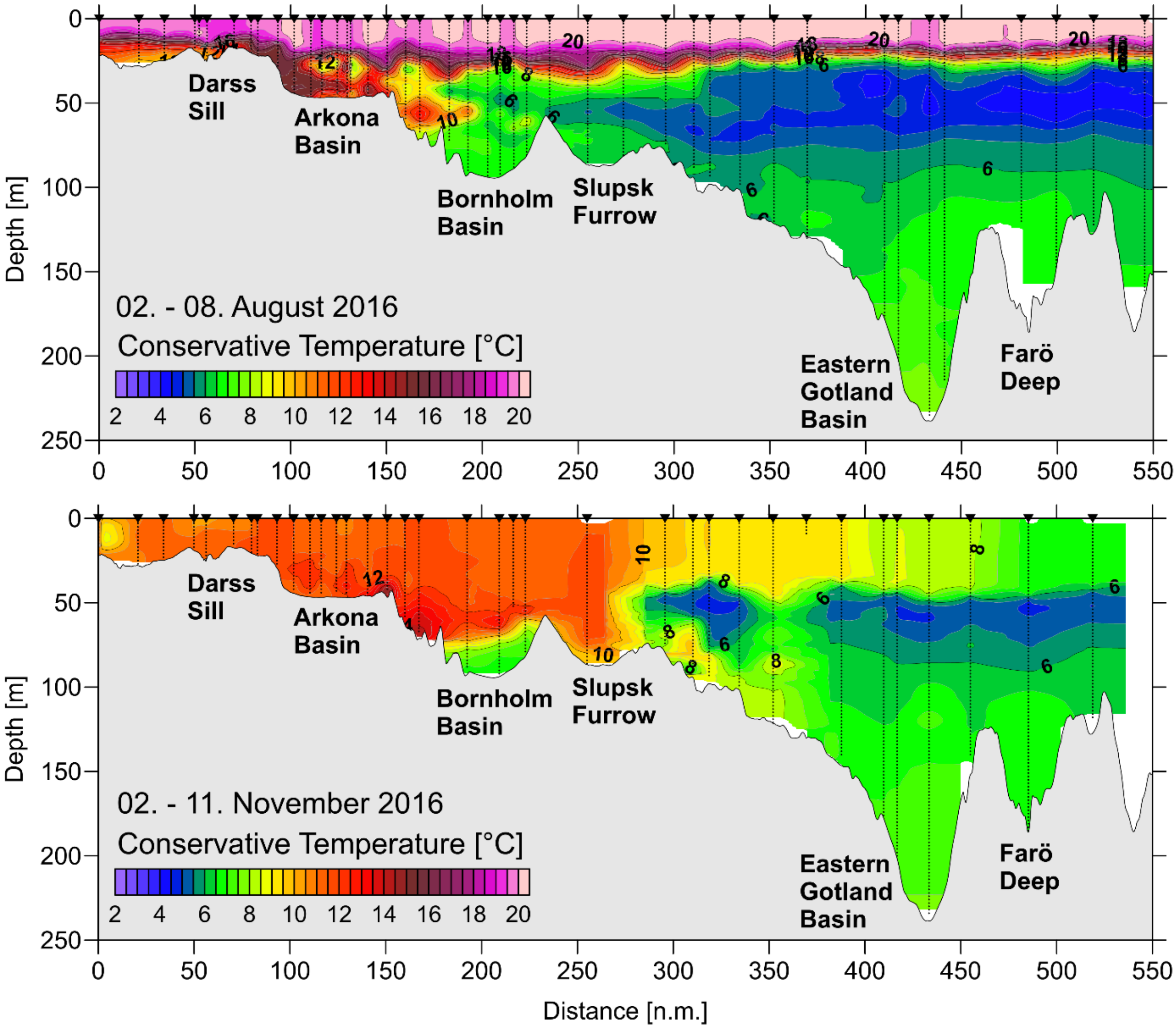

Fig. 25b: Temperature distribution along the talweg transect through the Baltic Sea between Darss Sill and northern Gotland Basin

As part of its long-term monitoring programme, IOW has operated hydrographic moorings near station TF271 in the eastern Gotland Basin since October 2010. In contrast to the Gotland Northeast mooring, in operation since 1998 which revealed the data for the well-known ‘Hagen Curve’, the mooring at TF271 was also collecting salinity data. The gathered time series data allow the description of the development of hydrographic conditions in the deep water of the Gotland Basin in high temporal resolution. This time series importantly supplemented the IOW’s ship-based monitoring programme. Figure 26 shows the temperature profile at five depths in the deep water of the eastern Gotland Basin between October 2015 and December 2016. The depicted temperature time series started in October 2015 after the saline water from the exceptional Christmas MBI 2014 has arrived in the eastern Gotland basin. The overall stratification is characterized by a downward increasing temperature. However, the vertical temperature gradient before January 2016 was weak. The temperature difference between the 140 m depth level and 190m depth was only about 0.3 K. In the bottom water layer between 190 m and the 233 m depth the temperature gradient almost vanished. In this layer the temperature increased only by 0.05 K. The bottom temperature was about 6.9 °C.

A moderate MBI in November 2015 brought about 133 km^3 of warm and saline water into the Baltic. These waters arrived in the eastern Gotland basin very quickly. In the beginning of February 2016 the bottom temperature increased rapidly by 1.0 K when the tip of the inflow water reached the eastern Gotland Basin. The main part of the inflow water arrived 20 days later, when also the temperature in 210 m and 190 m depth depicted a larger temperature increase. The uplift of former deep water by the inflow also caused a temperature increase in 160 m and 140 m depth, that continued till April 2016. A high variability of temperature was observed during the active inflow phase. The inflow increased the overall temperature gradient in the eastern Gotland basin considerably. The temperature difference between 140m depth and the bottom was about 0.8 K. The maximum bottom temperature of 7.8 °C was observed directly at the beginning of the inflow into the basin. This was also the highest bottom temperature ever observed since the beginning of the time series investigations in the eastern Gotland basin in 1997. Till December 2016 diapycnal mixing caused a continuous decrease of the bottom water temperature to 7.2 °C.

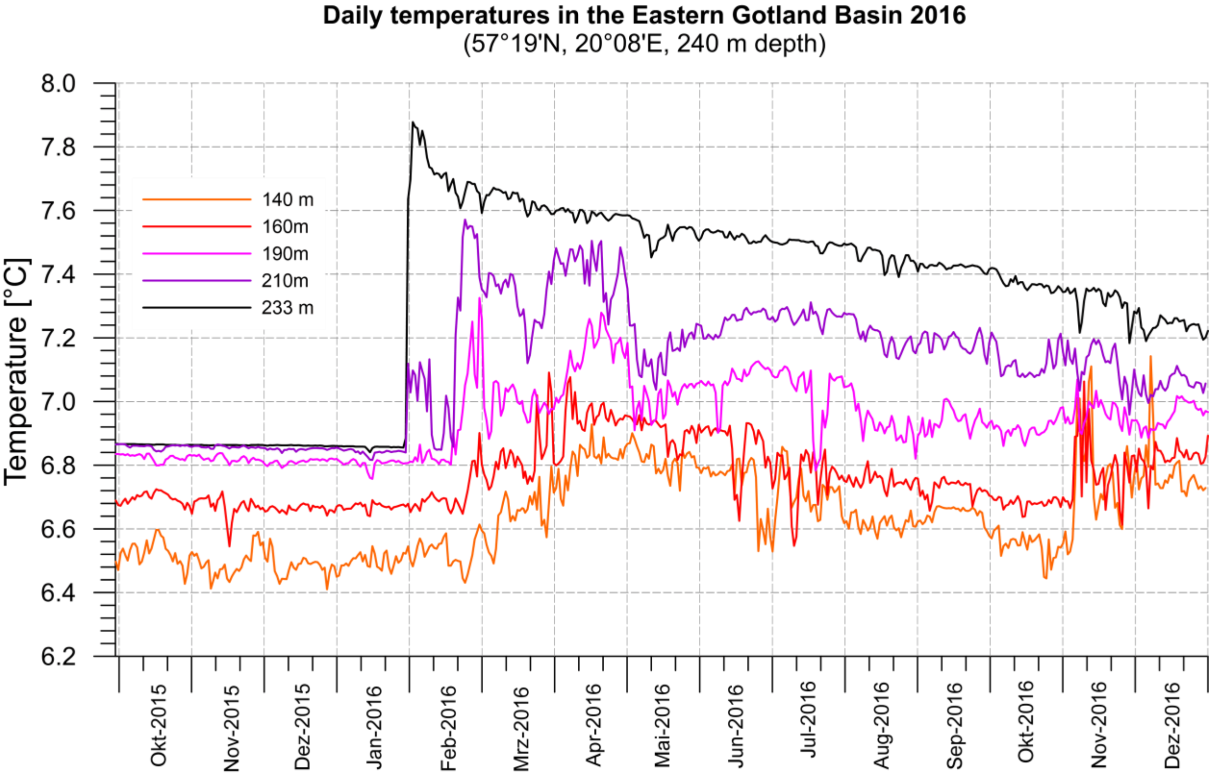

Fig. 26: Temporal development of deep water temperature in the Eastern Gotland Basin (station Tf271) from October 2015 to December 2016 (daily averages of original data with 10 min sampling interval)

Table 6 summarises the annual means and standard deviations of temperature in the deep water of the central Baltic based on CTD measurements over the past five years. The overall negative trend observed till 2014 in the central Baltic Basins was stopped by the series of inflow events in 2014/2015. Till 2016 deep water temperatures increased in all basins. In 2016 the strongest increase of 0.46 K was detected in the Landsort Deep. Illustrating, that inflow waters has now also reached the western Gotland Basin. In all deep basins the 2016 bottom temperature was the highest observed during the last five years. This correlates with the unusual warm temperature of the inflow water of the Christmas MBI 2014 and the moderate inflow in November 2015. The standard deviations of temperature fluctuations in 2016 were highest in the Bornholm Deep in the westernmost basin. Ongoing inflow activity with deep-water renewal caused the observed stronger fluctuations.

Table 6: Annual means and standard deviations of temperature, salinity and oxygen concentration in the deep water of the central Baltic Sea: IOW- and SMHI data (n= 5-15)

Water temperature (° C; maximum in bold)

Station	Depth/m	2012	2013	2014	2015	2016
213 (Bornholm Deep)	80	6.40 ±0.40	5.55 ±0.78	6.99 ±1.29	7.01 ±0.08	**7.06 ±0.63**
271 (Gotland Deep)	200	6.42 ±0.01	6.33 ±0.03	6.11 ±0.19	6.79 ±0.19	**7.06 ±0.12**
286 (Fårö Deep)	150	6.14 ±0.08	5.83 ±0.05	5.69 ±0.04	6.33 ±0.25	**6.56 ±0.06**
284 (Landsort Deep)	400	5.70 ±0.06	5.46 ±0.11	5.27 ±0.06	5.46 ±0.30	**5.92 ±0.10**
245 (Karlsö Deep)	100	5.15 ±0.12	5.22 ±0.07	5.00 ±0.04	5.03 ±0.06	**5.28 ±0.09**

Salinity (maximum in bold)

Station	Depth/m	2012	2013	2014	2015	2016
213 (Bornholm Deep)	80	15.16 ±0.49	15.16 ±0.24	16.06 ±0.41	**18.86 ±0.25**	18.26 ±0.40
271 (Gotland Deep)	200	12.13 ±0.04	12.00 ±0.04	12.06±0.11	12.95 ±0.35	**13.35 ±0.09**
286 (Fårö Deep)	150	11.52 ±0.06	11.28 ±0.17	11.36 ±0.08	11.93 ±0.22	**12.35 ±0.12**
284 (Landsort Deep)	400	10.50 ±0.03	10.43 ±0.05	10.37 ±0.08	10.63 ±0.33	**11.12 ±0.13**
245 (Karlsö Deep)	100	9.61 ±0.12	9.76 ± 0.18	9.58 ±0.11	9.64 ±0.17	**10.00 ±0.16**

Oxygen concentration (ml/l; hydrogen sulphide is expressed as negative oxygen equivalents; maximum in bold)

Station	Depth/m	2012	2013	2014	2015	2016
213 (Bornholm Deep)	80	1.68 ±1.45	1.62 ±1.05	2.07 ±1.47	**3.60 ±1.75**	1.30 ±0.93
271 (Gotland Deep)	200	-4.81 ±0.50	-5.30 ±0.83	-2.94 ±2.38	**0.93 ±0.80**	0.55 ±0.26
286 (Fårö Deep)	150	-2.20±0.38	-1.95 ±1.46	-2.35 ±0.53	-0.87 ±0.20	**-0.05 ±0.23**
284 (Landsort Deep)	400	-1.24 ±0.30	-1.11 ±0.24	-1.02 ±0.68	**-0.86 ±0.18**	-0.98 ±0.23
245 (Karlsö Deep)	100	**-0.17 ±0.44**	-0.72 ±0.73	-0.85 ±0.52	-0.87 ±0.51	-0.93 ±0.47

6.2 Salinity

The vertical distribution of salinity in the western and central Baltic Sea during IOW's five monitoring cruises is shown in Figure 27. Salinity distribution is markedly less variable than the temperature distribution, and a west-to-east gradient in the surface and the bottom water is typical. Greater fluctuations in salinity are observed particularly in the western Baltic Sea where the influence of salt-water inflows from the North Sea is strongest. The duration and influence of minor inflow events is usually too small to be reflected in an overall salinity distribution. Only in combination they can lead to a slow, long-term change in salinity. The salinity distributions shown in Figure 27 are mere 'snapshots' that cannot provide a complete picture of inflow activity. In 2016 the evolution of salinity distribution was mainly controlled by the moderate MBI of November 2015, which caused a significant increase in deep water salinity of the central Baltic. However, also the baroclinic inflows in late summer and autumn 2016 caused significant changes in the western Baltic. In 2016 a moderate MBI in February and a minor inflow in November/December occurred. Only the first one was recorded at different phases during IOW monitoring cruises. Two of the five data sets show an inflow event in the western Baltic. Based solely on these monitoring cruises, however, it is not possible to produce meaningful statistics on inflow events.

At the beginning of February the major fraction of the November MBI 2015 waters have passed the Slupsk Sill and the Slups Furrow towards the eastern Gotland basin. Two larger patches of higher saline water were detected between the eastern outlet of the Slupsk Furrow and the Gotland deep. These northward spreading water bodies contain the major part of the inflow water of November 2015 MBI. The deep layers of Bornholm Basin were still filled with high saline water from the inflow series in winter 2014/2015. Here the bottom salinity was about 18.9 g/kg. The halocline of the Bornholm Basin was occupied by a mixture of former deep water and warm water from the baroclinic summer inflows. The salinity of this water body ranged between 10 g/kg and 17 g/kg. The same water type filled also the deep layers of the Slupsk Furrow, with a maximum bottom salinity of about 14.7 g/kg. West of the Darss Sill and in the Arkona Basin the high saline water from the February 2016 inflow was visible. In the centre of the Arkona Basin, a 20 m to 25 m-thick salty bottom layer was observed. Bottom salinity in the Arkona Basin at this time was measured with a maximum of 23.9 g/kg. West of the Darss Sill high saline water covered the lower part of the water column with a maximum salinity of 22.5 g/kg. After the inflow series in winter 2014/2015 and the November 2015 inflow, salinity in the deep water of the central Baltic Sea was extremely high at the beginning of 2016. On the seabed in the Gotland Deep, salinity measured only 13.84 g/kg in February 2016. This was close to the overall maximum observed after the extreme inflow event in 1951. The 12 g/kg isohaline lay at a depth of around 127 m. In February 2015 the 12 g/kg isohaline was found at 163 m depth.

By the second half of March, first saline waters of the February inflow have reached the Bornholm Basin and the Slupsk Furrow. The pool of saline water in the Arkona Sea was thus strongly reduced. Here bottom salinity dropped to 21.5 g/kg. The densest part of inflow water has replaced the former bottom water in the Bornholm Basin. The bottom salinity increased slightly to 19.05 g/kg in the western part of the basin. In the Bornholm Basin the halocline was well above the sill depth of the Slupsk Sill, pointing to ongoing drainage of saline water into the Slupsk Furrow. There the pool of saline water was filled up, and the bottom salinity increased to 16.5 g/kg. North of the Slupsk Furrow some plumes of the November 2015 inflow water spreaded toward the eastern Gotland Basin. In the Gotland Deep, inflow of saline water led to a significant rise of the 12 g/kg isohaline from 127m to a depth of 117 m. In the Farö Deep the 12 g/kg isohaline was observed at 137m depth. The bottom salinity was only 12.36 g/kg here.

