Meereswissenschaftliche Berichte

Marine Science Reports

Leibniz-Institut für
Ostseeforschung
Warnemünde

No 107 2018

Hydrographic-hydrochemical assessment of the Baltic Sea 2017

Michael Naumann, Lars Umlauf, Volker Mohrholz, Joachim Kuss,
Herbert Siegel, Joanna J. Waniek, Detlef E. Schulz-Bull

"Meereswissenschaftliche Berichte" veröffentlichen Monographien und Ergebnisberichte von Mitarbeitern des Leibniz-Instituts für Ostseeforschung Warnemünde und ihren Kooperationspartnern. Die Hefte erscheinen in unregelmäßiger Folge und in fortlaufender Nummerierung. Für den Inhalt sind allein die Autoren verantwortlich.

"Marine Science Reports" publishes monographs and data reports written by scientists of the Leibniz-Institute for Baltic Sea Research Warnemünde and their co-workers. Volumes are published at irregular intervals and numbered consecutively. The content is entirely in the responsibility of the authors.

Schriftleitung: Dr. Norbert Wasmund
(norbert.wasmund@io-warnemuende.de)

Die elektronische Version ist verfügbar unter / The electronic version is available on:
http://www.io-warnemuende.de/meereswissenschaftliche-berichte.html

ISSN 2195-657X

Dieser Artikel wird zitiert als /This paper should be cited as:

Michael Naumann[1], Lars Umlauf[1], Volker Mohrholz[1], Joachim Kuss[1], Herbert Siegel[1], Joanna J. Waniek[1], Detlef E. Schulz-Bull[1]: Hydrographic-hydrochemical assessment of the Baltic Sea 2017. Meereswiss. Ber., Warnemünde, 107 (2018), doi:10.12754/msr-2018-0107

Adressen der Autoren:

[1] Leibniz Institute for Baltic Sea Research (IOW), Seestraße 15, D-18119 Rostock-Warnemünde, Germany

E-mail des verantwortlichen Autors: michael.naumann@io-warnemuende.de

Content

Kurzfassung

Die Arbeit beschreibt die hydrographisch-hydrochemischen Bedingungen in der westlichen und zentralen Ostsee für das Jahr 2017. 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 31,7 Kd. Im Vergleich belegt der Winter 2016/17 den 15. Platz der wärmsten Winter seit Beginn der Aufzeichnungen im Jahr 1948 und wird als mild klassifiziert. Mit einer Wärmesumme von 159,5 Kd rangiert der Sommer im Mittelfeld der 70jährigen Datenreihe und reiht sich auf Platz 28 der wärmsten Sommer ein. Das Langzeitmittel liegt bei 153,4 Kd.
Auf der Grundlage von satellitengestützten Meeresoberflächentemperaturen (SST) war 2017 das elft- wärmste Jahr seit 1990 und mit 0,24 K etwas über dem langfristigen SST-Mittel. März, April und Oktober - Dezember trugen durch ihre positiven Anomalien zum Durchschnitt bei. Juli und August waren durch negative Anomalien gekennzeichnet. Die Anomalien erreichten Höchstwerte von +2 K und -3 K.
Die Situation in den Tiefenbecken der Ostsee war im Wesentlichen geprägt durch bodennah einsetzende Stagnation im östlichen Gotland Becken und Belüftung der mittleren Wassersäule oberhalb 150 m im Zuge kleinerer Einströme. Zu Jahresbeginn wurde das im nördlichen Zentralbecken gelegene Farö Tief erstmals innerhalb der aktuellen Einstromphase belüftet. Im Jahresverlauf 2017 wurden zwei weitere schwache Einströme mit Volumina zwischen 210 km^3 und 188 km^3 im Februar sowie Oktober registriert. Zusammenfassend kann gesagt werden, dass die Auswirkungen der seit 2014 beobachten Phase von verstärkten Wasseraustauschprozessen mit entsprechenden Konsequenzen für die biogeochemischen Kreisläufe abklingen.

Abstract

The article summarizes the hydrographic-hydrochemical conditions in the western and central Baltic Sea in 2017. 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 31.7 Kd in Warnemünde amounted to a mild winter in 2014/15 and ranks as 15th warmest winter since the beginning of the record in 1948. The summer “heat sum” of 159.5 Kd ranks on 28th position of the warmest summers over the past 70 years and is slightly above the long-term average of 153.4 Kd.
Based on satellite derived Sea Surface Temperature (SST) 2017 was the eleventh-warmest year since 1990 and with 0.24 K slightly above the long-term SST average. March, April and October - December contributed to the average by their positive anomalies. July and August were characterized by negative anomalies. The anomalies reached maximum values of +2 K and -3 K.

The situation in the deep basins of the Baltic Sea was mainly coined by beginning stagnation at bottom-near water depths of the eastern Gotland Basin and ongoing ventilation of the upper part

of the deep-water above 150 m as a consequence of weak inflows. For the first time within this phase of intensified inflow activity, starting in 2014, the ventilation of the Farö Deep at the Northern Central Basin was registered at the beginning of the year. In the course of 2017 two weak inflows showing total volumes of 210 km³ (February) and 188 km³ (October) were registered. In conclusion, the impact of the observed phase of intensified water exchange processes with subsequent consequences for the biogeochemical cycles is weakening.

1. Introduction

This assessment of hydrographic and hydrochemical conditions in the Baltic Sea in 2017 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 2017 in all four seasons. 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. Figure 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*. 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 beginning-April to mid-December 2017; it was

taken out of service for a break over the winter of 2017/2018. A second system of a new buoy construction which is resistant against icing was tested in parallel observation at the Oder Bank position. 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). 2017 was assessed in relation to the mean values for 1990-2017 as the eleventh-warmest year since 1990. The results were also summarized in a HELCOM environmental fact sheet (SIEGEL & GERTH, 2018).

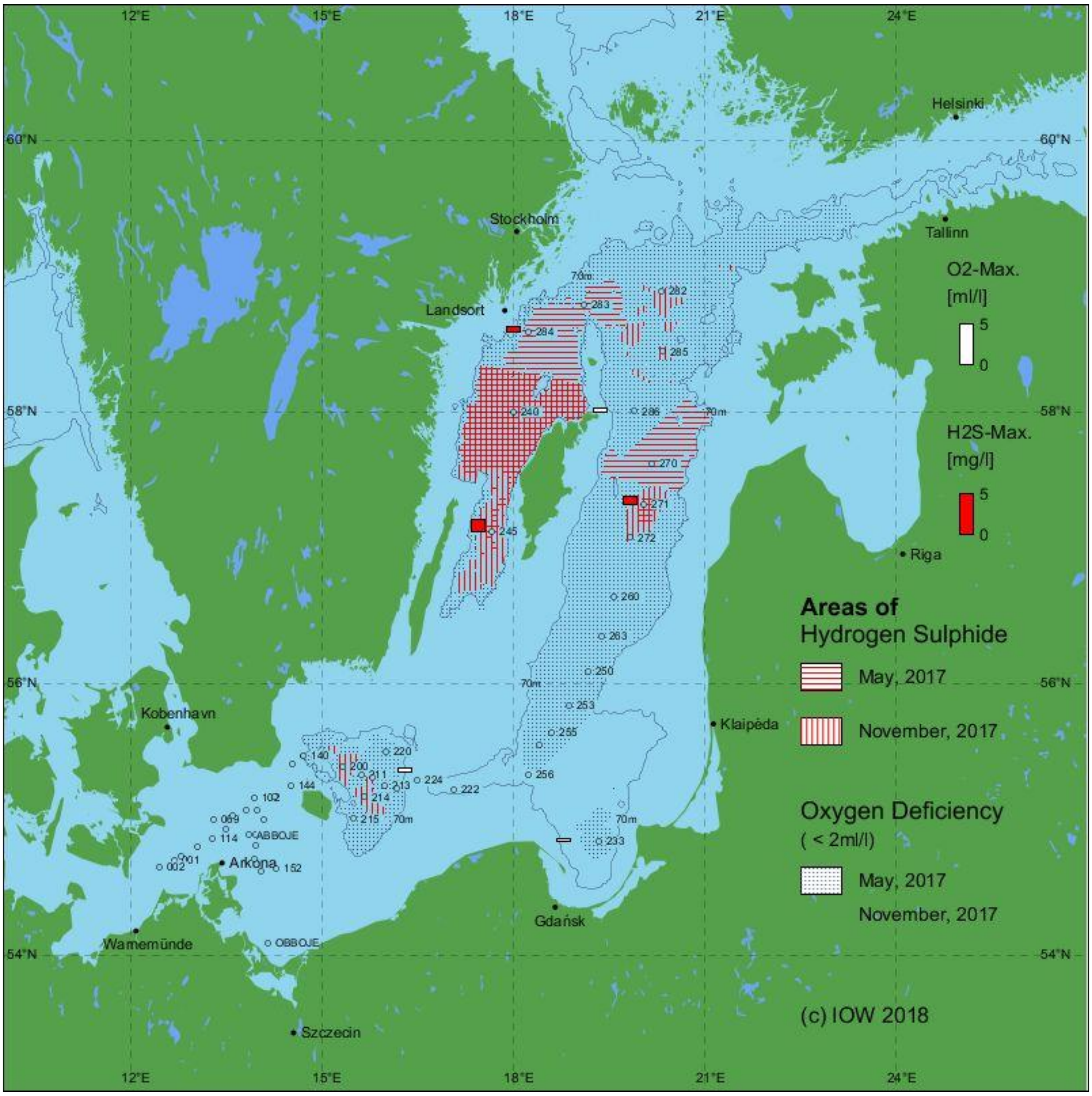


Fig. 1: Location of stations (■ MARNET- stations) and areas of oxygen deficiency and hydrogen sulphide in the near bottom layer of the Baltic Sea. Bars show the maximum oxygen and hydrogen sulphide concentrations of this layer in 2017; the figure additionally contains the 70 m -depth line

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 (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 of air temperature at Warnemünde weather station, and in comparison with Arkona, are listed in tables 2 and 3.

According to the analysis of DWD (DWD, 2017), 2017 was again a warm year on global and national scale. Nearly all regions in Germany recorded mean temperatures above the long-term mean of the reference period 1981-2010. March 2017 was the warmest since the beginning of continuous measurements in 1881. The mean annual temperature of 9.6 °C was about 0.7 K higher than the average for 1981-2010 and 0.1 K slightly higher than the previous year 2016. The year began in January with cold temperatures throughout Germany showing anomalies of monthly means up to -5.1 K in the south and -1.3 K in the north along the coast compared to 1981-2010. Along Germany's Baltic coast the winter situation changed to warmer temperatures in the mid of February and the months February to June each exceeded the thirty-year mean by 0.4-2 K. July was colder than usual by -1 K and August-September were balanced. The end of the year was warm again with anomalies of 1-1.6 K from October to December (c.f. Table 1).
Across Germany, the amount of precipitation was 854 mm, 6 % higher than the average of 808 mm and above 723 mm in 2016. In a regional comparison Schleswig-Holstein (985 mm) and Mecklenburg-Vorpommern (789 mm) showed values of 120 % and 128 % of their long-term average for 1981-2010. The driest months at the coast were January and May. The longest periods without precipitation in the German territory happened from March 22nd to April 14th at the stations Trier and Berus in south-western Germany. The most rain fall at the station Brocken (central Germany) with 280 mm in 4 days at the end of July.
The average annual sum of 1,596 hours of sunshine fall slightly below the long-term average by 0.3 % (5 hours) and were slightly lower than in 2016 with 1,607 hours. The national ranking is led by Stuttgart-Echterdingen (1,950 hours) in the south-western part. The station Arkona at the isle of Rügen is ranked on second place and recorded 1,764 hours. December was the least sunny month: with an average of 28 hours, it was 30 % below the long-term average. The peak value belonged to June: 241 hours, followed by May: 224 hours.

2.1 Ice Winter 2016/17

For the southern Baltic Sea area, the cold sum of air temperature of 31.7 Kd at Warnemünde station amounted to a warm winter in 2016/17 (Table 2). This value plots below the long-term average of 101.8 Kd in comparative data from 1948 onwards and ranks as 15th warmest winter in this time series. In comparison, Arkona station at 27.2 Kd (Table 3) is slightly lower, and represents a relatively low value like the previous winters 2015/2016 (36.1 Kd), 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 two short cold spells in January and February 2017 a very warm wintertime was recorded (Table 1). Overall, 43 days of slightly frost and 7 days of ice were recorded at Arkona compared to 37 days of frost and as well 7 days of ice in the mild winter of 2015/16 (NAUMANN et al., 2017). The winter's warm temperature profile was also reflected in icing rates.
According to SCHWEGMANN & HOLFORT (2017), this ice season in the Baltic Sea is classified as weak. Given warm weather conditions, the maximum extent of ice was reached at 12th February 2017 with an area some 103714 km². This ice coverage is ranked on 64th place since the year 1720, starting at the lowest value of 49 000 km² (year 2008) in this time series of 298 years. The maximum extent of ice corresponded to some 25 % 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 104 000 km² is only slightly lower than in the previous year 2016/2017 (114 000 km²) and recent years show similar maximum ice coverages: 51 000 km² in 2014/15, 95 000 km² in 2013/14 except 187 000 km² in 2012/13. By some 49 %, the year 2017 fell short of the average of 212 000 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 138 000 km².

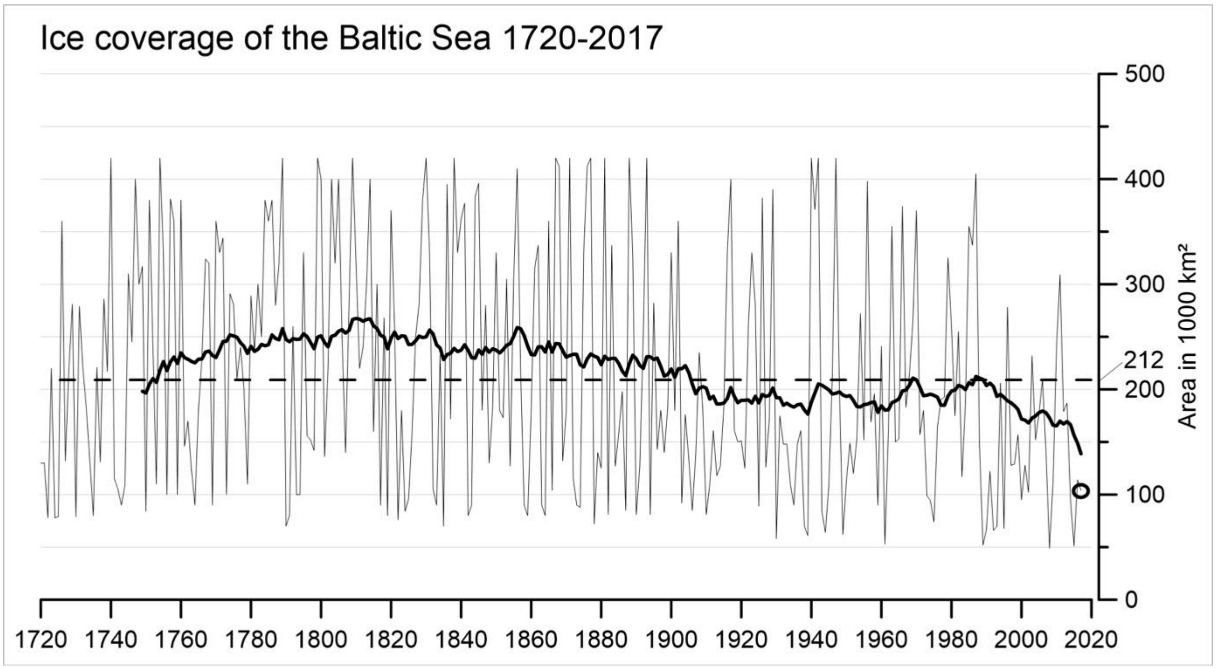


Fig. 2: Maximum ice covered area in 1000 km² of the Baltic Sea in the years 1720 to 2017 (from data of SCHMELZER et al., 2008, SCHWEGMANN & HOLFORT, 2017). The long-term average of 212 000 km² is shown as dashed line. The bold line is a running mean value over the past 30 years. The ice coverage in the winter 2016/2017 with 104 000 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 0.16 m (SCHWEGMANN & HOLFORT, 2017). After a slightly stronger value of 0.35 m in the previous year (SCHWEGMANN & HOLFORT, 2016), it is the fifth weak 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 0.16 m, the accumulated areal ice volume for winter 2015/16 is in line with low values of recent years: 0.35 m in 2015/16, 0.009 m in 2014/15, 0.37 m in 2013/14, 0.38 m in 2012/13 and 1.12 m in 2011/12. First icing was observed early at mid-November in the mouth of the river Schlei and three short icing periods of a few days occurred in sheltered areas of the German Baltic Sea coast between mid-November and beginning of December 2016. A longer period of 5-30 cm ice thickness was observed in this area between January 5th and February 20th. Along the Western Pomeranian lagoon chain icing of up to 48 days were registered in sheltered areas of the Oder lagoon (Kamminke harbour). At other areas, the number of recorded ice days was thus as follows: 43 at Dänische Wiek (inner Greifswald lagoon), 32 at Darss-Zingst lagoon chain and lagoon east of Rügen island (station Vierendehl), 11 days at Osttief (Pommeranian Bight, western part), 11 days at Rostock harbour; 13 days at Wismar harbour, 29 ice days at the mouth of the river Schlei and 2 days at the Flensburg Fjord. More open German sea areas all remained ice-free, according to the BSH maritime data portal and SCHWEGMANN & HOLFORT (2017). In the winter of 2016/17, an accumulated areal ice volume for the coast of Mecklenburg-Vorpommern of 0.22 m and Schleswig-Holstein of 0.09 m was calculated, which is lower than the previous winter season of 0.45 m and 0.23 m. At farther east lagoons at the southern Baltic Sea first icing occurred since January 8th in the Curonian Lagoon and since January 9th in the Vistula Lagoon and ended at March 15th. A maximum ice thickness of 25 cm was observed. In the northern part of the Baltic Sea icing occurred from November 8th and to beginning of June (Bothnian Sea). The maximum aerial extent was 20 % less compared to the previous wintertime, but the icing volume was remarkedly higher (17 %) in 2016/2017 (SCHWEGMANN & HOLFORT, 2017). This is the reason why melting went slow.

2.2 Weather Developments in 2017

Over the course of the year 2017, pressure systems and air currents were prevailing from westerly to south-westerly directions (cf. Figures 4a, 5b, 6). These wind directions account for about 75 % of the annual sum and the progressive wind vector curve of 2017 roughly follows the climatic mean situation (cf. 4a, b). The Institute of Meteorology at FU Berlin has given names to high and low pressure systems since 1954; a sponsorship deal (‘Wetterpatenschaften’) has also been in place since 2002 (FU-Berlin, 2016).

At the beginning of **January,** low pressure system “Deep Axel” (977 hPa) crossed Scandinavia and triggered a strong storm surge at the southern Baltic Sea in the night January 4th-5th (Fig. 3). The wind direction shifted from northwest to northeast and blew persistent around 6-7 Bft, gusts up to 26.8 m/s, inducing highstands of 1.83 m (Wismar Bight) above mean sea level. Especially, the coast of Usedom island showed strong coastal retreat by this event. Cold winter weather was typical during the month and caused by succession of extensive high-pressure cells across central Europe (highs “Angelika”, “Brigitta”, “Christa” and “Doris”). Outflow conditions were dominating, resulting in a sea level drop from 64 cm MSL (January 4th) to -2 cm MSL to the end of the month (Fig. 7a).
The temperature profile for January varied regional with slightly cold temperatures at the coasts (-0.2 K to -1.3 K) to very cold temperatures in southern Germany of up to -5.1 K (Freiburg) compared to the thirty-year average 1981-2010. Sunshine duration in most areas of Germany was above average, being the fourth sunniest January since 1951 (avg. 73 h, +43 %). For instance, at Arkona station a positive anomaly of sunshine duration of 138 % (62 hours) was recorded. Precipitation was generally low, mainly occurring as snowfall. The German Baltic Sea coast varied between -42 % at Schleswig-Holstein (station Schleswig) and -15 % to -12 % at stations Warnemünde and Ückermünde of Mecklenburg-Vorpommern.

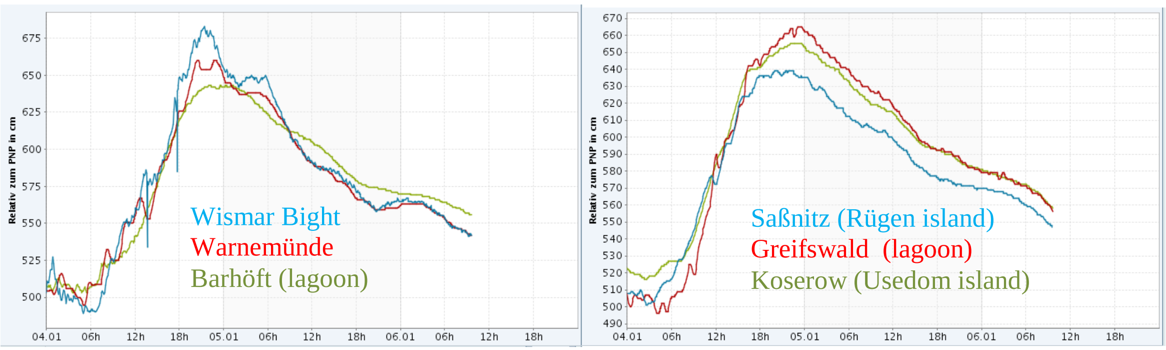


Fig. 3: Tide gauge data during at the German Baltic Sea coast during the storm surge from 2017 January 4^{th}-5^{th} (data: Pegelonline, www.pegelonline.wsv.de)

Too mid of **February,** high pressure was dominant across northern Europe (high “Erika”) and low-pressure cell passed southerly. Cold winter weather continued at the southern Baltic Sea coast. Since February 16^{th}, the situation changed to mild temperatures of 3-10 °C as daily mean. A succession of cyclones passed northern Europe (lows “Pierre”, “Qerkin”, “Rolf”, “Stefan”, “Thomas” and “Udo”) and westerly to south-westerly winds led to a rapid sea level rise of 61 cm at station Landsort Norra (February 13^{th} to March 3^{rd}) comprising a volume of 210 km^3 (Figure 7). Across Germany the weather situation was generally warm, with positive anomalies up to 3.4 K in the southern part and 0.5-1.1 K along the coast. Along Germany’s Baltic Sea coast temperature anomalies of 0.7 K occurred, increased precipitation (Arkona station: 141 %) and sunshine duration slightly below the long-term mean occurred.

In **March**, the warm temperatures continued, showing an anomaly of +2.9 K (nationwide). It was the warmest period in March ever recorded since the beginning of measurements in 1881. The weather regime changed a lot during the month from westerly cyclones to throughs across western and central Europe, high pressure in the mid of the month to westerly cyclones and again to a high-pressure situation at the end. No major storm events occurred and daily means wind speed varied between 3.3 and 13.7 m/s (4 days above 10 m/s). The mean sea level of the Baltic Sea slightly dropped, rose and dropped again, showing a variation between 24 cm MSL and -6 cm MSL (Figure 7a). Along the Germany’s Baltic Sea coast, monthly averages deviated by 0.3 K. At the station Arkona, a monthly mean of 4.9 °C (2 K deviation) was measured. Precipitation amounts between 85 % at Schleswig, 105 % at Rostock to 155 % at Arkona compared to the long-term average 1981-2010. The average sunshine duration was 114 hours, 30 % above the long-term average of 114 hours. The station Arkona registered 123 hours of sunshine (95 %).

April showed the typical changeable weather by dominance of low pressure systems crossing Northern Europe. Extensive high-pressure cells dominated the situation in the central to southern part. In general, low temperatures were registered nationwide (-0.9 K), ranging from -1.5 k in the south and -0.3 K to -0.7 K in the north. From April 10^{th}-14^{th} the wind blew stronger than 10 m/s five days in a role from west to west-northwest and the sea level rose from -10 cm MSL to 24 cm MSL (Figure 7a). Later on, the sea level decreased to -5 cm MSL (April 20^{th}) and increasing again to 27 cm MSL (April 24^{th}). Temperatures along Germany’s Baltic Sea coast varied between -0.7 K (station Ückermünde) and 0.4 K above the long-term average (station Arkona). Amounts of precipitation were generally to high but varied greatly from area to area: in Schleswig-Holstein, it was 58 % to wet in Schleswig; 11 % to wet in Rostock, 13 % to wet at Arkona and 38 % to wet in Ueckermünde on the Polish border. An average of 153 hours of sunshine across Germany was 10 % below the long-term average. In Northern Germany, the sun shone longer than in southern parts, for instance 194 hours in Rostock/Warnemünde and 193 hours at Arkona. The nationwide maximum was registered in Saarbrücken in the southwestern part of Germany (220 hours).

In **May**, the weather was mainly influenced by high pressure cells across Central Europe and Scandinavia. In the beginning, very strong north-easterly winds occurred between May 2nd-5th. Low-pressure “Victor” crossed central Europe with 18.1 m/s, the highest daily average of the year was measured at Arkona station (Figure 5a). Later on, only moderate winds occurred with daily means up to 8 m/s. At May 31th low-pressure “Gerhard” crossed Scandinavia showing westerly winds of 12.3 m/s (daily mean). The sea level at Landsort Norra dropped quickly to -23 cm MSL (March 17th) by easterly winds in the beginning of May (Figure 7). Afterwards the sea level fluctuated only slightly to the end of May. In general, too warm temperatures were recorded nationwide (1.1 K). Along the German Baltic Sea coast, the air temperatures showed warm values of 1.6 K at Schleswig, 0.9 K at Rostock and 0.5 K at Ückermünde. Arkona showed a monthly mean of 11.5 °C (+1.1 K). Amounts of precipitation varied locally, for example Schleswig -11 % to dry, Rostock -28 % to dry, Arkona -49 % to dry and Ückermünde 92 % (102 mm) to wet compared to the long-term average. The sunshine duration was with 224 hours in mean, 7 % above the long-term mean of 210 hours. Fürstenzell (south-east Germany, close to Austria) registered 284 hours as sunniest station, followed by Arkona with 272 hours (100 %).

During **June**, the weather changed often between influence of low-pressure and high-pressure. Dry, warm and sunny phases were interrupted by events of strong precipitation, hail and thunderstorms. Remarkable is that at the last three days of June fall more than 100 mm of rain in some areas of north-eastern Germany (lows “Quirin” and “Rasmund”). Airport Berlin Tegel registered the nationwide monthly maximum of 261 mm (458 %). Mainly western wind directions of moderate intensity were dominant, interrupted by a short phase of easterly winds from June 2nd-6th (Figure 5b). Only five days showed a stronger daily mean of 10-12 m/s (June 12th, 13th, 24th, 26th and 29th). The sea level rose stepwise from -2 mm MSL to 29 cm MSL at the central Baltic Sea during the month (Figure 7a). Along the German Baltic Sea coast the temperature was about 1.3 K warmer than the average 1981-2010, for instance Arkona of 15.3 °C (+ 1.1 K). Overall, June was too rainy with a mean of 90 mm precipitation compared to the long-term average of 77 mm (+18 %). Only a small area of central spanning from Düsseldorf (-48 %) to Magdeburg (-17 %) and Frankfurt am Main (-57 %) was to dry. In contrast areas at the Baltic Sea coast registered positive values, at Schleswig 123 mm (+64 %), Warnemünde 118 mm (+64 %), Arkona 89 mm (+53 %) and Ückermünde 114 mm (+90 %). At 241 hours, sunshine duration was about 19 % above the average of 204 hours, but at the coast the sun shone a bit less compared to southern Germany. Arkona registered a value of 264 hours (104 %).

The first half of **July** was influenced by low pressure cells crossing Scandinavia and Central Europe from the North Atlantic (lows “Rasmund”, “Saverio”, “Till”, “Uwe”, “Vincent”, “Xavier”, “Wolf” and “Ygit”) causing westerly winds (Figure 5b). Since July 18th high-pressures “Irmingard” and “Hanna” dominated the weather moving from central Europe to Scandinavia. Southerly low-pressures crossed central Europe (lows “Alfred”, “Bernhard”, “Christoph”) inducing easterly winds. Generally moderate winds occurred in July (daily means of 2-8 m/s). Only at the July 25th a daily mean of 10.8 m/s was recorded. The trend of sea level rise at the central Baltic Sea during June stopped at the beginning of the month and the level fluctuated between 29 cm MSL to 15 cm MSL up to June 20th. Afterwards the sea level dropped to the end of the month to -4 cm MSL by easterly winds (Figure 7). The monthly mean temperature accounts nationwide 18.1 °C (+0.1 K) and at the Baltic around -0.7 K to -1 K below the long-term average. Only central and southern Germany registered slightly positive mean values. The precipitation was generally much too high with 132 mm (+58 %), but varied across Germany from slightly higher values in the south to enormous values along the Baltic Sea coast (Rostock 138 mm (+116 %), Arkona 102 mm (+89 %) and Ückermünde 132 mm (+128 %). The sun shone 196 hours in average and was 11 % below the reference period 1981-2010. Longest sunshine duration was measured at station Fürstenzell (245 hours, 103 %) in south-east Germany. Arkona recorded 239 hours (-14 %).

In **August,** the inconstant weather development was similar compared to July. Starting with dominance of low pressures crossing Scandinavia (lows “Fritz”, “Hartmut”, “Ildefoms” and “Jürgen”) and high pressures “Jolanda”, “Katja” and “Lisa” in south-eastern and eastern Europe, westerly winds occurred in combination with relatively cold temperatures. At August 19th-23th, high-pressures “Nilüfer” and “Queena” across central Europe were decisive for the weather before westerly cyclones dominated again the situation. Only moderate winds of daily means between 3-6 m/s occurred, seldom up to 9.5 m/s. Westerly winds were only short (some hours up to a day) interrupted. The seal level fluctuated between -4 cm MSL to 15 cm MSL, with a slightly rising trend (Figure 7a). Nationwide more or less balanced mean temperatures occurred, the mean value of 17.9 °C was 0.4 K above the long-term average. At the German Baltic Sea coast, values around the average were reached (-0.4 K at Schleswig, 0.4 K at Rostock, 0.3 K at Arkona and 0.3 K at the station Ückermünde). The amount of precipitation was with 86 mm above the average of 78 mm (10 %). Along the Baltic Sea coast values varied a lot from west to east (+49 % in Schleswig, -42 % in Rostock, 36 % in Arkona to -45 % in Ückermünde). Across Germany as a whole, sunshine duration of 207 hours was around the average (206 hours). Values above the mean occurred mainly along the Baltic Sea coast and the Alps in the south. 255 hours were registered at Arkona (106 %), but the maximum of 274 hours showed again the station Fürstenzell.

September was also characterised by this inconsistent weather of the summer. Low-pressure cells brought mainly cloudy and rainy conditions which were only short interrupted by sunny late summer weather of high-pressure influence. During the month, mainly moderate wind conditions continued. Only four days of mean values above 10 m/s were registered (September 7th, 13th-15th). At September 13th gale “Sebastian” crossed the Baltic Sea showing maximum gusts of 26.1 m/s at Arkona, 33.6 m/s (12 Bft) at MARNET station Darss Sill and 29.5 m/s at MARNET station Arkona Basin. Significant wave heights of 3.41 m (Darss Sill) and 4.27 m (Arkona Basin) were measured. All instrumentation stayed in operation. The first two thirds of the month the sea level fluctuated at Landsort Norra between 9 cm MSL to 24 cm MSL with a slightly rising trend due to the south-westerly to westerly wind regime (Figure 7). Since September 24th a phase of easterly winds begun and the sea level dropped quickly from 11 cm MSL to -14 cm MSL at the end of the month.

The monthly mean temperature showed a nationwide average of 12.8 °C, 0.7 K below the long-term average. At Arkona a monthly temperature of 14.1 °C was reached, which is exactly in line with the long-term average. The stations Schleswig and Ückermünde reached as well their average and Rostock was slightly too warm (+0.2 K). Rainfall of 66.6 mm was as well at the average of 67 mm; at 121 hours of sunshine duration was 18 % below the long-term average 1981-2010. In the south-west of the Baltic Sea area, precipitation conditions varied a lot from 152 mm (+81 %) in the western part at station Schleswig to 47 mm (-23 %) at Rostock, 40 mm (-29 %) at Arkona and 37 mm (-24 %) at Ückermünde. In terms of sunshine duration, 121 hours (-18 %) was recorded nationwide. At the Baltic Sea coast and northeast Germany values slightly exceeded the long-term means. Arkona registered 134 hours (-22 %), but Rostock-Warnemünde had with 162 hours (+1 %) the national maximum.

The influence of westerly to south-westerly cyclones crossing northern Europe dominated the weather situation in **October**. Only between October 19^{th}-22^{nd} extensive high-pressure cell across Scandinavia induced a short phase of easterly winds (Figure 5b). At October 5^{th} gale "Xaver" crossed northern Germany, but showed stronger wind strength at western and central Germany. For example, the lake Steinhuder Meer close to Hannover registered gusts up to 29.8 m/s (11 Bft) whereas at station Arkona blew gusts up to 18.3 m/s (8Bft). A more significant event for the southern Baltic occurred to the end of the month, where from October 27^{th} to 30^{th} low-pressures "Grischa" and "Herwart" crossed Scandinavia inducing daily means of up to 15.6 m/s and maximum gusts 26.9 m/s from west-northwest to northern direction. At October 29^{th} a weak storm surge of +1.02 m measured at tide gauge station Warnemünde occurred. Stronger beach /cliff abrasion and longshore transport of sediments became apparent. The drop of the mean sea level starting end of September continued in the first days to a lowstand of -25 cm MSL at Landsort Norra (October 2^{nd}). Afterwards the sea level increased rapidly due to westerly wind forcing and a maximum of 26 cm MSL was reached at October 9^{th} comprising an inflow volume of 188 km^3 (Figure 7). Some days of minor fluctuations/stagnation occurred up to October 19^{th} and the subsequent easterly winds dropped the sea level again to -8 cm MSL. At the end of the month a second inflow to a level of 35 cm MSL occurred. The nationwide average temperature was 1.7 K (11.1 °C) too warm compared to the long-term mean of 1981-2010. Stations along the Baltic Sea coast recorded monthly temperatures that on average were in a range between 2.2 K at Schleswig, 2.3 K at Rostock, 1.6 K at Arkona and 2.1 K at Ückermünde. At 76 mm, precipitation was 21 % above the average value of 63 mm; at 97 hours, sunshine duration was 10 % below average of 108 hours. Along the Baltic Sea coast precipitation was very intensive and varied between +80 % (167 mm) at Schleswig, +136 % (106 mm) at Rostock, +45 % (77 mm) at Arkona and +200 % (117 mm) at Ückermünde. The sun shone at Arkona station 95 hours (-19 %) and 190 hours at the Zugspitze in the Alpes (nationwide maximum).

The generally mild weather continued during **November** and dominance of westerly to south-westerly cyclones were two times shortly interrupted by high-pressure "Xandy" (November 6^{th}-9^{th}) and "Yaprak" (14^{th}-17^{th}). Nine days showed mean values between 10-14 m/s and mainly southwest to west winds occurred. Only two days of south-east to eastern direction were registered (November 8^{th}, 22^{nd}). The sea level fluctuated between 9-48 cm MSL and showed a stepwise rising trend (Figure 7a). The nationwide mean temperature was 0.7 K too mild (5.1 °C), but northerly to north-easterly regions showed higher anomalies than the western and south-western part of Germany (Saarbrücken 0.1 K). At the German Baltic Sea coast the anomalies of mean temperatures increased from west to east (Schleswig +0.8 K, Rostock +1.5 K). Precipitation varied between +39 % (111 mm) at Schleswig, -6 % (46 mm) at Rostock, +31 % (63 mm) at Arkona and +29 % (58 mm) at Ückermünde. Generally, too wet conditions occurred in Germany with a mean of 81 mm (+22 %). The mean sunshine duration of 39 hours was 27 % below the long-term mean (1981-2010) and shone from 17 hours at Zinnwald (Erzgebirge mountains) to 104 hours at the Zugspitze (Alpes). Arkona registered 38 hours (-30 %).