At the beginning of May the halocline in the Bornholm Basin relaxed to the sill depth of the Slupsk Sill. Below the halocline the Basin was filled with a mixture of former bottom water and high saline waters of the February inflow. The bottom salinity dropped slightly to 18.85 g/kg. In the Slupsk Furrow the halocline depicted an eastward slope from 55m depth near Slupsk Sill to 70m at the eastern sill of Slupsk Furrow. The major part of saline water has left the Slupsk Furrow towards the eastern Gotland Basin. The deep part of the Basin was filled up with saline inflow water. Although the bottom salinity decreased to 13.7 g/kg in the Gotland deep, the 13 g/kg isohaline rose from 179 m in March to a depth of 158 m.

In August no significant changes of salinity distribution were detected in the western Baltic. In the Bornholm Basin mixing with overlaying water caused a slight dilution of deep water. The bottom salinity sunk little to 18.63 g/kg. The inflow process into the eastern Gotland Basin has finished in July 2016. In the Gotland Deep the depth of the 12 g/kg isohaline and the bottom salinity remaining practically unchanged.

At the beginning of November, salinity stratification west of the Darss Sill indicated a new inflow. Here the surface salinity exceeded 17 g/kg. In the Arkona Basin warm and high saline water from the baroclinic summer/autumn inflows covered the bottom layer. The maximum salinity amounted to 22.8 g/kg. The warm inflow was insufficiently dense to replace the deep water in the Bornholm Basin, and spreaded along the halocline through the Bornholm Basin.

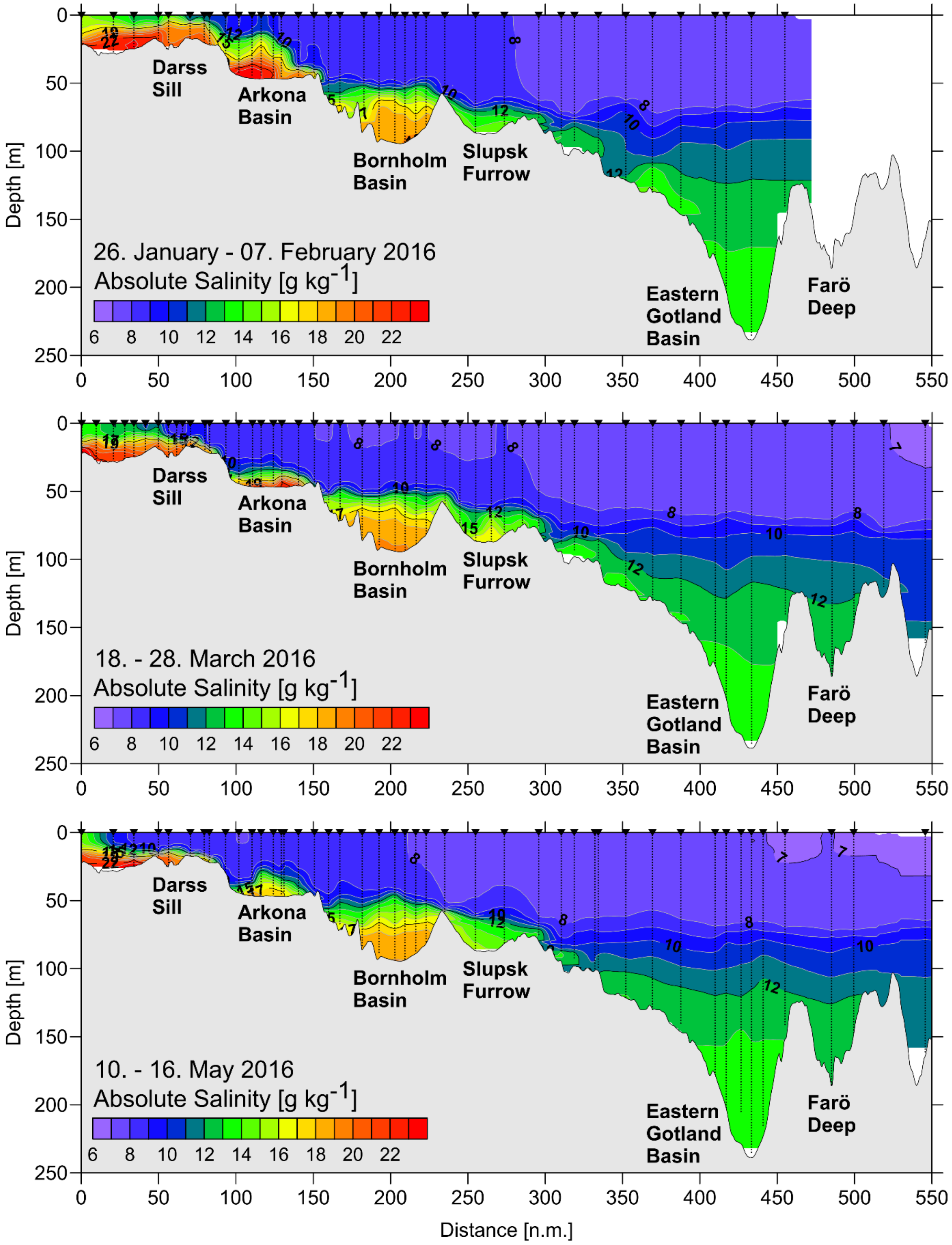

Fig. 27a: Salinity distribution along the talweg transect through the Baltic Sea between Darss Sill and northern Gotland Basin

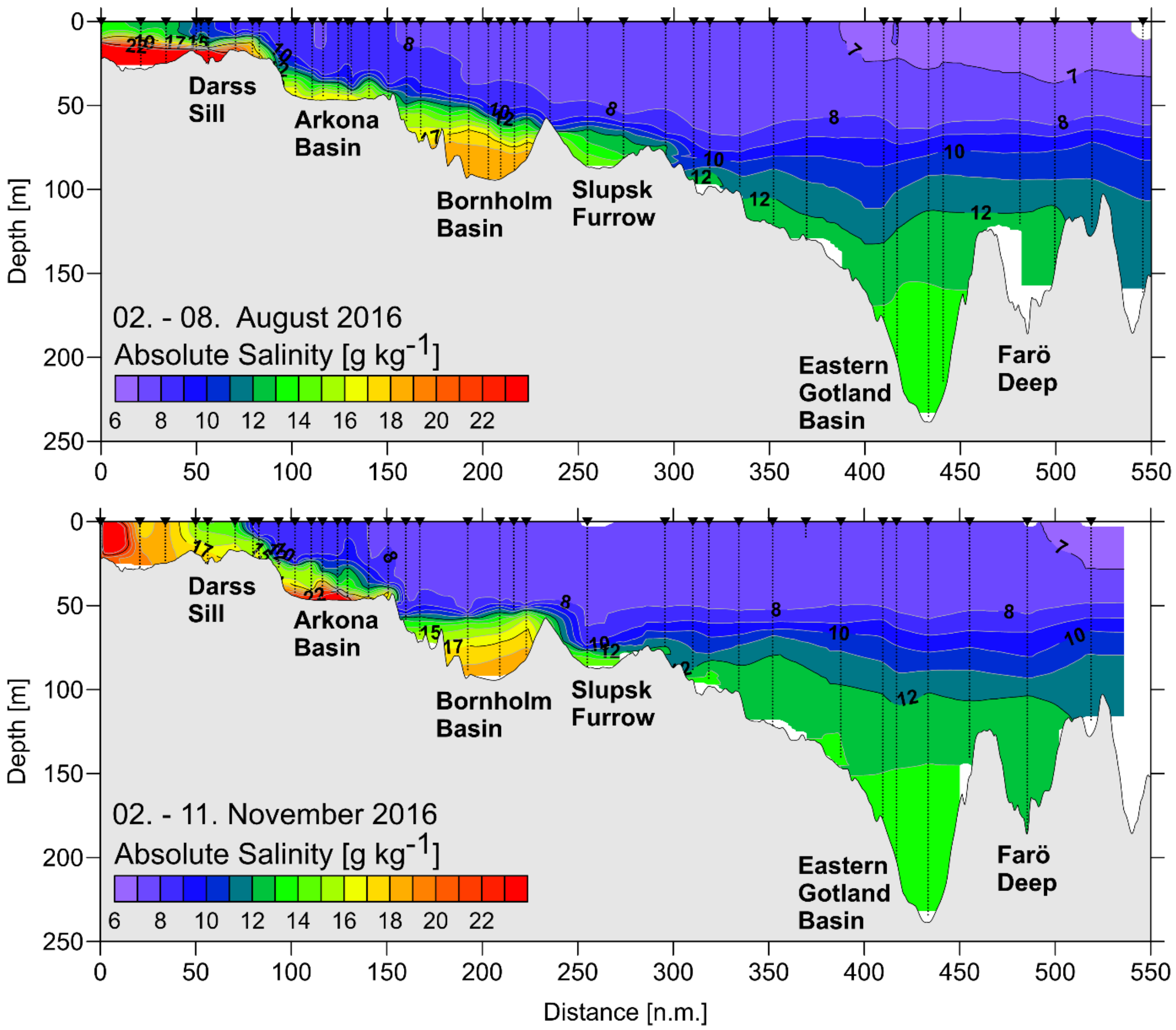

Fig. 27b: Salinity distribution along the talweg transect through the Baltic Sea between Darss Sill and northern Gotland Basin

Table 6 shows the overall trend of salinity in the deep water of the Baltic in the past five years. As a result of the recent series of inflow events the decline in deep water salinity has stopped in 2014. In all major basins of the central Baltic the salinity rose significantly. Due to the continuous series of inflow events since the extreme Christmas MBI 2014, the bottom salinity in the Gotland Deep, Fårö Deep, Karlsö Deep and Landsort Deep reached maximum values of the past five year period. Only in the Bornholm Basin a decrease of bottom salinity was observed in 2016. However, also here the salinity was still high, and well above the climatological mean. The high standard deviation of salinity in the Bornholm basin reflected rapid fluctuations, caused by the particular inflow events.

No clear trend emerges over the past five years for salinity in the surface layer of the Baltic. Table 7 summarises the variations in the surface layer salinity. Compared to values in 2015, surface layer salinity in the eastern Gotland Basin decreased slightly in 2016, whereas in the western Gotland Basin it increased. Standard deviations of surface salinity are roughly on a level with those of the long term average. Generally, the surface salinity will increase with a delay of about ten years after large inflow events. Thus, a significant increase in surface salinity was not expected for 2016.

Table 7: Annual means of 2012 to 2016 and standard deviations of surface water salinity in the central Baltic Sea (minimum values in bold, n= 8-25). The long-term averages of the years 1952-2005 are taken from the BALTIC climate atlas (FEISTEL et al., 2008)

Station	1952-2005	2012	2013	2014	2015	2016
213 (Bornholm Deep)	7.60 ±0.29	7.64 ±0.11	**7.28 ±0.12**	7.65 ±0.18	7.76 ±0.20	7.75 ±0.26
271 (Gotland Deep)	7.26 ±0.32	7.10 ±0.13	**6.78 ±0.28**	6.87 ±0.17	7.06 ±0.15	6.89 ±0.34
286 (Fårö Deep)	6.92 ±0.34	6.91 ±0.16	6.64 ±0.29	6.73 ±0.21	6.74 ±0.25	**6.63 ±0.33**
284 (Landsort Deep)	6.75 ±0.35	**6.27 ±0.38**	6.52 ±0.12	6.60 ±0.24	6.29 ±0.44	6.57 ±0.16
245 (Karlsö Deep)	6.99 ±0.32	6.97 ±0.21	**6.77 ±0.10**	7.00 ±0.13	6.91 ±0.25	6.98 ±0.17

Figure 28 shows the temporal development of salinity in the deep water of the eastern Gotland Basin between October 2015 and December 2016, based on data from the hydrographic moorings described above. Till January the data depict a strong vertical salinity gradient of about 0.01 g/kg m, established in the course of the series of inflow events since December 2014.

Concurrently with the jump in temperature (cf. Figure 26) also a steep increase in bottom salinity was observed in February 2016 when first patches of saline waters from the November inflow 2015 arrived in the Gotland basin. At this time only the deepest layer was affected. At 210 m and 190 m depth the first pulse of saline water arrived with 20 days delay. The major part of the November 2015 inflow reached the Gotland Basin by the end of March. Then in the entire deep water body a significant increase of salinity was observed, except close to the bottom. Till May the salinity in all deep water levels increased continuously. The maximum salinity was reached mid to end of April 2016. During the entire year 2016 the vertical salinity gradient remained at the high level, as observed in January 2016. The strong density stratification will effectively suppress the diapycnal mixing in the near future. Till December 2016 only a week decrease of deep water salinity was observed. As for temperature, the salinity time series reveal strong, short-term fluctuations whose amplitudes decreased with depth. Mostly, these fluctuations correlated well with the observed temperature variability.

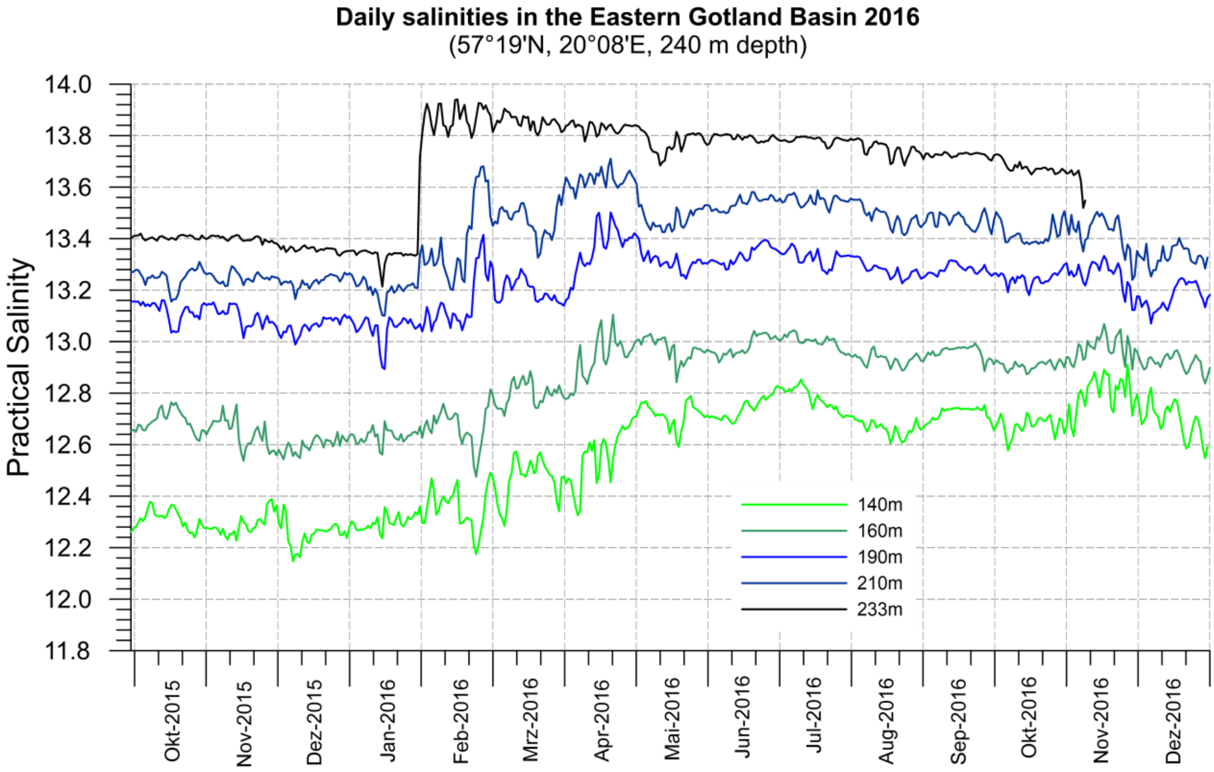

Fig. 28: Temporal development of deep water salinity in the Eastern Gotland Basin (station TF271) from October 2015 to December 2016 (Daily averages of original data with 10 min sampling interval)

Figures 25 and 26 depict the talweg transect of the Baltic in a relatively coarse spatial resolution based on CTD profiles. To investigate the inflow process in more detail a hydrographic transect with a towed undulating CTD (ScanFish) was performed during the cruise in March 2015. Figure 29 displays a section of this transect from the Slupsk Sill, via the Slupsk Furrow towards the eastern Gotland Basin. The figure shows the spreading of saline waters of the November 2015 inflow towards the central Baltic. The saline water pool of the Slupsk Furrow is filled to the height of the eastern sill by saline water with salinity >12 g/kg. This water body consisted of two different water masses and their mixing stages. First the warm waters from the baroclinic late summer/autumn inflows of 2015, and second the cooler waters from the November inflow in 2015. Both water types can be also distinguished by their oxygen content. The cold inflow water from the November MBI was well oxygenated with concentrations up to 4.5 ml/l. The warmer inflow water depicted already some oxygen losses and showed oxygen concentrations of about 60 µmol/l to 120 µmol/l (1.3-2.7 ml/l). The ongoing inflow towards the eastern Gotland basin was seen in the bottom layer right behind the eastern sill of the Slupsk Furrow. There a 10 m to 15 m thick layer of saline water spreaded northward. The plume can be easily identified by its oxygen content clearly exceeded the ambient water. However, the oxygen concentration inside the plume was not uniform. This pointed to an ongoing mixing of the inflow waters with ambient water. Along their pathway the inflow water lifts up the former bottom water. A second warm water body north of the plume indicates a patch of inflow water from the late summer/autumn inflows on the way to the eastern Gotland basin. Here the entire deep water column was moderately ventilated. At the entrance of the eastern Gotland basin the layer between the halocline and the bottom is covered by old hypoxic deep water with oxygen concentrations below 20 µmol/l (0.4 ml/l).

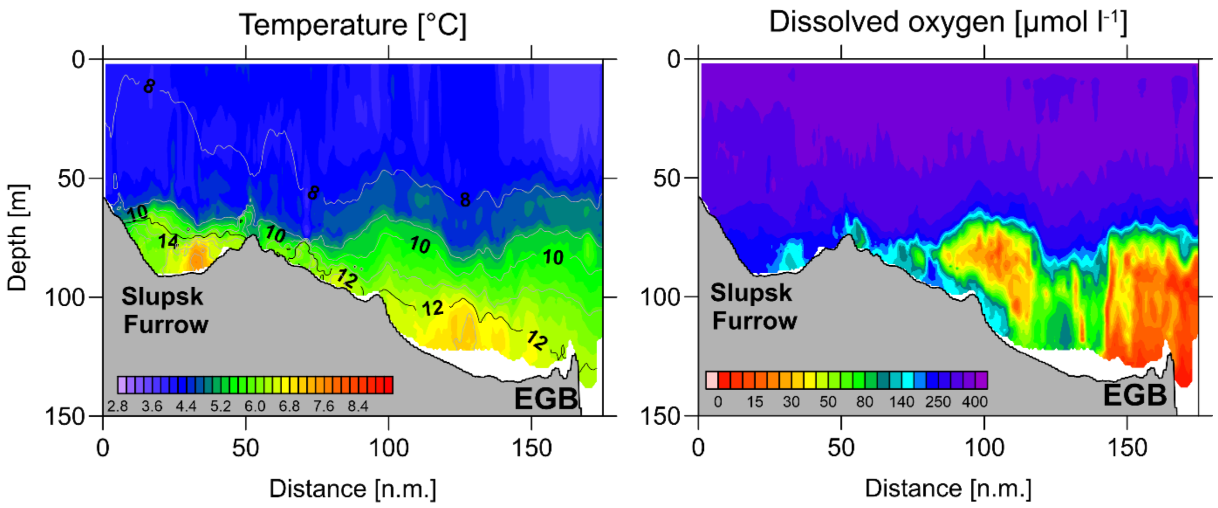

Fig. 29: Temperature (color contour) and practical salinity (isolines) distribution (left panel), and oxygen concentration (right panel) along the Slupsk Furrow towards the eastern Gotland basin on 24. - 26. March 2016 (High spatial resolution data obtained with ScanFish measurements).

6.3 Oxygen distribution

Exchange processes with the atmosphere and biogeochemical processes determine the oxygen content of seawater. In surface water (upper panel), the oxygen is usually close to saturation that is mainly controlled by temperature, but the salinity of seawater and air pressure play a role too. Increasing temperature could lead to intermediate supersaturation of oxygen in surface waters because equilibration with the atmosphere depend on wind speed and wave activity and could be slow at calm conditions. More important are assimilation and dissimilation processes on the oxygen content. During photosynthesis by phytoplankton large amounts of oxygen are released that in turn could lead to a strong supersaturation in the euphotic zone. Whereas, during respiration oxygen in consumed. In deeper water layers without contact to the atmosphere, oxygen concentration then clearly declines. In especially unfavourable hydrographic conditions, below permanent or temporary pycnoclines caused by strong temperature and/or salinity differences, lasting oxygen consumption during organic matter degradation can lead to total depletion of oxygen (lower panel). Denitrification and subsequent sulphate reduction is then used for on-going remineralization and in turn, toxic hydrogen sulphide is released.

Table 8: Oxygen concentration (ml/l) in deep waters of the Baltic Sea deeps
(Hydrogen sulphide is converted to negative oxygen equivalents; maxima are given in bold)

Station	Depth/m	2012	2013	2014	2015	2016
213 (Bornholm Deep)	80	1.68 ±1.45	1.62 ±1.05	2.07 ±1.47	**3.60 ±1.75**	1.19 ± 1.00
271 (Gotland Deep)	200	-4.81 ±0.50	-5.30 ±0.83	-2.94 ±2.38	**0.93 ±0.80**	0.62 ±0.24
286 (Fårö Deep)	150	-2.20±0.38	-1.95 ±1.46	-2.35 ±0.53	-0.87 ±0.20	**-0.05 ±0.22**
284 (Landsort Deep)	400	-1.24 ±0.30	-1.11 ±0.24	-1.02 ±0.68	**-0.86 ±0.18**	-0.92 ±0.33
245 (Karlsö Deep)	100	**-0.17 ±0.44**	-0.72 ±0.73	-0.85 ±0.52	-0.87 ±0.51	-1.15 ± 0.34

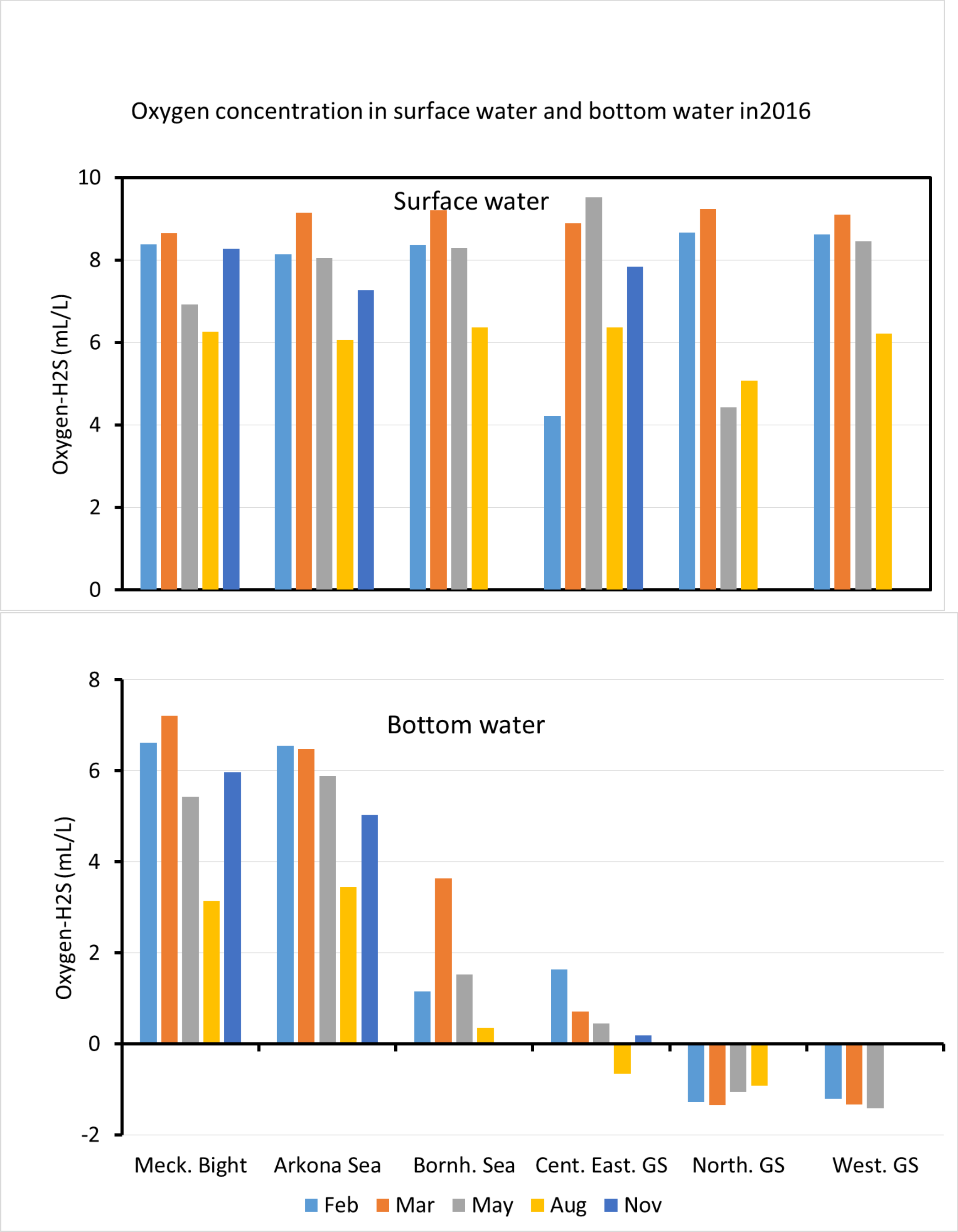

Fig. 29: Comparison of average oxygen/hydrogen sulphide concentrations in surface (upper panel) and bottom waters (lower panel) of the studied Baltic Sea areas Mecklenburgh Bight, Arkona Sea, Bornholm Sea, central Eastern Gotland Sea, Northern Gotland Sea, and Western Gotland Sea.

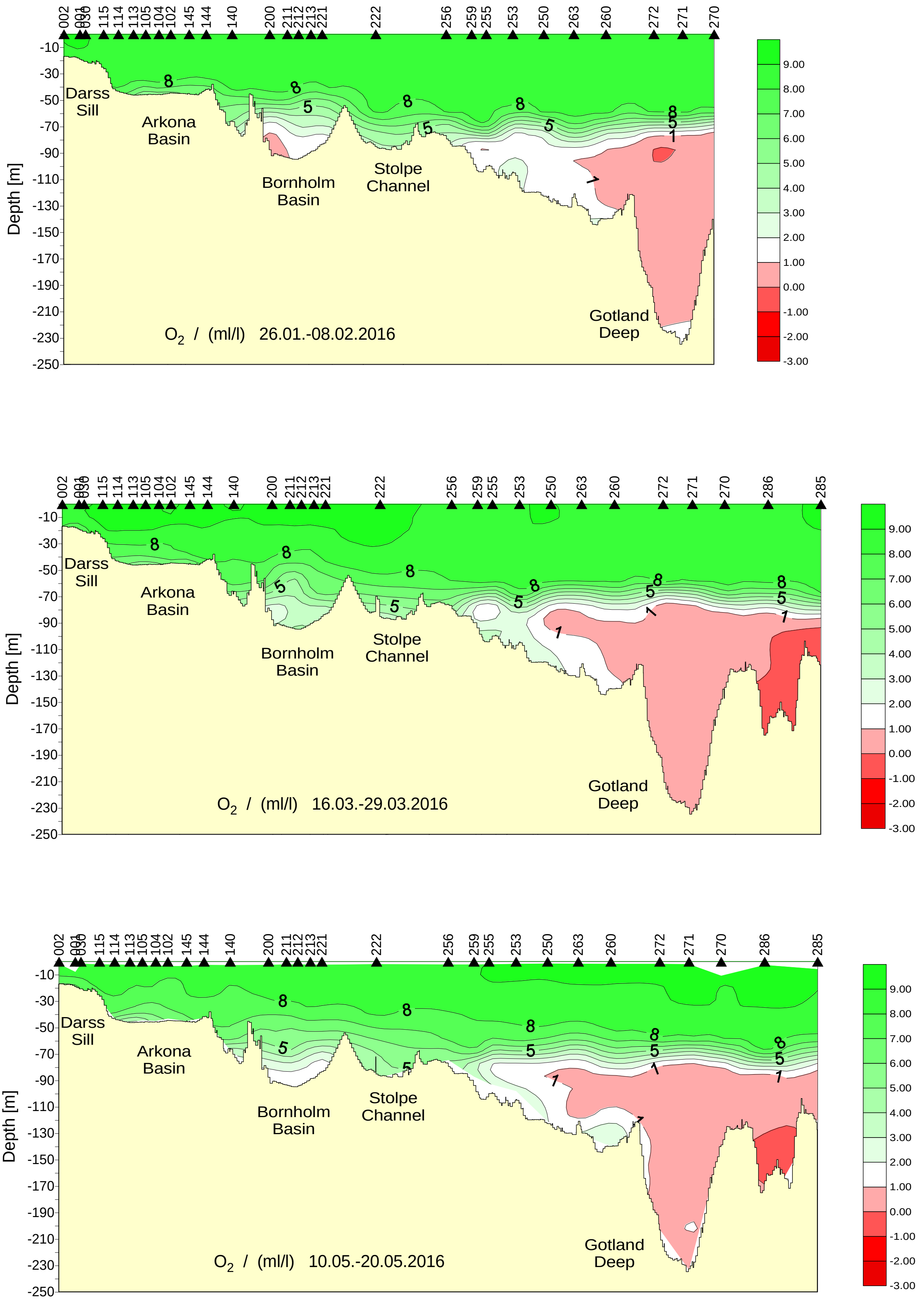

Fig. 30a: Vertical distribution of oxygen resp. hydrogen sulphide in 2016 between the Darss Sill and the northern Gotland Basin

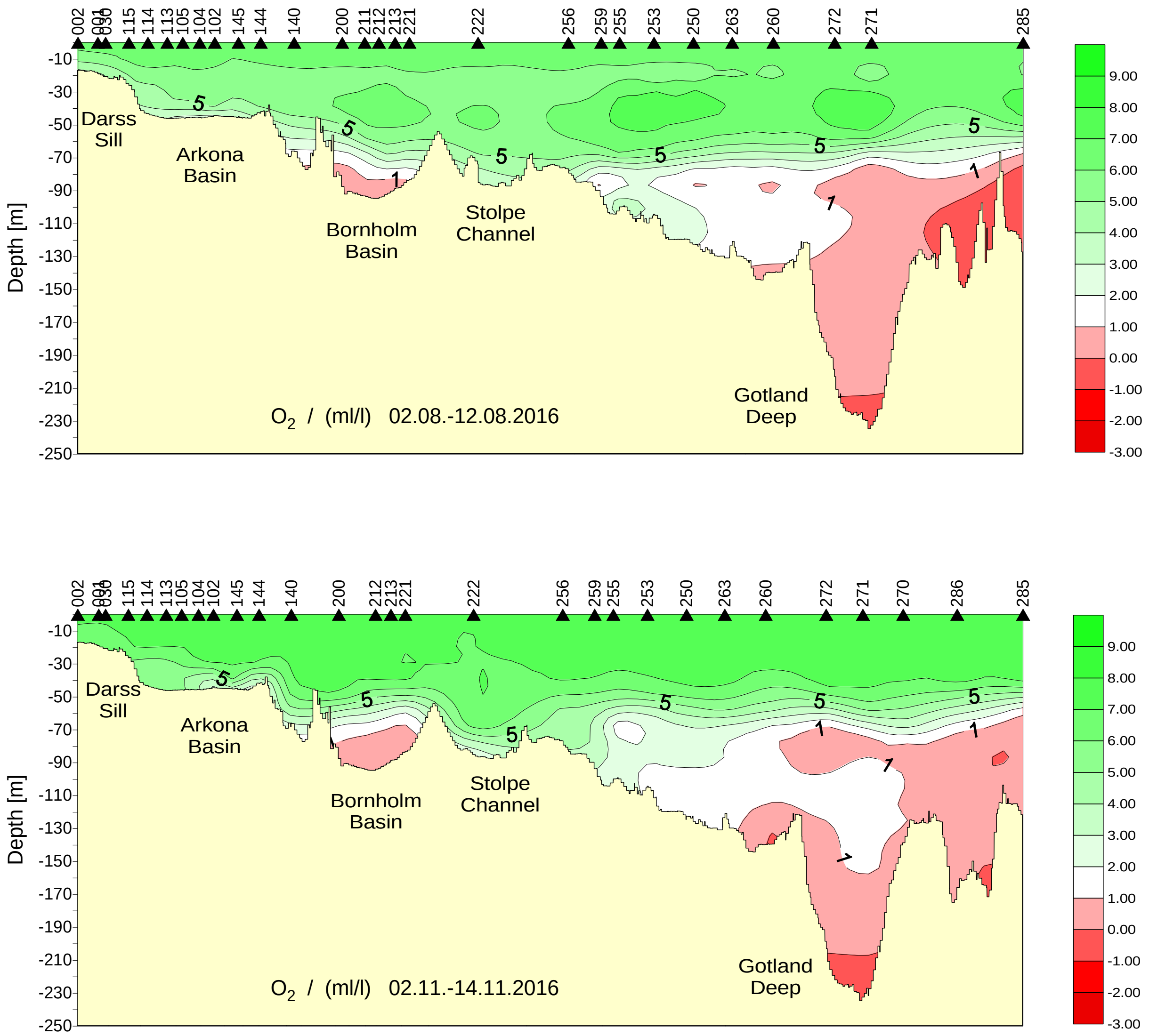

Fig. 30b: Vertical distribution of oxygen resp. hydrogen sulphide in 2016 between the Darss Sill and the northern Gotland Basin