In **December** the mild weather conditions continued across Germany by typical influence of westerly cyclones crossing northern Europe. Only four days of slight frost during night-time occurred in Rostock at the mid of the month, where high-pressure was dominant across central Europe (high "Carina"). The wind situation of south-westerly to westerly winds continued (Figure 4a) and 14 days of means between 10-17.7 m/s were registered at station Arkona. A further stepwise sea level rise occurred from 33 cm MSL (December 1st) to 50 cm MSL (December 26th (Figure 7a), but discontinuous phases of strong winds induced no classic inflow conditions for an overflow of larger volumes of highly saline water at the sills. Generally mild temperatures across Germany account to a mean temperature of 2.7 °C, which is 1.5 K above the long-term average. At the Baltic Sea coast station Arkona showed a mean temperature of 3.9 °C (+1.6 K) and Warnemünde 4.2 °C (+1.9 K). At 77 mm, precipitation was slightly too high compared to the average of 72 mm (+6 %). The sunshine duration was nationwide at 28 hours (-30 %). The German Baltic Sea coast varied from wet weather at Schleswig (108 mm, +37 %) to dry weather at Arkona (41 mm, -5 %) and Ückermünde (28 mm, -32 %). Arkona registered a sunshine duration of 30 hours (-21 %), but in the south of Germany at the mountain Zugspitze in the Alpes the national maximum of 123 hours was measured. The lowest value was registered with 2 hours at Bad Marienburg in western Germany

2.3 Summary of Some of the Year's Significant Parameters

An annual sum of **solar radiation** at Gdynia cannot be calculated for 2017, because of several days of missing data in February and August (personal communication, IMGW). The sunniest month was by far May (Table 1). At 63840 J/m², May comes at 10th place in the long-term comparison, 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 since 1956 (compiled by FEISTEL et al., 2008). The year's lowest value was 4854 J/m² in December, lying in 15 place above the long-term average of 4366 J/m². All other months showed solar radiation values in the mid-range compared to the last 61 years (January 21st; March 44th; April 43th; June 41th; July 48th; Sept 51th; Oct 48th; Nov 31$^{th)}$. In conclusion, the annual sum of the year 2017 should be around the long-term average of 373 754 J/m².

With a **warm sum** of air temperature of 159.5 Kd (Table 2), recorded at Warnemünde, the summer 2017 is ranked in the midrange over the past 70 years on 28th position and far below the previous year of 267 Kd on 6th place. The 2017 value is in the range of the long-term average of 153.4 Kd, and within the standard deviation, meaning that the year can be classified as a particularly moderate one. Average monthly temperatures from May, June and August were above the long-term average, whereas the months July and September showed colder temperatures of around 2/3 of their average. Especially May was far above the standard deviation. April and October showed usual temperature pattern around their average.

With a **cold sum** of 31.7 Kd in Warnemünde, the winter of 2016/17 is ranked in the upper midrange as 15th warmest winter in the long-term data series. Cold periods from 5th-7th January and 8th-14th February and the 12th November 2016 led to this cold sum which is far above the long-term average of 102.4 Kd, but within the standard deviation (Table 2). All winter months from November to April showed too high values compared with the average.

Table 1: Monthly averaged weather data at Arkona station (Rügen island, 42 m MSL) from DWD (2017). *t*: air temperature, **Δ***t*: 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 (2018). Percentages are given with respect to the long-term mean. Maxima and minima are shown in bold.

Monat	*t*/°C	Δ*t*/K	*h*/%	*s*/%	*r*/%	Frost	Eis	Solar
Jan	**0.8**	-0.4	87	**138**	**38**	23	3	6368
Feb	1.8	0.7	84	97	141	15	4	*
Mrz	4.9	**2.0**	84	95	155	-	-	23887
Apr	6.4	0.4	**80**	94	113	1	-	37828
Mai	11.5	1.1	81	100	51	-	-	**63840**
Jun	15.3	1.1	82	104	89	-	-	58338
Jul	16.1	**-1.0**	84	86	**189**	-	-	52282
Aug	**17.6**	0.3	81	106	136	-	-	*
Sep	14.1	0.0	86	78	71	-	-	27286
Oct	11.6	1.6	87	81	145	-	-	15734
Nov	6.5	1.0	**88**	**70**	131	-	-	6969
Dec	3.9	1.6	**88**	79	95	4	-	**4854**

* several days of missing data

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 1948–2016 are given.

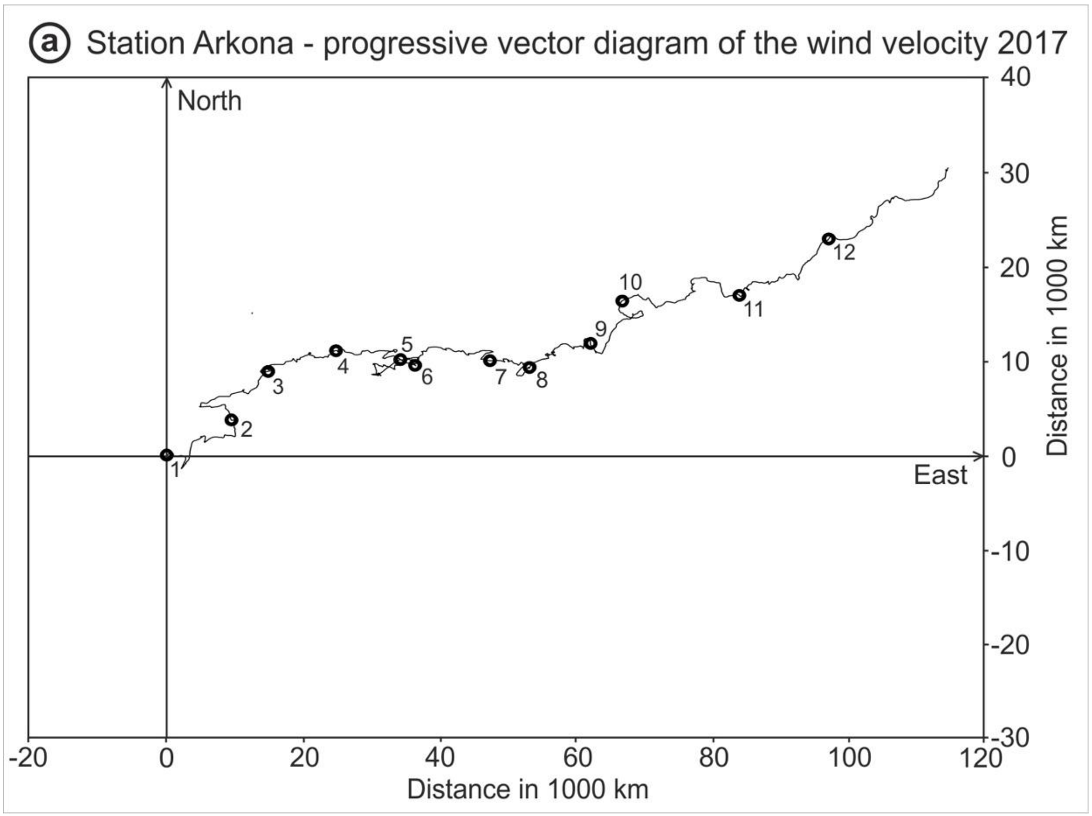
Month	CS 2016/17	Mean	Month	WS 2017	Mean
Nov	1.6	2.5 ± 6.1	Apr	0	1.0 ± 2.4
Dez	0	21.1 ± 27.9	Mai	17.7	5.7 ± 6.9
Jan	9.9	39.2 ± 39.3	Jun	32.2	23.3 ± 14.6
Feb	20.2	30.6 ± 37.8	Jul	36.2	57.7 ± 36.0
Mrz	0	8.2 ± 11.9	Aug	69.3	53.2 ± 31.9
Apr	0	0 ± 0.2	Sep	3.6	12.2 ± 13.1
			Okt	0.5	0,4 ± 1.1
∑ 2016/2017	31.7	101.8 ± 80.0	∑ 2017	159.5	153.4 ± 69.4

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	CS 2016/17	Monat	WS 2017
Nov	0	Apr	0
Dec	0	Mai	4.6
Jan	12.5	Jun	11.5
Feb	14.7	Jul	18.1
Mrz	0	Aug	49
Apr	0	Sep	0.1
		Okt	0
∑ 2016/2017	27.2	∑ 2017	83.3

Figures 4 to 7 illustrate the **wind conditions** at Arkona throughout 2017. 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 the 2017 assessment (Figure 4a), the long-term climatic wind curve is shown by way of comparison (Figure 4b); it was derived from the 1951-2002 time series. The 2017 curve (115 000 km eastwards, 30 000 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. The trend towards prevailing SW winds that began in 1981 and continues today (HAGEN & FEISTEL, 2008) is evident over the year. In January to February, April to May and September three longer periods of easterly winds were occurring (Figure 5b). As a result of change from easterly to westerly direction of the wind and low intensity (Figure 5a, b), the curve for May 2017 shows strong wind vector compensation, which is usual for this time of a year

compared with the average for 1951-2002 (Figure 4a, b). According to the wind-rose diagram (Figure 6), north-western to south-western directed winds account for about 75 % of the annual sum and dominated the course of the year. The mean wind speed of 7.2 m/s (Figure 5a) is slightly higher 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 3.7 m/s (Figure 5b) with the climatic mean of 1.7 m/s (HAGEN & FEISTEL, 2008), westerly winds were in 2017 much stronger than the mean. For example, figure 4a shows an eastward movement of 115 000 km compared to 52 000 km for the climatic mean. With an average speed of 0.97 m/s, the north component of the wind (positive southwards) shows a slightly higher value to the long-term average of 0.8 m/s.
In line with expectations, the climatic wind curve in Figure 4b is more smooth than the curves for individual years. It consists of a winter phase with a southwesterly 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 northeasterly 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).



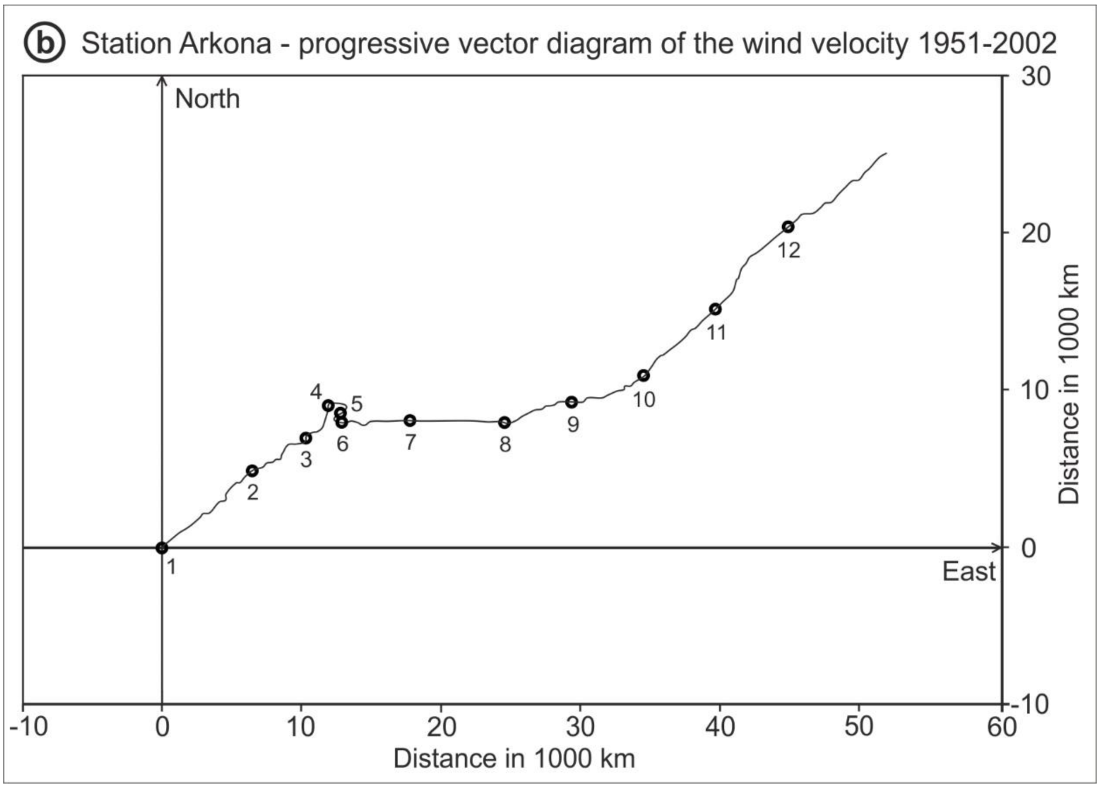
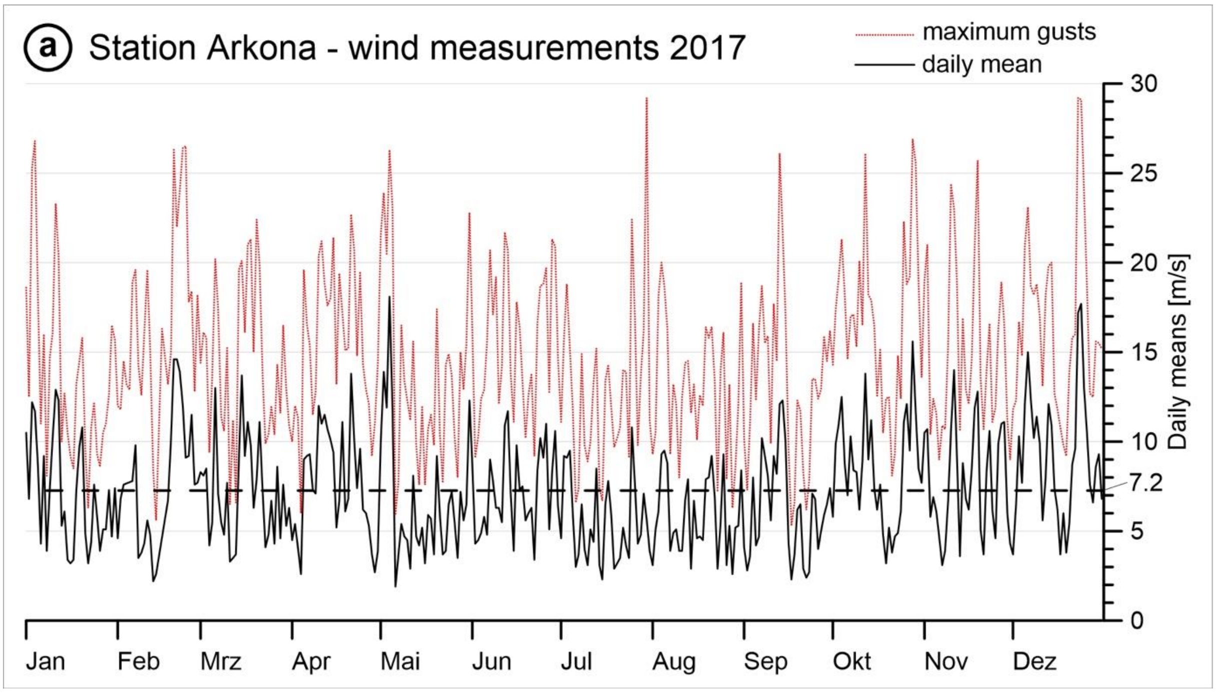


Fig. 4: Progressive vector diagram of the wind velocity at the weather station Arkona, distance in 1000 km, positive in northerly and easterly directions. The first day of each month is encircled. a) the year 2016 (from data of DWD, 2018) b) long-term average.



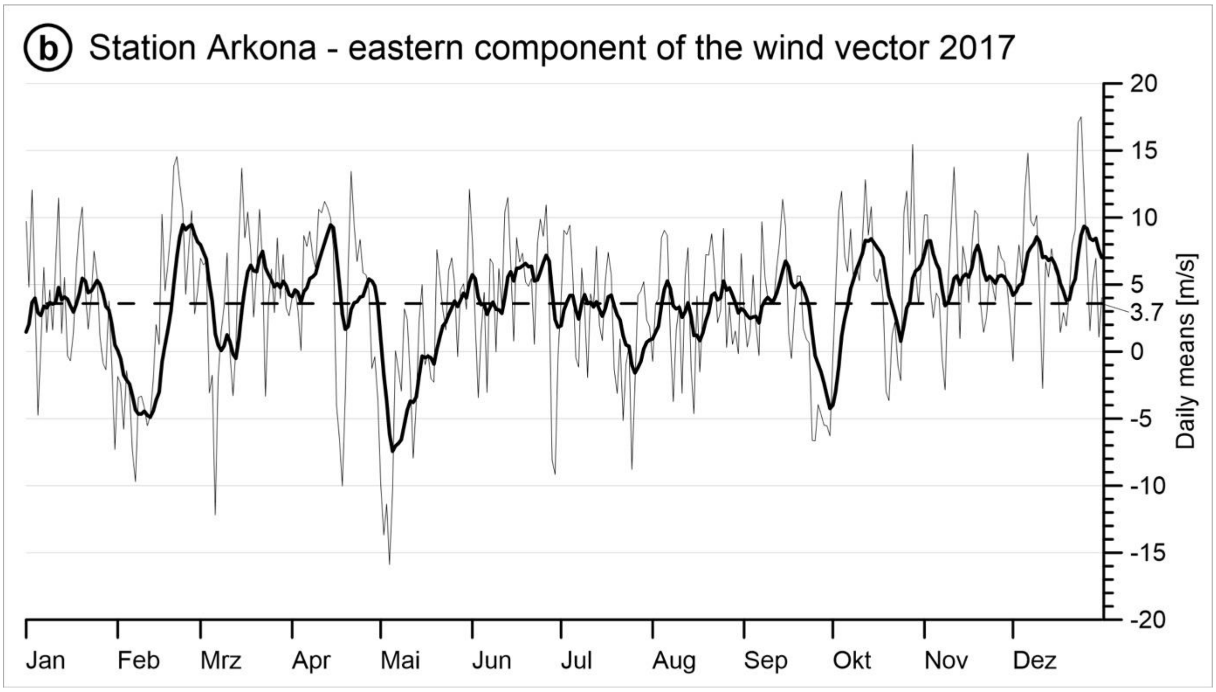


Fig. 5: Wind measurements at the weather station Arkona (from data of DWD, 2018). a) Daily means and maximum gusts of wind speed, in m/s, the dashed black line depicts the annual average of 7.2 m/s. b) Daily means of the eastern component (westerly wind positive), the dashed line depicts the annual average of 3.7 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). On 4th May a storm from north-eastern direction (low-pressure "Victor" crossing central Europe and high pressure "Sonja" across Scandinavia) occurred in the Baltic Sea as strongest wind event of the year, showing the highest daily average of 18.1 m/s and gusts up to 26.3 m/s

(Figure 5a). Other storm events occurred from western-south-western direction at Christmas time from 23rd-24th December (low pressures "Charly" and "Diethelm" across Scandinavia) with daily means of 17.2-17.7 m/s and gusts up to 29.2 m/s as well as on October 28th (low pressure "Grischa", daily mean of 15.6 m/s, gusts 26.3 m/s). The annual mean wind speed of 7.2 m/s is much higher than 2016's 6.5 m/s (NAUMANN et al., 2017). Previous years showed following annual mean values of 7.2 m/s (2015), 6.7 m/s (2014), 7.0 m/s (2013) and 7.1 m/s in the year 2012 (NAUSCH et al., 2013, 2014, 2015, 2016). Maximum wind speeds in excess of 20 m/s (>8 Bft) were recorded as hourly means only at December 24th (21.9 m/s), December 23rd (21.7 m/s) and May 4th (21.3 m/s). In 2016 a similar maximum value of 21.3 m/s was reached on 27th December (NAUMANN et al., 2017). These values falling well short of 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 2017.

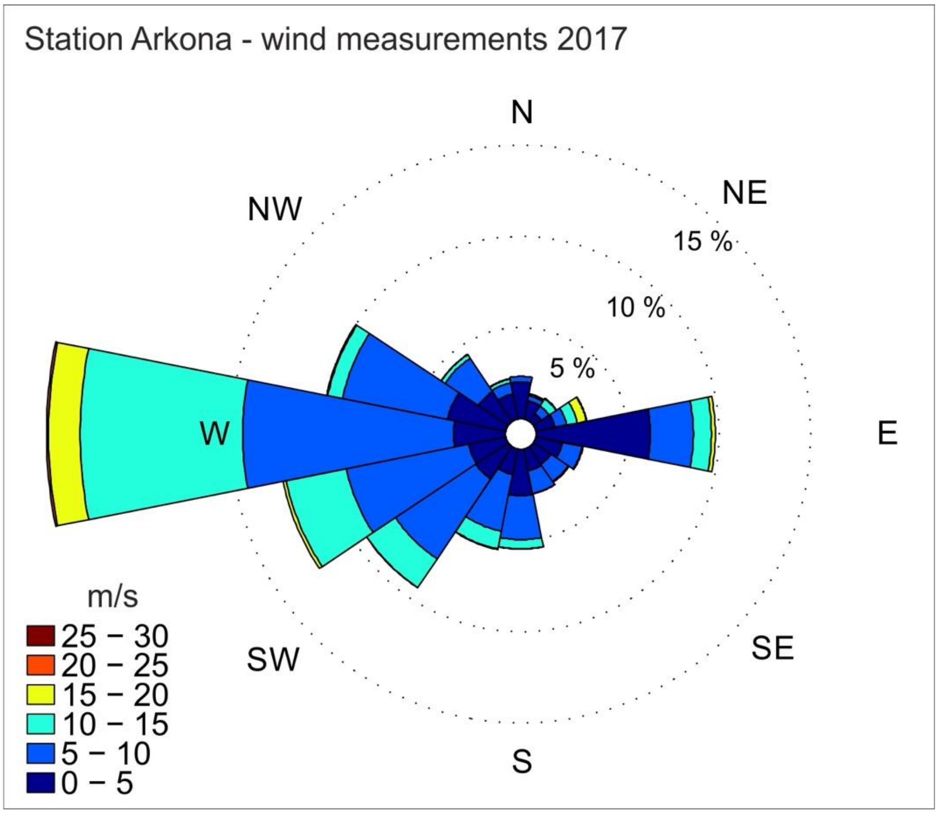


Fig. 6: Wind measurements at the weather station Arkona (from data of DWD, 2018) as wind-rose plot. Distribution of wind direction and strength based on hourly means of the year 2017.

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 2017, the Baltic Sea experienced two inflow phases with total volumes estimated between 210 km³ and 188 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:

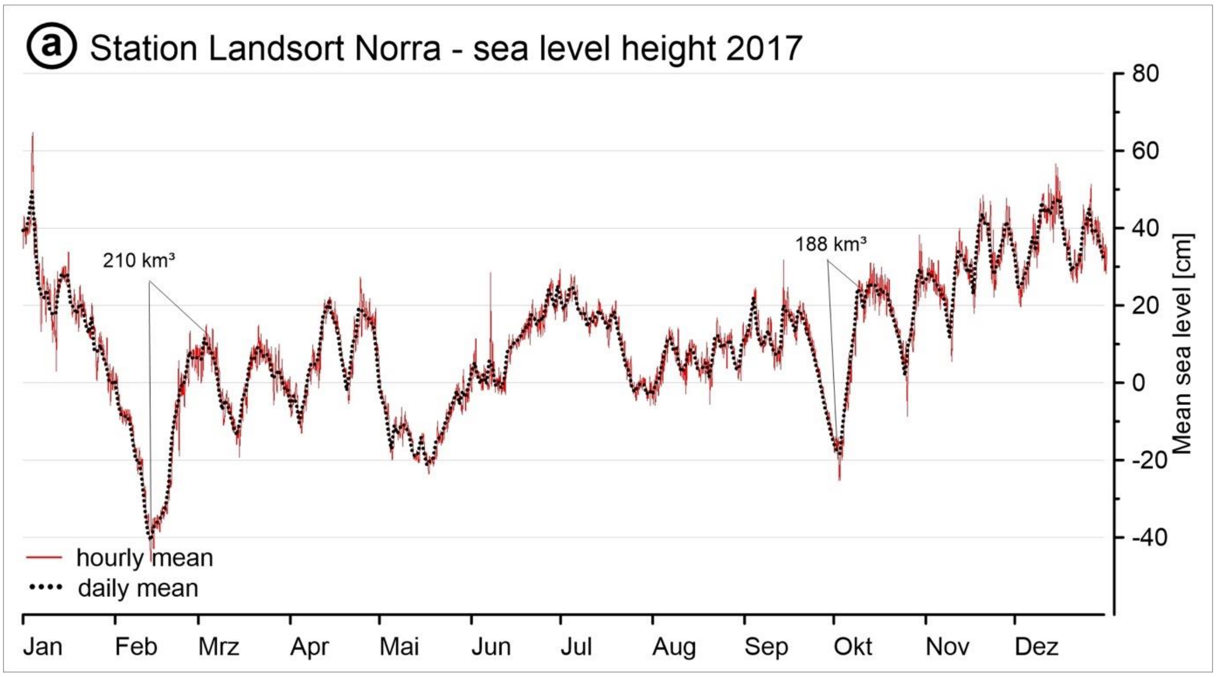
$$\bar{v}(t) = \int_0^\infty \mathrm{d}\tau\, v(t-\tau)\exp(-\tau/10\,\mathrm{d})$$

in which the decay time of 10 days describes the low-pass effect of the Sound 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 4th, the gauge at Landsort Norra recorded the highstand of the year of -65 cm MSL (Figure 7a) as a result of preceding long lasting strong westerly winds. A system shift to weak-moderate easterly winds caused a sea level drop to -46.5 cm (February 13th). Afterwards a rapid sea level rise to 15.6 cm MSL (March 3rd) occurred due to prevailing westerly winds and a resulting total volume of 210 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 1.3 Gt and highly saline volume transport of 68 km³ was calculated with data of the MARNET stations Darss Sill and Arkona Basin by MOHRHOLZ (submitted). The bottom salinity at the Darss Sill only for a short time exceeded 17 g/kg and the stratification was too high to classify this event as a Major Baltic Inflow described in NAUMANN et al. (submitted). Minor fluctuations between 15 cm and -15 cm MSL occurred up to May, before a longer period of easterly winds lowered the sea level to -21.6 cm MSL (May 19th). Afterwards events of westerly winds filled the Baltic Sea slowly and stepwise to 27 cm MSL (June 27th). Minor fluctuations between 0-20 cm MSL occurred again up to mid of September, before the sea level dropped to -25.4 cm MSL (October 2nd). Up to October 9th the sea level rose quickly to 26.4 cm MSL comprising a total inflow volume of 188 km³. Up to end of the year the sea level increased stepwise to 48.5 cm MSL (December 16th) by dominating westerly to south-westerly winds (Fig. 4a, 7a).



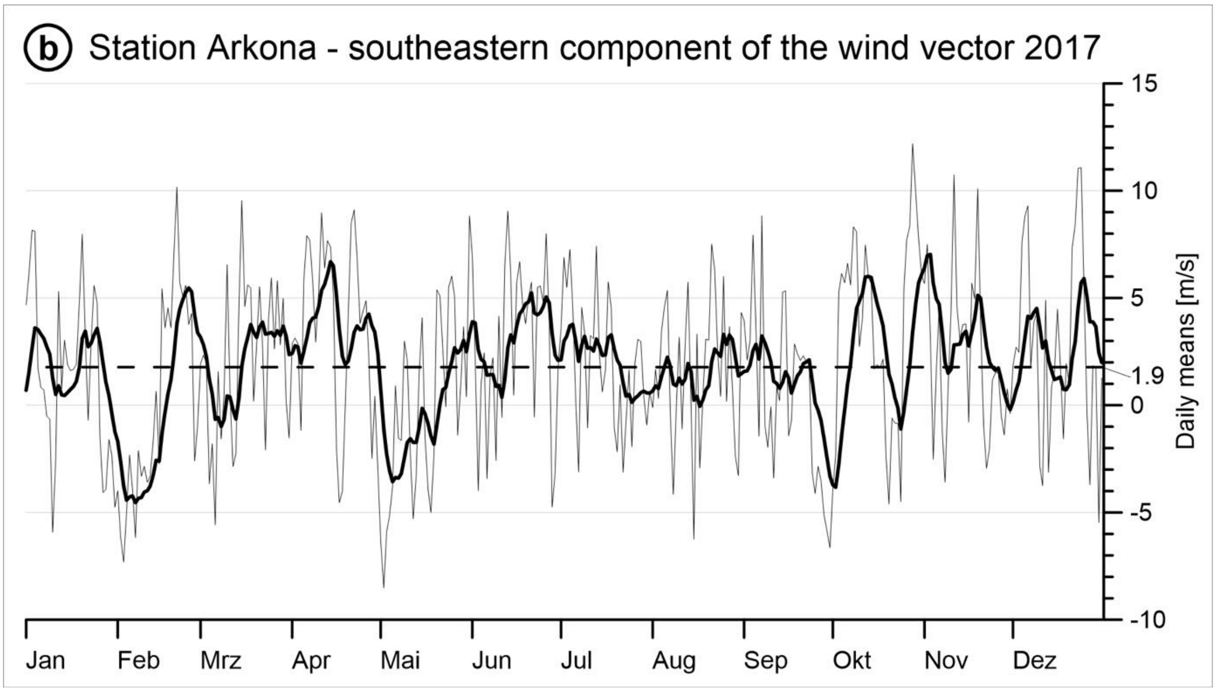


Fig. 7: a) Sea level at Landsort as a measure of the Baltic Sea fill factor (from data of SMHI, 2018a). b) Strength of the southeastern component of the wind vector (northwesterly wind positive) at the weather station Arkona (from data of DWD, 2018). The bold curve appeared by filtering with an exponential 10-days memory and the dashed line depicts the annual average of 1.9 m/s.

Compared to previous years of high inflow activity of four MBI's and various smaller events (NAUMANN et al., submitted) the year 2017 is characterized weak inflow year. This is visualized in figure 8 by the accumulated inflow volume through the Öresund (SMHI, 2014-2017), where the inflow curve of 2017 runs below the minimum of the reference period 1977-2016 from April up to the end of the year.

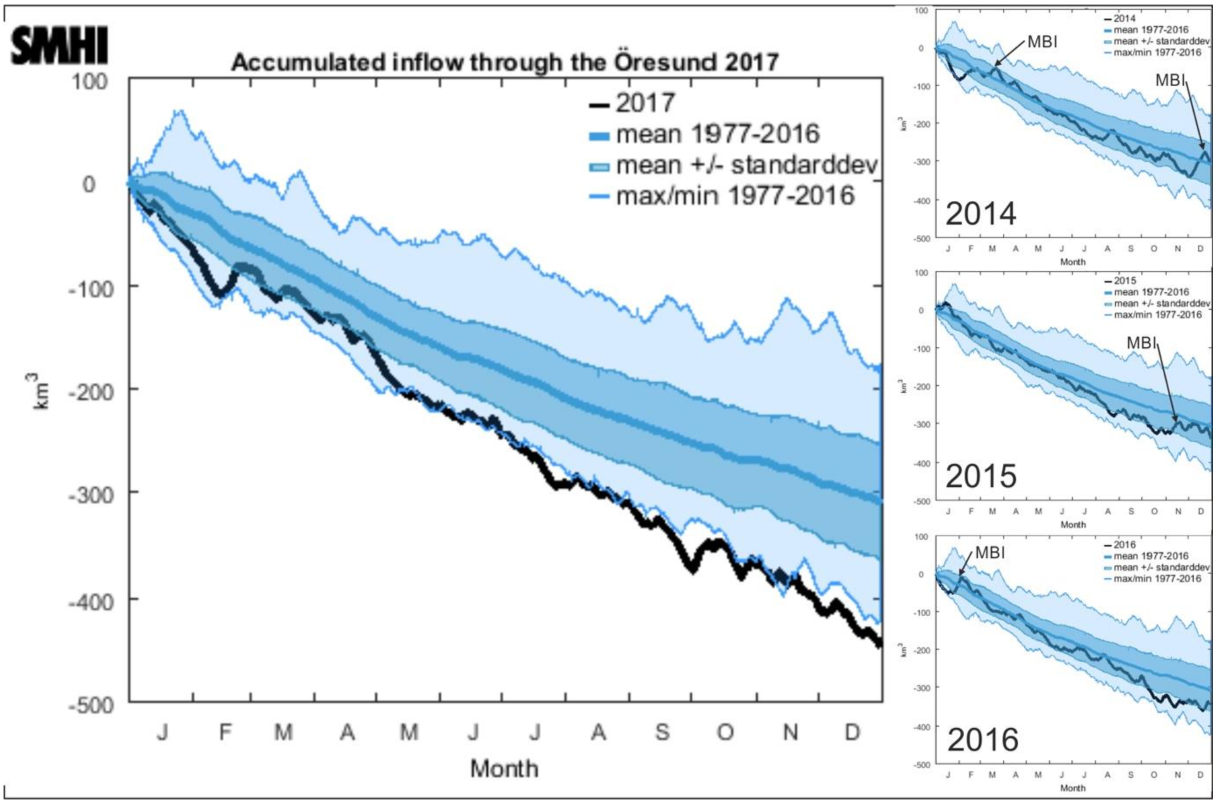


Fig. 8: Accumulated inflow (volume transport) through the Öresund during 2017 in comparison to previous years 2014-2016 (SMHI 2018b).

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

The monitoring station at the Darss Sill supplied nearly complete records during the year 2017, except for a few occasional data gaps due to hardware and battery problems. The largest data gap occurred in January and February, when sensor damage resulted in a complete loss of oxygen data in 19 m depth until replacement of the sensors on 27 February. Battery failure led to a gap in the CTD data at 5 m depth between 19 January and 01 March. And finally, a small gap in the CTD data between 27 February and 04 March occurred due to a hardware incompatibility problem that could, however, quickly be repaired. The ADCP provided full data records throughout the observation period. As usual, in addition to the automatic oxygen readings taken at 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 Darss Sill were determined from a statistical analysis based on the temperature and salinity time series at different depths. The small data gap between 27 February and 04 March at the 7-m depth level (see above) was filled by linear interpolation. Sensitivity studies showed that this had no significant effect on the statistics.

While significantly colder than record-setting previous years, the yearly mean temperatures (Table 4, Figure 9) for the year 2017 were clearly above average. Annual mean surface-layer temperatures are found on rank 6 of the entire record since 1992 (i.e. in the upper quartile), which is consistent with the climatic characterization of 2017 as a warm year in chapter 2. The standard deviation of the surface-layer temperatures, also shown in Table 4 and Figure 9, largely mirror the annual cycle. The values for 2017 are slightly smaller compared to the previous year, and close to the multi-year average. It is likely that the only moderately high surface temperatures in summer (see below) and the relatively mild winter temperatures resulted in an overall flat annual cycle, which is also reflected in the standard deviation. This is consistent with the atmospheric data discussed in section 2.3, which revealed a mild summer and a winter that was significantly warmer than the long-term average.

The mean salinities and their standard deviations at the station are shown in Table 4 and Figure 10. The values of the lowermost two sensors reflect the near-bottom variability in salinity, and are therefore a sensitive measure for the overall inflow activity. Different from the previous year, and the year 2014, both characterized by strong inflow activity, the year 2017 shows only small mean salinities and weak near-bottom salinity fluctuations. Only 4 of the previous years since 1992 exhibited a smaller mean value in 17 depth, and only 2 years in 19 m depth. Similarly, the standard deviations at these depth levels ranked among the 5-6 smallest so far observed, which is in line with the small water level fluctuations (and thus weak inflow activity) reported in section 2. The year 2017 was thus a year with particularly small inflow activity.

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
2017	9,67 ± 5,05	9,40 ± 1,58	9,23 ± 4,54	11,65 ± 2,50	9,20 ± 4,45	12,39 ± 2,61

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
2017	7,00	4.56	6,20	4,31	6,15	4,28

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 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 somewhat below the long-term average, and far below 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 0.25 – 0.3 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.