6.4 Inorganic Nutrients

Even after decades in which measures to reduce nutrient inputs to the Baltic Sea have been implemented, the Baltic Sea eutrophication is still of major concern. With “Eutrophication is … the increased supply of plant nutrients (phosphorus and nitrogen compounds) to waters due to human activities in the catchment areas which results in an increased production of algae and higher water plants” (EUTROSYM, 1976). A more drastic description of the consequences of eutrophication is given by DUARTE et al. (2009) “The effects of eutrophication include the development of noxious blooms of opportunistic algae and toxic algae, the development of hypoxia, loss of valuable seagrasses, and in general a deterioration of the ecosystem quality and the services they provide”. In the recent Pollution Load Compilation (PLC-5.5) the problem is quantified for the year 2010 as an example (HELCOM, 2015) “In 2010, the total waterborne and airborne inputs of nitrogen and phosphorus to the Baltic Sea were 977,000 Mg and

38,300 Mg, respectively. Atmospheric deposition of nitrogen amounted to 219,000 Mg or 22 % of the total nitrogen input. An estimated deposition of 2,100 Mg of atmospheric phosphorus deposited to the Baltic Sea annually, constituting nearly 5 % of the total phosphorus input to the Baltic Sea. In 2010, 62 % of the total nitrogen deposition to the Baltic Sea originated from surrounding HELCOM countries (including the areas which are outside the catchment areas that drains to the Baltic Sea, e.g. in Denmark, Germany and Russia), 6 % from Baltic Sea shipping, 18 % from the 20 EU countries which are not HELCOM Contracting Parties, and the remaining 14 % from other countries and distant sources outside the Baltic Sea region. The seven largest rivers entering to the Baltic Sea (Daugava, Göta älv, Kemijoki, Nemunas, Neva, Odra, and Vistula) cover 51 % of the catchment area. Fifty-three per cent of total waterborne nitrogen and 54 % of phosphorus inputs entered the Baltic Sea in 2010 via these rivers, but only 46 % of the total river flow. The aim of the European Union's ambitious Marine Strategy Framework Directive is to protect more effectively the marine environment across Europe. The Marine Directive aims to achieve Good Environmental Status (GES) of the EU's marine waters by 2020 and to protect the resource base upon which marine-related economic and social activities depend (http://ec.europa.eu/environment/marine/eu-coast-and-marine-policy/marine-strategy-framework-directive/index_en.htm).

In Germany, riverine inputs of total phosphorus fell between 1986/90 and 2004/08 by 61 %, mainly due to low loads from point sources. In the same time-period, Nitrogen input from mostly diffuse sources decreased only by 13 % (NAUSCH et al., 2011). Despite this positive development, German coastal waters and bordering sea areas are clearly hypertrofied based on the assessed data. To determine the effects of changes in nutrient inputs and to evaluate the results of reduction measures undertaken, the frequent monitoring of the nutrient situation is mandatory. Nutrients are core parameters since HELCOM established a standardized monitoring programme at the end of the 1970's. According to the Marine Strategy Framework Directive Article 8 (Table 1 of Annex III) the following chemical parameter need to be monitored: spatial and temporal distribution of nutrients (Dissolved inorganic nitrogen, Total nitrogen, Dissolved inorganic phosphorus, Total phosphorus, Total organic carbon) and oxygen, moreover pH, pCO2 profiles or equivalent information aimed at quantifying marine acidification.

6.4.1 Surface water processes

In the surface layer of temperate latitudes phosphate and nitrate exhibit a typical annual cycle (NAUSCH & NEHRING, 1996; NEHRING & MATTHÄUS, 1991). Figure 38 illustrates the annual cycle of nitrate and phosphate in the eastern Gotland Sea and in the Bornholm Sea in 2016. The data of five monitoring cruises of the IOW are supplemented by Swedish data of SMHI to get a better resolution of the seasonal patterns. In the central Baltic Sea, a typical phase of elevated concentration developed during winter which lasts two to three months (NAUSCH et al., 2008b). At increasing surface water temperatures, the spring bloom started in the central Gotland Sea in March/early April that lead to a rapid decline of nitrate. In the Bornholm Sea this process started in 2016 already one month earlier in the end of February/early March. After nitrate depletion the spring bloom terminated end of March in the Bornholm Sea and mid of April in the eastern Gotland Sea.

However, in the Bornholm Basin nitrate appeared to have recovered a bit in May/June during times of low production, but generally remained low until autumn. Phosphate's decline during spring is smoother and stretched until August, on a higher level in the Bornholm Sea compared to the changes in the Gotland Sea. The phosphate concentration then remained close to the detection limit during the period of elevated surface water temperatures of above ~12 °C.

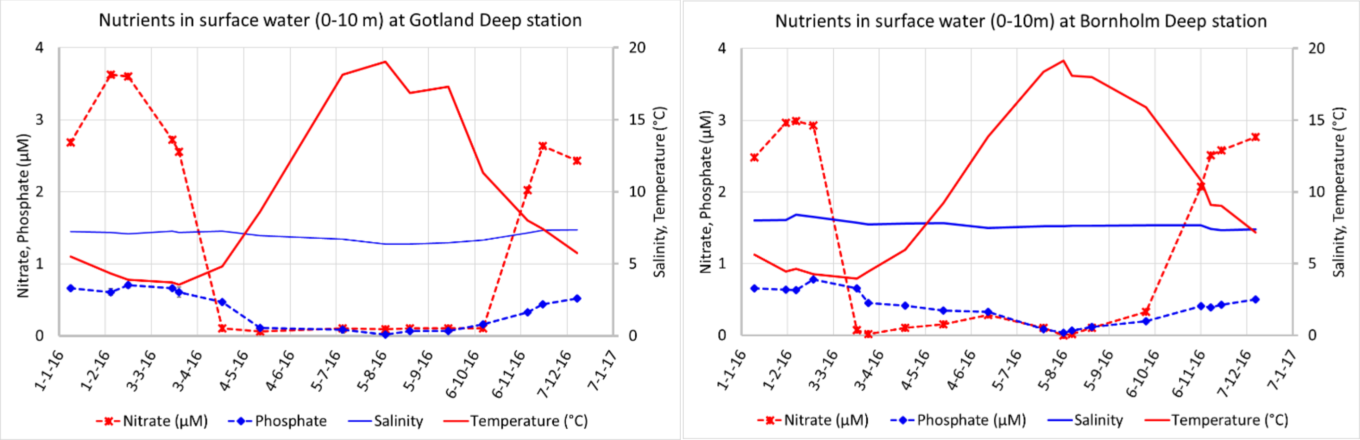

Fig. 31: Seasonal cycle of the average phosphate and nitrate concentrations in 2016 compared to temperature and salinity in the surface layer (0-10 m) of the eastern Gotland Basin (TF271 - left) and in the Bornholm Basin (TF213 – right)– IOW and SMHI data

In autumn, cooling enabled wind induced mixing and supply of nutrients from deeper layers. Mineralisation processes at depth caused an increase in nutrient concentrations that subsequently replenished the surface water until the end of the year.

The sluggish decline of phosphate is caused by the low N/P ratio present in the winter surface water of the Baltic Sea that already caused nitrate exhaustion before phosphate was consumed. The favourable uptake ratio is 16 according to an early study by Redfield (REDFIELD et al., 1963). In the investigated areas the values were slightly above 8 in the western Baltic Sea, reflected a maximum in the southeastern Arkona Sea ("Odra Bight") of 10.5, and scattered around 6 in the Bornholm Sea and Gotland Sea. The N/P ratio (mol/mol) was determined from the sum of ammonium, nitrate, and nitrite concentrations versus the phosphate concentration. This already indicated that nitrogen will become a limiting factor through the year 2016 giving diazotrophic cyanobacteria an advantage also in this year at increased surface water temperatures.

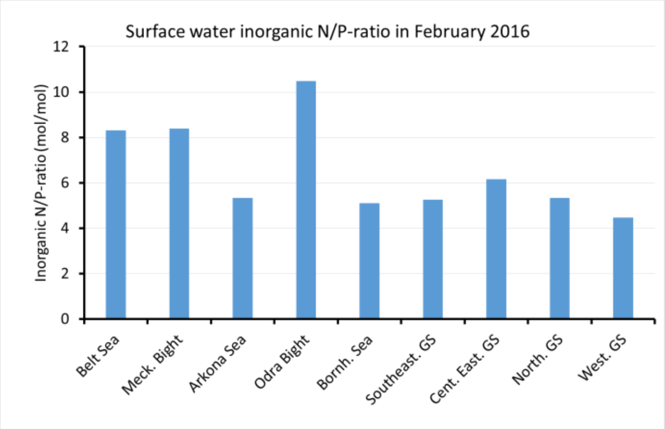

Fig. 32: Average total inorganic nitrogen versus phosphate ratio in surface waters of various Baltic Sea areas in February 2016.

In Table 9 winter nitrate and phosphate concentrations of surface waters are compiled. The values are in the range of previous years. However, it appears that a slight increase was determined for phosphate for all studied sites and a decline of nitrate in the western Baltic Sea and the Bornholm Sea and almost stable conditions in Gotland Sea since 2014. The clear variability of the values during the last five years indicate that the reductions in nutrient concentrations that have already been observed in coastal waters are up to now not reflected in the nutrients concentrations of the central Baltic Sea basins (NAUSCH et al., 2011). The partial weak decline of nitrate might be a consequence of the inflow that had replaced low nitrogen deep waters and may finally contribute to surface water outflow. Even a correlation analysis of the ten-year data series for 2004 to 2013 revealed no significant changes for all investigated sea areas (NAUSCH et al., 2014).

Table 9: Mean nutrient concentrations in the surface layer (0-10 m) in winter in the western and central Baltic Sea (IOW and SMHI data).

Surface water phosphate concentrations (µmol/l) in winter (Minima in bold)

Station	Monat	2012	2013	2014	2015	2016
360 (Fehmarn Belt)	Feb.	0.71 ± 0.01	0.72 ± 0.01	**0.57 ± 0.01**	0.64 ± 0.01	0.66 ± 0.04
022 (Lübeck Bight)	Feb.	0.71 ± 0.01	0.85 ± 0.01	0.71 ± 0.04	**0.63 ± 0.02**	0.79 ± 0.15
012 (Meckl. Bight)	Feb.	0.73 ± 0.02	0.85 ± 0.01	**0.56 ± 0.00**	0.60 ± 0.01	0.68 ± 0.01
113 (Arkona Sea)	Feb.	0.73 ± 0.00	0.63 ± 0.01	**0.53 ± 0.00**	0.56 ± 0.00	0.64 ± 0.01
213 (Bornholm Deep)	Feb.	0.66 ± 0.01	0.71 ± 0.0	0.70 ± 0.01	**0.60 ± 0.00**	0.67 ± 0.06
271 (Gotland Deep)	Feb.	0.64 ± 0.01	0.54 ± 0.02	0.52 ± 0.01	**0.50 ± 0.02**	0.67 ± 0.04
286 (Fårö Deep)	Feb.	0.56 ± 0.00	**0.50 ± 0.01**	0.78 ± 0.01	0.60 ± 0.00	0.65 ± 0.08
284 (Landsort Deep)	Feb.	0.63 ± 0.01	**0.56 ± 0.02**	0.84 ± 0.01	-	0.75 ± 0.01
245 (Karls Deep)	Feb.	0.80 ± 0.02	**0.60 ± 0.02**	0.85 ± 0.00	0.80 ± 0.00	0.87 ± 0.09

Surface water nitrate concentrations (µmol/l) in winter (Minima in bold)

Station	Monat	2012	2013	2014	2015	2016
360 (Fehmarn Belt)	Feb.	5.7 ± 0.1	**4.1 ± 0.0**	4.9 ± 0.2	7.5 ± 0.1	4.5 ± 0.5
022 (Lübeck Bight)	Feb.	**6.2 ± 0.2**	6.7 ± 0.1	6.6 ± 0.1	9.3 ± 0.2	6.3 ± 0.1
012 (Meckl. Bight) Bucht)	Feb.	**3.8 ± 0.2**	5.8 ± 0.0	4.5 ± 0.1	5.5 ± 0.0	4.8 ± 0.1
113 (Arkona Sea)	Feb.	**2.9 ± 0.0**	3.2 ± 0.0	5.2 ± 0.2	3.7 ± 0.0	3.2 ± 0.2
213 (Bornholm Deep)	Feb.	**2.6 ± 0.0**	3.0 ± 0.0	4.0 ± 0.1	3.3 ± 0.2	2.8 ± 0.2
271 (Gotland Deep)	Feb.	**2.6 ± 0.2**	2.9 ± 0.0	3.9 ± 0.0	3.1 ± 0.0	3.4 ± 0.4
286 (Fårö Deep)	Feb.	3.3 ± 0.0	**3.0 ± 0.0**	4.5 ± 0.1	3.4 ± 0.0	3.3 ± 0.5
284 (Landsort Deep)	Feb.	4.6 ± 0.1	4.4 ± 0.0	**3,8 ± 0,3**		3.9 ± 0.0
245 (Karls Deep)	Feb.	4.0 ± 0.1	3.8 ± 0.1	3.5 ± 0.2	**3.2 ± 0.0**	3.3 ± 0.3

6.4.2 Deep water processes in 2016

In the deep waters of the central Baltic Sea basins, nutrient distribution is primarily influenced by the occurrence or absence of strong barotropic and/or baroclinic inflows. Figures 33 and 34 illustrate the nutrients concentration distribution in the water column on transect between the Darss sill and the Northern Gotland Sea for the year 2016. It should be noted that anoxic conditions prevent mineralisation of organic matter until nitrate. Instead ammonium is formed and represents the end product of the degradation of biogenic material (Table 10).

Table 10: Annual means and standard deviations for phosphate, nitrate and ammonium in the deep water of the central Baltic Sea (IOW and SMHI data).

Annual mean deep water phosphate concentration (µmol/l; Maxima in bold)

Station	Tiefe/m	2012	2013	2014	2015	2016
213 (Bornholm Deep)	80	1.81 ± 0.85	1.62 ± 0.35	1.49 ± 0.31	1.57 ± 0.44	**2.23 ± 0.29**
271 (Gotland Deep)	200	5.87 ± 0.16	**6.32 ± 0.92**	4.50 ± 1.54	2.16 ± 0.29	2.56 ± 0.14
286 (Fårö Deep)	150	4.45 ± 0.23	**4.77 ± 0.58**	4.60 ± 0.67	3.26 ± 0.23	2.93 ± 0.22
284 (Landsort Deep)	400	**3.92 ± 0.25**	3.89 ± 0.21	3.85 ± 0.35	3.57 ± 0.26	3.25 ± 0.31
245 (Karls Deep)	100	3.47 ± 0.47	3.91 ± 0.53	3.99 ± 0.51	3.92 ± 0.19	**4.25 ± 0.34**

Annual mean deep water nitrate concentration (µmol/l; Minima in bold)

Station	Tiefe/m	2012	2013	2014	2015	2016
213 (Bornholm Deep)	80	7.9 ± 3.1	**6.4 ± 1.9**	8.2 ± 1.8	11.1 ± 2.5	10.4 ± 1.9
271 (Gotland Deep)	200	**0.0 ± 0.0**	**0.0 ± 00**	**0.0 ± 00**	7-5 ± 3.3	9-3 ± 0.7
286 (Fårö Deep)	150	**0.0 ± 0.0**	**0.0 ± 0.0**	**0.0 ± 00**	**0.0 ± 00**	1.4 ± 1.7
284 (Landsort Deep)	400	**0.0 ± 0.0**	**0.0 ± 0.0**	**0.0 ± 00**	**0.0 ± 00**	**0.0 ± 0.0**
245 (Karls Deep)	100	1.51 ± 2.08	01. ± 0.2	**0.0 ± 00**	**0.0 ± 00**	0.1 ± 00

Annual mean deep water ammonium concentration (µmol/l; Maxima in bold)

Station	Tiefe/m	2012	2013	2014	2015	2016
213 (Bornholm Deep)	80	0.1 ± 1.9	01. ± 0.1	0.1 ± 0.2	0.2 ± 0.1	0.2 ± 0.1
271 (Gotland Deep)	200	**26.2 ± 2.8**	22.1 ± 8.7	18.4 ± 10.9	1.6 ± 3.7	0.2 ± 0.0
286 (Fårö Deep)	150	12.2 ± 1.5	12.6 ± 3.0	**12.8 + 3.6**	7.2 ± 2.1	2.0 ± 2.0
284 (Landsort Deep)	400	**8.5 ± 1.6**	7.2 ± 2.3	7.9 ± 1.7	6.5 ± 1.1	7.8 ± 3.3
245 (Karls Deep)	100	4.4 ± 2.9	6.5 ± 3.1	7.7 ± 2.1	7.7 ± 1.2	**9.7 ± 1.7**

The Bornholm Basin is the westernmost of the deep basins, and barotropic and baroclinic inflows frequently ventilate its deep water. The last series of major Baltic Inflows began in November 2013 and terminated a longer stagnation that persisted since 2003 and was briefly interrupted in 2007, only. Hence since February and March 2014 hydrogen sulphide decline propagated through the Baltic Sea. Oxygenic conditions were established in the Bornholm basin and in the eastern Gotland basin until the Fårö Deep. The latter shows partial oxygenic and remains of sulphidic conditions (cf. Chapter 6.3). Moreover, the oxygen situation of the southern and eastern deeps improved even more by subsequent pulses of oxygenated saline water via the Arkona Sea and the Bornholm Sea to the eastern Gotland basin. Nutrients concentrations were impacted in various ways. Under oxic conditions nitrate re-appeared and phosphate is removed as particulate Iron phosphate during transition, thus reducing its concentrations to <2 µmol/l in the deep waters. Likely, by ongoing mineralization and supply from bottom sediments phosphate increased to 2.23 µmol/l in the Bornholm Deep and to 2.56 µmol/L in the Gotland Deep during oxic conditions in 2016. In the Fårö and Landsort Deeps the phosphate concentration decline went on since 2013 and reached 2.93 µmol/l and 3.25 µmol/l, respectively. The Karls Deep shows no inflow impact and phosphate increased in 2016 to 4.25 µmol/l.

As mentioned before, the presence of oxygen enables the nitrification of ammonium to nitrate. Thus, since 2012, ammonium concentrations were low 0.1-0.2 µmol/l in the Bornholm Deep and since 2016 in the Gotland Deep (Table 10). The Fårö Deep showed a decline of the ammonium concentration from 12.8 µmol/l to 2.0 µmol/l since 2014. Landsort and Karls Deep still show an ammonium concentration increase. Correspondingly, nitrate concentrations were high in the Bornholm Deep since 2012, 10.4 µmol/L in 2016, and in the Gotland Deep since 2015 (9.3 µmol/l in 2016). The oxic transition caused a jump from “0” µmol/l to 1.4 µmol/l nitrate in the Fårö Deep deep waters in 2016. Landsort and Karls Deeps still do not show a significant deviation of nitrate from the detection limit.

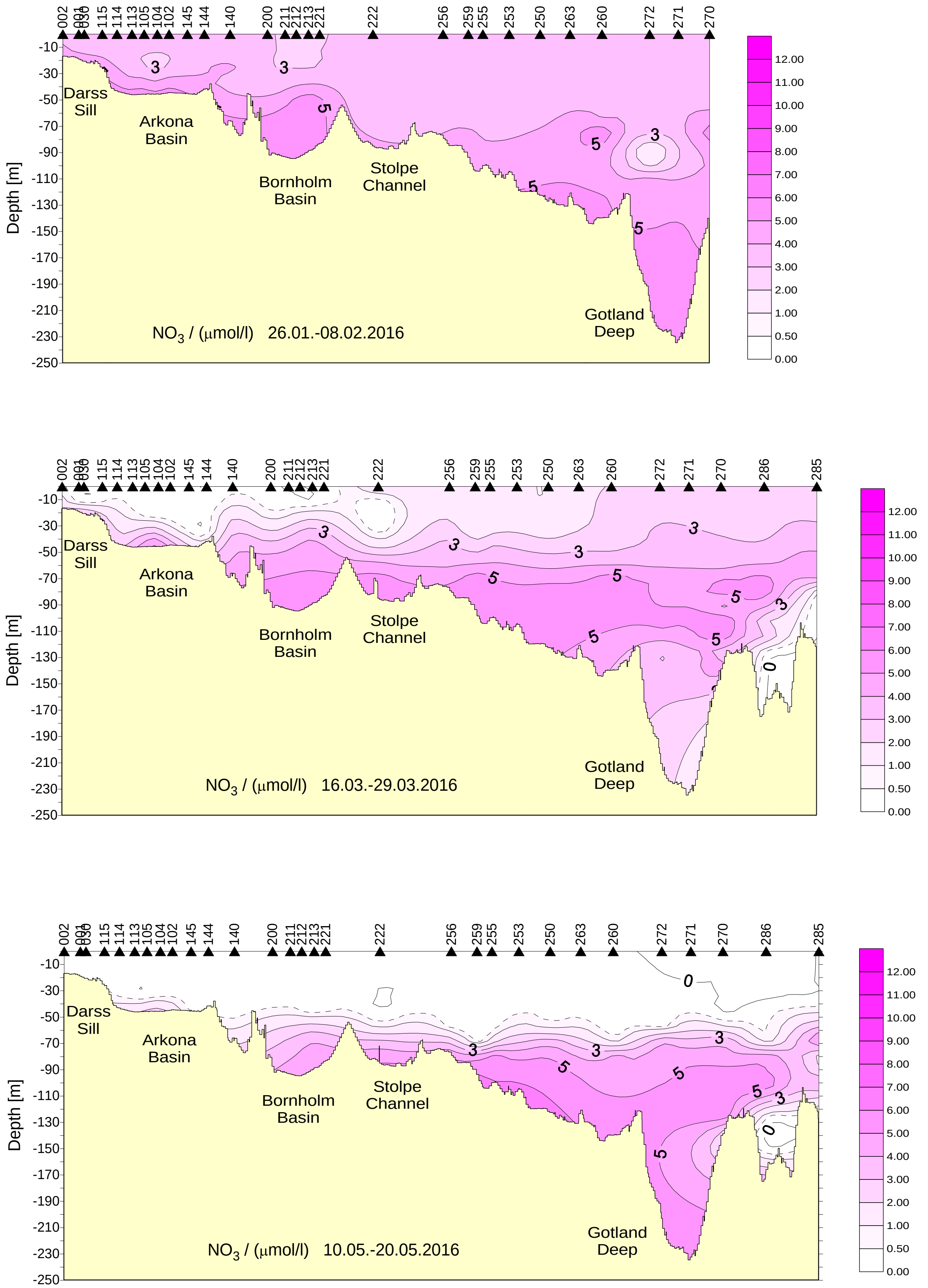

Fig. 33a: Vertical distribution of nitrate 2016 between the Darss Sill and the northern Gotland Basin

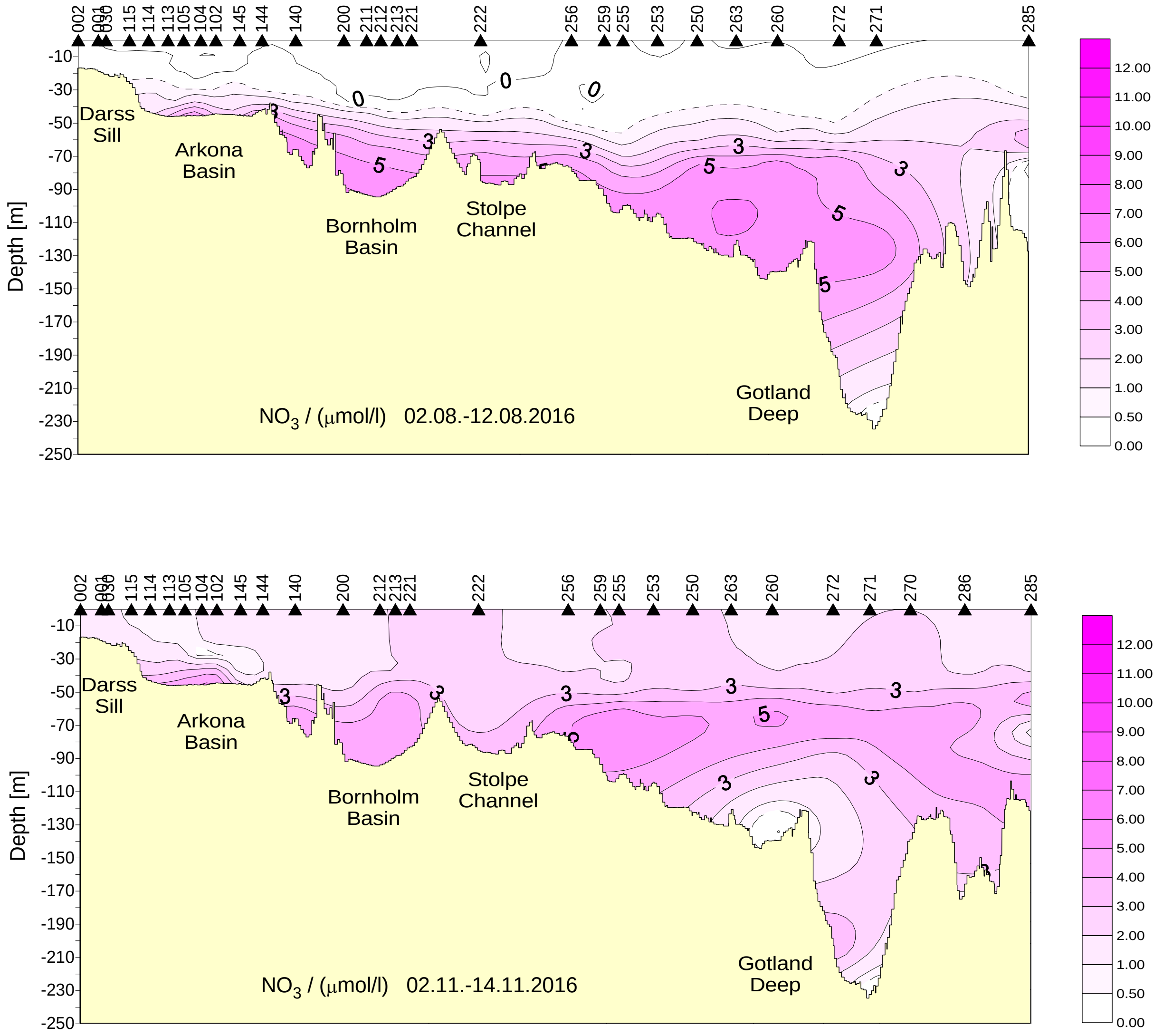

Fig. 33b: Vertical distribution of nitrate 2016 between the Darss Sill and the northern Gotland Basin

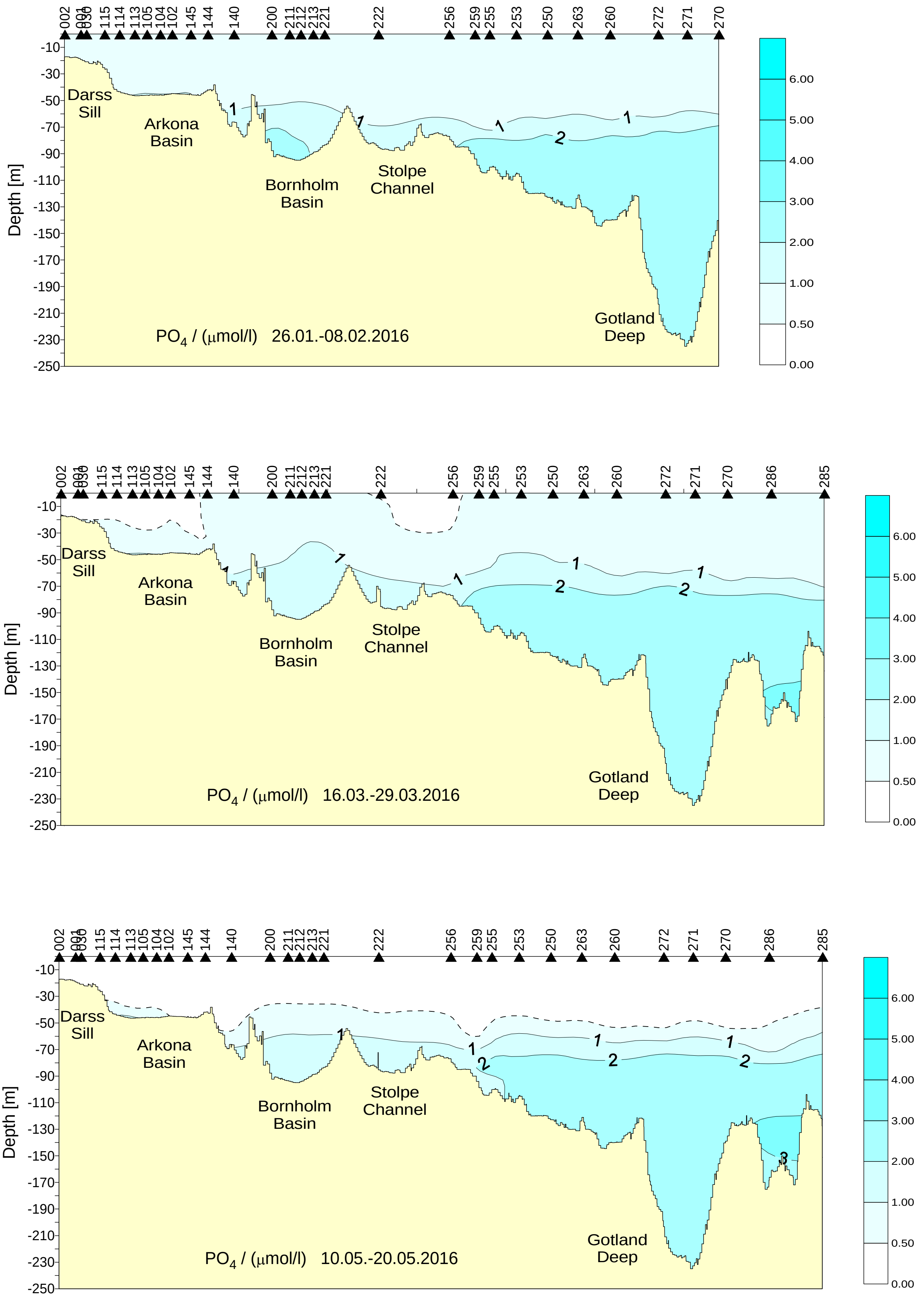

Fig. 34a: Vertical distribution of phosphate 2016 between the Darss Sill and the northern Gotland Basin