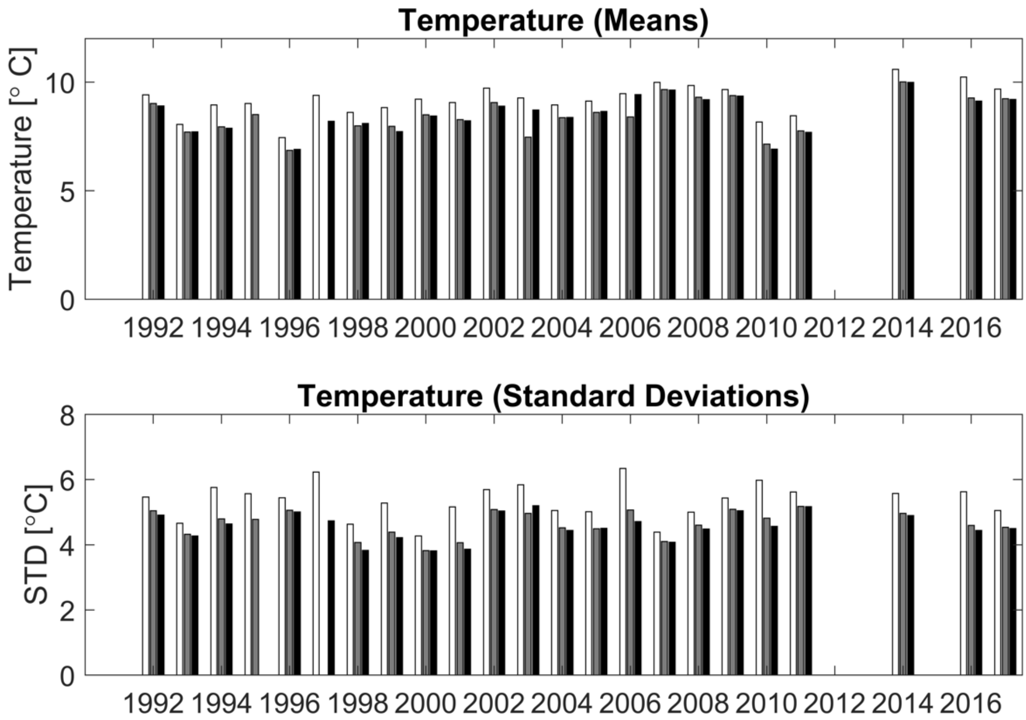


Fig. 9: Mean and standard deviation of water temperature taken over one year in the surface layer (7 m, white bars) and the bottom layer (17 m, grey bars and 19, black bars) at the Darss Sill

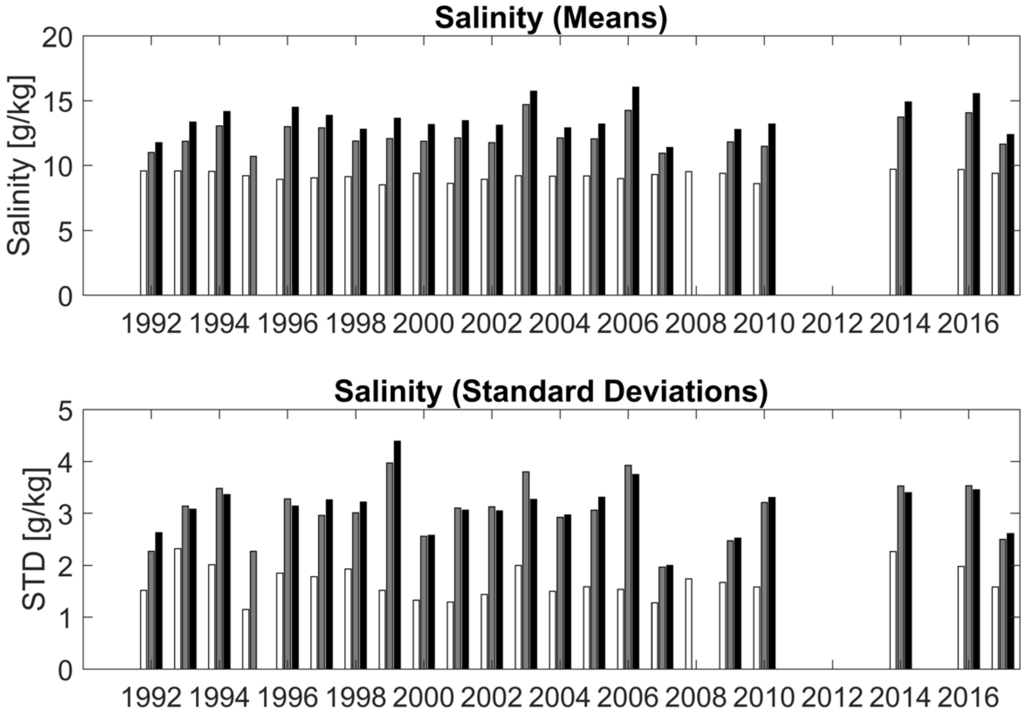


Fig. 10: Mean and standard deviation of salinity taken over one year in the surface layer (7 m, white bars) and the bottom layer (17 m, grey bars and 19, black bars) at the Darss Sill.

3.2 Warming Phase with Moderate Inflow in February

Figure 11 shows the development of water temperature and salinity in 2017 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 12 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 12, using the convention that positive slopes reflect inflow events.

The year 2017 started with high salinity concentrations that can be traced back to a 5-day barotropic inflow pulse observed in the last week of December 2016 (see NAUMANN et al., 2017). During a period of low wind speeds (Figure 5a) and strong pressure-driven outflow (Figure 12) in the second half of January, water levels gradually relaxed back to near-neutral levels until end of the month (Figure 7a), and bottom salinities decreased below 10 g/kg (Figure 11). The water column remained stratified throughout this period until homogenized by strong easterly winds starting with the beginning of February. These winds persisted until mid of February, and reinforced the pressure-driven outflow until water levels had reached a value of 40 cm below zero (the minimum value for this year). This situation formed the starting point for an inflow that, although only of moderate strength, formed the most important event of the year 2017.

With the turning of the winds to south-westerly directions on 15 February, and daily averaged wind speeds increasing up to 15 m/s (with gust above 25 m/s) at the Arkona station (Figure 5a), strong barotropic inflow (Figure 12) was observed during the following two weeks, causing a steady increase of the water levels at Landsort (Figure 7a). After the collapse of the winds in the first week of March, water levels had reached slightly positive values around 10 cm, and approximately 210 m^3 of salty water from the Kattegat had entered the Western Baltic Sea (see chapter 2). During the final stage of this inflow event, the intruding waters were characterized by bottom salinities slightly above 16 g/kg, temperatures around 2.8 °C, and oxygen levels near the saturation point (Figure 13). Waters with higher salinities might have entered via the second inflow pathway through the Öresund, where inflow activity was observed as well (Figure 8). It is worth noting that during this event, on 20 February, also the lowest water temperatures of the year (2.2 and 2.5 °C hourly and daily mean values, respectively) were observed in the surface layer during a winter storm with maximum hourly wind speeds exceeding 15 m/s.

The following weeks until approximately end of April were characterized by sporadic weak inflow pulses, resulting in highly variable salinities (Figure 11) and water levels that fluctuated slightly above the neutral level (Figure 7b). The current measurements (Figure 12) suggest a baroclinic tendency with weak net outflow at the surface and weak inflow near the bottom. The imprint of these inflow pulses can also be identified in the integrated current time series from the Öresund (Figure 8). A period of easterly winds in the first half of May forced a persistent outflow during which bottom salinities dropped towards the values in the surface layer, indicating a well-mixed water column (Figure 11).

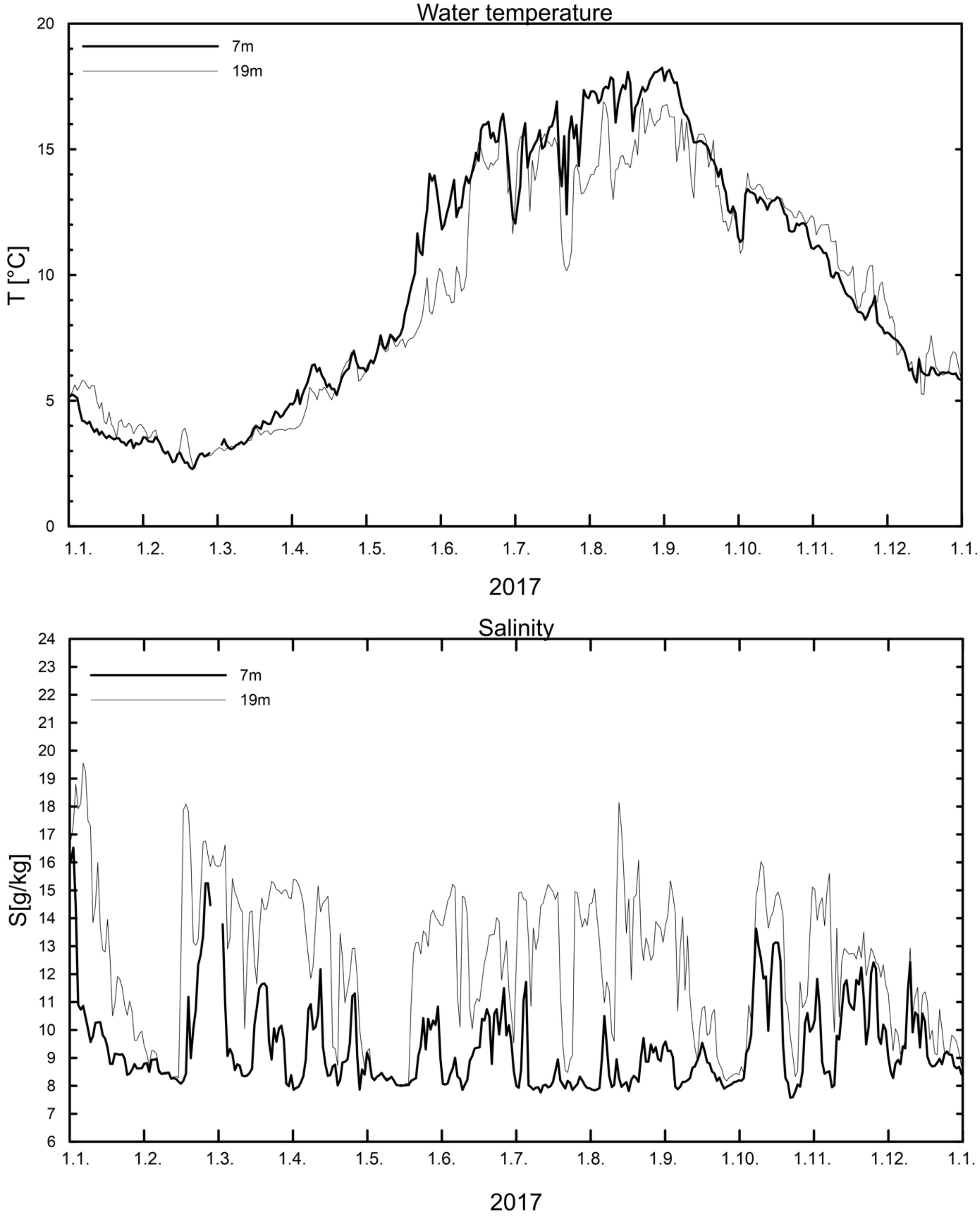


Fig. 11: Water temperature (above) and salinity (below) measured in the surface layer and the near bottom layer at Darss Sill in 2017

At the end of this outflow period, the water levels at Landsort reached a value -0.2 m, which formed the minimum of the spring and summer period (Figure 7a). The oxygen data (Figure 13) show an unusually strong indication of excess production during the spring bloom end of March, paralleled by a drop in the near-bottom oxygen concentrations. The latter is likely related to the sinking of organic material, causing a strong oxygen demand due to remineralization that was only partly compensated by the sporadic small-scale inflows mentioned above.

In the following 6 weeks between mid of May and end of June, winds fluctuated around westerly directions, and current measurements indicate a period of overall weak barotropic inflow, only occasionally interrupted by short outflow episodes (Figure 12). At the end of this period, water levels at Landsort had increased by approximately 40 cm to values around 20 cm above the neutral level (Figure 7a). Although weak, the inflow activity during this period prevented oxygen levels from falling below 70% saturation. As a side effect of the inflow of dense saline waters, the water column quickly restratified around 15 May at the end of the outflow period, and the surface layer decoupled from the deeper layers. Combined with low winds and strong solar heating, this resulted in a rapid heating response of the surface layer with temperatures increasing by more than 7 °C in a timespan of only 2 weeks. It is interesting to note that the near-bottom region showed a similarly strong but delayed temperature increase approximately a month later, when a front of warm and salty waters passed the station during one of the sporadic inflow events described above. This is one example illustrating the type of events that resulted in the overall delayed annual cycle in the deeper layer, as pointed out already in the context of the Fourier analysis in section 3.1 above.

The following summer months until approximately mid of September were characterized by slightly positive and nearly stagnant water levels, except for a short outflow period in the second half of July (Figure 7a). The months of August and September showed an overall weak baroclinic inflow tendency, evident from the spreading of the integrated velocities in the near-surface and near-bottom regions, respectively (Figure 12). Distinct examples of such baroclinic inflow periods in the near-bottom region can be identified from Figure 12 at the end of July and during the second half of August. Similar to other years, these events were generally characterized by low oxygen levels (Figure 13), which can be explained by enhanced (mostly sedimentary) respiration rates in the shallow Danish straits during summer conditions. While strong baroclinic inflows are known for their potential to import significant amounts of oxic waters, none of the summer inflows in 2017 was strong enough to show this effect. It is therefore not surprising that the lowest oxygen concentrations of the year were observed during this period: 28% of the saturation value on 30 July during the weak baroclinic inflow mentioned above, and 27% on 13 August (daily means). As shown below, the effect of the low-oxygen waters from these baroclinic inflow pulses can also be identified in the deep-water properties of the Arkona Basin.

An interesting anomaly in the T-S properties was observed during a 5-day reversal of the winds from westerly to easterly directions between 19 and 25 July. Already a day after the winds turned to easterly directions, the hourly mixed-layer temperatures dropped by 6 °C down to approximately 10 °C (this effect is somewhat less pronounced in the daily averaged values shown in Figure 11). It is likely that during this period, the Darss Sill station was affected by one of the cold upwelling filaments generated in the upwelling region near the island of Hiddensee during periods of westerly winds (hence northward Ekman transport).

Finally, in view of the fact that the year 2017 was characterized as a comparatively warm year (see chapter 2), it is surprising to see that maximum daily mean temperatures in the surface layer were reached late (31 August) compared to other years, and did not exceed the maximum of 18.5 °C (daily mean). The unusually cold month of July might provide an explanation for this.

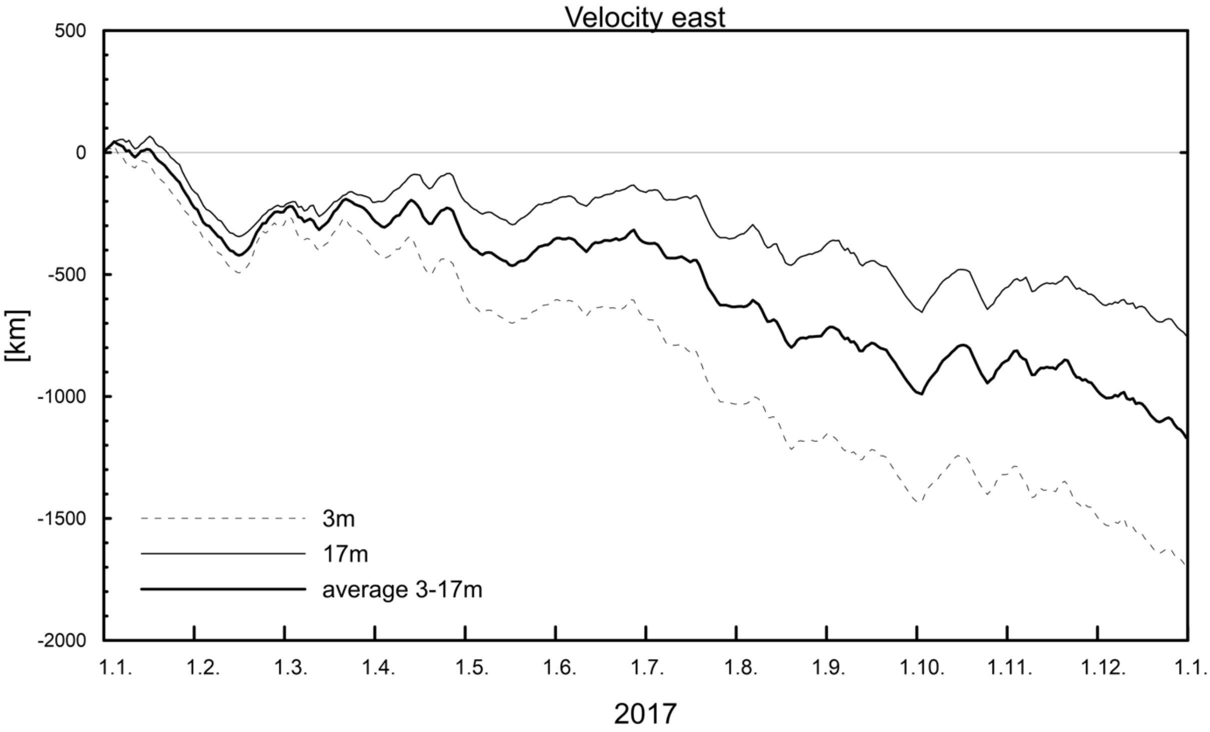


Fig. 12: East component of the progressive vector diagrams of the current in 3 m depth (solid line), the vertical averaged current (thick line) and the current in 17 m depth (dashed line) at the Darss Sill in 2017

3.3 Cooling Phase with Moderate Inflow Event in October

The second important inflow event of the year was pre-conditioned by an outflow period (Figure 12) forced by strong easterly winds in the second half of September (Figure 7b). As winds were weaker and of shorter duration compared to the outflow period in the first half of February, water levels only dropped down to approximately 20 cm below zero (vs. 40 cm in February). Winds turned to south-westerly directions on 02 October, increasing to above 10 m/s (daily mean at Darss Sill) already on the following day, when the ADCP data indicate the beginning of a barotropic inflow (Figure 12) that lasted until mid of the month. With decreasing south-easterly winds, the inflow stopped on 16 October at a water level of slightly above 20 cm (Figure 7a), corresponding to a net volume of approximately 190 km^3 that entered the Baltic Sea during this event (see chapter 2 for a discussion of this estimate). Bottom salinities during this inflow event reached 16 g/kg at temperatures of 13-14 °C (Figure 11) and oxygen levels only slightly below the saturation threshold (Figure 13). The current measurements in the Great Belt show clear indications for inflow also along this alternative pathway, which is usually associated with higher salinities compared to the Darss Sill (Figure 8). It is interesting to note (Figure 11) that this inflow event interrupted the ongoing cooling phase by inducing a sharp temperature increase triggered by the arrival of the warmer inflow waters.

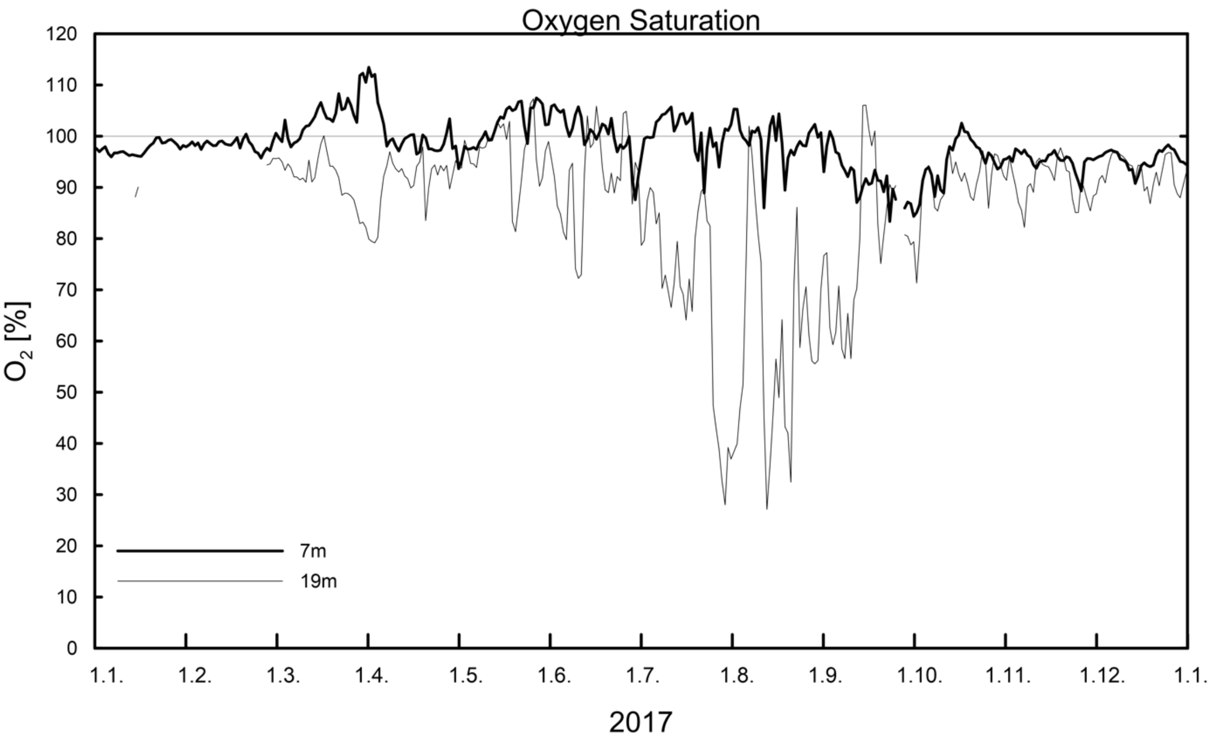


Fig. 13: Oxygen saturation measured in the surface and bottom layer at the Darss Sill in 2017

The following weeks until approximately mid of November were characterized by two smaller inflow events, interrupted by short outflow periods, that resulted in an overall steady increase of the water level at Landsort up to approximately 40 cm above the neutral level (Figure 7a), consistent with the mostly westerly winds during this phase. As a result of the weak but persistent inflow activity, near-bottom oxygen concentrations remained close to the surface values, and not far below the saturation level (Figure 13). In the following period until end of the year, water levels at Landsort fluctuated around 40 cm (Figure 7a), whereas the current measurements indicate weak outflow (Figure 12). This suggests an approximate balance between freshwater runoff and outflow during the final weeks of the year.

Overall, the current measurements at Darss Sill confirm that 2017 was year with particularly small barotropic and baroclinic inflow activity. The spreading of the time-integrated velocities at the surface and bottom layer, which can be interpreted as a measure for the baroclinic inflow activity, was approximately 1000 km in 2017, compared to 1800 km in the previous year (Figure 12). Similarly, the vertical average of the time-integrated velocities measures to which extent the overall outflow due to river run-off and precipitation is compensated by barotropic inflows. In 2017, the time integral of vertical averaged outflow velocity was more than 1000 km (Figure 12), whereas in 2016, only 400 km were observed. This indicates a much stronger overall compensation of the outflow due to run-off by barotropic inflows in 2016.

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. In 2017, the station worked without any technical problems and thus provided complete records of all relevant parameters. 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 analyzed during the regular MARNET maintenance cruises. Figure 14 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 as saturation values as in the previous chapter, are shown in Figure 15.

Similar to the measurements at the Darss Sill, also at station AB the first weeks of the year were characterized by a cooling phase that induced gradually decreasing temperatures in the surface layer. The smallest daily mean temperatures of the year, approximately 2.0 °C, were reached on 08 February (Figure 14), approximately 0.5 °C colder than the minimum temperatures measured 12 days later at the Darss Sill. While the surface temperatures in the Arkona Basin are largely determined by the local atmospheric fluxes, those at the Darss Sill are more strongly affected by lateral advection, which may explain the observed differences.

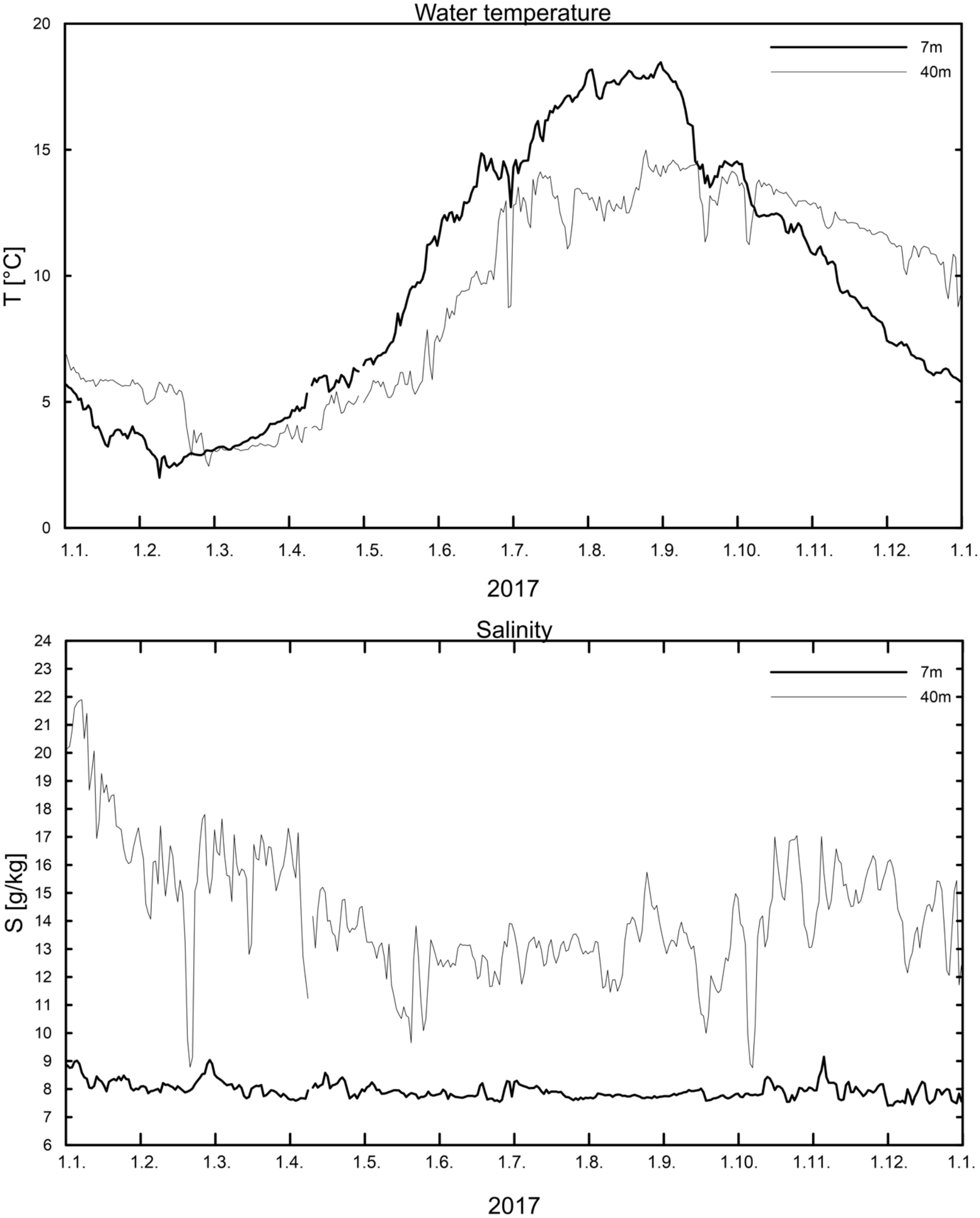


Fig. 14: Water temperature (above) and salinity (below) measured in the surface layer and near bottom layer at the station AB in the Arkona Basin in 2017

During this period, the water mass properties in the bottom layer were determined by the aftermath of a small inflow event that had occurred in the last week of December 2016 (see previous chapter). Nearly stagnant temperatures around 6 °C suggest that the near-bottom region was decoupled from direct atmospheric cooling, whereas the slowly decaying salinities indicate the draining of the bottom pool of salty and dense inflow waters through the Bornholm

Channel (Figure 14). The oxygen demand due to respiration is usually small during this time of the year due to low water temperatures, and oxygen concentrations therefore did not fall below approximately 80% of the saturation threshold (Figure 15).

On 19 February, 4 days after the intermediate-strength inflow described in chapter 3 had been detected at the Darss Sill station, near-bottom salinities in the Arkona Basin exhibited a rapid drop down to values below 9 g/kg, followed by a quick relaxation and a further increase to values above 18 g/kg (Figure 14). During this event, also the bottom temperatures dropped, but remained low around 3.5 °C. This peculiar evolution of the near-bottom water mass properties can be understood from a combination of reversible downwelling on the southern slope of the Arkona Basin, and the arrival of the cold and salt inflow waters from the Darss Sill. Around 18 February, winds had turned to south-westerly directions, and gradually increased in strength until they reached hourly mean values of 17 m/s on 20 February, almost exactly from East (the daily mean wind speed for this day was 14 m/s). The Ekman transport, directed southward under these conditions, resulted in a depression of the halocline that was strong enough to replace the salty bottom pool with the relatively fresh and cool surface-layer waters at the AB station. With decaying winds on the late afternoon of 21 February the halocline relaxed back to its original position, approximately at the same time when the salty and cold inflow waters from the Darss Sill arrived at the station: near-bottom salinities strongly increased but temperatures stayed low (Figure 14). As oxygen concentrations were high throughout the water column already before this event, the inflow water did not leave a significant imprint on the deep-water oxygen budget (Figure 15).

As described in chapter 3, the following weeks until approximately mid of May were characterized by smaller inflow pulses at the Darss Sill, with high oxygen concentrations and gradually increasing temperatures, followed by a two-week outflow period. Figures 14 and 15 show that these pulses were not sufficient to completely maintain constant salinity and oxygen levels in the bottom layer. They did, however, prevent salinities from sinking below 13 g/kg and oxygen levels below 70% saturation. The gradual increase in temperature during this period mirrors the heat supply by these inflow pulses that were characterized by steadily increasing temperatures at the Darss Sill (Figure 11). The clearest signal of the outflow period in the first half of May (Figure 12) can be identified in the quickly decaying near-bottom salinities.

Also in the following summer months, bottom salinities remained stable between 12 and 14 g/kg as a result of a series of smaller inflows. The arrival of these inflow pulses is most clearly seen in a stepwise increase in the near-bottom temperatures. One distinct example is the strong increase in near-bottom temperatures in the last week of June (Figure 14) that can be traced back to the arrival of warm inflow waters passing the Darss Sill after 13 June (as evident from the temperature jump in Figure 11). The near-bottom oxygen concentrations generally remained above 60% of the saturation value during this period.

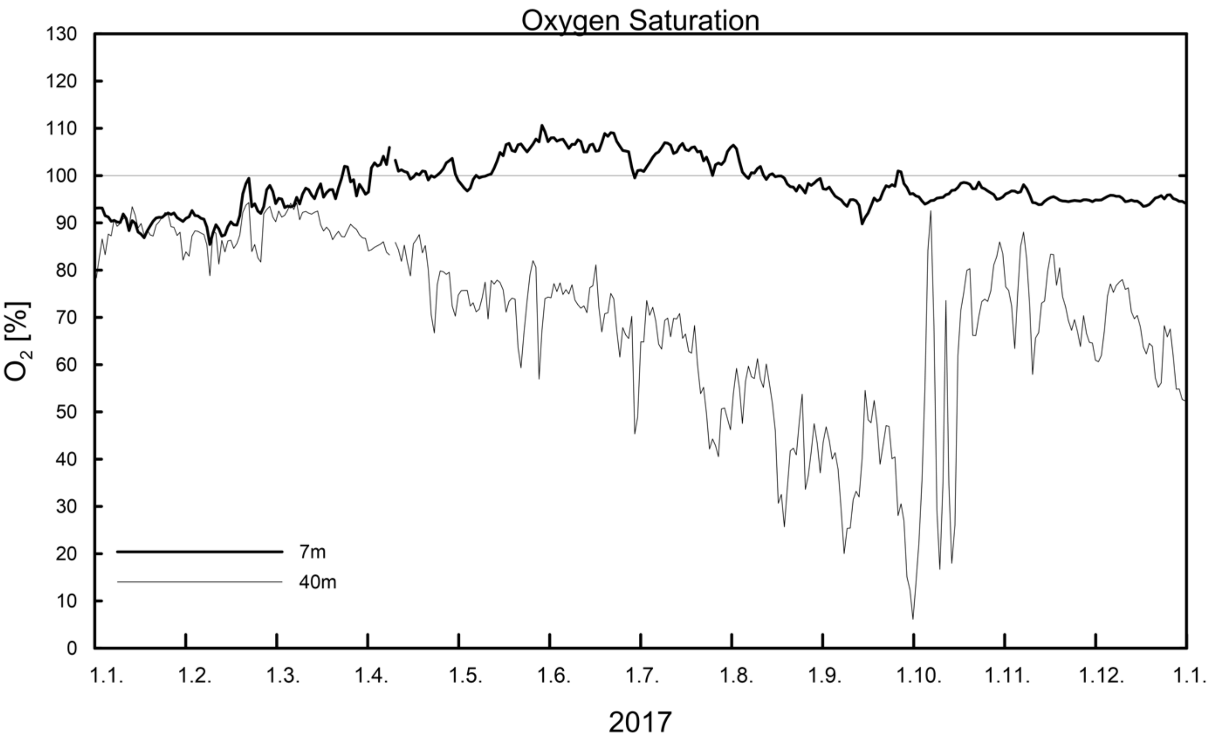


Fig. 15: Oxygen saturation measured in the surface and bottom layer at the station AB in the Arkona Basin in 2017

The situation changed qualitatively starting from the second half of July, when a series of outflow periods and inflows with a baroclinic tendency characterized the hydrodynamic situation at the Darss Sill (Figure 12). Bottom temperatures nearly stagnated, salinities strongly fluctuated and oxygen concentrations showed alternating patterns of rapid collapse followed by a gradual, incomplete recovery, respectively (Figures 14 and 15). The former mirror the arrival of low-oxygen baroclinic inflow waters that are also clearly evident, with a time shift of a few weeks, in corresponding oxygen minima at the Darss Sill. The arrival of the final pulse of these low-oxygen waters end of September induces the lowest oxygen concentrations of the year in the Arkona Basin. On 01 October, a daily mean of only 6% of the saturation value was found, and the minimum hourly values were as small as 2%. These nearly anoxic conditions in the deepest layers of the Arkona Basin are the combined result of the overall small inflow activity of the year 2017, and the low-oxygen baroclinic intrusions.

Figure 15 shows that the oxygen minimum at the beginning of October with concentrations close to zero was only of short duration: already by 07 October, oxygen concentrations above 90% were observed. This rapid increase should, however, not be misinterpreted as the result of the arrival of first inflow waters from the barotropic inflow event that started on 03 October at the Darss Sill (see chapter 3). The suspicious drop in salinity (Figure 14), perfectly correlated with the peak in oxygen concentrations around 07 October (Figure 15), suggests that a temporary downwelling of the halocline, rather than any inflow activity, explains the observed temporal variability. This is consistent with the meteorological observations at the Arkona station, showing that strong winds (up to 18 m/s) from westerly directions in the days before this event caused a southward Ekman transport, and thus a downwelling of oxygenated surface-layer waters across the southern slope of the Arkona Basin.

Conclusive evidence for the arrival of the October inflow cannot be found before mid of October, when salinities (Figure 14) show a clear increase up to values around 17 g/kg, and oxygen concentrations stabilize around 70-90% of the saturation threshold (Figure 15). As described in chapter 3, the following weeks until end of the year were characterized by a number of additional, small inflow events that, however, could not fully compensate the local oxygen consumption in the Arkona Basin and the drainage of the near-bottom pool of salty waters through the Bornholm Channel. As a result, both salinity and oxygen showed a mild decline until end of December. Oxygen concentrations remained, however, above 50% saturation.

The maximum daily mean temperature was 18.5 °C (also the hourly mean value remained below 19 °C), observed on 31 August in the surface layer of Arkona Basin. This temperature corresponds exactly to the maximum temperature at the station Darss Sill, measured on the same day. After this date, surface layer temperatures showed a rapid decline due to the cold and windy weather conditions beginning of September, quickly recovered in the second half of September, and then gradually dropped down to approximately 6 °C at the end of the year.