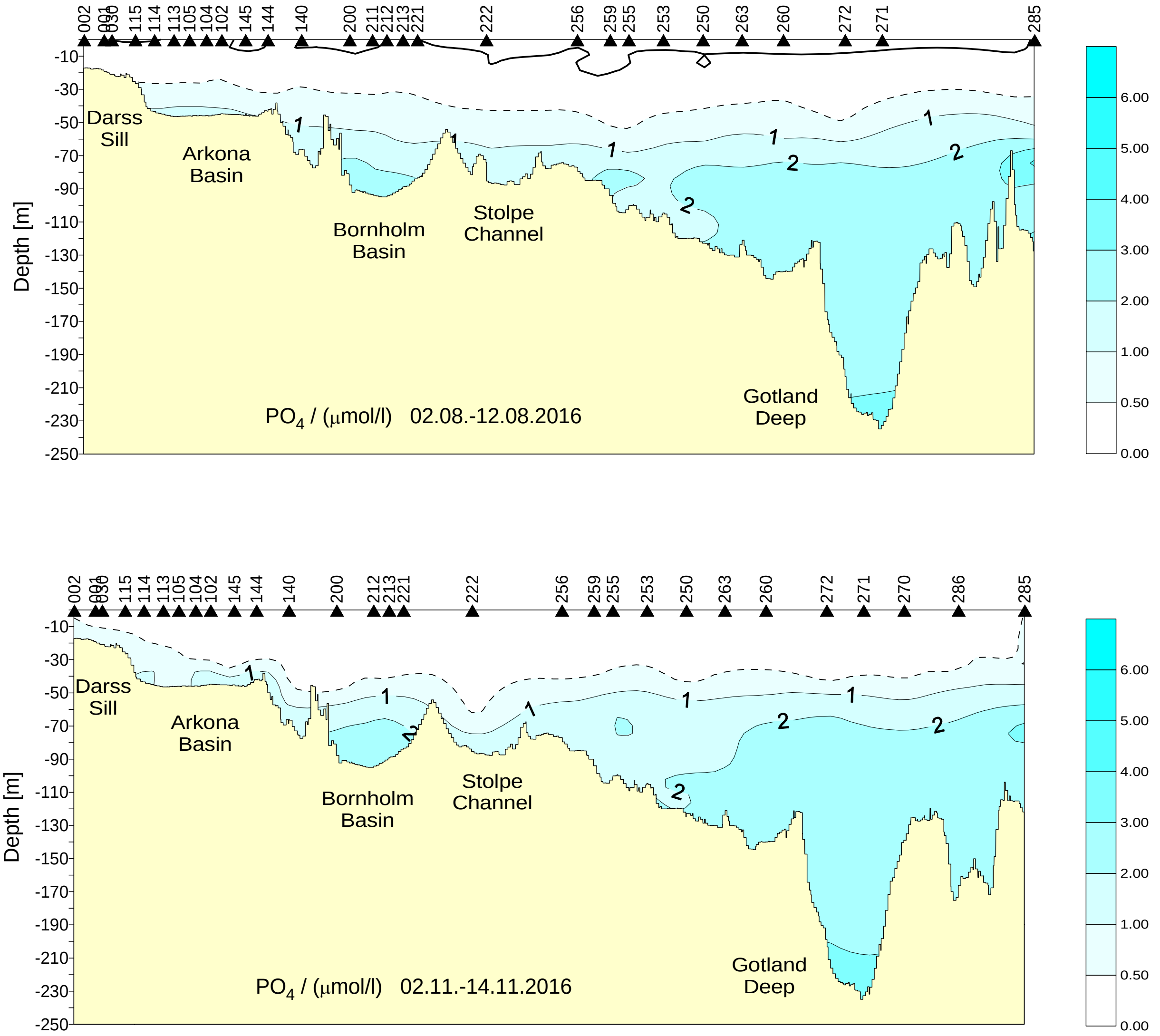

Fig. 34b: Vertical distribution of phosphate 2016 between the Darss Sill and the northern Gotland Basin

Figures 33 and 34 illustrate the horizontal and vertical distribution of nitrate and phosphate along the transects from the Darss Sill to the northern Gotland Basin for the five monitoring cruises performed in 2016.

Summary

Inflow pulses of saline oxygenated water since autumn 2013 influenced the nutrient situation in the deep water of the eastern Gotland Basin. Hydrogen sulphide removal propagated through the Baltic Sea and started to impact the Fårö Deep. Correspondingly, phosphate and ammonium concentrations declined and nitrate re-appeared in deep waters during oxic transition of the eastern Gotland Sea and further north.

6.5 Dissolved organic carbon and nitrogen

The dissolved organic matter (DOM) in the Baltic Sea is an important component within the carbon and nutrient cycles. Its distribution in Baltic Sea waters in linked to salinity. Higher dissolved organic carbon (DOC) values at low salinities reflect the input from terrestrial sources, whereas the high saline waterfrom the North Sea show relatively low DOM concentration. As a consequence the DOC in surface water of the Baltic Sea reflects higher concentration than the deep water at all stations. The concentration pattern of dissolved organic nitrogen (DON) is mainly modified by biogeochemical processes in the water column. The relation of DOC/DON (C/N ratio) shows generally higher values in surface (17-18) than in bottom waters (9-11).

The inflow events during the years 2014 – 2016 (MBI in December 2014) and the biogeochemical effects of the high salinity and oxygen rich water on the water masses in the Bornholm and Gotland Basin was one main scientific interest in the years 2015 and 2016. The replacement of the anoxic waters from the long stagnant period in the Gotland Basin took place between February and May 2015. The inflow water (see table 1 and report 2015) was characterized by salinity › 20, T about 6 °C and DOC concentrations of about 180-190 µmol/kg. In April 2015 first inflow water reached the deep Gotland basin. In May the increase in salinity in the GB and the oxygen concentration of 2 ml/l are clear indicators that the old water mass was replaced.

Methods

DOC was measured according to the accredited methods of the IOW analytic group. The devices TOC-V_{CPH} and TOC-L_{CPH} from Shimadzu were used to perform the direct method according to the HTC Method (High Temperature Combusting Method). First, samples were defrosted in an ultrasonic bath for five minutes and thoroughly mixed before being filled in an Autosampler-Vial. Inorganic carbon was extracted by acidifying (pH 2) and subsequently purging the sample with carbon--free air. Thus, all inorganic carbon was converted and expelled as CO_2. Next, the sample volume was injected into a combustion tube filled with platinum-coated —aluminium oxide spheres as a catalyst. At 680 °C all NPOC (non-purgeable-organic-carbon) was burned to CO_2, nitrogen compounds to NO . By reducing the temperature of the gases to 1 °C in a spiral-shaped cooling tubing, moisture was extracted in the dehumidifier. Before reaching the non-dispersive infrared detector, halogens were eliminated in the halogen scrubber by reaction with copper. Finally, CO_2 and NO were measured. For the measurement the content of each sample vessel was divided into two Autosampler-vials. Both samples were analyzed seperatetly whereby at least four to five valid injections of 75 µL from each vial were done and subsequently the mean DOC and DON concentrations calculated. The method is verified by laboratory experiments and regular intercalibration exercises, with results being published in Hedges and Lee (1993), Sharp et al. (2002a,b; 2004) and Nagel and Primm (2003). For the quality assurance of the procedure a reference material, the so called Consensus Reference Water (www.rsmas.edu/groups/biogeochem/CRM.html) is used.

The limit of quantification for DOC is deteremined as DOC ‹ 25 µmol/L, DON ‹ 5 µmol/L and the standard deviation of the procedure as DOC ± 3 µmol/L and DON ± 0.5 µmol/L. Our ongoing and accredited quality management ensures comparability of the results over long periods of time. The absolute measurement uncertainty for DOC is at 4.4 µmol/L C. Twice a year, quality control of the measurements is ensured by participation in the QUASIMEME intercalibration excercise. (Wageningen Evaluating Programmes for Analytical Laboratories, accredited since April 26, 2000 according tothe ISO 17043 requirements).

Table 11: Salinity (S), temperature (°C), oxygen (ml/l), DOC and DON (µmol/l) and C/N ratio in water samples near the bottom. Stations no.: Mecklenburg Bight 0012 (MB), Arkona Basin 0113 (AB), Bornholm Basin 0213 (BB) and eastern Gotland Basin 0271(GB) in 2016.

	MB 0012	MB	MB	MB	MB	AB 0113	AB	AB	AB	AB
	Febr.	Mar.	May	Aug.	Nov.	Febr.	Mar.	May	Aug.	Nov.
	24 m					46 m				
S	22.0	21.7	22.5	25.7	16.5	18.2	20.8	19.3	16.6	23.0
T	4.1	4.0	6.6	11.1	11.0	7.1	4.4	5.2	13.4	11.3
O_2	7.3	6.3	5.6	3.2	6.8	4.7	5.0	1.1	2.2	5.2
DOC	259	193	186	175	280	227	202	230	249	193
DON	k.A.	11.4	10.9	10.4	16.3	12.5	10.8	14.7	10.9	12.5
C/N	k.A.	16.9	17.0	16.9	17.2	18.2	18.7	15.6	22.8	15.5

	BB 0213	BB	BB	BB	BB	GB 0271	GB	GB	GB	GB
	Febr.	Mar.	May	Aug.	Nov.	Febr.	Mar.	May	Aug.	Nov.
	88 m					236 m				
S	19.2	18.8	18.8	18.6	18.3	13.8	13.9	13.8	13.8	13.6
T	8.4	5.7	6.2	6.6	6.7	7.9	7.6	7.5	7.5	7.3
O_2	1.5	4.0	1.5	0.3	0.1	1.8	0.7	0.2	0.0	0.0
DOC	208	212	215	214	210	249	242	247	255	247
DON	11.4	11.0	12.6	12.4	11.7	12.6	13.1	13.7	13.1	12.1
C/N	18.2	19.3	17.1	17.3	17.9	19.7	18.5	18.2	19.7	20.4

The DOC and DON changes at station MB, AB, BB and GB between February and November 2016 are shown in Figure 35 – 38. In the Mecklenburg Bight no influence of the inflow water from December 2014 could be monitored in 2016 (Fig. 35). The increase in DOC during the year is due to the biological production during spring and summer time in the surface layer.

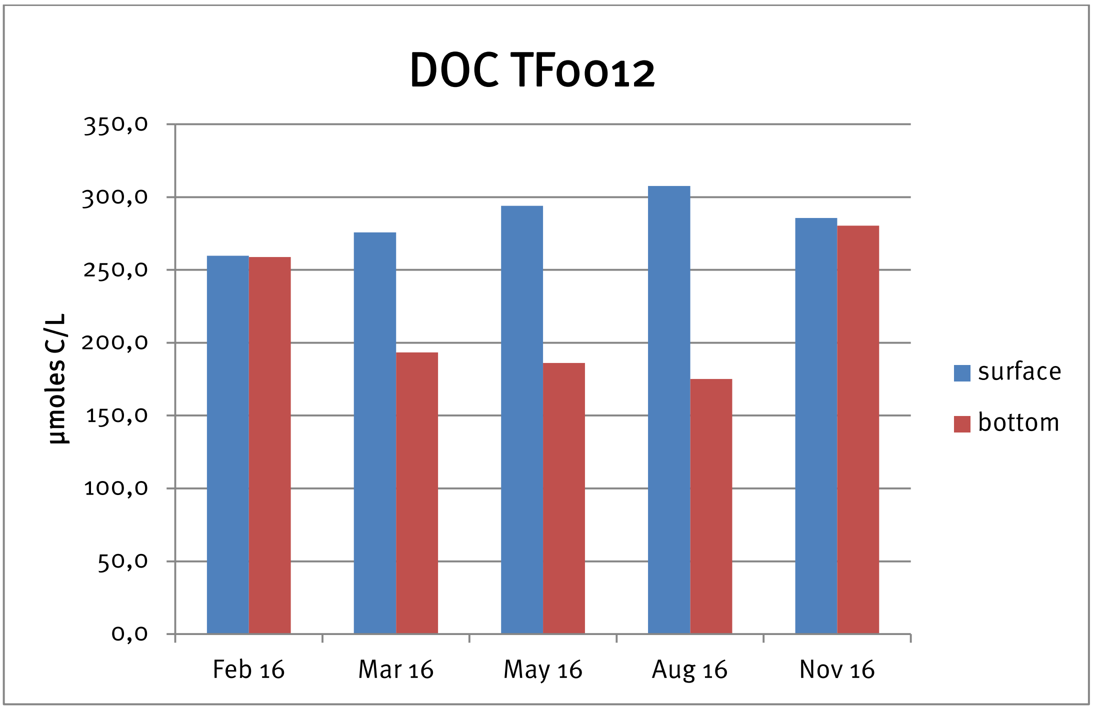

Fig. 35a: Surface (2 m) and bottom (24 m) dissolved organic carbon (µmol/l) at Station TF0012 in the Mecklenburg Bight

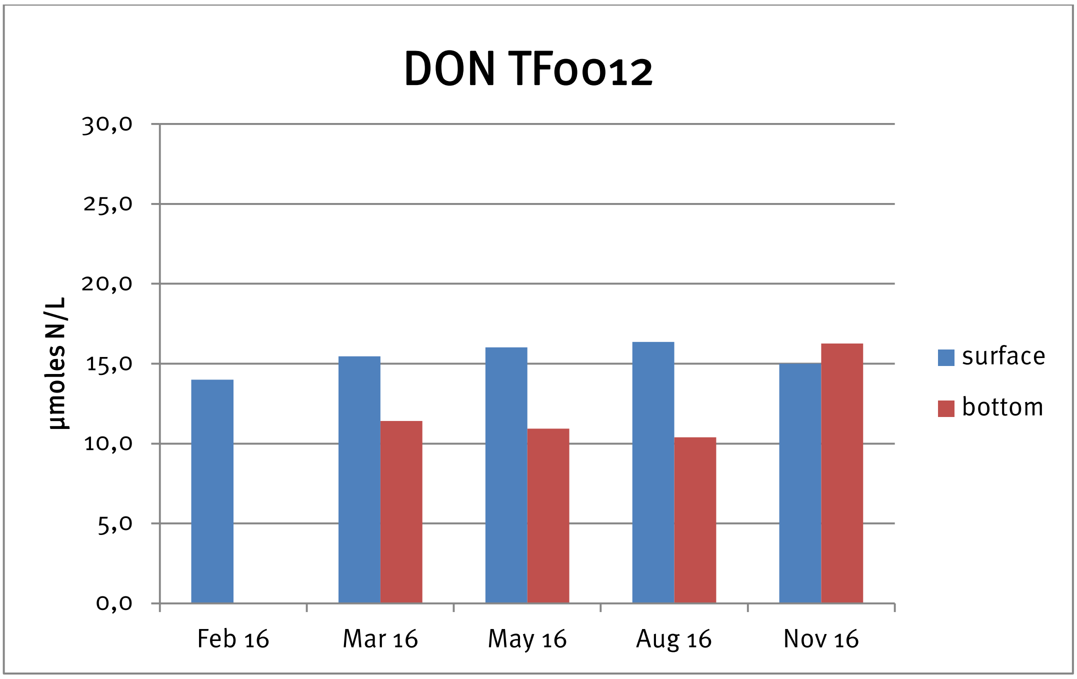

Fig. 35b: Surface (2m) and bottom (24m) dissolved organic nitrogen (µmol/l) at Station TF0012 in the Mecklenburg Bight. At station Arkona Basin the DOC and DON values (Fig 36b) were not noticeably changed. During the year the DOC and DON values were near the long-termaverage for this region.