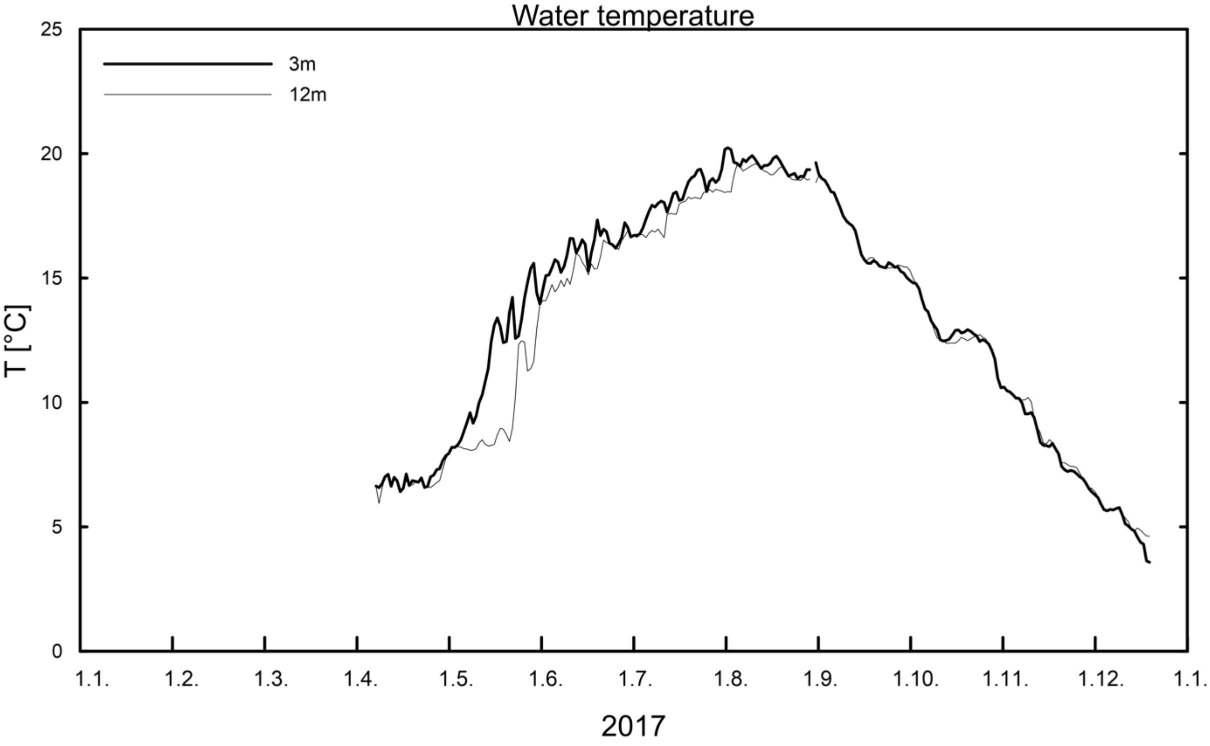
5. Observations at the Buoy "Oder Bank"

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 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 08 April 2017, approximately three weeks later compared to the previous year. Starting from that date, the station provided continuous time series of all parameters until 19 December, when it was again demobilized to avoid damage from floating ice.

Temperatures and salinity levels at OB are plotted in Figure 16; associated oxygen readings are shown in Figure 17. Similar to the other MARNET stations, the maximum temperatures that were reached during the summer period were slightly smaller compared to the previous year, and 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 2017, the maximum daily mean temperatures in the surface layer exceeded the threshold of 20 °C only during a 3-day period in the first week of August. The maximum hourly mean temperature, reached on 01 August, was 21.1 °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 11 and 14), which reflects the shallower and more protected location of this station.

There is also a dynamical reason for the stronger warming of the surface layer at station OB, related to the suppression of vertical mixing due to the transport of less saline (i.e., less dense) 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 a result of the reduced vertical mixing of oxygen.



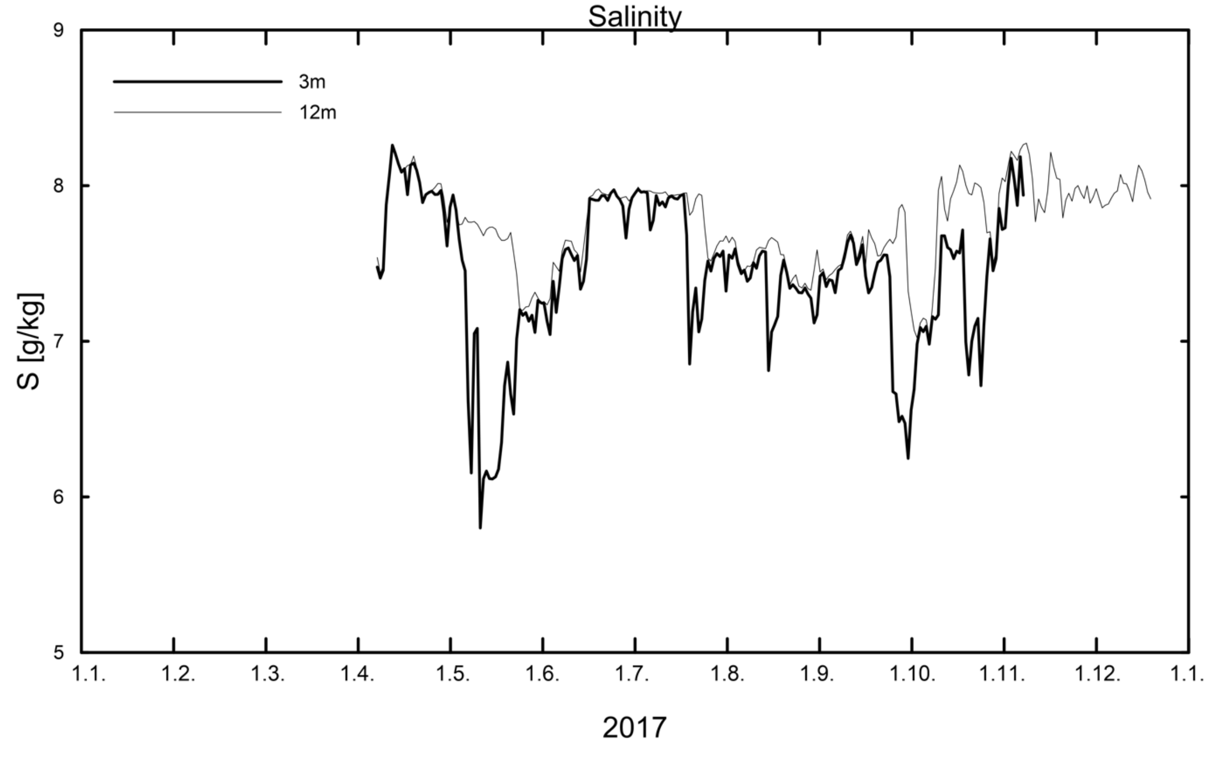


Fig. 16: Water temperature (above) and salinity (below) measured in the surface layer and near bottom layer at the station OB in the Pomeranian Bight in 2017

Presumably, due to the relatively cold summer conditions, events of this type were observed only rarely in 2017. The most notable event occurred in May, when decaying winds resulted in a collapse of surface layer turbulence. As an immediate consequence, pronounced saline stratification was observed starting from 05 May, decoupling the thin brackish surface layer from the cooler and saltier deeper layers (Figure 16). A strong positive heat flux observed in the meteorological record during this period was reflected in a rapid warming of the surface layer, while the decoupled bottom layer showed nearly stagnant temperatures. Shortly before the end of this event, maximum differences between surface and bottom waters of up to 4 °C were observed. Strong winds exceeding 10 m/s during a short wind pulse on 24 May, and a longer windy period starting around 31 May, mixed the water column, and hence terminated this event by end of the month.

Three similar events of this type were observed during the summer months in July, August and end of September; however, none of these was comparable in duration and strength to the event in May. Compared to previous years, all of the stratification events found in 2017 were exceptionally weak, thus mirroring the cool and windy summer conditions.

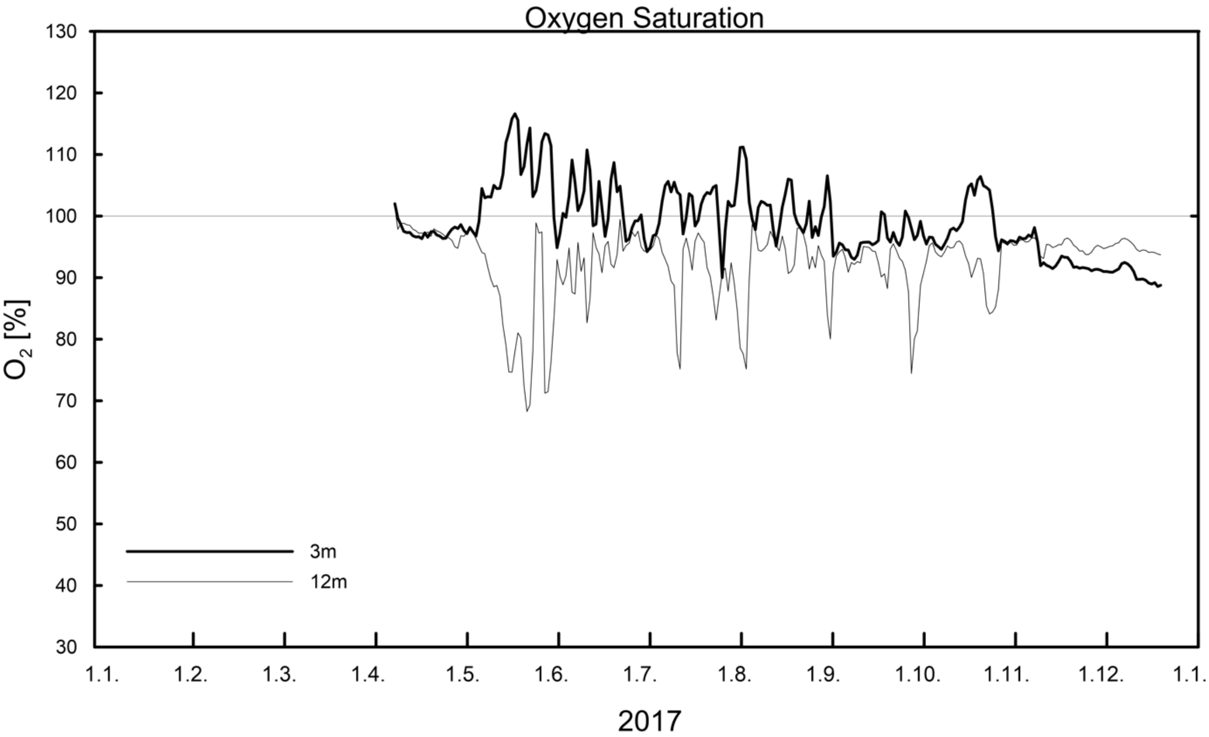


Fig. 17: Oxygen saturation measured in the surface and bottom layer at the station OB in the Pomeranian Bight in 2017

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 decoupling 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 17, showing oxygen concentrations at depths of 3 m and 12 m. For all stratification events, a distinct 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 the oxygen demand from remineralization, respectively.

Lowest near-bottom oxygen concentrations (see Figure 17) in 2017 were observed during the May event described above, with hourly saturation values as low as 63% (23 May). The other, less pronounced, stratification events during the summer period resulted in minimum oxygen saturations of 70% (11 July), 69% (03 August) and 71% (27 September). While the latter event was the strongest of these three secondary events in terms of duration and saline stratification (Figure 16), minimum saturation values were almost identical to the preceding events. This reflects the impact of decreasing temperatures on the respiration rates during the beginning of the fall period, which, in this case, almost exactly compensates the longer duration of the September event.

For the same reason, minima in near-surface salinity observed during the following fall and winter period (one event of this type can be identified in October, Figure 16), these occurrences did not leave an 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. In summary, the minimum near-bottom oxygen minima during the summer months were less pronounced compared to the previous year, and much less evident compared to the anoxic conditions observed during the record-breaking year 2010 (NAUSCH et al. 2011a).

Finally, it is worth noting that 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 17). Highest near-surface oxygen concentrations approximately 20% above the saturation level were found during the event in May, which is comparable to the concentrations found at the same time in the previous year. In addition, the lagoon water is known to export high nutrient concentrations towards the station. 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 points 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 2017 derived from Satellite Data

The development of Sea Surface Temperature (SST) of the Baltic Sea in 2017 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 NAUMANN et al. 2017 and in HELCOM Environment Fact Sheets (SIEGEL & GERTH, 2017). 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 2017 was the eleventh-warmest year since 1990 and with 0.24 K slightly above the long-term SST average. March, April and October - December contributed to the average by their positive anomalies. July and August were characterized by negative anomalies. The anomalies reached maximum values of +2 K and -3 K. The winter of 2016/2017 was comparatively warm, as shown in the cold sum of air temperature of Warnemünde but also in the SST. The coldest month was February, the coldest day the 14 February with 0-3 °C, and the day of maximum ice coverage the 12 February. The warming in spring followed the long-term average. Low wind periods after 10 - 15 May and warm air masses from the Atlantic Ocean supported the SST increase and first development of cyanobacteria confirmed by sampling during a monitoring cruise. The warmest day was in the period 31 July – 2 August. Daily mean temperatures of more than 20 °C were rarely achieved. A stable summer- situation started 28 July and lasted until beginning of September with SST's of 18-20 °C in the southern and western Baltic before the annual cooling started and steadily continued until the end of the year.

Cold and heat sums of air temperature of Warnemünde (Table 2, Chapter 2) deliver information about the severity of winter and the course of summer. The winter 2016/17 was with a cold sum of 31.7 K d below the long-term average (102.4 K d), which means the 15^{th} warmest winter since 1948. February contributed with 20.2 K d mainly to this value (Average 30.6 K d). The heat sum of the summer (159.5 K d) exceeded the long-term average (153.4 K d) only slightly and was the 28^{th} warmest summer since 1948. May, June and August exceeded the long-term means and contributed to the summer value.

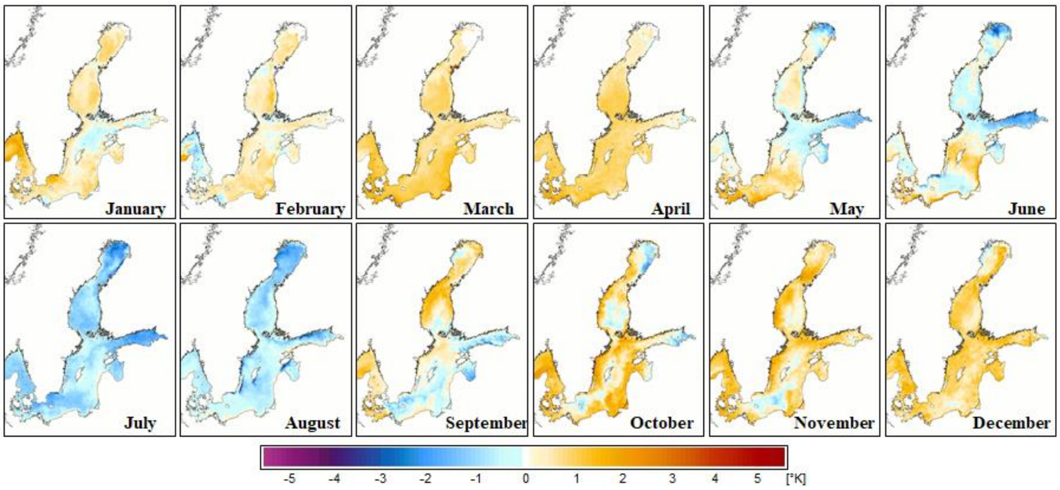


Fig. 18: Anomalies of the monthly mean sea surface temperature of the Baltic Sea in 2017 referring to the long-term means (1990-2017)

Anomalies of monthly mean SST for the entire Baltic Sea in Fig. 18 referring to the long-term means (1990-2017) are the basis for the discussion of overall thermal development in 2017. The seasonal development of monthly mean temperatures in the central areas of the Arkona, Gotland, and Bothnian Seas are presented in Fig. 19 in comparison to the long-term monthly means (1990-2017). Daily and weekly mean SSTs were the basis for the detailed description of temperature development.

In January and February 2017, the surface water of the Baltic was characterised by SSTs in the range of the long-term averages with only slight positive and negative anomalies less than ±1 K. In March and April, the anomalies increased to about +1 to +2 K before it reduces again in May to the long-term mean value except in the western Baltic with slight positive anomalies and in the Gulf of Finland with slight negative values. Despite the positive anomalies in air temperature in May and June, the warming of the surface water of the central basins of the Baltic took place as in the long-term mean. In July and August, the monthly mean SST was mostly below the long-term averages leading to negative anomalies with maximum values of up to -3 K in the northern Bothnian Bay and along the Finnish coast in the Gulf of Finland. Cold water patches starting from the western and northern coasts are initiated by upwelling during westerly winds. These negative anomalies in the monthly averages reflect unusual westerly winds in these months. The months September to December are characterised by positive anomalies particularly along the coasts, which reflect the absence of typical east or west wind situations and corresponding upwelling. The annual cycles of the Arkona Sea AS, Gotland Sea GS and Bothnian Sea BoS in Fig. 19 show that February was the coldest month in all regions. The winter was warmer than in average but the summer was colder particularly July in the western Baltic and July and August in the Bothnian Sea. August was the warmest month in all regions. In autumn, all regions followed the long-term averages.

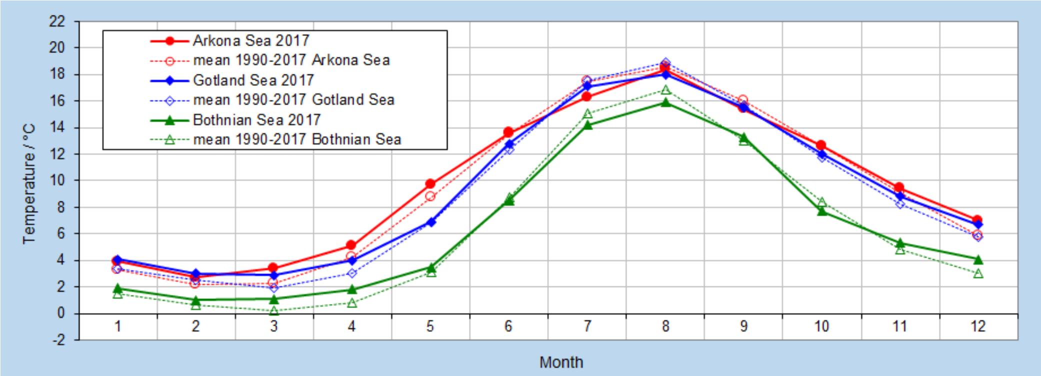


Fig. 19: Seasonal cycle of SST in the central Arkona-, Gotland- and Bothnian Sea in 2017 in comparison to the mean values (1990-2017)

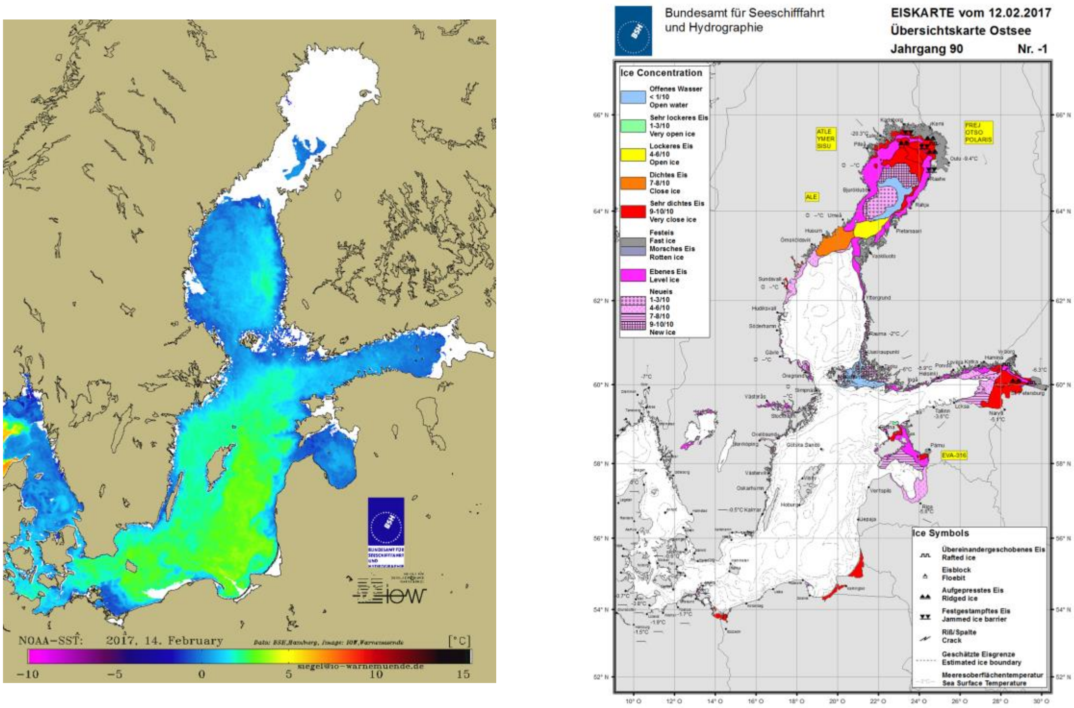


Fig. 20: Daily mean SST of the Baltic Sea on 14 February, the coldest day, and maximum ice coverage in the winter 2016/2017 on 12 February (Schwegmann, Holfort, 2017)

Beginning of 2017, the typical cooling took place that the monthly mean values stayed slight above the long-term mean values leading to 0-3 °C in the western and up to 5 °C in the central Baltic Sea end of January. The cooling occurred in the entire Baltic but particularly in the Belt Sea and in the western parts.

Cooling continued in the first half of February that 14 February became the coldest day of the year (Fig. 20, left image) with 0 °C in the shallow Pomeranian Bight, 0-2 °C in the western and northern Baltic, and up to 4 °C in the central Gotland Sea. The maximum ice coverage (Fig. 20, right image) was reached around 12 February (Schwegmann, Holfort 2017). The winter 2016/2017 belonged to the weak ice winters. Until end of February, the SST increased again to 2-4 °C particularly in the western and central parts.

In the first decade of March, the weather was rather variable, which prevented the SST from rising. The warming continued in the second half of March from the western part due to warm air masses coming from the Atlantic to the Baltic region. In Kattegat, Mecklenburg Bight and Pomeranian Bight up to 5-6 °C were observed. The transect of mean monthly mean SST through the entire Baltic in March is presented in relation to long-term average (1990-2017), previous year, and the variation range in Fig. 21 (upper panel) reflecting the impression from Fig. 18. SST of entire Baltic is higher than the long-term average except the northern most part.

April was characterised by phases of clear weather with high solar radiation particularly in the southern and central Baltic Sea. This led to SST between 3-5°C in the northern Gotland Sea and 7-9°C in the western Baltic Sea, which contributed to the positive anomalies in the monthly averages.

In May, mild air masses from the Atlantic Ocean raise air temperatures in the Baltic Sea region starting around 10-15 May, which influenced also the water temperature. Low wind periods supported the warming of the surface water in the western and southern Baltic Sea also partly in the eastern Gotland Sea. Around 20 May and thereafter, SSTs of 13-16 °C are partly reached in these regions. The second half of May contributed to the positive anomalies in the southern and western Baltic Sea (Fig. 21 lower panel).

After stagnation during deep pressure influence in the first decade of June a warming phase followed in the entire Baltic with maximum SSTs of 17-20 °C on 19 June in the western part. Wind mixing reduced the SST again to mainly 13-16 °C in the central and western Baltic and to 10-13 °C in the northern parts, which lasted until end of the month.

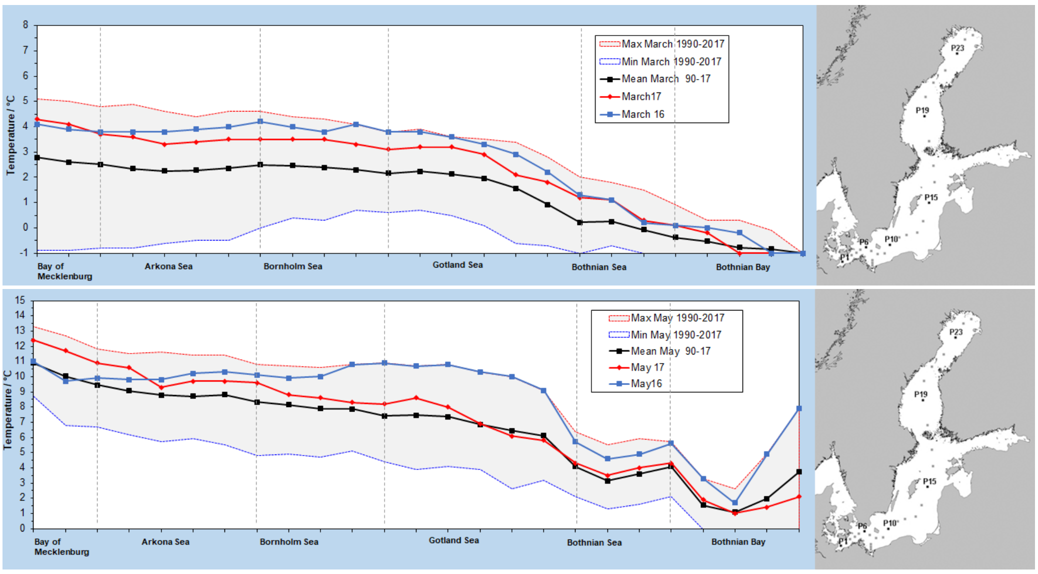


Fig. 21: Monthly mean temperature distribution along the transect through the central basins of the Baltic Sea in March and in May 2017 in comparison to the previous year, the long-term mean value of 1990-2017 and the variation range

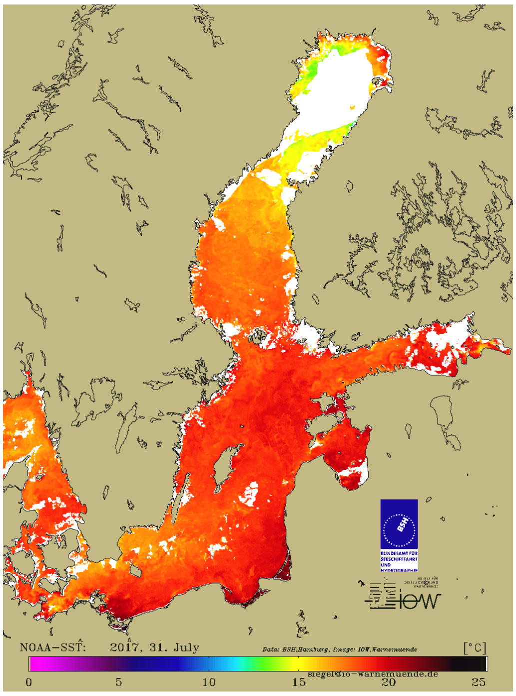


Fig. 22: SST distribution of the Baltic Sea on July 31, the warmest day of year 2017.

Beginning of July a stagnation period took place. The SST stayed rather similar in the entire Baltic except in Bothnian Bay where the SST was reduced to 8-11 °C on 6 July. After that, a continuous warming was observed until 15 July with 16-19 °C except the Gulfs of Bothnia and Finland with 12-16°C. The following days the warming occurred more in the northern Baltic with the highest SST on 27-28 July of 16-18 °C, which reduce again until the end of the month. In the other parts, 31 July was the warmest day with 17-20°C (Fig. 22).

This situation continued in the entire August. Around 15 August westerly wind induced upwelling in the Bothnian Bay reducing the SST to 9-14 °C until the end of the month.

The SST distribution along the transect through the central basins of the Baltic Sea in July and August shows the particularities in 2017 in comparison to the previous year, the long-term mean value of 1990-2017 and the variation range. In July, the SST was below the averages in the entire Baltic with highest deviations in the northern parts. In August, differences occurred only in the north.

In the first half of September, low-pressure systems with strong westerly winds crossed the Baltic Sea region, induced wind mixing and reduced the SST until about 15 September. After that, stagnation occurred until the end of the month (13-16 °C in Baltic proper and 9-13 °C in the northern gulfs).

From about 5 October, the next period of low-pressure systems with changing wind and cloudy conditions accelerated cooling. After a short stagnation mid-October the cooling continued until the end of the month leading to SSTs of 4-8 °C in the Gulf of Bothnia, 8-12 °C in the central and 10-13 °C the western part.

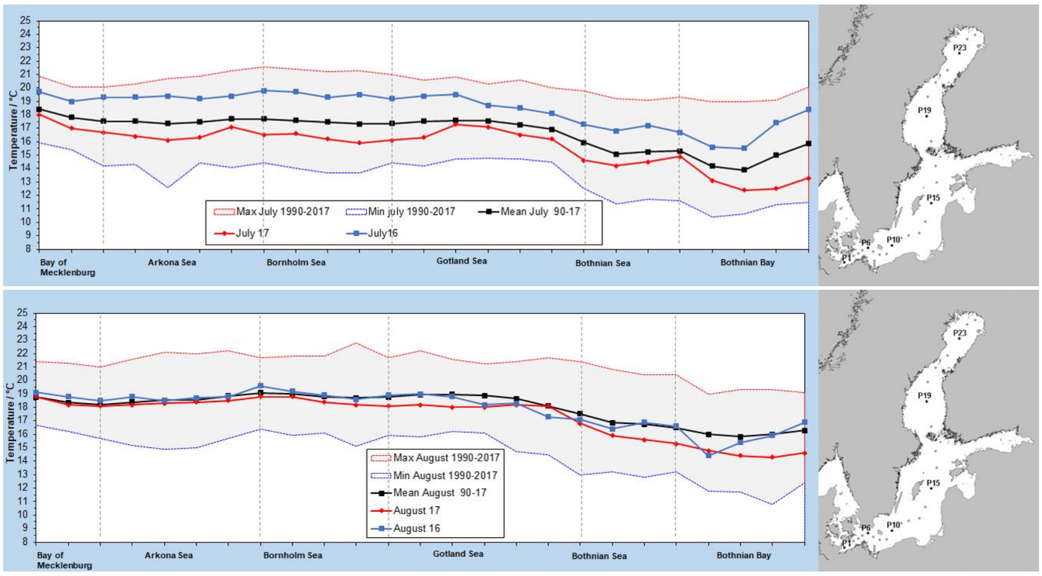


Fig. 23: Temperature distribution along the transect through the central basins of the Baltic Sea in July and August 2017 in comparison to the previous year, the long-term mean value of 1990-2017 and the variation range

The cooling continued in November particularly in the northern and western Baltic that end of the month temperatures of 0-5 °C occurred in Gulf of Bothnia and 6-9 °C from Western Baltic to the Gotland Sea.
In December, the SST decreased very slowly that 0-3 °C were observed in Gulf of Bothnia and 3-6 °C in the southern Baltic. Therefore, December was to warm compared to the long-term averages particularly in coastal regions of the entire Baltic Sea.

Overall, 2017 was in the SST of the Baltic not as warm as in global air temperature but the eleventh warmest year of the last 28 years since 1990 (Fig. 24). The annual temperature average throughout the Baltic Sea was about 0.3 K higher than the long-term average. The months March, April and Oct - December contributed by their positive anomalies.

Fig. 24: Anomalies of the annual mean sea surface temperature of the entire Baltic Sea during the last 28 years (1990-2017)

6.1.2 Vertical Distribution of Water Temperature

The routine monitoring cruises carried out by IOW provide the basic data for the assessments of hydrographic conditions in the western and central Baltic Sea. In 2017, monitoring cruises were performed in 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 Sweden's 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 leads to deeper mixing of the upper layer.
In the central Baltic, the development of vertical temperature distribution above the halocline follows with some delay the annual cycle of atmospheric temperature (cf. chapter 2). The winter of 2016/2017 was unusually mild, except the January with averaged temperature close to the long-term mean. This is reflected by the very small ice coverage of only 104 000km^2. From February to June 2017, temperatures clearly exceeded the long-term means (cf. chapter 2), similar to the year 2016. 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 air temperatures well above the long-term mean. From July to September the temperatures were below or close to the long-term mean. Whereas from October to December 2017 the air temperature was higher than the climatological mean.
The deep-water conditions in the central Baltic in 2017 were mainly controlled by the extreme Christmas MBI of December 2014 Baltic (MOHRHOLZ et al., 2015), and the subsequent minor inflow events in 2015 to 2017. The most recent barotropic inflow events were observed in November and December 2016, and in February 2017.

At the beginning of February 2017 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 (compare chapter 2), surface temperatures decreased in the shallow areas of the Mecklenburg Bight to values about 2.5 to 3.0 °C. Surface temperatures in the western part of Arkona Sea were below that. The minimum SST was observed at station 104 with 2.1 °C. Except on this station, the surface temperatures were 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 70 m, and reached the permanent halocline starting at the same depth. With 3.6 °C, the upper layer temperature at station TF271 exceeded the temperature of the density maximum by 0.8 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 between 3.0 and 3.6 °C were above the long-term average, but well below the extreme warm temperatures in February 2016. The situation was comparable with February 2015. Towards the northern Gotland Basin the SST was slightly decreasing. At the northernmost station near 59°N the sea surface temperature was about 2.1 °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 December 2016 dominated the bottom temperature distribution in the Arkona and the Bornholm Basin. Waters of the inflow covered a 15m thick bottom layer in the centre of the Arkona Basin, with a bottom temperature of 6.2 °C. Baroclinic late summer inflows and the moderate inflow in November 2016 have flushed the halocline of the Bornholm Basin with warm water. Till February 2017 this water was mixed up with ambient cooler water in the western and central Bornholm Basin. The majority of this inflow water was shifted eastward and filled the eastern part of the halocline in the Bornholm Basin and the entire deep layer of the Slupsk Furrow. It was characterised by temperature above 8 °C, with maximum value of about 9.5 °C in the Slupsk Furrow. The deep layers of the Bornholm Basin were covered by the cooler and high saline waters from the December inflow 2016. Here the bottom temperature was about 7 °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 warmer inflows of the recent years. The bottom temperature at station TF 0271 was at 7.2 °C, about 0.6 K below the value observed in February 2016. The Bottom water temperature in the Farö Deep of 6.7 °C was significantly lower. It compares to the temperature in the eastern Gotland Basin at 120 m, which is the sill depth between both locations.

The surface temperatures observed during the monitoring cruise in March were still comparable with the situation in February. As a result of the warm than normal air temperatures in February and March 2017, the surface temperature of the western Baltic was well above the temperature of density maximum. In the central Baltic Sea the SST remained closed to the level of early February. Only in the northern part of the Baltic transect the SST was decreased by about 0.5 K since the previous cruise. The maximum temperature of 3.8 °C was observed in the Fehmarn Belt. Other areas of the western and central Baltic Sea depicted similar surface temperatures of 3.5 °C in the Arkona Basin, 3.6 °C in the Bornholm Basin, and 3.3 °C in the eastern Gotland Basin. The minimum SST of 2.3 °C was observed in the northern Gotland Basin. Although the temperatures in the western and central Baltic clearly exceeded those of the density maximum the onset of seasonal warming temperature stratification in the surface layer has not started at that time.

In the second half of February 2017 a moderate barotropic inflow imported about 68 km³ of cold, saline water into the Baltic. This inflow water replaced the former bottom water in the Arkona Basin. The temperature of this water body ranged between 3.0 and 3.2 °C, and was slightly cooler than the surface layer. Partly the saline water of this inflow event has passed the Bornholm Gat and was spreading into the halocline in the north western Bornholm Basin. The temperature distribution in the deep and water of the Bornholm Basin depict a patchy structure. The warm water patches from the November 2016 inflow were mixed up with cooler water from the inflow in December 2016. The temperature in the halocline in March depicted a high variability in a range between 4.2 and 8.6 °C. The bottom water temperature in the Bornholm basin of 6.95 °C remained at the value observed in February. The warm water in the deep-water layer of the Slupsk Furrow has cooled due to mixing with cool inflow water from December 2016. Partly the former deep waters from the Slupsk Furrow have reached the eastern Gotland basin as a series of warm water patches spreading northward. According to its density the water will be sandwiched in the upper deep water of the eastern Gotland Basin. The vertical excursions of isotherm in the halocline layer of the eastern Gotland basin indicate the active inflow process. The bottom temperature at station TF 0271 (Gotland Deep) and in the Farö Deep did not changed significantly were at 7.14 °C and 6.7 °C respectively.

Between March and May, the surface water of Baltic warmed noticeably due to increasing air temperatures and solar radiation. Surface temperatures ranged between 8.7 °C in the Kiel Bight, 7.0 °C in the Arkona Basin, 6.1 °C in the Bornholm Basin, and 5.7 °C in the eastern Gotland Basin. Thus, the SST was about 2.5 to 3.0 K lower than in the extremely warm May 2016. In the western Baltic the seasonal thermal stratification was well pronounced. East of the Bornholm Basin the vertical temperature gradient was weaker, and the thermocline was at unusual deep layers. Thus, the winter water layer was thinner than in previous years, except in the norther Gotland Basin. Compared to the climatological value the intermediate layer was extremely warm. 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 4.0 °C in May 2017. It was slightly warmer (+0.2 K) than in the previous year. Only in the northern Gotland Basin, where the March SST were close to the temperature of density maximum, the winter water temperatures were lower but with about 3 °C still warmer than average.