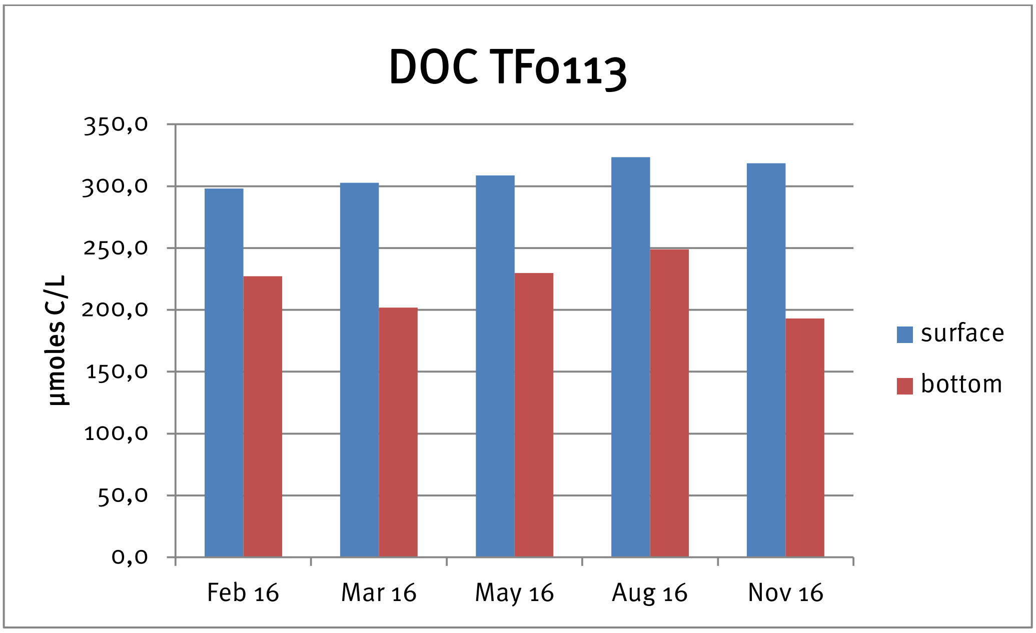

Fig. 36a: Surface (2m) and bottom (46 m) dissolved organic carbon (µmol/l) at Station TF0113 in the Arkona Basin

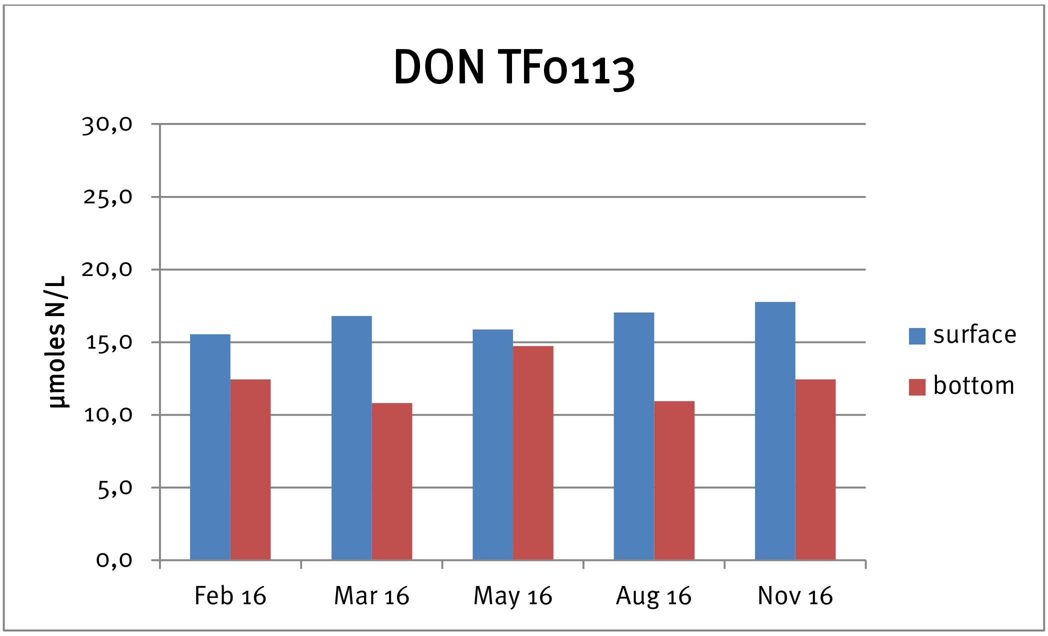

Fig. 36b: Surface (2m) and bottom (46 m) dissolved organic nitrogen (µmol/l) at Station TF0113 in the Arkona Basin

The Bornholm Basin showed two water bodies that were separated by a halocline at about 60 m depth. The surface water with lower salinities showed a maximum of DOC in August, whereas in deep water it remained constant. DON concentration appeared to slightly increasein surface water through the year 2016. The deep water DON concentration was variable and showed a maximum in May.

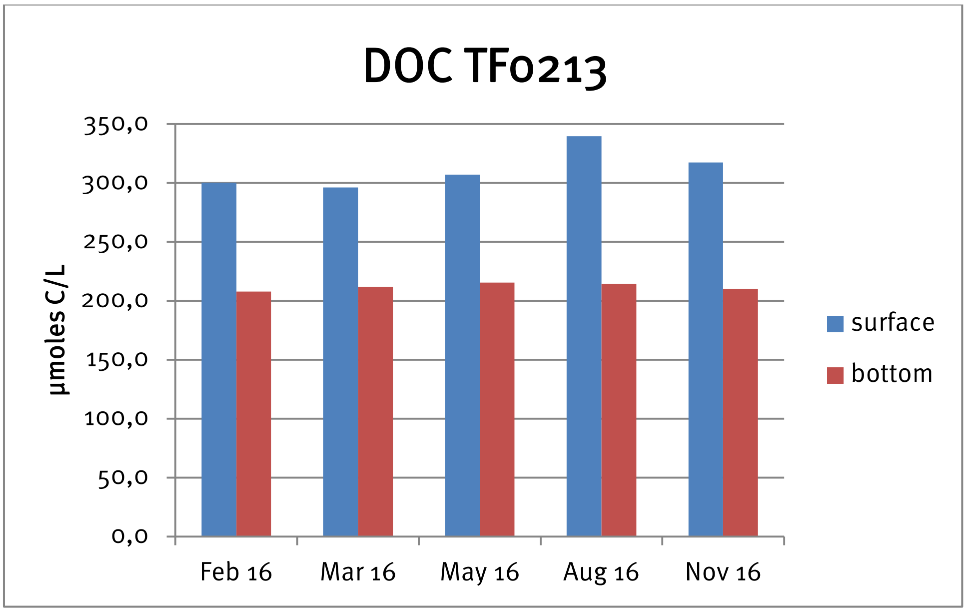

Fig. 37a: Surface (2m) and bottom (88 m) water dissolved organic carbon (µmol/l) at Station TF0213 in the Bornholm Basin

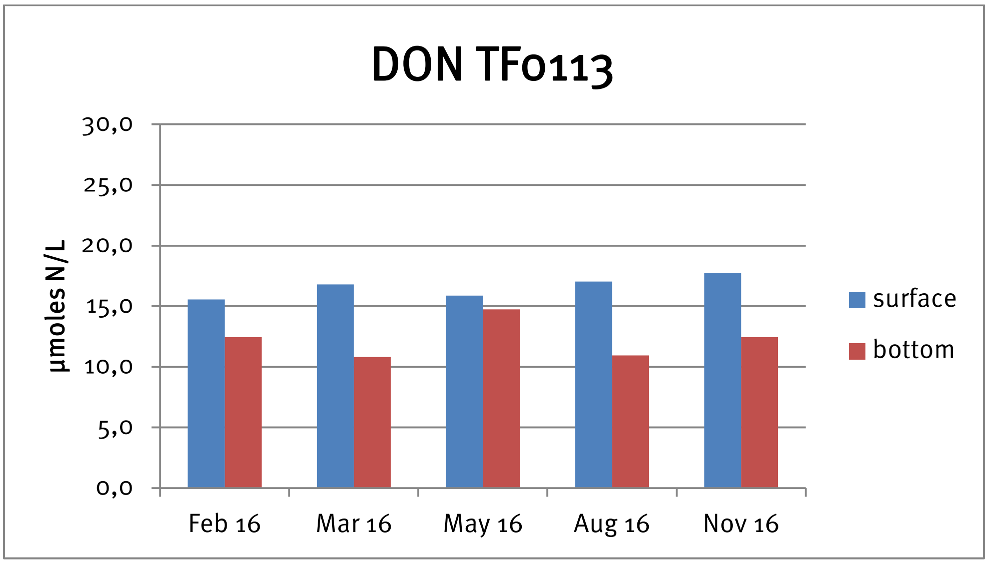

Fig. 37b: Surface (2m) and bottom (88 m) water dissolved organic nitrogen (µmol/l) at Station TF0213 in the Bornholm Basin

The inflow water arrived in the Gotland Deep (TF 0271) in April 2015. During the way from the western Baltic Sea towards the northeast the water was mixed with surrounding water bodies. As a result the salinity increased and the DOC concentration decreased in 2015 (Fig. 46a, report 2015). In 2016 the DOC and DON concentration did not change significantly in deep waters. The values were close to the measured long-term-means in the deep water. The usual seasonal cycle is documented for surface waters by an increase in DOC until August and a decline afterwards. DON showed highest values during potential bloom periods in March, August, and November in surface waters.

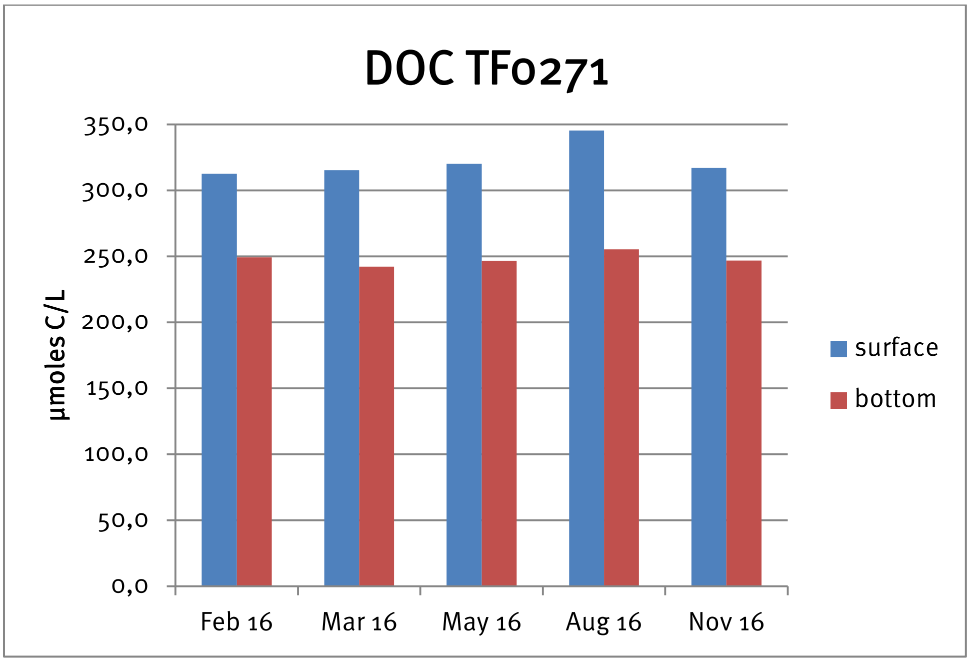

Fig. 38a: Surface (2m) and bottom (236 m) dissolved organic carbon (µmol/l) at Station TF0271 in the eastern Gotland Basin

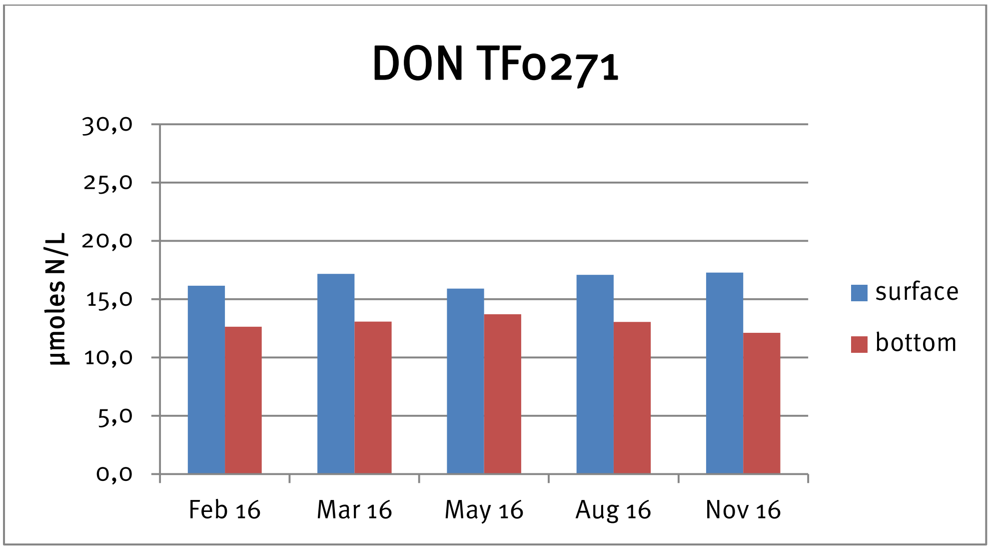

Fig. 38b: Surface (2m) and bottom (236 m) dissolved organic nitrogen (µmol/l) at Station TF0271 in the eastern Gotland Basin

Summary

For the southern Baltic Sea area, the cold sum of 63.5 Kd at Warnemünde station amounted to a mild winter in 2015/16. This value plots far below the long-term average of 102.4 Kd in comparative data from 1948 onwards and ranks in the upper midrange as 27th warmest winter in this time series. Only one cold period occurred during the first weeks of January which led to this cold sum, all other winter months were too warm.
With a warm sum of 267 Kd, recorded at Warnemünde, the summer 2016 is ranked in the "top ten" over the past 68 years on 6th position and far above the previous year of 182.3 Kd on 22nd place. The 2016 value exceeds the long-term average of 151.7 Kd, and exceeds the standard deviation, meaning that the year can be classed as a particularly warm one.

With respect to sea surface temperature, the year 2016 was after 2014 and 2015 the third warmest since 1990 and approximately 0.8 K above average for the period 1990-2015 and 0.3 K colder than the warmest year 2014. February to July and September contributed by their positive anomalies. With up to +5 K May was the warmest since 1990. June and September belonged to the warmest months in the southern Baltic and October in the Gulf of Bothnia. The resulting temperature trend was 0.6 K per decade.

Inflow events with estimated volumes between 171 km³ and 243 km³ occurred in the Baltic Sea on four occasions in 2016. Early in the year on January 17th, the gauge at Landsort Norra recorded a lowstand of -23 cm MSL as a result of preceding long lasting easterly winds. A system shift to strong westerly winds caused a sea level rise to 46.5 cm (February 3rd) and a resulting total volume of 243 km³ was calculated. This event is classified as Major Baltic Inflow of moderate intensity and a salt transport of 1.6 Gt and highly saline volume transport of 82 km³ passed the sills in the western Baltic Sea in the timespan January 31st and February 6th. A long lasting outflow period occurred in the timespan February to March and the sea level fluctuated stepwise between -26 cm MSL to +30 cm MSL during springtime and summer. The warm late summer weather in September of low winds induced a baroclinic overflow at the Darss Sill. In October, a next major outflow period occurred by strong easterly winds resulting in the lowest sea level of the year 2016 with a mark of -44.5 cm MSL at October 19th. In the following days up to November 2nd, the sea level rose to +8.8 cm MSL and a water volume of 184 km³ entered the Baltic Sea. After a short regression to -23 cm MSL (November 14th), the sea level rose stepwise within a month by single wind events to a mark of +31 cm MSL (December 11th) which presents a volume of 171 km³. During Christmas time the sea level rose again very quickly by 49 cm (December 22nd-27th) which correlates to a volume of 182 km³.

The annual cycle of oxygen saturation in the surface water was again typical in 2016. Oxygen conditions in the deep water of the basins of the central Baltic Sea are primarily influenced by the occurrence or absence of strong inflows. The Bornholm Basin is the westernmost of the deep basins. Barotropic and baroclinic inflows are often able to ventilate its deep water. The situation in 2016 was coined by the Major Baltic Inflows (MBI) of November 2015 and January-February 2016. The first one transported warm autumn water and crossed the Bornholm Basin just below the halocline, whereas the last one of cold winter water became apparent in the

bottom near water in March. Thus, the oxygen content increased in the 80 m horizon of the Bornholm Deep from beginning of February 2016 (1.47 ml/l) to 3.99 ml/l in mid of March. During the further course of the year oxygen concentrations decreased due to mineralisation processes to 0.06 ml/l in the mid of November.

The MBI of November 2015 reached again very quickly the near bottom water of the eastern Gotland Basin. At the end of January/beginning February oxygen concentrations of 1.7 ml/l were measured, but depleted during the year. Since August hydrogen sulphide was found at the bottom of the Gotland Deep and in November -0.56 ml/l were reached. Since May 2016 the following MBI of January-February 2016 ventilated the deep water of this largest Baltic basin between 100-200 m depth. Further north in the Northern Central Basin and Western Gotland Basin no oxygen as consequence of this ongoing inflow activity since 2014 was found in the deep water, but reduction in hydrogen sulphide occurred in the Farö Deep.

Nutrient conditions in the deep basins reflect the intensive inflow processes. In the Bornholm Basin, a low yearly mean phosphate concentration of 2.23 µmol/l were present because dissolved phosphate is precipitated under oxic conditions. On the other hand, oxygen permits the nitrification of ammonium to nitrate. Throughout the whole year, ammonium concentrations of 0.2 ± 0.1 µmol/l are in the range of the detection limit. Nitrate concentrations were in the course of the year 2016 of around 8-9 µmol/l.

The above mentioned inflow events in wintertime 2015/2016 influenced the nutrient situation in the deep water of the eastern Gotland Basin. Phosphate measured near-bottom 2.13 µmol/l in February and increased up to 3.9 µmol/l in August, but slightly decreased to 3.55 µmol/l up to November. Nitrate increased during springtime from 8.5 µmol/l to 12.5 µmol/l (February-May) as consequence of the MBI November 2015, but reduced in the bottom-water to zero in August. The following inflow water of January-February 2016 did not reach the bottom in the eastern Gotland Basin and stagnation began again at the sea floor. Like in previous years the nutrient situation stayed constant in the western Gotland Basin during this year. Absence of nitrate, yearly means of phosphate concentrations between 3.25-4.25 µmol/l (Landsort Deep, Karlsö Deep) and ammonium concentrations between 7.8-9.7 µmol/l (Landsort Deep, Karlsö Deep) were measured. Thus, no signs of inflow activity were observed in this distant areas.