In the halocline of the Bornholm Basin the warmer water body of was mixed up completely with the cold inflow water from the February 2017 inflow. Here the temperature was about 4 °C. The bottom water temperature of 6.93 °C in the Bornholm Basin remained at the level from March 2017. In the Slupsk Furrow the former deep water was replaced by a mixture of former Bornholm Basin halocline water and cold water from the February inflow. Compared to March the bottom temperature was decreased by 1.2 K to 6.43 °C in the Slupsk Furrow. Parts of this cool water have passed the eastern sill of the Slupsk Furrow and spreads northward. The warm water patches observed north of the Slupsk Furrow in March have reached the eastern Gotland basin. Here it reached the deep layers between to 150 and 210 m. However, the bottom layer temperatures were not changed and remained at 7.14 °C.

By the mid of August 2017, typical summer thermal stratification had become established throughout the Baltic Sea. The seasonal thermocline lay at depths between 20 m and 30 m, and separated the strongly warmed layer of surface water from the cool winter intermediate water. In minimum temperatures in the intermediate water was about 4.0 °C in the eastern Gotland Basin, and 3.5 °C in the northern Gotland Basin, which was slightly below the value of 2016. In the Bornholm Basin the winter water was nearly vanished, and replaced by a mixture of old and new inflow waters. Only in the eastern part few remains of the winter water were identifiable above the halocline with temperatures of below 5.0 °C.

The surface temperatures in spring were well above the long-term mean, and also the May and June 2017 were 1.1 K warmer than the long term average. However, since the July was comparable

cold and wet the sea surface temperatures in the western and central Baltic Sea were on a normal range between 17 °C about 19 °C. At station TF213 in the Bornholm Basin 17.7 °C was recorded on 15 August, and 17.6 °C was recorded at station TF271 in the eastern Gotland Basin. Generally, the SST was 1.0 to 1.5 K below the values of the previous year.
A calm period in the end of July favoured baroclinic inflow conditions at the Darss Sill. Warm saline water from the Kattegat entered the Baltic via the Belt Sea and formed a 10 to 15 m thick warm bottom layer in the western Arkona Basin. Here, bottom temperatures up to 16.3 °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 60 m. The core temperature of this layer was about 10.5 °C.
The cold inflow water from the February inflow has completely replaced the deep water in the Slupsk Furrow. Here bottom temperatures were about 5.6 °C. The major part of this inflow water has passed the eastern sill of the Slupsk Furrow and spreads into the halocline layer of the eastern Gotland Basin, visible as cold patch at the entrance of the basin. The bottom temperature in the eastern Gotland Basin decreased slightly to 6.95 °C.

The temperature distribution in mid of November 2017 revealed ongoing autumnal erosion of the thermocline in the surface layer. Since the months October and November depicted a high positive air temperature anomaly also the SST observed in November 2017 was higher than usual. The surface layer has deepened, extending to a depth of 35 m in the western Baltic and to 45 m depth in the eastern Gotland Basin. In the Arkona Basin surface temperature of 9.2 °C was observed. Towards the Bornholm Basin it decreases slightly to 8.5 °C (station TF213). In the Slupsk Furrow an SST of 8.8 °C was detected. Further to the eastern Gotland Basin and the Farö deep a decreasing surface temperature was found, except of a warm water body in the southern part of the eastern Gotland Basin were the SST reached 10 °C. The central station TF271 and the Faro Deep depicted surface temperatures of 8.5 °C and 7.6 °C respectively. The deepening of thermocline reduced the vertical extent of the intermediate winter water layer in the central Baltic to layer of 20 m to 35 m thickness, with minimum temperatures of 4.9 °C (station TF286). No layer of winter intermediate water was present in the Bornholm Basin and the western part of Slupsk Furrow.
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 12.4 °C was observed. 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. The density of the inflowing water was too low to replace the cooler bottom water in the Bornholm basin. At the time of the cruise 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.

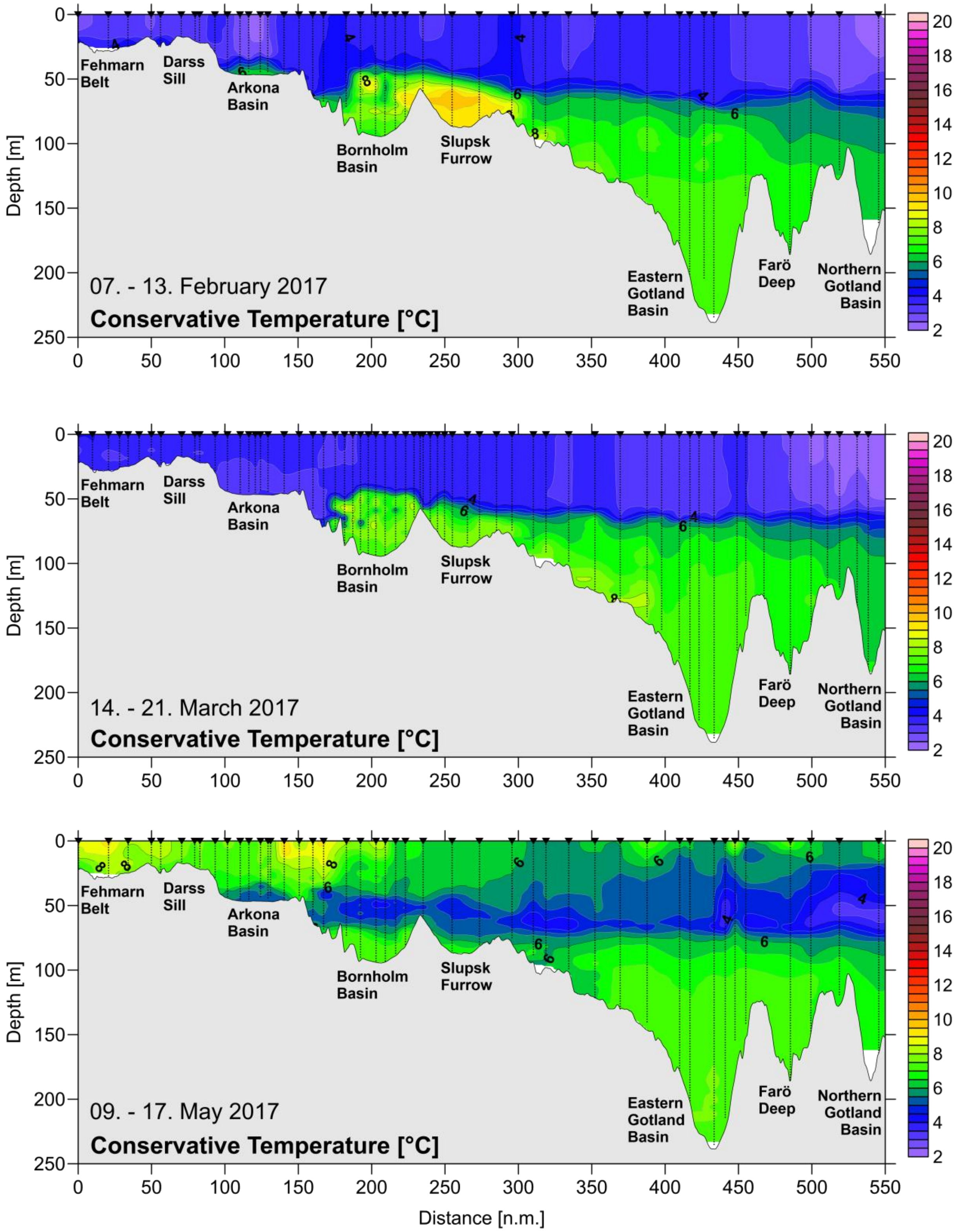


Fig. 25: Temperature distribution along the talweg transect through the Baltic Sea between Darss Sill and northern Gotland Basin

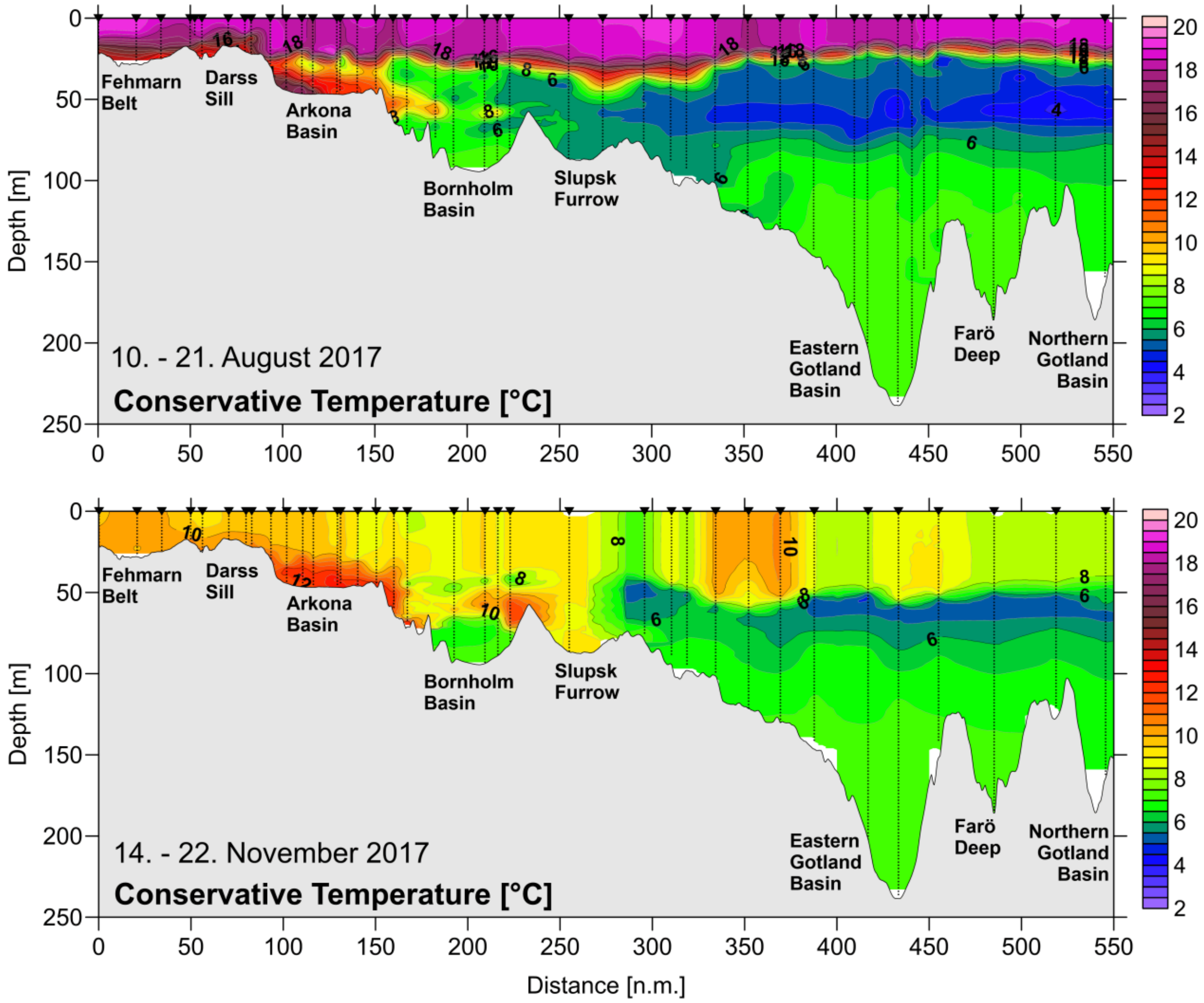


Fig. 25: Temperature distribution along the talweg transect through the Baltic Sea between Darss Sill and northern Gotland Basin

As part of its long-term monitoring programme, IOW operates hydrographic moorings near station TF271 in the eastern Gotland Basin since October 2010. In contrast to the Gotland Northeast mooring, operational since 1998 and from where the well-known 'Hagen Curve' is derived, the mooring at TF271 also collects salinity and oxygen 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 greatly enhances 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 2016 and December 2017. The temperature stratification in the deep water is characterized by a downward increasing temperature. The vertical temperature gradient in October 2016 was strong. The temperature difference between 140m depth and the bottom was about 0.8 K. Due to minor inflows into the halocline and diapycnal mixing the temperature stratification was significantly reduced till March 2017. Then the temperature difference between the 140 m depth level and 233 m depth was only about 0.35 K. In begin of April 2017 warm water from the autumn inflows 2016 reached the deep layers of the Gotland deep. It caused a temperature increase by about 0.3 K in the all water layers, except the bottom layer at 233 m depth. After this inflow the warmest deep water was observed at 210 m depth. The inflow caused a high temporal variability in the deep water and a further reduction of the vertical temperature differences. By mid of June another inflow pulse was visible. At that time the cooler water from February 2017 inflow reached the center of the eastern Gotland basin. The temperature gradient almost vanished and the temperature decreased by about 0.2 K. This inflow affected also the bottom layer, where the temperature dropped to about 7.0 °C. A high variability of temperature was observed during the active inflow phase till the end of July 2017. Afterwards the remaining gradient was low. The temperature difference between 140 m depth and the bottom was about 0.1 K, with downward decreasing temperatures. Till December 2017 no further inflow was observed and the conditions remained unchanged.

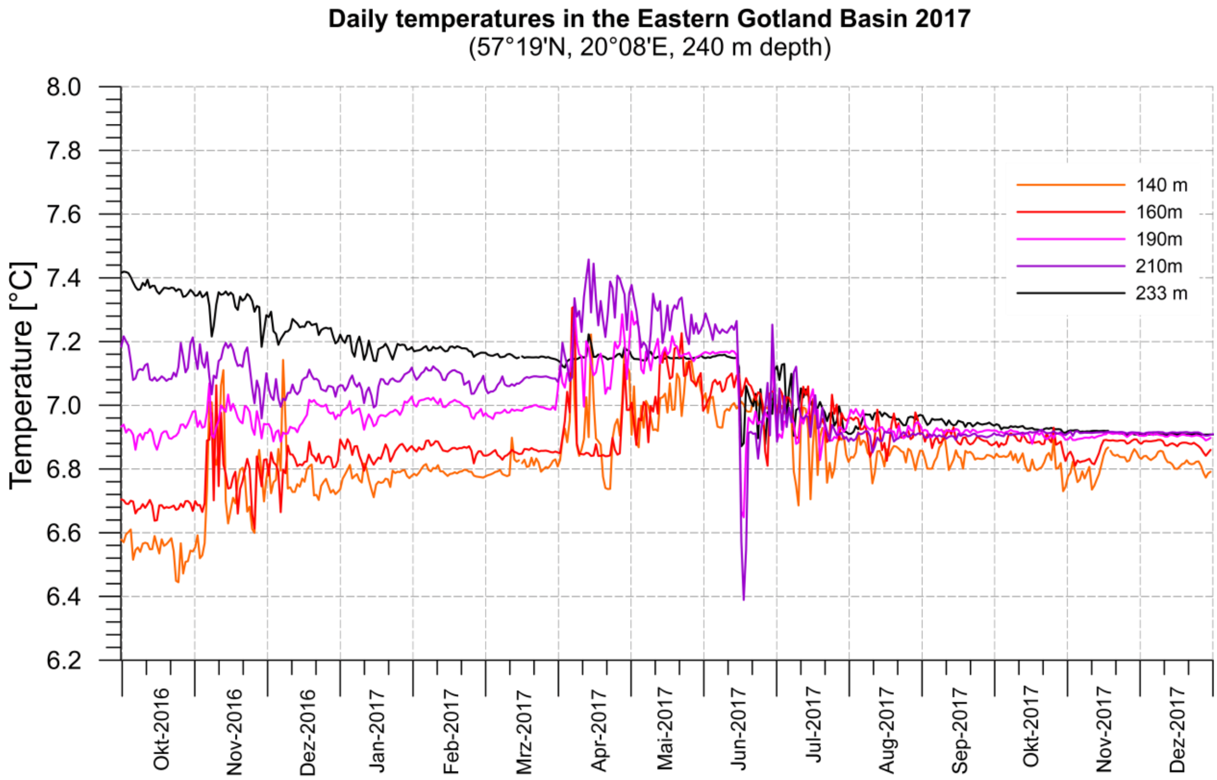


Fig. 26: Temporal development of deep water temperature in the Eastern Gotland Basin (station Tf271) from October 2016 to December 2017 (daily averages of original data with 10 min sampling interval)

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. Compared to 2016 the deep-water temperatures remained at the same level in the Bornholm Basin and the eastern Gotland Basin. However, this is not caused by stagnant conditions, but by a continuous sequence of minor inflow events. In the northern and western Gotland Basin the deep-water temperatures increased by 0.2 to 0.27 K. This continued the increasing trend since the extreme Christmas MBI in 2014. In 2017 the strongest increase of 0.27 °C was detected in the Faro Deep. However, also in the Landsort deep an increase of 0.25 °C was observed. This illustrates, that inflow waters of the recent barotropic inflows shifted former deep water from the eastern Gotland Basin towards north and further to the western Gotland Basin. In all deep basins the bottom temperature was the highest observed during the last five years. The standard deviations of temperature fluctuations in 2016 were highest in the Bornholm Deep in the westernmost basin.

The stronger fluctuations observed there are attributable to high inflow activity and the deep-water renewal associated with it.

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= 5-20)

Water temperature (° C; maximum in bold)

Station	Depth/m	2013	2014	2015	2016	2017
213 (Bornholm Deep)	80	5.55 ±0.78	6.99 ±1.29	7.01 ±0.08	**7.06 ±0.63**	**7.06 ±0.28**
271 (Gotland Deep)	200	6.33 ±0.03	6.11 ±0.19	6.79 ±0.19	**7.06 ±0.12**	**7.05 ±0.15**
286 (Fårö Deep)	150	5.83 ±0.05	5.69 ±0.04	6.33 ±0.25	**6.56 ±0.06**	**6.83 ±0.15**
284 (Landsort Deep)	400	5.46 ±0.11	5.27 ±0.06	5.46 ±0.30	**5.92 ±0.10**	**6.14 ±0.19**
245 (Karlsö Deep)	100	5.22 ±0.07	5.00 ±0.04	5.03 ±0.06	5.28 ±0.09	**5.53 ±0.06**

Salinity (maximum in bold)

Station	Depth/m	2013	2014	2015	2016	2017
213 (Bornholm Deep)	80	15.16 ±0.24	16.06 ±0.41	18.86 ±0.25	18.26 ±0.40	17.40 ±0.46
271 (Gotland Deep)	200	12.00 ±0.04	12.06±0.11	12.95 ±0.35	13.35 ±0.09	**13.30 ±0.04**
286 (Fårö Deep)	150	11.28 ±0.17	11.36 ±0.08	11.93 ±0.22	12.35 ±0.12	**12.58 ±0.07**
284 (Landsort Deep)	400	10.43 ±0.05	10.37 ±0.08	10.63 ±0.33	11.12 ±0.13	**11.29 ±0.19**
245 (Karlsö Deep)	100	9.76 ± 0.18	9.58 ±0.11	9.64 ±0.17	10.00 ±0.16	**10.28 ±0.11**

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

Station	Depth/m	2013	2014	2015	2016	2017
213 (Bornholm Deep)	80	1.62 ±1.05	2.07 ±1.47	3.60 ±1.75	1.30 ±0.93	0.90 ±0.83
271 (Gotland Deep)	200	-5.30 ±0.83	-2.94 ±2.38	0.93 ±0.80	0.55 ±0.26	0.13 ±0.11
286 (Fårö Deep)	150	-1.95 ±1.46	-2.35 ±0.53	-0.87 ±0.20	-0.05 ±0.23	**0.34 ±0.33**
284 (Landsort Deep)	400	-1.11 ±0.24	-1.02 ±0.68	-0.86 ±0.18	-0.98 ±0.23	-0.41 ±0.31
245 (Karlsö Deep)	100	-0.72 ±0.73	-0.85 ±0.52	-0.87 ±0.51	-0.93 ±0.47	-0.75 ±0.66

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 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 overall salinity distribution. Only combined they can lead to slow, long-term changes in salinity. The salinity distributions shown in Figure 27 are mere 'snapshots' that cannot provide a complete picture of inflow activity. In 2017 the evolution of salinity distribution was mainly controlled by the moderate inflows in November and December 2016, and the February inflow 2017. However, also the baroclinic inflows in late summer and autumn 2016 and 2017 caused significant changes in the western Baltic. None of the inflows could be completely covered by the IOW monitoring cruises. They supplied only snapshots of different stages of particular inflow events. Two of the five data sets show an inflow event in the western Baltic. However, it is not possible to produce meaningful statistics on inflow events, by using only the monitoring cruises.

At the beginning of February the major fraction of the November inflow 2016 waters have passed the Slupsk Sill. Here the bottom salinity increased to 15.2 g/kg. A patch of higher saline water of 13.2 g/kg was also detected between the eastern outlet of the Slupsk Furrow and the Gotland deep. In the Arkona Basin cooler saline water from the December 2016 inflow covered the bottom layer. Bottom salinity in the Arkona Basin at this time was measured with a maximum of 17.3 g/kg. Parts of this water have reached the halocline of the Bornholm Basin. The deep layers of Bornholm Basin were still filled with high saline water from the inflow series in winter

2015/2016. Here the bottom salinity was about 18.5 g/kg. The halocline of the Bornholm Basin was occupied by a mixture of former deep water, warm water patches from the baroclinic summer inflows and new inflow water from December 2017. The salinity of this water body raged between 10 and 17 g/kg. West of the Darss Sill first sign of the high saline water from the February 2017 inflow was visible with bottom salinities of about 21.7. After the inflow series in since the winter 2014/2015 the salinity in the deep water of the central Baltic Sea was at a high level at the beginning of 2017. On the seabed in the Gotland Deep, a salinity of 13.5 g/kg was measured in February 2016. This was still close to the overall maximum observed after the extreme inflow event in 1951. The 12 g/kg isohaline lay at a depth of around 103m, after 127m and 163m in February 2016 and 2015 respectively. The 123 g/kg isohaline was found at 154m depth.

By the second half of March first saline waters of the February inflow have reached the Bornholm Basin. The pool of saline water in the Arkona Sea was replaced by the inflow water from February 2017. However, the bottom salinity was still at the same level of 17.1 g/kg. The bottom salinity in the Bornholm Basin increased slightly to 18.75 g/kg in the central part of the basin. The halocline in the basin 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 halocline was filled up, and the bottom salinity increased to 16.13 g/kg. North of the Slupsk Furrow again a plumes of the November 2016 inflow water spread toward the eastern Gotland Basin as observed in February. In the eastern Gotland Basin the conditions remained nearly unchanged, despite an uplift of the 13 g/kg isohaline in the southern part of the Basin. At the Gotland deep the 12 g/kg and the 13 g/kg isohalines were found at 105 m and 160 m, respectively. In the Farö Deep was the 12 g/kg isohaline was observed at 108 m depth. The bottom salinity was 12.66 g/kg here.

At the beginning of May the saline water pool in the Arkona Basin was strongly reduced. The halocline was found at 35 to 40 m depth. The bottom salinity was only about 11.3 g/kg. In the Bornholm Basin the halocline 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 18.18 g/kg. In the Slupsk Furrow the halocline depicted an eastward slope from 55 m depth near Slupsk Sill to 70m at the eastern sill of Slupsk Furrow. A larger part of saline water has left the Slupsk Furrow towards the eastern Gotland Basin, where it formed two patches of higher saline water. At station TF271 (Gotland Deep) the bottom salinity was 13.45 g/kg. Here the 13 g/kg isohaline rose from 160 m in March to a depth of 153 m. The 12 g/kg isohaline did not changed their position.

In August changes of salinity distribution in the western Baltic were caused by the baroclinic summer inflow, which enhanced the stratification and bottom salinity in the Arkona Basin. In the Bornholm Basin mixing with overlaying water caused a slight dilution of deep water. The bottom salinity sunk little to 18.02 g/kg. The inflow process of the November 2017 water into the eastern Gotland Basin has finished. In the Gotland Deep the 13 g/kg isohaline was uplifted by about 10m to 142 m. The bottom salinity remained practically unchanged.

At the mid 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 18.6 g/kg.

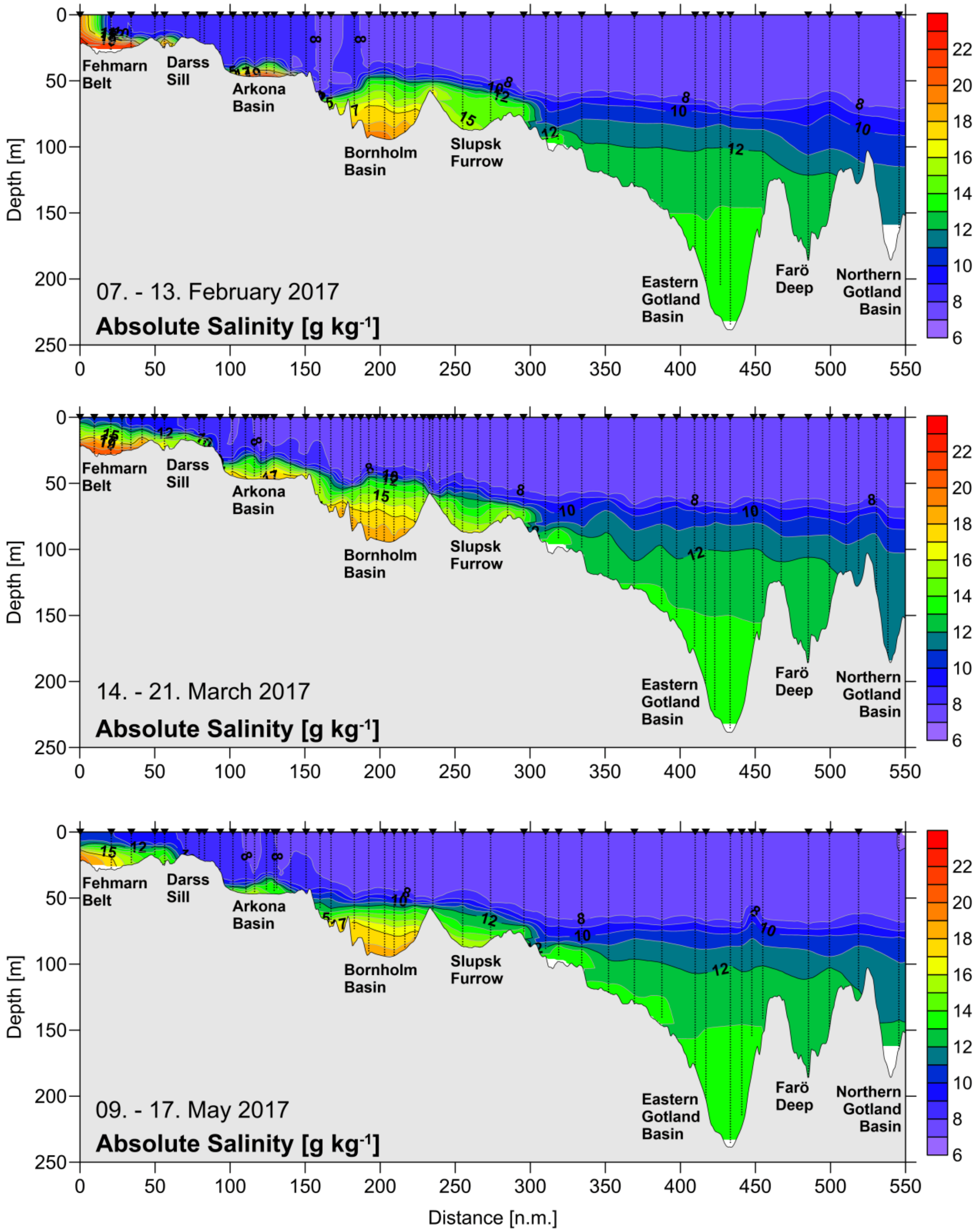


Fig. 27: Salinity distribution along the talweg transect through the Baltic Sea between Darss Sill and northern Gotland Basin

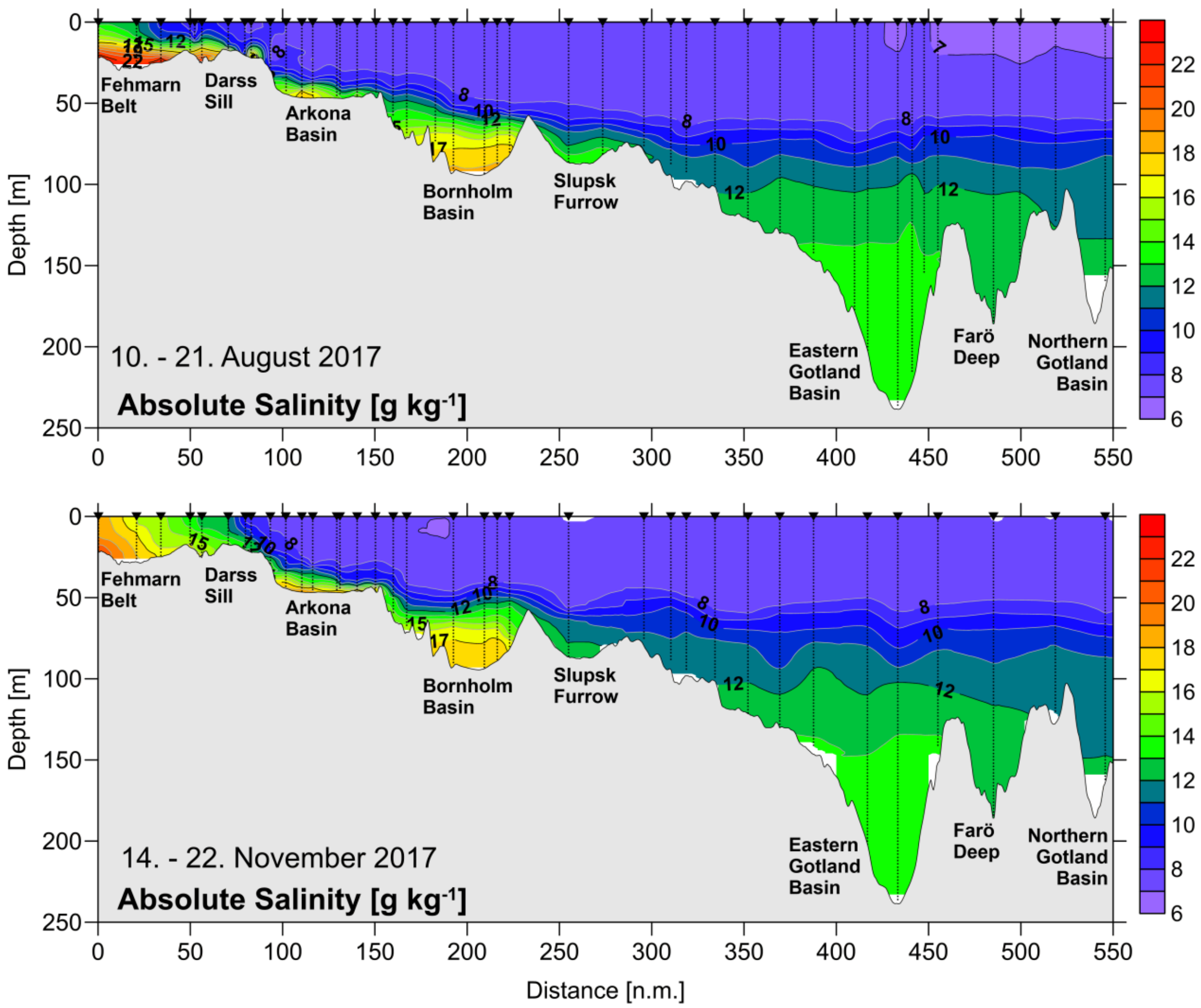


Fig. 27: Salinity distribution along the talweg transect through the Baltic Sea between Darss Sill and northern Gotland Basin

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 since 2014 the deep-water salinity depicted a positive trend in all major basins of the central Baltic. The bottom salinity in the Fårö Deep, Karlsö Deep and Landsort Deep reached maximum values of the past five year period. The deep-water salinity in the eastern Gotland Basin remained at the high level of the previous year. Only in the Bornholm Basin a decrease of bottom salinity was observed in 2017. However, also here the salinity was still high, and well above the climatological mean. The high standard deviation of salinity in the Bornholm basin points to rapid fluctuations, caused by the particular inflow events.

As in the recent year no clear trend emerges over the past five years for salinity in the surface layer of the Baltic. Table 7 summarises the variations in surface layer salinity. Compared to the values in 2016, surface layer salinity in the Bornholm Basin decreased significantly in 2017. The surface salinity increased in the eastern Gotland Basin and the Farö Deep, and remained at a high level in the western Gotland basin. Standard deviations of surface salinity are slightly above the level with those of the long-term average, but still in the usual range. 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 in 2017.

Table 7: Annual means of 2013 to 2017 and standard deviations of surface water salinity in the central Baltic Sea (minimum values in bold, n= 5-26). The long-term averages of the years 1952-2005 are taken from the BALTIC climate atlas (FEISTEL et al., 2008)

Station	1952-2005	2013	2014	2015	2016	2017
213 (Bornholm Deep)	7.60 ±0.29	**7.28 ±0.12**	7.65 ±0.18	7.76 ±0.20	7.75 ±0.26	7.46 ±0.20
271 (Gotland Deep)	7.26 ±0.32	**6.78 ±0.28**	6.87 ±0.17	7.06 ±0.15	6.89 ±0.34	7.33 ±0.22
286 (Fårö Deep)	6.92 ±0.34	6.64 ±0.29	6.73 ±0.21	6.74 ±0.25	**6.63 ±0.33**	7.13 ±0.43
284 (Landsort Deep)	6.75 ±0.35	6.52 ±0.12	6.60 ±0.24	**6.29 ±0.44**	6.57 ±0.16	6.54 ±0.34
245 (Karlsö Deep)	6.99 ±0.32	**6.77 ±0.10**	7.00 ±0.13	6.91 ±0.25	6.98 ±0.17	6.93 ±0.18

Figure 28 shows the temporal development of salinity in the deep water of the eastern Gotland Basin between October 2016 and December 2017, based on data from the hydrographic moorings described above. In October 2016 the data depict a strong vertical salinity gradient of about 0.01 g/kg m, established in the course of the recent series of inflow events since December 2014.

From November 2016 till January 2017 the temporal variability of salinity in all depth layers was enhanced, pointing to an active inflow. However, the salinity was only slightly increased in the upper deep water between 140 and 160 m depth. Below 180 m the salinity remained at the same level. Unfortunately, there are no data for the bottom layer between November 2016 and March 2017. The MicroCat mounted at this level could not be recovered during the mooring maintenance in March 2017. Thus, there is no information when the salinity in the bottom layer dropped from 13.7 g/kg in October 2016 to 13.45 g/kg in March 2017. Afterwards a weak increase in deep water salinity was observed between April and September 2017. The bottom water salinity depicted a small decrease to 13.4 g/kg during that time. Consequently, the vertical salinity gradient was reduced. Till December 2017 a week decrease of deep water salinity was observed. As with temperature, the salinity time series reveal strong, short-term fluctuations whose amplitude decreases with depth. For the most part, these fluctuations correlate well with the observed temperature variability.