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References

ARNEBORG, L., FIEKAS, V., UMLAUF, L. and BURCHARD, H. (2007): Gravity current dynamics and entrainment. A process study based on observations in the Arkona Basin.- J. Phys. Oceangr., **37**, 2094-2113.

BEZOLD, W.v. (1883): Die Kälterückfälle im Mai. – Abhandlungen der königlichen Bayerischen Akademie der Wissenschaften. Bd. **14**, Nr. 6, 71-108.

BSH (2009): Flächenbezogene Eisvolumensumme. http://www.bsh.de/de/Meeresdaten/Beobachtungen/Eis/Kuesten.jsp

v.BODUNGEN, B., GRAEVE, M., KUBE, J., LASS, H.U., MEYER-HARMS, B., MUMM, N., NAGEL, K., POLLEHNE, F., POWILLEIT, M., RECKERMANN, M., SATTLER, C., SIEGEL, H. and WODARG, D. (1995): Stoff-Flüsse am Grenzfluss – Transport- und Umsatzprozesse im Übergangsgebiet zwischen Oderästuar und Pommerscher Bucht (TRUMP). – Geowiss. **13**, 479-485.

BURCHARD, H., JANSSEN, F., BOLDING, K., UMLAUF, L. and RENNAU, H. (2009): Model simulations of dense bottom currents in the Western Baltic Sea.- Cont. Shelf Res., 29, 205-220.

DUARTE, C.M., CONLEY, D.J., CARSTENSEN, J. AND SÁNCHEZ-CAMACHO, M. (2009): Return to Neverland: Shifting Baselines Affect Eutrophication Restoration Targets. – Estuaries and Coasts **32(1)**, 29-36.

DWD (2016): WitterungsReport Express. Jahrgang 18, Nr. 1 – 13. Deutscher Wetterdienst

DWD (2017): Windmessungen der Station Arkona in Stundenmittelwerten des Jahres 2016 – ftp://ftp-cdc.dwd.de/pub/CDC/observations_germany/climate/

EUTROSYM (1976): UNEP-Symposium über Eutrophierung und Sanierung von Oberflächengewässern, EUTROSYM, Karl-Marx-Stadt/Chemnitz.

GRASSHOFF, K., ERHARDT, M. and KREMLING, K. (1983): Methods of seawater analysis. – 2nd Ed., Verlag Chemie, Weinheim.

Gräwe, U., Naumann, M., Mohrholz, V. and Burchard, H. (2015): Anatomizing one of the largest saltwater inflows in the Baltic Sea in December 2014. – J. Geophys. Res., **120**, 7676-7697.

FEISTEL, R. SEIFERT, T., FEISTEL, S., NAUSCH, G. BOGDANSKA, B. BROMAN, B. HANSEN, L. HOLFORT, J., MOHRHOLZ, V., SCHMAGER, G., HAGEN, E., PERLET, I. and WASMUND, N. (2008): Digital supplement. In: FEISTEL, R., NAUSCH, G. and WASMUND, N. (Eds.), State and Evolution of the Baltic Sea 1952-2005. – John Wiley & Sons, Inc., Hoboken, New Jersey, p. 625-667.

FU-Berlin (2016): Werden auch Sie Wetterpate! - http://www.met.fu-berlin.de/wetterpate/

HAGEN, E. and FEISTEL, R. (2008): Baltic climate change, in: FEISTEL, R., NAUSCH, G., and WASMUND, N. (Eds.), State and Evolution of the Baltic Sea 1952 – 2005. – John Wiley & Sons, Inc., Hoboken, New Jersey, p. 93-120.

HEDGES, J.J., LEE, C. (1993): Measurement of dissolved organic carbon and nitrogen in natural waters. – Proceedings of NSF/NOAA/DOE Workshop, Seattle, Wa, USA, 15-19 July 1991, Mar Chem **41**: 1-289.

HELCOM (2000): Manual of marine monitoring in the COMBINE programme of HELCOM. – Baltic Marine Environment Protection Commission, Helsinki, Updated 2002: www.helcom.fi/Monas/CombineManual2/CombineHome.htm

HELCOM (2015): Updated Baltic Sea Pollution Load Compilation (PLC 5.5). Balt. Sea Environ Proc. 145, 1-143. www.helcom.fi/Lists/Publications/BSEP145_lowres.pdf

IMGW (2016): Sonnenstrahlung in J/m^2 an der Station Gdynia des Jahres 2016 – unveröffentlichte Daten.

KOSLOWSKI, G. (1989): Die flächenbezogene Eisvolumensumme, eine neue Maßzahl für die Bewertung des Eiswinters an der Ostseeküste Schleswig-Holsteins und ihr Zusammenhang mit dem Charakter des meteorologischen Winters. – Dt. hydrogr. Z. **42**, 61-80.

KRÜGER, S., ROEDER, W., WLOST, K.-P., KOCH, M., KÄMMERER, H. and KNUTZ, T., (1998): Autonomous instrumentation carrier (APIC) with acoustic transmission for shallow water profiling. – Oceanology International 98: The Global Ocean Conf. Proc. **2**, 149-158.

KRÜGER, S. (2000a): Basic shipboard instrumentation and fixed autonomic stations for monitoring in the Baltic Sea. – In: EL-HAWARY, F. (Ed.): The Ocean Engineering Handbook, CRC Press, Boca Raton, USA, 52-61.

KRÜGER, S. (2000b): Activities of the Institut für Ostseeforschung (IOW), Germany. – Proc. Int. Workshop on the “Coordinated Adriatic Observing System” CAOS, 21-22 October 1998, Trieste, Italy, 53-60.

LASS, H.U. and MATTHÄUS, W. (2008): General Oceanography of the Baltic Sea, in: FEISTEL, R., NAUSCH, G., and WASMUND, N. (Eds.), State and Evolution of the Baltic Sea 1952 – 2005. – John Wiley & Sons, Inc., Hoboken, New Jersey, p. 5-43.

LASS, H.U., MOHRHOLZ, V. and SEIFERT, T. (2001): On the dynamics of the Pomeranian Bight. – Cont. Shelf. Res. **21**, 1237-1261.

MOHRHOLZ, V. (1998): Transport- und Vermischungsprozesse in der Pommerschen Bucht. – Meereswiss. Ber. **33**, 1-106.

MOHRHOLZ, V., NAUMANN, M., NAUSCH, G., KRÜGER, S. and GRÄWE, U. (2015): Fresh oxygen for the Baltic Sea – an exceptional saline inflow after a decade of stagnation. – Journal Mar. Syst. **148**, 152-166.

NAGEL, K., PRIMM, O. (2003): Verbesserte Bestimmung des Gesamtstickstoffgehaltes in Süßwasser, Brackwasser und Seewasserproben- Validierung der Analyseverfahren. – Umweltforschungsplan des Bundesministeriums für Umwelt, Naturschutz und Reaktorsicherheit-Wasserwirtschaft-; Forschungsbericht **200 22 231**, 2-91.

NAUMANN, M. (2016): Baltic Monitoring & Long term data program of IOW. Cruise- No. **EMB-120**, http://www.io-warnemuende.de/tl_files/forschung/pdf/cruise-reports/cremb120.pdf

NAUSCH, G. and NEHRING, D. (1996): Baltic Proper, Hydrochemistry. In: Third Periodic Assessment of the State of the Marine Environment of the Baltic Sea. – Balt. Sea Environ. Proc. **64B**, 80-85.

NAUSCH, G., FEISTEL, R., LASS, H.-U., NAGEL, K. and SIEGEL, H. (2002): Hydrographisch-chemische Zustandseinschätzung der Ostsee 2001. – Meereswiss. Ber. **49**, 3-77.

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

NAUSCH, G., FEISTEL, R., UMLAUF, L., MOHRHOLZ, V. and SIEGEL, H. (2011a): Hydrographisch-chemische Zustandseinschätzung der Ostsee 2010. – Meereswissenschaftliche Berichte Warnemünde **84**, 1-99.

NAUSCH, G., BACHOR, A., PETENATI, T., VOSS, J. und v. WEBER, M. (2011b): Nährstoffe in den deutschen Küstengewässern der Ostsee und angrenzenden Seegebieten. – Meeresumwelt Aktuell Nord- und Ostsee 2011/1.

NAUSCH, G., FEISTEL, R., UMLAUF, L., MOHRHOLZ, V., NAGEL, K. and SIEGEL, H. (2012): Hydrographisch-chemische Zustandseinschätzung der Ostsee 2011. – Meereswissenschaftliche Berichte Warnemünde **86**, 1-121.

NAUSCH, G., FEISTEL, R., UMLAUF, L., MOHRHOLZ, V. and SIEGEL, H. (2013): Hydrographisch-chemische Zustandseinschätzung der Ostsee 2012. – Meereswissenschaftliche Berichte Warnemünde **91**, 1-109.

NAUSCH, G., NAUMANN, M., UMLAUF, L., MOHRHOLZ, V., and H. SIEGEL (2014): Hydrographisch-hydrochemische Zustandseinschätzung der Ostsee 2013. – Meereswiss. Ber. Warnemünde **93**, 1-104.

NAUSCH, G., NAUMANN, M., UMLAUF, L., MOHRHOLZ, V., and H. SIEGEL (2015): Hydrographic hydrochemical assessment oft he Baltic Sea 2014. – Meereswiss. Ber. Warnemünde **96**, 1-93.

NAUSCH, G., NAUMANN, M., UMLAUF, L., MOHRHOLZ, V., SIEGEL, H., Schulz-Bull, D. E. (2016): Hydrographic-hydrochemical assessment oft he Baltic Sea 2015. Marine Science Reports **101**, 1-91.

NEHRING, D. and MATTHÄUS, W. (1991): Current trends in hydrographic and chemical parameters and eutrophication in the Baltic Sea. – Int. Revue ges. Hydrobiol. **76**, 297-316.

NEHRING, D., MATTHÄUS, W. and LASS, H.U. (1993): Die hydrographisch-chemischen Bedingungen in der westlichen und zentralen Ostsee im Jahre 1992. – Dt. Hydrogr. Z. **45**, 281-331.

NEHRING, D., MATTHÄUS, W., LASS, H.U., NAUSCH, G. and NAGEL, K. (1995): Hydrographisch-chemische Zustandseinschätzung der Ostsee 1994. – Meereswiss. Ber. **9**, 1-71.

REDFIELD, A.C., KETCHUM, B.H. AND RICHARDS, F.A. (1963): The influence of organisms on the composition of sea water. – In: M.N. Hill (Editor), The sea. J. Wiley & Sons, pp. 26-77.

SCHMELZER, N. (2015): Der Eiswinter 2014/15 an den deutschen Nord- und Ostseeküsten mit einem kurzen Überblick über die Eisverhältnisse im gesamten Ostseeraum. - http://www.bsh.de/de/Meeresdaten/Beobachtungen/Eis/Eiswinter2014-2015.pdf.

SCHMELZER, N., SEINÄ, A., LUNDQUIST, J.-E. and SZTOBRYN, M. (2008): Ice, in: FEISTEL, R., NAUSCH, G., and WASMUND, N. (Eds.), State and Evolution of the Baltic Sea 1952 – 2005. – John Wiley & Sons, Inc., Hoboken, New Jersey, p. 199-240.

SCHWEGMANN, S. and HOLFORT, J. (2016): Der Eiswinter 2015/16 an den deutschen Nord- und Ostseeküsten mit einem Überblick über die Eisverhältnisse im gesamten Ostseeraum. Eisdienst, Bundesamt für Seeschifffahrt und Hydrographie Rostock, 17 S. http://www.bsh.de/de/Meeresdaten/Beobachtungen/Eis/Eiswinter2015-2016.pdf

SELLSCHOPP, J., ARNEBORG, L., KNOLL, M., FIEKAS, V., GERDES, F., BURCHARD, H., LASS, H. U., MOHRHOLZ, V., UMLAUF, L. (2006): Direct observations of a medium-intensity inflow into the Baltic Sea. – Cont. Shelf Res., **26**, 2393-2414.

SHARP, J.H., CARLSON, C.A., PELTZER, E.T., CATLE-WARD, D.M. SAVIDGE, K.A., RINKER, K.R. (2002a): Final dissolved organic carbon brad community intercalibration and preliminary use of DOC reference materials. – Mar. Chem. 77, 239-253.

SHARP, J.H., RINKER, K.R., SAVIDGE, K.B., ABELL, J., BENAIM, J.Y., BRONK, D., BURDIGE, D.J., CAUWET, G., CHEN, W., DOVAL, M.D., HANSELL, D., HOPKINSON, C., KATTNER, G., KAUMEYER, N., MCGLATHERY, K.J., MERRIAM, J., MORLEY, N., NAGEL, K., OGAWA, H., POLLARD, C., PUJO-PAY, M., RAIMBAULT, P., SAMBROTTO, R., SEITZINGER, S., SPYRES, G., TIRENDI, F., WALSH, T.W., WONG, C.S. (2002b): A preliminary methods comparison for measurement of dissolved organic nitrogen in seawater. – Mar. Chem. **78**, 171-184.

SHARP, J.H., BEAUREGARD, A.Y., BURDIGE, D., CAWET, G., CURLESS, S.E., LAUCK, R., NAGEL., K., OGAWA, H., PARKER, A.E. PRIMM, O., PUJO-PAY, M., SAVIDGE, W.B. (2004): A direct instrument comparison for measurement of total dissolved nitrogen in seewater. – Mar. Chem. 84, 181-193.

SIEGEL, H., GERTH, M. and SCHMIDT, T. (1996): Water exchange in the Pomeranian Bight – investigated by satellite data and shipborne measurements. – Cont. Shelf Res **16**, 1793-1817.

SIEGEL, H., GERTH, M., TIESEL, R. and TSCHERSICH, G. (1999): Seasonal and interannual variations in satellite derived sea surface temperature of the Baltic Sea in the 1990s. – Dt. Hydrogr. Z. **51**, 407-422.

SIEGEL, H., GERTH, M. and TSCHERSICH, G. (2006): Sea Surface Temperature development of the Baltic Sea in the period 1990-2004 – Oceanologia **48** (S), 119-131.

SIEGEL, H., GERTH, M., and TSCHERSICH, G., 2008: Satellite-derived Sea Surface Temperature for the period 1990-2005. In: State and Evolution of the Baltic Sea, 1952 – 2005, Ed. By R. FEISTEL, G. NAUSCH, N. WASMUND, Wiley, 241-265.

SIEGEL, H., and GERTH, M., 2010: Satellite based process studies in the Baltic Sea. – Conference Proceedings “Ocean from Space”, Venice, 26-30 April 2010.

SIEGEL, H. and M. GERTH (2016). Sea surface temperature in the Baltic Sea in 2015. HELCOM Baltic Sea Environ. Fact Sheets. HELCOM Baltic Marine Environment Protection Commission - Helsinki Commission, –open access–

SMHI (2017): Tide gauge data at station Landort Norra in hourly means of the year 2016; geodesic reference level RH2000. http://opendata-download-ocobs.smhi.se/explore/

TRUMP (1998): Transport- und Umsatzprozesse in der Pommerschen Bucht (TRUMP) 1994-1996. – Abschlussbericht, IOW Warnemünde, 1-32 (unveröffentlicht).

UMLAUF, L., ARNEBORG, L., BURCHARD, H., FIEKAS, V., LASS, H.-U., MOHRHOLZ, V., and PRANDKE, H. (2007): The transverse structure of turbulence in a rotating gravity current. - Geophys. Res. Lett. **34**, L08601, doi:10.1029/2007GL029521.

UMLAUF, L. and ARNEBORG, L. (2009a). Dynamics of rotating shallow gravity currents passing through a channel. Part I: Observation of transverse structure. - J. Phys. Oceanogr. **39**, 2385-2401.

UMLAUF, L. and ARNEBORG, L. (2009b). Dynamics of rotating shallow gravity currents passing through a channel. Part II: Analysis. - J. Phys. Oceanogr. **39**, 2402-2416

UMLAUF, L., ARNEBORG, L., HOFMEISTER, R., and BURCHARD, H. (2010). Entrainment in shallow rotating gravity currents: A modeling study.- J. Phys. Oceanogr. **40**, 1819-1834, 2010.

Naumann, M., Umlauf, L.,
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Hydrographic-hydrochemical
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