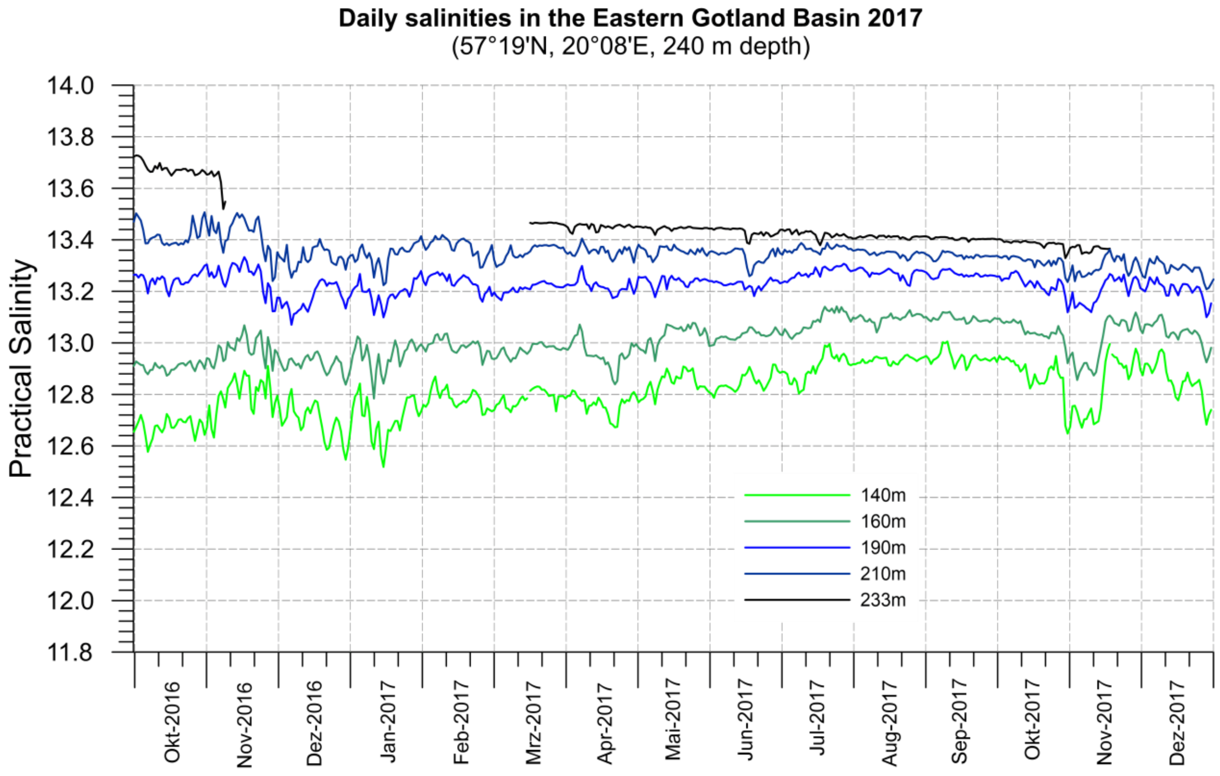


Fig. 28: Temporal development of deep water salinity in the Eastern Gotland Basin (station TF271) from October 2016 to December 2017 (Daily averages of original data with 10 min sampling interval)

6.3 Oxygen distribution

Exchange processes with the atmosphere and biogeochemical processes determine the oxygen content of seawater. In surface water (Fig. 29, 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 super-saturation of oxygen in surface waters because equilibration with the atmosphere depend on wind speed and wave activity and could be slow at calm conditions. However, 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 super-saturation in the euphotic zone. Whereas, during respiration oxygen is consumed. In deeper water layers without contact to the atmosphere, oxygen concentration then clearly declines (Fig. 29, lower panel). In especially unfavorable hydrographic conditions, below permanent or temporary pycnoclines that are 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 (shown as negative oxygen).

In terms of the deep-water oxygen concentration, the year 2017 still reflected the influence of the MBI of December 2014. The maxima of 2015 in the Bornholm and the eastern Gotland Sea seem to have further propagated along the thalweg to the Fårö Deep and the Landsort Deep that both currently reflect their maximum in 2017. However, the supplied oxygen is diluted and permanently consumed by degradation processes. Thus, the annual mean maximum of 3.6 ml/l oxygen that was recorded at the Bornholm Deep weakened to 0.93 ml/l at Gotland Deep in 2015. In 2017 the oxygen concentration at Fårö Deep and the Landsort Deep stations still increased. Meanwhile the Fårö Deep reached 0.33 ml/l oxygen in deep waters and at Landsort Deep the degradation of the hydrogen sulphide legacy went on from -1.11 ml/l in 2013 to -0.46 ml/l in 2017 (Table 8). However, some additional oxygen supply by entrainment along isopycnal surfaces may have contributed to the positive development.

Contributions to 6.1-6.3 Oxygen Distribution

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	2013	2014	2015	2016	2017
213 (Bornholm Deep)	80	1.62 ±1.05	2.07 ±1.47	**3.60 ±1.75**	1.19 ± 1.00	0.88 ±0.70
271 (Gotland Deep)	200	-5.30 ±0.83	-2.94 ±2.38	**0.93 ±0.80**	0.62 ±0.24	0.07 ±0.20
286 (Fårö Deep)	150	-1.95 ±1.46	-2.35 ±0.53	-0.87 ±0.20	-0.05 ±0.22	**0.33 ±0.33**
284 (Landsort Deep)	400	-1.11 ±0.24	-1.02 ±0.68	-0.86 ±0.18	-0.92 ±0.33	**-0.46 ±0.26**
245 (Karlsö Deep)	100	**-0.72 ±0.73**	-0.85 ±0.52	-0.87 ±0.51	-1.15 ± 0.34	-0.96 ± 0.58

The surface water oxygen concentration basically reflected the temperature course of the year with higher concentration in winter and deceasing values during warming of the surface water. This development is modulated by oxygen production during the spring time primary production (green bars) - earlier in spring in the western Baltic Sea and in May 2017 in the Gotland Sea surface water (Fig. 29). The bottom water of the western Baltic Sea showed a decreasing oxygen concentration during the development of the thermocline from March to May and further to August 2017 that indicated an ongoing decoupling of the bottom waters from the surface water oxygen reservoir and intensified remineralization in bottom waters and the sediments. The oxygen supply of the major Baltic inflow was almost consumed in the eastern Gotland Sea basin but its influence is distributed further north and to the western Baltic Sea deep waters as discussed above.

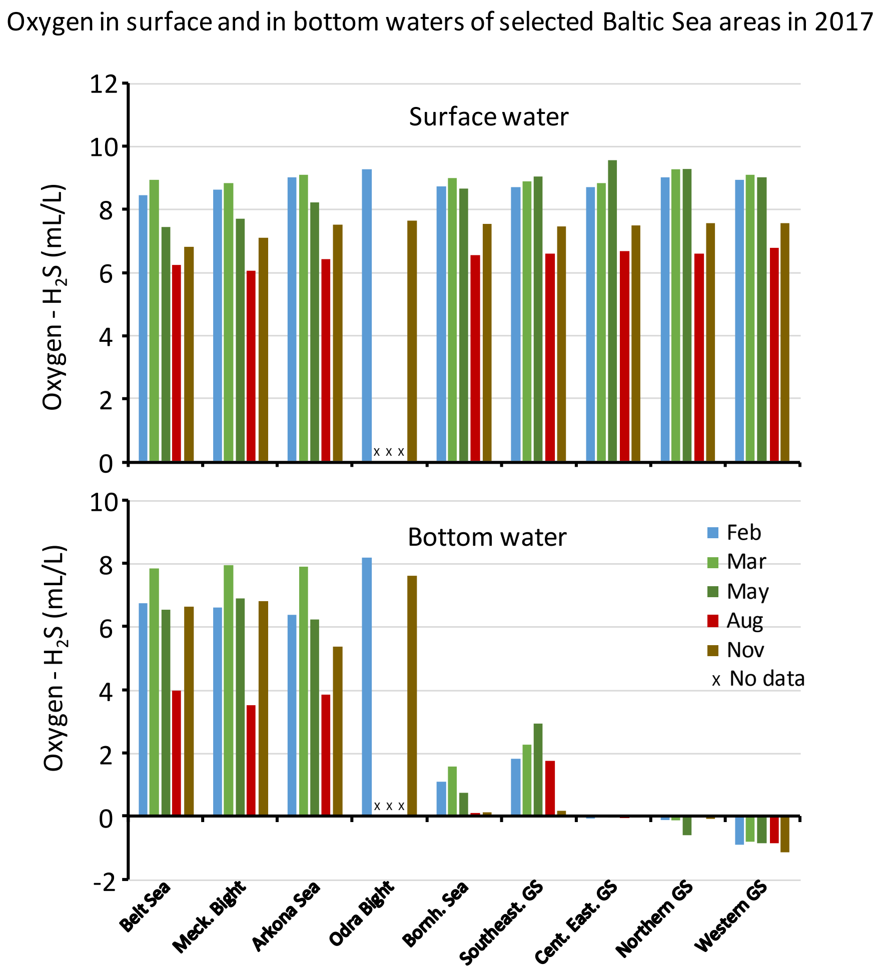


Fig. 29: Comparison of average oxygen/hydrogen sulphide concentrations in surface (upper panel) and bottom waters (lower panel) of the studied Baltic Sea areas Belt Sea, Mecklenburg Bight, Arkona Sea, Bornholm Sea, central Eastern Gotland Sea, Northern Gotland Sea, and Western Gotland Sea.

The period of greatest oxygen depletion is generally observed in late summer / early autumn – the time of the year not covered by IOW cruises. Nevertheless, the Landesamt für Landwirtschaft, Umwelt und ländliche Räume des Landes Schleswig-Holstein (LLUR) has for many years measured near-bottom oxygen concentrations at that time of the year. Investigations in 2017 were conducted from 28th August to 12th September. Near-bottom oxygen concentrations were measured at 36 stations, 29 of them at depths ›15 m (Figure 30).

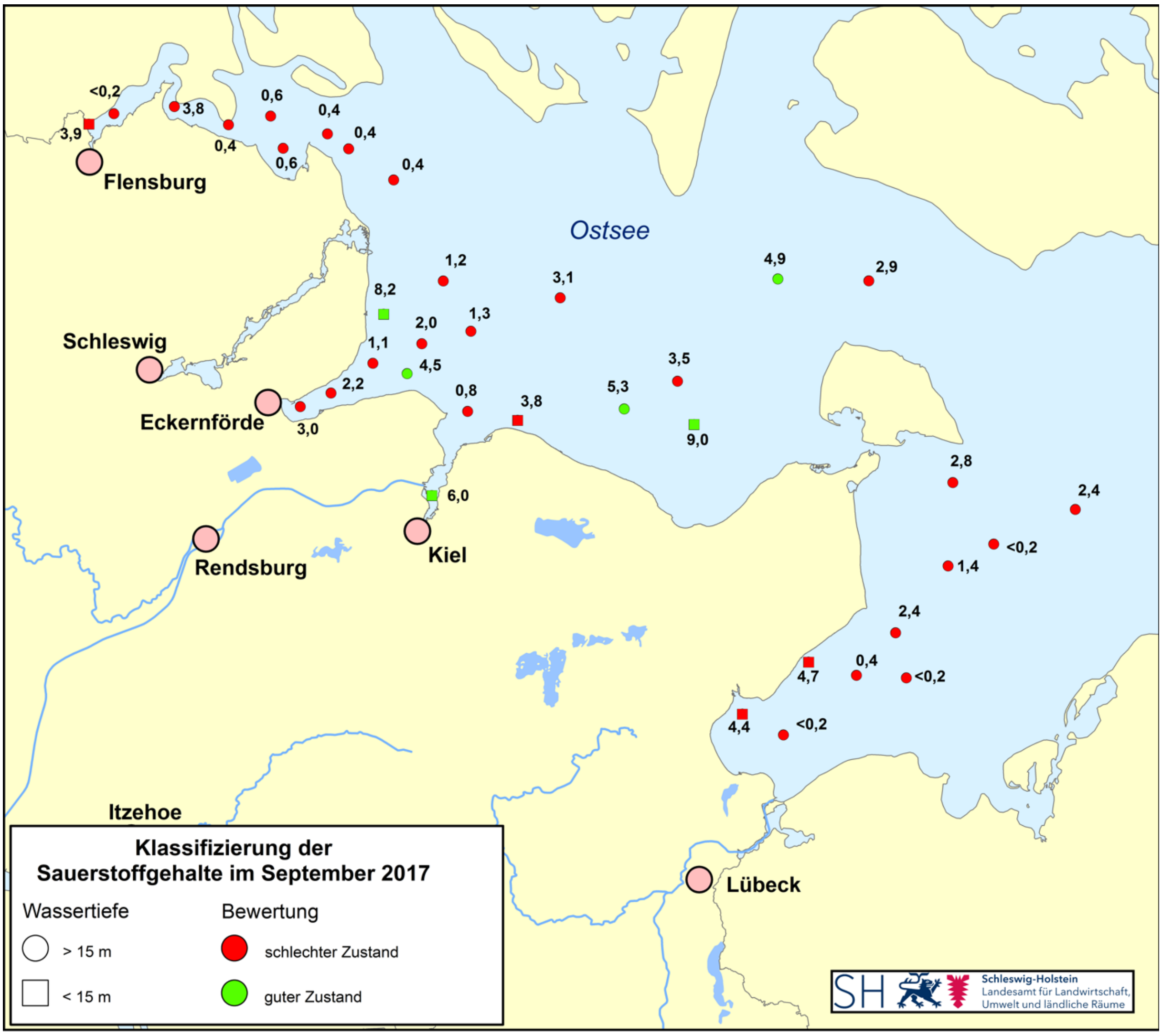


Fig. 30: Oxygen deficiency in the western Baltic Sea in September 2015 (LLUR, 2017) – O2 [mg/l] x 0.7005 = O2 [ml/l]

Evaluation of measurements from 2017 at stations with water depths >15 m shows that 90 % of all measurements were classified as *poor* or *inadequate* (<4 mg/l oxygen). At the bottom also hydrogen sulphide was detected at the regions Flensburg Fjord and Geltinger Bight. In 2016 these were 63 % measurements had been so classified. In conclusion, the oxygen conditions are much more worse than in the previous year and close to the poorest oxygen conditions so far in the year 2002, their share had been 91 %. According to LLUR (2017), fish kill of up to 20 species due to oxygen deficiency /hydrogen sulphide was observed at Eckernförde Bight as well as Kiel Fjord and Flensburg Fjord in beginning September. Persistent and strong south-westerly winds transported the well oxygenated surface water out of these bights and upwelling of hypoxic to euxinic bottom water occurred. If fish populations get trapped in these conditions, fish kill events can happen.

For a more detailed analysis of the seasonal development of oxygen saturation, see the measurements from Darss Sill (chapter 3), the Arkona Basin (chapter 4), and Oder Bank (chapter 5).

In the more easterly, deeper basins of the Baltic Sea, in contrast, deep-water conditions are primarily influenced by the occurrence or absence of strong barotropic and/or baroclinic inflows.

Figure 31 shows oxygen conditions along a transect from Darss Sill to the northern Gotland Basin during the five monitoring cruises undertaken in 2017.

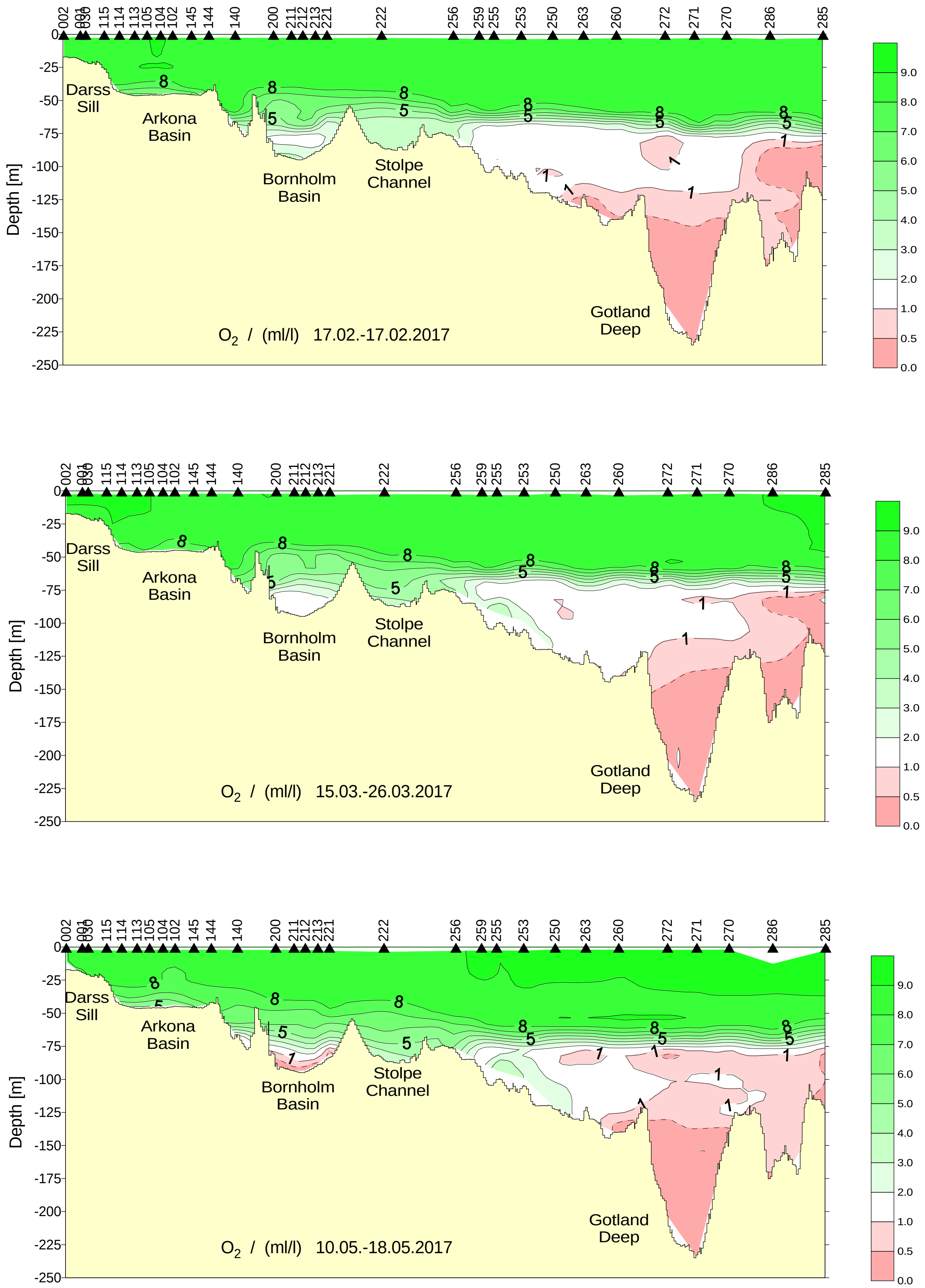


Fig. 31a: Vertical distribution of dissolved oxygen in 2017 between the Darss Sill and the northern Gotland Basin (February to May).

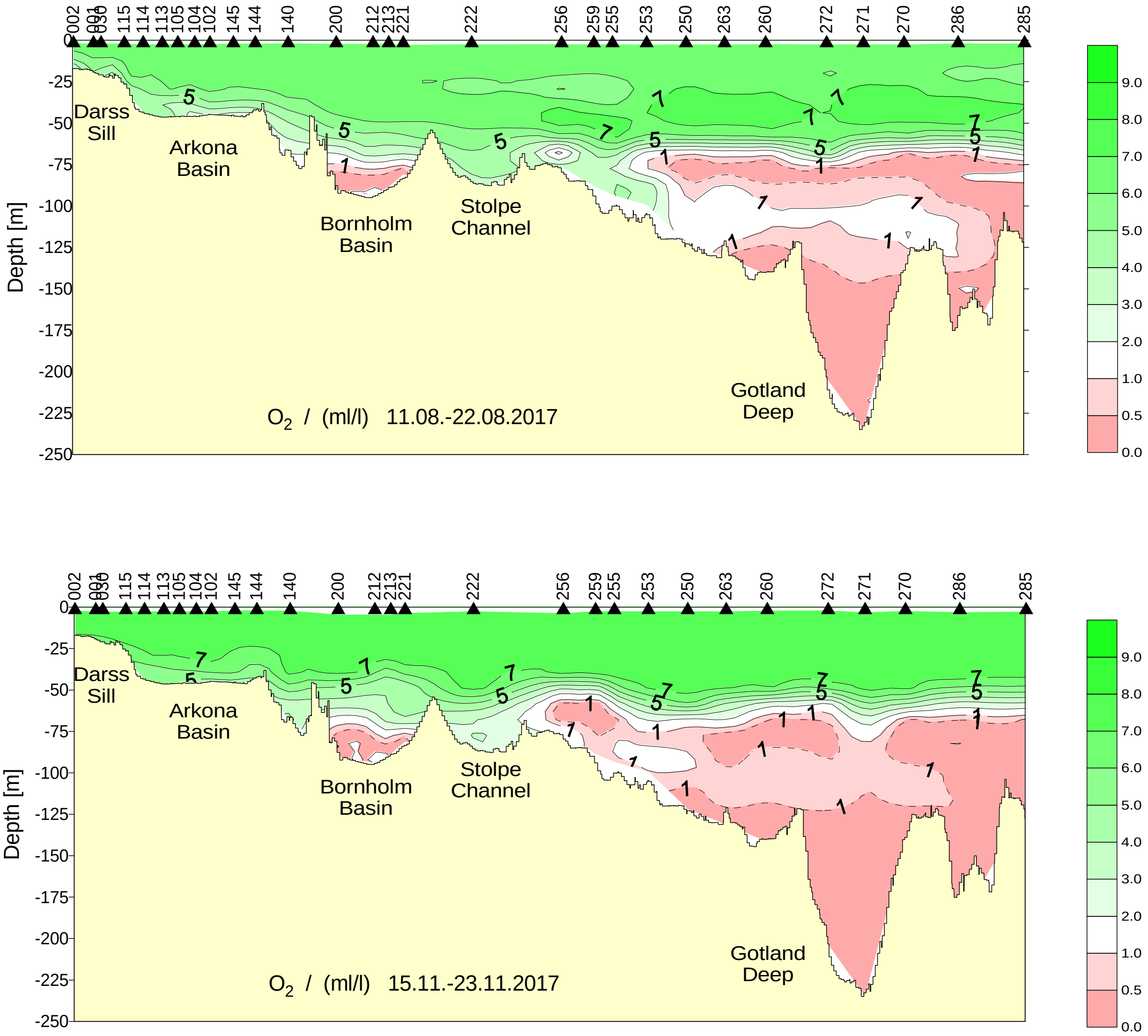


Fig. 31b: Vertical distribution of dissolved oxygen in 2017 between the Darss Sill and the northern Gotland Basin (August to November).

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".

Comparing the Pollution Load Compilation for the year 2010 (PLC-5.5) (HELCOM, 2015) with the for 2014 (PLC-6) (HELCOM, 2018) total waterborne and airborne inputs of nitrogen to the Baltic Sea decreased from 977,000 Mg to 826 000 Mg. For phosphorus the decline was given for 2006 to 2014 from 35,500 Mg to 31,000 Mg without accounting for the less important atmospheric deposition of about 2100 Mg determined for 2010.

Atmospheric deposition of nitrogen in 2014 amounted to 223,800 Mg or 27 %, riverine to 573,000 Mg (69 %), and direct point-sources to 28,900 Mg (4 %) of the total nitrogen input. By including the atmospheric deposition of 2,100 Mg of phosphorus to the Baltic Sea annually, the shares were 6 % atmospheric, 1600 Mg (5 %) from direct point-sources and 29,300 by rivers (89 %) of the total phosphorus input to the Baltic Sea.

In 2010, 62 % of the atmospheric deposition of total nitrogen 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, representing 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 again declined between 2006 and 2014 by 14 %. In the same time-period, total nitrogen input decreased by 31% (HELCOM, 2018). Despite this positive development, German territorial waters and bordering sea areas of the Baltic Sea remained hypertrophied by up to 50 % in the western and up to 100% in the eastern part (HELCOM, 2017). 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 1970ies. 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, pCO_2 profiles or equivalent information aimed at quantifying marine acidification.

6.4.1 Surface water processes

Phosphate and nitrate concentrations in the surface waters of temperate latitudes exhibit a typical annual cycle with high concentrations in winter, depletion during spring and summer, and recovery in autumn (NAUSCH AND NEHRING, 1996; NEHRING AND MATTHÄUS, 1991). Figure 32 illustrates the annual cycle of nitrate and phosphate concentrations in the eastern Gotland Sea and in the Bornholm Sea in 2017. 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 nutrient concentrations developed during winter which lasts two to three months (NAUSCH et al, 2008). In 2017 already at low surface water temperature of below 4 °C, the spring bloom started in the central Gotland Sea and in the

Bornholm Sea end of March to early April that lead to a rapid decline of nitrate. The phosphate concentration decreased only slowly until the limit of detection that occurred end of May at the Gotland Deep station and mid-June at the Bornholm Deep station. At nitrate depletion the spring bloom likely terminated mid-April almost parallel in the Bornholm Sea and the eastern Gotland Sea in 2017. However, in the Gotland Sea slightly elevated nitrate concentrations were measured in August in times of low nutrient availability. The phosphate concentration then remained close to the detection limit in the Bornholm Sea in August, whereas in the central eastern Gotland Sea this period stretched from mid-June to mid- September in 2017.

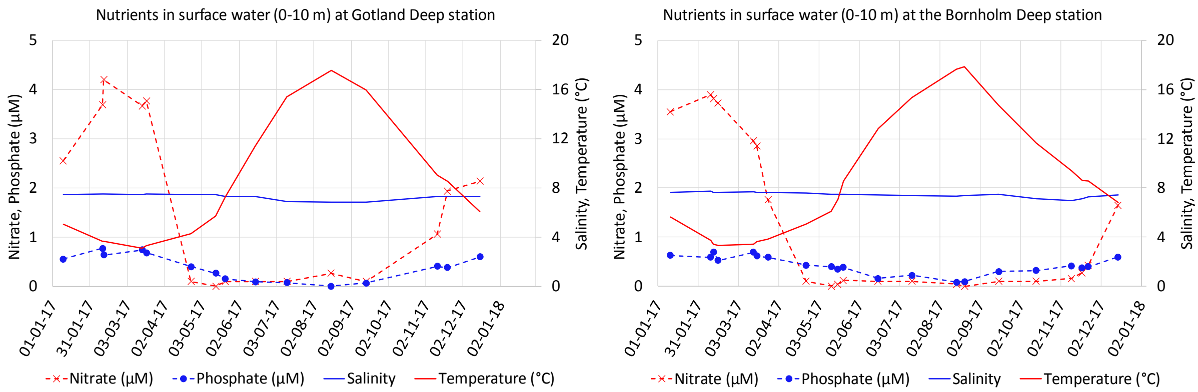


Fig. 32: Seasonal cycle of the average phosphate and nitrate concentrations in 2017 compared to temperature and salinity in the surface layer (0-10 m) at the Gotland Deep station (TF271 - left) and at the Bornholm Deep station (TF213 – right), respectively, by using IOW and SMHI data.

In autumn, cooling enabled wind induced mixing and supply of nutrients from deeper layers. Mineralization 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 likely caused by the low dissolved inorganic N/P ratio present in the winter surface water of the Baltic Sea that already caused nitrate exhaustion before phosphate was consumed. The favorable uptake ratio is about 16 that was already shown by an early study of Redfield (REDFIELD et al., 1963) and was shown to be a valuable approximation many times thereafter. The N/P ratio (mol/mol) was determined from the sum of ammonium, nitrate, and nitrite concentrations versus the phosphate concentration. In the investigated areas the values were on average 10 mol/mol in the western Baltic Sea, slightly elevated compared to 2016, and below 7 mol/mol in the Bornholm Sea and the Gotland Sea in 2016 and 2017. A clear decreasing trend is observed in 2017 from the Bornholm Sea to the southern Gotland Sea, further to the eastern, the northern, and the western Gotland Sea. The DIN/DIP ratio was found even above the "Redfield ratio" in the Odra Bank area of › 20 mol/mol. A clear decline of the DIN/DIP in the Bornholm Sea and Gotland Sea. This already indicated that nitrogen would become a limiting factor through the year 2017 giving diazotrophic cyanobacteria an advantage especially in the Gotland Sea.

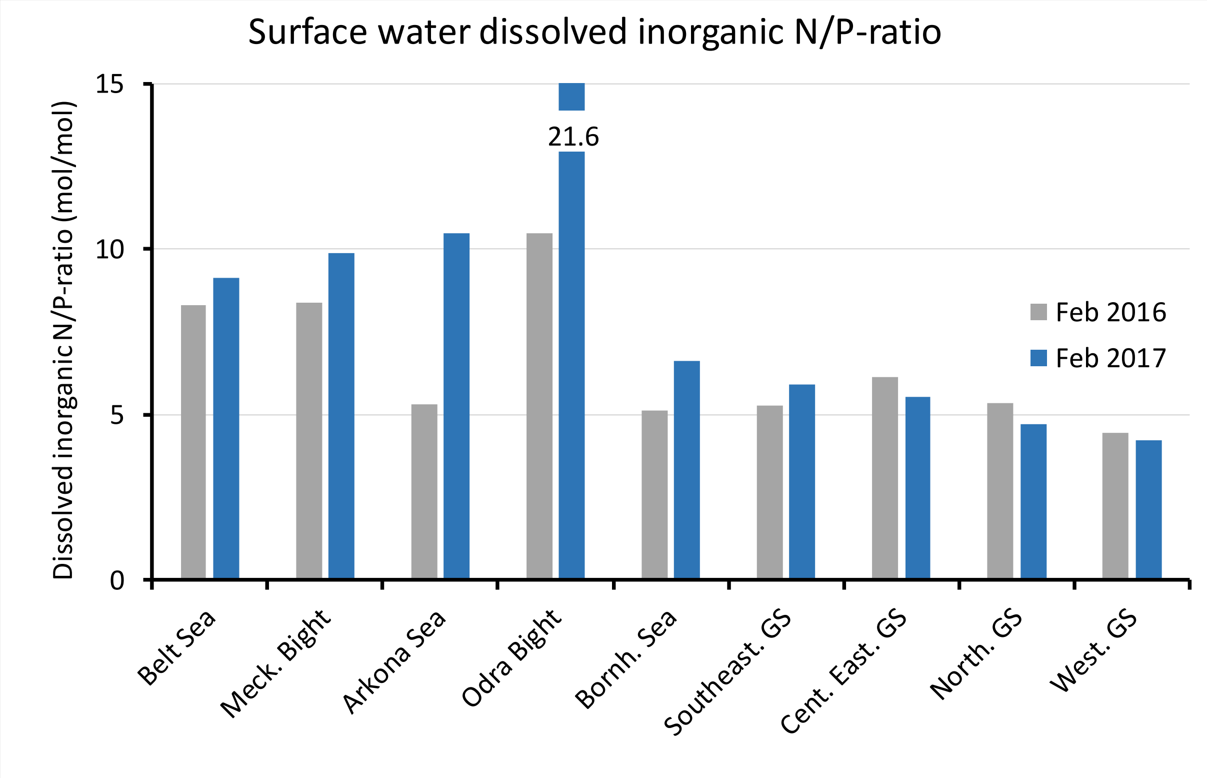


Fig. 33: Average dissolved inorganic nitrogen versus phosphate ratio in surface waters of various Baltic Sea areas in February 2016 and 2017.

In Table 9 winter phosphate and nitrate concentrations of surface waters are compiled. The values were in the range of previous years. However, slightly lower values were determined for the western Baltic Sea area, reflecting minimum values in 2017 compared to previous years and vice versa for the eastern Baltic Sea with elevated phosphate and nitrate values in the Bornholm Sea and the Gotland Sea in 2017. 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., 2011b). The partial weak decline of nitrate in tandem with a slight increase of phosphate might be a consequence of the inflow that had replaced low nitrogen and phosphate enriched deep waters that may finally contribute to surface water outflow. Also 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	2013	2014	2015	2016	2017
360 (Fehmarn Belt)	Feb.	0.72 ± 0.01	0.57 ± 0.01	0.64 ± 0.01	0.66 ± 0.04	**0.54 ± 0.01**
022 (Lübeck Bight)	Feb.	0.85 ± 0.01	0.71 ± 0.04	0.63 ± 0.02	0.79 ± 0.15	**0.53 ± 0.09**
012 (Meckl. Bight)	Feb.	0.85 ± 0.01	**0.56 ± 0.00**	0.60 ± 0.01	0.68 ± 0.01	**0.56 ± 0.00**
113 (Arkona Sea)	Feb.	0.63 ± 0.01	**0.53 ± 0.00**	0.56 ± 0.00	0.64 ± 0.01	**0.53 ± 0.00**
213 (Bornholm Deep)	Feb.	0.71 ± 0.0	0.70 ± 0.01	**0.60 ± 0.00**	0.67 ± 0.06	0.61 ± 0.06
271 (Gotland Deep)	Feb.	0.54 ± 0.02	0.52 ± 0.01	**0.50 ± 0.02**	0.67 ± 0.04	0.70 ± 0.08
286 (Fårö Deep)	Feb.	**0.50 ± 0.01**	0.78 ± 0.01	0.60 ± 0.00	0.65 ± 0.08	0.69 ± 0.01
284 (Landsort Deep)	Feb.	**0.56 ± 0.02**	0.84 ± 0.01	-	0.75 ± 0.01	0.79 ± 0.03
245 (Karls Deep)	Feb.	**0.60 ± 0.02**	0.85 ± 0.00	0.80 ± 0.00	0.87 ± 0.09	0.91 ± 0.07

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

Station	Monat	2013	2014	2015	2016	2017
360 (Fehmarn Belt)	Feb.	4.1 ± 0.0	4.9 ± 0.2	7.5 ± 0.1	4.5 ± 0.5	**3.2 ± 0.1**
022 (Lübeck Bight)	Feb.	6.7 ± 0.1	6.6 ± 0.1	9.3 ± 0.2	6.3 ± 0.1	**4.5 ± 0.7**
012 (Meckl. Bight)	Feb.	5.8 ± 0.0	4.5 ± 0.1	5.5 ± 0.0	4.8 ± 0.1	**4.4 ± 0.0**
113 (Arkona Sea)	Feb.	**3.2 ± 0.0**	5.2 ± 0.2	3.7 ± 0.0	**3.2 ± 0.2**	5.2 ± 0.0
213 (Bornholm Deep)	Feb.	3.0 ± 0.0	4.0 ± 0.1	3.3 ± 0.2	**2.8 ± 0.2**	3.8 ± 0.1
271 (Gotland Deep)	Feb.	**2.9 ± 0.0**	3.9 ± 0.0	3.1 ± 0.0	3.4 ± 0.4	3.9 ± 0.3
286 (Fårö Deep)	Feb.	**3.0 ± 0.0**	4.5 ± 0.1	3.4 ± 0.0	3.3 ± 0.5	3.9 ± 0.1
284 (Landsort Deep)	Feb.	4.4 ± 0.0	3.8 ± 0.3		3.9 ± 0.0	**3.4 ± 0.2**
245 (Karls Deep)	Feb.	3.8 ± 0.1	3.5 ± 0.2	**3.2 ± 0.0**	3.3 ± 0.3	3.3 ± 0.1

6.4.2 Deep water processes in 2017

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 34 and 35 illustrate the nutrient concentration distributions in the water column on transect between the Darss sill and the Northern Gotland Sea for the year 2017. It should be noted that anoxic conditions prevent mineralization 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	2013	2014	2015	2016	2017
213 (Bornholm Deep)	80	1.62 ± 0.35	1.49 ± 0.31	1.57 ± 0.44	**2.23 ± 0.29**	2.51 ± 1.15
271 (Gotland Deep)	200	**6.32 ± 0.92**	4.50 ± 1.54	2.16 ± 0.29	2.56 ± 0.14	2.91 ± 0.92
286 (Fårö Deep)	150	**4.77 ± 0.58**	4.60 ± 0.67	3.26 ± 0.23	2.93 ± 0.22	2.49 ± 0.12
284 (Landsort Deep)	400	**3.89 ± 0.21**	3.85 ± 0.35	3.57 ± 0.26	3.25 ± 0.31	3.08 ± 0.22
245 (Karls Deep)	100	3.91 ± 0.53	3.99 ± 0.51	3.92 ± 0.19	**4.25 ± 0.34**	3.77 ± 0.24

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

Station	Tiefe/m	2013	2014	2015	2016	2017
213 (Bornholm Deep)	80	**6.4 ± 1.9**	8.2 ± 1.8	11.1 ± 2.5	10.4 ± 1.9	7.5 ± 2.3
271 (Gotland Deep)	200	**0.0 ± 00**	**0.0 ± 00**	7.5 ± 3.3	9.3 ± 0.7	1.8 ± 2.2
286 (Fårö Deep)	150	**0.0 ± 0.0**	**0.0 ± 00**	**0.0 ± 00**	1.4 ± 1.7	5.5 ± 3.5
284 (Landsort Deep)	400	**0.0 ± 0.0**	**0.0 ± 00**	**0.0 ± 00**	**0.0 ± 0.0**	**0.0 ± 0.1**
245 (Karls Deep)	100	01. ± 0.2	**0.0 ± 00**	**0.0 ± 00**	0.1 ± 00	0.1 ± 0.0

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

Station	Tiefe/ m	2013	2014	2015	2016	2017
213 (Bornholm Deep)	80	01. ± 0.1	0.1 ± 0.2	**0.2 ± 0.1**	**0.2 ± 0.1**	**0.2 ± 0.3**
271 (Gotland Deep)	200	**22.1 ± 8.7**	18.4 ± 10.9	1.6 ± 3.7	0.2 ± 0.0	0.8 ± 0.9
286 (Fårö Deep)	150	12.6 ± 3.0	**12.8 + 3.6**	7.2 ± 2.1	2.0 ± 2.0	0.1 ± 0.0
284 (Landsort Deep)	400	7.2 ± 2.3	**7.9 ± 1.7**	6.5 ± 1.1	7.8 ± 3.3	3.8 ± 1.9
245 (Karls Deep)	100	6.5 ± 3.1	7.7 ± 2.1	7.7 ± 1.2	**9.7 ± 1.7**	8.4 ± 1.5

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. Oxic 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. Nutrient 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 about 2 µmol/l in the deep waters.

After the MBI of December 2014 the stagnation period has started in 2015 in the Bornholm and Eastern Gotland Sea showing increasing phosphate concentration in 2017 in the deep waters, whereas in the Northern and Western Gotland Sea phosphate is basically declining (Table 10). The almost complete depletion of oxygen in the Gotland Deep caused a rapid decline of nitrate and an increase of ammonium. On the Fårö Deep station the nitrate concentration was still decreasing due to oxygen residues in the inflow water. In the Karls Deep deep water the ammonium concentration was again high (7-9 µmol/l). However, the value was almost halved to 3.8 µmol/l in the deep water of the Landsort Deep since 2016.

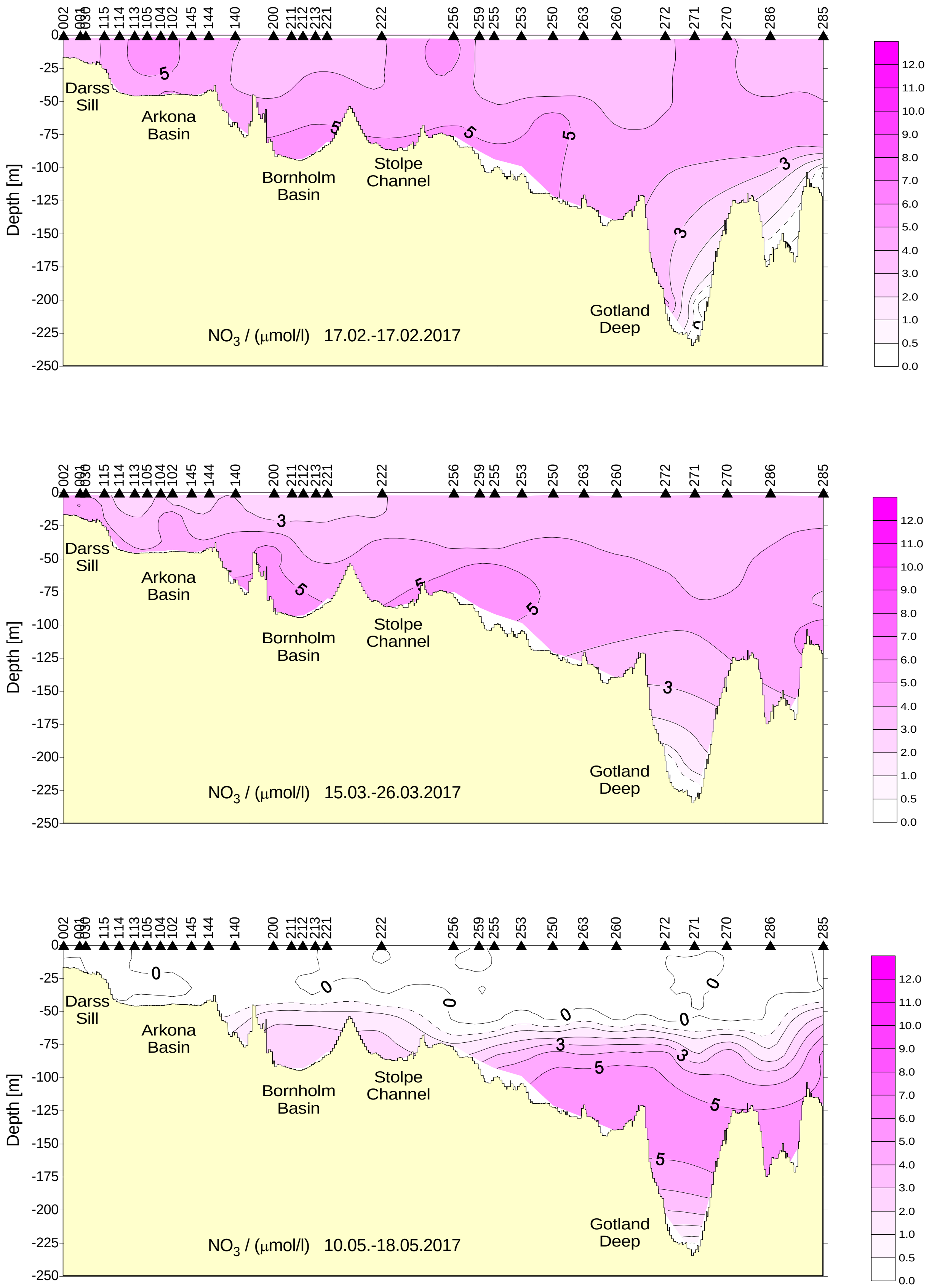


Fig. 34a: Vertical distribution of nitrate 2017 between the Darss Sill and the northern Gotland Basin (February to May).

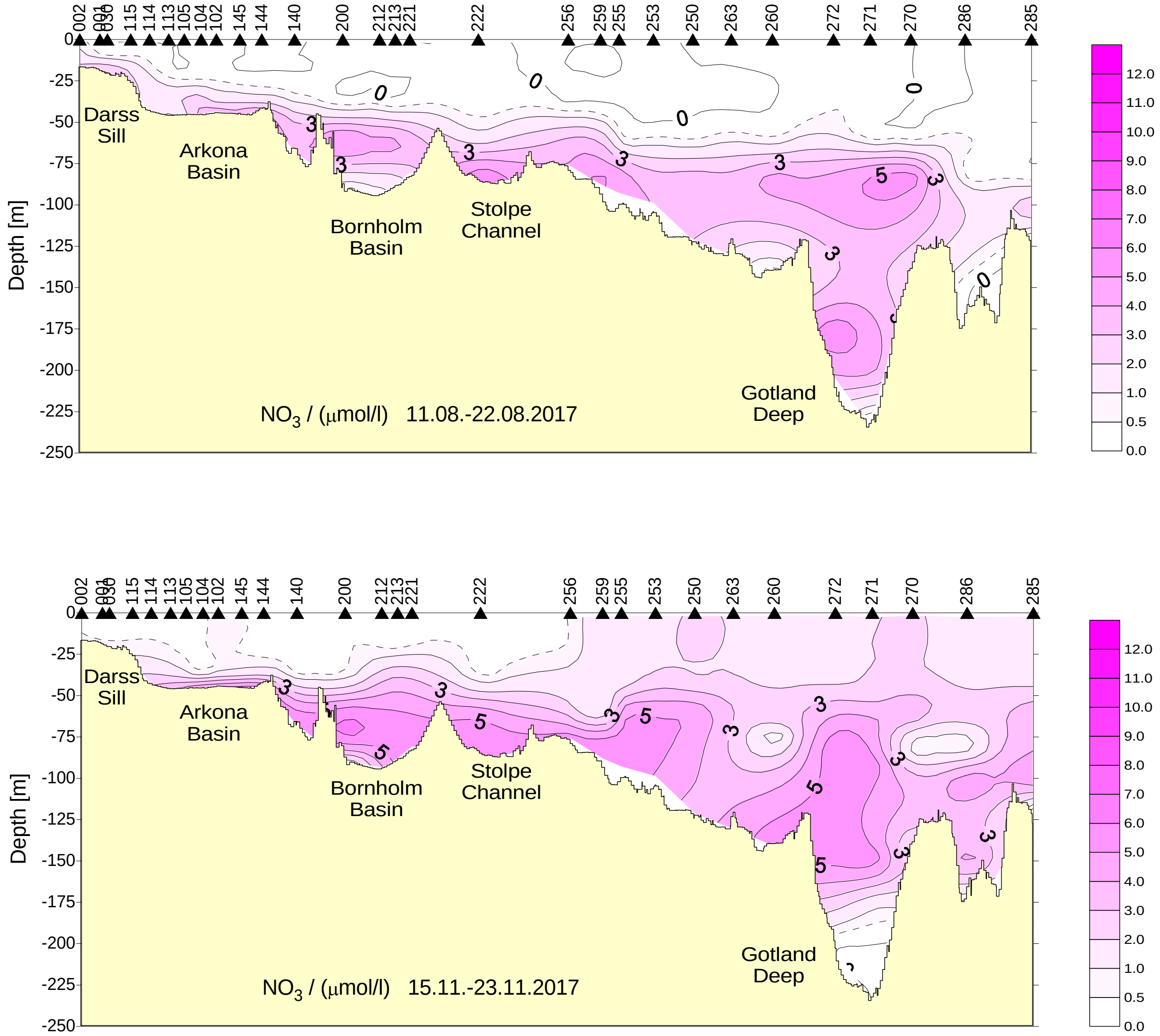


Fig. 34b: Vertical distribution of nitrate 2017 between the Darss Sill and the northern Gotland Basin (August to November).

In Figure 39a the depletion of nitrate in surface water from February until May is well shown. In the deep water of the Gotland deep the depletion (February to March and August to November) and the intermediate enrichment (March to May and further to August) of nitrate during the year is visible (Fig. 34). This was likely coupled to the oxygen concentration that in turn determined if remineralization stopped at the oxidation state of ammonium in the anoxic case or continued until nitrate in the oxic situation.

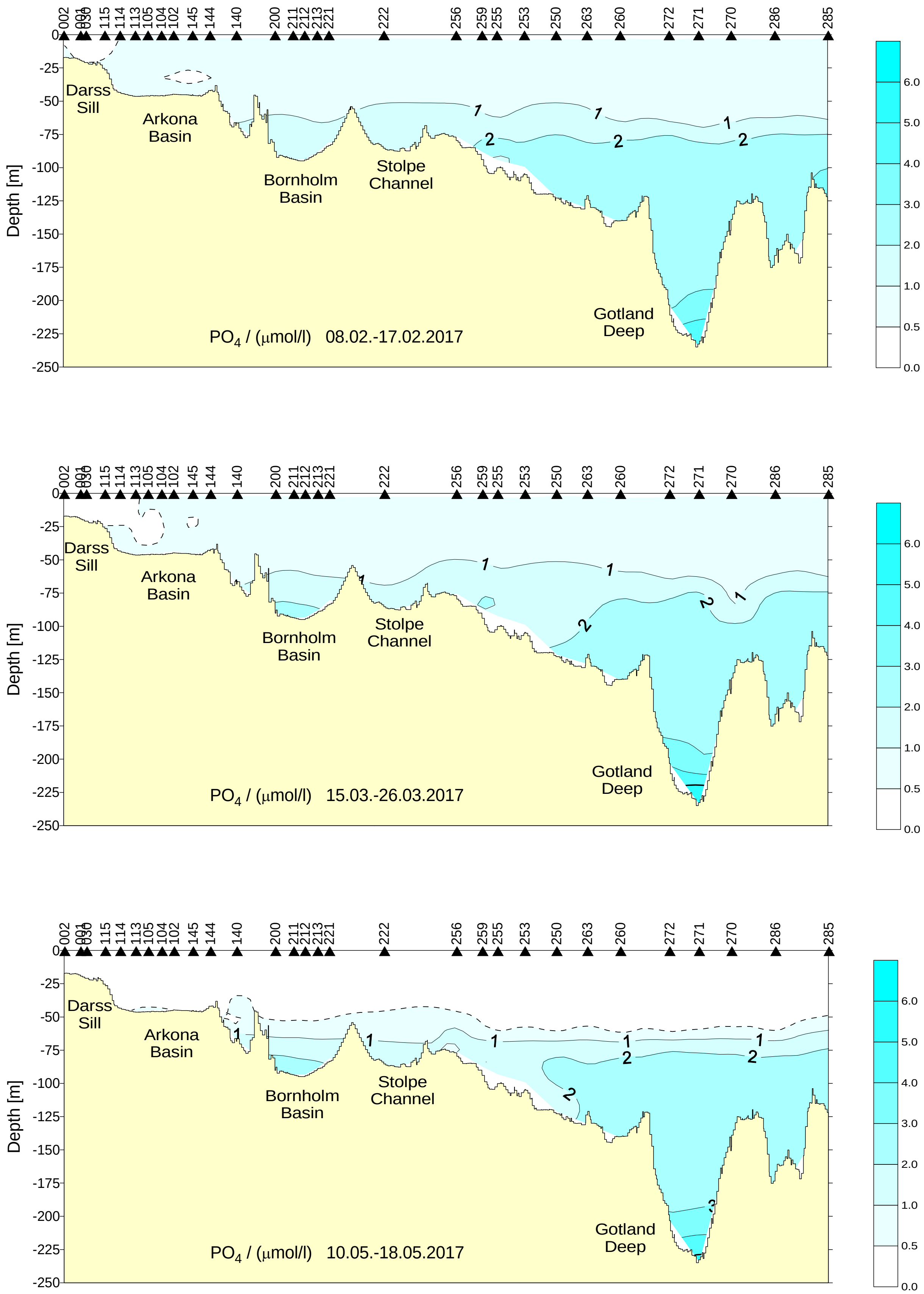
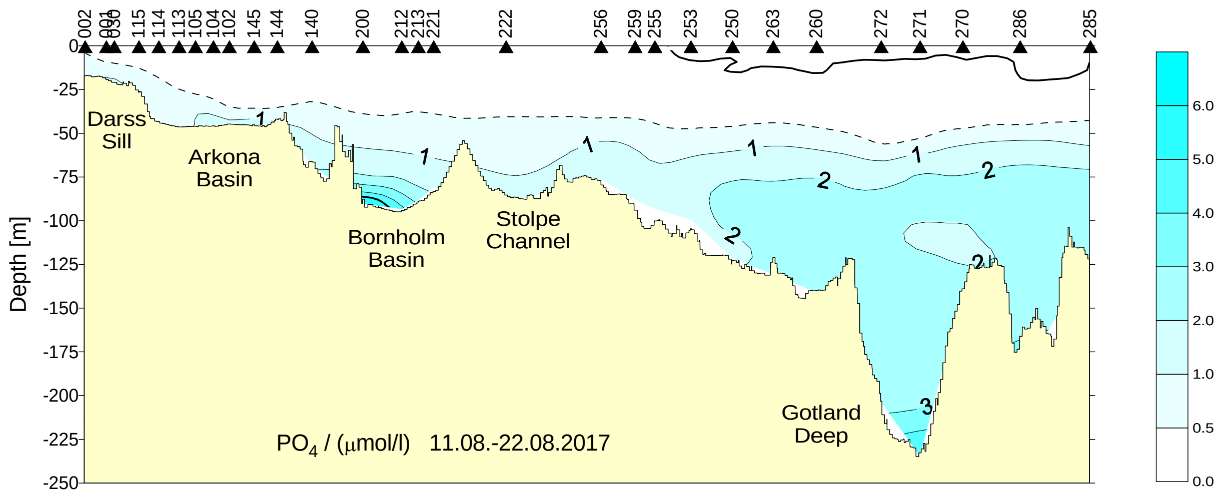


Fig. 35a: Vertical distribution of phosphate 2017 between the Darss Sill and the northern Gotland Basin (February to May).



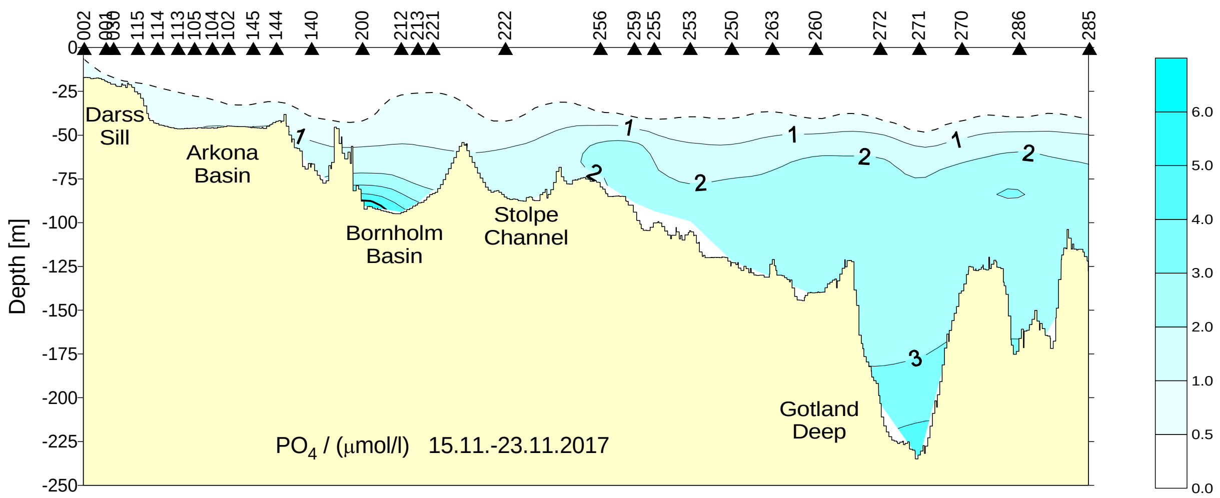


Fig. 35b: Vertical distribution of phosphate 2017 between the Darss Sill and the northern Gotland Basin (August to November).

Figures 34 and 35 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 2017.

In Fig. 35 the accumulation of phosphate in bottom waters of the Bornholm Sea and the Gotland Sea during the year 2017 is well displayed. This is caused by remineralization of the particulate organic material after the sedimentation of the spring bloom and subsequently of the summer bloom.

6.5 Dissolved organic carbon and nitrogen

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 placed in an Autosampler-Vial. Inorganic carbon was extracted by acidifying (pH 2) flushing the sample with carbon--free air. Thus, all inorganic carbon was converted and expelled as CO_2. Following, the sample volume was injected into a combustion tube filled with platinum-coated ammonium-oxide spheres functioning as a catalyst. At 680□ all NPOC (non-purgeable-organic-carbon) was burned to CO_2. By reducing the temperature of the gases to 1□oC 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 in consequence of oxidation with copper. Finally, CO_2 was measured. For the measurement the content of every sample vessel was separated in two Autosampler-vials. Both samples were analyzed independently whereby at least four to five valid injections of 75 µm/L of each vial were assessed and subsequently a mean DOC concentration calculated. The method is verified in the past in labor experiments and intercalibration exercises, with results being published in HEDGES AND LEE (1993), SHARP et al. (2002a, b; 2004) and NAGEL AND PRIMM (2003). For the procedere a refence material, the so called Consensus Reference Water (www.rsmas.edu/groups/biogeochem/CRM.html) is used.

The limit of quantification for DOC is set to DOC ‹ 25 µmol/L and the standard deviation of the procedure to DOC ‹ 3 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 as stated in the IOW accreditation reports. Regular, at least twice a year, quality control of the measurements is ensured by participation in the QUASIMEME calibration effort. This exercise is part of WEPAL (Wageningen Evaluating Programmes for Analytical Laboratories), which is accredited for the organization of Interlaboratory Studies by the Dutch Accreditation Council RvA since April 26, 2000 based on the ISO 17043 requirements (registration number R002).

The dissolved organic matter (DOM) in the Baltic Sea is an important participant within the carbon and nutrient cycles. In general, the DOM correlates with the salinity of the water. Higher dissolved organic carbon (DOC) values at low salinities reflect the input from terrestrial sources. The high saline and DOM less water originate from the North Sea.
A summary of all IOW long term data from 1995 – 2017 are shown in figures (36-40).
As consequence the DOC in surface water of the Baltic Sea has higher concentrations (200 – 500 µmoles C/dm^3) than the deep water (150 – 420 µmoles C/dm^3) at all stations. The concentration of dissolved organic nitrogen (DON) varies due to biogeochemical processes in the water column. The particulate carbon and nitrogen has 5-10 times lower levels than the dissolved forms (Fig. 39-40). Higher variability reflects the seasonality of the biological production and remineralisation processes.

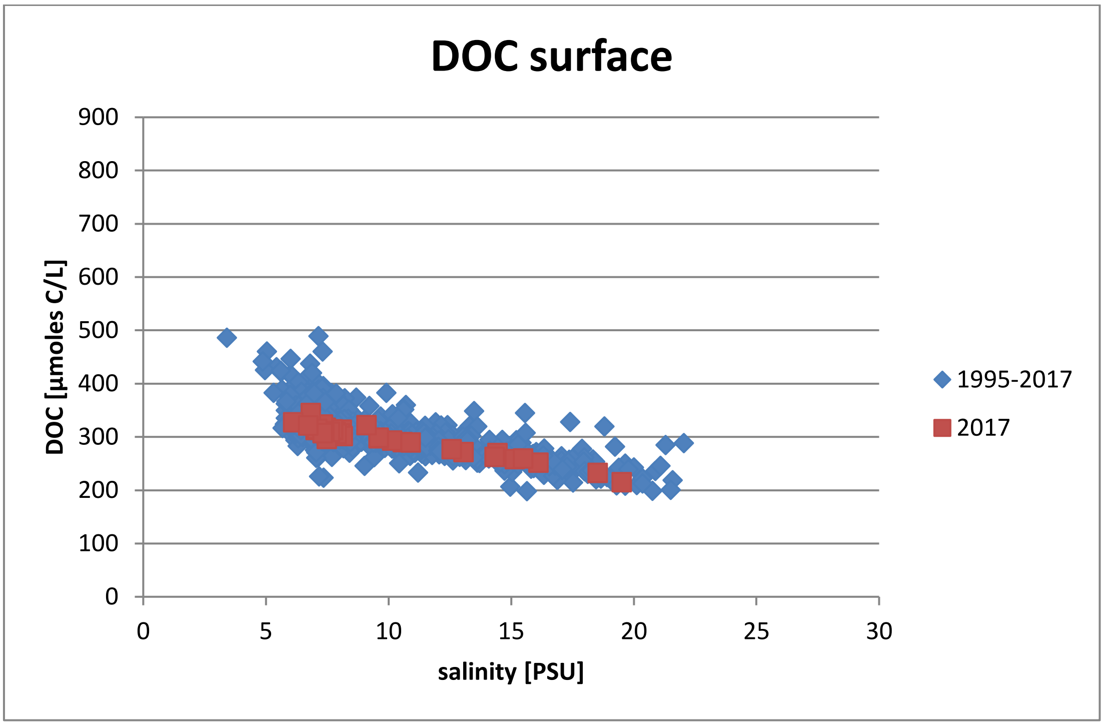


Fig. 36a: Dissolved organic carbon in the surface water from 1995-2017.

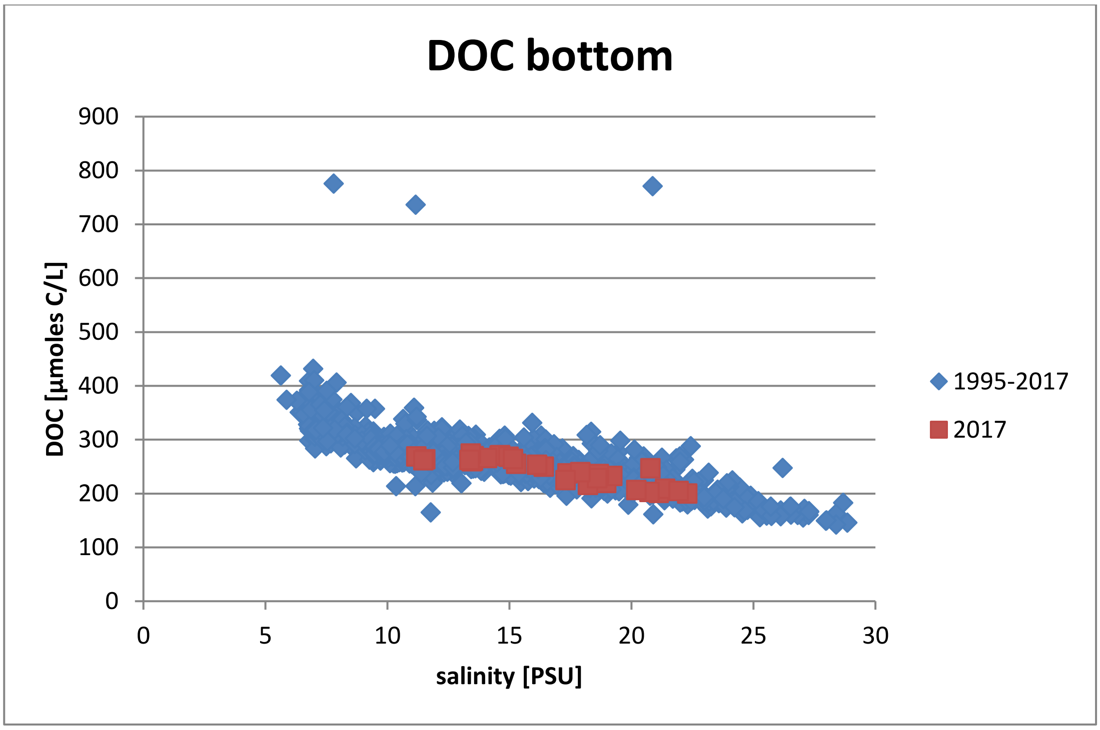


Fig. 36b: Dissolved organic carbon in the bottom water from 1995-2017.

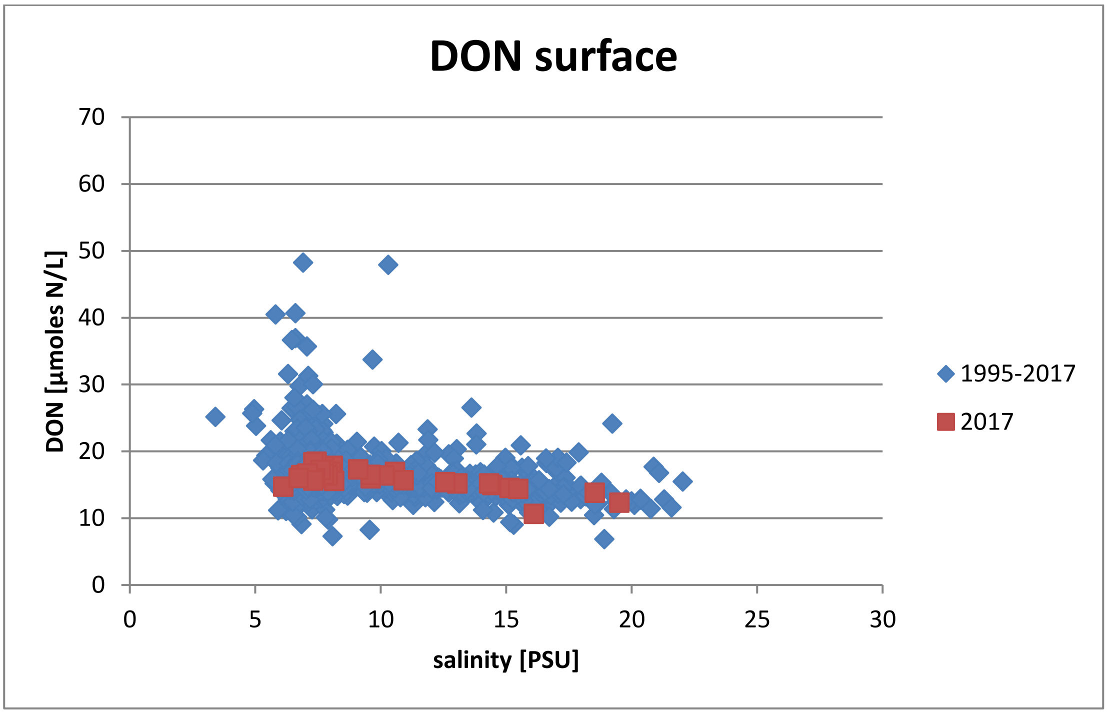


Fig. 37a: Dissolved organic nitrogen in the surface water from 1995-2017.

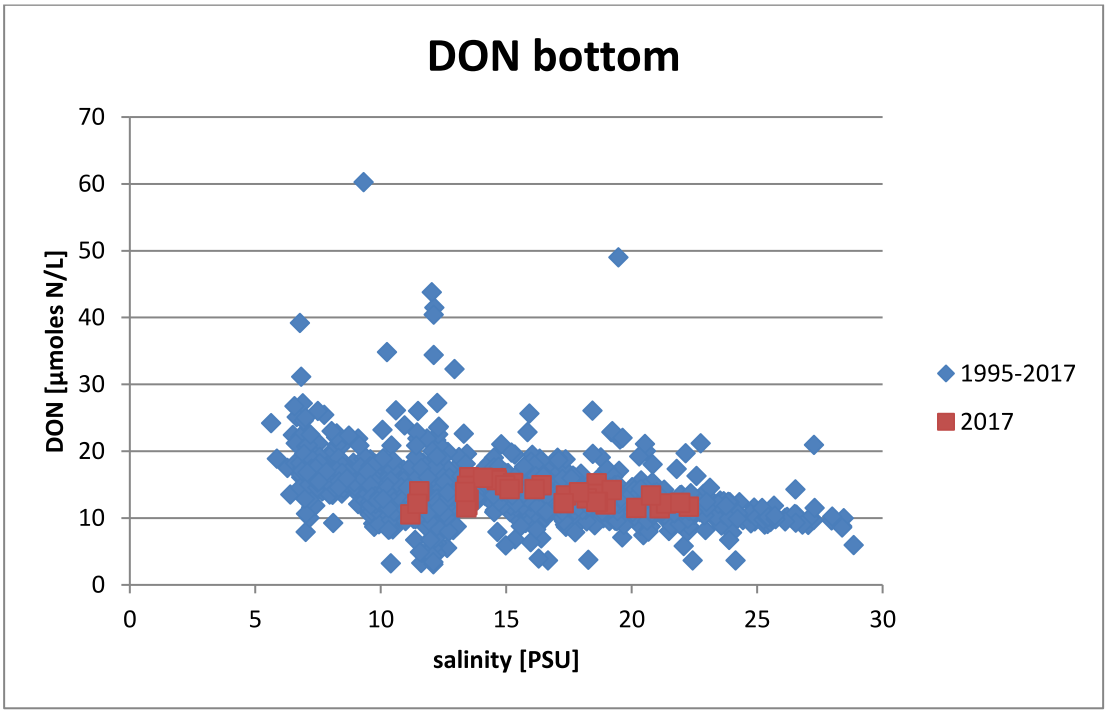


Fig. 37b: Dissolved organic nitrogen in the bottom water from 1995-2017.

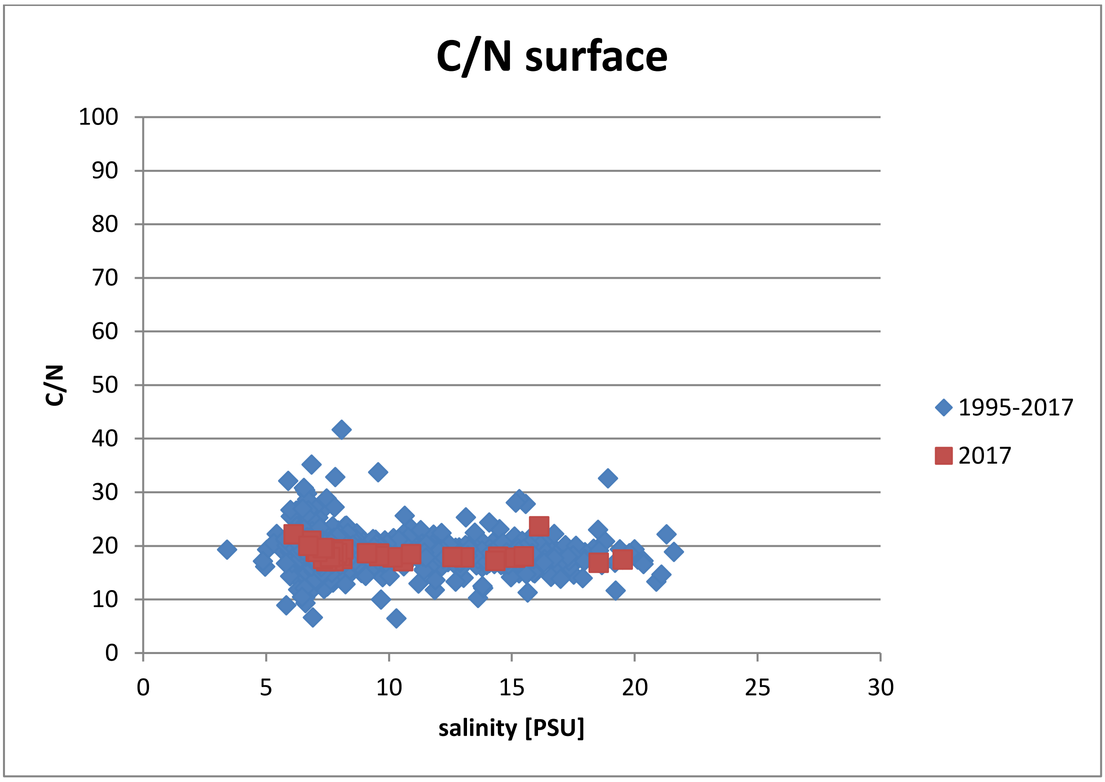


Fig. 38a: Relation of dissolved organic carbon and nitrogen in the surface water from 1995-2017.

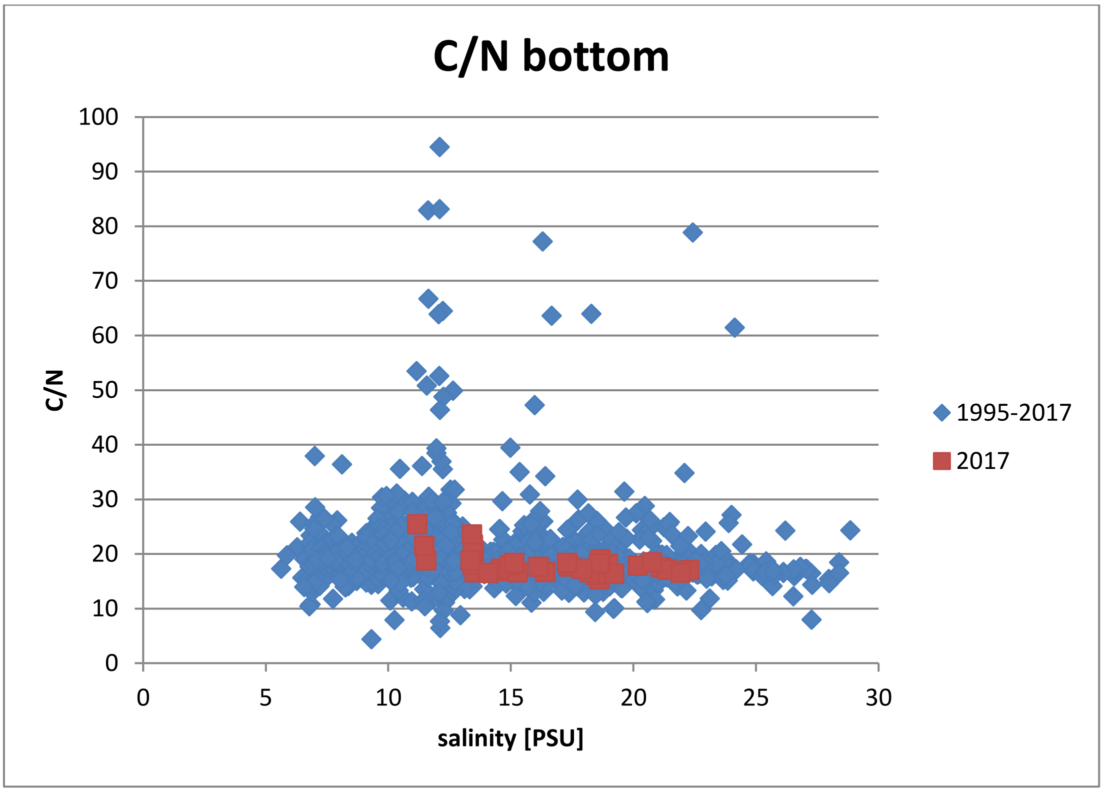


Fig. 38b: Relation of dissolved organic carbon and nitrogen in the bottom water from 1995-2017.

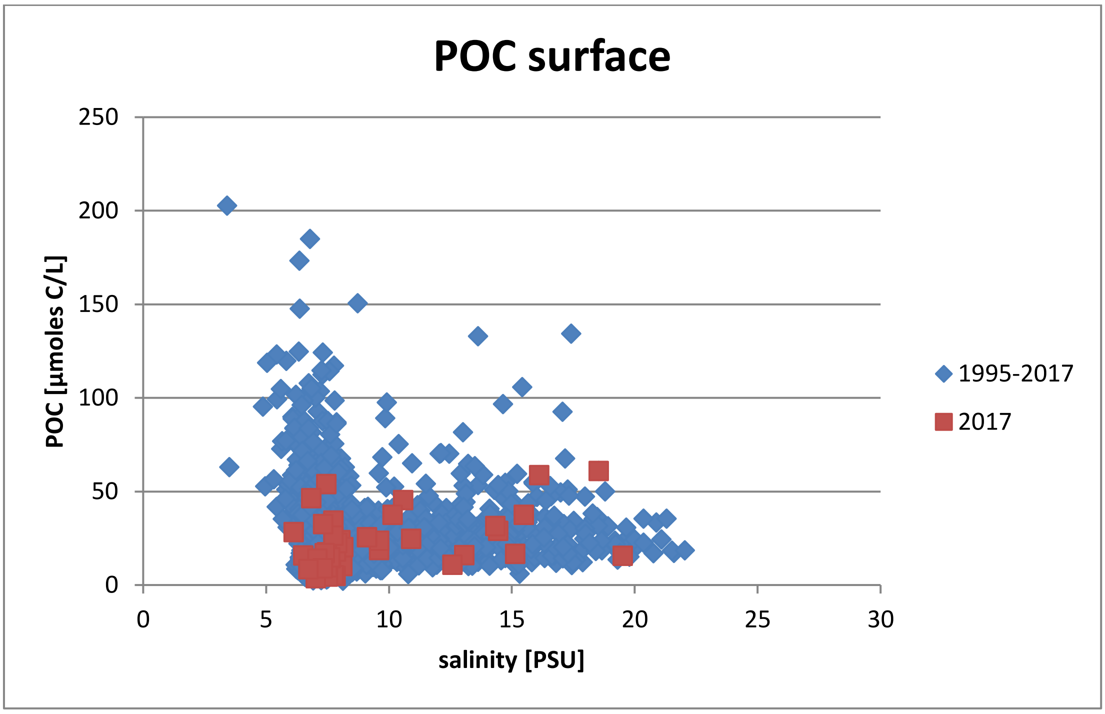


Fig. 39a: Particulate organic carbon in the surface water from 1995-2017.

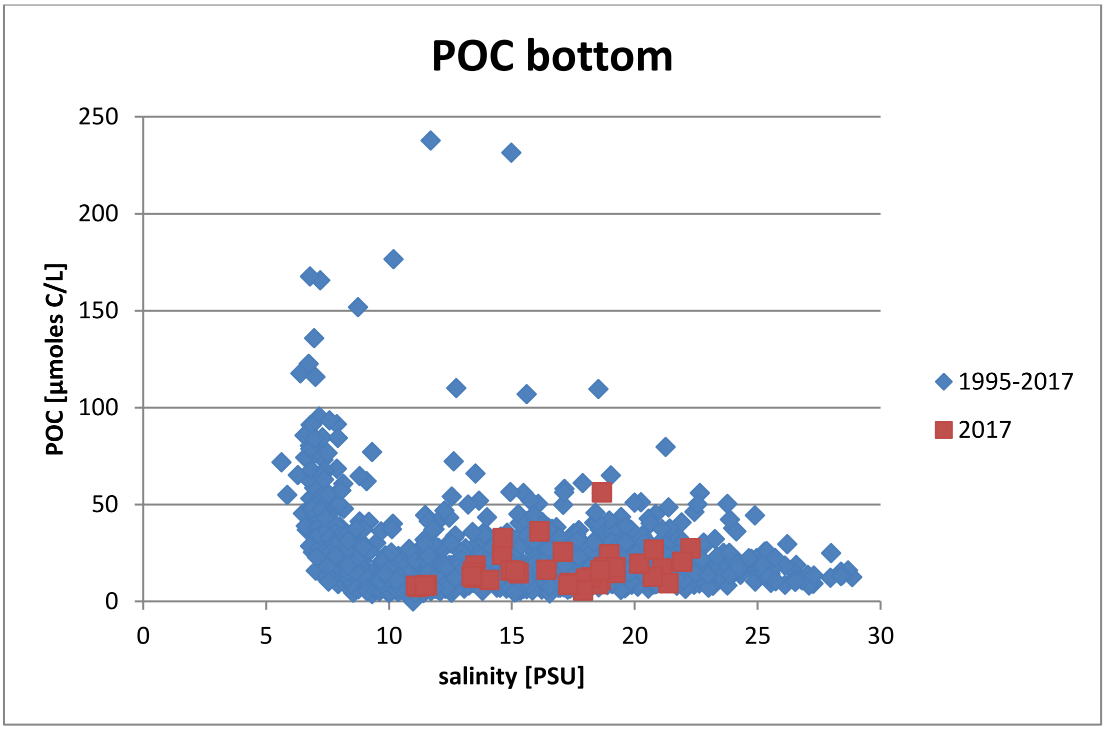


Fig. 39b: Particulate organic carbon in the bottom water from 1995-2017.

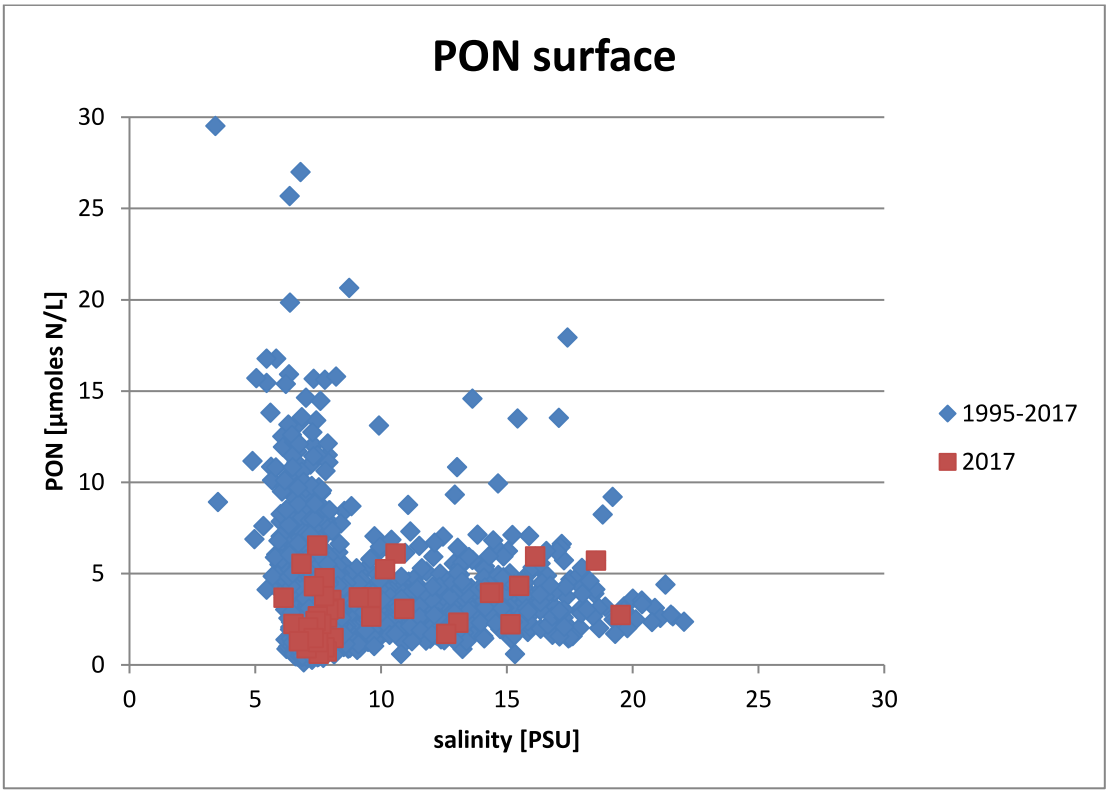


Fig. 40a: Particulate organic nitrogen in the surface water from 1995-2017.

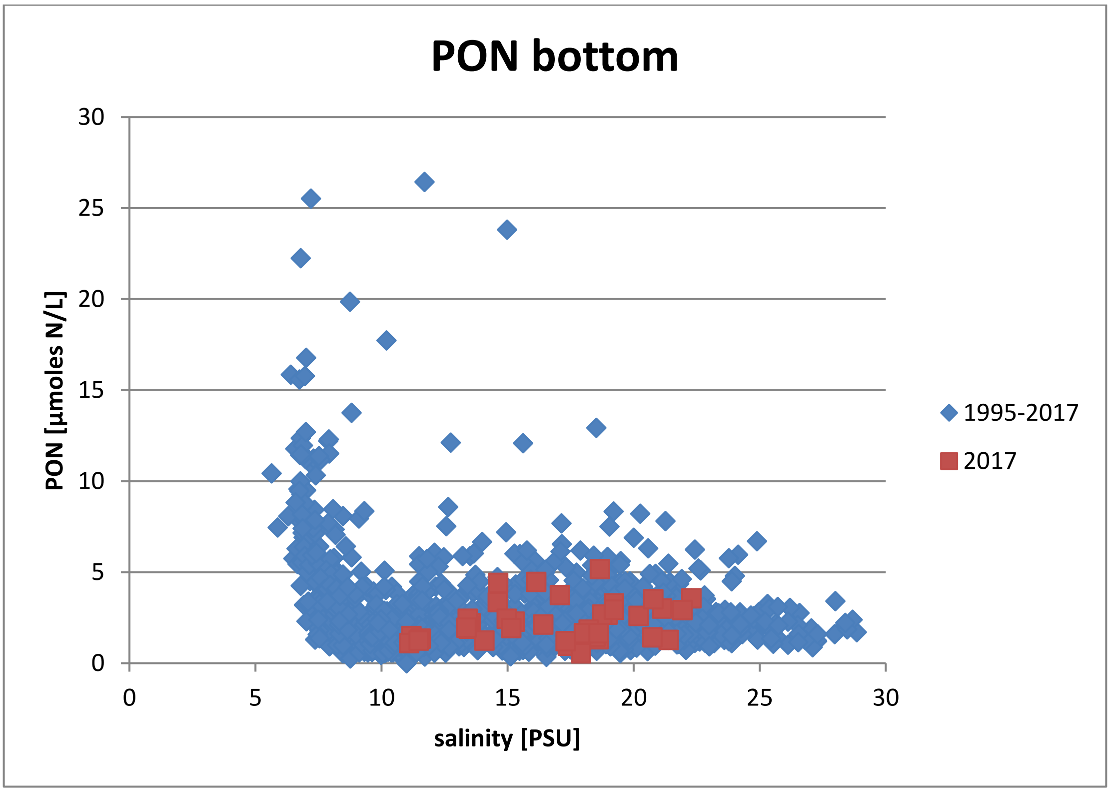


Fig. 40b: Particulate organic nitrogen in the bottom water from 1995-2017.

The relation of DOC/DON (C/N ratio) has in general mean values (16-20) near the redfield ratio in surface water and than bottom near water. The results from the year 2017 are in any parameter within the expected range.

The seasonal data of DOC, DON at the stations in the Arkona and Gotland Basin are shown in Fig. 41 and 42. Surface DOC, DON values at both stations are very similar around 300 mmol/L res. 15 mmol/L with no considerable seasonal changes.
The DOC/DON ration are similar too. Only the particulate (POC, PON) data shown higher values at station 271 in the Gotland basin in May and August due to the higher biological productivity in spring/summer 2017.

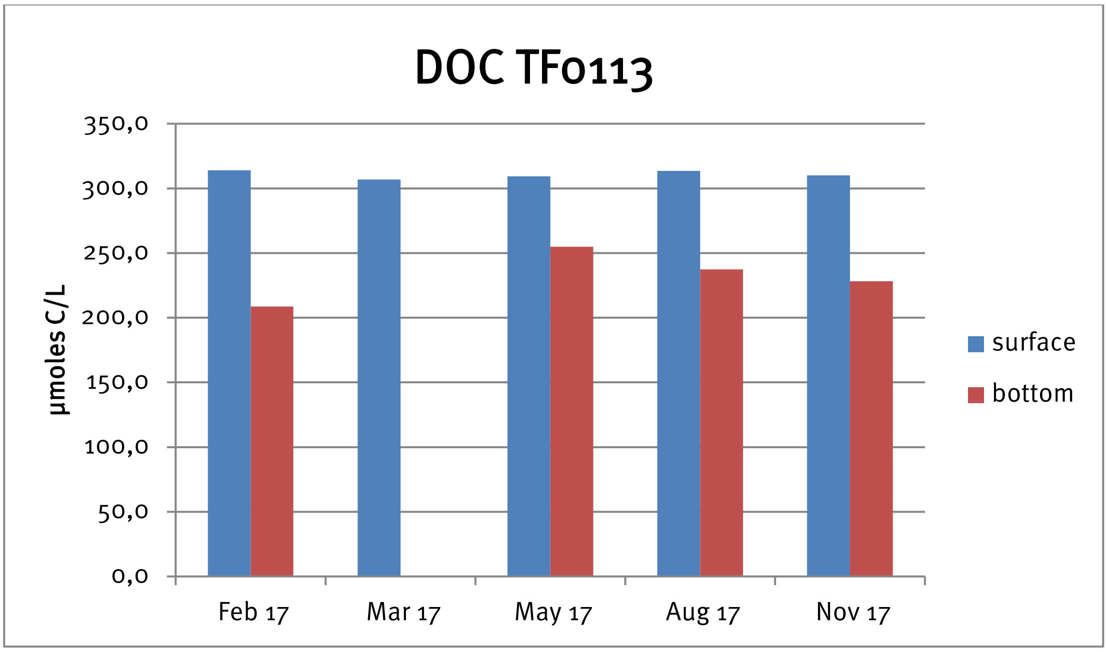


Fig. 41a: Surface (2m) and bottom (46 m) dissolved organic carbon (µmol/l) at Station TF0113 in the Arkona Basin.

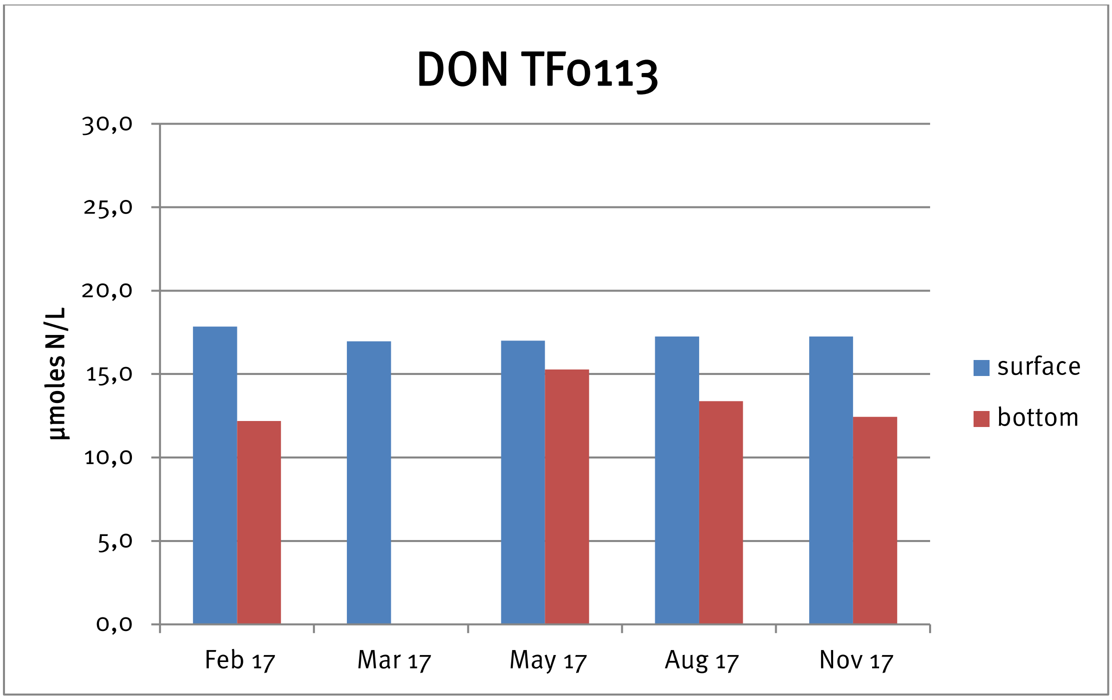


Fig. 41b: Surface (2m) and bottom (46 m) dissolved organic nitrogen (µmol/l) at Station TF0113 in the Arkona Basin.

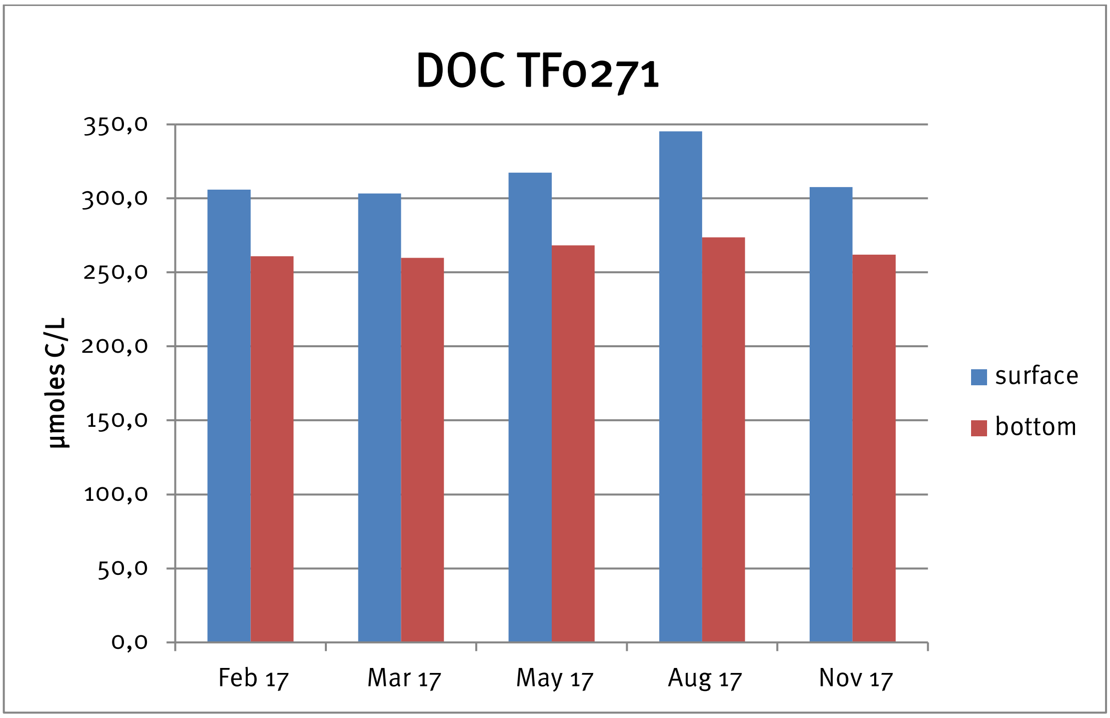


Fig. 42a: Surface (2m) and bottom (236 m) dissolved organic carbon (µmol/l) at Station TF0271 in the eastern Gotland Basin.

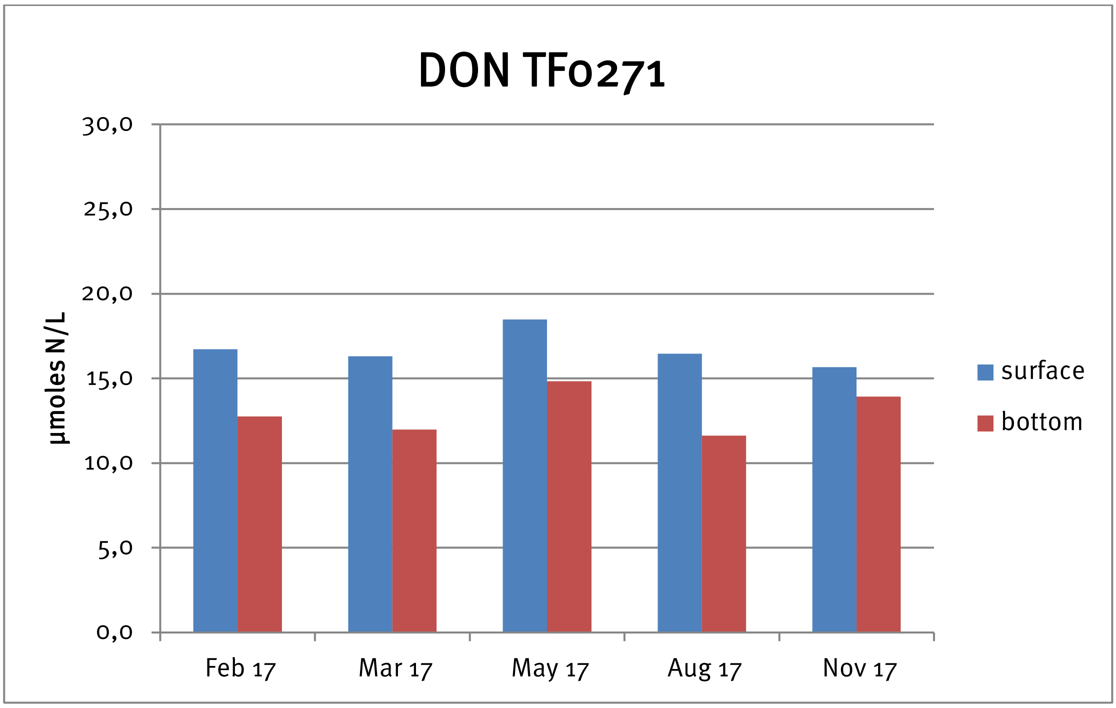


Fig. 42b: Surface (2m) and bottom (236 m) dissolved organic nitrogen (µmol/l) at Station TF0271 in the eastern Gotland Basin.

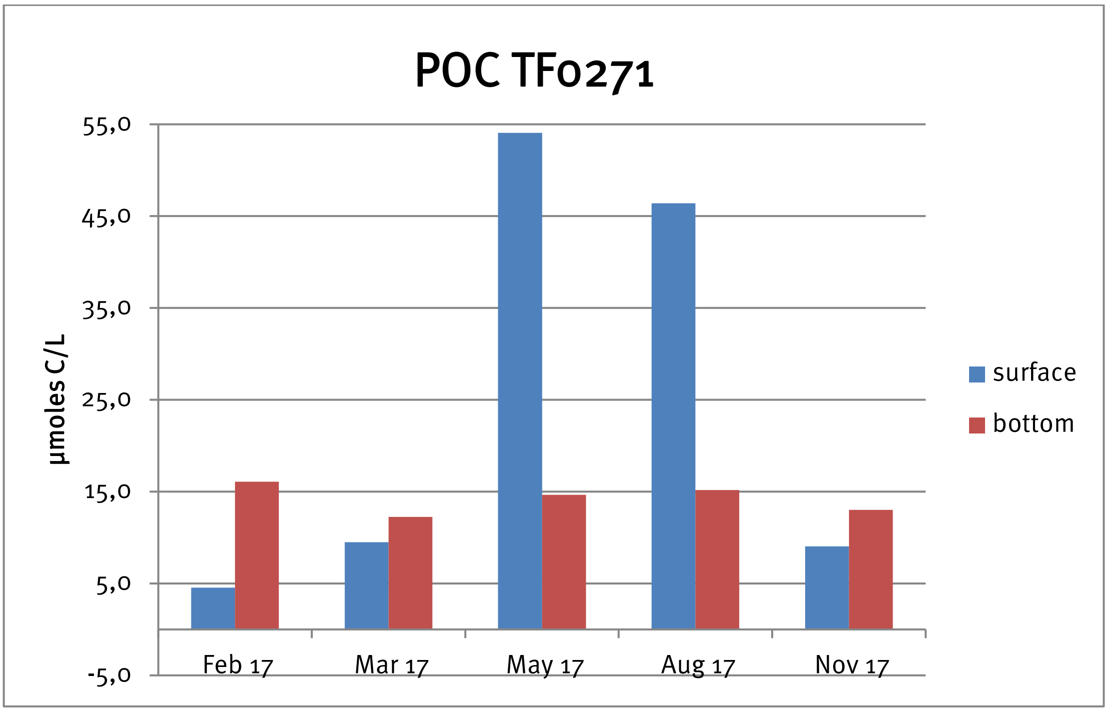


Fig. 42c: Surface (2m) and bottom (236 m) particulate organic carbon (µmol/l) at Station TF0271 in the eastern Gotland Basin.

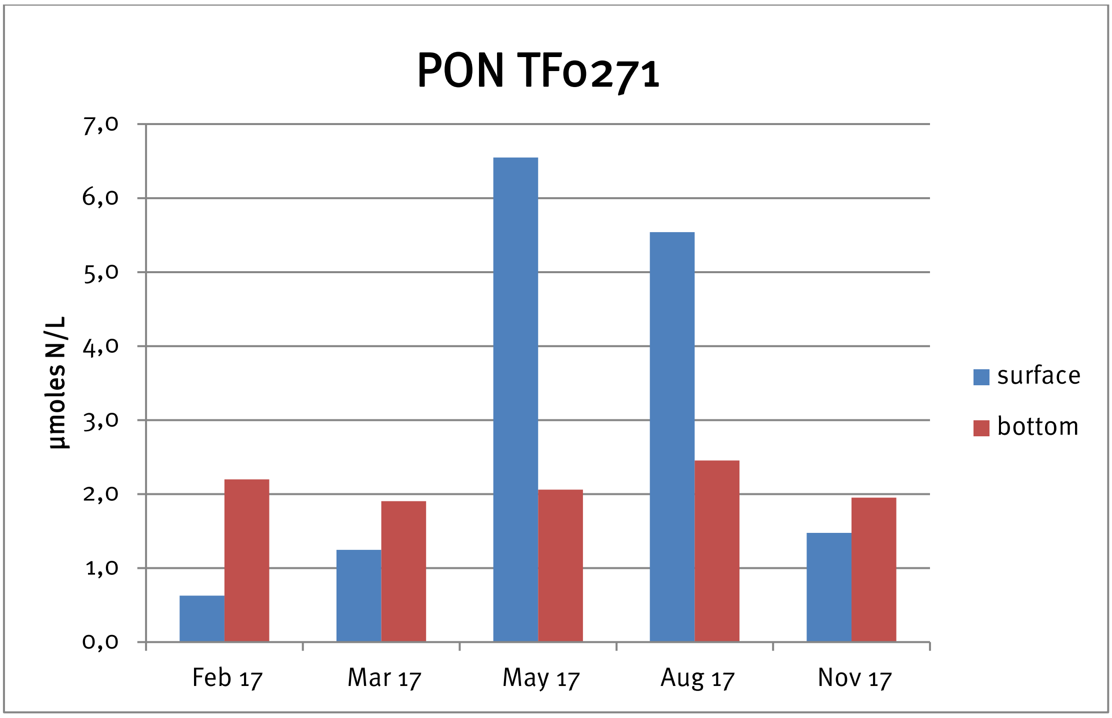


Fig. 42d: Surface (2m) and bottom (236 m) particulate organic nitrogen (µmol/l) at Station TF0271 in the eastern Gotland Basin.

Summary

For the southern Baltic Sea area, the cold sum of 31.7 Kd at Warnemünde station amounted to a mild winter in 2016/17. This value plots far below the long-term average of 101.8 Kd in comparative data from 1948 onwards and ranks as 15th warmest winter in this time series. Only three cold period occurred in mid-November, beginning of January and beginning of February which led to this cold sum. Only November 2016 and January 2017 showed monthly average temperatures below the long-term average, all other winter months were too warm.
With a warm sum of 159.5 Kd, recorded at Warnemünde, the summer 2017 is ranked in the midrange over the past 70 years on 28th position and around the long-term average of 153.4 Kd. The summer 2017 can be classified as moderate.

With respect to sea surface temperature, the year 2017 was the eleventh-warmest year since 1990 and with 0.24 K slightly above the long-term SST average. March, April and October - December contributed to the average by their positive anomalies. July and August were characterized by negative anomalies. The anomalies reached maximum values of +2 K and -3 K. The winter of 2016/2017 was comparatively warm, as shown in the cold sum of air temperature of Warnemünde but also in the SST. The resulting temperature trend was 0.6 K per decade.

Two inflow events with estimated volumes between 188 km³ and 210 km³ occurred in the Baltic Sea in 2017. On February 13th, the gauge at Landsort Norra recorded a lowstand of -46 cm MSL as a result of preceding long lasting easterly winds. A system shift to strong westerly winds caused a sea level rise to 15.6 cm (March 3rd) and a resulting total volume of 210 km³ was calculated. For this event a salt transport of 1.3 Gt and highly saline volume transport of 68 km³ was calculated with data of the MARNET stations Darss Sill and Arkona Basin by MOHRHOLZ (submitted). The bottom salinity at the Darss Sill only for a short time exceeded 17 g/kg and the stratification was too high to classify this event as a Major Baltic Inflow described in NAUMANN et al. (submitted). A second inflow phase of week classification occurred from October 2nd to 9th, the sea level rose rapidly from -25.4 cm MSL to 26.4 cm MSl comprising a total volume of 188 km³.

The annual cycle of oxygen saturation in the surface water was again typical in 2017. 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 2017 was coined by oxygen deficiency showing an annual mean of 0.88 ml/l bottom-near at 80 m water depth. At the bottom of the eastern Gotland Basin a decreasing trend of dissolved oxygen concentration continued after the oxygenation events from mid 2014 to mid 2016 caused by several Major Baltic Inflows and smaller intrusions. In 2017 an annual mean of 0.07 ml/l was measured at the bottom of Gotland Deep and hydrogen sulphide was present permanently. Since the beginning of the intensive inflow activity in 2014 farther north areas and the western Gotland Basin showed their lowest hydrogen sulphide concentrations during 2017, indicating the time delayed impact of these events. The Farö Deep showed a complete removal of hydrogen sulphide and a bottom-near mean oxygen concentration of 0.33 ml/l in 2017. The latest weak inflows of

wintertime 2016/2017 passed the 120 m sill depth between eastern Gotland Basin and Farö Deep and transported oxygenized water bodies to this northern/central part of the Baltic Sea.

Nutrient conditions in the deep basins reflect the the occurrence or absence of strong barotropic and/or baroclinic inflows. The very strong Major Baltic Inflow of December 2014 and subsequent intrusions still influenced the nutrient situation in the deep water of the Northern and western Gotland Basin in 2017. For example, the annual mean of nitrate increased from 1.4 µmol/l to 5.5 µmol/l and ammonium reduced nearly completely (0.1 µmol/l) at the bottom of the Farö Deep. In the eastern Gotland Basin the stagnation period has started in 2016. Correspondingly, phosphate and ammonium concentrations were increasing to 2.91 µmol/l (PO_4) and 0.8 µmol/l (NH_4) as annual mean in 2017 at the bottom of the Gotland Deep. Whereas the spatial and temporal dynamic of the nitrate concentration indicates that oxygen was partly slightly above zero and afterwards again zero or even below zero, with a spatial and temporal variability as well. The annual mean reduced from 9.3 µmol/l in 2016 to 1.8 µmol/l in 2017. In the southern located Bornholm Basin, the situation changed only slightly compared to 2016. Annual means of 2017 of bottom near water at the Bornholm Deep showed a slight increase of phosphate (2.23 µmol/l to 2.51 µmol/l), a slight decrease a nitrate (10.4 µmol/l to 7.5 µmol/l) and constant ammonium concentration of 0.2 µmol/l in both years.

Acknowledgements

The authors would like to thank the staff from the Leibniz Institute for Baltic Sea Research Warnemünde who carried out measurements as part of the HELCOM's Baltic Sea monitoring programme and the IOW's long-term measuring programme, and the captain and crew of the research vessel *Elisabeth Mann Borgese* for their effort and support during monitoring cruises in 2017. The authors are also grateful to a number of other people and organisations for help: Sandra Schwegmann and Jürgen Holfort of the Sea Ice Service at the Federal Maritime and Hydrographic Agency, Hamburg and Rostock for advice in the description of the ice winter, and especially for supplying the ice cover chart; the Deutscher Wetterdienst for supplying wind data from Arkona from its online data portal; Gisela Tschersich from BSH for providing NOAA weather satellite data; the Swedish Meteorological and Hydrological Institute, Norrköpping, for providing gauge data from its online data portal; Lotta Fyrberg from SMHI's Oceanographic Laboratory in Gothenburg for providing us with hydrographic and hydrochemical observations from Sweden's Ocean Archive (SHARK) relating to selected stations within the Swedish national monitoring programme; Włodzimierz Krzymiński at the Maritime Office of the Polish Institute of Meteorology and Water Management (IMGW) in Gdynia provided observational data from the Danzig Deep; Katarzyna Jabłońska, IMGW in Warsaw, provided data on solar radiation at Gdynia.

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 (2017): WitterungsReport Express, Nr. 1 – 13. Deutscher Wetterdienst.

DWD (2018): Windmessungen der Station Arkona in Stundenmittelwerten des Jahres 2017 – 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 (2017): 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

HELCOM (2017): First version of the 'State of the Baltic Sea' report – June 2017, Baltic Marine Environment Protection Commission – HELCOM, Helsinki, Finland. http://stateofthebalticsea.helcom.fi

HELCOM (2018): Sources and pathways of nutrients to the Baltic Sea - HELCOM PLC-6, Helsinki, Finland. www.helcom.fi/Lists/Publications/BSEP143.pdf

IMGW (2018): Solar radiation in J/m^2 at the station Gdynia 2017 – unpublished data

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.

LLUR (2017): Sauerstoffmangel im bodennahen Wasser der westlichen Ostsee 2017.

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

MOHRHOLZ, V. (submitted): Major Baltic Inflow statistics – reviewed. – Frontiers in Marine Science

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., NAUSCH, G., WANIEK, J.J., GRÄWE, U., MOHRHOLZ, V., PRIEN, R.D., SCHULZ-VOGT, H., UMLAUF, L., SCHMIDT, M., WASMUND, N., KUSS, J., KRÜGER, S., FEISTEL, S., SCHULZ-BULL, D.E. (submitted): The intense inflow activity 2013-2017 – a succession of four major events and their impact on the Baltic Sea ecosystem. – Frontiers in Marine Science

NAUMANN, M., UMLAUF, L., MOHRHOLZ, V., KUSS, J., SIEGEL, H., WANIEK, J.J., SCHULZ-BULL, D.E. (2017): Hydrographic-hydrochemical asessment of the Baltic Sea 2016. – Marine Science Reports, **104**: 90 pages.

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., NEHRING, D. and NAGEL, K. (2008): Nutrient concentrations, trends and their relation to eutrophication. In: FEISTEL, R., NAUSCH, G., WASMUND, N. (Eds.): State and evolution of the Baltic Sea, 1952-2005. – John Wiley & Sons, Inc. Hoboken, New Jersey, 337-366.

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. 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., 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

SCHWEGMANN, S. and HOLFORT, J. (2017): Der Eiswinter 2016/17 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/Eiswinter2016-2017.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 (2017). Sea surface temperature in the Baltic Sea in 2016. HELCOM Baltic Sea Environ. Fact Sheets. HELCOM Baltic Marine Environment Protection Commission - Helsinki Commission, –open access–

SIEGEL, H. and M. GERTH (2018). Sea surface temperature in the Baltic Sea in 2017. HELCOM Baltic Sea Environ. Fact Sheets. HELCOM Baltic Marine Environment Protection Commission - Helsinki Commission, –open access–

SMHI (2018a): Tide gauge data at station Landort Norra in hourly means of the year 2017; geodesic reference level RH2000. http://opendata-download-ocobs.smhi.se/explore/

SMHI (2018b): Accumulated inflow through the Öresund 2014-2017. http://www.smhi.se/hfa_coord/BOOS/Oresund.html

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.,
Mohrholz, V., Kuss, J., Siegel, H.,
Waniek, J.J., Schulz-Bull, D.E.

Hydrographic-hydrochemical assessment of the Baltic Sea 2017

CONTENT

Leibniz-Institut für Ostseeforschung Warnemünde